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BANGLADESH
ENHANCING COASTAL RESILIENCE IN A CHANGING CLIMATE

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GFDRR
Global Facility for Disaster Reduction and Recovery

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ACROYNMS AND ABBREVIATIONS

ADM	Adaptive Delta Management
ALARP	As low as reasonably practicable
BCCSAP	Bangladesh Climate Change Strategy and Action Plan
BDP 2100	Bangladesh Delta Plan 2100
BWDB	Bangladesh Water Development Board
CDSP	Char Development and Resettlement Project
CEIP-I	Coastal Embankment Improvement Project Phase I
CEP	Coastal Embankment Project
CZP	Coastal Zone Policy
DEM	Digital Elevation Model
DRR	Disaster Risk Reduction
ECRRP	Emergency 2007 Cyclone Recovery and Restoration Project
EWS	Early Warning Systems
EEWS	Erosion Early Warning Systems
EU	European Union
FCDI	Flood Control, Drainage and Irrigation
FEMA	Federal Emergency Management Agency
FLI	Field Level Institution
GBM	Ganges-Padma, Brahmaputra-Jamuna, Meghna
GDP	Gross Domestic Product
GFDRR	Global Facility for Disaster Reduction and Recovery
GHG	Greenhouse Gas
GoB	Government of Bangladesh
GPS	Global Positioning System
InSAR	Interferometric Synthetic Aperture Radar
IWM	Institute of Water Modelling
JICA	Japan International Cooperation Agency
LGED	Local Government Engineering Department
LRFD	Load and Resistance Factor Design
LSAC	Levee Safety Action Classification
MDSP	Multipurpose Disaster Shelter Project
MERIT	Multi-Error-Removed Improved-Terrain
MSL	Mean Sea Level
NAP	National Adaptation Plan
NAPA	National Adaptation Programme of Action
NDC	Nationally Determined Contribution
NGO	Nongovernmental Organization
NPDM	National Plan for Disaster Management
O&M	Operation and Maintenance
ODI	Overseas Development Institute
PPT	Parts Per Thousand
PWD	Public Works Datum
RCP	Representative Concentration Pathway
RSLR	Relative Sea Level Rise
SDG	Sustainable Development Goal
SEZ	Special Economic Zone
SLR	Sea level rise
SLS	Serviceability Limit States
SOD	Standing Orders on Disaster
SSP	Shared Socioeconomic Pathways
TA	Technical Assistance
TRM	Tidal River Management
ULS	Ultimate Limit States
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations International Children's Emergency Fund
UP	Union Parishad (Union Council)
USACE	U.S. Army Corps of Engineers
WMA	Water Management Association
WMG	Water Management Group
WMO	Water Management Organization
WMU	Water Management Unit

GLOSSARY

Adaptation: The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Bathymetric map: A map that depicts the submerged topography and physiographic features of ocean and sea bottoms.

Bullah: Pilings to build long-lasting stable foundations for structures on land and in water.

Capital costs: These include all costs incurred up to the completion of a project, including the cost of construction—the costs of material, person hours, land acquisition, oversight, planning, and design.

Char: A sandbar that emerges as an island within a river channel.

Climate: In a narrow sense, usually defined as the average weather of a particular location over a period of time. The World Meteorological Organization's more rigorous definition is "the measurement of the mean and variability of relevant quantities of certain variables (such as temperature, precipitation, or wind) over a period of time ranging from months to thousands or millions of years."[1] The usual period for averaging these variables is 30 years. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change: It refers to a change in the state of the climate that can be identified (for example, by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forces, such as modulations of the solar cycles or volcanic eruptions, or persistent anthropogenic changes in the composition of the atmosphere or in land use. The United Nations Framework Convention on Climate Change, in its Article 1, defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods," thus making a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

Climate risk: The potential for consequences from climate variability and change, where something of value is at stake and the outcome is uncertain. It is often represented as the probability that a hazardous event or trend will occur multiplied by the expected impact. Risk results from the interaction of vulnerability, exposure, and hazard.

Climate scenario: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information, such as about the observed current climate.

Coastal erosion: The erosion of coastal landforms resulting from wave action or currents, exacerbated by storm surge and sea level rise.

Coastal morphodynamics: The mutual interaction of coastal morphology with hydrodynamic agents—tides, currents, and waves.

Coastal resilience: Defined in this document as the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by both human and environmental factors, while adapting the essential functions of the systems to an improved state.

Crest: The top part of an embankment. Its elevation in comparison to the water level is often a measure of safety.

Earthworks: Operations connected with embankments of earth.

Embankment: An artificial, mostly soil-based structure that is able to retain water under extreme circumstances. In literature, the terms levee or dike are also used.

Extreme weather event: An event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be below the 10th or above the 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (for example, drought or heavy rainfall over a season).

Geobag: A sand-filled high-strength geotextile bag.

Geotube: A geo-container that is hydraulically filled with a slurry mix of sand and water.

Groyne: A rigid hydraulic structure built from an ocean shore or from a riverbank that interrupts water flow and limits the movement of sediment.

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, or environmental resources.

Hydraulic boundary conditions: A set of values for the water level and the wave height that represent the conditions during a storm, often associated with a given return period.

Khal: A small canal.

Longshore transport: The cumulative movement of beach and nearshore sand parallel to the shore by the combined action of tides, wind, and waves.

Maintenance costs: The costs for the upkeep of a structure, including regular monitoring, maintenance, repair, operation, and testing.

Mangrove: A species of tree that grows in intertidal areas in tropical and subtropical regions. They attenuate waves and currents, and favor sediment accumulation, which provides coastal protection in landward locations.

Mangrove afforestation: Establishment of a mangrove forest in an area where there was no previous mangrove cover.

Mangrove restoration: Return of a mangrove forest from a deteriorated condition to its previous state, before a devastating natural or human-induced disturbance.

Mitigation (of climate change): A human intervention to reduce the sources or enhance the sinks of greenhouse gases.

Polder: The Dutch term "polder" is used to designate areas that are enclosed on all sides by dikes or embankments, separating them hydrologically from the natural water system and offering protection against tidal floods, salinity intrusion, and sedimentation. Polders are equipped with inlets and outlets to control the water inside the embanked area. This is an enclosed low-lying area forming an artificial hydrological entity.

Resectioning of an embankment: This is done to increase the height and widen the slopes of an existing embankment. It allows for a relatively small change in alignment to cope with obstacles and/or to align and smooth transitions with new embankments.

Resettlement: Replacement of the asset base and rebuilding of the livelihoods of affected persons losing their land, source of income, or livelihoods because of an infrastructure development project, in the same or a new location.

Resilience: The capacity of social, economic, and environmental systems to cope with a hazardous event, trend, or disturbance by responding or reorganizing in ways that maintain their essential function, identity, and structure while maintaining the capacity for adaptation, learning, and transformation.

Retired embankment: A new embankment with an adequate setback from the riverbank, where bank erosion is threatening the existing embankment. This is an embankment that is shifted inland to increase the distance between the embankment and the eroding bank line and as such, creates a buffer zone against future erosion.

Return period: The average period of time between two events. Often used as a measure for the intensity of a natural event (for example, a 10-year storm, occurring on average once every 10 years).

Scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (for example, rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts but are useful to provide a view of the implications of developments and actions.

Sea level rise: The increase in the height of the sea with respect to a specific point on land.

Storm surge: The increase in the outside water level as a result of storm winds or a tropical cyclone.

Tetrapods: A tetrahedral-shaped concrete unit to dissipate wave energy and prevent erosion and failure of an embankment or sea dike.

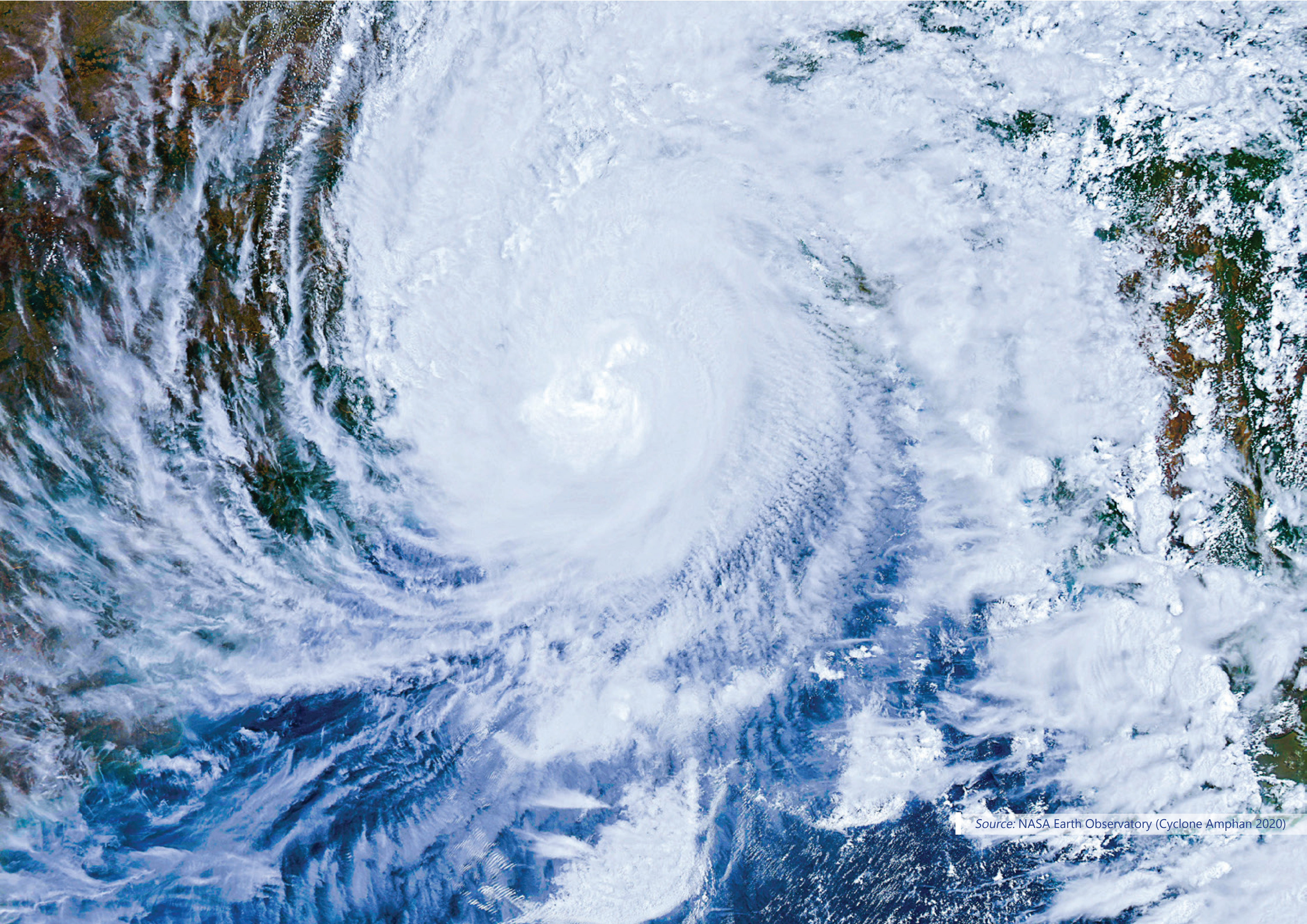
Union: The smallest rural administrative and local government unit in Bangladesh. Each union is made up of nine wards, comparable to a village. A union parishad administers a union, formed under the Local Government (Union Parishads) Act 2009.

Upazila: An administrative region of Bangladesh that functions as a subunit of a district, or a subdistrict. Rural upazilas are further administratively divided into union council areas.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Notes

1. “FAQs Climate,” World Meteorological Organization (website), accessed November 20, 2021, https://public.wmo.int/en/about-us/frequently-asked-questions/climate.



Source: NASA Earth Observatory (Cyclone Amphan 2020)

S M Mehedi Hasan

FOREWORD

As the World Bank and Government of Bangladesh celebrate 50 years of development cooperation this year, a key highlight is the journey towards addressing climate change and improving the resilience of the coastal zone. From the outset, the World Bank has been a long-standing partner in the Government's efforts to reduce the risks from disasters and enhance coastal resilience, resulting in a number of noteworthy achievements. Bangladesh demonstrated how investments in the entire chain of disaster risk reduction saves lives, reduces economic losses, and protects development gains. Proactive policies and sound investments in strengthening resilience across multiple fronts over the last five decades have resulted in a drastic decline in the number of casualties from cyclones. Bangladesh's approach has been an integrated one, from grassroots strengthening of community-level adaptation and community-based early warning systems, to investing in key protective infrastructure and promoting innovations, all founded on a strategic policy framework. With the success of these initiatives, Bangladesh has emerged as a global leader in climate resilience.

Although there has been significant progress, with the coastal population and economy expected to grow, and the intensity and magnitude of extreme events projected to increase due to climate change, hazard impacts still pose a great threat to the development ambitions of the country. Thus, further actions are needed to improve the resilience of the coastal zone. The *Bangladesh: Enhancing Coastal Resilience in a Changing Climate* report provides new perspectives and insights into how to address the impacts of climate-related hazards in the coastal zone.

The report provides evidence of the drivers of risks in Bangladesh's coastal zone, analyzes what has been achieved so far in reducing these risks, and reviews the lessons learned from these achievements. Supported by in-depth analytical work, the report explores innovative solutions illustrated with artist impressions and puts forward seven key recommendations to enhance coastal resilience in Bangladesh and build shared prosperity for decades to come. What is clear from the report is that investing in coastal resilience will bring multiple benefits, and that the time to act is now.

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ALEJANDRA GIJÓN MANCHEÑO is a postdoctoral researcher at Delft University of Technology. She is involved in projects related to mangrove restoration and the design of hybrid coastal solutions, which combine coastal vegetation with conventional structures like dikes. Alejandra graduated in Hydraulic Engineering cum laude at Delft University of Technology in the Netherlands in 2016 followed by a PhD at the same university in close cooperation with Deltares and Witteveen+Bos. During her PhD, Alejandra investigated mangrove restoration at the eroding coastline of Demak (Indonesia), where she conducted two field campaigns between 2017-2018. She also performed laboratory analyses and modelling work, in parallel to mentoring and teaching. Alejandra has carried out analytical work for the World Bank, in 2020 and 2022, where she investigated the potential for mangrove afforestation in Bangladesh. Her scientific work has been published in peer-reviewed journals and presented at several international conferences such as AGU (2021).

EXECUTIVE SUMMARY

Coastal Bangladesh, fringed by the Bay of Bengal and home to over 40 million people, is a dynamic, unique, and thriving environment full of opportunities. However, multiple risks are also at play, as the coast of Bangladesh sits on the frontlines in the battle against climate change. Among the most climate-vulnerable and disaster-prone countries in the world, Bangladesh, particularly the coastal zone of Bangladesh, is experiencing setbacks in its development because of natural hazard impacts. Tropical cyclones and floods are frequently recurring events, while coastal and riverine erosion and salinity intrusion are chronic phenomena affecting millions of people each year along the coast.

Protecting lives, livelihoods, and assets from disasters has been central to Bangladesh's development strategy, with the Government of Bangladesh (GoB) headlining impressive progress in making the coastal zone safer over the last several decades, highlighted by a hundred-fold decline in fatalities from cyclonic events. Taking an integrated approach, Bangladesh instituted policies and legal frameworks, enhanced systems and institutions, led hydrometeorological and forecasting advancements, and supported communities and community-based early warning systems, while also investing in critical infrastructure, such as cyclone shelters, coastal embankments, water management infrastructure, alongside afforestation initiatives. The result has been a drastic decrease in mortality, people affected, and overall losses from hazard impacts.

As Bangladesh celebrates 50 years since Independence, the country is recognized for proactively investing in disaster risk reduction and is considered a global leader in climate resilience. However, a rapidly growing population, environmental degradation, socioeconomic development, and climate change are putting pressure on the existing natural and infrastructure systems in the coastal zone. The ability to continue the ongoing rapid economic growth hinges critically on how hazard impacts are managed, and resilience is built into the economy and natural environment.

The *Bangladesh: Enhancing Coastal Resilience in a Changing Climate* report seeks to provide actionable guidance for enhancing coastal resilience based on in-depth analytical work supported by the World Bank. The work included extensive stakeholder consultations, expert interviews, field visits, data analysis, and numerical modeling, with the aim of contributing to the design of sustainable climate-resilient coastal investments. The target audience of this report is intentionally broad, encompassing those at the strategic, operational, and technical levels, from decision makers to practitioners, and all those who have an interest in the Bangladesh coast or are involved in programs to increase its resilience against natural hazards.

Overall, this report:

- Summarizes the key lessons from past interventions, which can guide the design for the next generation of coastal resilience programs;
- Takes a deep dive into how Bangladesh can adopt a more risk-based strategy following international best practices; and
- Provides inspiration for what future interventions oriented towards more nature-based solutions could look like.

Seven cross-cutting recommendations pave the way forward and offer an opportunity to strengthen the resilience of the coastal zone and build shared prosperity for decades to come.

A unique coastal environment facing increasing natural risks

Bangladesh's physical characteristics as well as the livelihoods of its people are defined by the Ganges-Padma, Brahmaputra-Jamuna, and Meghna (GBM) delta, which is one of the largest, most populated, active, and dynamic deltas in the world. Endowed with an abundance of natural resources, the coastal zone is controlled by the dynamic interaction between the influx of water and sediments, coastal processes such as tide and wave action, episodic events such as cyclones and monsoon rainfall, ecological processes, and human interventions (**Chapter 2**). The dynamic behavior of the delta is an ever evolving and complex process of nature adapting to constantly changing conditions at different temporal and spatial scales. Hence, uncertainties are prevalent and large, yet efforts should be made to quantify and better understand them.

The coastal zone faces several risks, which are shaped by the interaction of the spatial occurrence of natural hazards with the unique natural and human environment (**Chapter 3**). Overall, the most threatening hazards in the coastal zone, which include cyclones, storm surges, erosion, salinity intrusion, waterlogging, and coastal flooding, are significant and are likely to increase over time, both in frequency and intensity, as a result of changing climatic conditions. This will affect people, livelihoods, critical infrastructure, social and ecosystem services, the environment, and the economy.

The average annual losses from tropical cyclones alone were recently estimated to be about US$1 billion (0.7 percent of gross domestic product (GDP)) (Ozaki 2016). However, individual cyclone events can result in larger losses. The two tropical cyclones that have led to the largest losses on record in Bangladesh are Cyclone Sidr (2007, upper estimate of US$3.8 billion in losses) and Cyclone Gorky (1991, upper estimate of US$3.0 billion in losses) (Ozaki 2016). Furthermore, new analytics presented in this report find that at present, 27 percent of the coastal population is exposed to a 100-year coastal flood event, which is expected to increase to 35 percent in the future as a result of a rise of half a meter in the sea level. The risk to assets is about US$300 million per year at present and will almost double in size because of sea level rise (SLR) alone. Alongside an increase in coastal flooding, SLR will push saline water further into the tidal channels, threatening agricultural production, water supplies, and the diversity of coastal ecosystems.

Large parts of the coastal zone also face significant erosion, both along the coast and in the tidal channels. Within the tidal channels, over the last 30 years, river migration rates from 50 meters up to 500 meters have been observed, threatening the stability of large stretches of embankments and the people and livelihoods protected within them. Waterlogging is present, which can cause long-lasting disruptions (social, physical, and environmental) and result in income loss and social unrest. Often a range of drivers are the cause, including insufficient drainage, lack of adequate maintenance of water infrastructure, and reduced river flow from upstream. As all hazards have distinct spatial footprints, localized information is needed to perform risk analyses, including ways to capture these complex local characteristics in models to predict the evolution of these hazards in the future.

Evidence of success of coastal resilience interventions

The GoB has made significant strides towards implementing and scaling-up a wide variety of coastal resilience interventions, covering both structural and non-structural interventions, and in developing the country's legal, regulatory, and policy frameworks. An illustration of this is that since Independence, about US$10 billion has been invested in disaster risk management and preparedness in the coastal zone. Given the significant additional investments needed, it is imperative to learn from past experiences to evaluate the effectiveness of interventions and identify key focal points to guide future investments plans. This report provides a first-of-its-kind screening exercise of all large investment projects since the 1960s, after which a certain number of projects were selected for in-depth analysis (**Chapter 4**).

The reanalysis of the effectiveness of the coastal polders showed that they have a large positive benefit-cost ratio given their aim of reducing risk and boosting agricultural production. Despite their success, challenges remain with respect to proper operations and maintenance (O&M) of the infrastructure, resettlement and land acquisition, and erosion. In terms of combating coastal and riverine erosion, the traditional approach has been to build either temporary measures or hard engineering solutions. These measures can be effective but can also be expensive and require intensive maintenance. Softer nature-based solution approaches have also been implemented through the conservation and reforestation of mangrove forests throughout the coastal zone, which help in stabilizing shorelines while simultaneously providing sustainable community livelihoods opportunities and biodiversity benefits.

Alongside measures to directly prevent hazard impacts, approximately 5,000 multipurpose disaster shelters provide safe havens during cyclonic conditions, many of which serve as schools during normal times. In addition, advancements have been made with respect to early warning systems, the development of awareness programs for safe evacuation, and community-based disaster risk management and preparedness, for instance through the flagship Cyclone Preparedness Programme, which consists of a large corps of community volunteers. These initiatives have significantly reduced the losses suffered from cyclone impacts.

Finally, significant development has been made on the strategic front by creating a comprehensive set of policies, plans, and strategies that recognizes that climate change, disaster risk, and broader development objectives go hand in hand and should be addressed in tandem. In particular, the Bangladesh Delta Plan 2100 provides a policy document that stimulates long-term planning, while emphasizing flexible decision-making in view of uncertainties related to present and future risks, towards a Delta Vision of "achieving a safe, climate resilient and prosperous delta."

Risk as a guiding principle for action in Bangladesh

A key lesson learned from reviewing past interventions is that Bangladesh could benefit from a more intentional and structured application of a risk management framework for planning, designing, and maintaining coastal resilience interventions (**Chapter 5**). Risk management frameworks are particularly suitable for dealing with the many uncertainties planners face in terms of climate change and socioeconomic development, which are sometimes hard to quantify given the deep uncertainties. The report includes international best practices in risk management and how these can support efforts to improve coastal resilience. A comparison of these best practices with the current way of working in Bangladesh has revealed areas where risk management can add value on three levels:

- **Policy level:** A risk management framework can help direct and control the actions of different organizations in a coordinated manner. This needs to be supported by a clear institutional structure with associated duties and responsibilities for water management, as outlined by the Bangladesh Water Act. However, the legal basis for sustainable funding, continuous monitoring, maintenance, and rehabilitation of infrastructure assets is still needed in Bangladesh.

- **Program level:** A risk management framework facilitates the movement from a more reactive response with regards to risk management to one that is more continuous and forward-looking that allows the incorporation of uncertainty. The GoB has made steps towards this by endorsing a shared vision within the Bangladesh Delta Plan 2100, which helps with the prioritization of risk management actions and the design of future programs. However, strategies to translate this vision into practice, for instance by creating tolerable risk thresholds and a risk-based project prioritization, should be developed over the years to come.

- **Implementation level:** Thinking in terms of risk can help optimize the design of interventions and prioritize investments in the most cost-efficient way. For instance, as part of the new analytics undertaken, alternative polder designs show that by differentiating protection levels across the polder, higher benefit-cost ratios can be achieved compared to the current designs. Similarly, implementing probabilistic, or risk-based, design guidelines could cut costs by optimizing the design of infrastructure systems.

Given the vast extent of infrastructure in Bangladesh, any improvements in the risk management framework will pay off and ensure long-term sustainable risk financing. This does require, however, a coordinated set of actions across the policy, program, and implementation levels.

Innovative solutions for coastal resilience

Another key lesson learned from the past interventions is that there is significant potential in Bangladesh for nature-based solutions or a mix of green-grey infrastructure (hybrid solutions) (**Chapter 6**). Hybrid solutions are increasingly recognized as feasible alternatives in Bangladesh and help conserve natural resources while protecting communities. Several such innovative hybrid solutions are explored in this report, all of which were developed based on extensive stakeholder consultation, field visits, and numerical modeling. These solutions are also compared to the solutions implemented to date to understand the added value but also the potential implementation challenges.

- For Polder 35/1, a hybrid approach of dredging and bank protection has been proposed that can cost-efficiently help resolve the erosion problem the polder faces. The analysis indicates that dredging an additional channel in the river and disposing of the sediment at the erosion hotspot will naturally reduce the pressure on the existing bank protection.

- At Polder 48 (Kuakata) and Himchori Beach, Kolatoli Beach, and Inani Beach (along the Cox's Bazar-Teknaf Marine Drive Road), all existing or upcoming tourist hotspots, a multifunctional system that includes a beach nourishment in combination with an embankment has been proposed to reduce the retreat of the coastline, minimize the impacts of flooding, and provide an attractive beachfront for tourism purposes.

- The restoration of mangrove forests for coastal protection purposes has been assessed since mangroves have proven to be effective at reducing wave run-up. An analysis of the suitability of mangrove afforestation sites across the coastal zone shows that there are approximately 600 kilometers of coastal stretches suitable for natural colonization. For example, by combining mangroves with existing or new embankment systems, the required embankment height may be reduced, which would potentially decrease the direct cost of raising the embankments and the required footprint.

The initial results provide valuable evidence that such hybrid interventions can be cost effective, potentially lowering the upfront costs of infrastructure interventions, albeit with potentially higher maintenance requirements and enhanced monitoring needs. Still, the flexibility and wider co-benefits of such interventions make them attractive alternatives for coastal resilience in Bangladesh.

Moving towards a more resilient coast

This report provides new perspectives and innovative insights to address the impacts of climate-related hazards in the coastal zone (**Chapter 7**). Although Bangladesh has made significant steps towards reducing the vulnerability of the coastal zone, significant residual risks remain, and these risks will only increase with socioeconomic development and climate change. To achieve Bangladesh's aspiration to become a safe, sustainable, and resilient delta, seven key recommendations (**Box ES.1**) with specific short-, medium-, and long-term actions are suggested.

1. ***Strengthen O&M to extract maximum benefits from investments and nurture sustainable interventions.***

Solid O&M of all existing natural and human-made structural and non-structural assets is the foundation of coastal resilience. Investments in O&M activities and organizations should be prioritized to ensure that existing key assets provide their essential services to coastal communities. These include protecting communities and economic activities against the impacts of coastal hazards. The Bangladesh Delta Plan 2100 recommends that 0.5 percent of GDP be allocated for O&M of water management infrastructure compared to the 0.1 percent invested at present.

2. ***Embrace the uniqueness of the Bangladesh coast, recognize local knowledge, strengthen the application of state-of-the-art modeling tools and systems, and cultivate knowledge sharing.***

The unique landscape and dynamics of coastal Bangladesh requires a thorough understanding of the functioning of the present system in order to predict how future scenarios in coastal environmental conditions might change, as a whole, and what that means in terms of the design of interventions. Continuous development of knowledge and implementation of state-of-the-art modeling tools and technical guidelines should be prioritized, including knowledge transfer of these developments. The long-term monitoring and research

Box ES.1: Seven Recommendations

01 Strengthen operation & maintenance to extract maximum benefits from investments and nurture sustainable interventions.

02 Embrace the uniqueness of the Bangladesh coast, recognize local knowledge, strengthen the application of state-of-the-art modeling tools and systems, and cultivate knowledge sharing.

03 Apply risk as the guiding principle for adaptive delta management.

04 Complement infrastructure interventions with nature-based solutions to enhance resilience and effectiveness.

05 Incorporate risk-sensitive land-use planning to guide appropriate activities based on integrated coastal zone management practices.

06 Support inclusive community participation, local institutions, and livelihoods adaptation for sustainable resilience.

07 Establish an integrated framework of performance criteria of interventions that goes beyond risk reduction and includes growth, wellbeing, and sustainable development at its core.

program under the Coastal Embankment Improvement Project Phase I (CEIP-I) can act as an excellent step in this direction.

3. Apply risk as the guiding principle for adaptive delta management.

Given the changing climate and dynamic coastal processes of Bangladesh's coastal zone, adaptive delta management (ADM) should be the cornerstone of any attempt to achieve coastal resilience. ADM is about flexible decision-making in view of the uncertainties related to present and future risks. A risk management approach is well-suited to inform decisions about public safety given large uncertainties, and could help tie together strategic planning, design, and O&M, further improving the efficiency and effectiveness of coastal interventions in Bangladesh.

4. Complement infrastructure interventions with nature-based solutions to enhance resilience and effectiveness.

The natural environment provides an excellent opportunity to reduce risk while providing valuable services to society. Hybrids of traditional infrastructure with nature-based solutions, like sediment solutions and mangrove restoration for protection against cyclones and erosion, should be pursued in future programs. Developing and monitoring pilot projects are important for learning from best practices and developing guidelines for the implementation of such solutions in different parts of the coastal zone.

5. Incorporate risk-sensitive land-use planning to guide appropriate activities based on integrated coastal zone management practices.

Changes in land-use and socioeconomic characteristics will shape the composition of the coastal zone in terms of what is at risk, where, and how. Given the longevity of investment horizons, risk-sensitive land-use planning should be at the core of coastal zoning policies. Risk-sensitive land-use planning can take place on different scales and should be based on various plausible land-use and socioeconomic scenarios, contingent on the changing environmental conditions. Such scenarios not only help in testing the robustness of interventions but can also inform migration policies and policies for the spatial allocation of present and future economic activity.

6. ***Support inclusive community participation, local institutions, and livelihoods adaptation for sustainable resilience.***

Strengthening the adaptive capacity of coastal livelihoods ensures that coastal inhabitants have the ability and means to make a living under the various shocks and stressors they face. However, before such efforts can be scaled-up and mainstreamed into national adaptation plans, a systematic framework should be established that can track the development of adaptation efforts in communities and investigate drivers for, and barriers to, success. Furthermore, local institutions with a diverse representation of social groups, upgraded capacity, sufficient resources, and clear roles and responsibilities should be established or strengthened to make sure efforts are sustainable.

7. ***Establish an integrated framework of performance criteria of interventions that goes beyond risk reduction and includes growth, wellbeing, and sustainable development at its core.***

As coastal resilience efforts are often aligned with ongoing development efforts, it is important to ensure that development objectives are well integrated into these efforts to reap the large gains that can be made from adapting to a changing climate while also achieving the United Nations Sustainable Development Goals. Alternative policy evaluation frameworks should be developed that explicitly take development objectives into consideration alongside wider planning efforts to align different program objectives in order to benefit from positive cross-sectoral spillovers.

Bangladesh is currently at a crossroads. A do-nothing scenario would inevitably overwhelm the coping capacity of the coastal zone in a changing climate and socioeconomic landscape. Nonetheless, this report makes clear that there is ample opportunity to invest in coastal resilience that will bring multiple benefits in terms of avoided losses, wider economic benefits, and social and environmental benefits, and presents an opportunity to shift Bangladesh's trajectory from one of vulnerability to resilience and prosperity.

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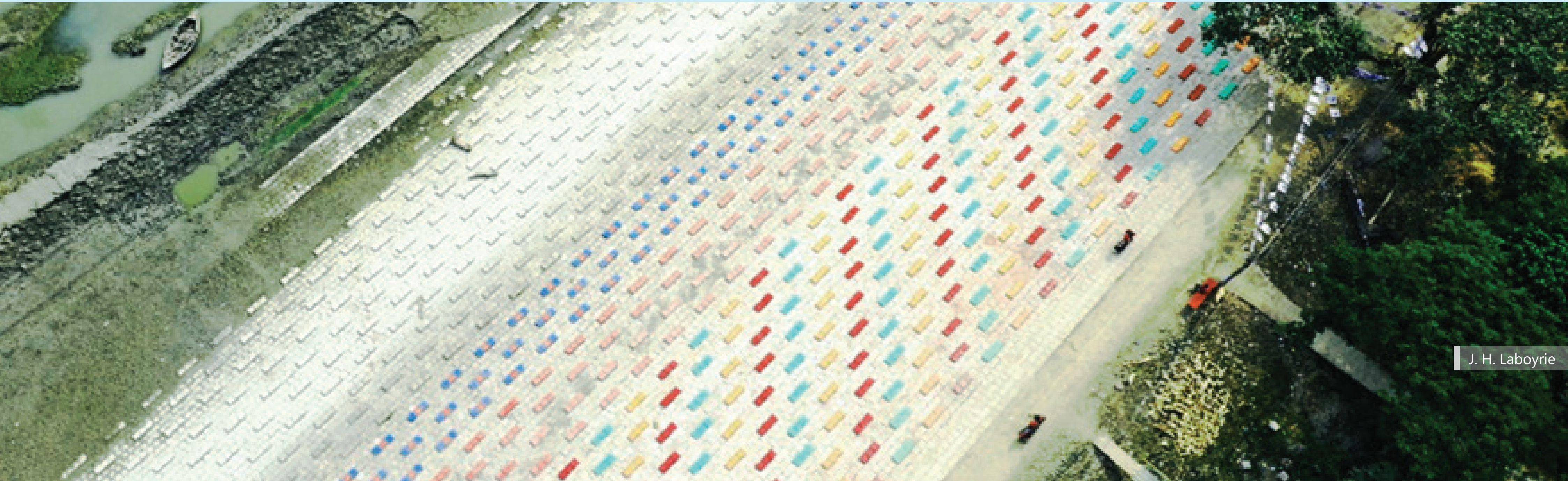

J. H. Laboyrie

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TOWARDS A RESILIENT COASTAL BANGLADESH

CHAPTER 1: TOWARDS A RESILIENT COASTAL BANGLADESH

For Bangladesh, situated in the most dynamic and populated delta in the world, coastal resilience is fundamental to its existence, development, and prosperity. The coastal zone of Bangladesh[2] covers an area of 47,201 square kilometers (32 percent of the country) (Ahmad 2019) and is inhabited by approximately 43.82 million people (around 26 percent of the population).[3] Fertile sedimentary soil has enabled the widespread adoption of agriculture, while large intertidal zones are home to a diverse array of flora and fauna, including the Royal Bengal tiger, which dwells in the world's largest mangrove forest, the Sundarbans, a coastal sanctuary to both Bangladesh and India and an ecosystem of global ecological significance. Coastal urban areas include Chattogram, an industrial seaport and the second largest city after Dhaka, the capital of Bangladesh. Coastal port cities and urban hubs are strategic gateways for economic growth and development, with Bangladesh being located between global powerhouses India and China. However, the coastal zone of Bangladesh, with its wealth of natural resources and economic opportunities, also faces significant risks, including coastal hazards, such as cyclones, sea level rise (SLR), salinity intrusion, and erosion, and the challenges associated with them. These hazards are expected to occur more frequently in a changing climate, which could permanently affect the life and livelihoods of coastal inhabitants. Shifting socioeconomic conditions and community preferences add to the overall uncertainty in planning for the future. The adverse but also uncertain impacts of climate change and extreme weather events threaten an evolving coastal Bangladesh as it continues to develop and could further hinder development gains and the economic growth of the nation and impede the development pathway of the regional economy.

Recognizing this, the Government of Bangladesh (GoB) developed the Bangladesh Delta Plan 2100 (BDP 2100) with the tagline: "Achieving a safe, climate resilient and prosperous delta" (General Economics Division, Bangladesh Planning Commission 2018). This plan provides a long-term vision of the delta for the end of the 21st century. The coastal zone is one of the identified BDP 2100 hotspots, where both climate-related challenges and socioeconomic development converge. Coastal resilience is the cornerstone of achieving a safe, resilient, and prosperous delta, and defined here as "*the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by both human and environmental factors, while adapting the essential functions of the systems to an improved state*." The concept is inherently linked to objectives such as poverty reduction, climate adaptation, and achieving the United Nations Sustainable Development Goals (SDGs).

Moreover, coastal resilience is not a static goal to be met, but rather a continuous process of adapting to changing conditions and finding synergies between different development objectives. It requires on the one hand a forward-looking approach to understand the various pathways the coastal zone may take, and

Standing on the frontlines in the battle against climate change in coastal Bangladesh.

the challenges and uncertainties associated with those pathways. On the other hand, it necessitates looking back at past efforts that have enhanced resilience to learn from and identify best practices. Furthermore, coastal resilience involves an integrated framework for decision-making towards achieving development outcomes. It means working together with an informed understanding of integrated coastal zone management and partnering in emerging sectors and innovations. It is based on a process of broad inclusive participation to answer the key questions of what the desired outcomes are and for whom, what the roles and responsibilities of the different stakeholders are, how to find the requisite resources, how to achieve the intended outcomes, and what the timeline is.

The objective of this report is to provide actionable guidance and inspiration for more resilient coastal interventions in Bangladesh through summarizing and integrating various pieces of analytical work supported by the World Bank. Its value added is that it summarizes key lessons learned for the design of future coastal programs based on a comprehensive review of past interventions. In addition, it takes a deep dive into how Bangladesh can adopt a more risk-based strategy following international best practices and what future interventions with more of an orientation towards nature-based solutions could look like.

An improved understanding of what a more resilient coast might look like is essential for the planning, design, and implementation of future interventions. The report provides evidence of the drivers of risks in Bangladesh's coastal zone, analyzes what has been achieved so far in reducing these risks, and reviews the lessons learned from these achievements. Supported by in-depth analytical work, interviews with experts, stakeholder consultations, and site visits, the report explores innovative solutions illustrated with artist impressions and puts forward a series of concise recommendations to enhance coastal resilience in Bangladesh.

Since coastal resilience is a broad subject with multiple dimensions, this report can only cover a portion of this topic and is not an exhaustive narrative. The focus of the analytical work has been primarily through a lens on water infrastructure systems and their associated interactions to reduce coastal risks, i.e. embankments, erosion protection, disaster shelters, and mangroves. Other aspects, such as drainage infrastructure, road networks, or housing, are touched upon in relation to these main systems. Based on the findings and analysis, seven recommendations for deepening coastal resilience options are presented with proposed strategic actions to strengthen the ambition of resilient coastal development.

The target audience of this report is intentionally broad, as increasing coastal resilience requires an integrated effort involving various types and levels of stakeholders and organizations, from the decision makers to the practitioners, in areas ranging from policy and planning, finance and economics, technical analysis and engineering, to social and environmental safeguards. Bringing together interdisciplinary insights in one report contributes to the mutual exchange of expertise and information on coastal resilience. **Table 1.1** provides a summary of the contents of the chapters of the report. Each chapter starts with a brief introduction and outline of the remainder of the chapter, which can guide the reader to chapters that are of specific interest to them in terms of their scope.

1.1. A Unique Coastal Zone

The coastal zone of Bangladesh spans over 710 kilometers along the Bay of Bengal and is part of one of the largest, youngest, and most active deltas in the world. The zone is located at the downstream end of the three great trans-Himalayan rivers—the Ganges-Padma, the Brahmaputra-Jamuna, and the Meghna (GBM)—and is the world's largest sediment dispersal system (Akter et al. 2016). While over 90 percent of the GBM catchment area lies outside of Bangladesh, over 400 rivers and tributaries of the GBM drain through the country via a constantly changing network of rivers, tidal inlets, and tidal creeks, before discharging into the Bay of Bengal (Bangladesh Water Development Board (BWDB) 2020).

Bangladesh's physical and cultural characteristics as well as the livelihoods of its people are defined by the GBM delta, which is endowed with an abundance of natural resources. The southwestern part of this coastal zone hosts the

Table 1.1: Report Overview by Chapter

Chapter 1: Towards a resilient coastal Bangladesh	These chapters provide a systematic overview and diagnosis. Chapter 1 is an introduction to the setting, the concept of coastal resilience, its relevance to sustainable development, and a framework towards achieving coastal resilience. Chapters 2 and 3 present a description of the coastal zone and its infrastructure and summarizes a coastal-wide risk assessment based on the latest data. Chapter 4 hones in on past interventions in the coastal zone and the lessons learned from these interventions.
Chapter 2: Overview and trends	
Chapter 3: Risks profile	
Chapter 4: Empirical evidence on selected coastal resilience interventions	
Chapter 5: Applying a risk-based approach to coastal resilience	These chapters aim to advance the knowledge of and insights into the areas that have been identified in the preceding chapters. Chapter 5 focuses on the added value of a more risk-based approach and Chapter 6 presents inspirational examples of how a more nature-based approach towards coastal interventions in the context of Bangladesh may look like in practice.
Chapter 6: Building with nature: innovative solutions for coastal resilience	
Chapter 7: A way forward: seven recommendations for a more resilient coast	This final chapter provides seven recommendations with concrete actions on how to increase coastal resilience in Bangladesh.

Sundarbans mangrove forest, which is the largest mangrove ecosystem in the world, covering an area of approximately 10,000 square kilometers, about 60 percent of which is within Bangladesh's territory, with the remainder in India. This World Heritage site is known for its extensive range of exquisite flora and fauna, with over 330 floral species, and a wide variety of wildlife, including the Royal Bengal tiger, the national animal of Bangladesh. The Sundarbans welcomes more than 250,000 national and international tourists every year, and green sustainable coastal tourism is a potential service sector for the growing economy.

The southwest and central parts of the coastal zone consist of vast tracts of low-lying, fertile land often surrounded by embankments and separated by large tidal water systems (see **Figure 1.1**). The eastern part of the coastal zone is a relatively narrow strip of land with a series of hills running parallel to the coast. It hosts a vast system of sandy beaches and dunes, such as in Cox's Bazar, home to one of the longest sandy beaches in the world. These are important areas for tourism, biodiversity, and recreational purposes. Fishing, agriculture, shrimp farming, and salt farming are the traditional main economic activities of the coastal communities throughout the entire coastal area (Hossain et al. 2016), although industrial manufacturing and the service sector have grown quickly over the last couple of years.

The coastal zone is continually affected by fluctuations of the GBM river system as well as regular coastal processes such as tidal propagation, salinity intrusion, and erosion. The Global Climate Risk Index ranks Bangladesh as the seventh most affected country in the world over the 2000 to 2019 period (**Figure 1.2**), with an average of 577 casualties and US$1.6 billion in losses every year (Eckstein, Künzel, and Schäfer 2021). Damages and losses associated with a

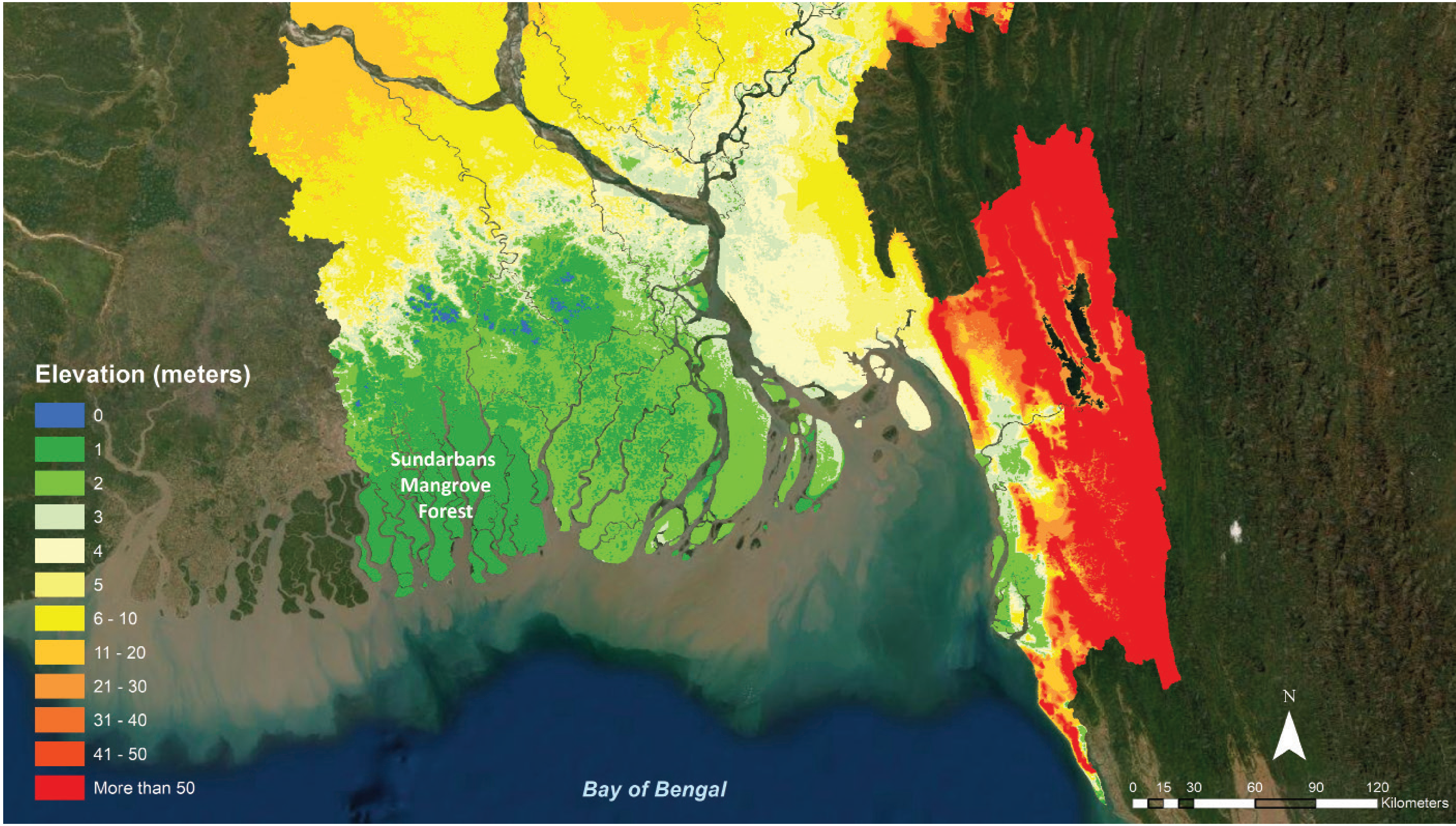
The Sundarbans mangrove forest.

single extreme event impose substantial costs on the national economy and can set back the achieved development gains multiple years.

Records from 1990 to 2014 show that over 90 percent of casualties and 40 percent of economic damage in Bangladesh are related to storms, with severe cyclone events contributing the most to the reported damages (CRED 2021). Cyclones, which are accompanied by powerful winds, heavy rainfall and large storm surges, are a regular phenomenon and pose a serious threat to coastal communities along the entire coastline (**Figure 1.3**). On average, about one cyclone makes landfall every year, striking the funnel-shaped and relatively shallow northern portion of the Bay of Bengal—a perfect natural amplifier—raising the water level more than 10 meters above mean sea level (MSL) during very intense cyclones. With 62 percent of the coastal land having an elevation of less than three meters above MSL (Bangladesh Water Development Board 2013), the potential for cyclone-induced inundation is widespread. The average annual losses from tropical cyclones alone have recently been estimated at approximately US$1 billion (0.7 percent of gross domestic product (GDP)) based on risk modeling (Ozaki 2016, Table 10). However, individual cyclone events result in larger losses. The two tropical cyclones[4] that have led to the largest losses on record are Tropical Cyclone Sidr (2007, upper estimate of US$3.8 billion in losses) and Tropical Cyclone Gorky (1991, upper estimate of US$3.0 billion in losses) (Ozaki 2016, 3).

A Royal Bengal tiger in the Sundarbans.

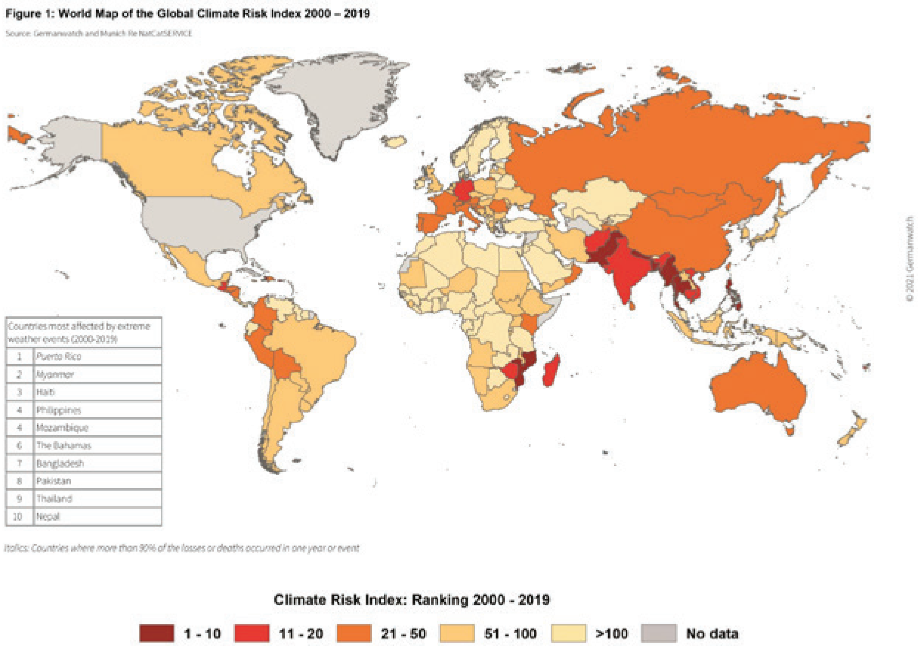
Figure 1.1: Elevation of Coastal Bangladesh



Source: Map developed by the World Bank for this report based on data from Humanitarian Data Exchange, the World Bank, ESRI ArcGIS, Maxar, Earthstar Geographics, USDA FSA, USGS, Aerogrid, IGN, IGP, and the GIS User Community.

Other more gradual and less visible hazards in the coastal zone are salinity intrusion (Dasgupta et al. 2015), erosion (World Bank 2021), subsidence (Brown and Nicholls 2015), and waterlogging (Alam et al. 2016). Salinity intrusion in the surface water system and in the soil from tidal propagation into low-lying coastal plains contribute to the risk of drinking water shortages (which are predominantly from groundwater sources), the spread of water-related diseases, and irrigation water shortages, which can impact food security and lead to the loss of employment opportunities for agricultural workers. Additionally, hundreds of kilometers of the coastal shoreline experience some degree of erosion. The continued retreat of the coastline poses a threat to the stability of embankments and further results in significant losses of valuable arable land. This is also true for the tidal and river channels, with migration rates observed of about 45 meters on average over the last 30 years, but up to 500 meters in some places (Jarriel et al. 2020), threatening bank protection works.

Figure 1.2: World Map of the Global Climate Risk Index Ranking (2000-2019)



Source: Eckstein, Künzel, and Schäfer 2021.

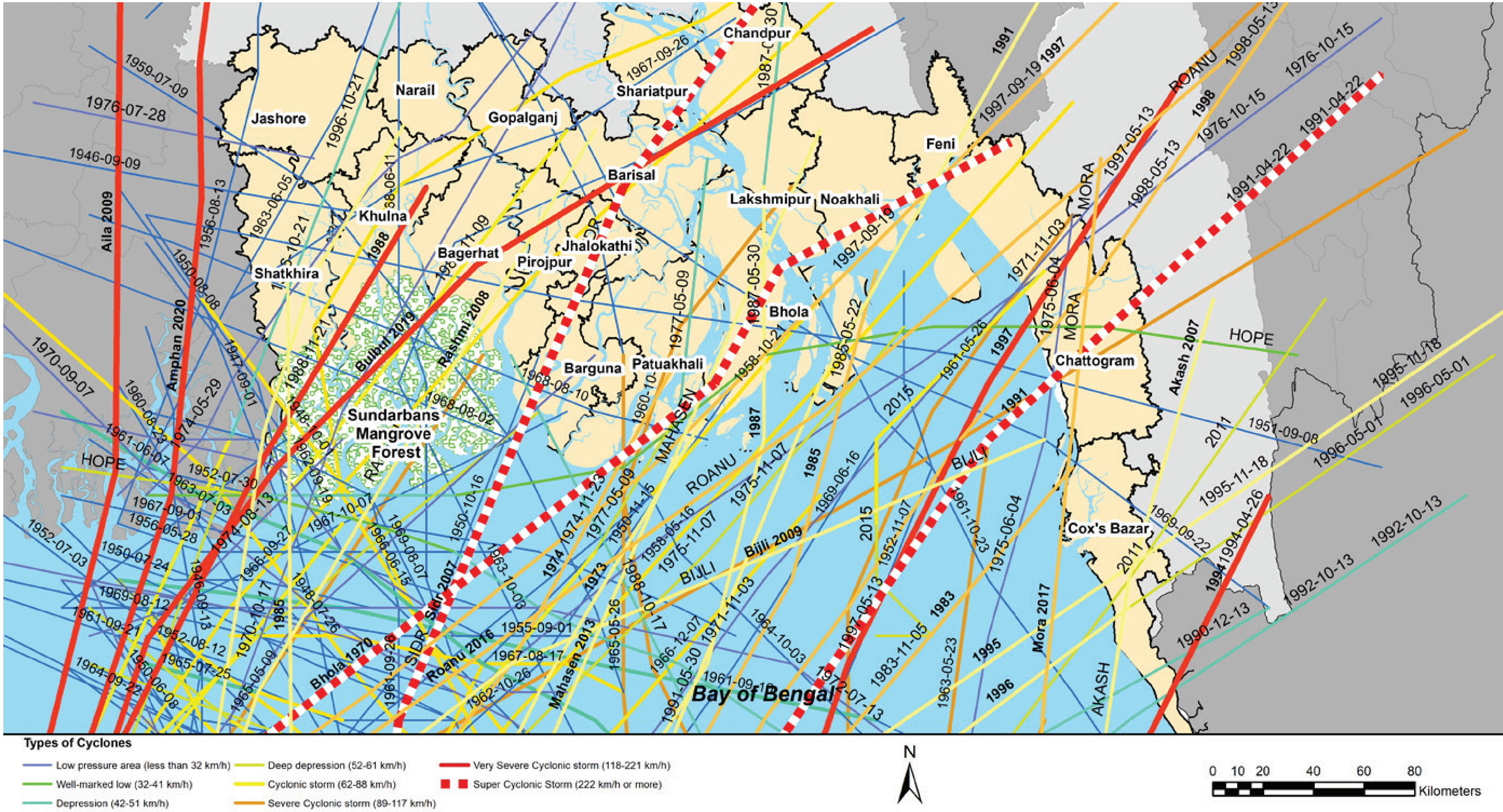
The impacts of the various threats are not equally distributed among households. Continuous exposure to both episodic (cyclones) and chronic (salinity, subsidence) hazards can push the country's poor further into poverty. The poor are often forced to live in at-risk areas, thereby being disproportionately exposed to hazards (Hallegatte et al. 2020), while also lacking the ability to cope and recover from the adverse impacts (Akter and Mallick 2013; Hallegatte and Rozenberg 2017).

1.2. Success in Creating a Safer and More Inhabitable Coast

The development of a safe and inhabitable coastal zone has long been a priority for Bangladesh. Compelled by increasing demand for food, intensive rice cultivation was promoted in the 1960s during the Green Revolution through the construction of a series of coastal polders (areas that are enclosed on all sides by dikes or embankments, separating them hydrologically from the natural water system, in which the water table is managed), which protected polder inhabitants from tidal flooding and salinity intrusion. The polders have proven to act as a first line of defense by effectively protecting people and crops from the adverse impacts of cyclones. The need for these investments in terms of risk reduction was clearly highlighted by Cyclone Bhola in 1970, one of the deadliest disasters on record, which resulted in about 300,000 lives lost per official estimates (Ministry of Disaster Management and Relief 2010), with unofficial estimates being significantly higher. Following this disaster, the GoB, with the support of donor partners, invested over US$10 billion towards the development of structural (flood protection infrastructure, cyclone shelters, cyclone-resistant housing) and non-structural (early warning and awareness-raising systems) disaster mitigation and preparedness systems.

Over the past several decades, the GoB has demonstrated that investments in the entire chain of disaster risk reduction (DRR) can save lives, reduce economic losses, and protect development gains. The number of casualties resulting from cyclones has dropped a hundred-fold over the last five decades due to

Figure 1.3: Cyclone Tracks Across the Bangladesh Coastline (1900-2020)



Source: Map developed by the World Bank for this report based on data from Humanitarian Data Exchange, United Nations Environment Programme, Bangladesh Meteorological Department, and the World Bank.

successful efforts on multiple fronts such as improved early warning systems (EWS), increased access to a network of cyclone shelters and evacuation roads, and awareness raising through a large-scale organized volunteer program (the Cyclone Preparedness Programme) (BDRCS, n.d.) and associated community-based initiatives for disaster preparedness and response.

With the coastal embankment system, there has been a reduction in coastal flooding and a boost in agricultural production in Bangladesh, with initial productivity increases of up to 200 to 300 percent in certain areas (Nishat 1988). Softer nature-based solutions have also been implemented through the conservation and reforestation of mangrove forests throughout the coastal zone, which have helped in stabilizing shorelines while providing sustainable co-benefits to communities.

These interventions have contributed to a considerable improvement in the living conditions of the coastal communities of Bangladesh. The national poverty rate fell from 48.9 percent to 24.3 percent between 2000 and 2016, while extreme poverty declined from 34.3 percent to 12.9 percent (Bangladesh Bureau of Statistics 2016). While this downward trend is mirrored in the coastal zone, poverty indicators show an above-average poverty incidence in the coastal zone (Akter and Mallick 2013). In particular, extreme poverty persists in the most at-risk areas near the coast (Dasgupta et al. 2021), where households disproportionally rely on natural resources that are degrading fast and are more vulnerable to hazard impacts.

1.3. Rising Risks Due to Climate Change

Climate-change-induced changes in the frequency and intensity of extreme events and chronic stressors can have major, and sometimes irreversible, implications for coastal livelihoods, the environment, and the provision of infrastructure services. Rising temperatures, which lead to more intense and unpredictable rainfalls during the monsoon season and a higher probability of catastrophic cyclones, are expected to result in increased inundation. On top of this, the coastal zone is recognized as one of the most at-risk areas globally

Mahfuzul Hasan Bhuiyan

due to SLR (Hooijer and Vernimmen 2021). The combination of SLR and the ongoing subsidence can elevate storm surges and push saline waters further into tidal channels. It is estimated that a 1-meter rise in sea levels would result in a loss of land of more than 4,800 square kilometers (roughly 3.2 percent of the country) (Rigaud et al. 2018), making a large part of the delta unsuitable for agricultural production due to elevated salinity concentrations (Dasgupta et al. 2015).

On the one hand, socioeconomic development will further exacerbate the coastal risks in the coming decades. The coastal population is projected to grow to 61 million by 2050 (Mainuddin and Kirby 2015), resulting in an increase in the exposure of people and assets. The increasing population, the loss of valuable land, and the climatic impacts to coastal livelihoods will likely result in climate migration away from the coastal zone, as indicated in a recent World Bank study (Rigaud et al. 2018), although it is expected that a large share of the population, including the most impoverished, will remain in this vulnerable area. Therefore, this study calls for the development of coastal zone strategies to adapt the coastal environment to accommodate "stay in place" areas that are relatively safe and provide sustainable livelihoods opportunities.

On the other hand, the economy of the coastal zone is expected to transition to become more diversified, with large welfare improvements. To ensure sustainable social and economic development in this area, climate-related and socioeconomic risks in the coastal zone and their inherent uncertainties need to be addressed. This will require both structural solutions and non-structural solutions, such as diversification of income and employment, financial protection systems, and access to finance.

1.4. Aspirations Towards a Safe, Climate Resilient, and Prosperous Coast

Bangladesh aspires to eliminate extreme poverty and become a middle-income country by 2030, and a prosperous country beyond 2041. To this end, the GoB has recognized the need to intensify efforts in coping with climate-related challenges. Over the years, it has instituted DRR plans, legal frameworks, and climate change strategies. It developed the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) and National Adaptation Programme of Action (NAPA) in 2009 (Ministry of Environment and Forests 2009)[5] to respond to climate-change-induced development risks, and the National Plan for Disaster Management (NPDM) for 2010-2015 (Ministry of Disaster Management and Relief 2010) to put in place sound DRR measures and respond to disasters. Since then, the NPDM has been updated twice, with the NPDM 2016-2020 (Ministry of Disaster Management and Relief 2017) and the NPDM 2021-2025 (Ministry of Disaster Management and Relief 2021). Similarly, the Second Perspective Plan of Bangladesh 2021-2041 (General Economics Division, Bangladesh Planning Commission 2020) emphasizes that managing climate change and implementing the BCCSAP is essential to achieving the vision of transforming the national economy.

In 2018, the GoB approved the BDP 2100 (General Economics Division, Bangladesh Planning Commission 2018), a techno-economic, water-centric, long-term vision and action plan. The BDP 2100 seeks to integrate the medium- to long-term aspirations of Bangladesh to achieve upper middle-income status and eliminate extreme poverty by 2030, and to become a prosperous country beyond 2041, with the longer-term challenge of sustainably managing the country's water, ecology, environment, and land resources in the context of their interaction with natural disasters and climate change. It looks primarily at the delta agenda up to 2050 and takes into account that decisions taken today have implications for 2050 and beyond. The plan sets out a long-term vision for the evolution of the Bangladesh delta with the aim to be "a safe, climate resilient, and prosperous delta" by the end of the 21st century and defines short- and medium-term goals as steps to reach that vision. This vision is associated with around a US$37 billion investment plan (covering 80 projects), financed by both the public and private sectors. These goals, associated strategies, policies, institutions, and investments are moving targets and are intended to be adaptive in nature to shift track if needed, given the large uncertainties. Alongside the BDP 2100, Bangladesh initiated the National Adaptation Plan (NAP) to fill the gap of institutional arrangements alongside a coordinated strategy for mid- and long-term climate change adaptation investments (UNDP 2017). The objective is "to formulate the Bangladesh National Adaptation Plan

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with a focus on medium to long term adaptation investments and enhance national capacity for integration of climate change adaptation in [the] planning, budgeting and financial tracking process." To achieve this, an estimated US$5.7 billion per year will be needed by 2050 in terms of adaptation finance, which is more than five times the current spending on adaptation (Ministry of Environment, Forest and Climate Change 2021).

A common thread in these strategies and action plans is the ubiquitous call for more resilience of areas under threat from natural hazards. This call is aligned with the global trend of aiming to enhance the resilience of coastal zones in policies and practices (Masselink and Lazarus 2019). The definition of resilience, let alone the metrics, is ambiguous. Slightly modified from the definition adopted by the International Panel for Climate Change, coastal resilience is defined herein as "*the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by both human and environmental factors, while adapting the essential functions of the systems to an improved state*." Applied to Bangladesh's coastal zone, resilience encompasses the coping capacity of the entire coastal system (physical, social, economic) given the exposure to episodic events (for example, cyclones) and chronic stressors (for example, SLR, salinity intrusion, erosion), which is enhanced by adapting the socioeconomic (such as housing, transport, tourism) and natural (such as mangroves, beaches) coastal systems to these shocks and stressors. The shocks and stressors are uncertain even now and more so into the future, thus requiring special attention and the development of resilient strategies that are robust yet flexible.

Achieving greater resilience in a human-dominated system like the coast of Bangladesh is a complex and costly endeavor. As outlined in the beginning of this chapter, Bangladesh's coast has a vast and dense network of polders and critical infrastructure systems, as well as tens of millions of people living in smaller and larger settlements that earn their livelihoods through a variety of economic activities. Moreover, the wellbeing of coastal inhabitants is inherently linked to the natural environment and ecosystem services they provide. These factors imply that working towards a more resilient coast will result in trade-offs between the natural environment and the socioeconomic system. However, synergies between both can also be identified and utilized, for instance by enhancing the ability of the natural system to buffer against extreme events and provide valuable livelihood opportunities (for example, mangroves, beaches).

As Bangladesh further develops, the challenge of coastal management is to balance the needs of both the socioeconomic and natural coastal systems in the near- and long-term future, and to increase the resilience of both (Masselink and Lazarus 2019). Coastal resilience is a continuum, and at the heart of coastal resilience is the vision of the Draft Mujib Climate Prosperity Plan (Government of Bangladesh 2021), which is the aspiration to shift Bangladesh's trajectory from one of vulnerability to resilience to prosperity.

1.5. Guidance and Inspiration Towards a More Resilient Coast in Bangladesh

Bridging theory and practice, the central question of this report is how greater resilience of Bangladesh's coast can be achieved in the coming decades. Attempting to answer this question requires a thorough analytical understanding of the physical characteristics, social structures, and cultural norms for this specific context. This requirement is also reflected in the BDP 2100, which particularly emphasizes the need for a sound knowledge base supported by analytical work to inform future investments.

Practical questions to be answered are: What have we learned regarding coastal resilience from past interventions in Bangladesh? Are there ways to improve the planning, design, construction, and maintenance of embankment systems? How can these systems be embedded more attractively into the landscape and benefit the coastal environment and population? Are there alternative ways to deal with coastal erosion? Are there opportunities for better integration and use of mangroves in upgrading coastal protection? How can maintenance be improved for a more resilient coast? How will trade-offs between the uncertain dynamics of the natural system and enabling safe livelihoods for coastal communities be balanced? This non-exhaustive list of questions will be addressed in this report and sets the scene for recommendations to enhance coastal resilience in the future.

1.6. Notes

2. The administrative delineation of the coastal zone comprises 19 districts, 147 upazilas, and the Exclusive Economic Zone. A distinction is made between upazilas facing the coast or estuary and upazilas located behind (Kamal Uddin and Kaudstaal 2003). The 48 upazilas in 12 districts that are exposed to the sea or lower estuaries are referred to as the *exposed coast* and the remaining 99 upazilas of the coastal districts are termed the *interior coast*. The delineation of the coastal zone was approved at the 6th Inter-Ministerial Technical Committee meeting of the Integrated Coastal Zone Management Plan Project on October 25, 2003, chaired by the Secretary of the Ministry of Water Resources.

3. Population numbers are based on the Preliminary Population and Housing Census 2022 (Bangladesh Bureau of Statistics 2022).

4. The Regional Specialized Meteorological Centre, New Delhi, refers to these events as "tropical cyclones," whereas the Bangladesh Meteorological Department refers to these climate events as "cyclonic storms."

5. The updated 2009 NAPA for Bangladesh kept the format of the NAPA 2005, and incorporated the findings of studies on impacts, vulnerabilities, and needs assessment adaptations carried out over the last few years. The NAPA was prepared by the Ministry of Environment and Forests (which in 2018, was renamed to be the Ministry of Environment, Forest and Climate Change) as a response to the decision of the United Nations Framework Convention on Climate Change (UNFCCC).

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2

OVERVIEW AND TRENDS


J. H. Laboyrie

CHAPTER 2: OVERVIEW AND TRENDS

The coastal zone of Bangladesh is a dynamic and densely populated zone with numerous opportunities and multiple risks. From the Sundarbans Forest in the west (bordering West Bengal, India) to Chattogram in the east (near India's Northeastern Region and Myanmar), the coastal zone is between 50 and 150 kilometers wide, with almost flat topography, interrupted by large tidal tributaries that are part of the GBM delta. South of Chattogram, towards the Naf estuary (bordering Myanmar) near Teknaf, the character of the coast is different, with a narrow coastal plain that is only 10 to 50 kilometers wide, hills a short distance from the coast, and small river catchment areas draining into the sea. Home to approximately 43.82 million people in 2022,[6] the coastal zone is densely populated, with an average of around 930 people per square kilometer (Bangladesh Bureau of Statistics 2022). Agriculture and aquaculture are the main economic activities in the western part of the coastal zone, whereas tourism, trade, and industrial activities dominate the eastern part.

Although significant development progress has been made, the frequent occurrence of natural hazards, which are expected to become more intense because of climate change, poses a great threat to the development ambitions of the country. Despite the progress made in recent decades, access to transport networks (roads, rail) and public services such as health, sanitation, and drinking water remains limited in the coastal zone, partly because of natural hazards. Powerful events such as cyclones but also slow-moving threats such as SLR, subsidence, coastal and river erosion, and salinity intrusion impede development progress, since damage to infrastructure, decreasing crop yields, and disruption of public services directly affect the wellbeing of coastal livelihoods. Across a sample of 48 deltas globally, the GBM delta has been identified as the second most at-risk delta in terms of flood risk (Tessler et al. 2015). The combination of fluvial and coastal flood hazards and the large population located in the low-lying coastal zone makes for a high-risk profile of the GBM delta, despite the efforts taken to reduce the vulnerability of the people and assets exposed.

Enhancing resilience of coastal livelihoods requires a thorough understanding of the existing and future challenges arising from natural hazards, climatic changes, and changing socioeconomic conditions in the coastal zone. As outlined in Chapter 1, coastal resilience refers to an ever-evolving framework. It entails the coping capacity of the entire coastal system (physical, social, economic) against natural shocks (such as cyclones) and chronic trends (such as SLR, subsidence, salinity intrusion, erosion), while also maintaining essential functions (for example housing, transport, tourism) through long-term adaptation. To ultimately understand and define which interventions improve coastal resilience within the context of the GBM delta, a thorough understanding of the existing coastal system is imperative. This holistic view of the coastal system needs to be multidimensional, requiring insight into the physical, social, and economic functioning of the coastal zone at present as well as of future trends to support long-term planning.

A common way to better understand coastal resilience against natural hazards is to look at this concept through the lens of risk. Risk is defined as the product of hazard, exposure, and vulnerability.

- ***Hazards*** are inherently connected to the coastal zone. The most prominent hazard in the coastal zone is cyclone activity, but riverbank and coastal erosion, salinity intrusion, and land subsidence are also important hazards in this area. Long-term trends such as SLR as well as the possible change in cyclone activity may exacerbate the frequency and magnitude of these hazards. These hazardous events are not deterministic events (such as the tide) but have a certain probability of occurrence now and in the future, both in terms of intensity and of spatial occurrence (for example, the landfall location of a cyclone). Therefore, these types of events are generally expressed in terms of probabilities, which facilitate a risk-based planning approach.

- ***Exposure*** refers to the entire inventory of elements in the coastal zone that can be impacted by coastal hazards. This includes the population and their assets (homes and belongings), transport and water infrastructure (such as roads, drinking water, sanitation, drainage, and flood protection infrastructure), social infrastructure (healthcare and school facilities), agri-and aquaculture areas, and environmental assets, such as mangrove systems and sediment buffers. This inventory is not static, but dynamic in time due to, for example, changes in physical processes, socioeconomic growth, migration, and changes in the economic structure (for example, a shift from agriculture to more aquaculture).

- ***Vulnerability*** is the degree to which exposed elements, such as human beings, their livelihoods, and infrastructure and natural assets suffer adverse effects when impacted by a certain hazard. Hazards can cause casualties, direct damage to assets, and disruption of services in the coastal zone. The vulnerability of built infrastructure is often related to the engineering design standards of these structures (such as the type of housing and the construction materials used for embankments). Differences in human and social vulnerability are, however, more complex to quantify as they are associated with the sociodemographic profile, livelihoods strategies, the strength of social networks, and households' access to basic services (Nath, van Laerhoven, and Driessen 2019; Rabby, Hossain, and Hasan 2019).


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Thinking in terms of risk is very useful for understanding and enhancing resilience across the Bangladesh coastal zone. First, hazardous events have a probabilistic nature and therefore have a likelihood of occurrence. Cyclones are the best example of this for Bangladesh; different parts of the coast are frequently struck by relatively weak and small tropical storms with minor impacts, but now and then a major cyclone hits the coast with devastating and long-lasting impacts. Thinking in terms of risk forces one to look across all probable events and their impacts on the exposed assets and population. Second, interventions can reduce the hazard, the exposure, or the vulnerability of the assets and population, or a combination of these. Therefore, disentangling the contributions of hazard, exposure, and vulnerability to overall risk helps in better understanding what interventions to target to enhance resilience. For example, flood protection infrastructure reduces the probability of flooding, whereas early warning and evacuation of the population to cyclone shelters reduce the exposure and vulnerability of communities to cyclone winds and floods. Both interventions affect risk but in a different way, and DRR strategies often consist of a set of complementary interventions to reduce risk (Jongman 2018).

This chapter sets the stage for enhancing coastal resilience by providing an overview of the coastal system in terms of the biophysical landscape, the socioeconomic characteristics, and the natural hazards and associated risks. First, the coastal zone is described from a detailed "exposure perspective" to understand the existing physical and ecological system and present the current infrastructure and the communities occupying the coastal zone (Section 2.1). Next, a detailed "hazard perspective" is provided, depicting the types and frequency of hazards that currently affect communities and infrastructure (Section 2.2). This is followed by a detailed description of the relevant ongoing trends in terms of both hazard and exposure that will very likely continue in the decades to come as a result of climate change (such as SLR) and socioeconomic developments (such as population growth and migration) (Section 2.3). Finally, the concluding remarks set the stage for the next chapters of this report (Section 2.4).

2.1. Coastal Landscape and Dynamics

2.1.1. Landscape and Dynamics

Bangladesh's semitropical climate is humid, warm, and primarily driven by the southwest monsoon and partly by pre-monsoon and post-monsoon circulations. Average temperatures are about 26 degrees Celsius and generally vary between 15 and 34 degrees Celsius throughout the year. The warmest months coincide with the rainy season (March-September), while there is less rainfall during the winter months (December-February). Nearly 80 percent of the country's annual precipitation occurs during the summer monsoon season, bringing large amounts of fresh water to the coastal zone. Severe local storms and cyclone events frequently occur during the months of March-May and October-November, driven by the formation of local depressions due to low-pressure conditions in the Bay of Bengal.

The coastal landscape of Bangladesh is predominantly shaped by the confluence of three large rivers: the Ganges-Padma, Brahmaputra-Jamuna, and Meghna (GBM), forming the largest delta in the world and delivering an enormous amount of sediment to the Bay of Bengal. This system discharges approximately 1 billion tonnes of sediment per year, which accounts for about 10 percent of the world's sediment input from rivers to the ocean (Brown and Nicholls 2015). The natural shape of Bangladesh's coastal zone is controlled by the underlying geology and topography of the delta and the dynamic interaction between the influx of water and sediment, coastal processes such as tides and wave action, and episodic events such as cyclones and monsoon rainfall. This interaction between water motion, sediment movements, and the topography of the coastal zone is called "morphodynamics" which governs the spatial and temporal changes of the coastline and the tidal rivers (Syvitski and Saito 2007). It is common to encounter tidal riverbanks eroding and accreting, chars (newly deposited land in the river) being formed and then migrating and disappearing, and eroding and accreting coastlines. This is an ever-evolving process of nature adapting to constantly changing conditions at different temporal and spatial scales and is an inherent characteristic of coasts in general, and the Bangladesh coast in particular (see **Box 2.1**).

Especially over the past 200 years, human interventions in the coastal zone have resulted in changes to the pristine coastal landscape. The most prominent change is the transformation of the southwest and southern part of the coast. Previously, the footprint of the Sundarbans mangrove forest in the southwest was twice as large, covering the coastal zone further north and further east up the Meghna estuary. Between roughly 1841–1954, mangrove forests were cleared and transformed into areas suitable for agriculture (International Water Association 2019). Initially, these areas were only protected from coastal flooding through seasonal infrastructure provision, but gradually—and especially since the 1960s—more permanent embankments were constructed, resulting in the present system of 139 polders. Other relevant large-scale infrastructure interventions affecting the coastal landscape have been various closure dams (such as the Meghna Cross Dams, the Feni Closure) to reclaim land in the Meghna estuary, and the construction of the two main seaports (Chattogram and Mongla) and their access navigation channels with associated dredging requirements. These interventions have caused, and are still causing, changes in physical processes such as the propagation of the tide into the estuary, and sedimentation and erosion patterns along the coast and tidal rivers.

Today, this evolving coastal landscape has an ecosystem in which physical and biological processes are at play at different temporal and spatial scales with many interactions. From an ecosystem perspective, the coastal zone can be divided into four different abiotic and biotic environments (**Figure 2.2**, that can be characterized as follows (Haque and Nicholls 2018 and Rashid 2019):

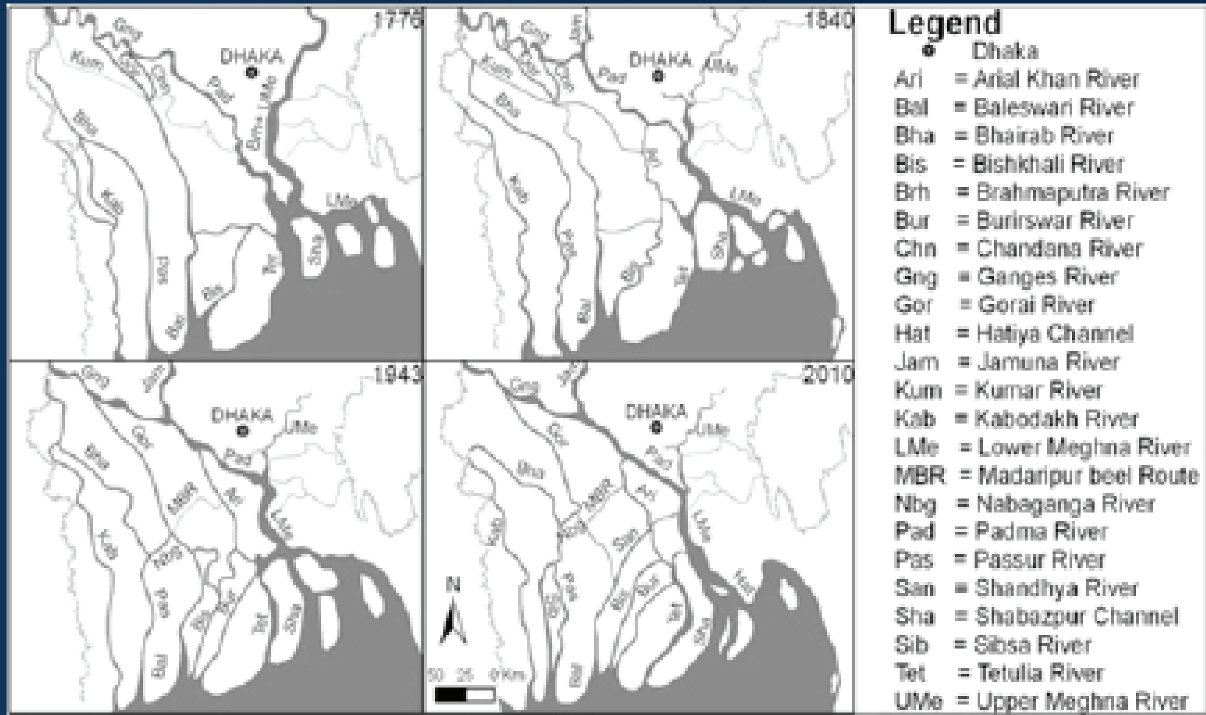
The Ganges Tidal Plain West includes the Sundarbans mangrove forest, which creates a natural coastal buffer zone of about 50 to 60 kilometers. Upstream of the Sundarbans, until about 125 kilometers from the coastline, is a vast system of low-lying polders surrounded by a complex river network. This area has a dense network of drainage channels with low gradients with overall limited freshwater inflow from the Ganges, mostly through the Gorai River. Still, the interior part of the coastal zone is subject to monsoon flood events. The semi-diurnal tide has a tidal range of up to 3 meters at the coast, causing it to propagate far upstream through the large tidal rivers (for example, the Pussur-Sibsa system). For instance, near the city of Khulna, the tidal range is still 1.5 meters. There is

Box 2.1: Delta Morphology

The three large rivers, the Ganges-Padma, Brahmaputra-Jamuna, and Meghna deliver most of the water and sediment to the GBM delta, which is separated from the Chattogram region by the Feni River. The Ganges-Padma discharges water at an average rate of 11,000 cubic meters per second and about 550 million tonnes of sediment per year (Akter et al. 2016). The Brahmaputra-Jamuna brings an additional 20,000 cubic meters per second of water and approximately 600 million tonnes of sediment towards the GBM delta region. These two rivers join the Meghna River and deliver approximately 1 billion tonnes of sediment through the Lower Meghna River to the coastal zone (Akter et al. 2016). It is considered a tide-dominated delta, meaning the tide, compared to waves and rivers, is the driving force in delta morphology. In some places, the tide can propagate more than 100 kilometers inland (Brown and Nicholls 2015). Although its relative importance may change because of human interventions, it is expected that the tide will become even more dominant in the future (Nienhuis et al. 2020).

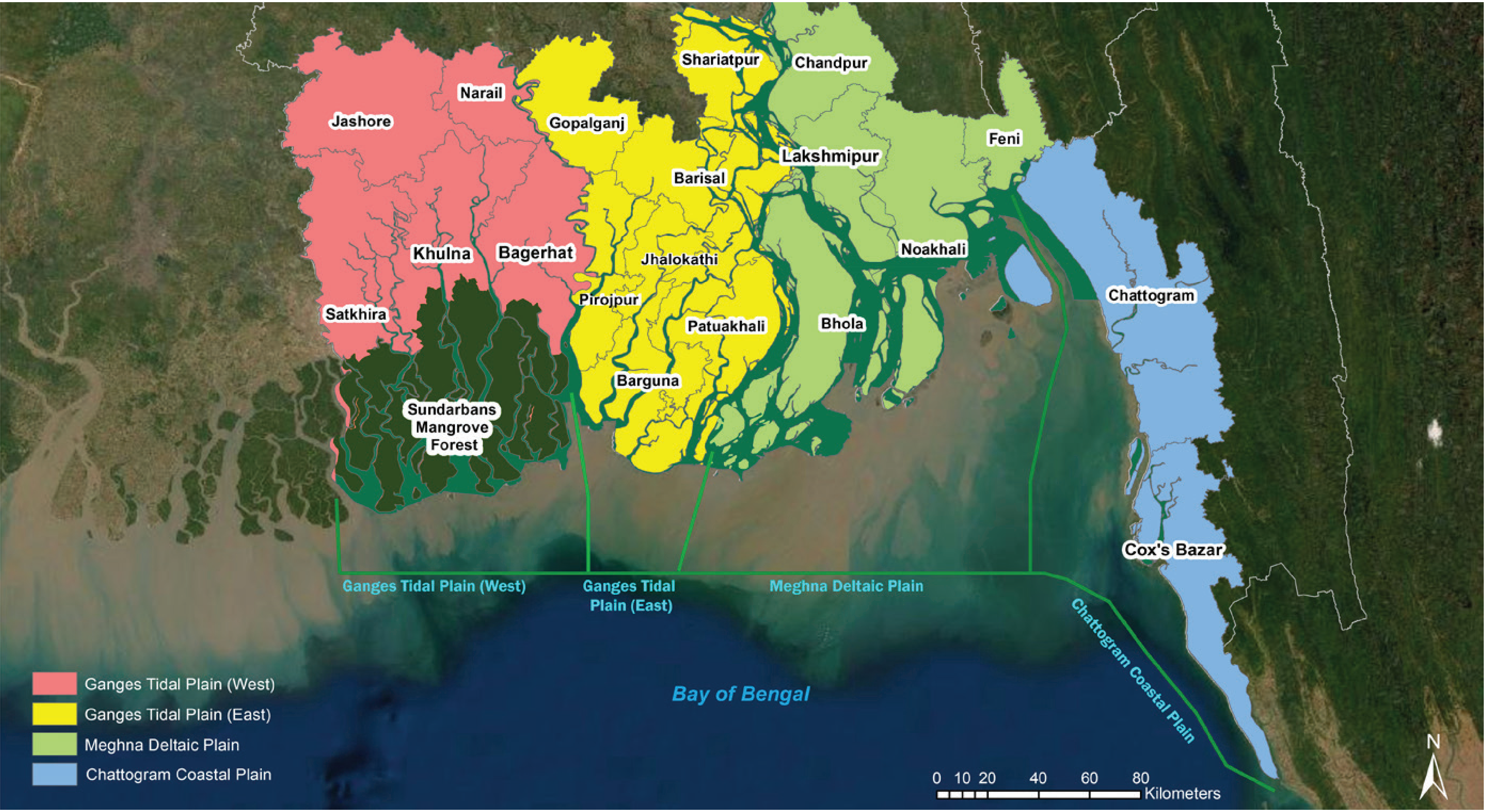
Over the course of multiple decades, the landforms of the delta have constantly changed, resulting in the shifting and disappearance of existing rivers and the creation of new rivers. This can be seen clearly in **Figure 2.1,** which illustrates the evolution of rivers over the last 250 years. The modification of the river network has also changed the distribution of water and sediment to different parts of the coast. The result of this is a progradation of the delta towards the east and a large accretion of land in this region (Sarker, Akter, and Rahman 2013). This shifting process is expected to continue in the coming decades, although it may be altered by human modifications upstream (such as dam development).

Figure 2.1: Shifting of the Main Rivers in Bangladesh over the Last 250 Years



Source: Sarker, Akter, and Rahman 2013.

Figure 2.2: Delineation of the Four Ecosystem Zones in the Coastal Region



Source: Map developed by the World Bank for this report based on data from the BDP 2100 (Baseline Volume 1, pg. 403), Humanitarian Data Exchange, World Bank, ESRI ArcGIS, Maxar, Earthstar Geographics, USDA FSA, USGS, Aerogrid, IGN, IGP, and the GIS User Community.

Biodiversity in the Sundarbans mangrove forest: (clockwise from top left) the crested serpent eagle, the king cobra, the masked finfoot, and the spotted deer.

Fishermen and birds coexisting in coastal Bangladesh.

Waterbirds of the Meghna Estuary: (clockwise from top left) the Spoon-billed Sandpiper, Indian Skimmers, the Asian Dowitcher, and Egrets.

some cyclic erosion and sedimentation occurring along the tidal rivers, while the open coast is predominantly eroding. Cyclones can generate extreme water levels and wind speeds in this area. Apart from the open coastline, waves are generally limited to locally generated wind waves.

The Sundarbans mangrove forest (including the part located in India) is a globally unique ecosystem because of its size, the variety of mangrove species, and the abundance and diversity of its flora and fauna. It covers 6,017 square kilometers in Bangladesh (Dasgupta et al. 2021) and has 13 out of the 35 known mangrove types. The biotic diversity comprises 400 species of fish, 53 species of reptiles, over 330 species of birds, and 50 species of mammals, and includes large animals such as spotted deer, crocodiles, and tigers. Fish species include finfish and shellfish, such as shrimp and prawn, lobster, crabs, snails, mussels, cuttlefish, and squid. Marine animals like sharks, rays, seahorses, whales, dolphins, turtles, and sea snakes also live in this region. The mudflats exposed during low tide are rich in microorganisms that are ideal feeding grounds for migratory birds. The Sundarbans are home to 17 globally threatened species, including the Pallas's fish eagle (Haliaeetus leucoryphus), the Gyps bengalensis vulture, and the Aquila clanga spotted eagle (Sarkar 2017). The Bangladesh portion of the Sundarbans was declared a Ramsar site in 1992 under the Convention on Wetlands and is therefore recognized as a wetland site of international importance. In addition, the GoB has created three wildlife and three dolphin sanctuaries in the north of the Sundarbans along the Pussur, Shela, and Bhola Rivers.

The Ganges Tidal Plain East has a flat topography with most areas located just above MSL. There is an extensive system of polders from the open coastline to about 60 kilometers inland. The area is intersected by several rivers that receive fresh water from the Lower Meghna River and from the Padma River via the Arial Khan River. The tidal range along the coast is high (3.5 meters) but decreases further inland. The tidal rivers show cyclic behavior of erosion and sedimentation, with morphological hotspots often located in the laterally migrating river bends. However, the magnitude is generally limited to a few meters per year. Most of the coastal area is subject to structural erosion at a similar rate. Cyclones are the predominant cause of extreme wind speeds, water levels, and waves in this area, especially in the more exposed regions near the coast. Patches of the Sundarbans mangrove forest (although limited in number) are located at the coastline, with similar biotic characteristics as described above.

The Meghna Deltaic (Estuary) Plain is a very dynamic and flat estuarine coastal system as a result of the main outflow of the GBM system being in this area. It has several very large polder systems, such as Bhola island, which has a surface area of more than 300,000 hectares. Some interior parts of the Meghna Estuary experience elevated water levels during the monsoon season. Storms and cyclones can further generate high water levels in this area. The tidal range is very high, with values of up to 6 meters near Sandwip island. Large quantities of sediment are continuously transported to the shallow coastal shelf, where it is reworked by the interaction of tides and waves. The Meghna Plain has an outbuilding coastline, indicating that new land is being formed at a rate faster than the erosion of existing land in this area. Therefore, the planform of the region is rapidly changing, with certain areas advancing more than 100 meters or more per year.

The Meghna Estuary is an extraordinarily rich ecosystem due to the mix of tidal and river waters, the continuous supply of sediments and nutrients, and remote intertidal areas. The islands in the estuary mouth are a strategic location in the East Asian-Australasian Flyway, housing waders and other waterbirds during the winter months. More than 100,000 birds visit this area, among which are critically endangered birds like the Spoon-billed Sandpiper, Nordmann's Greenshank, the Asian Dowitcher, and the Great Knot. As per a shorebird and waterbird survey conducted in the Meghna Estuary in 2016, Spoon-billed Sandpipers were counted, along with nine globally near threatened and threatened species of shorebirds—Spotted Greenshanks, Great Knots, Eurasian Curlews, Black-tailed Godwits, Bar-tailed Godwits, Red Knots, Curlew Sandpipers, Little/Red-necked Stints, and Asian Dowitchers (S. U. Chowdhury et al. 2018). These birds feed themselves with benthic organisms, mollusks, crustaceans, and marine worms. The intertidal areas in the estuary also serve as the nursery and feeding ground for many fish species, such as the Hilsa and Panga.

The Chattogram Coastal Plain is a relatively narrow and flat coastal area with a steep gradient in the coastal hinterland. Between Chattogram and Cox's Bazar, there is a narrow strip of small polders along with a few polders further south of this point. The tide ranges from 6 meters in the far north to about 3 meters near Teknaf (the southernmost upazila in Bangladesh). The coastal strip is directly exposed to winds and storm surges originating from cyclones and tropical depressions. Additionally, the steep gradient, and the tendency of hills to generate intense rainfall events, produce rapid runoff events. The rivers and other drainage channels across the flat coastal plain cannot safely convey these episodic downpours, leading to flash floods in the region. Sediment is delivered to the coast by small rivers originating from the hilly hinterland. The predominant wave direction from the south generates a large longshore transport of sediments towards the north, redistributing river sediments along the coast and causing time-varying erosion and deposition.

This region has a large variety of ecosystems, with some small pockets of natural mangrove forests, small estuaries, sand dunes, and beaches. One mangrove area of ecological importance is located in the low-lying (saline) swamp at the mouth of the Matamuhuri River delta (near Cox's Bazar). This area, known as Chakoria Sundarbans, provides a habitat for a variety of marine and terrestrial organisms (Prince et al. 2018). Another area of ecological interest is the Teknaf Peninsula, which has one of the longest sandy beach ecosystems in the world (80 kilometers) (M. S. N. Chowdhury et al. 2011). This area has a mixture of mangroves, mudflats, lagoons, beaches, and sand dunes. It provides breeding grounds for two globally threatened species of marine turtles and is located along multiple international bird migration flyways. To protect the rich biodiversity along the coast, the region has three protected areas: Cox's Bazaar – Teknaf Wildlife Sanctuary, Himchhari National Park, and Inani National Park.

2.1.2. Infrastructure Systems

The coastal zone houses various infrastructure systems that provide essential services to coastal communities, as well as being of strategic importance to the economy of Bangladesh. They ensure protection against flooding (polder embankment systems), enable the transportation of people and goods (roads, waterways, ports), provide essential health and social services (health centers, schools), and allow agriculture, aquaculture, and other economic activities to take place in the polder systems (water management systems). The four main infrastructure systems—water management infrastructure, road and rail infrastructure, inland waterway transport infrastructure, and social infrastructure—are briefly summarized below.

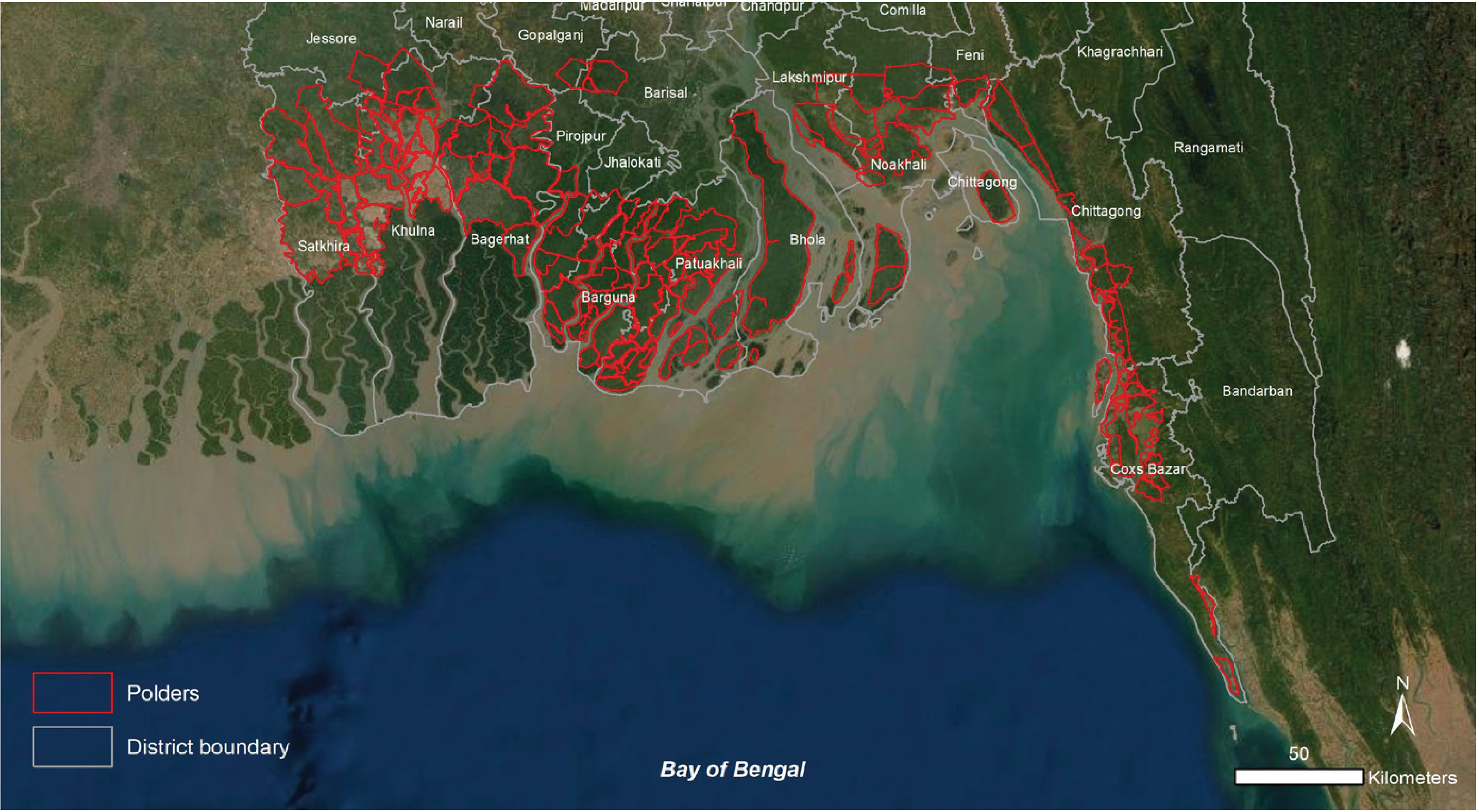
Water Management Infrastructure

In the early 1960s, the first set of 108 coastal polders was constructed within the Coastal Embankment Project (CEP), reshaping the coastal zone and forming the infrastructure backbone of the coastal districts. Polders prevent saline water from entering agricultural fields, thereby boosting agricultural productivity and providing food security for the millions of people living in the polder areas. On top of that, they protect against frequent tidal flooding, thereby preventing damage to people and crops and stimulating economic development for the local polder communities (M. Zaman 1983).

Currently, there are 139 polders across the coastal zone, covering an area of 1.2 million hectares (25 percent of the coastal zone). While the average size of a polder is about 9,000 hectares, they vary widely, with roughly 80 percent of the polders having a size of between 2,000 and 20,000 hectares (see **Figure 2.3**). Although originally the polders were designed to protect against tidal flooding only, recently, as part of the Coastal Embankment Improvement Project Phase I (CEIP-I), the first set of polders are being rehabilitated to protect against storm surges in addition to tidal flooding. Moreover, these upgraded designs being implemented by CEIP-I have taken projections of climate change into consideration.

The polders are characterized by two main water infrastructure elements: coastal embankments surrounding the polder and an extensive drainage system inside the polder. In total, there are about 6,000 kilometers of embankments in the coastal zone (Dasgupta et al. 2011), most of which are earthen embankments with a grass cover and a road on top. The elevation of these embankments varies but is typically 2 to 4 meters above ground level. Where necessary, there

Figure 2.3: Location of Embankments that Delineate Polder Boundaries



Source: Map developed by the World Bank for this report based on data from the BWDB, World Bank, ESRI ArcGIS, Maxar, Earthstar Geographics, USDA FSA, USGS, Aerogrid, IGN, IGP, and the GIS User Community.

Water management infrastructure (a drainage sluice) under construction.

Water management infrastructure (a drainage sluice) for Polder 35/3).

is slope protection on the outer side of the embankment to protect against cyclone-induced waves and to ensure stability at places where river and coastal erosion is taking place. Given the lack of rock in Bangladesh, slope and bank protections are typically designed and made using cement concrete blocks.

The polders are crisscrossed by a gravity-based drainage network that consists of small canals (khals), and large drainage and flushing sluices to regulate the water level and drain excess water out of the polder. The khals are typically a few meters wide and relatively shallow and connect the drainage structures with the interior of the polder. When originally built, drainage structures within the embankment system connected the internal drainage system with the adjacent river network to drain excess water from the polder area. As time went on, agricultural practices developed among farmers to cultivate winter Boro rice inside the polder. For this winter agriculture, farmers started to take fresh water and store it for later use. As such, sluices constructed initially only for drainage purposes started being used for drainage and flushing. However, the use of a one-way drainage sluice to allow reverse flows has damaged these structures. The CEIP-I is now constructing both drainage and flushing structures as two-way regulators to drain excess water from the polder to the river but also allow the river water to enter into the polder area.[7] It is estimated that the 139 polders together have approximately 8,000 kilometers of canals, more than 1,300 drainage structures, and more than 1,700 regulators.[8]

Road and Rail Infrastructure

The coastal zone has a dense road network connecting the rural communities to the large urban centers (Chattogram, Khulna, Barisal). Moreover, the primary roads form the main hinterland transport network that connects the three

Coastal embankment, slope protective works, slope plantation, and turfing in Polder 32.

A khal (small canal) in a coastal polder.

coastal seaports (Chattogram, Mongla, and Payra) with the rest of Bangladesh. In Bangladesh, there are six categories of roads: national highways, regional highways, zila roads, upazila roads, union roads, and village roads A and B. The arterial network of national highways, regional highways, and zila roads are under the jurisdiction of the Roads and Highways Department. They comprise a length of 13,700 kilometers in the coastal zone, most of which is paved. The Local Government Engineering Department (LGED) is responsible for the remaining road categories, of which approximately 65 percent of the roads are unpaved. LGED's earthen unpaved road network is extensive in the coastal zone, covering a total of about 83,556 kilometers (**Table 2.1**), and includes the roads that are located on top of the many polder embankments.

The main road access to the coastal zone is through the national highway system. Towards the west, national highway N8 connects Dhaka with Jashore and further to the Indian-Bangladesh border (see **Figure 2.4**). The important economic locations, including Mongla port and Khulna (via the N7), Gopalganj (on the N805), and Barisal (on the N8), are also connected to this national highway system. Travel times between the western coastal zone and the northern and eastern areas of the country will be significantly reduced when the Padma Multipurpose Bridge project is completed in 2022, enabling the transport of passengers and freight across the Padma River (the main distributary of the Ganges). The main highway towards the eastern part of the coastal zone is national highway N1, which connects Feni, the city and port of Chattogram, and Cox's Bazar, and runs towards Teknaf Upazila and the border with Myanmar.

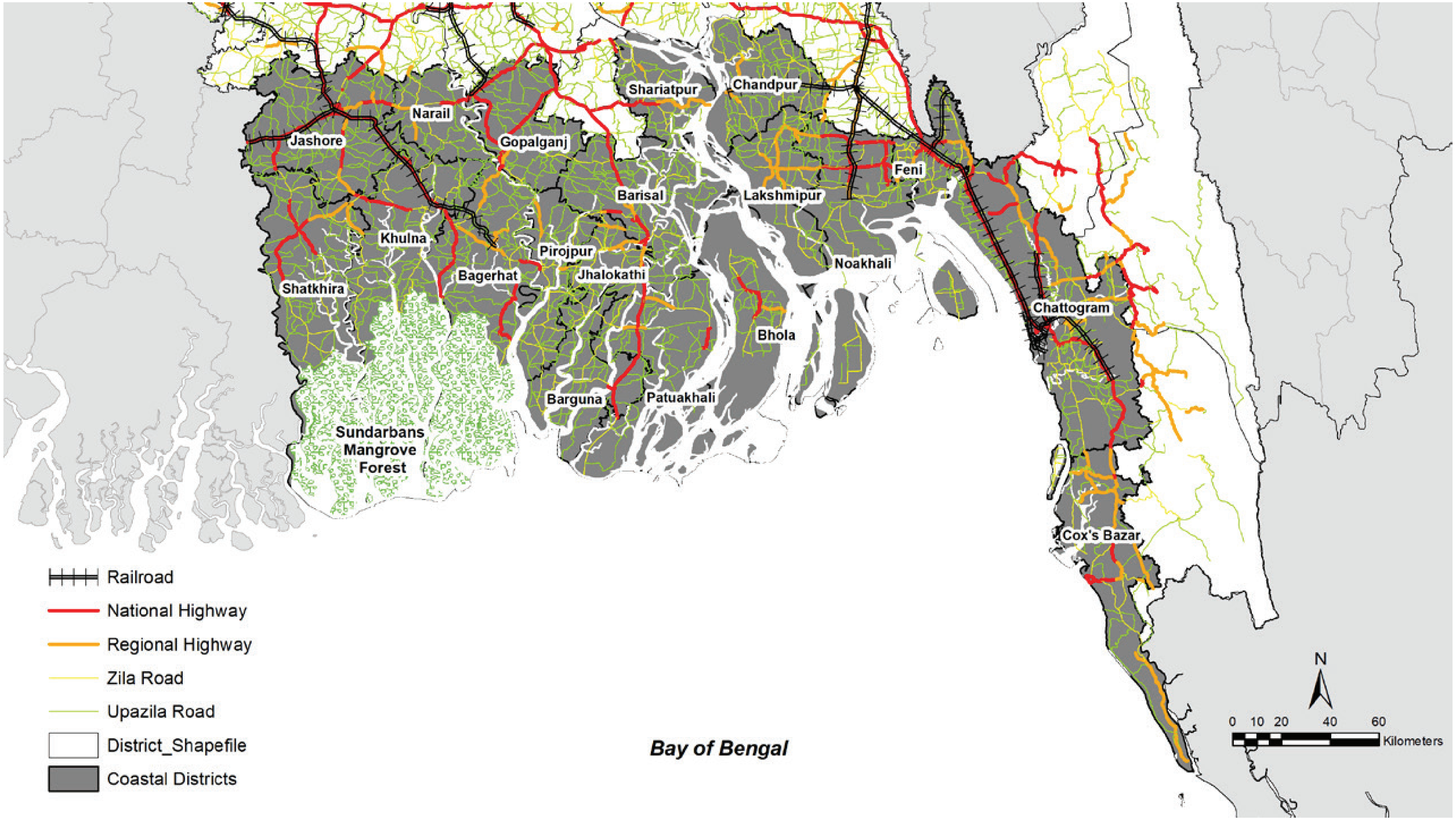
Rail networks are scarce in the coastal zone. The western railroad ends in Khulna and connects the city with India and northwestern Bangladesh. The eastern railroad connects the city of Chattogram with northern Bangladesh, including Dhaka. This railroad is particularly important for freight movement between the port of Chattogram and Dhaka, which is more cost and time efficient than if done by truck or inland water transport. On a yearly basis, almost 90,000 20-foot equivalent units of containers travel between the port of Chattogram and the Dhaka Inland Container Depot (JOC 2019).

Table 2.1: LGED Coastal District Road Network

Coastal District	Earthen Road (km)	Paved Road (km)	Total (km)	Earthen Road (%)	Paved Road (%)
Khulna	3,224	3,211	6,435	50%	50%
Bagerhat	4,197	2,548	6,745	62%	38%
Bhola	3,039	2,518	5,557	55%	45%
Barisal	7,745	2,933	10,678	73%	27%
Shatkhira	4,075	2,422	6,497	63%	37%
Patuakhali	9,812	2,525	12,337	80%	20%
Noakhali	6,599	3,696	10,295	64%	36%
Chattogram	9,290	4,782	14,072	66%	34%
Cox's Bazar	2,887	1,543	4,430	65%	35%
Jashore	5,979	3,260	9,239	65%	35%
Narail	1,997	994	2,991	67%	33%
Gopalganj	2,511	2,322	4,833	52%	48%
Pirojpur	2,889	1,877	4,766	61%	39%
Jhalokathi	3,047	1,114	4,161	73%	27%
Barguna	4,872	1,470	6,342	77%	23%
Shariatpur	2,014	1,479	3,493	58%	42%
Lakshmipur	3,850	1,948	5,798	66%	34%
Chandpur	3,642	2,098	5,740	63%	37%
Feni	1,887	2,112	3,999	47%	53%
Total	**83,556**	**44,852**	**128,408**	**65%**	**35%**

Source: LGED Road and Market Database as of June 2021 (https://oldweb.lged.gov.bd/ViewRoad2.aspx).

Figure 2.4: Overview of the Road Network in the Coastal Zone



Source: LGED Road and Market Database as of June 2021 (https://oldweb.lged.gov.bd/ViewRoad2.aspx).
Note: Only highways, zila roads, and upazila roads are shown.

Inland Waterway Transport Infrastructure

Water transport is a major mode of transport for the movement of goods and people in Bangladesh. The country has about 6,000 kilometers of waterways that are navigable for mechanized vessels, of which about 3,800 kilometers are accessible year-round (World Bank 2007). This navigable river system falls under the jurisdiction of the Bangladesh Inland Water Transport Authority and can be categorized into four classes with different characteristics in terms of minimum draught (Classes I – IV). The Bangladesh Inland Water Transport Authority, together with the Bangladesh Inland Water Transport Cooperation, manages a total of 2,000 passenger launches and 22 inland ports, which include about 800 launch ghats and terminals, throughout the country (W. Zaman 2020). Apart from mechanized vessels, traditional country boats have been plying inland and coastal waters for hundreds of years. Several hundred thousand of these country boats still operate in Bangladesh and play a key role as a rural mode of transport.

The coastal zone has a dense network of navigable waterways, especially in its western portion. There is a Class I navigable waterway with a maximum draft of about 4 meters between Dhaka and Chattogram, and between Dhaka, Barisal, and Khulna via the port of Mongla. The two largest inland ports in the coastal zone are the ports of Chattogram and Mongla. Oceangoing vessels can enter these ports with a maximum draft of 8.5 and 6 meters, respectively, from the Bay of Bengal. To accommodate the expected growth in trade in the future, a number of new port projects are being prepared or are already under development. These projects include terminal expansions for the ports of Chattogram and Mongla, the construction of a new deep-sea port near Cox's Bazaar (Matarbari Port), and further development phases of the newly constructed Payra Seaport (Port Strategy 2020). These port developments should facilitate the expected doubling of container traffic by 2040 (Asian Development Bank 2015), and better connect the coastal zone with international land and sea corridors (such as the Belt and Road Initiative).

Social Infrastructure

Educational and Healthcare Facilities

Educational and healthcare facilities are the main types of social infrastructure in the coastal zone. In total, the coastal zone has about 21,500 educational facilities, ranging from kindergartens to universities (HDX, n.d.).[9] There are more school facilities in the interior coastal zone (13,250) than the exposed coastal zone (8,250), reflecting the difference in population density. In Bangladesh, many of these primary educational facilities are constructed by the LGED. In recent investment programs (for example, the Multipurpose Disaster Shelter Project (MDSP), school facilities have been integrated into the construction of cyclone shelters, also known as multipurpose disaster shelters (see the following discussion).

There are a total of 719 healthcare facilities in the coastal zone — 483 located in the interior coastal zone and 236[10] located in the exposed coastal zone. Information regarding the size and service level of these facilities was not available at the time of reporting.

Multipurpose Disaster Shelters

Multipurpose disaster shelters are a specific type of infrastructure and are found throughout the entire coastal zone. At present, approximately 5,000 multipurpose disaster shelters are strategically located across the coastal zone, with a higher density in the most at-risk areas. They have been built to provide a safe haven for millions of people during cyclone events. One of the first major projects to construct cyclone shelters was the World Bank supported Cyclone Protection and Coastal Area Rehabilitation Project, which began in 1971 after devastating Cyclone Bhola hit the country in November 1970. Since then, there have been more multipurpose disaster shelter projects. Following Cyclone Sidr (2007), new programs, such as the Emergency 2007 Cyclone Recovery and Restoration Project (ECRRP) and the MDSP have been initiated to rehabilitate and build new shelters. The MDSP, which was approved in 2014, is expected to result in the construction of 550 new shelters, the rehabilitation of 450 shelters, and the construction of 550 kilometers of rural roads to improve accessibility. It is estimated that a total of approximately 7,000 multipurpose disaster shelters will be needed by 2025 to improve disaster resilience across the coastal zone (World Bank 2020).

Generally, disaster shelters are multistory buildings (2 or 3 floors) with about 300 square meters of floor space made of concrete with an open space at ground level (Miyaji, Okazaki, and Ochiai 2020). The capacity of existing shelters typically ranges between 600 to 1,500 people, with an average of 1,000 people (LGED 2010). The density of shelters and their accessibility differ by location. An analysis of the locations of households and shelters (see **Box 2.2**) found that an estimated 50 percent of the coastal population have a shelter within a 2-kilometer distance from their house, although this number ranges from 0.6 kilometers in Cox's Bazar and Bhola to more than 4 kilometers in Khulna, Noakhali, and Barisal.

These cyclone shelters often serve multiple purposes, functioning as schools, community centers, and medical facilities throughout the year, and as disaster shelters during cyclones. For instance, of the 4,000 shelters included in the LGED's shelter database (LGED 2010), approximately 80 percent function as educational facilities, while only 7 percent have no multipurpose use. The shelter programs instituted after Cyclone Sidr included innovations such as inclusive design elements of universal accessibility, consideration of gender-sensitive requirements (for example, separate sanitary facilities and rooms for nursing mothers), water supply, rainwater harvesting, and solar panels (Faruk, Ashraf, and Ferdaus 2018). Ramps were also included for livestock accessibility as were designated spaces for the animals. In addition, more recent shelter designs use materials that can withstand very high wind speeds.

2.1.3. Population, Livelihoods, and Wellbeing

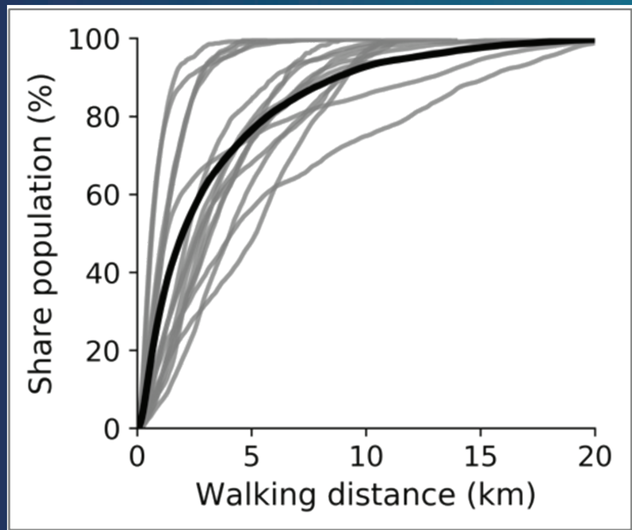
Coastal communities are spread across the entire coastal zone and engage in different economic activities. Four aspects of these communities are discussed in the following sections—population, housing and public services, economic activities, and poverty and wellbeing.

Box 2.2: Accessibility of Cyclone Shelters

The accessibility of cyclone shelters is an important factor that determines the success of large-scale evacuations (Mallick 2014). As a first order indicator, the walking distance between households and the closest shelter can be used to measure accessibility. In Figure 2.5, the distribution of the population with respect to their walking distance to the closest shelter is depicted for 16 of the 19 coastal districts (grey lines) that have shelters and the population weighted average across these districts (black line). The data is based on synthetic household data of the districts (Rubinyi, Hall, and Gussenbauer 2021), including the geographical locations of households, and of cyclone shelters.

Across all coastal districts, 50 percent of the population live within a 2-kilometer radius of a cyclone shelter, while 90 percent live within an 8.7-kilometer radius.

Figure 2.5: Walking Distance between Households and Cyclone Shelters



Source: Analytics performed by the World Bank for this report.
Note: The light grey lines depict the distribution per district, and the thick black line is the distribution for the coastal zone as a whole.

Swarna Kazi

A multipurpose disaster shelter and primary school in coastal Bangladesh.

A multipurpose disaster shelter functioning as a primary school.

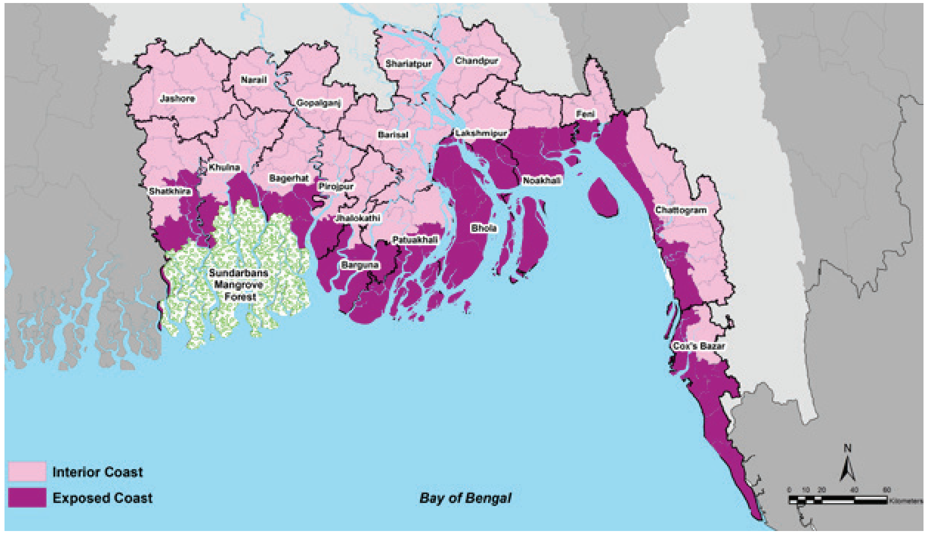
Population

The coastal zone has 19 districts with approximately 43.82 million people of which around 27.04 million live in the interior coastal zone, while the remaining 16.78 million live in the exposed coastal zone (see **Figure 2.6**). The average density in the coastal zone is some 930 persons per square kilometer (Bangladesh Bureau of Statistics 2022).[11] The population density generally increases away from the coast: the interior coast has roughly a 50 percent higher population density than the exposed coast (1,180 versus 770 people per square kilometer) (see **Figure 2.7**). Despite this coast-inland divide, the population is quite evenly spread throughout the coastal zone. About 70 percent of the upazilas in the coastal zone have a population density of between 500 and 1,500 people per square kilometer.

There are 10 upazilas with a high population density (greater than 10,000 people per square kilometer); five upazilas west of the Meghna Estuary—Jashore, Khulna, Khalispur, Sonadanga, and Palong—which are all located in the interior coast, and five upazilas east of the Meghna Estuary—Chattogram port, Double Mooring, Pahartali, Panchlaish, and Chandgaon—which are all located in the exposed coast (all within Chattogram district). Approximately 77 percent of the coastal population reside in rural areas, with Satkhira district considered the most rural, and Khulna and Chattogram the most urban districts.

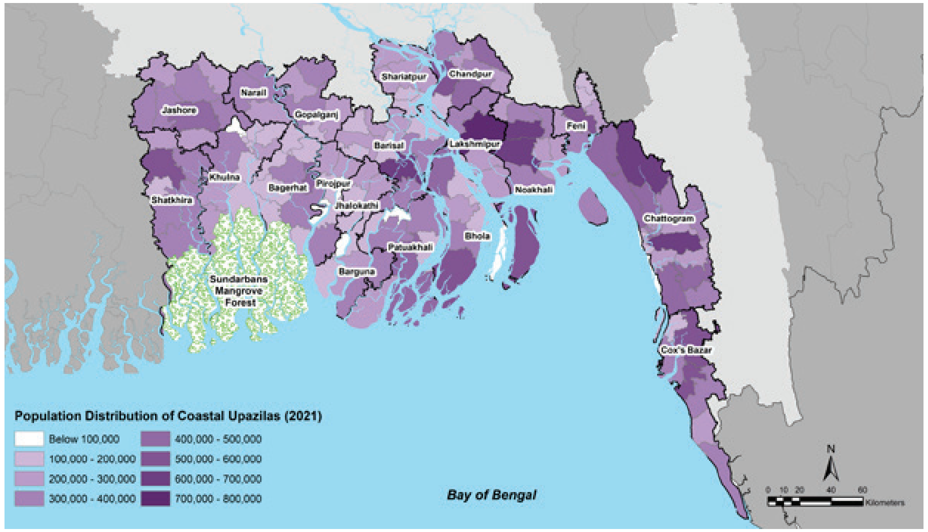
The demographics of the coastal zone are similar to Bangladesh as a whole, on most levels. The country has a relatively young population, with about 40 percent under 20 years old. The average number of people per household in the coastal zone is about five, although this is slightly declining, which mirrors

Figure 2.6: Coastal Upazilas of Bangladesh by Exposed Coast and Interior Coast



Source: Map developed by the World Bank for this report based on data from the Humanitarian Data Exchange, the Program Development Office for Integrated Coastal Zone Management Plan, and the World Bank.

Figure 2.7: Population Distribution of the Coastal Upazilas of Bangladesh, 2021



Source: Map developed by the World Bank for this report based on data from the Bangladesh Bureau of Statistics, the Humanitarian Data Exchange, and the World Bank, projected for 2021.

the national average (Szabo, Ahmad, and Adger 2018). Although more men than women are born, the sex ratio across the entire population is 0.95 (i.e. 95 men for every 100 women). The fertility rate has decreased significantly, from approximately seven in the 1960s to approximately two in 2020. Life expectancy has increased significantly, from about 40 years in the early 1950s to over 70 years in 2018, with women living longer than men (74 versus 71) (Bangladesh Bureau of Statistics 2019). However, some districts have lower life expectancies than the average, for example in Barisal, it is only 70 years for women (Szabo, Ahmad, and Adger 2018). Infant mortality in Bangladesh dropped to about 65 percent over the period between 1989 and 2014 (Khan and Awan 2017). Infant mortality tends to be lower than the national average in the western coastal zone, while the eastern districts are lagging behind (Szabo, Ahmad, and Adger 2018).

Housing and Public Services

Residential housing quality varies widely throughout the coastal zone. The types of housing in the coastal zone range from permanent to temporary and can be classified into four categories based on the quality of the roof and walls: pucca (improved housing made of brick and concrete), semi-pucca (improved housing with the foundation made of brick and concrete, and the walls and roof made of corrugated iron sheets), kutcha (unimproved housing made of earthen plinths with bamboo and walls made of organic material), and jhupri (unimproved temporary housing made of straw or bamboo). Typically, the housing quality in urban centers is better compared to more rural areas. On average, about 20 percent of the coastal population live in improved housing, although there is a large variation between districts (for example, 7 percent live in improved housing in Barguna compared to 42 percent in Khulna) (Bangladesh Bureau of Statistics 2011). The number of houses of better quality has been increasing over the last several years and it is expected that by 2050, the vast majority of households will live in improved housing (Dasgupta et al. 2014).

Sanitation and drinking water are two essential public services for coastal communities. The coverage of sanitation was about 55 to 57 percent in 2010 (Joint Monitoring Programme 2012) and does not differ very much between urban and rural areas in Bangladesh. Still, disparities between income groups are prevalent. People living in poor households are 10 times more likely to use unimproved sanitation than households in the richest quantile (Bangladesh Bureau of Statistics and UNICEF Bangladesh 2014). Access to clean drinking water is much higher (85 percent) and predominantly achieved by piped water and tube wells. The number of households utilizing piped water has increased in the coastal zone, yet the main source of water remains tube wells (Argos et al. 2010; Hossain, Dearing, et al. 2016). Arsenic is a major threat to the water supply in both rural and urban areas. Arsenic in water has adverse health impacts, and an estimated 50 million people in Bangladesh are currently exposed to arsenic through drinking water (Ahmad, Khan, and Haque 2018). In the coastal zone, this issue is particularly relevant for the Khulna and Chattogram divisions. There is similar access to electricity as there is to sanitation, with 53 percent of the coastal population having access to an electricity supply, although with large disparities between upazilas (from a low of 7.1 percent to a high of 99.2 percent) (Bangladesh Bureau of Statistics 2011).

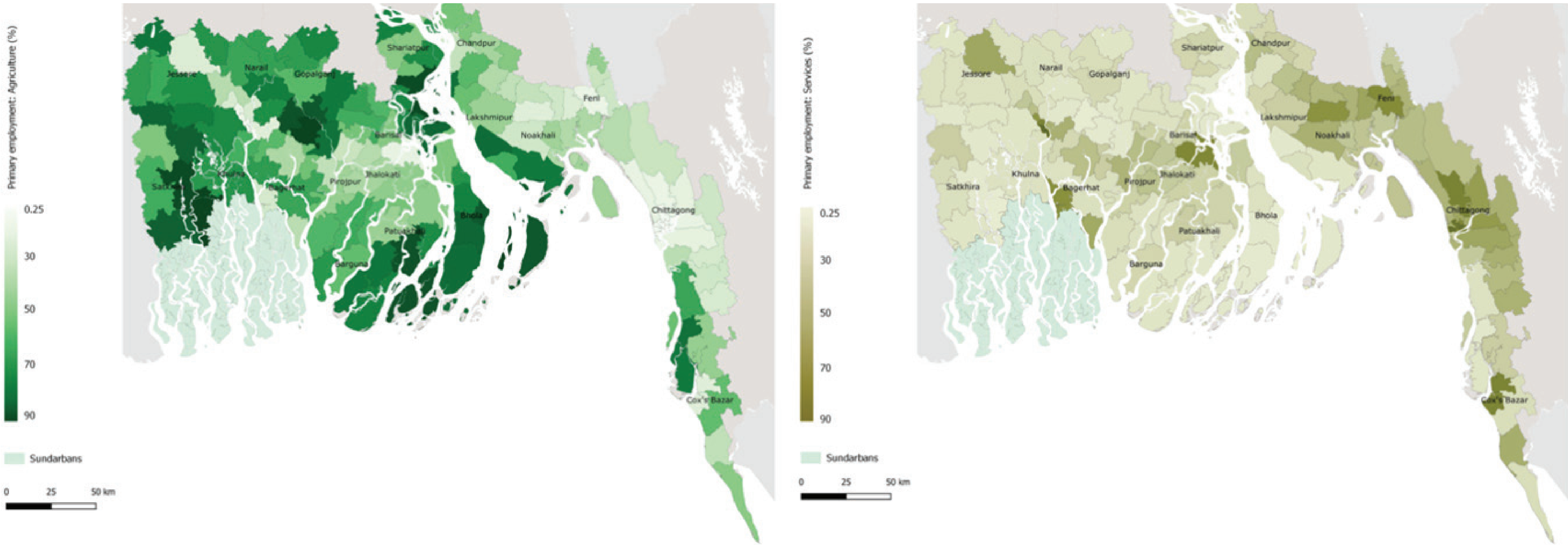
The access to and quality of education and healthcare also provide insight into the living conditions of coastal communities. As of 2019, the literacy rate in Bangladesh was about 75 percent (UNESCO Institute for Statistics, n. d.). A literacy survey from 2008 found that the literacy rate in rural areas is 12 percent lower than that of urban areas, whereas differences across the country and between men and women are small (Bangladesh Bureau of Statistics 2008). Access to primary education has improved significantly in the coastal zone, from 23 to 47 percent between 1993 and 2010, including a closing of the gender gap in education access (Hossain, Johnson, et al. 2016). Access to necessary healthcare remains challenging for people living in the coastal areas, particularly the marginalized and disabled (Huda et al. 2020). These areas suffer from a lack of appropriate health facilities and skilled healthcare providers. Still, between 1993 and 2010, the percentage of births attended by skilled personnel increased from about 10 to 40 percent in the coastal zone (Hossain, Johnson, et al. 2016).

Economic Activities

A majority of the coastal population is highly dependent on agriculture as a source of income and for food security. This is especially true for the polder areas, which are dominant in the Ganges Tidal Plain West and East and the Meghna Estuary. In 2013, 1.2 million hectares of land were being utilized for agricultural purposes within the embankment system, which represents almost 15 percent of Bangladesh's total arable land (World Bank 2013).

The main crops in the coastal zone are cereals, pulses, vegetables, fruits, and cash crops like jute and sugarcane. Rice is the predominant crop, and includes variants like Aus, Boro, and Aman rice. The traditional cropping pattern is to plant Boro rice during the Rabi season (mid-November to mid-March), allow the land to lie fallow during the Karif-1 season (mid-March to mid-July), and use transplanted Aman rice during the Kharif-2 season (mid-July to mid-November) (Lázár et al. 2015). In total, the agricultural sector employs 4.6 million people, which is 46 percent of total coastal employment. This number is even higher in some upazilas (up to 81 percent), as can be seen in **Figure 2.8**.

Figure 2.8: Primary Employment in the Agriculture (left) and Services (right) Sectors at the Upazila Level



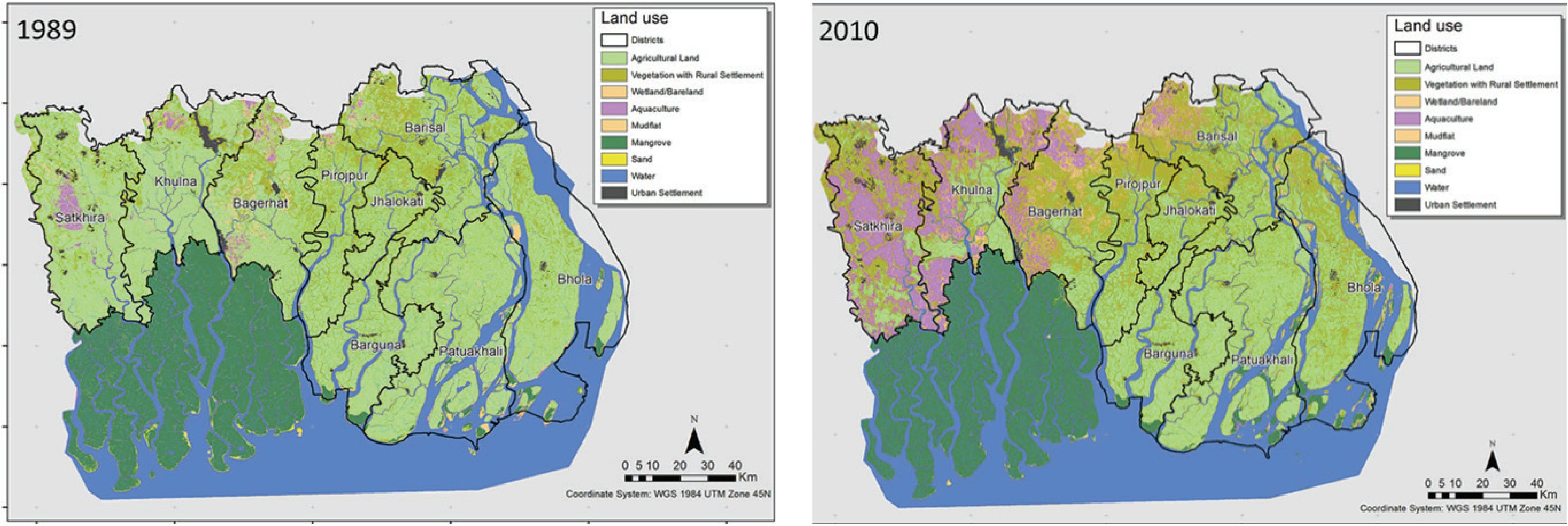
Source: Bangladesh Bureau of Statistics 2011.

The ship-breaking and recycling industry is another important economic activity, mainly concentrated in Chattogram. This activity converts end-of-life ships into steel and other recyclable parts. It provides direct employment to about 30,000 people and contributes to the creation of indirect jobs (such as downstream recycling and services). Employment in the service sector is high near Chattogram, Cox's Bazar, and Barisal (**Figure 2.8**).

Fishing is an increasingly important economic activity in the coastal zone, generating income and employment for around 2.5 million people. The amount of marine captured fish was approximately 650,000 tons in 2018 (Shamsuzzaman et al. 2020), of which Hilsa shad is the predominant species.

Aquaculture has grown rapidly in the past few decades in the polders around Cox's Bazar and Chattogram in the southeast, and near Jashore and Khulna in particular in the southwest (see **Figure 2.9**). Bangladesh exports about 40,000 tons of shrimp, which is equal to approximately 2 percent of the global shrimp market (Shamsuzzaman et al. 2020). Shrimp farming is predominantly carried out in aquaculture ponds in areas where the soil and water have become too saline for agricultural production. Both brackish water shrimp (bagda) and freshwater shrimp (galda) are produced in small-sized farms that cover more than 200,000 hectares (Mukhopadhyay et al. 2018). Shrimp farming has large monetary benefits compared to agriculture, explaining its widespread adoption. Households engaged in shrimp farming earn three to four times

Figure 2.9: Rapid Expansion of the Aquaculture Area in the Western Coastal Zone between 1989 and 2010



Source: Mukhopadhyay et al. 2018.

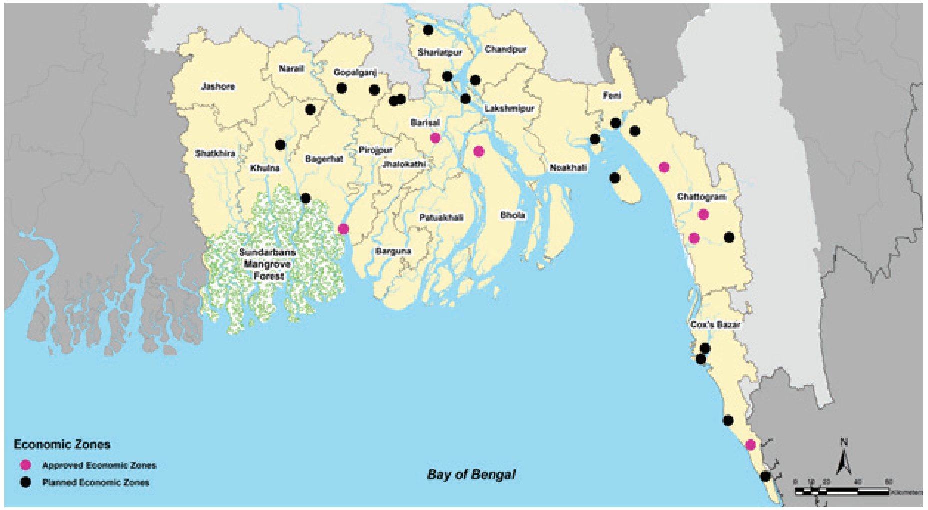
more compared to households engaged in agriculture (Hossain, Johnson, et al. 2016). However, shrimp farming is associated with negative consequences, such as livelihood displacement, income loss, environmental impacts (such as soil toxicity) and food insecurity (Mukhopadhyay et al. 2018; Nath, van Laerhoven, and Driessen 2019). Hence, despite the economic benefits of shrimp farming, studies indicate that it may not be a sustainable solution to counteract poverty and could even increase local poverty rates (Amoako Johnson et al. 2016).

Other important activities in the coastal zone are industrial and commercial activities, services, forestry, salt production, ship-breaking and recycling, and tourism (General Economics Division, Bangladesh Planning Commission 2018). The three main city centers of Chattogram, Khulna, and Barisal are hubs for commercial and industrial activities. In addition, several special economic zones (SEZs) have been established in Bangladesh, which are intended to boost foreign direct investment, employment, and exports, all contributing to economic growth (**Figure 2.10**). As of 2019, there were a total of 88 SEZs. Most of the large SEZs in the coastal zone are near the airports and seaports, thereby benefiting from efficient transport networks and logistics services. By 2025, the GoB intends to establish another 12 SEZs throughout the country, including in the coastal zone.

Salt production has a long tradition in Bangladesh and is concentrated in the southeast near Chattogram and Cox's Bazar. This activity is economically important for about 1 to 1.5 million people in the coastal zone.

Tourism, although still in its infancy in Bangladesh, is a major contributor to the service sector. In 2018, the tourism sector comprised 4.4 percent of total GDP. The country has seen a rise in international tourists, with 1.02 million visiting Bangladesh in 2017—23 percent higher than 2016 (Deb and Nafi 2020). However, domestic tourists far outweigh international tourists, with about 10 million people travelling domestically within Bangladesh every year (Deb and Nafi 2020). Cox's Bazar is a well-developed tourist destination, with natural and cultural attractions. The Sundarbans, Kuakata Beach, and St. Martin's Island also attract both local and foreign visitors.

Figure 2.10: Locations of Approved and Planned Special Economic Zones in Coastal Bangladesh



Source: Map developed by the World Bank for this report based on data from the Humanitarian Data Exchange, BEZA 2020, and the World Bank.
Note: Only the planned SEZs that could be geolocated are included in the map and therefore not all planned SEZs are depicted.

Poverty and Wellbeing

Wellbeing covers multiple dimensions of the quality of human development, reflected, among others, by the differences in livelihoods opportunities and living standards. Poverty and wellbeing are intrinsically linked (ODI 2012). The coastal belt of Bangladesh is among the poorest regions of the country, with a GDP per capita (in 15 out of the 19 coastal districts) that is below the national average, notwithstanding that Chattogram and Khulna are relatively advanced among the coastal districts of Bangladesh. However, defining and measuring poverty is often controversial, as measuring poverty in terms of income (as GDP per capita) alone does not capture the multidimensional nature of poverty.

Mahfuzul Hasan Bhuiyan

Ismail Ferdous


Mahfuzul Hasan Bhuiyan

Mahfuzul Hasan Bhuiyan

Agricultural activity in a coastal polder.

A fisherman in coastal Bangladesh.

Bangladesh uses a "Cost of Basic Needs" approach to measuring poverty, which calculates the cost of a bundle of basic consumption needs (food and non-food allowances) compared to income. Using this approach, the poverty rate in Bangladesh was equal to 24.3 percent in 2016. Poverty is more prevalent in the coastal region, with almost 60 percent of all coastal upazilas having an above average poverty incidence and the more urban areas, such as Chattogram, having considerably lower poverty rates (Bangladesh Bureau of Statistics 2016).

Multidimensional poverty indices combine both monetary indicators and non-monetary indicators (for example, school attendance, nutrition, electricity, cooking fuel) (Alkire and Foster 2011). For instance, malnutrition in children is prevalent in Bangladesh; in 2012, 33.8 percent of children were underweight and 7.9 percent were severely underweight. The underweight rates in the coastal zone are somewhat lower than the national average. The numbers indicate that 47 percent of coastal upazilas have an underweight percentage that is higher than the national average and 53 percent have a lower one. Moreover, 43 percent of the coastal upazilas have a severe underweight percentage that is higher than the national average, and 57 percent have a lower one (World Food Programme 2012). Indicators of education and living standards have been discussed in previous sections.

Migration

Migration is a complex phenomenon, driven by a diverse set of push (i.e. low wages, environmental degradation, natural disasters) and pull (i.e. more jobs, higher wages) factors. Migration can be either temporary or permanent. Temporary migration is common in the coastal zone and involves seeking temporary opportunities (of about six months) in terms of better earnings, schooling, and urban amenities (Bernzen, Jenkins, and Braun 2019). In terms of permanent migration, two-thirds of permanent migration is from rural to urban. In 2011, almost 10 percent of the total population of Bangladesh were lifetime migrants (Bangladesh Bureau of Statistics 2011). The main driver for migration out of the coastal zone is a combination of environmental stressors, economic vulnerability, and the prospect of remittance income (Szabo, Ahmad, and Adger 2018). Exposure to natural hazards can spur migration, although the evidence is mixed. For instance, one study showed that households exposed to crop failures and flood events are more likely to migrate (Gray and Mueller 2012), while others report that certain factors prevent people from migrating, with migration seen as a last resort (Penning-Rowsell, Sultana, and Thompson 2013). For instance, after Cyclone Aila in 2009, a study (Saha 2017) found that households were reluctant to migrate but felt they had no other option than to move to the city of Khulna.

2.2. Coastal Hazards

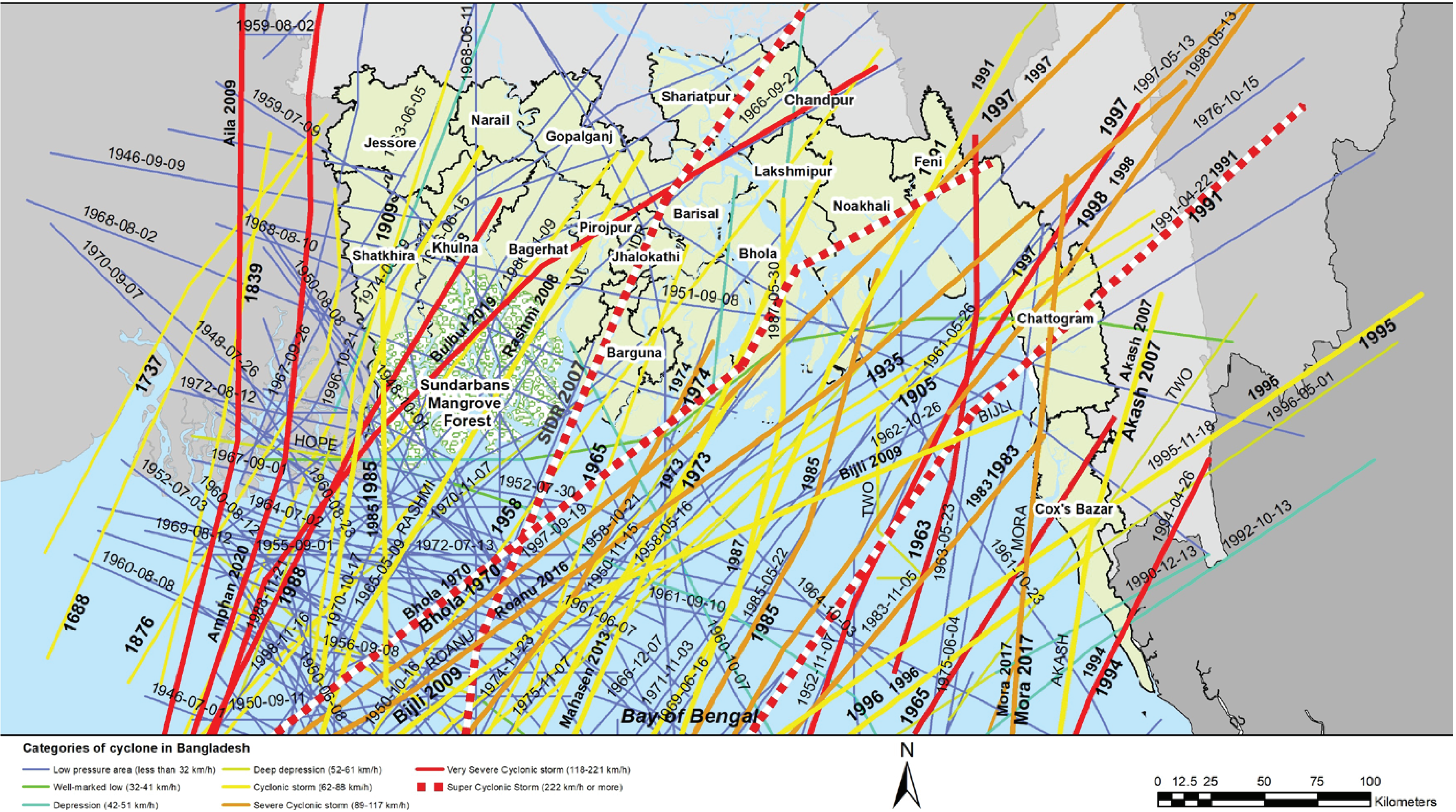
The coastal zone of Bangladesh is prone to climate-related coastal hazards, including episodic events and long-term stressors. The most pronounced hazard is the occurrence of cyclone events. Slow-moving chronic stressors are also prevalent, such as coastal and river erosion, waterlogging, subsidence, and salinity intrusion. These chronic stressors can result in loss of land, infrastructure failures, difficulties in operating the polder drainage systems, and reduced agricultural productivity. A synopsis of these coastal hazards is provided below.

2.2.1. Cyclones

The coastal zone of Bangladesh is prone to tropical cyclone events, originating from low atmospheric pressure fields over the Bay of Bengal. Cyclones generally occur in early summer (April-May) and the late part of the rainy season (October-November) and usually follow a northeasterly track. They are accompanied by strong winds, storm surges, waves, and rainfall. Although cyclone activity in the Northern Indian Ocean alone accounts for only 5 percent of global cyclone activity, 65 percent of all reported loss of life occurred in this area (Woodruff, Irish, and Camargo 2013). Indeed, numerous devastating cyclone events have occurred in the past, following different tracks and intensities (see **Figure 2.11**). On average, Bangladesh is hit by one cyclone per year (winds > 63 km per hour). Cyclones affecting the region with strong sustained winds (> 118 km per hour) have an average frequency of once every three years (Islam and Peterson 2009; Dasgupta et al. 2014). The spatial variation of cyclone landfall locations in Bangladesh is limited. Analysis of historical records (between A.D. 1000 and 2009) shows that the major urban centers of the coastal zone (Khulna, Barisal,

Asif Aminur Rashid

Figure 2.11: Tracks of Major Cyclones along Coastal Bangladesh (1685-2020)



Source: Map developed by the World Bank for this report based on data from the Humanitarian Data Exchange, the United Nations Environment Programme, the Bangladesh Meteorological Department, and the World Bank.

Chattogram) have each been struck by a comparable number of 40 to 50 tropical cyclones (Alam, Momtaz, and Calgaro 2012). However, other analysis has found that the frequency of occurrence of landfalling cyclones is slightly higher in the west of the coastal zone (0.25 cyclones per year) than the east (0.16 cyclones per year) (Islam and Peterson 2009).

The cyclone wind speeds in the coastal zone vary depending on inland decay, differences in topography, and the presence of vegetation, such as the Sundarbans mangrove forest. Typically, there is an abrupt change in wind speed when a cyclone crosses the coastline because of the cutoff of the moisture supply that fuels the cyclone (Kaplan and DeMaria 1995; Li and Chakraborty 2020). As it moves inland, maximum sustained winds decrease further due to the friction of the land surface. This decay depends on a range of factors, such as the forward speed of the cyclone, the type of vegetation, and the topography. The highest wind speeds along the coastal zone are found in the Ganges Tidal Plain, the outer islands in the Meghna Estuary (Sandwip), and a small strip along the Chattogram-Cox's Bazar coastline. In these areas, the 50-year wind speed exceeds 280 km per hour (Housing and Building Research Institute 2018). Further inland, near coastal cities such as Khulna and Barisal, the wind speed for this extreme condition is somewhat lower but still very significant (240 km per hour). The Sundarbans mangrove forest dampens the wind speed for the western part of the coastal zone, resulting in lower extreme wind speeds.

In addition to strong winds, cyclones are accompanied by storm surges striking the coastal zone. Storm surges generated by tropical cyclones are further amplified close to the coast (especially in the eastern part of Bangladesh), which can be attributed to the phenomenon of the re-curvature of tropical cyclones in the Bay of Bengal and the shallow, funnel-shaped, coastal shelf that amplify surges (Islam and Peterson 2009; Dasgupta et al. 2010). The tidal phase and amplitude are also key factors that determine storm surge levels. Due to the interaction of the aforementioned factors, the Meghna Estuary region has experienced the highest storm surges. Typical storm surge levels for severe cyclones range from 3 to 5 meters but reached more than 10 meters during Cyclone Bhola in 1970, which was the most devastating event in recent history (Dasgupta et al. 2010). Storm surges can travel far inland along the tidal river branches and thus cause high water levels around polder embankments, even a long distance from the coast. For instance, surge levels in the western tidal channels can be as high as 4 to 6 meters for extreme surges (for a 100-year event) (see Chapter 3).

Cyclone winds also generate waves, which mainly affect exposed locations along the coast. These waves are generated by strong winds in the deep ocean and propagate towards the shoreline. The shallow bathymetry near the coast results in the partial breaking of these waves, which limits the wave height. The coastal areas that are most exposed to these waves are the polder areas along the coastline west of the Meghna Estuary, the polders in the mouth of the Meghna Estuary, and the Chattogram-Teknaf coastal strip. Typical nearshore wave heights during cyclones in these areas are 2 to 4 meters. Within the tidal rivers and the Meghna Estuary, locally generated wind waves occur, but these are often smaller (1 to 2 meters) due to the limited width of the rivers and the reduced wind speed further inland.

Cyclones can also bring a large amount of rainfall, severely compounding a cyclone's impact, although rainfall during the monsoon period is generally higher. The low-lying flat areas in the Meghna Estuary and the western part of the coastal zone often experience high precipitation intensities during cyclone activity. Since water levels are also elevated and drainage sluices are manually operated, the drainage of excess rainwater during these events is generally limited, potentially causing waterlogging problems. However, the impact of heavy rainfall during cyclones is most severe in the southeast because of its steep topography inland. For example, Cyclone Komen (2015) brought 800 millimeters of rainfall to Chattogram in three days and 1,000 millimeters to Cox's Bazar over a period of 10 days (Wiltgen 2015), resulting in flash floods and a number of landslides in the area.

2.2.2. Coastal and River Erosion

A dynamic boundary between land and water is a key feature of the coastal zone of Bangladesh. Erosion is the process of inland movement of the land-water boundary, while accretion is defined as land movements in the opposite direction. The dynamics of erosion and sedimentation is the result of a complex interplay between currents and waves, and the transport of suspended (ranging from fine sand to silt and clay) and mobile bed sediments. These dynamics are partly the result of inherent natural dynamics ("free behavior") but are increasingly driven by human interferences ("forced behavior") (De Vriend 2003). The land-water boundary can naturally move hundreds of meters per year in some locations in the coastal zone. While a large part of the coastline experiences erosion, some large patches of land have emerged due to a surplus of sediment, in particular in the Meghna Estuary (Brammer 2014). Examples of human-induced impacts in the coastal zone resulting in erosion are dredging activities to deepen port access channels and the construction of coastal and riverbank protections, which interrupt sediment flows.

There are three types of erosion in the coastal zone of Bangladesh: tidal riverbank erosion in the Ganges Tidal Plain areas, estuarine erosion in the Meghna Estuary, and shoreline erosion at the exposed coastline.

- ***Riverbank erosion*** along the tidal rivers in the Ganges Tidal Plains West and East occurs mainly in river bends (**Figure 2.12**). Erosion here is primarily caused by the regular tidal currents. In the outer bends of the river, the current velocities are high, causing the cohesive sediment to erode because of the hydrodynamic forces exerted on the riverbank. In addition, cyclones and monsoon events can accelerate erosion in certain cases. The typical erosion rate in these river bends can be in the order of 10 meters per year in some cases.

- ***Estuarine erosion*** in the Meghna Estuary is part of a continuous and gradual cycle of delta formation (Sarker, Akter, and Rahman 2013) and is by far the most severe type of morphological change in the entire coastal zone. The large supply of sediment from the GBM river system towards

Coastal erosion in coastal Bangladesh.

the estuary results in net accretion, with the estuary mouth building in the southward direction at an average annual growth rate of 19 square kilometers (**Figure 2.12**). During this process, large tidal channels change course, resulting in considerable land loss. A typical erosion rate in this area is several tens of meters per year but can well exceed hundreds of meters per year in certain places.

- ***Shoreline erosion*** along the Bay of Bengal can be seen west and east of the Meghna Estuary (**Figure 2.12**). To the west of the Meghna Estuary, a consistent pattern of slow but structural erosion has been observed over the past few decades. The typical erosion rate in this area is about 10 meters per year, with waves and tides reworking the sediment lost. Structural erosion is likely a combination of long-term changes in river flow and sediment supply, and changes in the division of water and sediment over the various rivers in the delta. These changes can be attributed to both human and natural causes, such as SLR, the construction of dams upstream, increased tidal asymmetry from the construction of polders, and siltation in upstream rivers. East of the Meghna Estuary, there is structural erosion both south and north of Chattogram, mainly due to wave-induced longshore sediment transport. Further south, the coast shows pockets of net erosion as well as accretion. This area experiences alternating periods of accretion and erosion associated with the dynamic coastal environment.

2.2.3. Subsidence

A combination of natural and anthropogenic processes causes structural subsidence in the delta area, although with large spatial variations. Vertical land movements are driven by several factors, including tectonics, glacial-isostatic adjustment, and subsidence. Natural subsidence occurs from the compaction of young sediments in deltas (Brown and Nicholls 2015). Moreover, human-induced subsidence from groundwater extraction, drainage of organic soils, and the starvation of sediments due to the construction of engineering structures locally (e.g. flood defenses) or upstream (e.g. dams) can accelerate the sinking of deltas (Nicholls et al. 2021). For instance, it was estimated that the compaction from sediment loading over the last 11,000 years in the coastal zone is between 1.5 and 2.4 millimeters per year (Krien et al. 2019). In total, subsidence is estimated to be approximately 5 to 10 millimeters per year in the coastal zone within the CEIP-I (CEIP-I 2021a), which is in line with estimates found in the literature (Brown and Nicholls 2015; Becker et al. 2020). However, locally, there can be variations in the subsidence rate. For instance, for the city of Khulna, the largest part of the city experiences vertical land movements of between +5 millimeters per year (uplift) and -5 millimeters per year (subsidence), while other parts experience up to -17 millimeters per year (subsidence) (see **Box 2.3**).

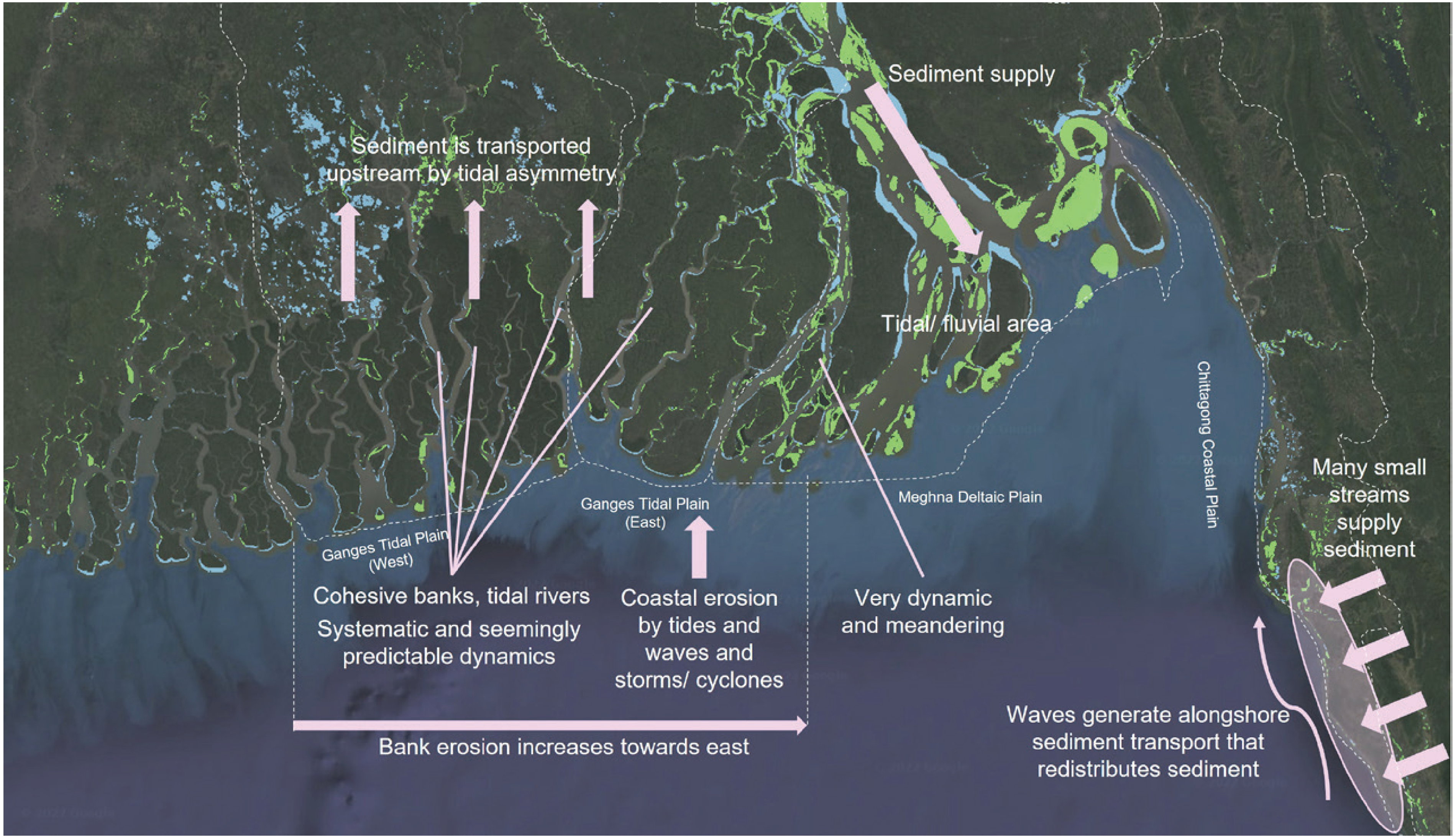
2.2.4. Salinity

Saline water intrusion in coastal areas is highly seasonal in Bangladesh due to the dynamic interaction between freshwater inflow and the salinity intrusion of tidal waters in the Bay of Bengal. Soil salinity is driven by salt accumulation in the soil because of water salinity, drainage, and evaporation. Water salinity is high in the coastal region from the deep inland propagation of the tide, in particular during low river flows (Clarke et al. 2015). Average salinity concentrations of the rivers generally increase almost linearly from October to late May, co-occurring with the gradual seasonal reduction in upstream freshwater inflow. In 2010, the Soil Research Development Institute stated that 63 percent of coastal land is affected by soil salinity of various degrees, with major impacts observed within the Khulna and Barisal districts (**Figure 2.14**). The reduction in freshwater inflow from the Ganges, but also the effects of the construction of the polder system, have increased dry season salinity levels in the western part of the Ganges Tidal Plain (**Figure 2.14**). Soil salinity is the dominant factor behind low crop productivity in the exposed areas. Salinity levels of up to four parts per thousand (ppt) are still suitable for farming, but values above five ppt will start affecting agricultural yields (Salehin et al. 2018).

2.3. Climate and Socioeconomic Change

Climate change is responsible for rising temperatures, changing precipitation patterns, intensifying extreme weather events, and an increase in sea levels. Bangladesh is one of the countries at the forefront of increased risk for climate-

Figure 2.12: Schematic Overview of Dominant Processes at the Coast Combined with Surface Water Changes Between 1985 and 2016 Reflecting Land Losses and Gains

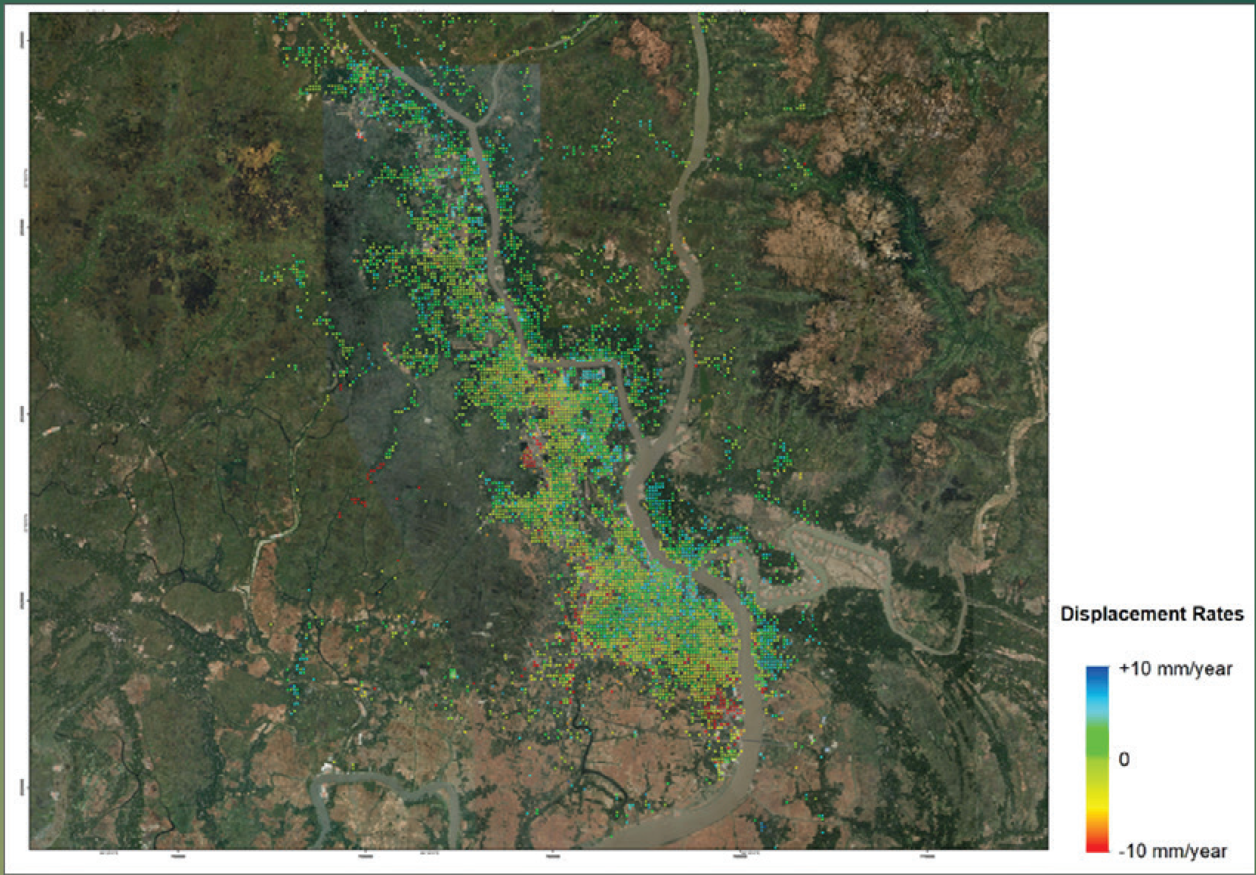


Source: Aqua Monitor, Deltares (http://aqua-monitor.appspot.com/) and based on Donchyts et al. 2016.
Note: Green and blue colors represent areas where surface water changes have occurred during the last 30 years. Green pixels show where surface water has been turned into land (accretion, land reclamation, droughts). Blue pixels show where land has been changed into surface water (erosion, reservoir construction).

Box 2.3: Measuring Subsidence from Space

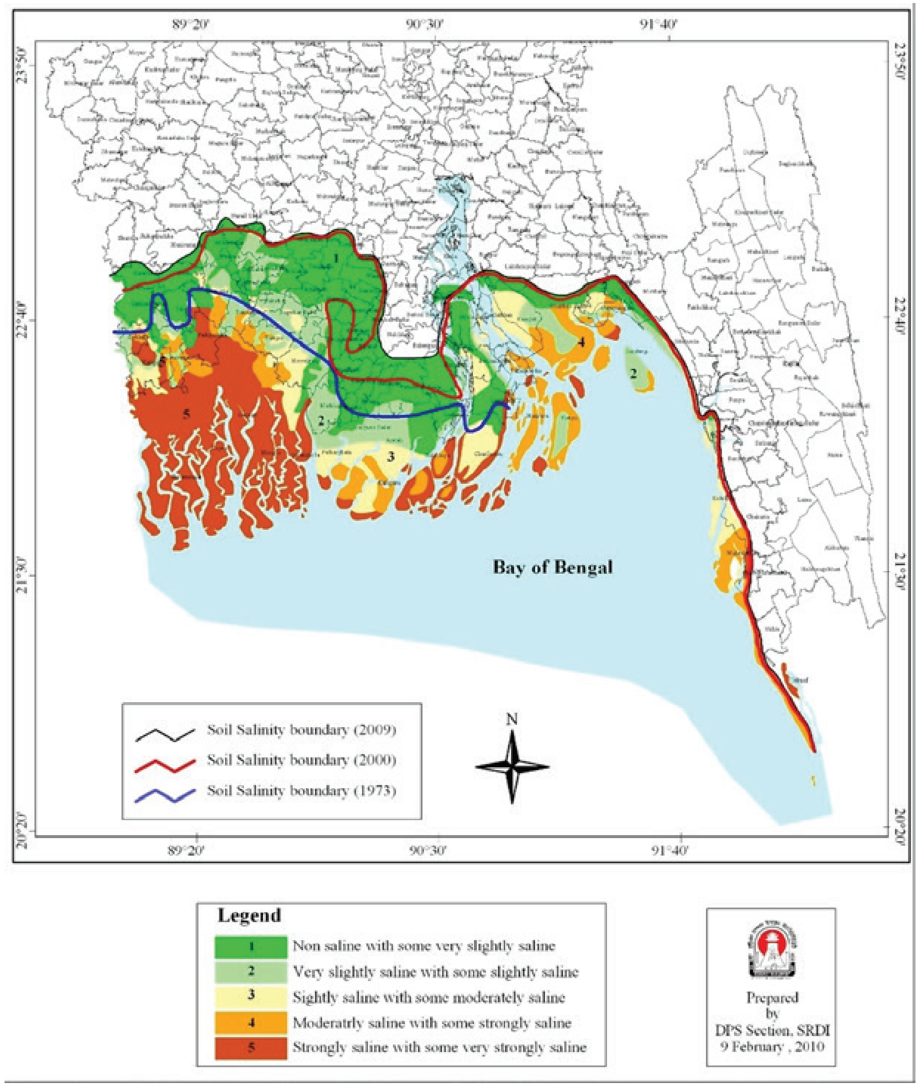
Measuring subsidence is often difficult because of the local variations in subsidence rates that require a dense measurement network, and the high cost of installation and maintenance of traditional measurement instruments (leveling or GPS). In recent years, the use of interferometric synthetic aperture radar (InSAR) allows measuring changes in land surface elevation from space at a high spatial resolution (Solari et al. 2018). This can be done for areas with stable radar reflectors (such as buildings, bridges) over time by making high resolution measurements of the change in the position of the reflectors by comparing two radar scans made for the same area but at different times. The example for the city of Khulna below was derived within the Earth Observation for Sustainable Development Project (European Space Agency 2020), which is an initiative of the European Space Agency. The change in elevation was measured for a period of three years (February 2017 to December 2019), during which 7,900 measurement points were obtained. It was found that 91 percent of the area of interest experiences a change of between -5 and +5 millimeters per year change, 6 percent between -5 and -10 millimeters, and 2 percent more than -10 millimeters per year. The uplift happens close to the riverbanks, while the large subsidence was measured in the western and southern parts of the city (**Figure 2.13**).

Figure 2.13: Local Displacement Rates in Khulna, February 2017 to December 2019



Source: European Space Agency 2020.

Figure 2.14: Salinity Map of the Coastal Zone indicating Soil Salinity Boundaries for 1973, 2000, and 2009



Source: Soil Resource Development Institute 2010.

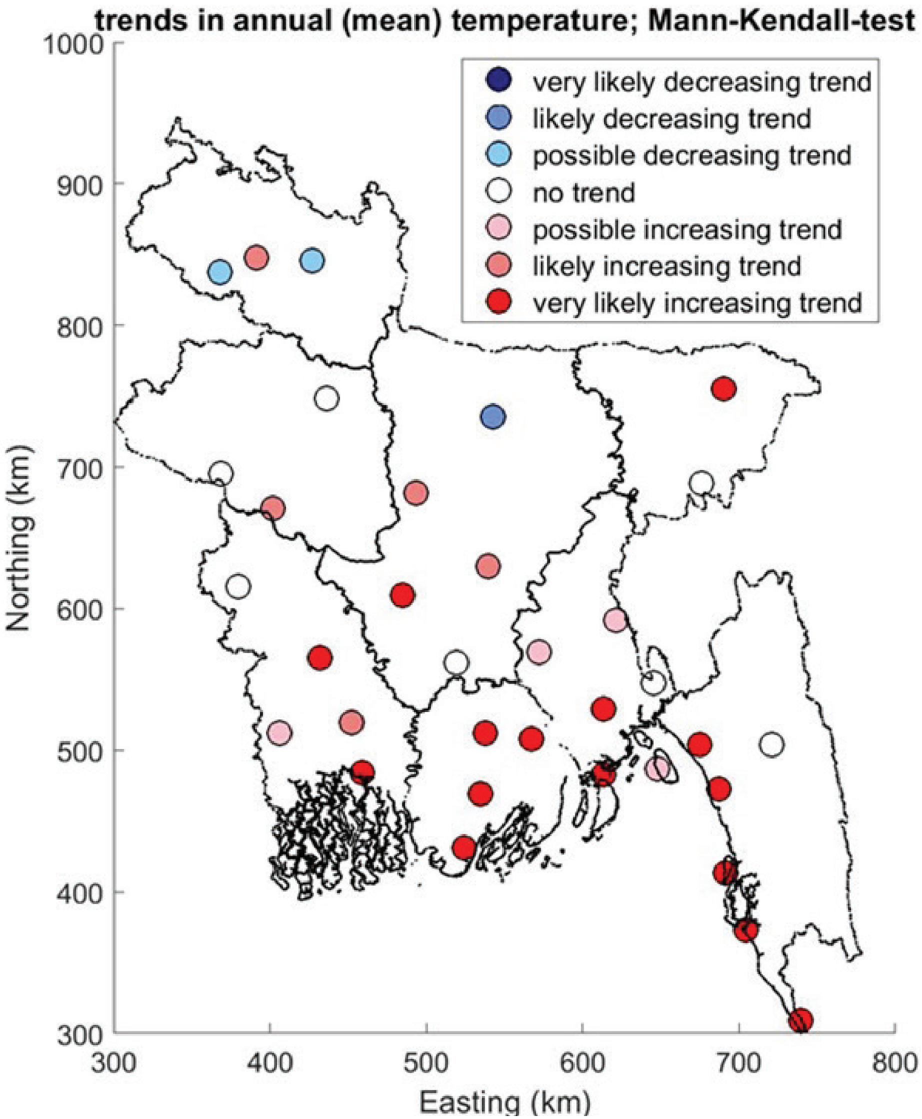
change-induced hazards. More specifically, it is particularly prone to SLR, more intensified flooding, and cyclone events. Moreover, the country is expected to experience high socioeconomic growth, leading to increasing pressures on the delta system. This section outlines the key climate and socioeconomic trends in the coastal zone.

2.3.1. Temperature

Temperatures are expected to rise, with a stronger rise in winter temperatures. There is agreement among predictions that the average temperature will increase significantly in Bangladesh. Across all climate models included in the Coupled Model Intercomparison Project Phase 5, a warming between 1.2 and 1.9 degrees Celsius is expected by 2050, depending on the emission scenario adopted (relative to 1986-2005). By the end of the century, the temperature is expected to have risen by 1.3 to 3.9 degrees Celsius. However, both the daily maximum and minimum temperatures are changing more rapidly than the daily mean temperature (10 to 20 percent higher). Warming is generally expected to be more pronounced for the winter months (see **Box 2.4**). By the end of the century, the average temperature will increase between 1.7 and 4.5 degrees Celsius during the winter months (December-February), while warming of 0.6 to 3.4 degrees Celsius is projected for the summer months (June-August). The warming is expected to be relatively uniform across the country (World Bank 2021).

As a result, heatwaves are expected to become more frequent. For the country as a whole, the number of days that the critical heat threshold (35 degrees Celsius) is exceeded could potentially double by the 2090s under the highest emission scenario (representative concentration pathway (RCP) 8.5) (World Bank 2021). A Mann-Kendal test of the annual mean temperature shows a likely increasing trend in the coastal zone (**Figure 2.15**).

Figure 2.15: Trends in Annual Mean Temperature – Mann-Kendal Test



Source: CEIP-I 2021b.

2.3.2. Rainfall and Discharge

Rainfall patterns are projected to change, although changes in future precipitation are highly uncertain. Overall, rainfall is expected to increase slightly (5 to 10 percent). However, projecting changes in the onset and magnitude of monsoon rainfall is difficult, given that climate models do not represent the monsoon well (Turner and Annamalai 2012). Using regional climate models, a significant increase in pre- and post-monsoon rainfall is found in previous work (Fahad et al. 2018). There seems to be agreement that light precipitation during the monsoon will decrease, but that this will be offset by an increase in the frequency of high precipitation events (World Bank 2021). In contrast to the temperature projections, regional differences in future precipitation projections are more pronounced. The coastal zone is expected to see only a small increase in rainfall, while further inland, rainfall will increase more considerably (see **Box 2.4**).

The increase in monsoon rainfall will result in larger monsoon river flows reinforced by enhanced glacier melt. Climate-driven changes in the upstream areas of the GBM, both from changing rainfall patterns and melting glaciers, will increase the extreme discharge of the three main rivers. The extremely high flow in the GBM river system, with a discharge threshold that is exceeded 1 percent of the time, is expected to increase by 27 to 54 percent for the Ganges, 8 to 63 percent for the Brahmaputra, and 15 to 81 percent for the Meghna for warming scenarios ranging between 1.5 and 4 degrees Celsius (Mohammed et al. 2018). In particular, the Brahmaputra and Meghna extreme river discharge will increase steeply for the highest warming scenario. For these rivers, the strongest change will be seen for the month of May (Yu et al. 2010).

Box 2.4: Climate Change Projections for Bangladesh

Future climate information is derived from a set of global climate models that form the basis for the Coupled Model Intercomparison Project Phase 5. These models are forced by four different RCPs, which represent the total cumulative greenhouse gas (GHG) emissions by 2100 (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). RCP2.6 represents a strong mitigation scenario, whereas RCP8.5 reflects a business-as-usual, or high emission, scenario.

Table 2.2 shows the projected rise in average temperature for the winter and summer months in Bangladesh for the 2050 to 2059 and 2080 to 2099 time periods per emission scenario. For both the mid-century period and the end-century period, the winter months are expected to experience higher warming compared to the summer months, ranging from 0.6 to 0.9 degrees Celsius higher warming for the mid-century time period and 0.7 to 1.1 degrees Celsius higher warming for the end-century time period. The values in brackets show the intermodel range (10th to 90th percentiles), illustrating that larger uncertainties persist and that warming could be considerably higher or lower.

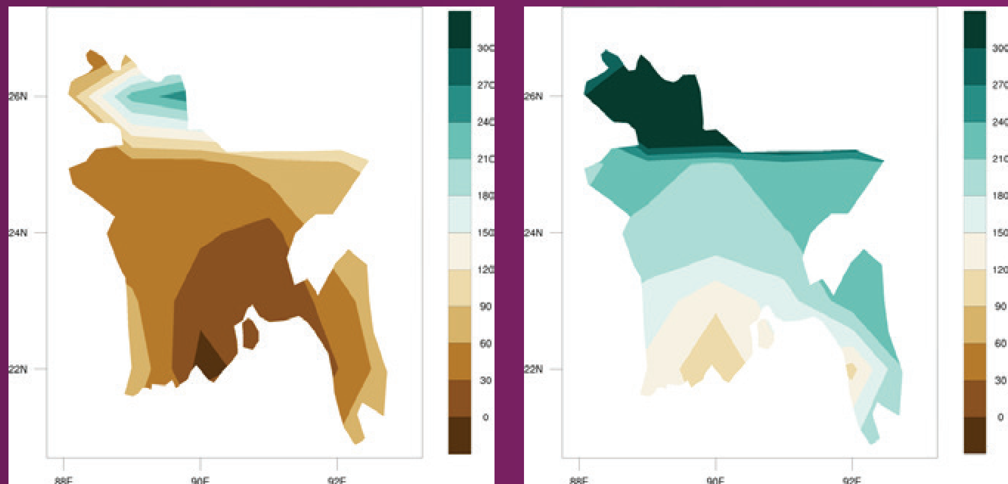
Table 2.2: Changes in the Annual Average Temperature Relative to the 1986 to 2005 Baseline Period per Season for Different Time Horizons and Climate Scenarios

Scenario	2040-2059		2080-2099	
	Jun-Aug	Dec-Feb	Jun-Aug	Dec-Feb
RCP2.6	0.6 (-1.1, 2.9)	1.5 (-0.7, 2.8)	0.6 (-0.9, 3.2)	1.7 (0.7, 2.9)
RCP4.5	1.0 (-0.6, 3.3)	1.6 (-0.4, 2.9)	1.6 (-0.1, 4.2)	2.3 (0.3, 4.0)
RCP6.0	0.7 (1.1, 3.4)	1.5 (-0.7, 2.8)	1.8 (0.1, 4.8)	2.9 (0.8, 4.5)
RCP8.5	1.6 (0.0, 4.0)	2.2 (0.0, 3.8)	3.4 (1.7, 5.9)	4.5 (2.4, 6.2)

Source: World Bank 2021.
Note: The top number is the multimodel mean and the values in brackets show the intermodel spread (10th to 90th percentiles).

Compared to the rise in temperature, which is relatively uniform across the country, precipitation changes have distinct spatial patterns. **Figure 2.16** shows the changes in annual precipitation for the 2040 to 2059 time period (left) and the 2080 to 2099 time period (right). The north of the country is expected to see the largest precipitation change, with a possible increase of more than 200 millimeters for the mid-century period and 300 millimeters or more for the end-century period. There are mixed signals for the coastal zone. For the mid-century time period, the western and southeast coastal zone will experience an increase in precipitation, whereas the areas in between will experience limited change. For the end-century time period, all areas of the coastal zone will experience an increase in annual precipitation, with the highest values in the Meghna Estuary and near Chattogram, whereas the western coastal zone will experience a lower increase in precipitation.

Figure 2.16: Spatial Changes in the Annual Average Precipitation Relative to the 1986 to 2005 Baseline Period for the 2040 to 2059 Time Horizon (left) and the 2080 to 2099 Time Horizon (right)

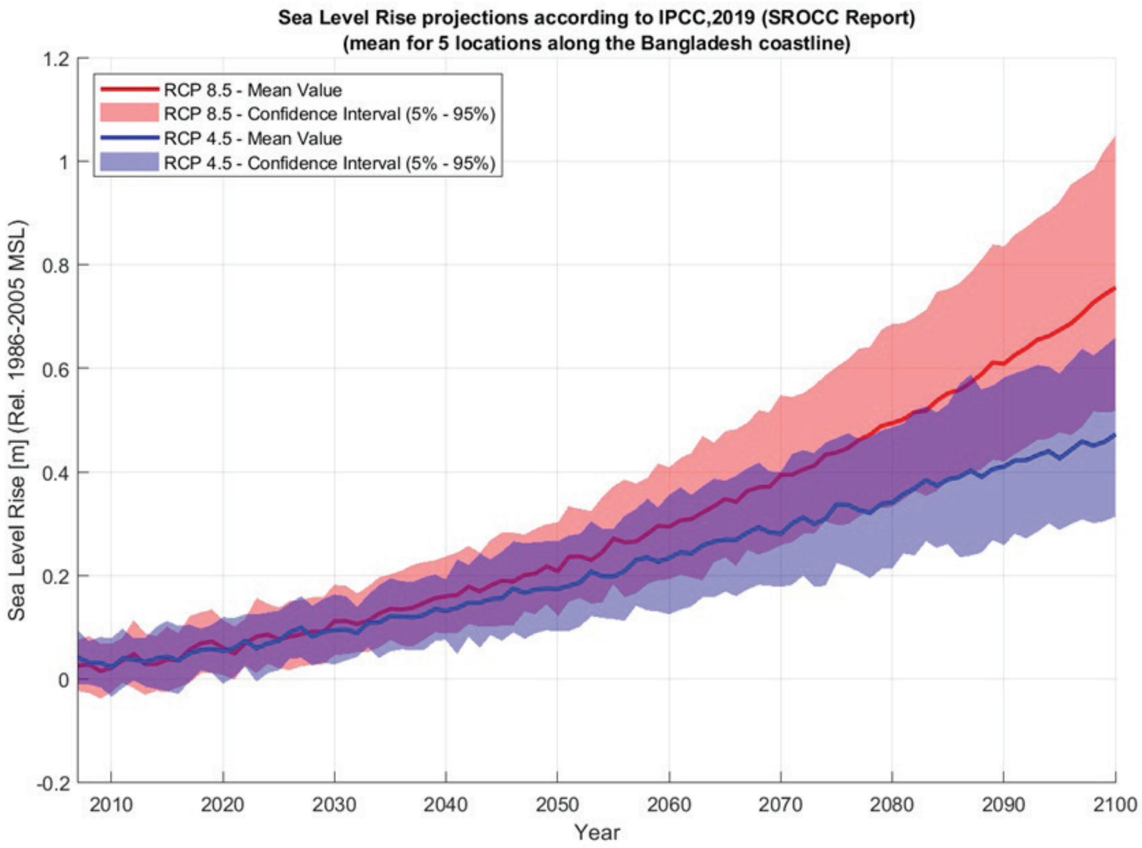


Source: World Bank 2021.
Note: Data is based on the RCP8.5 emission scenario.

2.3.3. Relative Sea Level Rise

Relative SLR (RSLR) is greater in Bangladesh than in many other countries, due to the simultaneous rise in the MSL and subsidence in low coastal areas. The current SLR measured at the Bangladesh coast is in the order of 3 millimeters per year, which is larger than the global average (Becker et al. 2020). Predictions indicate that the Bay of Bengal will be subject to SLR ranging between 0.5 and 0.7 meters by 2100 using a mid-level emission scenario (RCP4.5), although this number would be approximately 20 centimeters higher under a rapid warming scenario (RCP8.5) (Jackson and Jevrejeva 2016). This means that 20 percent of the Bangladesh population would be living below the high-tide line in 2100 under the mid-level scenario, while under the rapid warming scenario (RCP8.5), this number increases further to one-third of the population (Kulp and Strauss 2019). Together with the ongoing subsidence in the area, the expected RSLR is in the order of 1 to 1.5 meters at the end of the century relative to present-day levels. Averaged SLR values along the Bangladesh coastline are shown in **Figure 2.17** for both the RCP4.5 and RCP8.5 scenarios and include a 5-95 percent confidence interval.

Figure 2.17: Averaged SLR Projections for the 21st Century and Associated Uncertainties



Source: CEIP-I 2021b.

2.3.4. Tropical Cyclones

The intensity of cyclonic storm surges as well as the depth and extent of coastal inundation are likely to increase in a changing climate through rising sea surface temperatures and SLR. Although the changes in cyclone frequency and intensity are hard to predict and differ considerably per model, there seems to be a consensus that the frequency of tropical storms might decrease in the Northern Indian Ocean, but extreme cyclones (category 4 or 5) might increase (Knutson et al. 2020). In addition, the maximum wind speed is expected to increase between 4 percent and 12 percent, and precipitation between 23 percent and 38 percent (Yoshida et al. 2017). The combination of increasing wind speed and a rise in the MSL along the coast will make the occurrence of extreme water levels, and resulting coastal flooding, more likely. For instance, projections by Jisan, Bao, and Pietrafesa (2018) found that the potential inundated area from an event like Cyclone Sidr (2007) or Cyclone Aila (2009) at the end of the century would increase by 53 percent and 47 percent, respectively, as a result of SLR. In another study (Haque, Kay, and Nicholls 2018), the extent of future inundation was modeled based on changes in both upstream water levels and SLR, showing that a Cyclone Sidr-like event at the end of the century could raise maximum flood depths by 40 centimeters and increase the total inundated area by almost 300 percent.

2.3.5. Salinity Intrusion

Changes in salinity intrusion threaten agricultural production and aquatic ecosystems. The increase in SLR and changes in upstream river discharge will also modify the spatial and temporal patterns of salinity intrusion in the coastal zone. A study conducted by the World Bank (Dasgupta et al. 2015), which modeled present and predicted changes in river salinity across the coastal districts, revealed that salinity will move further inland by 2050, leading to a decrease in areas that are slightly saline (-22 percent) and slightly to moderately saline (-35 percent), and an increase in river areas that are moderately to highly saline (+8 percent) and highly saline (+35 percent). Although the whole western coastal zone is expected to experience some change, the most significant changes will be in the Sundarbans and parts of Barguna and Patuakhali, which will experience high salinity levels. The area with a salinity level of 4 to 5 ppt, the critical threshold for agriculture, is expected to increase from a baseline of 1.7 percent to 4.8 or 11.1 percent in 2050, depending on the scenario adopted. Irrigation water with a salinity level of 5 ppt will likely decrease average crop yields by 25 percent (Clarke et al. 2015). This means that groundwater will need to increasingly be used as a source of irrigation water, or alternative agricultural practices such as rainwater harvesting, different seed bed shapes and seed placements, and furrow irrigation will need to be adopted (Clarke et al. 2015). In the past, saline-tolerant rice varieties were adopted by coastal farmers, thereby increasing rice production in saline areas (Rabbani, Rahman, and Mainuddin 2013). On top of the implications for agriculture, the freshwater habitat of many fish species will be affected by changes in salinity. For instance, the optimum surface water salinity is less than 4 ppt for the giant freshwater prawn and 10 to 20 ppt for the black tiger shrimp (Dasgupta et al. 2015).

2.3.6. Socioeconomic Growth and Economic Transition

Over the course of the 21st century, Bangladesh is expected to grow significantly in terms of population and economic output, alongside a structural transformation of the economy. Some predict that by 2050, assuming an average growth rate of about 5 percent per year, Bangladesh will become the 23rd largest economy in the world (PWC 2017). The total population is expected to increase from 163 million in 2016 to between 177 and 192 million by 2050, depending on the socioeconomic scenario adopted. This population growth is accompanied by demographic changes, in particular a continuing decline in fertility, yielding a lower dependency ratio and a larger working population by 2050 (Rigaud et al. 2018). By 2030, almost half the population is expected to live in towns and cities. The growth in population will be accompanied by an increase in the demand for food. For instance, projections show that by

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2050, total rice production will need to increase by 63 to 134 percent to meet national food requirements (Mainuddin and Kirby 2015). Bangladesh has made significant progress in agricultural productivity growth, mainly in terms of technological change (World Bank 2016). In the future, it is expected that the agricultural sector will transform given the fast-growing demand for a more diverse, sophisticated, and nutritious diet (World Bank 2016).

Bangladesh has the ambition to transition to a more diversified economy with better integration into global supply chains. In particular, the technology, IT, and garment sectors are expected to grow rapidly. Integral for this transition is private sector investment (foreign direct investment) in small and large-scale manufacturing and infrastructure. Public infrastructure investment is low (2 percent of GDP) compared to some of the country's regional competitors and will need to increase to about 10 percent to sustain current growth rates (World Bank 2016). In order to diversify the economy and promote export growth, both inland (such as the Dhaka to Chattogram inland waterway) and international (for example, Bangladesh to India) transport connectivity and logistics need to be improved.

However, large uncertainties remain with regards to the economic transition of the country. The BDP 2100, for instance, uses four plausible scenarios for the delta, two in which the delta remains a more traditional economy (more agriculture focused) and two where a more diversified economy is envisioned. The diversified economy scenarios include high out-migration, high GDP growth, moderate to high urbanization, and a decentralized economy with high connectivity. The traditional economy scenarios include low GDP growth, an economy based on low-value industries, centralized urbanization, and poor connectivity, leading to urban-rural isolation.

2.4. Concluding Remarks

This chapter has highlighted the uniqueness of the coastal zone, which creates many opportunities and challenges given the interaction of the biophysical and socioeconomic systems. To safeguard the sustainable economic growth of the coastal zone, risk planning is essential to target interventions that are effective, cost-efficient, and robust against future changes. Bangladesh is not starting from scratch; it has a long-standing tradition of putting into place measures to reduce the coastal risks for its communities. This chapter has already highlighted various natural and human systems and interventions, such as mangroves and polder infrastructure, as well as EWS and shelters for evacuation during cyclones. A thorough understanding of the implementation and functioning of these interventions, and of the lessons learned to date, is essential to further build resilience. However, before additional measures can be implemented, risk has to be quantified to understand where and how interventions should be prioritized and designed. Therefore, the next chapters provide an in-depth overview of the risk profile of the coastal zone (Chapter 3), and a detailed assessment of key interventions, including an evaluation of their effectiveness (Chapter 4).

2.5. Notes

6. Population numbers are based on the Preliminary Population and Housing Census 2022 (Bangladesh Bureau of Statistics 2022)
7. From a functionality perspective, these sluices (both drainage and flushing) are called "regulators" to allow both drainage and flushing. However, for ease of reference (as per BWDB standard technical specifications), the BWDB identifies these structures separately as drainage sluices and flushing sluices.
8. These numbers are estimated based on the CEIP-I documentation for 10 polders and scaled to the entire polder system of 139 polders.
9. Data from 2017 from the LGED at https://data.humdata.org/dataset/bangladesh-education-facilities-by-lged. This publicly available dataset is likely not complete.
10. Data from Humanitarian Data Exchange Bangladesh. Spatial dataset provided with location data for health facilities data of Bangladesh. The source of the data is LGED and dataset updated by WFP, Map Action and OCHA (last updated on August 15, 2018), link: https://data.humdata.org/dataset/bangladesh-health-facilities-by-lged. This publicly available dataset is likely not complete.
11. Population figures are based on the latest Bangladesh census data (2011) (Bangladesh Bureau of Statistics 2011) projected using the World Bank's year-wise population growth rate.

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RISK PROFILE

CHAPTER 3: RISK PROFILE

As described in Chapter 2, the interaction of the biophysical and socioeconomic systems in the coastal zone provides many benefits, but also creates various risks to the people, infrastructure, and livelihoods. These risks are the result of a complex interplay of multiple factors that vary across different parts of the coastal zone. To improve coastal resilience, the drivers of risk need to be identified within the local context. Further, risks are not static, but change if there are changes in the natural landscape, the socioeconomic characteristics, or the occurrence of natural and climatic hazards. Both climate change and socioeconomic growth are expected to gradually increase the risk over time, threatening the development ambitions of Bangladesh.

Therefore, it is imperative to obtain an overview of the present-day risk profile of the coastal zone, and to determine the main underlying drivers of change and how the risk might evolve in the future. The four main risks identified in this report, based on Chapter 2, are risks associated with tropical cyclone impacts, erosion, waterlogging, and climate-induced migration. To quantify any type of risk, information on the hazard, the exposure (to people, infrastructure, land use) and vulnerability need to be collected and integrated into a comprehensive risk management framework. Some of these risks can be quantified on a large scale, given current risk modeling capabilities, while others are more context specific and need detailed local quantitative or qualitative analysis. In this chapter, we combine quantitative risk modeling, through analytics that quantified the present and future cyclone-induced flood risk, and qualitative and descriptive evidence to analyze the current and future risk profile of the four main risks identified.

3.1. Tropical Cyclone Flood Risk

Tropical cyclone impacts are considered the main risk to people, infrastructure, and livelihoods, and result in major flood damage, which could increase significantly with climate change. The largest risk is the exposure of people and infrastructure to the impacts of storm surges and extreme wind originating from intense tropical cyclones. Cyclone-induced flooding can lead to loss of life and damage to housing and critical infrastructure (such as road, rail, and educational and health facilities), which often need a considerable amount of time to restore. For instance, the impact of tropical Cyclone Aila (2009) led to breaches of the coastal embankments in Polder 32 that took 11 years to fully restore, causing widespread disruptions to the livelihoods of the polder inhabitants **(Box 3.1)**. Extreme winds can also cause considerable damage to assets, especially to poor quality houses. During Cyclone Sidr (2007), the major cause of destruction of houses was storm surge impacts, whereas extreme wind damaged mostly non-pucca houses, but these were generally quickly repaired (Government of Bangladesh 2008).

A risk modeling approach was adopted to quantify the exposure of people and assets from cyclone-induced inundation for present-day conditions and a future climate scenario (see **Box 3.2** for technical details). Only the impacts from storm surges were considered here. Moreover, risk was expressed in terms of monetary asset damage only, thereby neglecting the wider economic and welfare losses to households, which can be substantial (Verschuur et al. 2020), but still hard to quantify in practice. It should be emphasized that the most at-risk areas from an asset damage perspective might not be the same as from a welfare perspective, which can bias any decision made based on these risk estimates (Hallegatte and Engle 2019).

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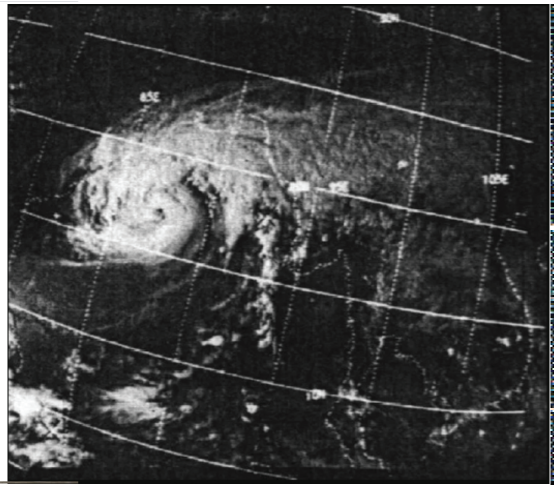
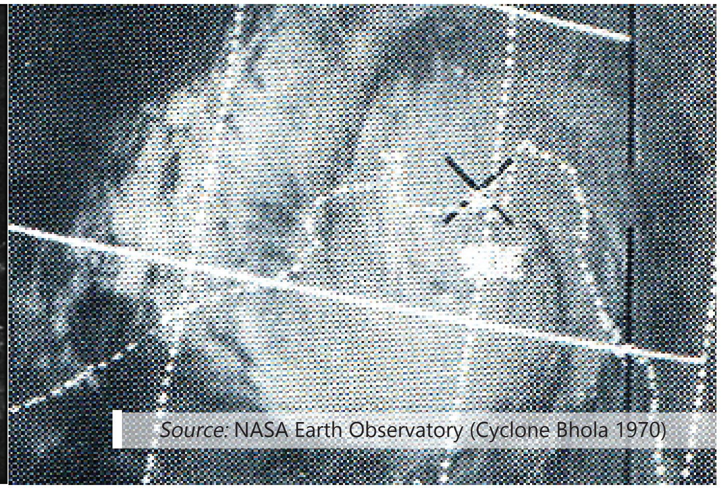




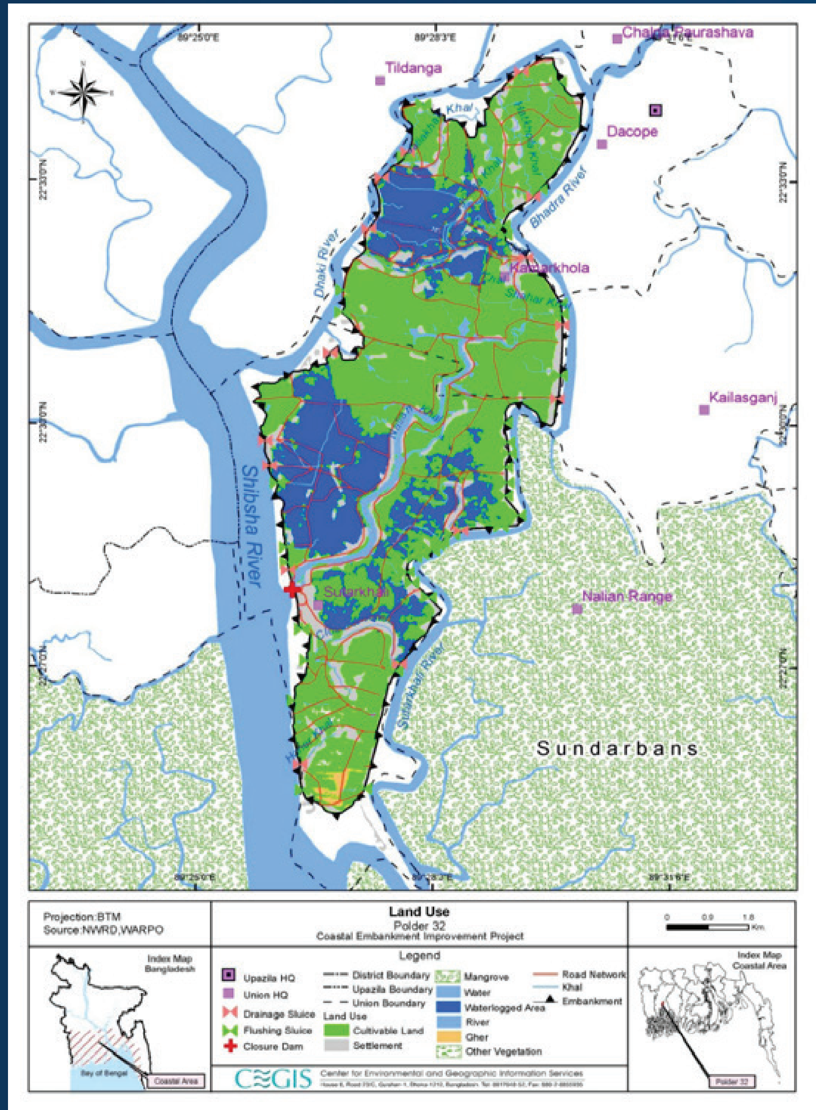
Source: NASA Earth Observatory (Cyclone Bhola 1970)

Box 3.1: Embankment Breach of Polder 32

Polder 32, located in the west of the coastal zone just north of the Sundarbans, is home to about 40,000 inhabitants. The impact of Cyclone Aila (2009) caused a breach in part of the embankment, leading to inundation of the low-lying polder, which resulted in significant crop damage, asset damage (many people lost their homes), and loss of life (330 deaths). While being repaired, the area was inundated for almost 10 hours each day because of the incoming tide that flooded the area. The flooding damaged the hydraulic structures, leading to internal drainage congestion and saline water entering the polder area (see **Figure 3.1**) (Bangladesh Water Development Board 2013).

Despite the efforts of the GoB to close the breach with temporary measures, which turned out to be extremely challenging given the ever-changing hydrodynamics at play; it was not until 2020 that the breached embankment was closed (referred as the Nalian closure) by the GoB as part of CEIP-I activities. This event highlights the importance of having reliable coastal protection works to protect people and assets, but it also illustrates that relying solely on coastal protection works is not enough, as failure can lead to large-scale losses. Therefore, residual risks can be significant and need to be accounted for and effectively managed in large-scale DRR portfolios.

Figure 3.1: Land Use of Polder 32



Source: CEIP-I project documents.
Note: Waterlogged areas are the result of the breach of the embankment system after Cyclone Aila in 2009.

Box 3.2: Modeling of Cyclone Flood Risk

To evaluate the exposure of assets and people and estimate cyclone flood risk, a detailed modeling framework was developed. The risk analysis consisted of the following elements: (1) hazard modeling using present-day and future climatic boundary conditions, (2) creating an asset inventory, (3) analyzing the exposure and the damages as a result of exposure of assets, and (4) estimating risk by integrating the probability of hazard occurrence and the resulting damages. In this analysis, only the risk of cyclone-induced flooding is considered. Damages as a result of extreme winds and waves are not included.

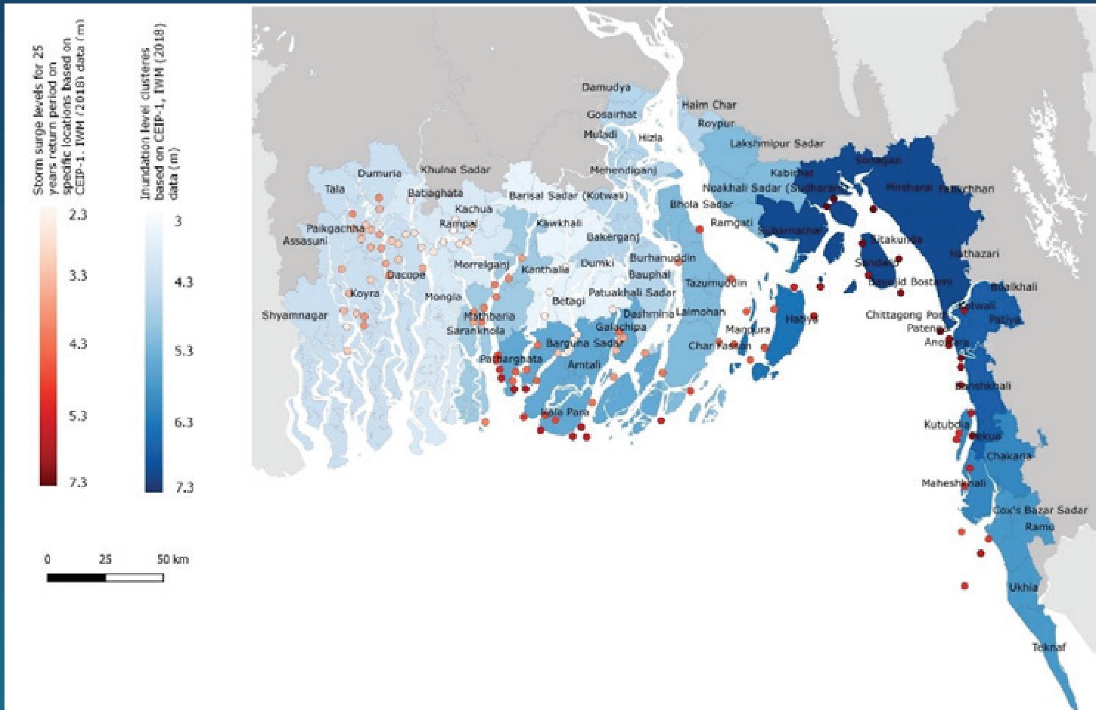
Present and future hazard modeling

Scenarios of storm surges along the coast and in the tidal channels were estimated based on the output of a detailed hydrodynamic numerical model for the coastal zone developed by the Institute of Water Modelling (IWM) (CEIP-I 2018). This model used observed wind speed and central pressure data from historical tropical cyclone events to force the hydrodynamic model for the whole area. The model is able to simulate how these storm parameters translate into storm surges and waves, and how they propagate into the tidal channels. By running multiple simulations for different extreme conditions, multiple storm surge hazard output can be generated. Within this work, three simulations were run for both the present and future scenarios. The three simulations correspond to 10-, 25-, and 100-year cyclone events. For the future scenario, an SLR value of 0.5 meter was added to the hydrodynamic model, and wind speeds were assumed to increase by 8 percent. Storm surges are clustered at the upazila level for the analysis. An example of this clustering is illustrated in **Figure 3.2.**

The output of the storm surge model is overlaid with the elevation of the coastal zone based on the Multi-Error-Removed Improved-Terrain (MERIT) digital elevation model (DEM). Figure 3.3 shows the extent of inundation in the coastal zone for present and future 10-year and 100-year events.

Digital elevation models, such as the MERIT DEM, have known inaccuracies in the low-lying coastal zone of Bangladesh. For instance, a study using another DEM that corrected some of the inaccuracies in the existing DEM showed that the low-lying coastal zone might actually be lower than previously thought, which could lead to an underestimation of the potential

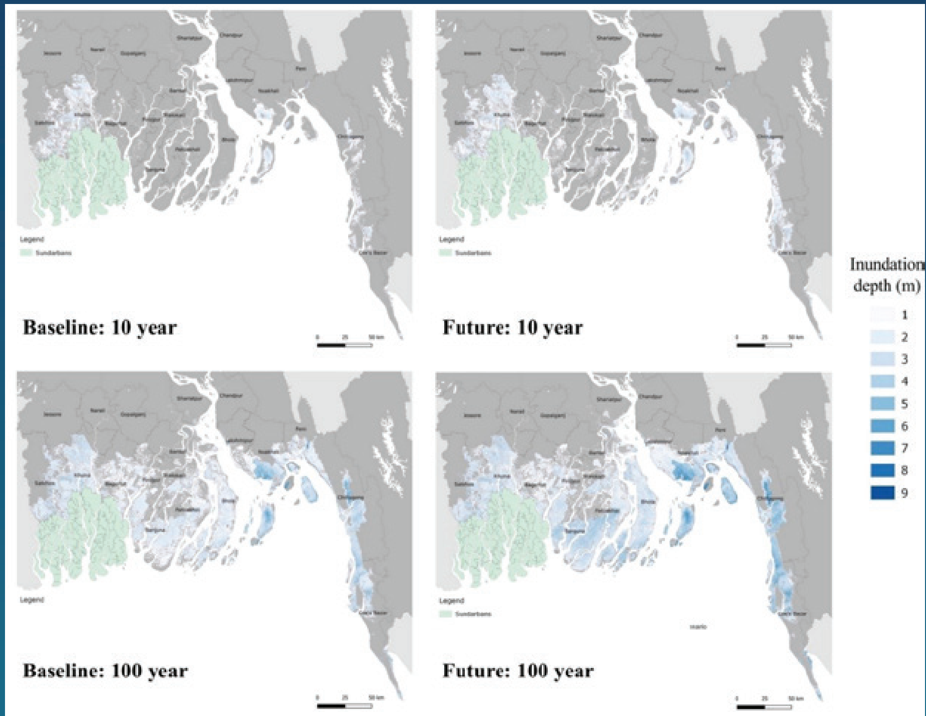
Figure 3.2: Clustering of Inundation Levels for Cyclone Flood Risk Analysis



Source: Analytics performed by the World Bank for this report using data from CEIP-I 2018.
Note: This example shows the modeled (red) and clustered (blue) storm surge values at the upazila level for a once in 25-year storm surge event.

inundation (Kulp and Strauss 2019). This has been confirmed by more recent work that used LIDAR elevation data, with a much higher vertical accuracy (though lower spatial resolution) and showed that the elevation of the Bangladesh coastal zone might be lower than estimated using freely available DEM products (Hooijer and Vernimmen 2021). However, inundation is not only a function of elevation but also of storm surge levels, which are also uncertain. Therefore, it is difficult to say whether or not the inundation maps are over- or underestimating the potential risk.

Figure 3.3: Inundation Depth Maps for the Baseline and Future Scenarios



Source: Analytics performed by the World Bank for this report using data from CEIP-I 2018, and MERIT DEM (http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/).
Note: The top panels show a 10-year storm surge event, and the bottom panels show a 100-year storm surge event.

Asset inventory

An asset inventory and land-use map for the coastal zone was assembled, which includes all roads, railways, educational facilities, health facilities, agricultural areas, economic zones, and housing. This inventory comprises all assets that are potentially at risk. The housing units were determined separately by type of housing (pucca, semi-pucca, kutcha, jhupri), since different housing types have different vulnerabilities (because of the quality of the housing) and damage values (because of the reconstruction costs). The location of houses is also used as a proxy for population exposed.

Exposure analysis

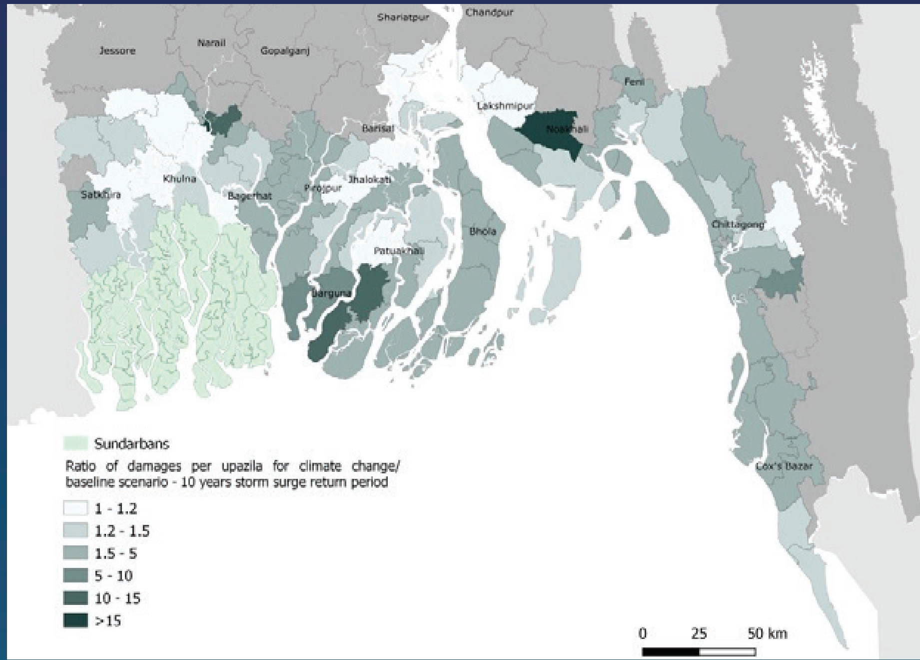
The inundation maps were overlaid with the location of the assets. The inundation and the physical vulnerability of the asset determine to what extent a specific asset will be damaged as a result of inundation. Physical vulnerability thus refers to the expected damage to physical structures from a hazard ranging from zero (no damage) to one (full destruction). This was combined with the reconstruction cost of each of the assets, which is equal to the amount of money that is needed to restore the asset to its original pre-disaster condition (expressed in US$ per m2). To estimate the physical vulnerability, depth-damage functions were used, which translate the depth of inundation to the expected damages of the asset or land-use class. Asia-specific depth-damage curves and reconstruction values for the different asset types were obtained from previous work (Huizinga, De Moel, and Szewczyk 2017). The maximum damage values were corrected for inflation (as they were expressed in 2010 prices) and converted from Euros to US dollars.

Several correction factors were applied to the damage calculation. Buildings in semiurban and rural areas were considered to be of lower quality and less expensive to rebuild. Therefore, rural houses were considered to be 25 percent of the value of urban houses, and semiurban houses were assumed to be 60 percent of the value of urban houses. For roads, the damage was scaled to the width of the road, which is different for highways (4 meters), zila and upazila roads (3.7 meters), and union and village roads (3 meters). The exact location of housing and population is not known. Therefore, it was assumed that exposure scales linearly with the fraction of land inundated per upazila (for example, 50 percent of land inundated means that 50 percent of housing and population is exposed). A similar approach was followed for estimating agricultural losses, with the area of agricultural land per upazila taken as the maximum area that can be damaged. To estimate impacts to industrial areas, an outline of the SEZ was taken and then it was assumed that industrial facilities cover only a fraction of that land. The maximum damage values were multiplied by 50 percent to account for this.

The protection levels of the existing embankment system were taken into account. Sixty percent of the exposed coastal upazilas have protective structures in place, which protect against storm surge levels equivalent to a 10-year event (for the baseline scenario). However, for future storm surge events, these polders may only offer partial protection against a 10-year event. Here it was assumed that the flood protection will not fail, even at higher return periods, and that the damages scale with the difference between the damages from a given extreme cyclone event and the damages associated with a 10-year event at present. Hence, in some upazilas, the future scenarios will only marginally increase the damage, whereas in other upazilas the damage will increase sharply with an increase in extreme water levels, as can be seen in **Figure 3.4.**

To determine whether the modeled damage values are realistic, a comparison between the reported damages after Cyclone Sidr (2007) and the modeled damages was performed. For every coastal district, the return period corresponding to the observed water levels was taken and the damage (corrected for the presence of embankments) estimated. The aggregated coastal-wide damage value was compared to the asset damages reported in the damage, loss, and needs assessment report for Cyclone Sidr (Government of Bangladesh 2008). The reported damages were corrected for inflation, and it was further assumed that of the total reported damages, approximately 75 percent were associated with storm surge induced flood damage (with the remaining being caused by extreme wind speeds). This comparison resulted in a correction factor equal to 0.67 (that is, the modeled damages were overestimated), which was applied to the resulting risk values.

Figure 3.4: Ratio of Damages per Upazila for the Climate Change Scenario versus the Baseline Scenario



Source: Analytics performed by the World Bank for this report using data from CEIP-I 2018.
Note: The ratio is found by calculating the damages for a 10-year event assuming no protection standards in place.

Risk analysis and risk correction

The risk expressed in expected annual damages was found by integrating the damage associated with the different return periods. The trapezoidal rule was used to perform this integration, resulting in an aggregate asset risk value per upazila. This upazila-level risk map is included in **Figure 3.5** showing the risk for both the baseline and the future scenarios.

The future scenario includes a 0.5-meter SLR scenario, equivalent to the conditions likely to occur in the second half of this century, and wind speeds that are 8 percent stronger than under present-day conditions. Three flood events were compared, reflecting the inundation associated with a 10-year, a 25-year, and a 100-year cyclone flood event.[12] The assets considered in this analysis include houses, roads, railways, educational facilities, healthcare facilities, agricultural land, and economic zones.

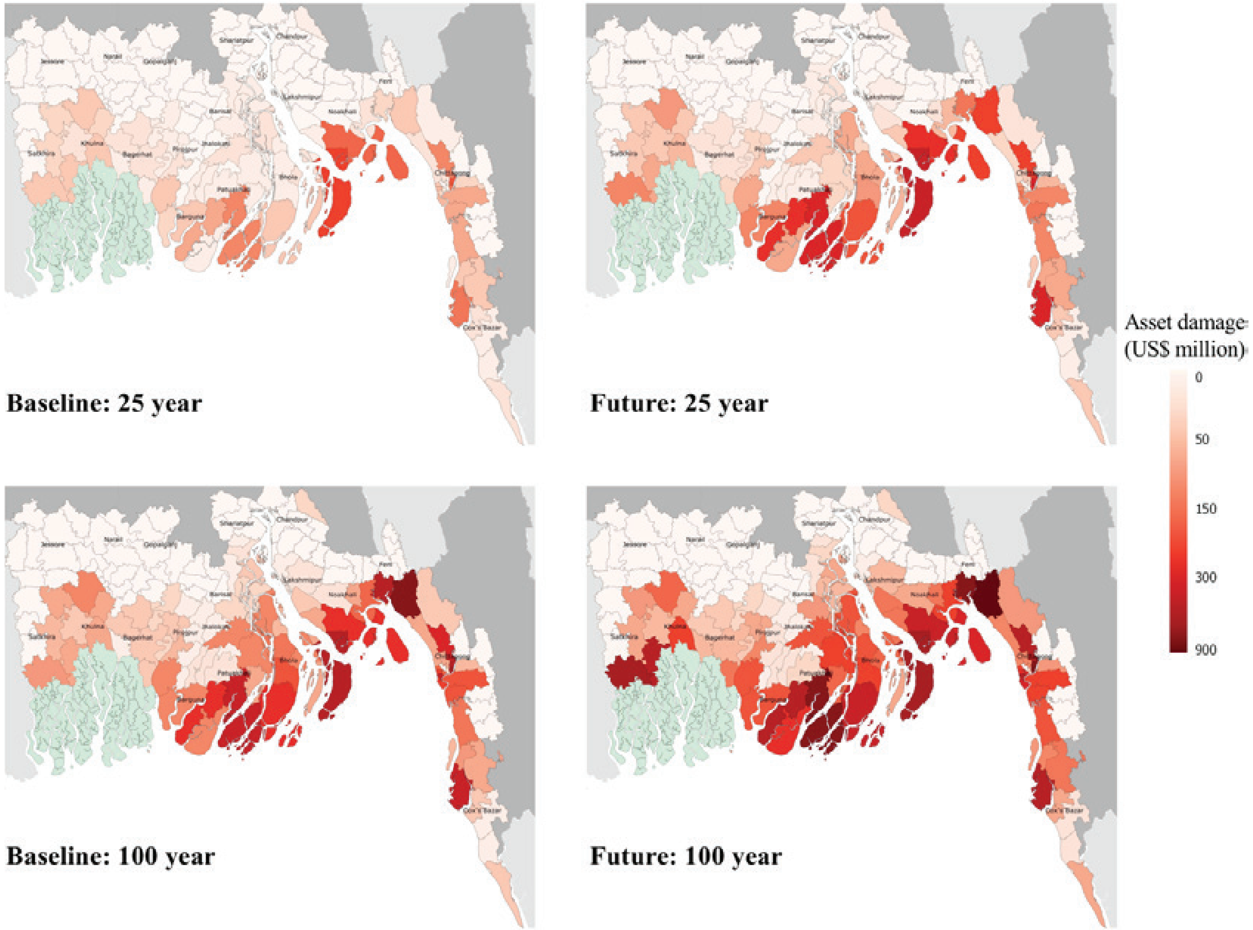
At present, 6.4 percent of the coastal population are exposed to a 10-year flood event, which could increase to 10.2 percent in the future scenario. For the 100-year event, 27.3 percent of the coastal population are exposed to flooding under present climatic conditions, and 34.5 percent in the future. The breakdown of damages per asset type and return period is shown in **Table 3.1.** The largest damage is from damage to households and agricultural land, followed by roads and industrial areas. The total damages for a 10-year event, a 25-year event, and a 100-year event are expected to increase by 59.8 percent, 61.4 percent, and 43.3 percent, respectively (without considering protection), as a result of climate change. At the moment, the current elevation of the polders should protect the assets within the polder from flooding under the baseline 10-year storm surge event. Thus, although the embankments prevent damage for a 10-year storm surge event under the baseline scenario, damages will likely increase rapidly when no further adaptation measures are taken. Damages are not equally distributed across districts, as can be seen in **Figure 3.5.** The damage is highest in the populated areas of Khulna, Chattogram, and Cox's Bazar, and for the coastal upazilas. The spatial differences become even more pronounced for the 100-year event, with a clear divide in damages between the exposed and interior coastal zones.

Table 3.1: Expected Damages by Asset Type, Baseline and Future Return Period Flood Scenarios

	Households	Economic Zones	Agriculture	Educational Facilities	Healthcare Facilities	Roads	Railways	Total
	Damages (US$ million)							
	Baseline							
10 year	1,321.6	224.6	1,271.2	20.5	2.3	336.0	2.0	3,178.2
25 year	2,617.1	502.2	2,671.7	47.0	4.7	841.6	5.8	6,690.1
100 year	5,925.2	1,596.2	5,224.7	127.4	10.7	1,833.2	13.2	14,730.6
	Future							
10 year	2,073.9	393.2	2,051.7	35.7	3.6	515.6	3.7	5,077.4
25 year	3,990.5	943.0	4,497.1	92.0	7.3	1,262.4	7.8	10,800.1
100 year	7,892.6	2,143.1	7,536.9	169.6	10.8	3,338.8	17.5	21,109.3

Source: Analytics performed by the World Bank for this report.

Figure 3.5: Estimated Asset Damages per Upazila for the Baseline and Future Storm Surge Scenarios for Different Return Periods, Assuming No Protection



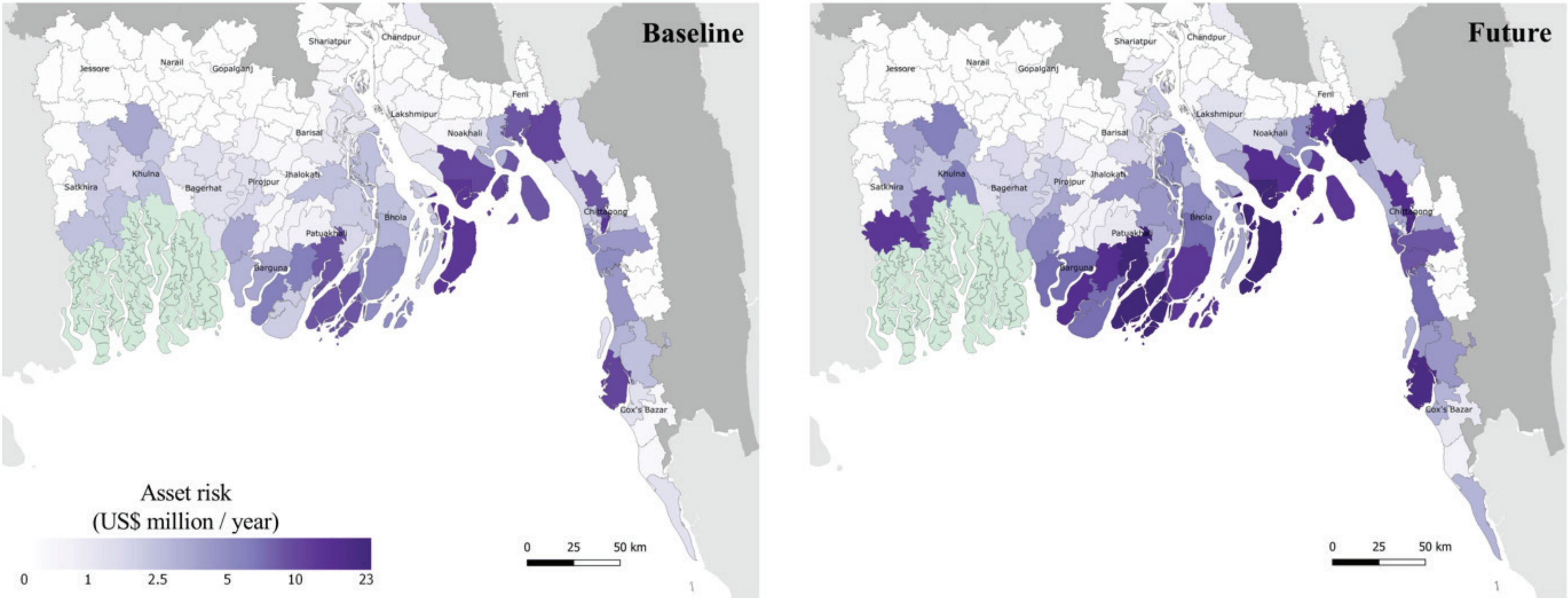
Source: Analytics performed by the World Bank for this report.
Note: The top panels show a 25-year storm surge event, and the bottom panels show a 100-year storm surge event.

The aggregate asset risk per upazila is found by integrating the probability of occurrence and the resulting damage to infrastructure assets for the various flood hazards. Risk is expressed as the expected annual damage in US dollars per year. Across the coastal zone, the risk from cyclone-induced flooding is equal to US$300 million per year under the baseline scenario, which is expected to increase to US$570 million per year (a 90 percent increase) in the future because of changing climatic conditions. Some upazilas face a higher level of risk than others. The spatial distribution of risk is shown in **Figure 3.6** for the baseline and future scenarios.

Under the baseline scenario, eight upazilas—in Noakhali (Hatiya, Subarnachar), Chattogram (Mirsharai, Bakalia, Chandgaon, Hathazari, Sandwip), and Patuakhali (Galachipa) districts—face a very high level of risk (more than US$25 million per year). The high levels of risk in Chattogram and Cox's Bazar districts are driven by the high concentrations of assets, while Noakhali and Patuakhali districts have high levels of risk as a result of the high inundation levels that could be reached in those areas. In Khulna district, inundation is caused by the propagation of storm surges inland, potentially flooding a large number of assets.

Under the future scenario, an additional eight upazilas will face a very high level of risk. Among the upazilas that already experience a large risk under the baseline scenario (the top 15 upazilas), the most climate sensitive are three that will experience a risk increase of more than 100 percent under the future scenario—Galachipa upazila (Patuakhali) with a 123 percent increase, Amtali (Barguna) with a 124 percent increase, and Char Fasson (Bhola) with a 112 percent increase.

Figure 3.6: Aggregate Asset Risk from Cyclone-Induced Coastal Flooding, Baseline and Future Scenario



Source: Analytics performed by the World Bank for this report.

Risk to infrastructure assets does not cover the entire spectrum of losses. A proportion of the exposed population might lose their lives if they do not evacuate in time, or do not evacuate at all. However, this is particularly difficult to estimate and therefore has not been taken into consideration here. In addition, losses of infrastructure can lead to wider welfare losses to households, as people derive income from the services that infrastructure and productive assets provide. Poor households could be disproportionately affected by this, as they have fewer financial means (such as savings or insurance) to recover from an income shock (Hallegatte and Rozenberg 2017; Hallegatte, Fay, and Barbier 2018). Although predicting these welfare losses is tricky, some studies show that every dollar in asset losses results in an average of 1.5 dollars in welfare losses, although this number can be much higher for poorer households (Hallegatte, Bangalore, and Vogt-schilb 2016; Verschuur et al. 2020). Welfare losses could increase in the future because of SLR and population growth, but they could also decrease because of improvements in welfare, in particular increased access to financial products, improved housing, and higher household wages, from a transition out of agriculture for some households (Verschuur et al. 2020).

3.2. Erosion Risk to People, Land, Infrastructure, and Coastal Amenities

Erosion in some parts of the coastal zone could have major impacts on people, land, infrastructure, and coastal amenities. Land is scarce in the coastal zone and therefore valuable. High erosion rates, as experienced in some parts of the coastal zone, can lead to significant loss of land (see **Box 3.3** and **Figure 3.7**). Examples of erosion hotspots in the coastal zone are shown in **Figure 3.8.**

In addition, erosion can lead to significant impacts on the livelihoods of the people that live on that land or derive income from it. In Bangladesh, erosion has mainly affected poor small landowners that are bound to these at-risk areas (Hutton and Haque 2004; Rahman and Gain 2020). For instance, a field survey looking at the impacts and coping strategies of households affected by riverbank erosion in the Koyra riverine area in 2017 and 2019 (Khulna district) showed that 83 percent of the interviewed households reported that their house was severely damaged by erosion (Rahman and Gain 2020). As a coping strategy, respondents mentioned that they had to take their child out of education (91 percent), reduce their food intake (94 percent) or internally displace, migrate, or become homeless (Rahman and Gain 2020). On the other hand, large accretion in other areas, sometimes accelerated by the construction of cross-dams, has resulted in significant land gains, most notably in the Meghna Estuary. The net economic gain or loss is determined by the economic value of the land lost to erosion and the opportunities newly accreted land offers. Currently, the accreted land is only sparsely populated and mainly used for resettlement and afforestation activities.

Erosion can also have large impacts on the stability of coastal infrastructure. Monsoon and tidal river flows have led to the erosion of embankments and slope and bank protection works at several places in the coastal zone, mainly along inland river channels. According to a recent study that analyzed the movement of the river network in the coastal zone using satellite imagery, the migration rate was on average 47 meters over 30 years, although it was more than 500 meters over 30 years in some places (Jarriel et al. 2020). A quarter of

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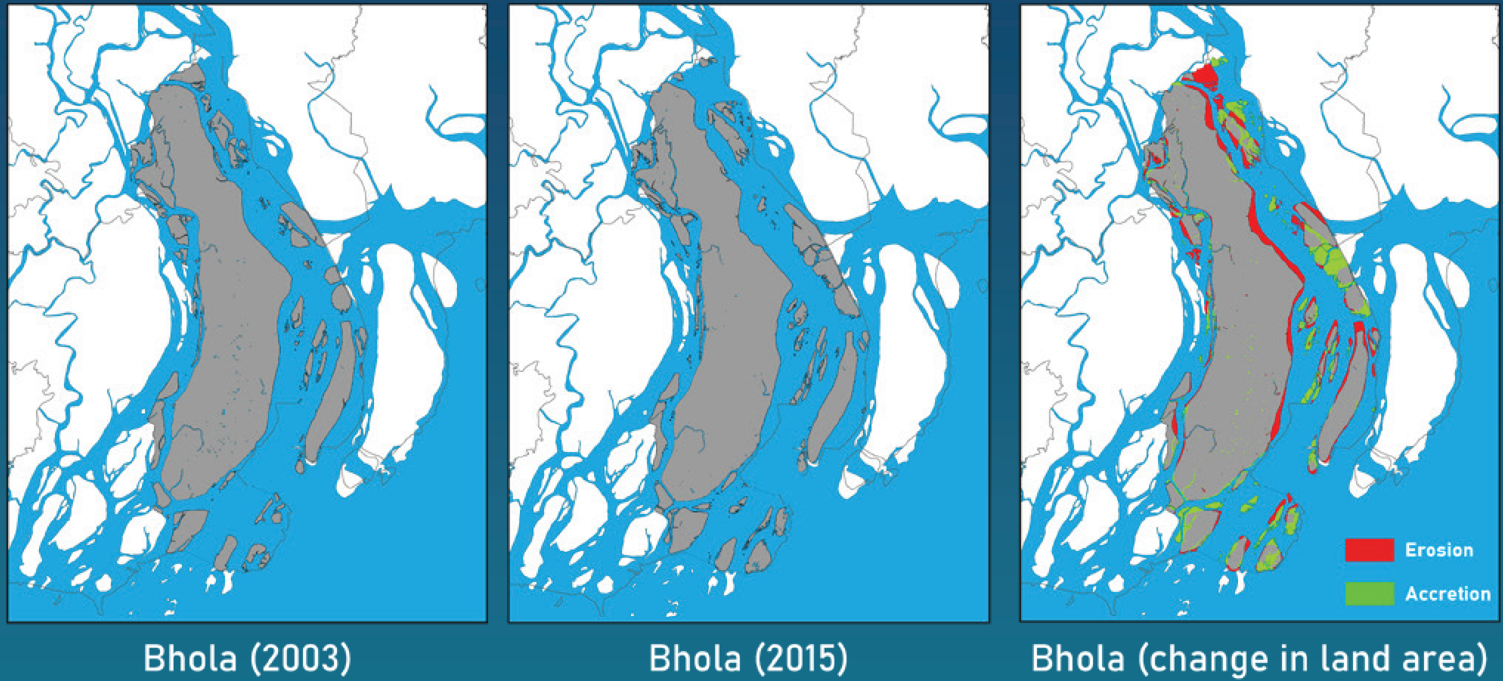
Box 3.3: Bhola Island Change in Land Area

Bhola, the largest island in Bangladesh, is located in the Meghna Deltaic Plain, and surrounded by the Meghna River in the north and east, and the Tetulia River in the west. The population of approximately 1.7 million live mainly along the edges of the island (Biswas and Islam 2020). Since 1990, erosion has become prevalent along the island's shoreline, particularly on the eastern side. Erosion accelerated over the 2003-2015 period (Figure 3.7), with a land loss equivalent to 7,324 hectares over this period. The major erosion hotspot is the stretch of shoreline of about 130 kilometers in the east that erodes at a rate of 5 to 10 square kilometers per year, destroying fertile land, houses, and embankments, resulting in forced migration as livelihoods are lost. Some accretion has also taken place as a result of, among others, the construction of various cross-dams in the 1990s, although the land gain is small compared to the land lost. Various plans have been proposed to design additional structural protection measures in the erosion-prone regions, including an erosion early warning system (EEWS). The EEWS includes the monitoring of erosion along large stretches of protection works using sensors embedded in the design. This is combined with underwater acoustics to detect faults and weak points in the submerged bank and toe protection at an early stage, which is difficult in the operation and maintenance (O&M) of traditional protection works.

Figure 3.7: Change in the Land Area of Bhola, 2003 to 2015



Source: Map developed by the World Bank for this report using Landsat 7 and Landsat 8 satellite imagery based on description in Biswas and Islam 2020.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the channels migrated more than 60 meters over the last 30 years, underlining the scale of the channel migration issues that might occur, and the widespread risk to coastal infrastructure. Although in some cases the embankments are left to erode, with a new embankment constructed further inland, in other cases, engineering solutions are applied to protect the embankment against erosion, often at large costs (Nazrul Islam, n. d.). For the coastal embankments, episodic erosion during cyclones, although often short-lived, can affect the toe and slope structures of the embankments.

Finally, structural erosion of coastlines can diminish the coastal amenities these systems provide. Healthy sandy shorelines buffer against storm events and provide benefits for human recreation, tourism, and ecosystems (de Schipper et al. 2021). Therefore, preserving these sandy beaches is essential to meeting the GoB's ambition to grow the tourism sector in the coastal zone. Maintaining sandy ecosystems goes hand in hand with the preservation of other coastal ecosystems, such as mangrove forests.

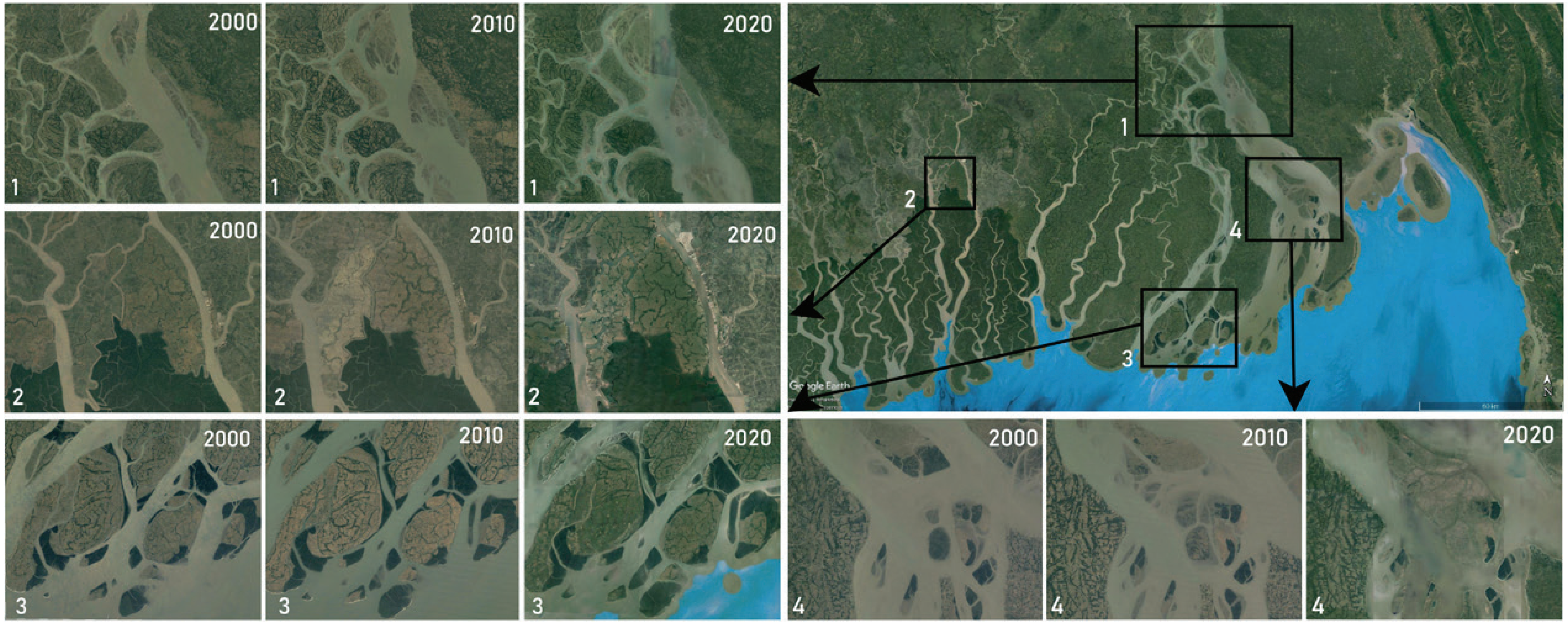
Deltaic areas are continuously changing and will continue to do so in the future. Predicting how the risk of erosion in the coastal zone might change in the future is difficult, given the complexities with regard to the morphodynamics and the interactions between humans and the environment. For instance, some studies predict that the sediment supply of the GBM rivers to the coastal zone will decline in the future as a result of climatic and socioeconomic changes and the construction of dams upstream (Dunn et al. 2018). Given the estimated growth in population, and the planned transition to a more diversified economy, including tourism, the need for coastal land and the coastal services and amenities it provides will only increase in the future.

3.3. Risk of Waterlogging

Waterlogging, the seasonal or permanent inundation of polder areas, is a widespread problem in many of the polders, although with varying underlying factors. The drainage of excess water from the polder systems has become increasingly challenging over the past few decades because of changing conditions inside and outside the polders. This is especially true for the southwestern districts (Khulna, Satkhira, Jashore districts) and Noakhali district (see **Figure 3.9**) In total, 30 percent of polders are experiencing waterlogging issues. Long-lasting waterlogging results in social disruptions (from flooding of schools, health facilities), income loss (from decreasing agriculture), transport disruptions (from flooding of roads), social unrest, and an accelerated transition from agriculture to shrimp farming (FAO 2015). See **Box 3.4** for more details on the impacts waterlogging has on livelihoods in the coastal zone.

Among others, insufficient drainage, lack of management, siltation of rivers, and reduced upstream river flow have been identified as possible causes of waterlogging (Alam, Sasaki, and Datta 2017). For instance, waterlogging can be caused by the siltation of the drainage canals within the polder area from sediments that have drained into the canals. This siltation blocks the water flow through the drainage network, making it harder to flush water out of the polder through the drainage structures (Alam, Sasaki, and Datta, 2017). The underlying causes of waterlogging do, however, differ per polder. In Khulna, for instance, surveys in three polders illustrated that the lack of silt removal, water

Figure 3.8: Examples of Erosion Hotspots in the Coastal Zone of Bangladesh between 2000 and 2020

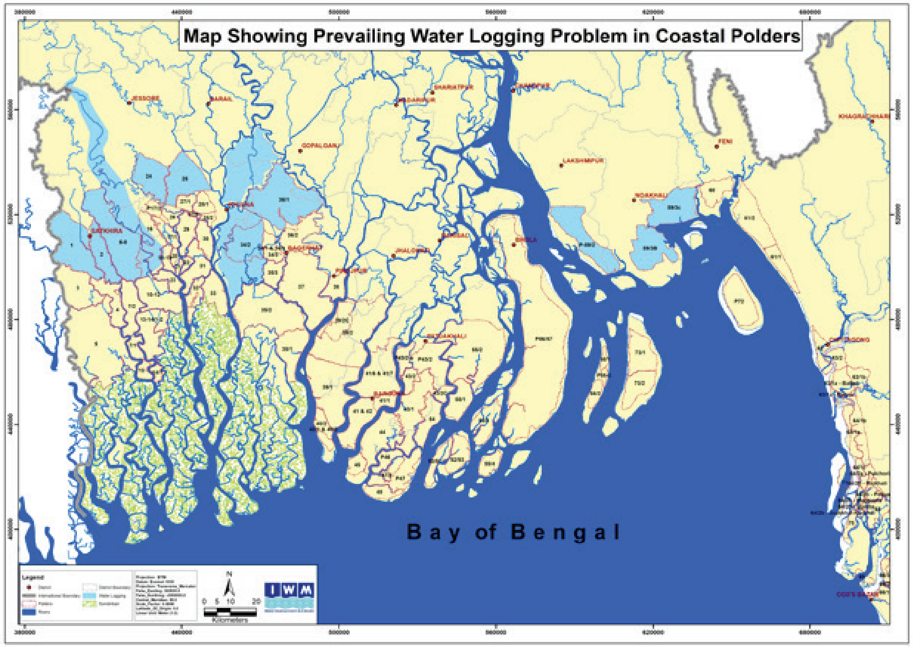


Source: Prepared by the World Bank using Google Earth Pro satellite images based on FAO 2015.

flow reduction in the canals, and encroachment of the canals were the main causes of waterlogging (Alam et al. 2016).

Changes outside the polders can also impede drainage. Parts of the Ganges Tidal Plain West have seen a reduction of freshwater inflow during the dry season from the Ganges and a reduction in the tidal prism (the volume of water moving through the river between high and low tides). For instance, in the Pussur catchment, the tidal prism has decreased by over 1 billion cubic meters since the construction of the embankments, resulting in an increase of the tidal range and siltation of the channels (Pethick and Orford 2013). Increasing water levels have in turn reduced the time window of low water periods for draining excess water (Wilson et al. 2017). In the Noakhali region, a major factor has been the construction of several cross-dams for land reclamation purposes (Rashid, Hossain, and Islam 2013). As a result, the pathways for drainage have become much longer, worsening the drainage capacity of these areas. However, as mentioned previously, the underlying drivers of waterlogging are complex and often associated with multiple factors, making it hard to attribute the issue to a single driver only.

Figure 3.9: Map of the Polders in the Coastal Zone that Experience Waterlogging Issues



Source: Khan 2018.
Note: The light blue areas are the coastal polders that experience waterlogging issues.

How waterlogging might change in the future is still unknown. RSLR could reduce the time window for gravity drainage, which can exacerbate waterlogging issues in areas that already experience shorter periods of low water levels. While some issues can be resolved by improved O&M of water management infrastructure, external issues are harder to counteract, which means that sustainable solutions need to be found to adapt the water management system to these changing conditions.

3.4. Climate Migration

Climate-induced migration is expected to increase in the future, although the spatial patterns are still largely unclear, with some studies showing a net out-migration while others predict a net in-migration. Although climate-driven migration is not widespread at present, it is expected to become more prevalent in the future. Rising soil salinity, permanent inundation of land because of SLR, changing crop productivity due to changing temperature and rainfall patterns, and changing economic activities (such as an increase in manufacturing) have been identified as the main drivers of future climate migration (Chen and Mueller 2018; Rigaud et al. 2018). For example, Chen and Mueller (2018) found a direct relationship between an increase in salinity levels and a drop in crop revenue, resulting in some households deciding to migrate. In their study, they predicted that an increase in salinity (from the first to the fifth quantile) will cause 140,000 people to move within their district (to cities like Khulna and Chattogram), and 60,000 people to move to other districts, mostly to Dhaka or other coastal districts. They posit, however, that the attractiveness of shrimp farming under high salinity levels may offset some of the migration, in particular international migrants. In a study by Rigaud et al. (2018), future migration

Box 3.4: Livelihoods Impacts of Waterlogging

Waterlogging can have multiple impacts on the livelihoods of affected households. In the early 1990s, a hundred thousand hectares of land in Khulna, Jashore, and Satkhira became waterlogged. Waterlogging was particularly prevalent after the 2011 monsoon season, which affected an estimated 1 million people in the three districts. Flood water stayed in the polder for 60 to 90 days, although some places became permanently waterlogged, affecting approximately 130,000 hectares of cropland (Awal 2014). In total, about 34,000 houses were fully damaged and 58,000 houses were partially damaged (Awal and Islam 2020).

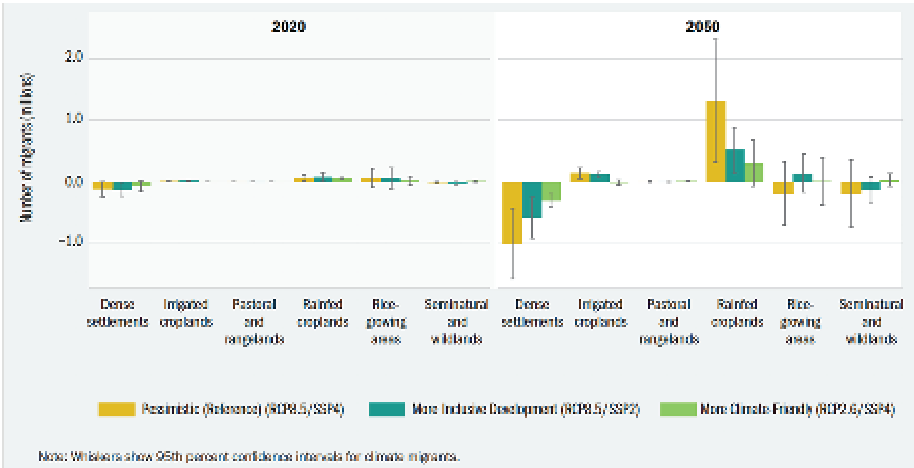
Apart from the direct impacts to cropland and houses, waterlogging can affect the wellbeing of polder inhabitants in other ways. For instance, a survey among households in three waterlogged polders showed that 85 percent of the interviewed households reported that waterlogging severely affected their lives and livelihoods, in particular by damaging crops or causing a delay in crop cultivation (Alam, Sasaki, and Datta 2017). Moreover, the stagnant water results in transportation and communication disruptions for large parts of the year, often making schools inaccessible. Food prices rose during the 2011 waterlogging event, and latrines and drinking water sources were affected (from the inundation of tube wells).

As an adaptation strategy, some farmers transformed their waterlogged fields into fishponds, while others had to change jobs or became jobless. For instance, in Bhutiar Beel, more than 37,000 farmers became day laborers as a result of the waterlogging in this area (Awal and Islam 2020). A detailed household survey among affected and unaffected households in Satkhira showed that affected persons had significantly lower expenditures than unaffected persons within the same wealth group (approximately 75 percent of the level of unaffected persons' expenditures) (FSC 2014).

Thus, measures that reduce waterlogging not only result in a reduction of damage to crops and housing but can also have wider positive impacts on the wellbeing of affected inhabitants.

patterns as a result of both SLR and changing crop productivity were evaluated for the country as a whole. The researchers found that 2 to 7.5 percent of the population, depending on the climate and socioeconomic scenario, will become internal climate migrants by 2050. In the most pessimistic scenario, the population density along the coast could decrease by up to 40 percent, except in the southwestern corner of the coastline and near Chattogram, where an increase in population was projected. **Figure 3.10** shows the predicted net migration per land-use type in Bangladesh under different scenarios. A large migration flow from rainfed cropland to dense settlements is predicted under all scenarios for 2050, although the absolute numbers are considerably smaller for the climate-friendly scenario (RCP2.6 and shared socioeconomic pathways (SSP) 4). The rice growing regions, which cover most of the coastal zone, will experience a net out-migration under the pessimistic climate scenario (RCP8.5 and SSP4), while in the other two scenarios these areas will experience a net in-migration or limited change in population (Rigaud et al. 2018).

Figure 3.10: Predicted Net Migration Numbers by Land-Use Type in 2020 and 2050 for Various Climatic and Socioeconomic Scenarios



Source: Rigaud et al. 2018.

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The two studies referenced above mainly focus on the environmental factors that cause people to migrate. Other studies state that coastal out-migration may be overpredicted given that large-scale migration to urban areas leads to an oversaturation of labor and housing markets, resulting in a net migration to the high-risk coastal zone. This effect was taken into account in another study that looked at migration flows in 2100 as a result of SLR and demographic changes (Bell et al. 2021). This study showed that out-migration will likely not take place in the coastal zone, and in fact predicts a net in-migration to the coastal zone. This is mainly associated with the economic transition from agricultural to non-agricultural sectors, thereby attracting migrants to the coastal cities for work. The districts with the largest in-migration also have large "trapped" populations, referring to households that lack access to credit and hence are constrained in their decision to migrate. However, most of the studies neglect any type of adaptation or policy interventions that could prevent or steer migration. For instance, the GoB has announced plans to establish and transform cities and towns to make them migrant-friendly (Khan et al. 2021). Therefore, quantitative modeling tools could help evaluate various policy initiatives to better predict the movement of climate migrants in the future, in particular refining if and when coastal cities could expect an influx or outflux of people, and how adaptation efforts should be prioritized with respect to that.

3.5. Concluding Remarks

Multiple risks come together in the coastal zone, some of which are driven by the same underlying factors and drivers, while others have distinct spatial patterns. Therefore, any location will have a slightly different risk profile, and thus, spatially explicit risk analyses is needed to understand where the risk hotspots are, what the major contributors are to the local risk, and what types of interventions are needed to address and reduce the risk. This chapter has provided examples of risk information that has helped identify risk hotspots in the coastal zone. However, having an overarching risk management framework (Chapter 5) can help in providing guidance, as expressing multiple threats in terms of risk can help identify priorities and balance trade-offs. In Chapter 4, an overview of the different types of interventions, and their effectiveness in reducing risk in some of the risk hotspots will be discussed, as well as the key benefits and challenges identified for the design of future interventions.

3.6. Notes

12. A 10-, 25-, or 100-year event refers to an event with a 10%, 4%, or 1% annual exceedance probability of happening every year, and should not be confused with an event happening only once every 10, 25, or 100 years. In fact, a 100-year flood event that happened last year can happen again before the end of the century, or even next year. Please refer to https://www.gfdrr.org/en/100-year-flood for more information on this.

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4

EMPIRICAL EVIDENCE ON SELECTED COASTAL RESILIENCE INTERVENTIONS

Ismail Ferdous

CHAPTER 4: EMPIRICAL EVIDENCE ON SELECTED COASTAL RESILIENCE INTERVENTIONS

Over the years, Bangladesh has undertaken significant efforts to develop an inhabitable, productive, and resilient coastal zone. Within a relatively short timeframe, about 60 years, a DRR portfolio of both structural and non-structural interventions[13] has been implemented in Bangladesh through a wide variety of projects and programs. In effect, noteworthy improvements in terms of EWS and last mile connectivity, disaster preparedness and response, and improved livelihoods activities, which have led to a reduction in the loss of life and assets, has made Bangladesh a global leader in DRR and climate change adaptation.

For example, a series of polders have been constructed to reduce the risk of tidal flooding and saline water intrusion while boosting agricultural production. Many of these polder projects included the construction of major water infrastructure such as embankments, drainage sluices, and canals, as well as roads on top of the embankments to improve connectivity in the coastal zone. A vast network of erosion control structures has been designed to better control the highly dynamic coastal and tidal river movements. In addition, thousands of shelters have been constructed over the past few decades to reduce the vulnerability of the coastal population during cyclones. Non-structural interventions such as raising awareness and improving preparedness in combination with early warning have also been part of the strategy to increase the resilience of the coastal population. Furthermore, the GoB has improved the governance of integrated coastal planning and has been a global initiator of community-based disaster risk management.

Since Independence, Bangladesh has invested over US$10 billion in the development of disaster mitigation and preparedness systems in the coastal zone (World Bank 2013). Given the large investment needed to improve coastal resilience in Bangladesh in the future, it is imperative to evaluate the effectiveness of these interventions, learn from past experiences, and identify key focal points to guide future investment plans.

This chapter provides an integrated assessment of past and current interventions in Bangladesh aimed at identifying lessons learned from these projects, which will ultimately help to inform the design of future interventions (see **Box 4.1**). The results of the assessment, along with relevant experience from other countries, are used to present a case for building coastal resilience in a meaningful and effective manner. The focus is on interventions that are intended to reduce vulnerability against coastal erosion and cyclone-induced winds and storm surges, which have been identified as the most prominent hazards and the key threats in the coastal zone (see Chapter 3).

For this purpose, projects were screened and classified according to their risk reduction potential (see the cascade of coastal resilience strategies in **Box 4.1**). This initial screening process was followed by an in-depth assessment of a selection of interventions covering nine projects using interviews with key stakeholders, field visits, and literature studies, resulting in the identification of four key intervention categories: (1) flood/tidal/storm surge protection works, (2) shoreline stabilization works, (3) cyclone EWS and emergency shelters, and (4) efforts to improve integrated coastal zone management. This in-depth assessment helped to identify the performance and impact of past interventions with respect to coastal resilience and cost-benefit ratios.

Additionally, modeling was carried out to reevaluate the benefits of some of the key interventions. Combining the qualitative information gathered with the quantitative modeling outcomes enabled the evaluation of the expected performance of these projects so as to draw conclusions on lessons learned for future investments.

This chapter highlights that based on the assessments done, embankments and shelters in combination with EWS are proven interventions for reducing the risk from cyclones in the coastal zone, and thereby have improved the livelihoods of millions of people. In addition, strategic mangrove restoration has been successful in stabilizing the coastline in the targeted areas. However, to date, mixed success has been achieved in tackling severe coastal erosion. The evaluation of past interventions found that they were not always embedded in a long-term strategy, and thus, could be better aligned with existing policies (such as land-use regulations) and broader development outcomes. Another finding is that interventions should make better use of state-of-the-art knowledge (for example, taking a risk-based approach in planning, design, and maintenance). In the next chapters (Chapters 5 and 6), some of these key findings are explored in more detail and newly developed work on nature-based and hybrid solutions are presented that can partly solve the aforementioned shortcomings and pave the way towards improved resilience in the coastal zone.

4.1. High-Level Assessment of Coastal Interventions

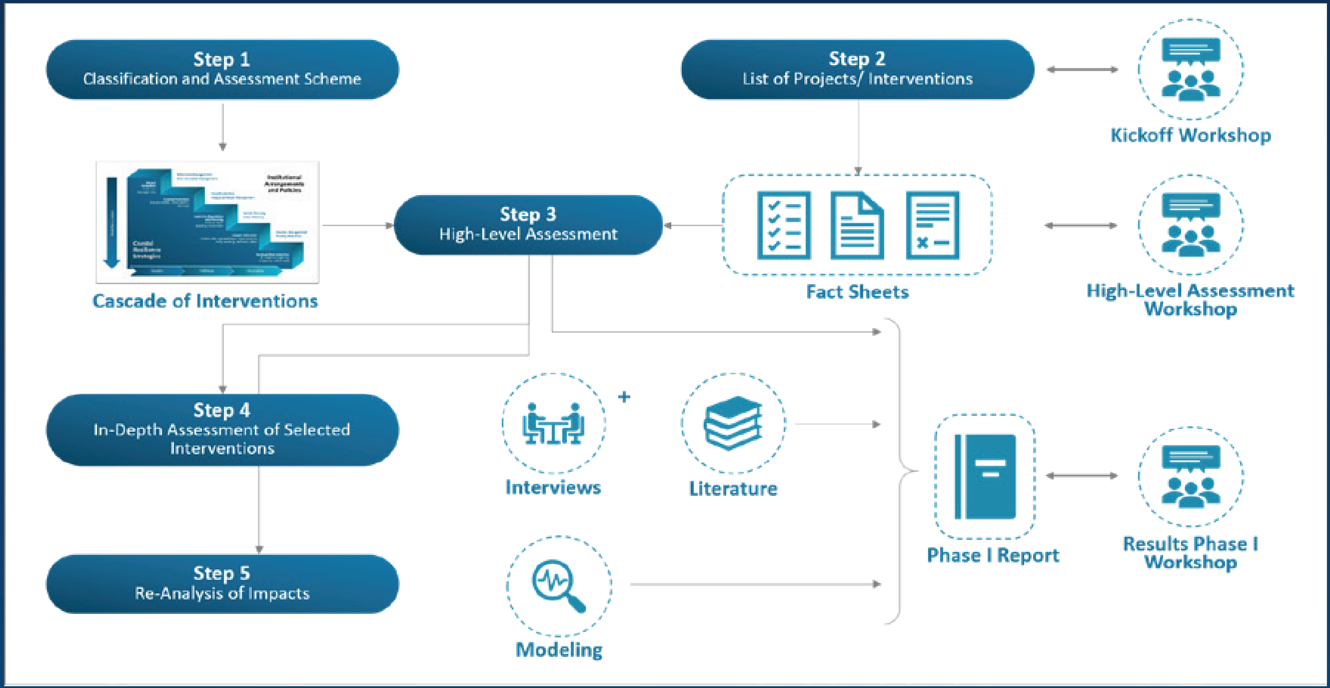
Different types of interventions have been developed and implemented in the coastal zone of Bangladesh to reduce the risk of coastal hazards. Examples range from multipurpose cyclone/flood shelters, hydrometeorological services enhancements, early warning and dissemination systems, and coastal embankments to community-based disaster risk management and strategies to improve coastal governance. For the high-level assessment, a set of criteria was applied to select appropriate interventions for evaluation. The focus was on large coastal projects (at least US$1 million, but preferably larger) implemented after 1950, resulting in a set of 36 projects for which sufficient information could be found. This set of projects represented a total investment of US$4 billion, which is likely a low-end estimate since not all budgets could be traced. The

Box 4.1: Steps in the Assessment of Ongoing and Historical Projects

To be considered relevant for this analysis, the current and historical projects had to meet the following criteria:

- The project should be located in or focused on the coastal zone either on land or at sea, up to approximately the 5m+MSL line;
- The project objectives should at least partly relate to coastal risk reduction;
- The project should be sufficiently large (at least US$1 million but preferably larger); and
- The project should have started after 1950.

Figure 4.1: Overview of Methodology for Review of Interventions



Source: World Bank 2021.

The factual bases of the projects identified were recorded in factsheets, covering, among others, their objectives and targets, sustainability aspects, success and failure factors, and lessons learned.

A high-level assessment of the projects was enhanced by an in-depth assessment of a subset of projects, aimed at deriving concrete lessons learned. The tools for the in-depth assessment included detailed analysis of available documents and interviews with key stakeholders (see **Figure 4.1**).

The assessment of the strategies using multiple analytical approaches—literature reviews, interviews, and modeling—enabled triangulation of the same phenomenon, namely interventions that enhance (or are supposed to enhance) coastal resilience, overcoming the weaknesses and intrinsic biases that come from single method, single observer, and single theory studies.

majority of these projects (26) were implemented after the year 2000 and most of the projects were donor funded.

A multicriteria analysis was used as an assessment framework to make a comparative high-level overview of all interventions. The framework was designed to capture the main components of each intervention or project and enable a characterization of each of them. The framework contained criteria and subcriteria (**Table 4.1**) that provided an indication of the performance and contribution to resilience of each selected intervention.

There are various ways to classify how coastal interventions contribute to risk reduction. For this report, a "cascade of coastal resilience strategies" was adopted, which reflects a logical cascading sequence for evaluating the risk reduction measures. The cascade starts at the source of the hazard, followed by the pathways that affect the exposure of assets and population, and ends with the receptor of the hazard (see **Figure 4.2**). The cascade also illustrates that for each risk reduction measure, there is often a corresponding policy and management area, and sometimes more than one, that is relevant (indicated at the right side with "Institutional Arrangements and Policies"). Coastal resilience strategies against storms, flooding, and erosion generally include measures from different steps of the cascade, forming an integrated risk reduction portfolio. Typical interventions in each category are listed (see also **Table 4.2**).

Table 4.1: Assessment Criteria and Subcriteria for the Multicriteria Analysis

	Criteria	Subcriteria
Effectiveness	Storm surge risk	Reduction in expected annual number of affected people
		Reduction in expected annual number of fatalities
		Reduction in average annual losses
	Coastal erosion risk	Reduction in annual coastal retreat (structural erosion)
		Reduction in event-driven coastal retreat
	Wind risk	Reduction in average annual losses
Sustainability	Environmental values	Ecosystem and biodiversity effects
		Energy efficiency
		Ambient environment/spatial quality
		Carbon emissions
	Social values	Resettlement/impacts on marginalized groups
		Local employment/livelihoods improvement
		Effect on gender conditions
		Human health
		Effect on cultural, historic, archaeological sites and landscapes
	Economic values	Cost effectiveness
		Cost-benefit ratio
		Direct effects on local or regional economy (e.g. tourism, agriculture, fishery, logistics, energy)
		Co-benefits, synergies, or spin-off effects on other sectors' revenues (e.g. transportation)
Implementation	Success/ failure factors	• Funds/finance, also for O&M, business model • Stakeholder involvement/community participation and ownership • Knowledge and design guidelines • Governance, management, institutional arrangements • Force majeure/external events • Asset management
	Time – space	Implementation time, exit strategy
		Flexibility and robustness ("future proof" in view of climate change)
		Upscaling opportunities
	Applied innovations and know-how	Technical innovations
		Nature-based solutions
		Capacity building and knowledge transfer

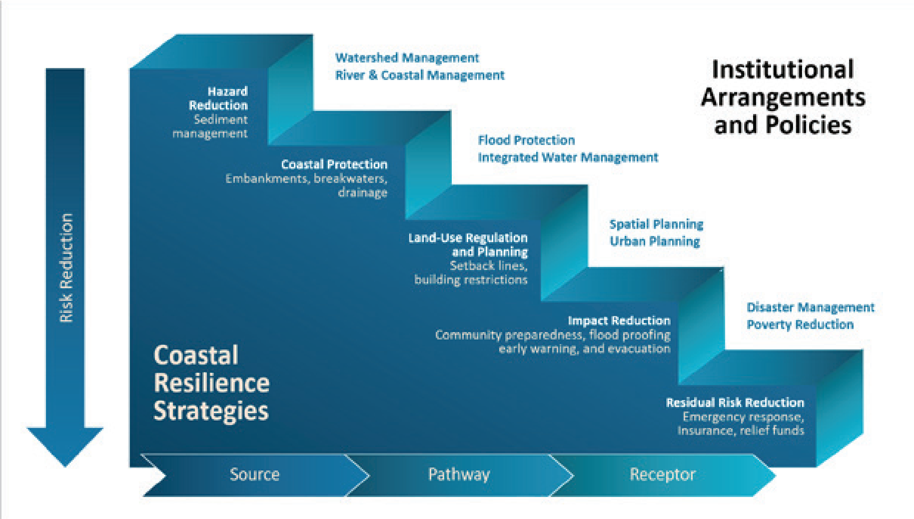
Source: World Bank 2021.

The use of the cascade of coastal resilience strategies is instrumental in that it provides insight into whether the full range of complementary interventions was used, and if not, what the reason for this could have been. As there is probably no single intervention that yields maximum resilience, it is important to understand what combinations of interventions can be used, how they complement each other, and what their combined effectiveness is.

For the selected coastal risk reduction interventions, a classification scheme (**Table 4.2**) was developed to identify all possible categories of interventions and outline the particular aspects of resilience they seek to enhance. It does not say that all measures are intrinsically resilient, as this very much depends on local conditions and the way the interventions are implemented. For instance, the Coastal Protection category includes a wide range of measures, from protective hard infrastructure to mangrove shelter belts. Under certain circumstances, an infrastructure solution may well be the right intervention to increase a community's resilience by protecting its village, although it does not improve the morphological resilience. Further, the perceived impact of a particular coastal resilience measure may vary across different communities along the coast depending on the prevailing social, economic, ecological, and morphological systems.

The high-level assessment of the 36 projects underlined that the main emphasis to reduce coastal risk in Bangladesh has been on three (out of the five) categories of the coastal resilience cascade: Coastal Protection (polder embankment rehabilitation and improvement programs), Impact Reduction

Figure 4.2: Cascade of Coastal Resilience Strategies



Source: World Bank 2021.

Table 4.2: Coastal Risk Reduction Strategies

Category	Interventions
Hazard Reduction	• Restore sediment balance (e.g. reservoir flushing), bypasses, tidal river management (TRM), etc.
Coastal Protection	• Hard measures (embankments, dikes, groynes, revetments, slope protection, breakwaters, closure dams, etc.) • Soft measures (mangroves, sand nourishment, dune restoration, etc.) • Hybrid solutions
Land-Use Regulation	• Setback lines, zoning, managed realignment • Building restrictions, protected areas • Policies and plans
Impact Reduction	• Early warning, evacuation plans, and infrastructure improvement (roads, telecom) • Cyclone shelters and refuge areas • Flood proofing of houses and infrastructure (power lines, water supply) • Community-based disaster risk management and awareness raising
Residual Risk Reduction	• Emergency response • Relief and recovery programs • Insurance • Livelihood improvement programs

Source: World Bank 2021.

(cyclone shelters and EWS programs), and Residual Risk Reduction (livelihoods improvement, and awareness and preparedness programs). Much less attention has been given to the Hazard Reduction and Land-Use Regulation categories, but there are good reasons for this. For instance, reducing the storm surge hazard is very hard to do. With respect to coastal erosion, the situation is more nuanced: here one could imagine that the cause of coastal erosion (i.e. a sediment imbalance) can be mitigated through better sediment management. The underrepresentation of the Land-Use Regulation category can be partly explained by the fact that such interventions often do not materialize in a stand-alone investment project, but rather through legislation and regulation by the government. Major steps have been taken in this area, illustrated by the Coastal Zone Policy (CZP) (2005),[14] the Coastal Zone Strategy (2006), and the recent BDP 2100,[15] but the tools and institutional capacity for implementation are still very limited.

It should be noted that many projects include interventions that do not focus solely on coastal protection; they are coupled with interventions that reduce the impact of hazards and residual risk should the protection fail. This corroborates the ongoing trend to complement protection measures with other disaster reduction measures (Jongman 2018). Overall, projects seem to be less clear on arrangements for O&M, asset management, and exit strategies. A lack of O&M and asset management may hamper the long-term sustainability of interventions and should be an important point of attention. The lack of O&M is complicated by the fact that many donor-aided projects do not provide funds for O&M, although some recent donor-funded projects in Bangladesh have started to include O&M funds in infrastructure projects (for example, the Char Development and Settlement Projects III and IV). Recently, in order to have a good knowledge repository of O&M processes, the Japan International Cooperation Agency (JICA) supported the preparation of the BWDB O&M Manual 2017.[16]

Based on this high-level assessment, a subset of nine projects divided into four intervention categories (Sections 4.2 – 4.5 elaborate on these four intervention categories in more detail) was selected for in-depth assessment, as outlined in **Table 4.3.** The selected interventions can be classified under three main coastal resilience strategy categories: (1) Coastal Protection; (2) Impact Reduction; and (3) Land-Use Regulation. Interventions under Hazard Reduction were not included since the hazards themselves (that is, cyclones and storm surges) cannot be reduced. The reason that interventions under Residual Risk Reduction were not selected is that these were not specifically linked to the coast. Emergency responses, relief and recovery programs, insurance, and livelihoods improvement programs are more generic in nature. Although they are still crucially important to increase the resilience of coastal communities, the study of their success or failure factors are hardly linked to the specific coastal zone under consideration.

Table 4.3: Most Significant Projects Selected for In-Depth Assessment

Intervention	Projects in Bangladesh
Category: Coastal Protection	
Flood prevention	Blue Gold
	Coastal Embankment Improvement Project Phase I
	Emergency 2007 Cyclone Recovery and Restoration Project
Measures to combat coastal erosion	Integrating Ecosystems for Resilience of Coastal Island in Times of Climate Change
	Sundarbans project
	Coastal Hydraulic and Morphological Study and Design of Protection Measures for Marine Drive
Category: Impact Reduction	
Cyclone EWS and emergency shelters	Multipurpose Disaster Shelter Project
	Emergency 2007 Cyclone Recovery and Restoration Project
	Improvement of Meteorological Radar System at Cox's Bazar and Khepupara
Category: Land-Use Regulation	
Policy, planning, and regulation	BDP 2100, CZP (2005)

Source: World Bank 2021.

The analysis was conducted with certain limitations being recognized upfront: (1) it was focused on specific interventions in a local area rather than the entire program or project as a whole; (2) the selection of interventions was based on an extensive literature review and stakeholder consultations, but they may not be fully representative of all past interventions implemented; (3) both the quality and quantity of data were limited, since interventions were considered from 1960 onward, and it was impossible to obtain all past records; (4) it focused on larger, often donor-aided projects, because it was possible to obtain historical documents and information relatively easily for those; and (5) there was a certain subjectivity in the evaluation as it arrived at the key factors for success, importance, or relevance through the judgments of experts and other key stakeholders.

4.2. Flood Prevention and Embankments

In Bangladesh, the current polder concept to protect the coastal zone against flooding was introduced in the 1960s following several technical missions from the United Nations in the 1950s. To provide context, the commencement of the formal water management institutional structure and planning was an outcome of the successive floods of 1954, 1955, and 1956, which led the GoB to seek international support through the United Nations. The mission published its report in 1957, popularly known as the Krug Mission Report, leading to the formation of the East Pakistan Water and Power Development Authority in 1959. Publication by the authority of the first 20-year Master Plan for Water Management in 1964 marked the beginning of water sector planning in what is now Bangladesh. The master plan was based on a strategy for flood control

Example of coastal embankment and turfing (Polder 35/1).

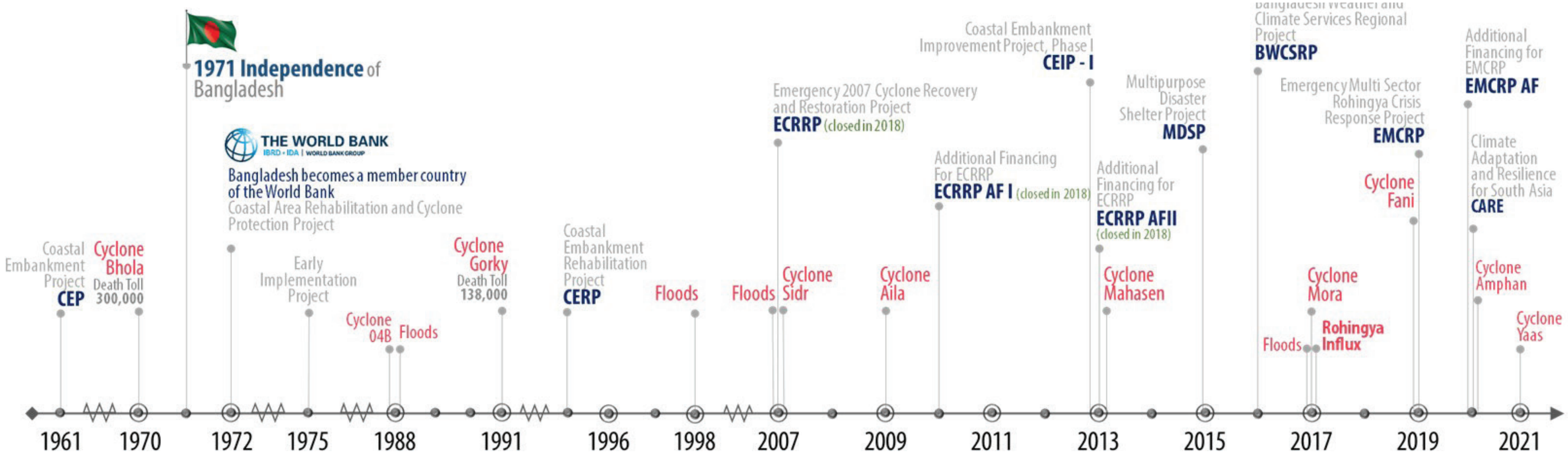
and drainage improvement aimed at increasing agricultural production, which is intrinsically linked to the beginning of the polder system, tidal flood management, and food security for Bangladesh.

The concept of using polders to prevent tidal flooding and (partly) protect against storm surges can be found all over the world, including in Egypt, Morocco, China, Belgium, the Netherlands, the USA, and Argentina (UNEP 2017). In the Netherlands, for example, polders have been used since the 11th century and have resulted in prosperous and inhabitable zones for communities. Polders typically consist of embankments, drainage and flushing systems, and water management infrastructure (for example, sluice gates).

The GoB's decision to construct polders and complementary interventions was aimed at protecting communities and key economic sectors (such as agriculture and fisheries) from hazards such as coastal inundation and saline water intrusion, thereby ensuring food security and enabling these key economic sectors to grow over time. The polder concept has been taken forward through a series of projects in Bangladesh that have led to the current system of 139 polders across the coastal zone. At present, the 139 polders protect an estimated 1.2 million hectares of land (around 43 percent of the coastal zone), and more than 8 million people depend on the land contained within the polders for their food security and livelihoods.

During implementation of the CEP, which started in 1961, approximately 4,000 kilometers of embankments were constructed to reshape the coast into 108 polders, comprising about 1 million hectares of land. A series of projects followed to create new polders, and rehabilitate and improve existing polders, including the Early Implementation Project (1975), the Coastal Embankment Rehabilitation Project (1995), and CEIP-I (2013) (see **Figure 4.3**). Within the CEIP-I, the design of a number of polders was enhanced to protect against present and future storm surges along with meeting the initial objective of protecting the land from regular saline tidal flooding.

Figure 4.3: Key Projects in the Coastal Zone



Source: World Bank, original figure developed for this report.

Improvements in agricultural production as a result of strengthened polder systems.

Improvements in agricultural production as a result of strengthened polder systems.

The impoldering has provided benefits for the communities living within the polder areas by improving their livelihoods conditions because of increased agricultural production and less frequent floods and associated damages to private and public assets and infrastructure. In the CEIP-I, a number of polder systems were rehabilitated and upgraded, with embankments designed to withstand a 25-year water level, and the polder drainage system to effectively drain a 10-year rainfall event with a five-day duration. Improved crop productivity because of better drainage is an important contribution to total benefits (39 percent) according to the CEIP-I economic analysis. The avoided damage to assets such as roads and property is another significant benefit (in total 47 percent). The economic analysis of the most recent polder rehabilitation program under the CEIP-I has shown an overall benefit-cost ratio of 2.4 for the project (World Bank 2013). Other independent research confirms these findings, underlining that there is a strong economic rationale for increasing the current (relatively low) protection levels of the polder embankments in Bangladesh (Zaman and Mondal 2020).

To highlight the benefits of polders in more detail, a reanalysis of the benefits of the embankment improvement work during the CEIP-I for Polder 35/1 was performed. In particular, the reanalysis focused on the effects of the improvement of the embankments along the Baleshwar River with regards to the avoided damage from flooding. A detailed assessment (see details in **Box 4.2**) shows significant positive benefits, with avoided damages of approximately US$1 million per year, excluding the impacts of climate change, land value increases, and enhanced agricultural production. In addition, the improvements to the embankment have directly resulted in 2,000 people being less affected by coastal flooding on an annual basis, which is roughly 2 percent of the total polder population (approximately 100,000). The reduction in risk is considerable compared to the investment costs. Construction of the embankment at the Baleshwar bank of Polder 35/1, with a lifespan until 2050, cost approximately BDT 480 million (US$5.5 million) (Bangladesh Water Development Board 2013).

Despite the overall success of the polders, several challenges have partially hindered the past effectiveness of the polder system (see **Table 4.4**). First, a lack of proper O&M of both the embankments and the drainage systems is one of the major concerns, amplifying the deterioration rate of such structures and ultimately resulting in stability issues of the structures and inefficient water management practices. In addition, rising sea levels and ongoing subsidence put an additional strain on the sustainable lifecycle of the polders. Only a limited number of embankments and drainage/flushing systems have been

Table 4.4: Benefits and Challenges of Preserving the Polder System

Item	Benefits	Challenges
Agriculture	Agricultural output has increased significantly.	New problems, such as waterlogging, have emerged in certain polders.
Water management	Polders facilitate water management.	Problems include siltation of peripheral channels, no proper maintenance of the drainage network because of a lack of working institutional arrangements and/or conflicts between different user groups, and waterlogging. These have become an impediment for the traditional cropping pattern with rice and shrimp farming.
Flood protection	In locations where embankments are present, they have provided significant protection from cyclone storm surges.	The significant wave attack and increased currents that have occurred over the years have caused previously constructed embankments to suffer from erosion and breaches. These negative impacts are amplified by the lack of O&M.

Source: World Bank, original table compiled for this report.

Box 4.2: Reanalysis of the Effects of Embankment Improvement – A Case Study of Polder 35/1

The main objective of the reanalysis was to quantify the reduction in risk as a result of the improvement of artificial levees (dikes, embankments) of low-lying coastal areas (polders) in the Bangladesh coastal zone. The effect of the embankment improvements executed within the CEIP-I was considered for the analysis, with a specific case study of Polder 35/1.

The following aspects were taken into account for computation of the crest level of embankments in the CEIP-I:

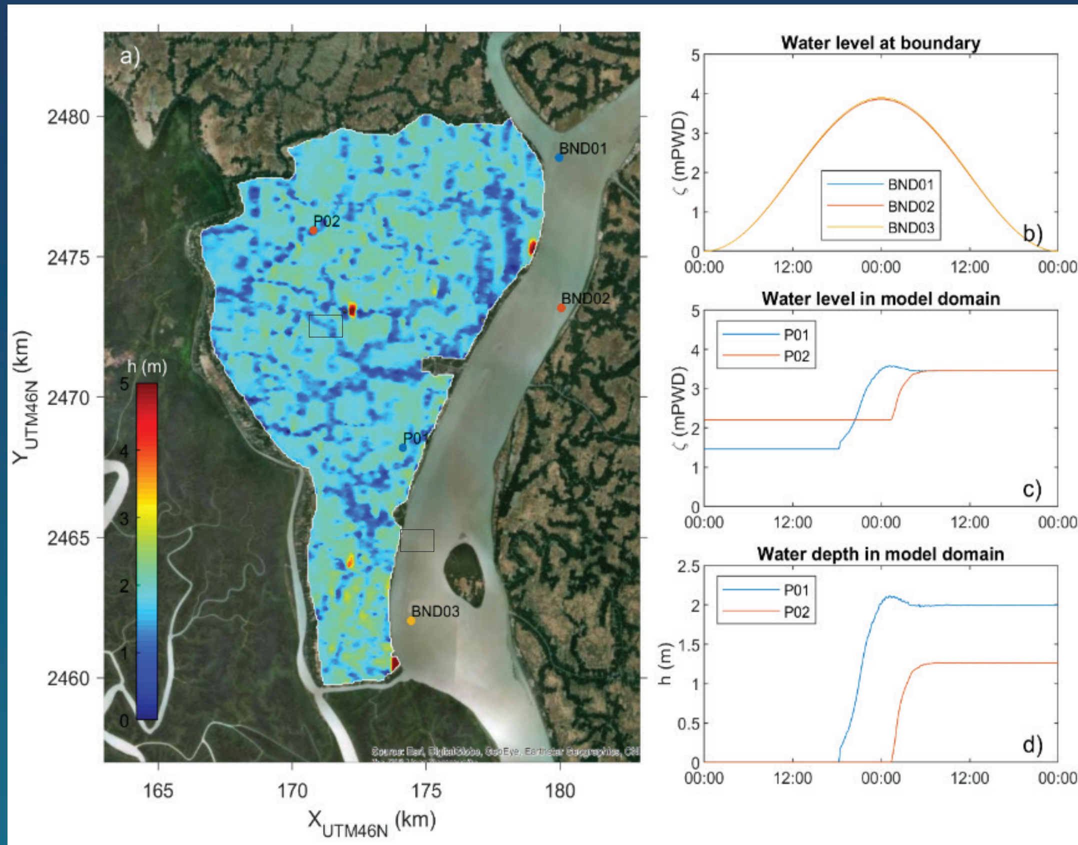
- 25-year storm surge event
- 25-year monsoonal flood level
- Alternatives for freeboard depending on an overtopping limit of 5 liters per meter per second for several possible embankment slopes and roughness
- An additional margin to allow for subsidence

A flood inundation model was set up for Polder 35/1 to estimate the extent of flooding under the extreme surge levels and wave heights determined in the CEIP-I, which then delivered inputs for the risk modeling. The result of the inundation modeling was a spatial distribution of flood depth for each scenario modeled.

Figure 4.4 shows the spatial distribution of the maximum flood depth (panel a) during the simulation with the old crest level of the embankment (Public Works Datum (PWD) 3.80 m) and hydrodynamic conditions corresponding to a 50-year return period (top right). Panel b) shows the forcing of surge levels on the three boundary points, panel c) shows the water level, and panel d) shows the water depth (with respect to bed level) on the two indicated points in the model domain.

The goal of the risk analysis was to assess the risk reduction (that is, the reduction in annual direct impacts to exposed assets and people at Polder 35/1) resulting from the increase of the dike crest level from a height of PWD 3.8 meters to a height of PWD 6.0 meters.

Figure 4.4: Map Showing the Spatial Distribution of the Maximum Flood Depth



Source: World Bank 2021.

Example of coastal embankment slope protective works in Polder 35/1.

Example of coastal embankment, drainage sluice, canal, and agriculture in Polder 35/1.

renovated to cope with changes in the design conditions as a result of climate change. Hence, significant additional investments are needed to incorporate climate change adaptations into the design of the other polders. Finally, river and coastal erosion due to waves and tidal flow currents has led to the erosion of embankment slopes and bank protection works, indicating that the initially designed revetment and toe structures may have been underdesigned. Therefore, the designs of these structural works need to be revisited to improve their reliability and reduce the risk of structural failure.

For instance, alternative embankment designs, such as "smart embankments," have been proposed, which consist of improved bed protection, bank protection, and embankments in combination with the use of EEWS. The EEWS enables monitoring of the erosion locally, which can help water managers maintain the embankments.

Recent projects, such as the CEIP-I and the Blue Gold Program,[17] are taking initiatives to respond to the challenge of improving the O&M of the polder infrastructure. Both projects have a strong focus on the involvement of local communities through participatory water management practices (see also **Box 4.3**). The 1999 Bangladesh National Water Policy[18] formally recognized the role of all stakeholders in the management of water and mandated their participation in any scheme to promote sustainability to ensure the long-term integration of social and environmental conditions. Specifically, the GoB decreed Participatory Water Management Rules in 2014, which resulted in the formation of water management organizations (WMOs)[19] having responsibilities within water resource projects. WMOs stimulate the engagement of local stakeholders (such as water users) in water management groups (WMGs), with the objective that the water users take over full responsibility for the operation and partial responsibility for the maintenance of the water management infrastructure. As per the Participatory Water Management Rules, women must form 30 percent of the WMO constituency and are to be given leadership training and encouragement by the project.

Another challenge is waterlogging in the polders, particularly in Satkhira, Jashore, Khulna, and Bagerhat districts, as a result of the interruption of sedimentation

Box 4.3: Maintenance of Embankments Jointly by WMOs and Union Parishads

Context: As originally conceived, responsibility for the O&M of the water management infrastructure in the polders was under the implementing agency—the BWDB. After its restructuring, there were not sufficient local-level staff to handle the O&M work. Therefore, the GoB and BWDB realized that sustainable O&M of the infrastructure is not possible without the participation of local stakeholders. In this context, the Ministry of Water Resources and the BWDB took the initiative to organize communities and build their capacity to take over responsibility for the operation and routine maintenance of the infrastructure under different projects. The Blue Gold Program has an emphasis on sustainability through community participation and constructive engagement of the local government institutions, especially the Union Parishads (UPs), in water management activities. As part of the program, the WMOs and UPs were briefed about their roles and responsibilities, and both agreed to work together and have already set an example in this regard.

Description: WMG members and the UP jointly worked together to protect the embankment at Polder 43/2A from river erosion. The WMG members contributed their labor free of charge and the UP arranged the funding for the work. Upon a request from the UP, villagers donated materials (bamboo, wood, rope etc.) to use in protecting the embankment.

In July 2014, the embankment at Balaikathi village, Polder-43/2B under the Awliapur UP was breached by river erosion because of high tides and flooding. The WMGs and UP jointly repaired the breached portion of the embankment following the same procedure mentioned above.

Strengths:
- Joint initiative by the WMG and UP
- Avoids dependence on the implementing agency
- Utilizes local resources

Challenges:
- Regular maintenance of water management infrastructure
- WMGs lack funds for regular maintenance of water management infrastructure

Source: Blue Gold 2015.

inside the embankments combined with accelerated compaction, removal of forest biomass, and a regionally increased tidal range. For context, the land enclosed by the embankments in the southwest of Bangladesh has lost up to 1.5 meters in elevation relative to the mean height of the surrounding bodies of water (Auerbach et al. 2015). Due to poor drainage, these polders face long-standing and recurring flood problems during the rainy monsoon period. Plinth rising and elevating the local habitats and physical infrastructures have been put forward as short-term measures (Awal 2014). Alternatively, a potential long-term solution to combat waterlogging to be considered is TRM. With TRM, the low-lying land is reconnected with the tidal channel through a breach in the embankment (for four to eight years), which prevents the rivers from silting up and raises low-lying land by means of the sediment influx. Some studies have quantified the potential benefits of TRM on the sustainability of the polders (Adnan et al. 2020). It was found that TRM has the potential to raise land by 0.5 to 2.0 meters and has co-benefits by reducing flood risk, improving conditions for freshwater agriculture, and improving the ecology in the polder. However, despite the promising outlook, a number of social and technical constraints have also been identified (see **Box 4.4**) that limit widespread adoption of the concept in the coastal zone. Furthermore, compensation is a large component of the total cost (65 to 80 percent), which makes it quite costly and difficult to implement. The use of TRM will be further studied as part of a large research program under the CEIP-I.

Past polder projects in Bangladesh have faced several implementation challenges, resulting in longer implementation time and higher costs than originally anticipated. A key issue affecting the duration of implementation has been timely acquisition of the land necessary for the construction works and timely compensation for resettlement. Functional systems for land ownership and citizen registration as well as early communication with and involvement of the stakeholders are key ingredients to handling these aspects in a timely fashion and are still challenges in Bangladesh. It is noted that delays or cost overruns in public works projects are not unique to Bangladesh but happen across the world (Durdyev and Hosseini 2019). More effective and proper planning in view of the project characteristics (such as land acquisition and resettlement payments) and location characteristics (weather/climate conditions, remote sites) is one of the key focal points for improvement of future project performance.

Overall, despite the challenges identified (see **Table 4.4**), the rehabilitation and strengthening of embankments have proven quite successful, safeguarding villages, household property, and agricultural land during cyclones and storm surges. In addition, embankments have protected drinking water sources from salinity intrusion and improved transport connectivity through road construction on top of embankments during normal times and emergencies. In terms of effectiveness, use of proper morphodynamic studies and modeling is critical when planning and designing the infrastructure. However, O&M funds and sufficient monitoring of embankment stability remain key to sustainability.

4.3. Shoreline Stabilization

The coastal zone of Bangladesh is a dynamic environment and certain areas suffer from erosion, threatening communities and infrastructure (see Chapter 2). Combating coastal erosion can be done in many ways and requires a site-specific approach that takes the local physical and ecological characteristics into consideration (see **Box 4.5**). Hard solutions generally refer to structures such as sea walls, coastal groynes, and granular or block revetments at the bank or slope of the tidal riverbank or shoreline. Soft solutions, often classified as nature-based solutions or green infrastructure, use natural processes and materials for coastal protection, helping to maintain the natural landscape and coastal habitats. Examples include sand (or gravel) nourishments, vegetation/mangrove planting, oyster breakwaters, and coral reef restoration. Hybrid solutions are combinations of hard and soft solutions, such as revetments covered with sand providing a natural habitat and attractive areas for recreation. Managed realignment (or managed retreat) is widely used in Bangladesh if erosion cannot be stopped or is acceptable at a certain location. This is implemented by removing structures and restoring natural intertidal habitats. A more proactive and well-recognized global practice is the establishment and enforcement of setback lines or zones. These are buffer zones to accommodate the ongoing erosion that have certain use restrictions, such as on housing, industry, or infrastructure.

The most widely used approach to combat erosion in Bangladesh has been to build either temporary measures or hard engineering solutions. The presence

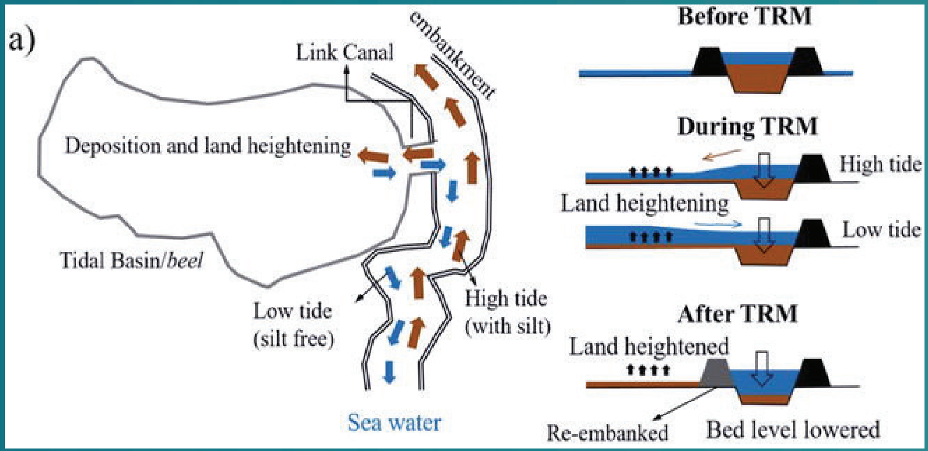
Box 4.4: Tidal River Management

TRM enables the natural movement of sediment-loaded tidal river water into an embanked low-lying area (a “beel”) during high tide. This leads to sediment deposition in the beel as flow energy is significantly reduced. During low tide, the outgoing sediment-free water picks up river sediment, erodes the riverbed and increases the drainage capacity of tidal rivers. TRM requires a cut in the river embankment, or a link canal between the river and the beel, to allow for the daily transport of water and sediment into the low-lying area for a period of at least several years (see Figure 4.5) During these years, the beel is flooded daily with water and sediment. TRM is capable of elevating land within the beel between 0.2 meters (at the far end) and 2 meters (near the cutting point) and increasing river flow as the tidal river deepens (by 9 to 12 meters) and widens (by 2 to 8 times the pre-TRM width) (Seijger et al. 2019).

There are current and past formal and informal TRM projects in the Lower Bengal Delta in the southwest of Bangladesh. TRM was executed in the Kobadak River Basin and in the Khulna-Jashore Drainage Rehabilitation Projects. It is understood that TRM was introduced by the local people themselves during the latter project once it was clear that the project’s proposed solutions to overcome waterlogging were not satisfactory.

However, the application of TRM is not without problems. In particular, the social complexity of the intervention poses hurdles in its implementation. TRM often creates conflict within local communities related to issues such as resettlement, affected economic activities, the effect on agriculture, and compensation for the (temporary) loss of land. For instance, compensation during the TRM in Beel Khuksia in 2006 proved difficult, as less than 10 percent of the farmers who lost their land temporarily were given compensation at the time, although the GoB committed to compensating other farmers at a later stage, and we understand that this is still pending (Gain et al. 2017). Furthermore, TRM often raises conflicts among local stakeholders (such as between shrimp pond owners, farmers, and landless people). During TRM applications, some communities rejected the cutting of embankments and favored embankment construction and increased flood prevention (Van Staveren, Warner, and Khan 2017) to avoid inundation-induced short-term losses in agricultural production and aquaculture practices.

Figure 4.5: Tidal River Management Conceptual Diagram



Source: Talchabhadel, Kawaike, and Nakagawa 2021.

of assets (including cultural sites) in erosion-prone areas and the scarcity of land are some of the key deciding factors for implementing measures to counteract erosion or use realignment as a last resort. Traditionally, temporary measures consist of geotubes and/or geobags to mitigate erosion. In terms of hard solutions, concrete block revetments, seawalls, and concrete block protection works have been used extensively in the coastal zone. However, even though these structures can provide sufficient protection, they are generally expensive and may have negative effects on the local sediment balance. In particular, sediment losses at the toe or at the sides of the structure require additional measures and/or intensive maintenance over the design lifetime.

Soft solutions to cope with coastal erosion have been applied in the coastal zone as well, in particular the use of mangrove forests or other root species for shoreline stabilization. Mangrove forests have the ability to stabilize shorelines, and even keep up with SLR by trapping sediment and dissipating wave energy through their complex aerial root system (Spalding et al. 2014). The Sundarbans mangrove system in the southwest of the country provides enormous value in shoreline stabilization and acts as a large soft solution against coastal erosion. Bangladesh has a long-standing mangrove afforestation program dating back to 1966, mainly concentrated on the islands in the eastern part of the delta and some coastal areas north of Chattogram. However, mangrove loss is continuing, with conversion to aquaculture and agriculture being the most common cause (Thomas et al. 2017). The mangrove loss in the Sundarbans area has resulted in a large amount of coastal erosion in the area in recent years (Dasgupta et al. 2021), which has been recognized as a global erosion hotspot of a World Heritage site (Sabour et al. 2020). In addition to mangroves, other species have been increasingly used for slope and foreshore stabilization, for instance Durba grass and Vetiver grass (see **Box 4.6**).

Mahfuzul Hasan Bhuiyan

Reversing the ongoing trend of declining mangrove forests is critical for shoreline stabilization. Alongside the benefits of mangroves from a hazard perspective, such as effective protection against storm surges, a healthy and wide mangrove forest has important co-benefits, as a natural habitat for fish and other ecosystem services, a source of wood, and a carbon sequestration mechanism. Rahman, Jiang, and Irvine (2018) have shown that the economic value of mangroves in terms of storm protection equals US$12.60 per hectare per year, and in terms of coastal erosion, US$2.07 per hectare per year. In recent years, mangroves have been increasingly used to protect the outer slopes of the embankments and reduce the wave runup of coastal polders. By 2013, approximately 60 kilometers of embankments of sea-facing polders had mangrove forests in their foreshore areas (Dasgupta et al. 2019). A reanalysis of Cyclone Sidr suggests that the existence of the mangrove forest reduced surge height by 4 to 17 centimeters and reduced the water flow velocity substantially (Dasgupta et al. 2019). However, there is no evidence from the past projects that Bangladesh is using other large-scale soft solutions, such as sediment nourishments to stabilize eroding coastlines (see examples in **Box 4.5**), although there are some small-scale nature-based pilot protection initiatives in Kutubdia Island.

Managed realignment of existing polder embankments is also a well-known tool in Bangladesh for erosion management. This solution, known as “retired embankments,” in Bangladesh, covers the abandonment of the existing embankment and the construction of a new embankment alignment at a certain setback distance from the river. This setback distance, which is typically 50 to 100 meters, functions as a buffer zone for the migrating river. The feasibility

Dumping of cement concrete blocks.

S M Mehedi Hasan

Box 4.5: Shoreline Stabilization Practices Around the World

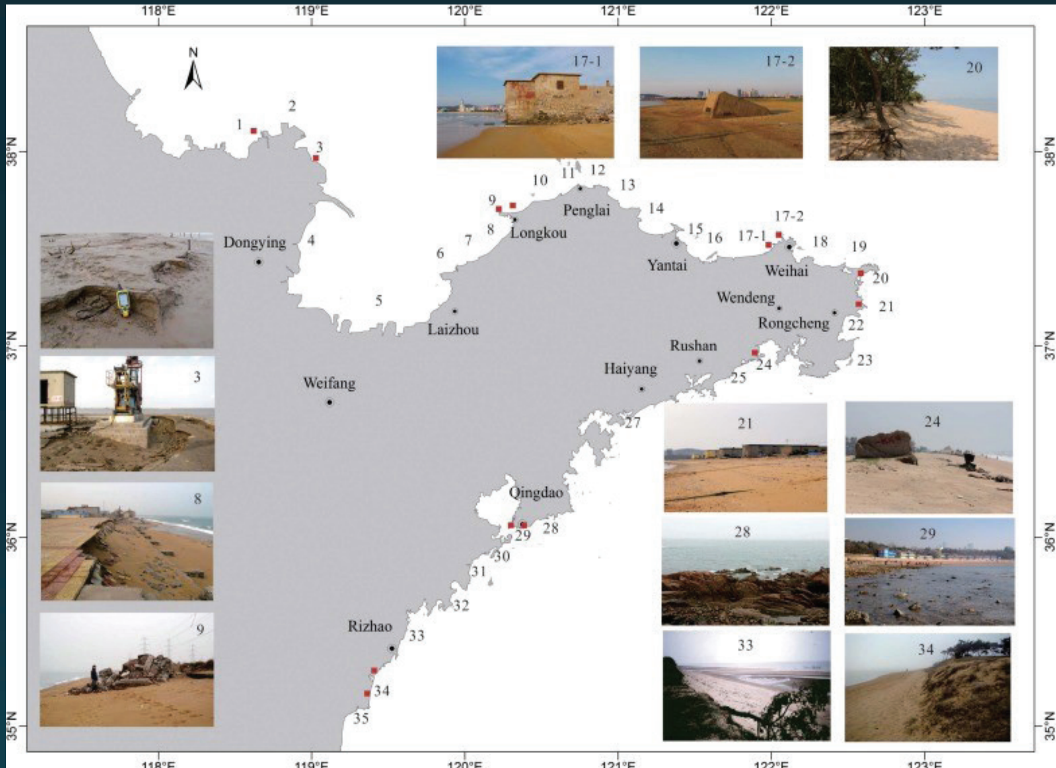
China

China has an extensive coastline and numerous islands and is severely hit by storms. Principal protection measures are coastal defenses such as seawalls (13,000 km of seawalls, most of them built after the 1980s) (Liu et al. 2019), breakwaters, and coastal shelter belts.

It is estimated that over their lifetime, these seawalls could recoup their construction and maintenance costs threefold in preventing storm damage (Liu et al. 2019). They are a simple and easily implemented defensive tactic, blunting the force of floodwater and storm winds. However, that does not mean hard engineered defenses are without risk. Increased coastal erosion and other ecological damage can undo the benefit of seawalls and similar engineered structures. In the worst-case scenario, these structures trade one problem for another. And combined with SLR, significant erosion can be devastating to a coastline (see **Figure 4.6**).

Although solutions, such as seawalls, did reinforce the coast, they also caused inconvenience during construction (Cai et al. 2009). Therefore, a new strategy of positive coastal protection has since been put forward where sand is positioned in front of the coast protection works and new types of groynes and offshore dikes and their combinations were built in different regions. The aim of this strategy is to dissipate waves and tidal energy in front of the foreshore before they cause erosion, transform the previous integral protection into segmented protection, reduce financial costs, and beautify the coastal environment. Over the past 10 years, there has been a greater focus on a soft structural approach (such as beach nourishment and biological protection by mangrove planting) (Cai et al. 2009).

Figure 4.6: Coastal Erosion in Shandong, China



Source: Yin et al. 2018.

United States of America

In the United States, coastal erosion is responsible for roughly US$500 million per year in coastal property loss, including damage to structures and loss of land. To mitigate coastal erosion, the federal government spends an average of US$150 million every year on beach nourishment and other shoreline erosion control measures (U.S. Climate Resilience Toolkit 2021).

In the past, protecting the coast often meant "hardening" the shoreline with structures such as seawalls, groynes, rip-rap, and levees. Over the years, as understanding of natural shoreline function has improved, many states have incorporated non-structural shoreline stabilization techniques as well.

Cliff erosion on the West Coast. (U.S. Climate Resilience Toolkit 2021)
Source: U.S. Climate Resilience Toolkit 2021

India

India's coastline suffers significantly from coastal erosion and makes use of both hard and soft solutions, although the latter more seldomly. For example, there are seawall type structures in Puducherry, Uppada geotubes, Pentha sea defense, and Digha-Sankarpur. Additionally, groynes are often used for coastline stabilization. An example of a detached breakwater using geotextiles is the shore protection at Kadalur village (Tamil Nadu). Soft solutions, such as beach nourishments, have been carried out in Puducherry, where about 0.2 million cubic meters of sand was dredged from the mouth of the nearby port to replenish the shoreline. A cost-benefit analysis was not carried out before starting the project because it was a demonstration project, however the local inhabitants have reported an increase in tourism activities and fish catches after the installation of the submerged breakwater (which acts as an artificial reef that accumulates marine biomass) (World Bank 2021).


Ismail Ferdous

Cement concrete block preparation.

Slope protective works.

Seawall constructed with geotubes and tetrapods at Marine Drive.

Cement concrete blocks for shoreline stabilization west from Kuakata Sea Beach in Polder 48 in CEIP-I.

Seawall constructed with geobags west from Kuakata Sea Beach in Polder 48.

of this solution depends on many factors, such as the availability of land, the presence of houses on the embankments, and the need for resettlement. Given the scarcity of land, as well as the social implications of this solution, it is typically a last resort if a temporary or hard engineering solution cannot be implemented. Although managed realignment is often used, Bangladesh does not have established setback lines for the entire coastal zone, with planning happening on a site-by-site basis.

The review of past projects on shoreline stabilization highlights that structural solutions such as groynes, geotubes, and seawalls have been the main strategies used to control erosion, with some success. Although these hard solutions stop local erosion, they sometimes shift the problem to neighboring coastal stretches or increase the scour near the toe of these structures, which can still result in instability problems. Hard solutions therefore require good monitoring and O&M practices, which are often not adequately in place. For instance, geosynthetic tubes can deteriorate after several years due to harmful ultraviolet light and the energetic wave conditions along the coastline and are easily vandalized. Therefore, the design could be improved by overlaying them with other material, such as rock gabions. Ongoing monitoring is needed to detect if small maintenance work is necessary and to prevent early degradation of these structures during their lifetime. The design guidelines of the typical hard solutions in Bangladesh, such as slope and bank protection, can also be improved, and should include morphodynamic studies and modeling for a proper understanding of the system.

View of the Sundarbans mangrove forest.

Box 4.6: Slope and Foreshore Stabilization using Afforestation and Grass Turfing

As part of the CEIP-I, afforestation programs are intended to provide nature-based solutions to protect the polders from tidal flooding and storm surges. Social afforestation programs aimed at including communities in the construction and maintenance of foreshore and slope plantations have been implemented in Bangladesh over the years.

However, several questions remain in terms of best practices, such as the most suitable plant species for afforestation, their structural integrity in terms of embankment protection, ecosystem services they can provide, and the social costs and benefits. Research has been undertaken to investigate these aspects, particularly the species selection criteria within a bioengineering framework and within a framework of sustainable environmental development and poverty alleviation. The research suggests that species selection for afforestation programs should be based on (1) tolerance to local edaphoclimatic conditions, (2) suitability for bioengineering purposes, (3) potential to assist in the conservation of specified aspects of biodiversity (birds, bats, small mammals, etc.), (4) ability to act as a framework species to speed up natural regeneration, (5) potential to improve livelihoods, and (6) potential to act as a nutritional supplement (Webb et al. 1984).

An assessment of suitability as a nature-based bioengineering approach for Bangladesh compared Vetiver grass (*Vetiveria zizanoides*), a grass native to tropical and subtropical India and known for its robustness and long life, to Durba grass (*Cynodon dactylon*), a small creeping sward grass commonly found on grazed land (Newman and Mukul 2021). Durba grass has been used in past polder reinforcement programs to protect the soil in the slope and crest of the embankments from erosion caused by rainfall, and wave and wind action.

A key benefit of using grass is its cost, which can be five to eight times cheaper than hard protection using brick or stone. However, environmental factors play a critical role in the suitability of different grass types. For instance, Vetiver grass has a salinity threshold of 8mS cm^{-1}, which is slightly higher than Durba grass (6.9 mS cm^{-1}) (Truong and Loch 2004). The benefits of Vetiver grass are that it reinforces the shear strength of the rooted soil by a factor of eight compared to soil without grass, it grows quickly, it can endure a range of pH and salinity levels, and it is tolerant of drought, flood, and submergence conditions (Islam et al. 2013). On top of the structural integrity of Vetiver grass, farmers can use it as forage, mulching, and thatching material, while aromatic oil can be extracted from the leaves and roots (Islam, Bhuiyan, and Hossain 2008).

The findings of the assessment indicate that Vetiver grass is superior to Durba grass in its ability to withstand high wind and wave action and heavy rainfall. Moreover, the salinity threshold is moderately high, making it suitable for most of the polders throughout the year.

Regarding soft solutions, the review shows that forest conservation and restoration has proven to be a successful soft solution in stabilizing coastlines along the Bay of Bengal. Moreover, mangroves and other plant species provide important co-benefits, and the combination of forests (such as mangroves and Durba grass and Vetiver grass) with embankments appear to be a successful strategy for the protection of the outer slopes of the embankments under the CEIP-I. The assessment also shows that other soft solutions, such as sediment nourishments, coral reefs, and oyster reefs, are promising but not yet widely implemented in Bangladesh. One of the reasons for this may be that they are not yet included in the current design guidelines applied in Bangladesh. In addition, the wider acceptance of these types of solutions is not yet established, as their effectiveness is highly dependent on the local conditions, exposure to extreme events, and knowledge of the morphodynamics of the system. Still, pilot projects, such as the oyster breakwater project on Kutubdia Island, are ongoing and show promising results as soft solutions to stabilize shorelines locally (see **Box 4.7**).

The effectiveness of both hard and soft solutions also depends on community involvement (see **Table 4.5**). During design, the involvement of local communities is crucial to maximize the (co-) benefits and mitigate the negative impacts. More specifically, a good understanding of the rationale of the project will likely result in community support, which can improve the design of the intervention. Once implemented, local community involvement may also help to identify maintenance needs early on, which is a crucial aspect of increasing the lifetime and reliability of interventions. Although community involvement has gained traction in the design and maintenance of water infrastructure, it is less well established in the project implementation of erosion prevention measures.

4.4. Cyclone Shelters, Early Warning, Evacuation Roads, and Awareness Raising

Based on the experience in Bangladesh, the amalgamation of cyclone shelters, EWS, access and evacuation roads, and timely dissemination of early warnings to communities of impending disasters has proven highly successful in minimizing fatalities and suffering, and the loss of critical assets.

For example, the associated mortalities from cyclones have greatly declined during the past 50 years (Haque et al. 2012). The two deadliest cyclones occurred in 1970 (as per official estimates approximately 300,000 deaths) and 1991 (almost 140,000 deaths). The strong willingness to change this has resulted in outstanding progress made over the past decades. For instance, the most recent severe cyclone, in 2007 (Sidr), caused 4,234 deaths, a hundred-fold reduction compared to the devastating 1970 cyclone (Ministry of Disaster Management and Relief 2010). The strategy to reduce these huge fatalities involved the development and implementation of an integrated cyclone response system consisting of advanced EWS, cyclone shelters, and community awareness and preparedness programs. To be effective, EWS needs the active involvement of the people and communities at risk. Community involvement ensures that there is a good awareness and perception of the risk people face, messages and warnings are efficiently disseminated, and there is a constant state of preparedness that enables proactive evacuation to cyclone shelters.

Since 1972, a warning dissemination system has been in place in Bangladesh and has been continuously improved over the past few decades. The Bangladesh Meteorological Department has five meteorological radar stations—in Dhaka, Rangpur, Khepupara, Moulvibazar, and Cox's Bazar—that transmit minute-by-minute weather updates. Since 1988, JICA has helped to improve the weather forecast service in Bangladesh through the establishment of meteorological radars, improvements in the weather analysis and forecasting system, and capacity building. The Meteorological Department also receives information from the National Oceanic and Atmospheric Administration of the United States and from a Japanese satellite via the Bangladesh Space Research and Remote Sensing Organization (Haque et al. 2012). The GoB is currently implementing the Weather and Climate Services Regional Project, which seeks to further modernize the country's climate information systems for forecasting and strengthen service delivery in priority sectors and communities.

The construction of a large number of cyclone shelters has been another cornerstone of this cyclone response system. One of the first major projects that took up the construction of cyclone shelters was the Cyclone Protection and Coastal Area Rehabilitation Project, which started in 1971 after the devastating

A CEIP-I foreshore plantation of Golpata mangroves

Box 4.7: Nature-Based Eco-Engineered Coastal Defenses

Kutubdia, an island off the coast of southeast Bangladesh, is highly susceptible to erosion and flooding. The ECOengineered Coastal Defense Integrated with Sustainable Aquatic Food Production in Bangladesh Project, led by research institutes and a consultancy firm in the Netherlands and Bangladesh, is being implemented on the island. It aims to provide an alternative approach for adaptation to coastal erosion and flooding. By using the concept of eco-engineering, the project proposes an integrated approach, where oyster reefs reduce flow and dampen wave energy, thereby trapping sediment and protecting against coastal erosion and flooding, while delivering a source of aquatic food to local communities (Chowdhury et al. 2019).

The project investigated the technical, social, and economic feasibility of eco-engineered coastal defenses through (1) ecological and socioeconomic field studies, (2) morphodynamics analysis, and (3) the construction and testing of pilot oyster reefs.

Several key lessons were learned from the field experiments included in this project (Tangelder et al. 2015):

- Knowledge of the environmental conditions (salinity, pH, dissolved oxygen) is essential to assessing the potential for oyster growth.
- Sedimentation and smothering (sediment suffocation) were the main threats to oysters during the monsoon period, in particular for structures placed directly on the mudflats.
- The reef structure should be made of a more solid substrate with high vertical relief (to prevent smothering of the structure by mud). Bamboo reef structures could not withstand high-water dynamics during the monsoon period.

From a hydromorphological point of view, the main findings of the project are (Tangelder et al. 2015):

- Oyster reefs can result in the accretion of sediment on the lee (the back) side of the reef, which can allow salt marshes and mangroves to develop and expand.
- The accretion behind the reef can create a more extended foreshore, which dampens wave energy for the primary defense (that is, the earthen embankment). Wave reduction is, however, dependent on water levels (if there is a high water level, there is less wave reduction).
- Sediment accretion rates on the lee side can be up to 30 centimeters per year, which is more than six times that observed in a similar pilot in the Netherlands.

A social cost-benefit analysis found that the combination of earthen embankments with oyster reef structures and mangroves have considerable benefits compared to the current situation (an embankment only) and other adaptation strategies analyzed (such as embankments and either mangroves or oysters) (Tangelder et al. 2015). These benefits could be higher if additional co-benefits (such as crab production, wood) are included in the evaluation. For instance, two to three families can generate livelihoods from selling mud crabs caught in a small oyster reef.

In short, artificial oyster reefs can prevent coastal erosion and grow fast enough in height to keep pace with SLR. Moreover, they can increase biodiversity, provide shelter and substrate for fish and crabs, and create a source of food for the local population. Where technically feasible, the combination of earthen embankments with oyster reef structures and mangroves may be considered since it has been shown to have relatively high benefits.

Table 4.5: Benefits and Challenges of Measures to Combat Coastal Erosion

Item	Benefits	Challenges
Implementation of hard solutions	The current design procedure is straightforward and allows for quick implementation. These solutions have been widely used and there is extensive experience in Bangladesh with a variety of hard solutions.	Bank and slope protections follow design guidelines introduced in the 1980s and do not allow for tailor-made solutions or account for the optimization of costs. These solutions also require extensive maintenance and have potential side effects, such as shifting the erosion issue elsewhere. Additionally, they create beachfronts that are not easily accessible, thus dampening the potential for tourism.
Implementation of soft solutions	They are flexible, climate proof, and can often grow with rising sea levels. Mangroves are a successful solution with proven co-benefits.	If not aligned with stakeholders to create proper incentives their effectiveness may be reduced. They also require a proper understanding of the morphodynamics of the system. Design guidelines and implementation experience for soft solutions (apart from mangroves) are still limited in Bangladesh; there is potential for further exploration and implementation.

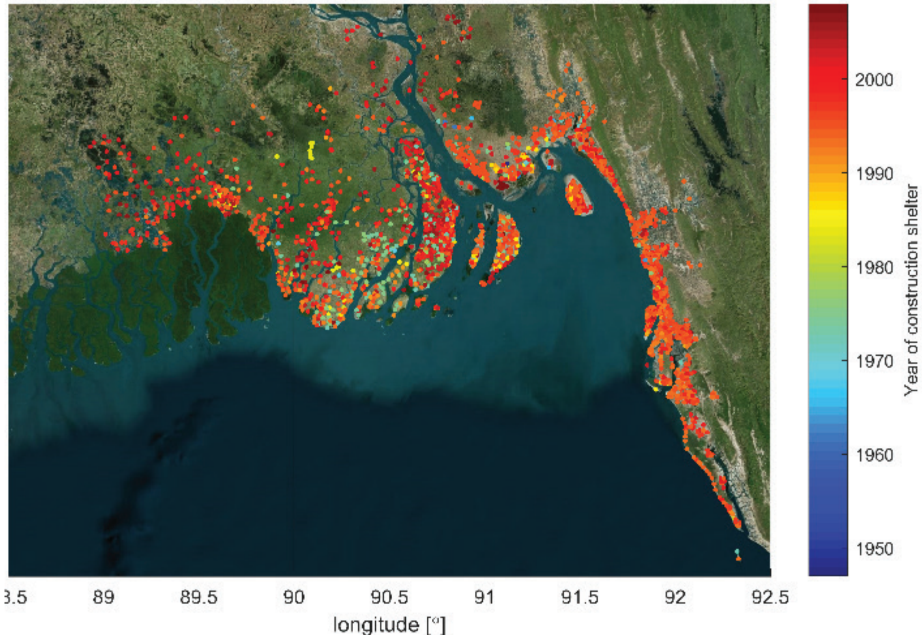
Source: World Bank, original table compiled for this report.

Cyclone Bhola in 1970. Since the initiation of this project, many more cyclone shelter projects have been implemented, hitting a peak in the mid 1990s (see **Figure 4.7**). Following Cyclone Sidr (2007), new shelter programs such as the ECRRP, the MDSP, and the Emergency Multi-Sector Rohingya Crisis Response Project were initiated to rehabilitate and build new shelters. These programs included multiple innovations compared to the original design. At present, approximately 5,000 multipurpose disaster shelters are located across the coastal zone with a capacity of over 5 million people.

Several lessons have emerged from both the construction and usage of cyclone shelters: (1) constructing a shelter for multipurpose use, such as by a school or community center, allows it to be optimally used and maintained; (2) involving the local community in the design and construction ensures sustainability in usage, ownership, and maintenance, this includes the provision of areas for the community to bring their livestock; (3) investments in cyclone shelters, access roads, and EWS alone do not automatically lead to a reduction in the vulnerability of communities if people are not aware of the EWS and emergency actions. Therefore, along with the construction of structural measures, the focus has to be on increasing awareness and holding emergency drills; and (4) including in the design aspects related to gender (including for pregnant women) and the specific needs of poor households and those with disabilities ensures not only higher usage but also better protection of key household assets. Water supply and sanitation facilities, rainwater harvesting options, and solar panels and renewable energy options have been included in recently built shelters and rehabilitated ones, which are beneficial both during disasters and non-disaster times. Another good practice that has emerged is the formation of disaster management committees at the union level that ensure improved coordination between communities and government agencies, resulting in better maintenance of coastal resilience assets and mitigation of disaster-related impacts. These union disaster management committees consist of 36 members and have the mandate to act as the rural disaster management entity, making sure that local communities are kept informed and are prepared to make appropriate decisions during disaster situations.

The effectiveness of the cyclone emergency response also critically depends on the commitment of community volunteers to help out during large-scale evacuations. The Cyclone Preparedness Programme (BDRCS, n. d.), a joint program of the GoB and the Bangladesh Red Crescent Society, plays a central role

Figure 4.7: Cyclone Shelters in Bangladesh with Construction Date by Color



Source: World Bank 2021.

in this; it is recognized globally as a model program in the disaster management field. The program aims to minimize the loss of lives during cyclone disasters by developing and strengthening the disaster preparedness and response capacity of coastal communities. The program's activities, executed by a few hundred staff and tens of thousands of volunteers, include the dissemination of cyclone warning signals issued by the Bangladesh Meteorological Department through an extensive telecommunications network, providing and assisting in first aid, rescue, relief, and rehabilitation operations, and coordinating and building community capacity, disaster management, and development activities (Haque et al. 2012).

Bangladesh's cyclone response system, although not without its challenges, is viewed as a constantly evolving, but overall, very efficient mechanism to reduce losses, which has proven its success time and time again (Haque 1995). Additionally, it is an example of a community-based program that takes advantage of indigenous knowledge for DRR (Habiba, Shaw, and Abedin 2013). During recent cyclone events, like Mora (May 30, 2017), Fani (May 3, 2019), Bulbul (November 9, 2019), and Amphan (May 21, 2020), many people took refuge in shelters. More specifically, a record 2.1 million people were evacuated to cyclone shelters across 14 districts prior to Cyclone Bulbul making landfall (November 2019) (International Federation of Red Cross and Red Crescent Societies 2020).

The effectiveness of this cyclone response system of early warning, shelters, and awareness is also confirmed through a reanalysis of historical cyclones (see **Box 4.8**). The effectiveness of each of the components in this chain cannot be assessed, as it is their combination that makes the difference. Data from Bangladesh shows that after the mid-1990s, there was a reduction in reported fatalities from similar severe cyclones by an order of magnitude. The sharp reduction in fatalities between 1991 and 1997 is very likely the direct result of the efforts taken to improve the cyclone response system.

Notwithstanding the great achievements of the cyclone response system in Bangladesh, there are still some areas that require special attention. The safety and lifetime of the cyclone shelters could be improved by enhancing the maintenance of the building structures. Additionally, the routes linking the residential areas to the shelters could be improved or restructured to promote a more efficient evacuation response time (ADB 2020). It should furthermore be ensured that there is an adequate power supply, together with adequate water and sanitation facilities, which currently are often not usable during emergency conditions (see **Table 4.7**).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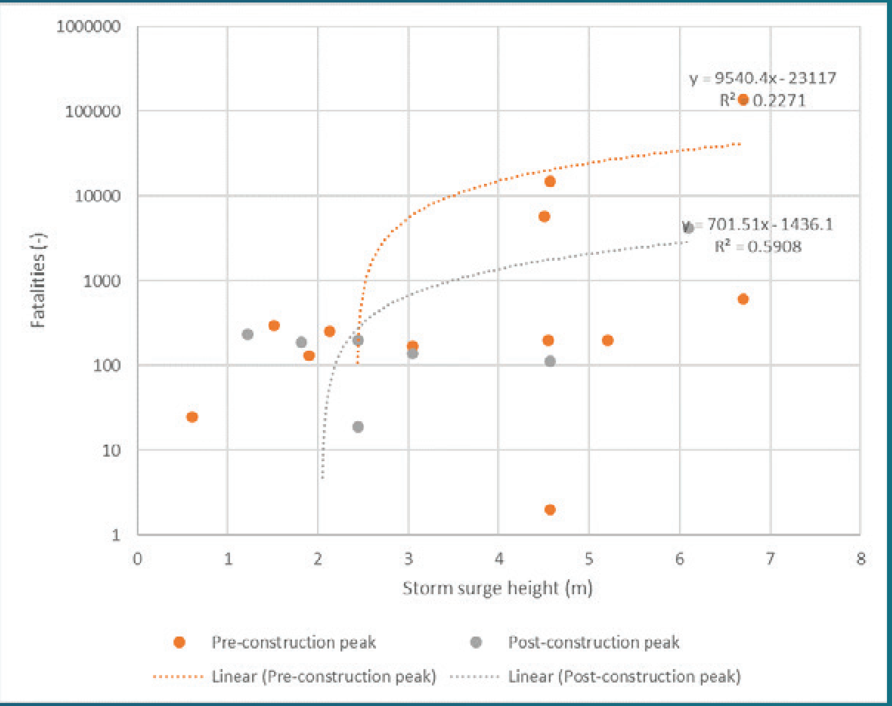
Box 4.8: Reanalysis of the Effectiveness of Cyclone Shelters

Figure 4.8 shows a similar regession analysis as performed by Alam and Dominey-Howes (2015), but subdivided into a pre- and post-construction period, defined at 1995. The year 1995 was chosen because it was the peak year for the construction of cyclone shelters in Bangladesh. Although the correlation coefficient for the pre-construction fit is a bit low (r = 0.23), it does suggest a significant reduction in the number of fatalities with one order of magnitude (Y-axis is logarithmic) for similar cyclone-induced storm surge levels in the post-construction period.

Figure 4.8: Reported Fatalities in Bangladesh and Total Storm Surge Height (tide + surge), 1974-2009



Source: Data from Alam and Dominey-Howes 2015.

In addition, two cyclonic storm events along the Chattogram coast with similar physical characteristics were compared: one that occurred in 1991 and one in 1997 (Table 4.6). The data show the characteristics and striking differences in the number of fatalities. Although the 1997 cyclone had a similar strength, the timing was different (low tide), it resulted in a disproportionately lower number of fatalities compared to the one in 1991.

It should be noted that the reduction in fatalities is an equation of not only the construction of new shelters, but also better warnings, better awareness, community preparedness, and infrastructure improvement, and it is therefore difficult to quantify the shelters' contribution alone, although the two examples do indicate at least a strong correlation.

Table 4.6: Meta-Information and Impact Statistics of Defined Cyclone Events in the Pre- and Post-Intervention Periods

Type	Cyclone Characteristics	1991	1997
Physical	Date of landfall	29 April 1991	19 May 1997
	Time of year	Summer	Summer
	Maximum wind speed (3-minute sustained)	225 km/h	232 km/h
	Category (Saffir-Simpson scale)	4	4
	Storm surge (including tide)	6.7 m (high tide)	4.57 m (low tide)
	Fatalities	**138,866**	**111**
Impacts	People injured	138,849	10,000
	People affected	15,000,000	2,042,738
	People homeless	300,000	1,000,000
	Total damage	US$1.78 billion	-
	Number of cyclone shelters constructed in Bangladesh	**450**	**1,900**

Source: World Bank 2021, based on data from Alam and Dominey-Howes 2015.

Table 4.7: Benefits and Challenges of the Effectiveness of Cyclone Shelters and Early Warning Systems

Item	Benefits	Challenges
Early warning and emergency response	The current system has been continuously improved and has proven to be effective. New technologies can easily fit into the current scheme.	The current system relies heavily on external support. Moreover, emergency and evacuation rely on a large number of volunteers. Financing and partnerships should be maintained to ensure the longevity of the intervention. Some barriers to evacuation still exist that should be addressed.
Cyclone shelters	Cyclone shelters have been shown to be effective in reducing loss of life. The multipurpose character and other improvements made to recently built and rehabilitated shelters are good examples of inclusive solutions with multiple co-benefits.	The O&M of cyclone shelters can be improved. Moreover, the effectiveness of the shelters is driven by complementary measures in place, such as improvements in access roads, places for livestock, and water and sanitation facilities.

Source: World Bank, original table compiled for this report.

4.5. Institutions and Policies for Coastal Zone Management

The NPDM 2010-2015 (Ministry of Disaster Management and Relief 2010) and the Disaster Management Act 2012[20] signaled a significant shift in disaster management in Bangladesh from a relief-centric approach to one of proactive prevention, mitigation, and preparedness for all kinds of disasters. In 2015, Bangladesh adopted three international agreements—the Sendai Framework for Disaster Risk Reduction, the SDGs, and the Paris Agreement on Climate Change. These created an enormous impact on both the approach and practice of disaster management in the country, marking a strong shift towards proactive DRR. The Sendai Framework provides key directions on the inclusion of climate change in DRR, a stronger focus on disaster risk management vis-à-vis disaster management, the concept of "building back better," and the realization of measurable outcomes from DRR initiatives. The SDGs enjoin Bangladesh to pursue a path of inclusive development and poverty eradication through the integration of the economic, social, and environmental dimensions of sustainable development. Improved coastal resilience is an essential element of Bangladesh's Nationally Determined Contributions (NDCs) under the Paris Agreement, enhancing investment in sectors vulnerable to climate change, including coastal regions.

Alongside international commitments, Bangladesh has a huge groundswell of experimental learning from living with natural hazards for decades, which is reflected in the various climate change and DRR policies adopted over the last decade and a half, when Bangladesh began anticipatory adaptation planning, starting with the development of the NAPA (Huq, Khan, and Brief 2017). Since then, Bangladesh has recognized that adaptation to natural hazards and climate change impacts should be a national priority, with the gradual integration of adaptation needs into national sustainable development and coastal zone planning (see **Box 4.9**). Within this context, Bangladesh has outlined its BCCSAP, which focuses on long-term adaptation planning and has also integrated adaptation more broadly into development planning. For instance, it includes social protection efforts so that the poorest and most vulnerable are protected from climate change and aims to better understand the linkages between climate change and poverty in order to increase the resilience of the poor. To mainstream the BCCSAP, the recent Second Perspective Plan 2021-2041 (General Economics Division, Bangladesh Planning Commission 2020) emphasizes the importance of managing climate change and implementing the BCCSAP in its vision for economic production over the next 20 years. The 2012 Disaster Management Act focuses on protecting against disaster and coping with residual risk. The emphasis is on rehabilitation (building back and building back stronger) by rebuilding infrastructure to present conditions or better and bringing livelihoods back to normal. The 2013 National Sustainable Development Strategy (General Economics Division, Bangladesh Planning Commission 2013) further aims to support economic growth while maintaining social and environmental sustainability. DRR is seen as a cross-cutting element for long-term sustainable growth by finding synergies with DRR and climate change adaptation. Such approaches have also been incorporated in the most recent NPDMs of 2016-2020 (Ministry of Disaster Management and Relief 2017) and 2021-2025 (Ministry of Disaster Management and Relief 2021), which also place a large emphasis on risks associated with urbanization.

Hence, Bangladesh has recognized that climate change adaptation and the broader development objectives, including achieving the SDGs, go hand in hand and should be addressed conjointly. Alongside this growing recognition of the link between DRR, climate change adaptation, and development, climate change adaptation has also been integrated into coastal zone disaster preparedness plans and the 25-year water sector plan (Rai, Huq, and Huq 2014). In parallel to the adaptation policies, two main policies/plans (partly) focus on the coastal zone's strategic planning and management: the CZP of 2005 and the BDP 2100 of 2018 (see **Box 4.9**).

The GoB has thus consistently emphasized the importance of adapting to climate change in combination with DRR policies. To translate this desire into practice, it has established climate change steering committees to incorporate climate adaptation into national-level planning. In addition, the GoB has facilitated access to several climate-relevant project funds (Bangladesh Climate Change Resilience Fund and the National Disaster Management Fund) and mandated that any project submitted to the Planning Commission has to be checked for alignment with climate change issues (Pervin 2013). In parallel, the BWDB acts as the major governing body for the overall development and management of water resources and is also responsible for the design of coastal interventions, with the Chief Engineer of Design the main decision-maker in the design process.

Although Bangladesh has made significant strides in reducing disaster risk, several barriers still exist that slow down the process of mainstreaming and implementing the country's adaptation ambitions (Ayers et al. 2014). Areas for improvement include the need to enhance coordination between the various ministries involved in adaptation planning and strengthen synergies between cross-ministerial plans and programs (Tye, Waslander, and Chaudhury, 2020). In addition, despite the mandates to mainstream adaptation, only a few lead ministries receive funding, which suggests that mainstreaming is being done relatively selectively and ministries do not equally benefit from it (Rai, Huq, and Huq 2014). Also, increased community participation in decision-making, transfer of research and knowledge across ministries, and strengthened institutional capacity could benefit the DRR and climate adaptation process (Huq, Khan, and Brief 2017).

In relation to coastal policies, the initiated CZP has not led to a measurable effect to a more coordinated and sustainable development of the coastal zone. Reasons for this lack of progress include limited institutional capacity with regard to the development of coastal zone policies, the failure to assemble a regular workforce, the rather land-centric view of the coastal zone, and the limited monitoring and follow-up plans of the policies outlined (Ahmad 2019). Proper communication between the agencies involved in drafting such follow-up plans is essential for the successful implementation of coastal strategies.

The recent BDP 2100 has built upon the CZP and proposes a large number of concrete coastal projects that address the current coastal challenges, such as local water management and char development, while having a long-term planning outlook. Under the BDP 2100, a portfolio of interventions, worth approximately US$11 billion, is planned. Implementation of this portfolio of interventions has a high expected success rate, since the BDP 2100 is closely linked to the Planning Commission and is taking into consideration the successive Five-Year Plans of the commission (Seijger et al. 2017). The BDP 2100 is an encouraging development that can contribute to coastal resilience but requires the addressing of institutional limitations in coastal planning to be successful.

Box 4.9: Plans and Policies for Disaster Risk Reduction and Climate Adaptation Planning

The Coastal Zone Policy 2005 was initiated by the GoB because many aspects of the coastal zone's socioeconomic development were lagging behind, the initiatives to cope with different disasters were lacking, the environment was gradually deteriorating, and lastly, because the coastal zone has the potential to strongly contribute to national development. Adoption of the CZP by the GoB was a significant step towards implementing the Integrated Coastal Zone Management Plan, which would provide general guidance on the management and development of the coastal zone so that it is done in a manner that allows those living in the coastal zone to pursue their lives and livelihoods within a secure and conducive environment. The CZP suggested measures for protection of the coastline from soil erosion, floods, and storm surges, which were later adopted by the NAPA.

Recognizing that climate impacts were undercutting hard-won human development gains, Bangladesh took strides on adaptation planning, by, among others, implementing the NAPA 2005, updated in 2009. The basic approach in preparing the NAPA was to develop it in consideration of the SDGs and the country's recognition of the necessity of addressing environmental and natural resource management issues with the participation of stakeholders bargaining over resource use, allocation, and distribution.

The GoB's vision to eradicate poverty and achieve economic and social wellbeing for all people was enhanced through a pro-poor Bangladesh Climate Change Strategy and Action Plan 2009, which prioritizes adaptation and DRR, and also addresses low carbon development, mitigation, technology transfer, and the mobilization and international provision of adequate finance. It outlines the first set of activities that are to be undertaken in line with the needs of communities and the overall development program of Bangladesh.

In addition, the National Plan for Disaster Management 2021-2025, a successor of the previous NPDMs of 2010-2015 and 2016-2020, places importance on emerging risks linked to urbanization and climate change, and the necessity of DRR for sustainable development, and is flexible and adaptive in recognition of the changing nature of risks in Bangladesh. In view of the special long-term challenges for development outcomes presented by climate change and natural hazards, the GoB formulated the long-term Bangladesh Delta Plan 2100 (approved in September 2018) to move Bangladesh forward to the end of the 21st century. The GoB is firmly committed to the implementation of national-level strategic plans such as the Five-Year Plans and the Perspective Plans, and meeting the targets under the SDGs.

Finally, Bangladesh introduced the Standing Orders on Disaster (SOD) in 1997, which were then revised in 1999, 2010, and most recently in 2019. The SOD is an important part of the disaster regulatory framework in Bangladesh (UNDP 2020). The SOD was prepared to clarify the duties and responsibilities of ministries, divisions, agencies, organizations, committees, public representatives, and citizens to cope with natural disasters. The most recent update in 2019 focused on linking the SOD with five frameworks—the Sendai Framework, the SDGs, the Paris Agreement on Climate Change, the Five-Year Development Plan of Bangladesh, and the BDP 2100. The revision of the SOD constitutes a disaster preparedness activity as well as a DRR activity, as it will facilitate coordination of an emergency response and consequently, prevent the further loss of lives following a major disaster.

4.6. Lessons Learned from the Assessment of Past Projects

The assessment of past interventions in Bangladesh presented in this chapter reveals various lessons learned that should be considered in the development of future investment programs. Six key issues identified are summarized below:

- A stronger link is needed between the strategy/policy for the coastal zone and the implemented interventions. The recent BDP 2100 has built upon the CZP, proposing a large number of concrete coastal projects but also recommendations to develop a more detailed strategy for the various coastal subzones (Southwest, South, Meghna Estuary, Southeast) to justify and prioritize the investments to reduce risk in the coastal zone (such as new embankment programs).

- Project implementation requires more realistic planning but also more and earlier communication with local stakeholders. Large-scale structural interventions in polders (e.g. raising and widening embankments but also TRM) require land, and resettlement or compensation of the population. Past programs have shown that this entails a very intensive and time-consuming process with the communities in the polders, resulting in significant delays during implementation of these programs. This is a global challenge for public infrastructure works, and knowledge exchange with international partners to share best practices in this respect can also support improvement of the implementation process.

- The O&M of all infrastructure assets providing water management and flood and erosion protection services needs much more attention. O&M of the investments (whether they be embankments, khals, drainage structures, cyclone shelters, EWS) is essential to make these investments sustainable. Although various programs have been and are working towards a better O&M organization, there are shortcomings regarding roles and responsibilities, capacity, ownership, and funding.

- Tidal riverbank and coastal erosion are becoming an increasing risk in the coastal zone due to the increasing number of people and assets located in erosion-prone areas. Erosion has been combatted predominantly by means of temporary or hard solutions, which have been only partially successful. There is good evidence on the effectiveness of nature-based solutions with mangrove restoration and better sediment management, which could be considered more often in the future as a feasible alternative when supported by evidence of global best practices and improved understanding of the morphological dynamics.

- Waterlogging in polders is a major issue in the southwest of Bangladesh. Water management in the polders suffers from impeded drainage through limited maintenance, and declining gradients between sinking land (because of subsidence and sediment cut-off) and rising water levels in the rivers from siltation and SLR. TRM applications have demonstrated their usefulness to increase sediment deposition and polder levels. However, the implementation of TRM in polders is not without hurdles because of resettlement and compensation issues.

- A better analytical knowledge base can help support decision-making. The review of the interventions underlined that there is room for improvement in the planning, design, and implementation of coastal interventions and the use of state-of-the-art information tools and practices. Specifically, a comprehensive framework and application of a more risk-based approach to guide the planning and design of investments using the vast amount of data on the Bangladesh coast can be further utilized. For example, the risk analyses of the historical interventions can be expanded in terms of determining the full range of economic benefits beyond only direct damage as one dividend (that is, the Triple Dividend approach (see Section 7.8 for further details)), and the planning and design of coastal interventions such as embankments could benefit from better knowledge of the morphodynamics.[21] Embedding this knowledge into the planning and design process is critical for sustainable embankments and any other infrastructure investments nearshore and along the tidal riverbanks.

The next chapters address some of these lessons learned in that they provide further analytical work on two specific aspects: the added value of a more risk-based approach in the entire cycle of planning, design, and O&M of coastal interventions (Chapter 5), and the opportunities for hybrid and soft solutions to deal with coastal protection and shoreline stabilization (Chapter 6).

4.7. Notes

13. In this chapter, we make a distinction between structural and non-structural solutions and interventions. Structural interventions are positioned in the physical space; examples are embankments, sluices, afforestation. Examples of non-structural interventions are raising awareness and EWS. Within structural solutions, a distinction is made between soft and hard structures. Hard structures are largely made of concrete or rock, like bank protections and drainage sluices, whereas soft structures are made of materials or structures available in nature like mangroves, sand nourishment, and earthen embankments.

14. http://nda.erd.gov.bd/files/1/Publications/Sectoral%20Policies%20and%20Plans/Costal-Zone-Policy-2005.pdf.

15. https://oldweb.lged.gov.bd/UploadedDocument/UnitPublication/1/756/BDP%202100%20Abridged%20Version%20English.pdf.

16. https://openjicareport.jica.go.jp/pdf/12292587_02.pdf.

17. The Blue Gold Program is a donor-funded project aimed at empowering community organizations to sustainably manage water resources. For more information, see bluegoldbd.org.

18. Available at http://nda.erd.gov.bd/files/1/Publications/Sectoral%20Policies%20and%20Plans/National%20Water%20Policy%201999.pdf

19. WMOs refer to all types of organizations within a polder or scheme for participatory water management. A Water Management Group (WMG) is formed for each hydraulic boundary, known as a Water Management Unit (WMU), within a polder/scheme. There are several WMUs in a polder/scheme having a WMG for each. An apex body of the WMGs is formed with representatives from each WMG called a Water Management Association (WMA) for each polder/scheme. The WMGs and the WMA in a polder/scheme are known as WMOs.

20. Available at https://www.humanitarianresponse.info/sites/www.humanitarianresponse.info/files/documents/files/disaster-mgt-act-2012-english.pdf.

21. The CEIP program is currently executing a long-term research program to improve the knowledge base on morphodynamics in the coastal zone, embedding, leveraging, and expanding this knowledge base into new programs and relevant institutions.

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5

APPLYING A RISK-BASED APPROACH TO COASTAL RESILIENCE

CHAPTER 5: APPLYING A RISK-BASED APPROACH TO COASTAL RESILIENCE

Identifying and managing the risk from natural hazards is one of the key objectives of adaptive delta management (ADM). Catastrophic events such as Cyclone Bhola (1970), Cyclone Gorky (1991), and the more recent cyclones Sidr (2007) and Aila (2009) can wreak significant havoc and undo years of development progress. Reducing the risk from natural hazards is therefore vital to achieving development goals. Risk is the product of hazard, exposure, and vulnerability. Together, these three components determine the probability of occurrence and the resulting consequences of harmful events. The consequences may include, among others, loss of life, economic loss, welfare impacts, and environmental damage. These risk components include many uncertainties not only because of the limited ability to predict extreme weather events and impacts, but also because of uncertain future developments and changes (e.g. socioeconomic changes or climate change). Hence, identifying and managing risk from natural hazards must take these uncertainties into consideration.

Risk management frameworks are used in various countries and industries to inform decisions about public safety and mitigate risk. These frameworks emerged in high-hazard industries such as aviation, chemical manufacturing, and nuclear power generation (Ball and Floyd 1998). Developments were strongly driven by high-profile disasters such as the Seveso industrial disaster (1976), the Bhopal chemical disaster (1984), the Chernobyl nuclear disaster (1986), and the Piper Alpha disaster (1988), which laid bare the limitations of previously adopted management practices. Risk management frameworks are now used in countries such as the Netherlands, Vietnam, and the United States to manage various types of risk. Within the scope of DRR, risk management frameworks are particularly well established when looking at flood risk, allowing these countries to control the risk of flooding in a more effective and cost-efficient way than they could using more traditional approaches.

Bangladesh could benefit from a more intentional and structured application of a risk management framework for the planning, design, and maintenance of coastal resilience interventions. With over US$10 billion invested in coastal resilience (World Bank 2013) since Independence, and significant additional investment needed over the next several decades, implementing a risk management framework could further improve the effectiveness and efficiency of interventions by better aligning the actions of different organizations. It could also help the country to manage the risk related to natural hazards (such as storm surges, cyclone winds, erosion) more proactively, which is likely to become increasingly important in light of increased economic development and climate change.

This chapter shows how a risk management framework could directly support efforts to improve coastal resilience. It does so by showcasing the international state of practice, providing examples from other countries, and discussing their relevance to Bangladesh. Herein, the focus is on the risk of coastal and riverine flooding, but a risk management framework could also be applied to other risks, either natural or human-induced. Section 5.1 gives an overview of the key components of flood risk management frameworks. Section 5.2 discusses tolerable risk and decision-making guidelines that are essential to ensure consistency throughout the risk management process. The last three sections discuss how risk could be used to aid, and tie together, three activities that are essential to achieving coastal resilience: planning (Section 5.3), design (Section 5.4), and O&M (Section 5.5). In each of these three sections, the risk management approach is applied to a specific polder to illustrate its potential.

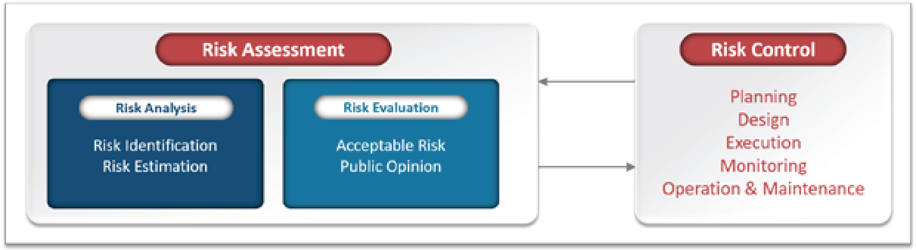
5.1. Risk Management Frameworks

Successful risk management requires people to work in coordination. Establishing strategic priorities, developing action plans, prioritizing interventions, designing measures, and implementing O&M schemes are closely related activities. Yet they are typically carried out by different people who work for different organizations. In Bangladesh, for instance, coastal resilience interventions involve different ministries, such as the Ministry of Finance, the Ministry of Planning, the Ministry of Water Resources, the Ministry of Local Government, Rural Development, and Cooperatives, and the Ministry of Environment, Forest, and Climate Change; their respective agencies, such as the BWDB, the LGED, the Department of Environment, the Bangladesh Forest Department; and international development partners. It is important that their efforts are closely aligned to ensure that goals are met effectively and efficiently given resource constraints. If agencies use a different rationale for decision-making (such as life safety considerations, cost-benefit analyses) without a joint evaluation framework, the end result is unlikely to be as effective.

A risk management framework is a scheme that directs and controls organizations with regard to risk. The key components of flood risk management frameworks are risk analysis, risk evaluation, and risk control (**Figure 5.1**) (US FEMA 2015). Risk analysis involves risk identification and risk estimation, which is the estimation of the probabilities and consequences of the hazard on the one hand, and exposure and vulnerability on the other. Risk evaluation is the process of deciding on the tolerability of risk and the need for interventions. Together, risk analysis and risk evaluation are commonly referred to as risk assessment (US FEMA 2015). Risk control involves the implementation of risk management actions. It includes planning, design, execution, monitoring, and O&M. An example from the United States of how this is applied in practice is shown in **Figure 5.2.**

Risk communication, while not portrayed separately in **Figure 5.1**, is an activity that plays a critical role throughout the entire risk management process. It involves two-way communication between agencies and stakeholders to better understand the risk and to ensure appropriate actions are taken. The power of risk communication in Bangladesh is clearly demonstrated by the massive life-saving evacuations that happen as a result of the developed cyclone EWS.

Figure 5.1: Schematic Overview of the Key Components of a Flood Risk Management Framework

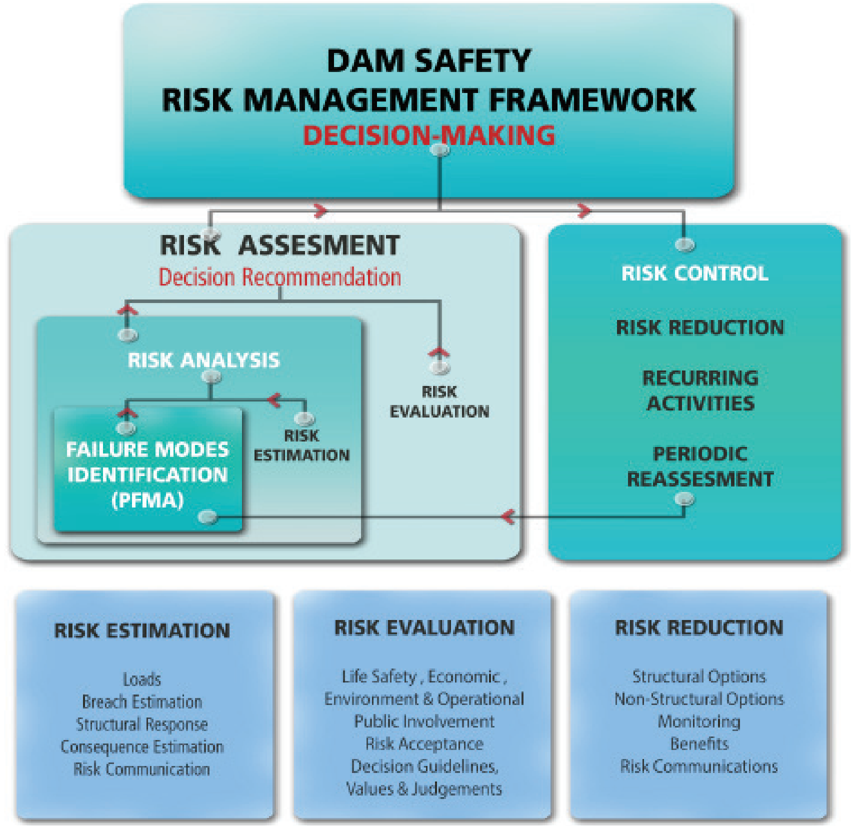


Source: US FEMA 2015.

The risk management process is a cyclical process with repetitive steps for continuous improvement and learning. Since Bangladesh's coastal zone is far from static, achieving coastal resilience will require constant adaptation to changing conditions. These dynamics have different timescales. For instance, newly constructed embankments may suffer from bank erosion, warranting timely intervention to avoid collapse. Economic development, population growth, and changes in land use may gradually increase exposure and vulnerability, creating a need for better protection. Furthermore, climate change may increase the flood hazard and aggravate issues such as waterlogging and salinity intrusion, creating a need for additional or different types of interventions. These examples clearly illustrate that coastal resilience cannot be achieved through one-time interventions, and show why continuous O&M, reassessment, and adaptation are indispensable. **Box 5.1** describes how these are integrated into a levee safety program in the United States.

Implementing a risk management framework relies on the establishment of a clear institutional structure, with a set of formal and informal norms and

Figure 5.2: Dam Safety Risk Management Framework



Note: Potential failure modes analysis (PFMA)"

Source: US FEMA 2015.

procedures that ensure a continuous, balanced, and internally consistent risk management process. It does not require merging projects into a single long-running project of uncontrollable size or concentrating powers in the hands of a single authority. For instance, in the Netherlands, flood protection is the shared responsibility of the country's 21 Water Boards and the national government. The Dutch Water Act (the main legal framework) plays an important role in

Box 5.1: The Continuous USACE Levee Safety Program Management Process

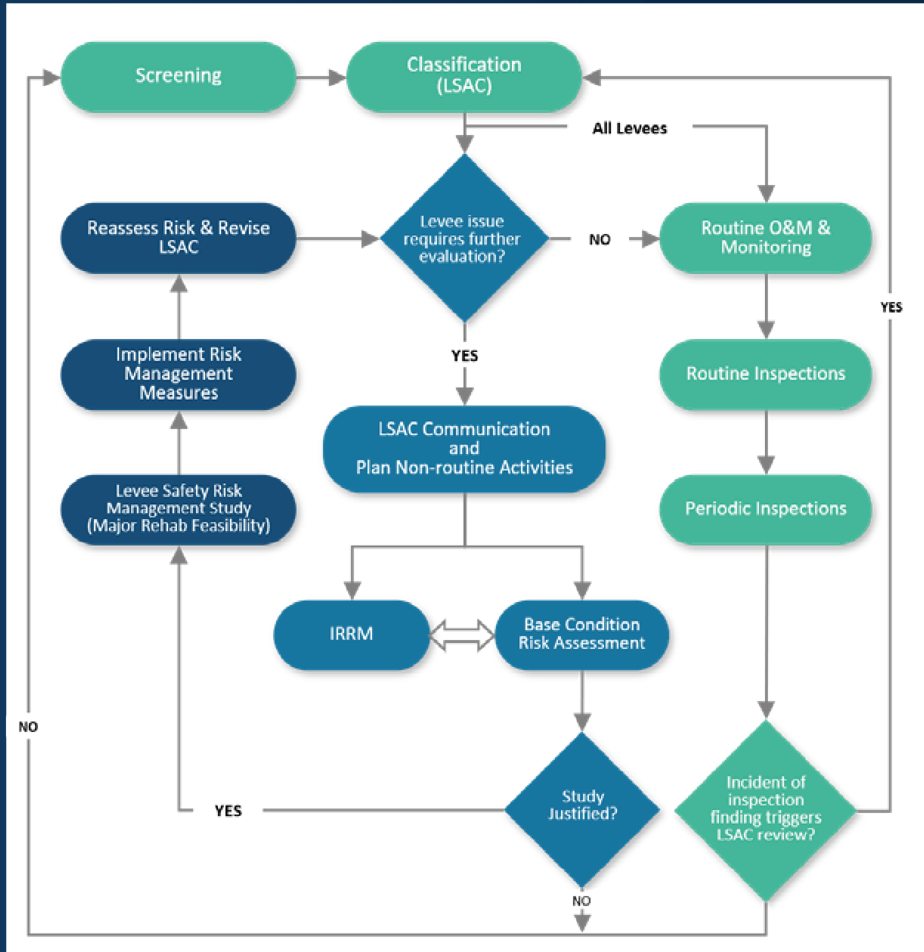
In 2006, in the wake of the flooding of New Orleans caused by Hurricane Katrina, the U.S. Army Corps of Engineers (USACE) established the Levee Safety Program. The program's mission is to assess, manage, and communicate the risk of flooding from embankment failure. The USACE Levee Safety Program follows a risk-informed management process for managing a portfolio of embankments with a total length of approximately 40,000 kilometers based on the most recent information (USACE 2021). Two hurricane-prone states with large embankment systems are Louisiana and Texas, which have about 17% of the total portfolio in their territories (USACE, n.d.). In terms of sheer scale, this is comparable to the roughly 6,000 kilometers of embankments in Bangladesh's coastal zone.

The USACE portfolio management process is a continuous, cyclical process, as shown in **Figure 5.3**. It includes the following two types of activities:

- Routine risk management (outer loop): These include inspections, screening, classification, O&M, and emergency response planning that are an essential part of an effective levee safety risk management approach. Screening is used to inform the classification process, which leads to the prioritization of further risk management actions.
- Non-routine risk management (inner loop): These include identification of levee safety issues that require further investigation, risk assessments, identification of options for managing inundation risks, prioritization of activities, and implementation of interim and permanent risk management measures.

The routing of the levee systems through the portfolio management process is determined by the Levee Safety Action Classification (LSAC). When levees require further evaluation, a Levee Safety Risk Management Study is carried out to support decision-making on rehabilitation. Once measures have been implemented, the levee system is reassessed and the LSAC revised. If no further issues remain, the levee system will enter the outer loop of routine levee safety activities. This process ensures that risks are managed effectively, efficiently, and continuously.

Figure 5.3: USACE Levee Safety Portfolio Risk Management Process



Source: USACE 2011.

combining their efforts in a continuous risk management process (**Box 5.2**). Similar to the Bangladesh Water Act, the Dutch Water Act lays out the duties and responsibilities for water management. However, the Dutch Water Act goes further; it provides a legal basis for sustainable funding, which is of paramount importance, and prescribes a process of continuous monitoring, inspections, maintenance, (re)assessment, and restoration.

Embedding DRR projects in Bangladesh in a more intentional and structured risk management framework could further enhance their effectiveness. The project evaluations from Chapter 4 show that past DRR projects in Bangladesh have been highly successful in reducing the risks from natural hazards in Bangladesh's coastal zone. However, the evaluations also show that often projects are initiated in response to disasters, not as part of a continuous risk management process. For instance, the ECRRP was created in response to the destruction caused by Cyclone Sidr in 2007. While disaster response is essential to facilitate recovery, a more proactive, forward-looking approach that exploits synergies between projects, ensures adequate O&M, and allows for constant readjustment is vital to taking the next step in increasing the resilience of the coast. This way of thinking is also reflected in the BDP 2100 and the closely aligned Second Perspective Plan of Bangladesh 2021-2041. The implementation of a risk management framework could greatly help to realize the ambitions of these strategic plans.

The commitment of the GoB to initiate a more continuous, forward-looking risk management process is illustrated by projects such as the World Bank-funded Coastal Embankment Improvement Project Phase 1. The project's long term end objective is to increase the resilience of the coastal population to tidal flooding, storm surges, and natural disasters in a changing climate, while supporting the development of polder livelihoods by upgrading the entire embankment system. With an estimated 6,000 kilometers of embankments for 139 polders, this is a huge undertaking (World Bank 2013). Hence, a multiphase approach has been proposed, with each phase building on the next. CEIP-I is the first phase of this potential long-term endeavor. It focuses on a group of 10 prioritized polders where risk management actions are considered most urgent. While O&M is largely outside the scope of CEIP-I, the project is piloting engaging local communities in minor maintenance works (see Chapter 4). The

Box 5.2: Public Law as the Basis for Continuous Flood Risk Management in the Netherlands

The Netherlands is protected from large-scale flooding by a system of primary flood defenses. These dikes, dunes, dams, and structures must comply with the flood protection standards specified in the 2009 Dutch Water Act. These standards play a key role in a cyclical risk management process that aims to lower the risk of flooding to the politically established levels of ambition for 2050. Similar to the 2013 Bangladesh Water Act, the Dutch Water Act lays out the duties and responsibilities of the agencies responsible for water management in the Netherlands. The 21 Water Boards and the Rijkswaterstaat (an agency under the Ministry of Infrastructure and Water Management) are the key players. The Dutch Water Act has three unique elements:

- It includes financial provisions to ensure the availability of continuous funding for flood risk management actions. For instance, the Dutch Water Act requires the establishment of a Delta Fund, administered by the Minister of Infrastructure and Public Works, to fund water management measures and related research activities. It also provides the legal basis for the National Flood Protection Programme, from which 90 percent of the costs of the restoration projects carried out by regional Water Boards are subsidized. However, the costs of O&M are borne by the Water Boards themselves.

- It specifies that Water Boards have a statutory duty of care for the primary flood defenses they own and operate. The law thus obliges them to implement adequate O&M schemes, which is verified by an independent inspectorate. To avoid a shift from O&M to restoration, the Water Act sets out eligibility conditions that effectively mean that restoration related to inadequate O&M is not eligible for subsidy from the National Flood Protection Programme.

- It obliges the Water Boards and the Rijkswaterstaat to assess the safety of the country's primary flood defenses once every 12 years. If a flood defense fails to pass a statutory assessment, measures must be taken. In addition to this 12-year reassessment cycle, the Water Boards and the Rijkswaterstaat carry out inspections, maintenance, and repairs. This also includes licensing and enforcement to avoid encroachments, such as buildings and vegetation, on flood defenses that could affect their performance.

inclusion of prioritized polders based on urgency and O&M into the project are essential elements towards a more forward-looking risk management process and should be further enhanced in its next phases.

5.2. Tolerable Risk Guidelines

Tolerable risk guidelines are decision-making aids that can greatly improve the consistency of risk management decisions. Such guidelines make explicit when risks are adequately controlled, when action is considered urgent, and when it is not. They help maximize efficiency by ensuring that decisions are all geared towards achieving the same objectives. Tolerable risk guidelines have proven to be useful in explaining risk mitigation strategies and actions to stakeholders and policymakers (Hall et al. 2012). Moreover, they allow the identification of alternative strategies for managing risk in relation to tolerable risk guidelines. On its own, CEIP-I already involves a multitude of risk management decisions, ranging from its overall strategy of embankment rehabilitation, the prioritization of polders, the selection of restoration works within the polders, the choice of a 25-year design standard for river embankments, to the detailed design decisions and standards. Although the elements of a risk-based approach are in place, aligning such decisions is currently challenging, since explicit decision-making guidelines are not yet established.

Tolerable risk guidelines have been developed in various countries for supporting flood risk management decisions. These international examples could serve as inspiration for the development of tolerable risk guidelines that are tailored to Bangladesh (see **Box 5.3** for one example). Although the tolerable risk guidelines developed by the agencies in different countries vary, they show many similarities. They typically involve quantitative evaluation criteria or guidelines, to be used against the backdrop of general guiding principles, such as the principle that risks ought to be reduced to levels that are “as low as reasonably practicable” (ALARP). These quantitative guidelines typically focus on individual risk, societal risk, and economic risk.

- **Individual risk concerns the exposure of a person to a hazard.** It is typically expressed as the probability that a person will die as a direct consequence of contact with a hazard, such as an explosion, toxic chemical, or floodwater. Guidelines for evaluating individual risk are widely used for identifying and avoiding gross disproportionalities within populations at risk. Individual risk guidelines for flood risk management are typically 10^{-4} or 10^{-5} per year in developed countries such as the United States, the Netherlands, and Australia. For instance, a guideline of 10^{-4} per year has been adopted for existing flood-control and hydropower dams by the USACE (USACE 2014), the United States Bureau of Reclamation (Bureau of Reclamation 2011), the Australian National Committee on Large Dams (ANCOLD 2003), the New South Wales Dam Safety Committee (New South Wales Government Dams Safety Committee 2006), and the Canadian Dam Association (Canadian Dam Association 2007). For new dams and major augmentations, these organizations have adopted a stricter guideline of 10^{-5} per year. Finally, the Dutch have adopted a limit of 10^{-5} per year for evaluating the local individual risk of flooding.

- **Societal risk concerns the risk related to the potential occurrence of an event that may cause societal concern and a loss of confidence in regulatory agencies and government (HSE 2001).** Such an event is widely understood to be an event that leads to substantial loss of life. Societal risk is therefore typically measured in terms of probabilities and the potential numbers of fatalities. It is often portrayed on charts with probabilities plotted along one axis and the number of fatalities along the other. Different types of societal risk charts and guidelines are used worldwide, reflecting subtle differences in both the meaning of societal risk and the factors that determine its tolerability (Jonkman, van Gelder, and Vrijling 2003). Exceedance probability curves of the number of fatalities (so-called F-N curves) are most common, which include reference lines for evaluating the acceptable level of societal risk. These are used in various countries for evaluating third party risks from major industrial hazards, and used in Australia, the Netherlands, the United States, and Vietnam to portray and evaluate societal risks from flooding (Ball and Floyd 1998; Jonkman, Vrijling, and Vrouwenvelder 2008; US FEMA 2015) (**Figure 5.4**). Similar guidelines could be developed for evaluating the risk of flooding in polders in Bangladesh.

Box 5.3: Risk-Based Flood Protection Standards for Coastal Embankments in Vietnam

The Technical Standards in Sea Dike Design (Vietnam Ministry of Agriculture and Rural Development 2010) provide guidance for the design and rehabilitation of various types of coastal embankments and other types of coastal defenses. Sea dikes are classified into five grades (Grades I to V). The grade determines the safety standard of the protected area, which in turn depends on two aspects: the size of the protected area and the size of the population. The larger the protected area and the higher the number of people, the higher the safety standard (see **Table 5.1** below). The highest safety standard (Grade I) is a return period of 150 years, while the lowest is between 10 and 30 years (Grade V).

Table 5.1: Vietnamese Standards for Sea Dikes

Characteristics of the Protected Area	Safety Standards (return period: years)
Developed industrial urban area: • Protected area > 100,000 ha • Population > 200,000 people	150
Rural areas having developed industry and agriculture: • Protected area: 50,000 – 100,000 ha • Population: 100,000 – 200,000 people	100
Developed rural and agricultural area • Protected area: 10,000 – 50,000 ha • Population: 50,000 – 100,000 people	50
Medium-developed rural and agricultural area • Protected area: 5,000 – 10,000 ha • Population: 10,000 – 50,000 people	30
Underdeveloped rural and agricultural area • Protected area: < 5,000 ha • Population: < 10,000 people	10 < Safety Standard < 30

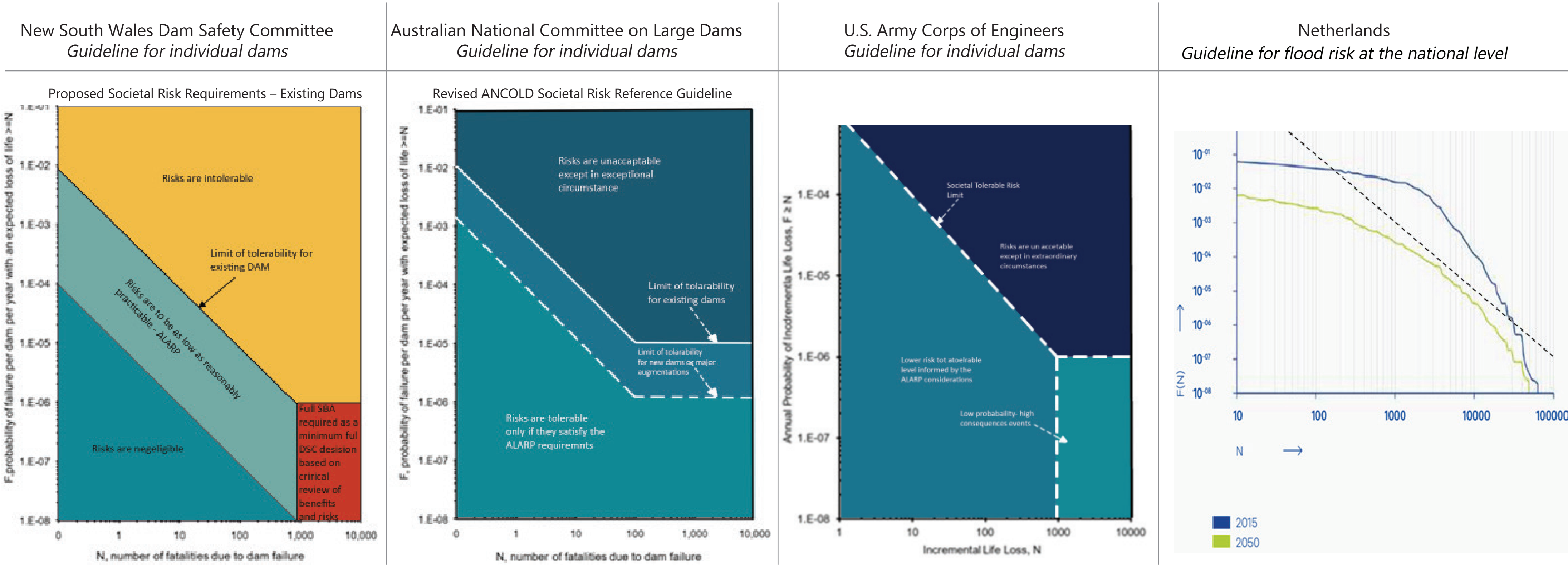
Source: Vietnam Ministry of Agriculture and Rural Development 2010.

Notes:

- Developed industrial and agricultural areas are determined on the basis of the percentage of economic structures in the protected area. If the industrial rate is greater, then it is a developed industrial area and vice versa.
- When using Table 5.1, first the protected areas must be classified using the given criteria. Then the two criteria are considered in order to determine the safety standard. If the protected area meets only one criterion, the level is lowered by one. The spatial planning must take the planning for socioeconomic development up to 2020 and the vision for 2050 into consideration.

The classification system above is the result of a decision-making process that was informed by evaluations of the individual, societal, and economic risks of flooding in Vietnam (Mai Van, van Gelder, and Vrijling 2010). The system has been used to establish a safety standard for each stretch of Vietnam's coastal protection system.

Figure 5.4: International Examples of Societal Risk Guidelines



Source: New South Wales Government Dams Safety Committee 2006; ANCOLD 2003; Bureau of Reclamation 2011; Van der Most et al. 2014.

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- **Economic risk** is typically measured in terms of the annual expected losses of the direct and indirect economic impacts of a hazardous event. Economic risk plays a role in project appraisal and the optimization of risk management actions. The former involves comparing the costs and benefits of interventions, the latter balancing the cost of risk reduction (that is, the investment and maintenance costs of interventions) against the reduction in economic risk. Here it is important to realize that the dollar value of damages to assets and production losses is not necessarily a good proxy for aggregate welfare loss. Losing a dollar is likely to mean less to a millionaire than a poor person. How to account for distribution in the evaluation of total output has occupied scholars since the early days of welfare economics and cost-benefit analysis (Hicks 1939; Kaldor 1939; Arrow 1963). The matter is particularly relevant in evaluating DRR projects for the poor, since a focus on damage to assets and production losses may mean a lack of emphasis on the plight of the poor (Hallegatte et al. 2017). For instance, a study focusing on the impacts of Cyclone Sidr in coastal Bangladesh found that poor households experienced on average 7 percent of the asset damages but 42 percent of the welfare losses (Verschuur et al. 2020).

The BDP 2100 lists several general principles that could be used as the starting point for developing tolerable risk guidelines for natural hazards in Bangladesh. Turning principles such as "leave no one behind," "support economic development," and "climate-proof Bangladesh" into practical decision-making guidelines could lead to a tolerable risk management framework of the type used in other countries. For instance, an individual risk guideline could give substance to the principle to "leave no one behind." After all, such a guideline could be a tool for identifying those that are disproportionately at risk. Similarly, the principle that interventions should "support economic development" could easily be related to guidelines for cost-benefit testing. This way of operationalizing the general principles from the BDP 2100 would be very similar to the way in which policy objectives were translated into tolerable risk guidelines in the Dutch Delta Programme.

5.3. Risk-Informed Planning

Coastal resilience is an ongoing process that requires careful planning. Funds are limited and organizational resources are finite. Priorities must therefore be established. As an example, the BDP 2100 lists three separate, yet related, strategies for flood risk management. The first strategy concerns the protection of economic strongholds and critical infrastructure. The second strategy focuses on the maintenance and redesign of flood risk reduction schemes to prepare them for the future. The third strategy outlines the protection of the livelihoods of vulnerable communities. Implementing these strategies will require considerable time and effort. This necessitates the prioritization of risk management actions and the design of risk management programs in ways that are consistent with these long-term goals.

Using risk in the planning process improves the effectiveness of disaster reduction plans. Flood defenses, dredging, EWS, and shelters all impact coastal resilience in different ways. Yet their benefits can be measured in terms of risk reduction. As such, risk provides a basis for comparing and prioritizing seemingly incomparable interventions, and for establishing the optimal mix of measures for selected regions. As an example, shelters and flood defenses both reduce life safety risks. Building shelters may therefore lower the urgency of upgrading flood defenses, and vice versa. Hence, when shelter and flood protection programs are developed in conjunction rather than in isolation, efficiencies will likely be gained due to better alignment.

For instance, large synergies between interventions were found when constructing portfolios of interventions to reduce both damage and welfare losses from cyclones (Verschuur et al. 2020). These portfolios of interventions combine protective interventions with interventions that reduce vulnerability (such as improved housing and preparedness) and increase the coping and recovery ability of households (for example, post-disaster support). This clearly demonstrates the added value of having a risk-based framework to evaluate the benefits of various interventions in a coherent way. Stronger coordination to align the objectives in terms of risk reduction and define the synergies and trade-offs between various interventions could thus increase their effectiveness.

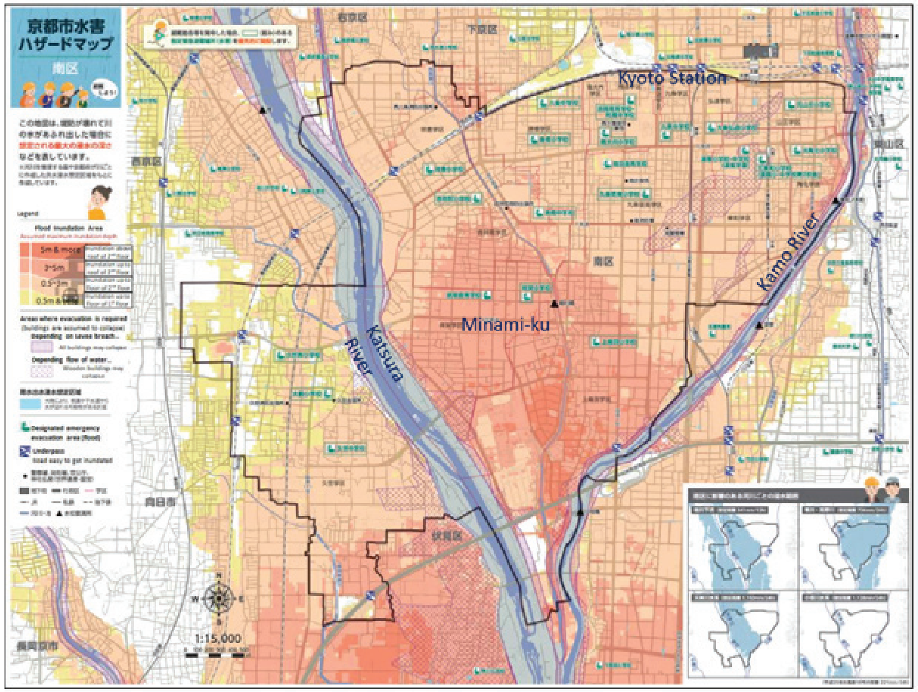
Nonetheless, the interventions can still be implemented under separate programs as long as they are not planned in silos.

- A prerequisite for risk-informed planning is the availability of information about the level of risk and the underlying hazard, exposure, and vulnerability. Hazard and risk maps are typically used to depict the extent and intensity of hazards and the magnitude of risk. These maps are used by agencies worldwide to support risk-informed decision-making and facilitate communication among stakeholders. The EU Floods Directive, for instance, obligates all European Union (EU) member states to develop flood hazard and risk maps, and to draw up flood risk management plans for areas at risk of flooding. These maps and plans must be reviewed every six years. As another example, the Japanese Flood Fighting Act of 2005 obligates municipalities to prepare and distribute flood hazard maps, and to keep them up to date (**Figure 5.5**). These maps serve to help residents act appropriately in case of flooding, and support municipalities in developing flood management plans and guidelines for land-use planning (Japan MLIT 2005; Udmale et al. 2019). In all of these cases, the level of detail and the information shown is tailored to local use.

The Bangladesh Risk Atlas (Department of Disaster Management 2017), which was developed by the GoB, provides valuable insight into the hazards, risks, and vulnerabilities throughout the country for a range of natural hazards. As an example, Figure 5.6 shows storm surge inundation maps for 25- and 50-year return periods for the entire coastal zone. Maps such as these are essential for, among others, risk-informed decision-making on national and regional priorities, developing action plans, and informing the people at risk. Yet, unlike the abovementioned examples from other countries, the Risk Atlas was not developed as part of a broader and continuous institutional design or risk management process that ensures it remains up to date and is embedded in the different planning activities. The experiences from other countries underline the importance of developing maps with a specific application in mind to ensure that they meet the information needs of their users.

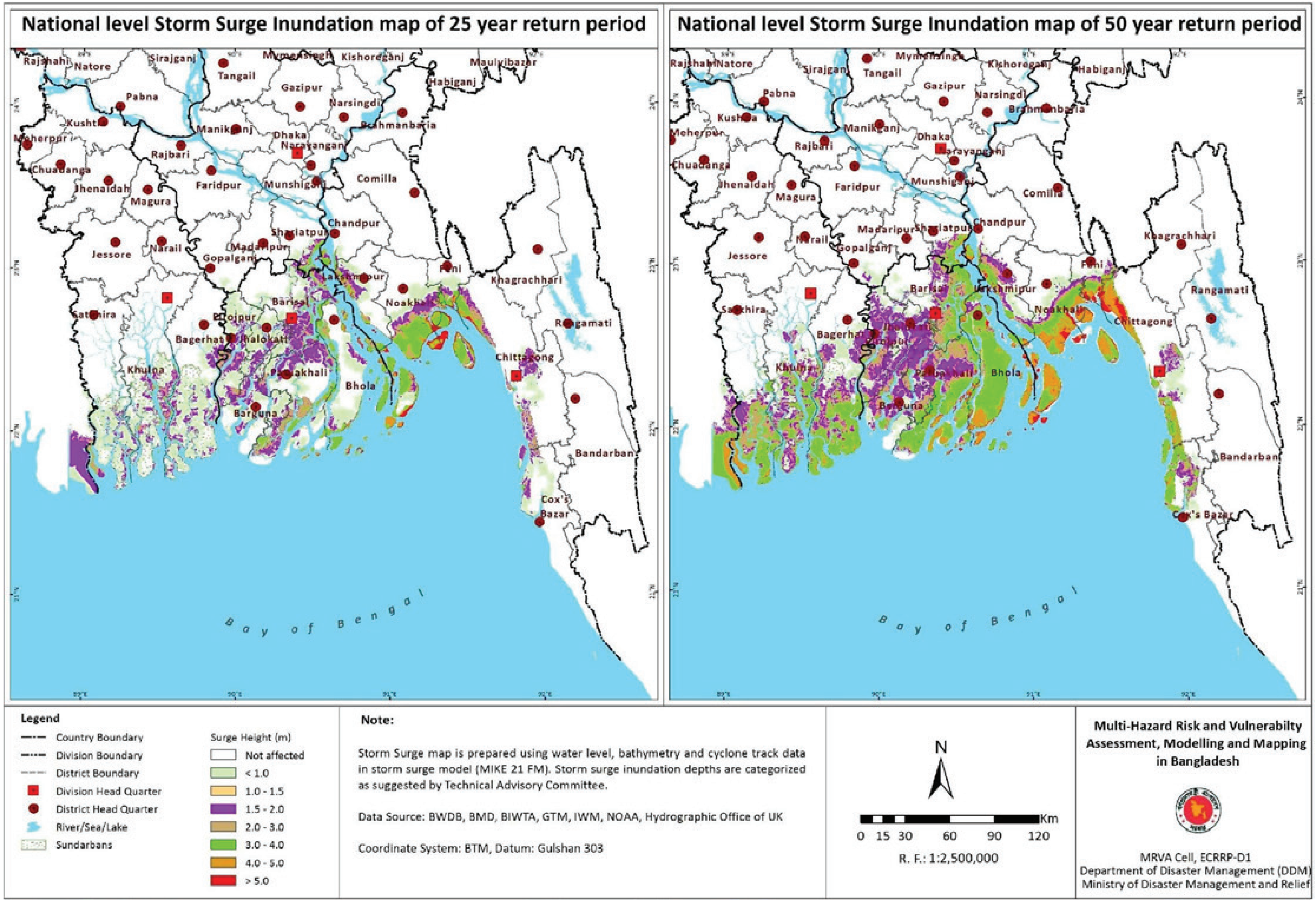
In addition to understanding present risks, it is imperative to understand how hazard, exposure, and vulnerability may change over time. The precise impact of climate change on, for instance, sea levels, weather patterns, salinity, erosion, cyclone paths, and the strength of cyclones, is highly uncertain. The same applies to economic development, changes in land use, population growth, and shifting community preferences. When certain types of risk management actions perform differently under varying future conditions, the optimal mix of measures may change in ways that are impossible to predict. Alternative risk evaluation methods, such as robustness or adaptation pathways analyses as described in the BDP 2100, can indicate to what extent decision alternatives

Figure 5.5: Flood Hazard Map for Kyoto City, Minami-ku



Source: Udmale et al. 2019.
Note: The map provides information for citizens on what to expect in case of flooding and where to find shelter.

Figure 5.6: Storm Surge Inundation Maps for 25- and 50-year Return Periods for Bangladesh



Source: Department of Disaster Management 2017.

are able to accommodate potential future changes. Still, uncertainties will always remain, which should be clearly documented and communicated for risk-planning purposes.

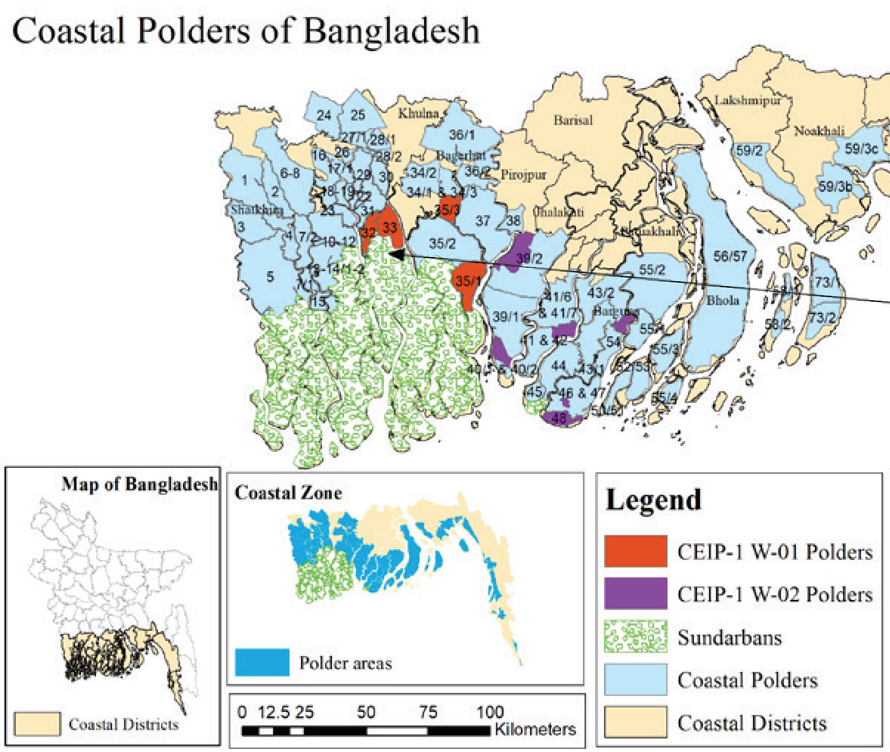
Fortunately, a risk-informed planning approach is well suited for dealing with present and future uncertainties. This is because risk is all about uncertainty. After all, if there were no uncertainty about hazard, exposure, or vulnerability, there would be no risk. In a risk-informed planning approach, uncertainties are dealt with in a balanced and explicit manner, regardless of whether they concern the hazard, vulnerability, or exposure, lend themselves to statistical analysis, or concern the present or the future. For instance, the uncertainty related to mean SLR influences the probability of an embankment being overtopped in a given number of years, much like the uncertainty related to the occurrence of an extreme weather event does. Increasing the robustness and flexibility of interventions are two ways to address the uncertainties related to future changes in the design of civil engineering works. In general, this uncertainty can be dealt with by designing measures that are flexible, requiring frequent reinvestment, or are robust, with safe margins to absorb uncertain future changes.

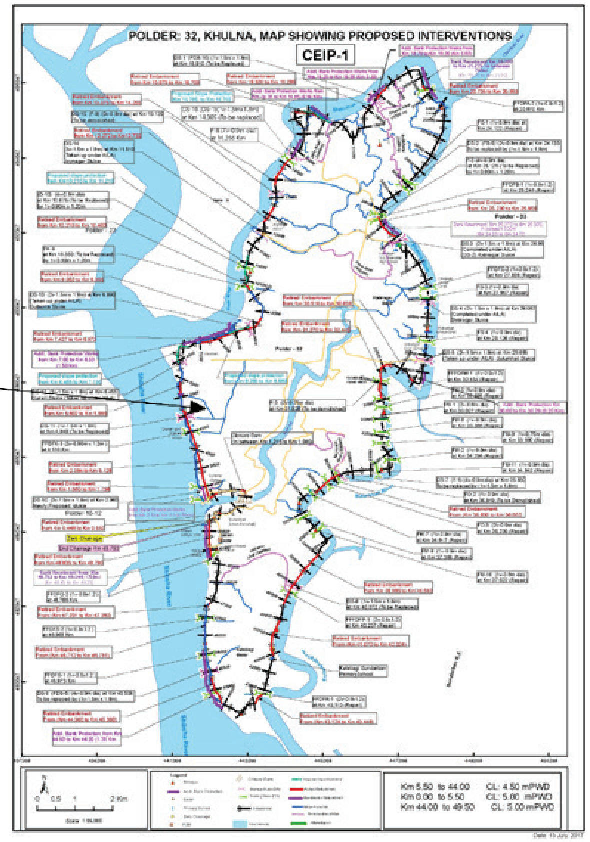
Various decision-making tools are available that can support the risk-based planning process of investments in the face of present and future uncertainties (see for example Kalra et al. 2014). The key difference between these "robust" decision-making tools and the traditional approach is how uncertain future scenarios are handled. Traditionally, the decision-making process was designed to agree upfront on various assumptions regarding future climate change or socioeconomic scenarios, thereby often greatly limiting the number of scenarios. In addition, the assumptions could be biased and did not reflect the inherent uncertainty that is associated with the long-term future. Robust decision-making tools evaluate interventions for a large number of uncertain scenarios, improving the likelihood that decisions (for example, infrastructure upgrades) will perform well under a large variety of future scenarios. This is often referred to as decision-making under deep uncertainty, and various tools exist with successful applications, including managing flood risk (see for an overview Marchau et al. 2019).

To illustrate how risk could be used to support the development of disaster reduction plans, a recent study by the World Bank compared different options for protecting Polder 32 against tidal flooding. Polder 32 is located in Khulna District, along the Shibsa river, and was one of the first polders to be rehabilitated within the CEIP-I (**Figure 5.7**). The polder has a gross area of 8,097 hectares and has a total of 38,400 inhabitants (about 9,600 households). The main economic activities are agriculture and fish farming. The principles of project appraisal (**Box 5.4** and **Figure 5.8**) were used to study three different strategies for flood risk reduction in the polder: "Hold the Line," "Set Back," and "Differentiating Protection" (see **Figure 5.9, Figure 5.10,** and **Figure 5.11**). The analysis accounted for relative SLR, assumed an economic growth of 3 percent and applied a discount rate of 10 percent (as per CEIP-I documentation). Cost estimates for flood defenses were based on an analysis of the Bill of Quantities of the CEIP-I. The total potential damages for Polder 32 were estimated at US$47 million based on the damage assessment done under the CEIP-I. For reasons of simplicity, the case study ignored the important distinction between (in)direct damages and welfare losses. It also ignored the practical difficulties of implementing some of these strategies in Bangladesh's coastal zone. The purpose of the case study was merely to illustrate the differences, in terms of costs and benefits, of protection strategies that are used worldwide, whether or not these are implementable at present in Bangladesh (World Bank 2013).

In Polder 32, the expected annual damage from tidal flooding is relatively high and it is expected to continue to increase in the future, which provides a strong rationale for a significant investment in flood protection. Prior to the CEIP-I, Polder 32 was surrounded by embankments protecting the land against high tides, with an estimated level of protection of (only) a one in 10-year return period. If flooded, the total direct damage is estimated at US$47 million. A first order estimate of the flood risk in the polder is about US$5 million per year (probability times damage). In the next 30 years, which is the design lifetime of the interventions in the CEIP-I, the risk of flooding is expected to increase ten-fold to about US$50 million per year, due to the combined effects of subsidence and SLR, as well as economic growth (~3 percent per year in the agricultural sector in Bangladesh). The net present value of the expected damages over this period amounts to about US$125 million. This amount could serve as a

Figure 5.7: Polders in the Coastal Zone of Bangladesh (left) and a Map of Polder 32 (right)





Source: CEIP-I project documents.

reference for evaluating investments to reduce the risk of tidal flooding.

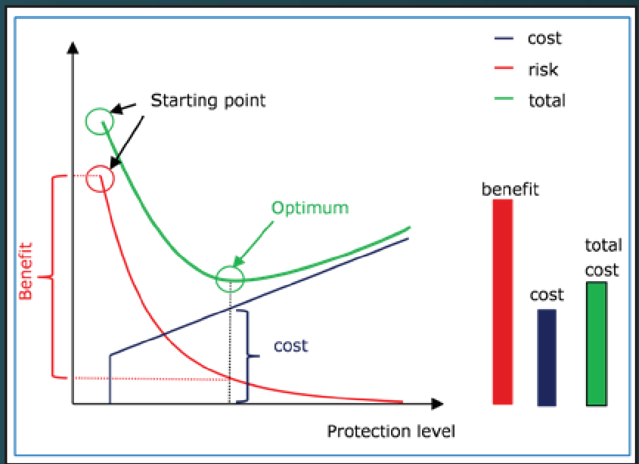
The current strategy of the CEIP-I for Polder 32 is to provide flood protection against a level of one in 25 per year throughout the lifetime of the project by upgrading the existing polder embankment alignment. These upgrades include heightening embankments and providing bank and slope protection at locations that are currently vulnerable to erosion (about 5 percent of the polder perimeter). This strategy has a benefit-cost ratio of about 3. The optimal protection level turns out to be slightly higher than that adopted in the CEIP-I and varies between protection levels corresponding to the 50- to 100-year return period. However, satisfying the 25-year protection level during a design working life of 30 years is likely to require extensive maintenance and additional bank and slope protection works, which have currently not been accounted for in this calculation. Considering this, the 25-year protection level in the CEIP-I appears to be broadly reasonable from an economic perspective.

Box 5.4: Project Appraisal and Optimization

Project appraisal is often based on cost-benefit analyses, the criterion being a minimum benefit-cost ratio, internal rate of return, or net present value. The costs consist of the initial investment and the present value of the subsequent O&M cost. The benefits expressed in the potential risk reduction are estimated by the present value of the reduction in the economic risk over the lifetime of a project.

While a project with a certain design standard may have a positive benefit-cost ratio, optimizing the design standards could yield an even higher net present value. This is illustrated in **Figure 5.8**. The figure shows the cost of flood protection measures (blue line) and the present value of the economic risk (red line) as a function of the protection level. The green line shows how the total cost (the sum of the investment cost, O&M, recurring investments, and expected damages) varies with the protection level. The protection level where the green line (the total cost of a project over its lifetime) is the lowest is the optimal protection level.

Figure 5.8: Benefit and Cost of Flood Risk



Source: World Bank, original figure developed for this report.

A "Hold the Line" strategy, with extensive bank and slope protection to maintain the current polder alignment, can be cost-effective if the necessary upgrades are limited to 50 percent of the total length of the polder embankment. The key difference with the strategy of the CEIP-I concerns the lowering of O&M costs during the lifetime of the project due to larger upfront investments in bank and slope protection works. Such works would protect the polder embankments against bank erosion (up to 10 meters per year) and wave attack from the Shibsa river. If more than 50 percent of the polder's perimeter requires extensive bank and slope protection works to effectively "hold the line", then the costs of such measures would exceed the benefits, making this strategy ineffective from an economic point of view. The optimal protection level turns out to be slightly lower than the current strategy, varying between a one in 25- to 100-year event.

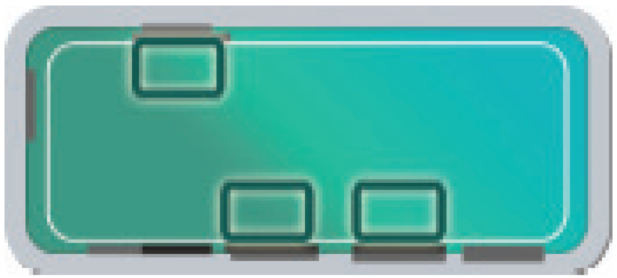
A "Set Back" strategy, in which embankments are moved inland to accommodate bank erosion and avoid additional bank and slope protection, could be more efficient than the "Hold the Line" strategy, but it would require major resettlement. This strategy proves most cost effective when the area protected is maximized while avoiding the necessity for bank and slope protection. If about 90 percent of the current polder area is maintained, the "Set Back" strategy yields a benefit-cost ratio of about 2 for an optimal protection level of about 250 to 500 years. However, with time, more and more land will be lost, and inhabitants will have to be resettled. Ultimately, the alignment of the embankment will have to be changed again, or bank and slope protection works will have to be carried out in the future to avoid erosion.

A "Differentiating Protection" strategy, in which higher protection levels are adopted for areas in Polder 32 with higher economic value, would be relatively cost efficient. The current 25-year protection level appears optimal for agricultural land, while a higher protection level (up to a 250-year level) would be optimal for residential and industrial land use. The polder would effectively be compartmentalized into areas with higher embankments for residential and industrial areas, and lower embankments at the polder's perimeter to protect the surrounding agricultural land. Besides reducing the probability of (direct)

Figure 5.9: Plan View of "Hold the Line" Strategy

Figure 5.10: Plan View of "Set Back" Strategy

Figure 5.11: Plan View of "Differentiating Protection" Strategy



economic damages to high-value areas, this strategy could also help lower fatality risk if inhabitants are resettled to the areas that are best protected or are able to reach these safe havens in case of imminent danger.

In summary, the case study of Polder 32 shows how the current 25-year protection level (applied in the CEIP-I) seems to be a reasonable protection level for individual polders with predominantly agricultural land use, while higher protection levels (100- to 250-year) seem justified for areas that are mainly used for residential and industrial purposes. **Table 5.2** provides an overview of the costs and benefits of each of the abovementioned strategies. This case study only looked at Polder 32. This type of analysis could also be used for evaluating alternative protection strategies at the coastal system level (multiple polders). Examples include adopting a more flexible polder alignment, building safe havens, combining multiple polders to shorten the coastline, or reclaiming land and constructing new polders. Also, the case study considered a simplified situation with only one future growth and SLR scenario to show the potential of using risk to support decision-making. For further development and real-life applications, the presented risk-based approach should be further extended by modeling many future climate and socioeconomic scenarios and evaluating the behavior of the various polder strategies. This will generate a deeper understanding of the effectiveness of these strategies under a large range of possible future scenarios to support a well-informed decision.

Table 5.2: Comparison of Polder 32 Protection Strategies

	Cost (US$ million)	Benefit (US$ million)	Benefit-Cost Ratio	Optimal Protection Level
CEIP-I	30	95	3	50 to 100-year
Hold the Line	112	114	1	25 to 100-year
Set Back	43	91	2	250 to 500-year
Differentiating Protection	10	45	4.5	25 to 250-year

Source: World Bank, original table compiled for this report.

Measuring the impact of flooding in terms of welfare losses rather than asset and production losses would place greater weight on the consequences of flooding. Doing so would lead to higher benefit-cost ratios than those shown in **Table 5.2.** It would also lead to higher optimal protection levels (that is, smaller probabilities of flooding). For instance, differentiating between protection levels and realigning embankments would still appear more efficient than "holding the line." This, however, ignores the difficulty of implementing such strategies. For instance, successfully implementing a strategy that involves resettlement, such as in Japan (see **Box 5.5**), is fraught with difficulty in a place such as Bangladesh's coastal zone. Issues such as land scarcity, illiteracy, the absence of an easily accessible land registry, and complex bureaucratic approval processes make it difficult to carry out projects that involve large-scale land acquisition and resettlement

5.4. Risk-Based Design

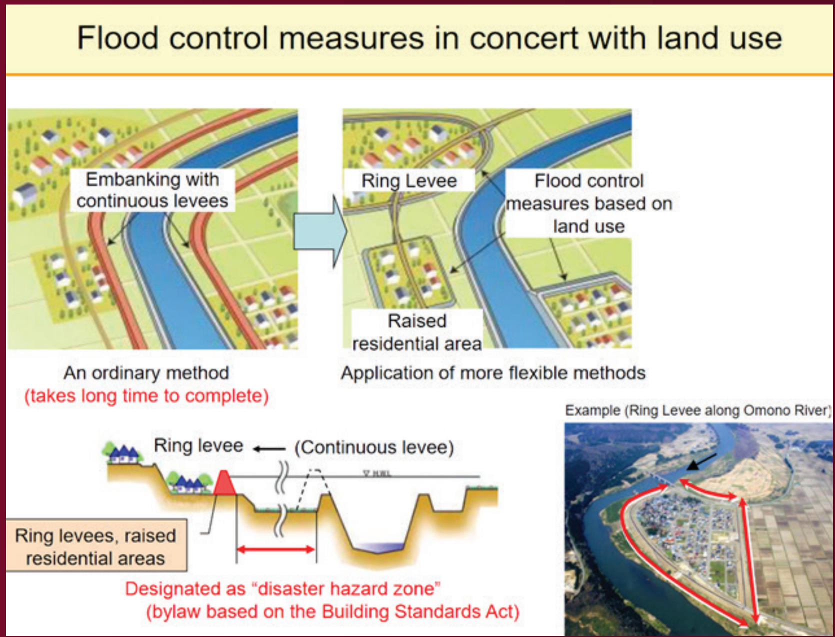
The essence of risk-based design is to ensure that designs satisfy tolerable risk guidelines that are established within the risk management framework. Designing measures based on the same tolerable risk guidelines that are used for strategic planning and O&M ensures consistency throughout the risk management process. If, for instance, the selection of a DRR plan is based on economic considerations, design criteria could similarly be based on economic considerations. As an example, the case study for Polder 32 from Section 5.3 showed how optimal protection levels could be obtained from cost-benefit analysis. To achieve such levels in practice, however, guidelines are needed for the design of coastal embankments that are tailored to these protection levels.

Developing risk-based design guidelines involves several simplifications. By considering the consequences of a failure (such as a flood with a certain economic loss) as a given, a tolerable risk guideline yields a target failure probability (**Figure 5.13**). A target failure probability (protection level) can then be used as a basis for probabilistic design. This involves estimating the probability of failure of a design using advanced statistical methods. Since probabilistic design is relatively complex, the use of a Load and Resistance Factor Design (LRFD) method is more common in practice. This method involves the use of design guidelines with safety factors that are calibrated to target failure probabilities. Such LRFD methods are also called semi-probabilistic design methods since they approximate the results of probabilistic analyses. These LRFD-based guidelines are used worldwide for the design of civil engineering works, in for instance, the United States, the EU (in its technical design standards known as Eurocodes), Mozambique, Malaysia, and Vietnam.[22]

Box 5.5: Flood Protection and Resettlement in Japan

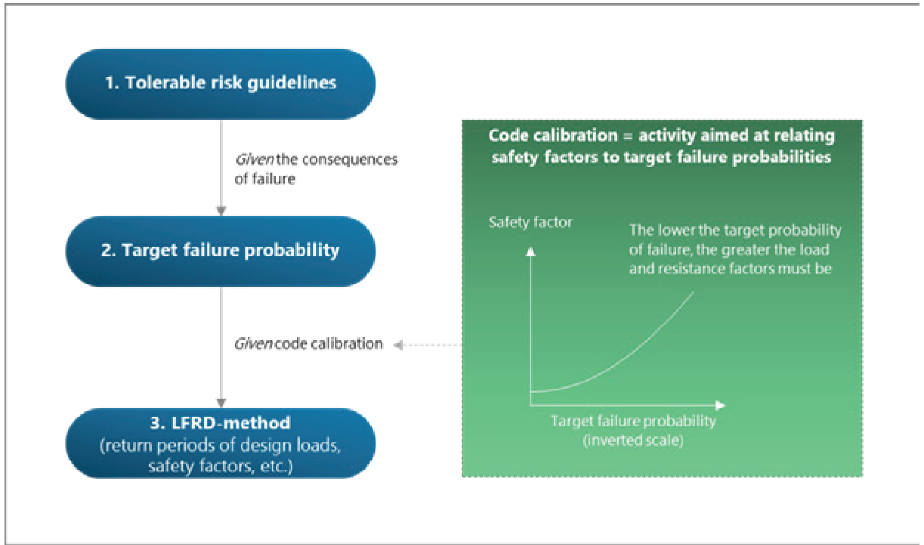
In Japan, building ring levees around vulnerable areas or building secondary embankments may sometimes be more cost effective than building or upgrading primary river embankments (**Figure 5.12**). Yet such solutions could leave some people highly exposed, thereby requiring them to resettle to safer places. In 2010, the Japanese National Government launched a subsidy system to provide financial assistance for resettling residents from flood-prone areas if this makes it possible to more efficiently protect areas from flood protection.

Figure 5.12: Japanese Flood Control Measures in Concert with Land Use



Source: van Alphen et al. 2011.

Figure 5.13: From Tolerable Risk to Calibrated LRFD-based Guidelines



Source: World Bank, original figure developed for this report.

Since the consequences of damage to a structure and a complete failure of a structure are not the same, design guidelines distinguish between different limit states. According to Eurocode EN1990, section 1.5.2.12, limit states are "states beyond which the structure no longer fulfils the relevant design criteria." Defining limit states is essentially about defining failure. In general, a distinction can be made between Ultimate Limit States (ULS) and Serviceability Limit States (SLS). ULS are "states associated with collapse or with other similar forms of structural failure" (Eurocode EN1990, section 1.5.2.13). SLS are "states that correspond to conditions beyond which specified service requirements for a structure or structural member are no longer met" (Eurocode EN1990, section 1.5.2.14). Since the consequences of SLS exceedances are typically smaller than those of ULS exceedances, the target failure probabilities for the SLS are typically less strict than those for the ULS. As an example, the economically optimal probability of damage to a flood defense (SLS exceedance) is typically smaller than the economically optimal probability of flooding (ULS exceedance).

Distinguishing between ULS and SLS in the design of coastal embankments in Bangladesh can save costs. Bangladesh's coastal embankments may sustain heavy damage without being breached. This is illustrated by the performance of flood defenses during recent cyclone events. The following images show damage (SLS exceedance) without breaches (ULS exceedance). This means that the probability that an embankment segment is breached is likely to be lower than 25-year when embankments are designed to withstand a 25-year overtopping discharge without substantial damage, as is the case in the CEIP-I. This difference between ULS and SLS is expected to be considerable for overtopping failures due to the relatively short duration of large-scale overtopping. Defining the ULS more accurately may show that lower embankments will suffice for the same tolerable risk level, freeing up resources for use elsewhere.

Furthermore, the use of more advanced probabilistic methods could help to optimize design. As an example, consider the design of slope protections. The slopes of embankments are currently protected using blocks of the same size based on the design for a 25-year wave height. Yet the required block size could vary along the slope of an embankment. This is because cyclone events that generate relatively high waves often also generate relatively high water levels. Hence, the highest wave impacts most likely occur at higher water levels. Larger blocks are then required higher up a slope, whereas smaller blocks suffice lower down. Slope protections in the Netherlands are designed with the dependence between water levels and wave conditions taken into consideration (**Box 5.6**). This yields more cost-effective designs, with protection measures that are tailored to the hydraulic conditions at various parts of the structure.

To be able to improve design guidelines from a risk perspective, more information is needed concerning both the load side and the strength side of embankment design. For instance, on the load side, optimizing the design of slope protection works requires wave statistics for given water surface elevations. Such statistics are not yet available. However, the IWM has already developed an advanced probabilistic hazard model for the design of coastal embankments (IWM 2018), which is based on computer simulations of historic cyclones. The hazard model is used in the CEIP-I for separately estimating

25-year water levels and 25-year wave heights. Yet in principle, it is possible to derive joint distributions from simulation-based hazard models, as well as the probability distributions for the wave height and wave period for given water levels. On the strength side, optimizing the design of slope protection works requires accurate methods for predicting the stability of armour units under extreme wave conditions. The design formulas for single layer cubes used in the CEIP-I may include safe margins that make them unsuitable for use in probabilistic analyses. This means that new methods would have to be developed, which may require wave flume experiments. Good quality physics-of-failure methods are also required for making the distinction between ULS and SLS. For instance, a breach due to overtopping is initiated not only from damage to the grass cover, but also to progressive erosion, which is harder to predict using empirical formulas. It is hitherto unclear when a grass-covered embankment or an embankment made of locally sourced clay will start to erode, given that most existing empirical formulas are based on experiments using other types of materials.

Pursuing these research opportunities will require time and effort but given the 6,000 kilometers of embankments in the coastal zone, it will surely pay off. Differences in soil properties, construction methods, and vegetation make it impossible to accurately predict the performance of embankments in the coastal zone using physics-of-failure models from other countries. The results from in-situ overtopping experiments performed in the Netherlands and Vietnam simply cannot be generalized to embankments in Bangladesh, where grass covers have different characteristics. Country-specific experiments and in-situ tests will be essential for making it possible to move embankment design methods forward. Considering the sheer length of embankments in the coastal zone, even small improvements could pay large dividends in the long term.

5.5. Operation and Maintenance

O&M is an essential component of the risk management process. While monitoring is sometimes portrayed as separate from O&M, it is treated as an integral part of O&M in the remainder of this section. As such, O&M includes both routine and non-routine inspections, the use of advanced monitoring systems, preventive maintenance, and repairs. O&M is vital to ensure that issues are identified and addressed before they are too costly to resolve. O&M has to be a recurrent activity during the entire lifetime of a project. It also provides the information that is needed for strategic planning and adaptation. In short, O&M is what turns the risk management process into a truly continuous process.

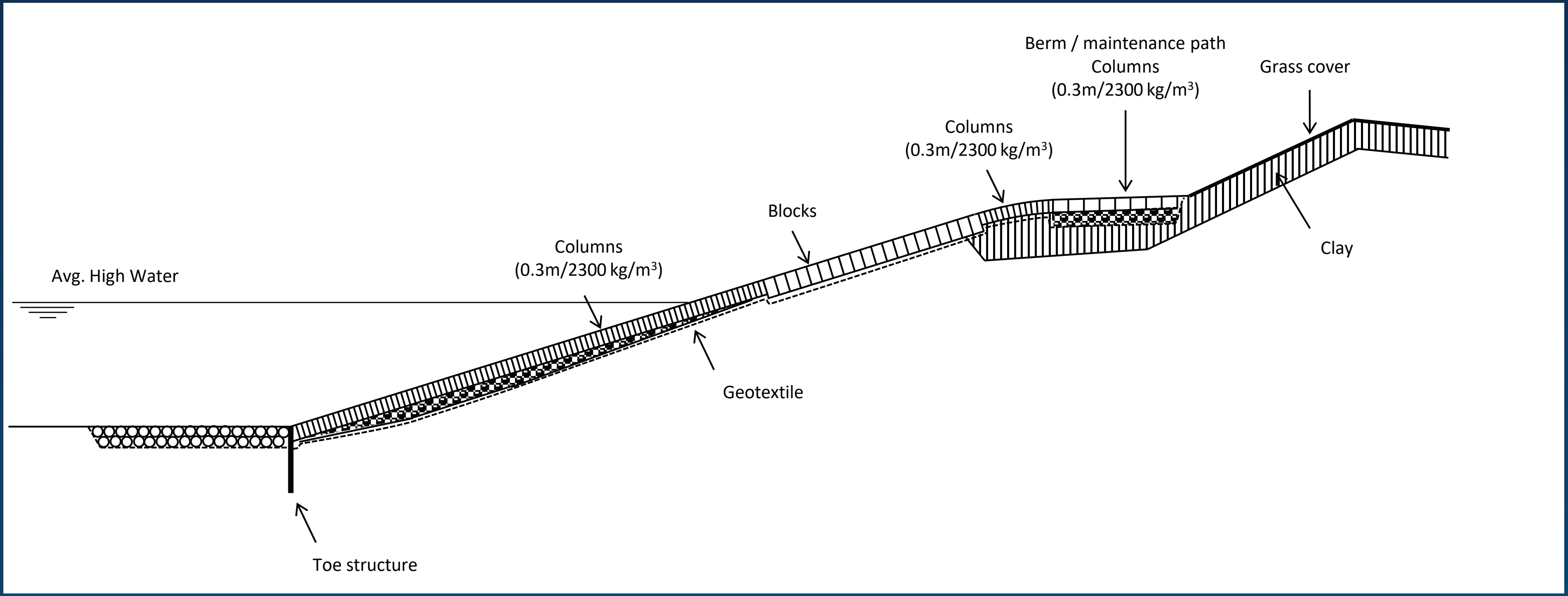


Damage to the landside slope of a coastal embankment from overtopping caused by Cyclone Sidr.
Photo credit: Government of Bangladesh 2008 (first 2 photos); Islam et al. 2011 (right photo).

Box 5.6: Slope Protection Design in the Netherlands

Slope protections in the Netherlands are designed using hydraulic load models that account for the dependence between water levels, wave loads, and the angle of wave incidence. This makes it possible to tailor the design of slope protections to the varying design wave load along the outer slope of a sea dike. The example shown in **Figure 5.14** shows the design of a slope protection for a sea dike in the Netherlands. The largest blocks are placed in the zone just below the berm, where the design loads are highest. Above the berm, a grass cover suffices. Developing similar load models for optimizing the design of slope protections in Bangladesh's coastal zone could yield considerable cost savings considering the hundreds of kilometers of flood defenses that have to be protected from wave attack.

Figure 5.14: Design of Slope Protection for the Sea Dike at Biezelingsche Ham in Zeeland, the Netherlands



Source: World Bank, original figure developed for this report.

Aerial image of the sea dike at Biezelingsche Ham in Zeeland, the Netherlands. (Photo from https://beeldbank.rws.nl/MediaObject/Details/503542.)

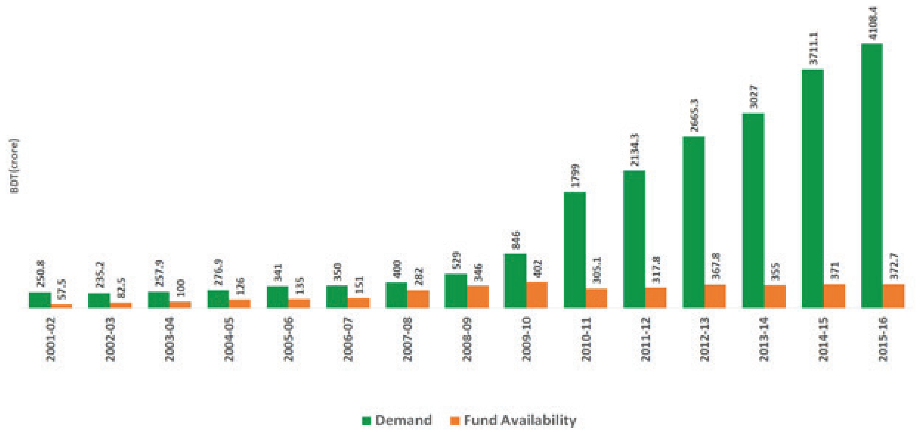
Well-organized O&M activities can save considerable costs. In reality, however, budgetary, organizational, and political constraints can easily lead to a focus on grand schemes rather than mundane O&M needs. Inadequate O&M may give rise to a rapid and uneconomical need for restoration or renewal. For example, unchecked bank erosion can lead to the loss of an entire flood defense. Also, minor damage to slope protection, such as a single missing block or small crack, can strongly affect the stability of the entire slope protection under extreme wave conditions. Since restoring flood defenses is typically far more expensive than maintaining existing ones, the gains from O&M often far exceed its costs.

Therefore, efficient risk management frameworks include mechanisms to ensure that O&M is given sufficient attention. Such mechanisms could take many forms. For example, the Dutch Regional Water Authorities have a statutory duty of care for the primary flood defenses they own and operate (see **Box 5.2**). O&M serves to prevent avoidable degradation and damage from encroachments and hence, the need for restoration projects. Involving local communities in O&M practices could also be an effective way to strengthen the position of O&M in the risk management process. Such an approach is currently being piloted in the CEIP-I, where local communities are given minor responsibilities for the maintenance of flood control, drainage, and irrigation (FCDI) works.

O&M in Bangladesh suffers from a lack of resources. This was confirmed by the BDP 2100 baseline study on water resources, as shown in **Figure 5.15.** Rather than becoming smaller, the funding gap for FCDI projects has grown considerably, and is set to widen even further in the years to come. This not only hinders maintenance and repairs, but also forms an obstacle to monitoring and inspections, which are essential for taking informed and timely measures. For instance, assessments and predictions of bank erosion are largely based on site visits in response to local people reporting bank erosion. Routine monitoring, satellite imagery, and bathymetric surveys could help to identify where bank protection is needed before it is too late, and another round of embankment restoration is needed (**Box 5.7**).

Putting a price on O&M inadequacies may help to (re)direct strategic investments to this prerequisite for successful risk management. For instance, assuming newly restored flood defenses will perform as designed for a period of 30 years only seems realistic with a professionally organized and fully funded O&M scheme in place. Without adequate O&M, another round of restoration activity will probably be necessary within 30 years, or the early loss of functionality will have to be accepted. Using realistic assumptions in the cost-benefit analyses about the O&M state of practice will lower the benefit-cost ratios of projects that do not involve adequate O&M relative to those that do. Making O&M part of the equation will help to give sound O&M practices the attention they deserve and will be essential to closing the risk management cycle.

Figure 5.15: The Widening O&M Funding Gap for FCDI Projects



Source: General Economics Division, Bangladesh Planning Commission 2018.

Box 5.7: Advances in Monitoring Riverbank Erosion

In Bangladesh, riverbank erosion occurs simultaneously at many places in vast and remote areas. This poses great challenges to the monitoring required for the identification of erosion hotspots and the prioritization and design of interventions. Remote sensing is a powerful tool to assist with this. Retreating riverbanks because of erosion can be derived from comparing the water and land distinctions on satellite images from different years, as illustrated by the Aqua Monitor.[23] These multitemporal images can be based on visible or infrared light, but also on radar, which has the advantage that it is not hindered by the clouds that abound during the monsoon season.

At erosion hotspots, the conditions and processes responsible for bank erosion can be monitored in more detail by remote sensing from the water surface or the ground, rather than from space. Echosounders provide information on water depth and elevation of the riverbed—single-beam echosounders in the form of sectional profiles, and multibeam echosounders in the form of bathymetric maps. Acoustic doppler current profilers provide information on the three-dimensional flow under water. Radar provides information on flow patterns at the water surface. Flow velocities are also measured by direct contact using flow meters and float tracks. The topography of shallow or emerged areas is measured by traditional land survey techniques.

The monitoring of riverbank erosion supports decisions as to whether banks need to be protected or buffer zones of permissible erosion need to be broadened by setting back embankments. Tools for mapping and forecasting are hence essential components in addition to the tools for observation and measurement. Geographical information systems provide the tools for mapping. Erosion forecasts can be made through an array of methods ranging from simple empirical predictors to sophisticated numerical morphodynamic models.

5.6. Notes

22. The latter three countries have adopted or are in the process of adopting the Eurocodes, like many non-EU countries.

23. See https://aqua-monitor.appspot.com/.

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BUILDING WITH NATURE: INNOVATIVE SOLUTIONS FOR COASTAL RESILIENCE

6

CHAPTER 6: BUILDING WITH NATURE: INNOVATIVE SOLUTIONS FOR COASTAL RESILIENCE

Bangladesh has made significant progress in managing disaster risks and making the coastal region safer through multiple investments in structural and non-structural risk reduction measures and the adoption of extensive legal, regulatory, and policy frameworks to guide coastal development in a safe and sustainable manner.

As discussed in Chapter 4, the GoB has successfully implemented a wide range of interventions to lower the risk of tidal flooding and storm surges in coastal communities, from building disaster shelters and implementing EWS to rehabilitating embankments and stabilizing shorelines through large-scale bank and slope protection works. Such traditional infrastructure-focused initiatives have been largely successful, and given the extremely at-risk coastline, a necessity for the safety of vulnerable coastal communities in Bangladesh. However, Chapter 4 also highlighted that such "grey" infrastructure interventions are often expensive, need extensive maintenance, and can interfere with the local environment.

This chapter focuses on options for inspirational and innovative solutions that could lower the vulnerability of Bangladesh's coast, embracing and working with the natural dynamics of the coastal zone, while providing additional benefits to local communities and ecosystems. Such innovative nature-based solutions work alongside and take advantage of the forces of nature by, for instance, using natural currents for transporting sand to combat erosion or redirecting river flows to keep waterways open. Another example is mangrove afforestation and restoration of original mangrove forests to protect local embankments while providing livelihoods benefits for the local community. These solutions are flexible and adaptable to rising sea levels.

In the face of uncertainties related to future impacts of climate change as well as the need to protect and conserve marine natural resources, nature-based solutions, and a mix of green-grey infrastructure (that is, hybrid solutions) are increasingly recognized as feasible options. Often hybrid solutions consisting of a combination of hard structures, such as protection works, and soft measures, such as sand nourishments or vegetation, are found to be economically viable for areas with large population densities and high land value (such as tourist or residential areas) (See **Box 6.1**). Such hybrid solutions can be less intrusive to natural coastal processes as they consist of dynamic solutions that are more adaptable to changing natural circumstances. They can be cost effective in the long run and offer benefits such as improved livelihoods opportunities, reduced maintenance costs, and synergies with natural resource systems by conserving and enhancing valuable natural resources. For example, in the CEIP-I, embankments have been combined with mangrove belts to provide greater protection as well as reduce the maintenance requirements of the embankments. Notably, mangrove restoration in Bangladesh has yielded a wealth of experience on technical, institutional, and social aspects, and contributed to enhancing coastal resilience. As has been the experience in the CEIP-I, benefits in terms of protection from storms and erosion, forest products, and good community participation ensure the sustainability of the approach.

Over the years, innovative hybrid solutions have been developed across the world that would be suitable for use in Bangladesh. For instance, a multifunctional embankment[24] in combination with sand nourishment is a good example of a hybrid solution applied in multiple places globally. It can be considered in locations with high economic value that are prone to erosion and flooding and can generate livelihood opportunities and economic growth (see **Box 6.2**).

This chapter provides several inspirational examples of nature-based and hybrid design solutions based on a Technical Assistance (TA) that was carried out to develop innovative and integrated conceptual designs for coastal areas of Bangladesh, with specific emphasis on coastal erosion. The purpose was to guide future investment plans for building long-term coastal resilience by operationalizing state-of-the-art knowledge from global experiences and incorporating local context into conceptual designs for Bangladesh. The TA had

Box 6.1: Combining Green and Grey Nature-Based Solutions in Vietnam's River Deltas

The Mekong Delta is densely populated and home to 22 percent of Vietnam's population, most of whom are near-poor households living in rural coastal areas, highly dependent on rice or shrimp farming for their livelihoods. The region is facing increased salinity intrusion, erosion, and flooding from land subsidence and SLR in the southern part of the Ca Mau Peninsula that is affecting the livelihoods of delta communities.

The Mekong Delta Integrated Climate Resilience and Sustainable Livelihoods Project used a combined green-grey approach to coastal protection consisting of a mangrove belt outside the sea dike to serve as the first line of defense, followed by sea dikes (where appropriate), and then a more extensive mangrove belt inland of the sea dike. The project also supports subprojects that include the construction of coastal defenses consisting of combinations of compacted earth embankments and coastal mangrove belts. The nature-based solutions provide flexibility and can adapt to the delta's natural dynamics and climate change impacts. This approach has led to increased economic opportunities (for example, mangrove shrimp systems) and increased tourism activities in Ca Mau Province.

Source: Browder et al. 2019.

four phases: Phase 1: inception; Phase 2: review existing practices on coastal erosion; Phase 3: develop conceptual designs for three coastal hotspots; and Phase 4: scale up the lessons learned from the hotspot analysis and disseminate to a broader audience to inspire resilient and sustainable coastal investment programs.

For the selection of potential sites and design solutions, understanding the causes of coastal erosion at the various proposed locations was imperative. A preliminary assessment analyzed the boundary and environmental conditions. When preparing the conceptual designs, the physical and institutional contexts were taken into consideration by means of field visits and consultation meetings. The physical context was assessed through validation of the proposed design solutions with numerical modeling, considering the boundary and environmental conditions.

The premise was that the conceptual designs should be new, innovative, and inspirational, but must also take the Bangladesh local setting into account for reasons of practicality of implementation and acceptance. Artist impressions of the conceptual designs were made to easily communicate the solutions to a wide range of stakeholders and generate comprehension and commitment to the solutions.

The following steps were taken:
1. Review coastal erosion
2. Assess possible causes
3. Assess the effectiveness and sustainability of past and current interventions
4. Gain insight into the governance structure regarding coastal erosion management
5. Select three erosion hotspots
6. Assess the coastal system in the selected hotspot locations
7. Propose suitable solutions
8. Develop conceptual designs
9. Validate designs based on physical conditions by means of numerical modeling

Box 6.2: Multifunctional Embankment "Scheveningen Boulevard" in the Netherlands

The boulevard at Scheveningen, The Hague, is a good example of combining coastal protection with recreation and tourism. The multifunctional embankment at Scheveningen Boulevard was conceptualized to incorporate a sturdy embankment within the coastal beachfront, improving the relation between land, beach, and sea. Housing several restaurants and recreation facilities with a beachfront, the boulevard follows the undulating course of the old dunes and has different height levels that separate pedestrians, cyclists, and motorists. Built between 2009 and 2013, the beach was first widened by 50 to 70 meters through sand nourishment over a length of 2 kilometers using 2.6 million cubic meters of sand. A kilometer-long multipurpose dike was then constructed, with the boulevard situated on top of the dike.

The embankment has several levels that can be accessed by stairs or ramps. Additionally, the area below the crest of the embankment is filled with sandy material and in some locations, a hollow area can be created, which can be used for parking. From a functional point of view, the concept of a multifunctional embankment involves an underground protection below the embankment that is invisible to the public, which in the case of an extreme event, would function as the primary protection. As such, in an extreme event of a 50-year return period, it is expected that the outer paved surfaces of the Scheveningen Boulevard will collapse, and the underground seawall will provide the primary protection. In that respect, the materials used for construction of the outer layer of the embankment are softer.

Multifunctional embankments fix the shoreline and often embed erosion protection measures to combine protection with improvements in accessibility and mobility, recreation, and commercial activities. The key to creating a sustainable solution with long-term benefits is the integration of flood safety with waterfront development and beautification of public spaces, with flood safety as the main driver.

For more information:
https://denhaag.com/en/scheveningen-boulevard and https://youtu.be/SsaDoyp3fzU.

Annual Bangla Channel Open Water Swim (16.1 km seaway from Teknaf to St. Martin’s island).

10. Visualize conceptual designs via illustrations and artist impressions
11. Conduct a preliminary cost-benefit analysis
12. Upscale potential interventions.

As per the TA, three erosion hotspots were selected for which conceptual design solutions were made to enhance coastal resilience and reduce risk. The three hotspots were to reflect three distinct coastal erosion processes that are common in Bangladesh. Given the large number of erosion problems and the diversity, dynamics, and complexity of the Bangladesh coastal system, it was not possible to define three hotspots that cover all the different coastal erosion processes and the different forcing mechanisms (tides, waves, cyclones, SLR) at play in Bangladesh. Also, given the budget and time available, it was agreed at the outset that the analysis would focus on one design with visuals for each hotspot.

It was envisaged that in the process of developing the conceptual design, the team would track the various key design decisions (and document the potential alternatives that were considered) and provide rationale as to why certain choices were made, given the context of Bangladesh, but also based on international experience.

The analysis created a link between prevailing hydrodynamic processes and the resulting erosion, which enabled the identification of the location-specific main drivers of coastal erosion in the Bangladesh coastal zone. Large parts of the coast are affected by erosion as a result of a combination of factors, and thus require detailed local morphological analysis. The Meghna Estuary is considered the main source of sediment along the Bangladesh coast, partly transporting sediment towards the west, which is thereafter moved inland into the many estuaries of the Sundarbans by tidal interactions. In addition, large-scale changes and processes contribute to changes in hydrodynamics and sediment transport in the coastal system, for instance the construction of dams in upstream rivers and development of polders, which lead to a reduction in the intertidal area of the coastal system. All these developments have affected hydrodynamics and sediment transport, resulting in siltation in the upstream branches and a sediment deficit along the coast. Natural morphodynamics also affect hydrographs and reduce the amount of water and sediment distribution to the downstream branches.

An analysis of the system with regard to erosion was made by subdividing the coastal zone into four areas with similar morphodynamics, as also outlined in Chapter 2—the Ganges Tidal Plain West, the Ganges Tidal Plain East, the Meghna Deltaic (Estuary) Plain, and the Chattogram Coastal Plain:

- **The Ganges Tidal Plain West** is protected against hydrodynamic energy from the Bay of Bengal by the Sundarbans but is characterized by tidal penetration and lateral river migration causing erosion in river bends. The polders just north and east of the Sundarbans suffer mostly from erosion from a combination of high river discharge during the monsoon period and residual sediment transport.

- **The Ganges Tidal Plain East** is characterized by a younger stage of estuary development. The polders facing the sea are subject to coastal erosion, as well as being exposed to cyclonic storm surges and waves. Erosion due to lateral migration of the river branches, cyclone storm surge, and tidal variation are dominant processes for the polders located more inland.

- **The Meghna Deltaic (Estuary) Plain** is outbuilding as new land is being formed at a rate faster than the erosion of older land in this area. Most of the islands are exposed to cyclonic storm surges and erosion. Some areas are also increasingly subject to prolonged waterlogging from encroachment and land reclamation, and as a result of closing of the tidal channels.

- **The Chattogram Coastal Plain** is directly exposed to cyclones and storm surges. Sediment is delivered to the coast by small rivers originating from the hilly hinterland. The main causes of erosion at this location are the gradients in longshore transport because of wave-driven currents that are redistributing the sediment along the coastline.

In view of the rationale of selecting hotspots that show an ample range of typical forcing mechanisms causing erosion and are in parts of the coast with different typical characteristics, three hotspots were selected—Polder 35/1, Polder 48, and Cox's Bazar – Teknaf Marine Drive (see **Table 6.1** and **Figure 6.1**). Additionally, both Polder 48 and Cox's Bazar – Teknaf Marine Drive are considered tourist destinations in Bangladesh, with room for further development of sustainable tourist activities. Initial conceptual designs were taken further and validated by mathematical models, and additional information was collected. It was also recognized that the 80-kilometer length of Cox's Bazar – Teknaf Marine Drive would not allow for sufficiently detailed conceptual designs, and therefore sub-hotspots were introduced there, each with a length of some 3 to 6 kilometers.

During the inception phase, the reason why no hotspots were selected in the Meghna Deltaic Plain was clarified. In this area, morphologic changes strongly depend on various physical factors such as river discharge, wind, waves, tides, and tide-induced circulation currents. The sediment–water dynamics within this estuary are very complex due to its irregular shape, wide seasonal variations, and the role of the tides. In view of the complexity of the Meghna Deltaic Plain, it would not be realistic to achieve a detailed analysis within the context of the TA. In addition, the intention of the TA was to develop integrated design solutions to combat erosion caused by different processes, not to select hotspots that are representative of the entire Bangladesh coast. The approach developed here can then be applied to other hotspots governed by different processes.

The erosion hotspots were confirmed in close consultation with the Bangladesh stakeholders and the World Bank during the Inception Workshop and thereafter. In summary, the rationale used to define the three hotspots includes the following key points:

- Show a wide range of typical forcing mechanisms behind erosion
- Cover a broad range of types of coastal zones with typical characteristics
- Be already known as erosion hotspots
- Enable application at and extension to other sites.

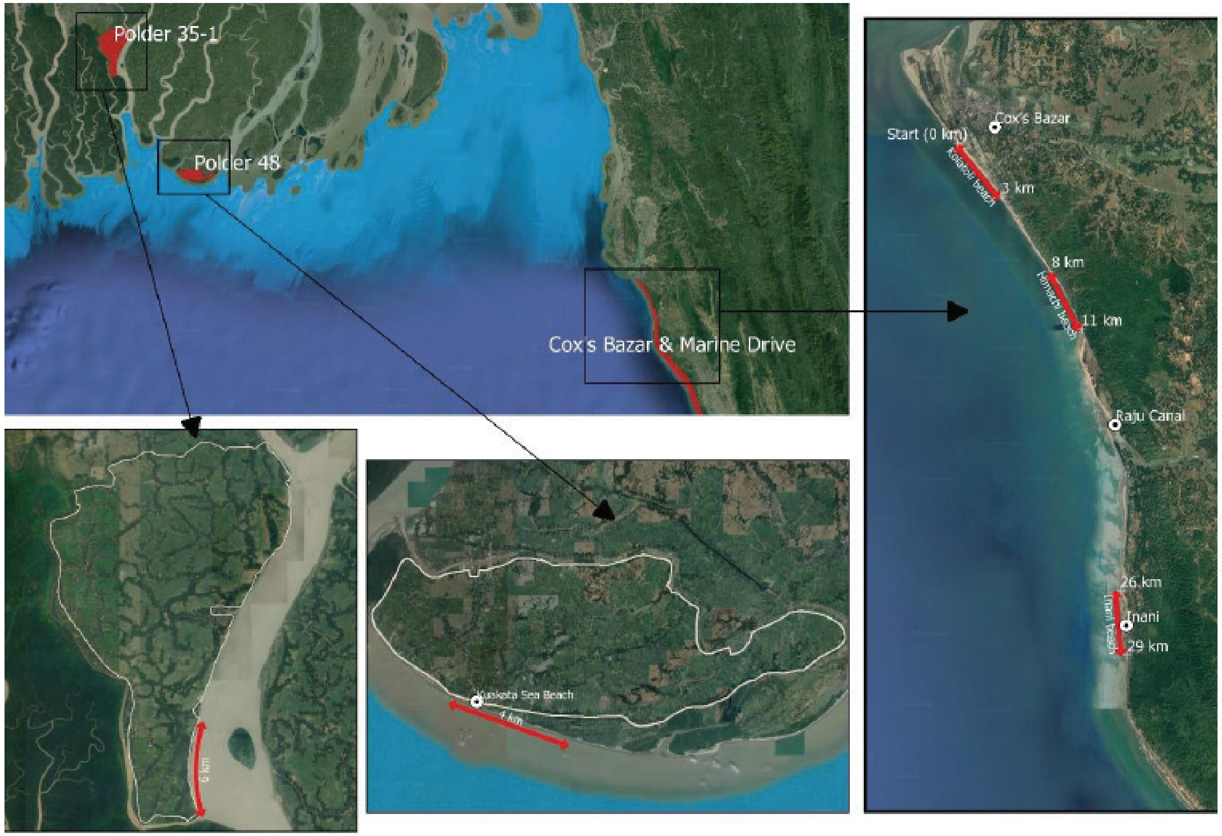
Section 6.1 covers an example of a design for Polder 35/1 that combats bank erosion through a combination of traditional and nature-based solutions. Section 6.2 discusses an example of a nature-based design solution for Kuakata Sea Beach (Polder 48) that addresses bank erosion issues and opens new opportunities for tourism activities. Section 6.3 covers the example of Cox's-Bazar, where nature-based flood protection works could be embedded in a design that enhances the area's economic potential. Finally, Section 6.4 discusses how mangrove afforestation programs could help lower the probability of flooding while enhancing environmental quality. Sections 6.1 to 6.3 are based on the TA described above, and Section 6.4 is based on the findings of another analysis carried out on mapping mangrove opportunities along the coast of Bangladesh using open-source data.

Table 6.1: Considerations for Defining the Hotspots

Hotspot	Coastal Area	Main Erosion Threats				
		River	Waves	Tides	Cyclonic waves	Storm surge
Polder 35/1	Ganges Tidal Plain West	√		√		√
Polder 48	Ganges Tidal Plain East		√	√	√	√
Cox's Bazar – Teknaf Marine Drive	Chattogram Coastal Plain		√		√	√

Source: World Bank 2021a.

Figure 6.1: Overview of the Three Erosion Hotspot Locations for Detailed Analysis



Source: World Bank 2021a.

6.1. Polder 35/1: A Hybrid and Nature-Based Solution for Combating Erosion

6.1.1. Polder Description, Social Context, and Coastal Dynamics

Polder No. 35/1 is located in two upazilas in Bagerhat District: Sharankhola and Morelganj. The polder lies in the agro-ecological zone of the Ganges Tidal Plain West and was originally constructed between 1961 and 1968 under the CEP. Over the last few decades, several infrastructure works have taken place, including the construction of a closure dam, drainage sluices, flushing inlets, and the re-excavation of canals. The polder is home to a population of around 103,876 (2010/2011). The average family size in the polder is about 5.63 people. Among the male population, many in the project area are employed in business (14 percent), in agriculture (13.6 percent), as daily laborers (13.3 percent), in fisheries (7.3 percent), and in services (2.7 percent) for their livelihoods. Among the female population, most are homemakers (57.7 percent), some are daily laborers (2.4 percent), and a few are employed in services (0.6 percent) and tailoring (0.3 percent) (World Bank 2021a).

The polder is a low-lying area with an elevation just above MSL surrounded by tidal rivers. The area is hydrologically linked with the Baleshwar River in the east and the south, the Sannasir Khal in the north, and the Bhola River towards the west. The main rivers of the area—the Baleshwar and the Bhola—flow from north to south. During the monsoon, the river flow increases, and rising waters overflow their banks into the floodplains. The rivers are saline throughout the year in the west. In the east, the rivers carry fresh water to the coast during the rainy season and (only) become saline during the dry season. As a result, most of the eastern half of the region remains non-saline throughout the year. The surrounding rivers have tidal influence with a maximum tidal range of about three meters. Besides tidal flooding, cyclones can generate a significant storm surge, raising water levels around the polder one to two meters above normal tide levels, depending on the track and intensity of the storm.

The polder protects agricultural land from salinity intrusion caused by tidal inundation from the sea and adjacent river. Siltation of rivers and channels causes drainage congestion and waterlogging during the monsoons, while natural hazards (such as cyclones and storm surges) threaten agricultural production. Scarcity of suitable non-saline water for irrigation during the dry months (December through April) is a major impediment to the expansion of irrigated agriculture in the polder. The polder contains about 10,400 hectares of net cultivable area, which is about 80 percent of the entire polder area. The remaining 20 percent is used by settlements, water bodies, and other road and water management infrastructure. Of the net cultivable area, single-, double-, and triple-cropped areas amount to about 49 percent, 40 percent, and 11 percent, respectively. The overall cropping intensity of the polder area is about 162 percent. The conditions prevailing in the area limit the variety of crops grown, with rice being the main crop because of its adaptability to diverse ecological conditions (**Figure 6.2**).

Polder 35/1 is currently being rehabilitated as part of the CEIP-I. This includes bank and slope protection works to prevent erosion of the riverbank and embankment slopes as well as rehabilitation of embankments, which includes crest level heightening to mitigate SLR and extreme surge events, and retirement and resectioning of embankments that are or have been under threat of erosion. Generally, the existing embankment around Polder 35/1 is located approximately 50 to 100 meters from the present riverbank. However, at some locations it has reached the toe and the slope of the embankment. Over a stretch of 4 kilometers, significant slope protection works (with concrete blocks) have been carried out to prevent further erosion of the embankments that are now under wave attack (**Figure 6.3**). The works also include replacement or construction of new structures to improve the drainage system, such as drainage sluices and flushing inlets.

A specific design challenge in Polder 35/1 remains the riverbank erosion in the Bogi[25] area along the Baleshwar River (see **Figure 6.4**). As part of the CEIP-I, emergency embankment repair works have been carried out along this river stretch to prevent flood water intrusion into the polder area from riverbank erosion. The emergency temporary measures included earthworks, geobags, and wooden bullah. The CEIP-I is currently enhancing the emergency protection works in this area, as their condition is rather poor. The cost of implementing a

Figure 6.2: Land Use in Polder 35/1

Source: CEIP-I project documents.

Figure 6.3: CEIP-I Interventions in Polder 35/1

Source: CEIP-I project documents.

complete bank protection in this area is high, warranting the need for further investigation of potential design alternatives to combat further bank erosion and the loss of part of the land to the river.

6.1.2. Riverbank Erosion in Bogi

The erosion hotspot is located at the southeastern side of the polder, where it is bordered by an outer bend of the Baleshwar River. The river is significantly influenced by the tides, reflected by a high tidal range of over 3 meters during spring tides in the dry season. In contrast, during monsoons, the water levels rise about 60 centimeters from increased river discharge. The erosion at this location (**Figure 6.5**) has caused a very steep river profile, as the flow channel is protruding into the polder, with the highest flow velocity located close to the existing riverbank. **Figure 6.6** shows the bed profile at the hotspot, with a steep profile of 1:1 to 1:2 from -10 mPWD upwards to ~1.5 mPWD at the riverbank. Opposite the erosion hotspot, along the eastern riverbank, is a river char.

Satellite imagery of the water line over a period of 30 years reveals an almost linear erosion of the banks at the erosion hotspot in the order of 10 meters per year. At the erosion hotspot, the riverbed topography (**Figure 6.7**) shows a straight main channel upstream that is attached to the east bank in the north and the erosion hotspot in the south. This suggests that ebb currents are stronger than flood currents. More detailed analyses, as part of the CEIP-I (CEIP-I 2019), show that recently (2019) an ebb chute has developed, which incises at the northwestern side of the char (see the upper arrow). Simultaneously, the shoal at the southwestern side of the char has increased in height and extended in a southwesterly direction (see lower arrow). These linear bank erosion trends do not show or identify sudden changes to the bed topography, which could have been induced by events like cyclones. Therefore, the analyses suggest that the erosive behavior of the hotspot is more structural than event driven.

Figure 6.4: Works Undertaken by the CEIP-I in the Bogi Area of Polder 35/1

North direction 20+700 km.

North direction 21+500 km.

North direction 22+700 km.

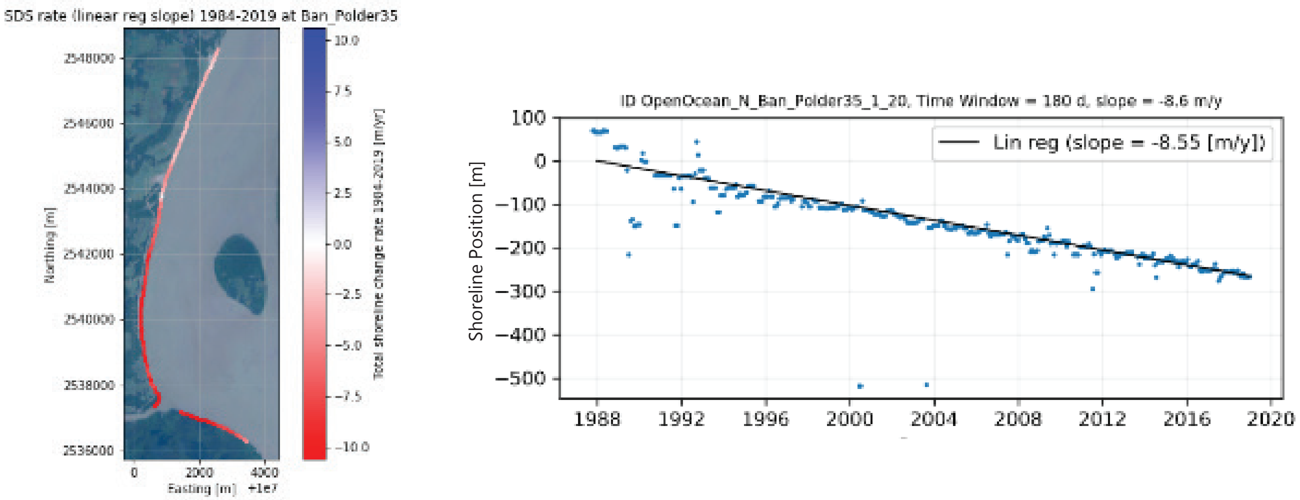
North direction chainage 24+000 km – initiation of works for retiring embankment.

South direction chainage 24+000 km emergency protection works.

Existing char in Baleshwar River.

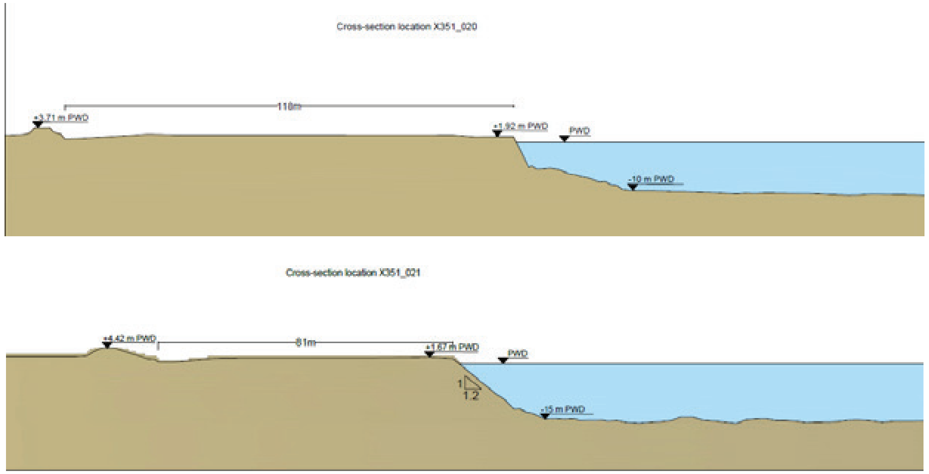
Source: CEIP-I project documents.

Figure 6.5: Erosion Hotspot, Southeastern Side of Polder 35/1 (left) and Erosion Rates (right)



Source: World Bank 2021a.

Figure 6.6: Schematic Representation of the Present Situation with Basic Dimensions in Two Cross Sections



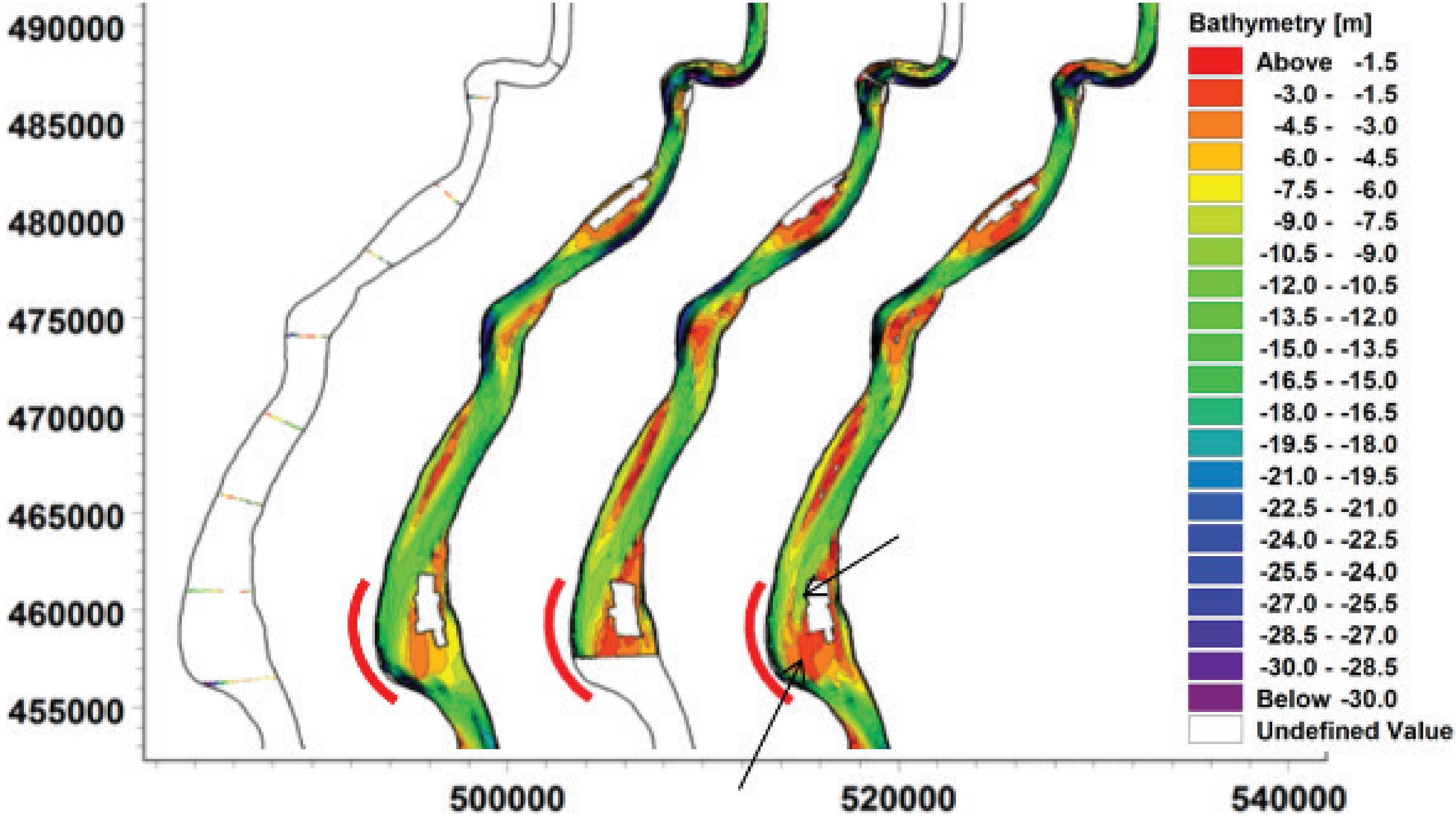
Source: World Bank 2021a.

6.1.3. A Hybrid Approach to Riverbank Protection

Originally, only bank protection works were considered for combating erosion along the riverbanks of Polder 35/1. Bank protection in Bangladesh typically consists of various layers of small concrete blocks or a layered system of geobags with concrete blocks on top that are placed against the eroding riverbank. Since the river channel is very deep, a large volume of material is needed. On top of that, extra material is necessary at the toe of this construction to mitigate ongoing toe erosion ("falling apron"). The typical cost for this type of bank protection in the coastal zone of Bangladesh is in the order of US$4 to US$8 million per kilometer under the CEIP-I and is a major cost component of the overall program.

A hybrid approach has been developed that combines dredging as a primary measure and bank protection works as a secondary measure to deal with the bank erosion along this polder. Based on the morphological analysis, the primary idea of the hybrid approach is to reduce the erosion pressure on the

Figure 6.7: Observed Bed Topography of the Baleshwar River during (from left to right): 2009, 2011, 2015, and 2019



Source: World Bank 2021a.
Note: The red line along the bank indicates the erosion hotspot considered.

coastline by accelerating the current morphodynamic development of the river. This is done by dredging an additional channel in the river, optionally combined with a sediment disposal (nourishment) at the erosion hotspot. The dredged channel in the center of the Baleshwar River would provoke this channel to enlarge and take most of the hydrodynamic conveyance, thus relieving flow and the associated erosion of the Baleshwar riverbanks. In addition, depositing the dredged material along the riverbanks would further enforce flow through the dredged channel and reduce (or even halt) bank erosion. Two project examples that have approached the subject of changing the loads in a similar manner are the Payra River dredging project (Islam and Al Kibriya, n. d.) and a project in Westkappelle in the Netherlands (Deltares 2014).

Four dredging alternatives were explored, and their effectiveness was evaluated with numerical modeling. The simulations tested the impact of several lengths and depths of the proposed channels on the morphodynamic behavior of the river (**Figure 6.8**). A shallow, shorter channel (original channel length reduced by 30 percent) appears an attractive alternative in combination with a sediment disposal at the Polder 35/1 bank and at the opposite side of the river (Alternative 1). The shorter channel attracts flow and thereby reduces the current velocities at the riverbank, which in turn reduces the bank erosion significantly. Therefore, a channel of some 4.5 kilometers in length and a dredging level of a -9 meter new PWD proved most attractive in terms of reduction of current loads along the riverbanks of the erosion hotspot (the Bogi area). Subsequently, this would result in a decrease of the annual average erosion rate while also causing limited backfilling rates of the dredged channel and, therefore, limited maintenance requirements.

The hybrid solution limits the need for bank protection works along the entire riverbank by reducing the acting forces on the banks. While this hybrid solution may limit the total length of bank protection works needed, it will not replace them entirely. However, the remaining bank protection needed can be designed against lower current velocities with lower capital and maintenance costs. **Figure 6.9** shows an artist's birds-eye view impression and provides an illustration of how the Bogi area would look with the proposed hybrid solution. Additionally, using an EEWS in combination with the proposed dredging solution could facilitate monitoring the rate of erosion at the riverbank where the material is dumped and also the backfilling rate in the channel.

The combined cost of the hybrid solution with dredging works and limited bank protection works represents a significant savings in initial costs compared to the original solution of only bank protection works, with similar annual maintenance costs. The main reason for the lower initial cost is the reduced length of bank protection works needed (about 3.5 kilometers less). A channel of some 3.25 kilometers in length and a dredging level of -9m PWD proved most economical to deal with erosion in this area. The shorter, shallower channel moves the river flow away from the riverbanks, thus reducing the need for (and cost of) substantial bank protection works. In addition to yielding cost savings, it substantially lowers the risk of flooding to local communities in Polder 35/1 because of a lower risk of embankment breaching. With that, the hybrid solution could be an attractive alternative to using only bank protection works.


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Figure 6.8: Proposed Dredging and Dumping Alternatives to Reduce Erosion at Polder 35/1.

Existing situation

- Existing embankment improved under CEIP-1
- Area of development of new char
- Retired embankments

Proposed interventions

- Dredging of channel (-10m PWD)
- Areas of dumping dregded material (-8m PWD)

Potential areas of development after implementation of interventions

- Recreational area
- Afforestation
- Shipbuilding and fishery area

0 500 1,000 m

Alternative 0

Legend

- **Chainage Coastal Embankment Improvement Project (CEIP-1)**
- **Proposed dredged channel (Length 4.5km and Depth -9m PWD)***
- **Proposed deposition extent of dredged material**

0 500 1,000 m

*Dredged channel length as 70% of length of Alternative 0, and less deep

Alternative 1

Alternative 2

Alternative 3

Source: World Bank 2021a.

Figure 6.9: Artist Impressions: Birds-Eye View and Typical Cross Section of Proposed Hybrid Solution

Source: World Bank 2021a.

6.2. Kuakata Sea Beach (Polder 48): A Hybrid and Multifunctional Solution for Combating Coastal Erosion and Enhancing Tourism

6.2.1. Polder Description, Social Context, and Coastal Dynamics

Polder 48 is located in Kalapara upazila in Patuakhali District. It is home to 44,168 people spread over 9,846 households and has a total area of 5,087 hectares. Of the total population (44,168 people), 7,403 (16.8 percent) are economically active—3,744 (41 percent) are employed, 121 (1.3 percent) are looking for jobs/work, and 3,538 (37.8 percent) are engaged in household work. The main income in the polder comes from agriculture, with about 3,715 hectares of net cultivable area and an overall cropping intensity of 157 percent (2012) (**Table 6.2**). Besides agriculture, the polder provides opportunities for tourism, fisheries, and livestock (World Bank 2021a).

Polder 48 is a rather flat, low-lying polder located within a saline tidal floodplain. There is a wide foreshore along the embankment at the southeastern side of the polder. Some parts of the wide foreshore are submerged during flood tide and exposed during ebb tide. The polder area further consists of several seasonal and perennial canals/khals, which constitute some fish spawning and nursery grounds. The depth of the seasonal canals in the polder area is decreasing with time due to siltation, decreasing the area for sheltering fish juveniles. Local people reported siltation rates of 2 to 3 centimeters per year.

Table 6.2: Present and Future Cropping Intensity in Polder 48

Polder Number	Present Cropped Area & Cropping Intensity		Future Cropped Area & Cropping Intensity		Cropping Intensity Increase
	Cropped Area 2012 (ha)	%	Cropped Area (ha)	%	(%)
48	5,836	157	7,095	191	34

Source: World Bank 2021a.

Kuakata Sea Beach, located in the southern part of Polder 48, has the potential to become one of the major tourist attractions of Bangladesh. This is the second largest beach of the southern part of Bangladesh and attracts a large number of Bangladeshi tourists. If the beach is developed to its full potential, it could further contribute to the livelihoods and socioeconomic development of local communities. It is about 70 kilometers from the district headquarters of Patuakhali, 320 kilometers from Dhaka, and about a one-hour trawler journey from the Sundarbans. Infrastructure development and marketing are essential to take this tourism destination to the international level.

The foreshore at Kuakata Sea Beach is a long sandy expanse that used to be very wide, but over the years has decreased in width because of coastal erosion. The beach ridge is a continuous linear mound of rather coarser sediment near the high-water line. The erosion is caused by longshore and cross-shore sand transport. Longshore transport of sand is caused by daily regular wave conditions that move the sand to the adjacent coast just west and east of the beach. Cross-shore transport, however, is caused by storm waves, which move sediment from the beach to the lower part of the profile (that is, to the deeper, underwater parts in front of the beach). After Cyclone Sidr (2007) damaged the forest along the Kuakata coast, the local community found that the erosion of the foreshore and the sea beach became more severe.

Polder 48 falls within the CEIP-1 and improvement works have been applied and are still ongoing. The works specifically include slope protection works together with increasing the crest level of the embankment to protect against SLR and extreme storm surge events, resectioning embankments, afforestation, replacement of structures, and construction of new structures such as drainage sluices and flushing inlets. **Figure 6.10** and **Figure 6.11** illustrate the current works being carried out within the CEIP-I.

6.2.2. Coastal Erosion at Kuakata Sea Beach

The erosion hotspot is located at Kuakata Sea Beach, where a divergence point of the longshore transport is located (**Figure 6.12**). A divergence point is a location where the net longshore sediment transport equals zero and changes

Mangrove forest in Polder 48 (February 2020).

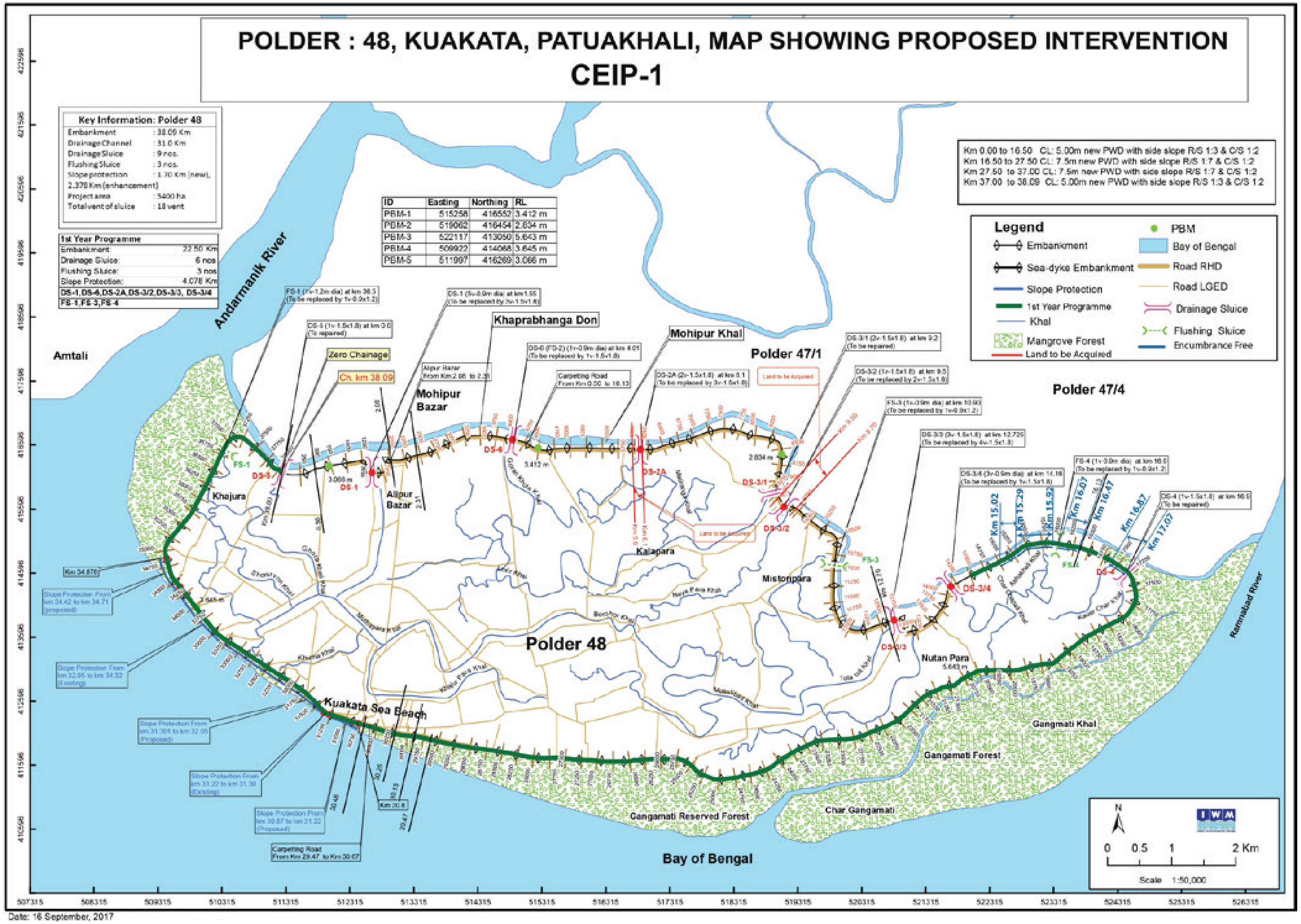
Figure 6.10: Works undertaken by CEIP-I adjacent to Kuakata Sea Beach

Slope protection works west of Kuakata Sea Beach.

direction. At this point, the waves approach the coast perpendicularly. The increasing longshore transport pattern towards the west and east causes a structural retreat of the entire coast. In contrast to this, accretion is observed near the entrances of the tidal rivers at the flanks of the polder where the sediment accumulates, creating sand spits that cause the coastline to advance over time.

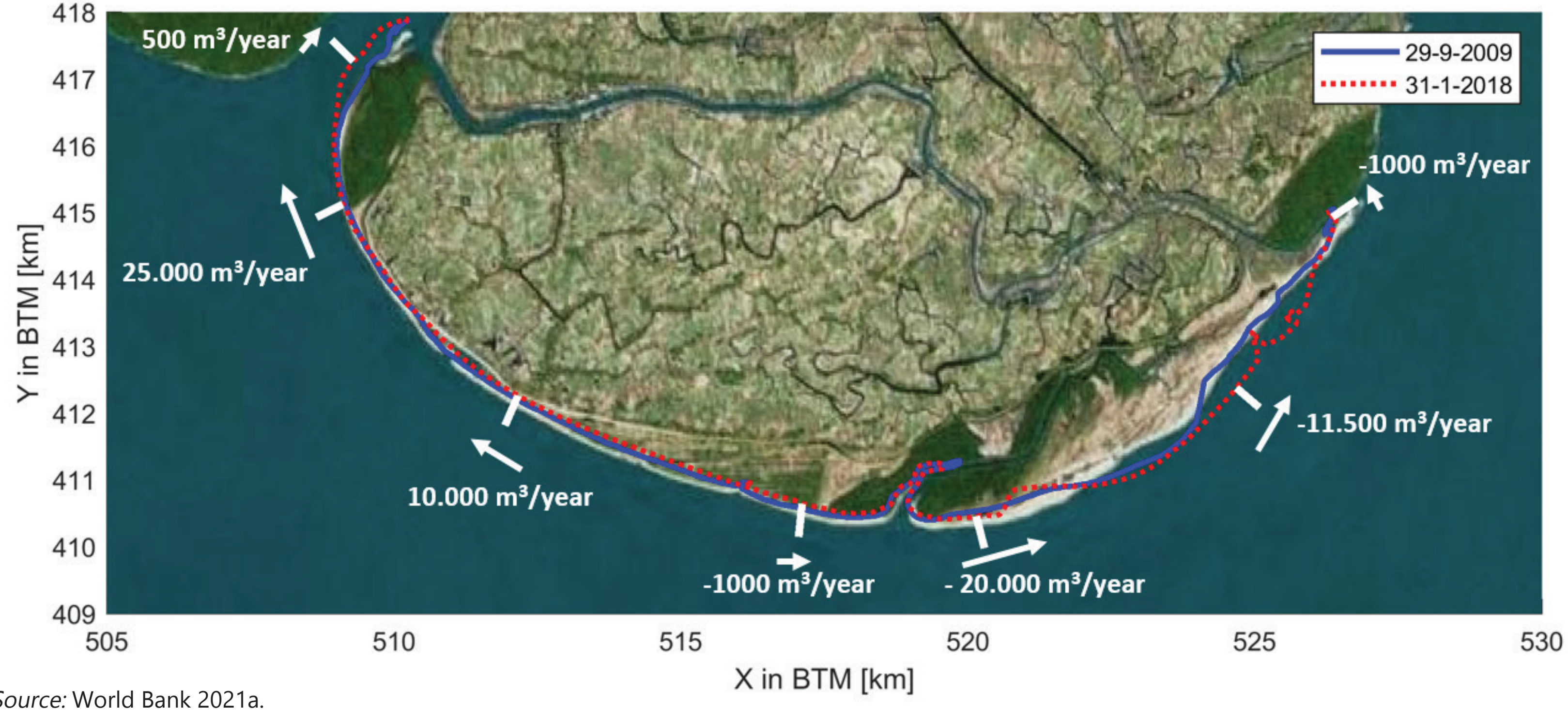
Satellite imagery of the water line over the last few decades reveals incessant beach erosion in the area at a rate of about 5 to 10 meters per year. The longshore transport is further enhanced by the tide, stimulating transport gradients and local erosion or sedimentation. The erosion trend is expected to persist over the next several decades due to a disequilibrium triggered by a large-scale and long-term reduced sediment inflow and a locally continuous wave and tidal forcing. Much like adjacent coastlines in Bangladesh, the area surrounding Kuakata Sea Beach is (probably) suffering from reduced sediment supply from upstream rivers and upstream sediment transport into its nearby estuaries.

Figure 6.11: CEIP-I Interventions in Polder 48



Source: CEIP-I project documents.

Figure 6.12: Yearly Sediment Transport per Transect Considering only the Wave Climate (including tides) during the SW Monsoon



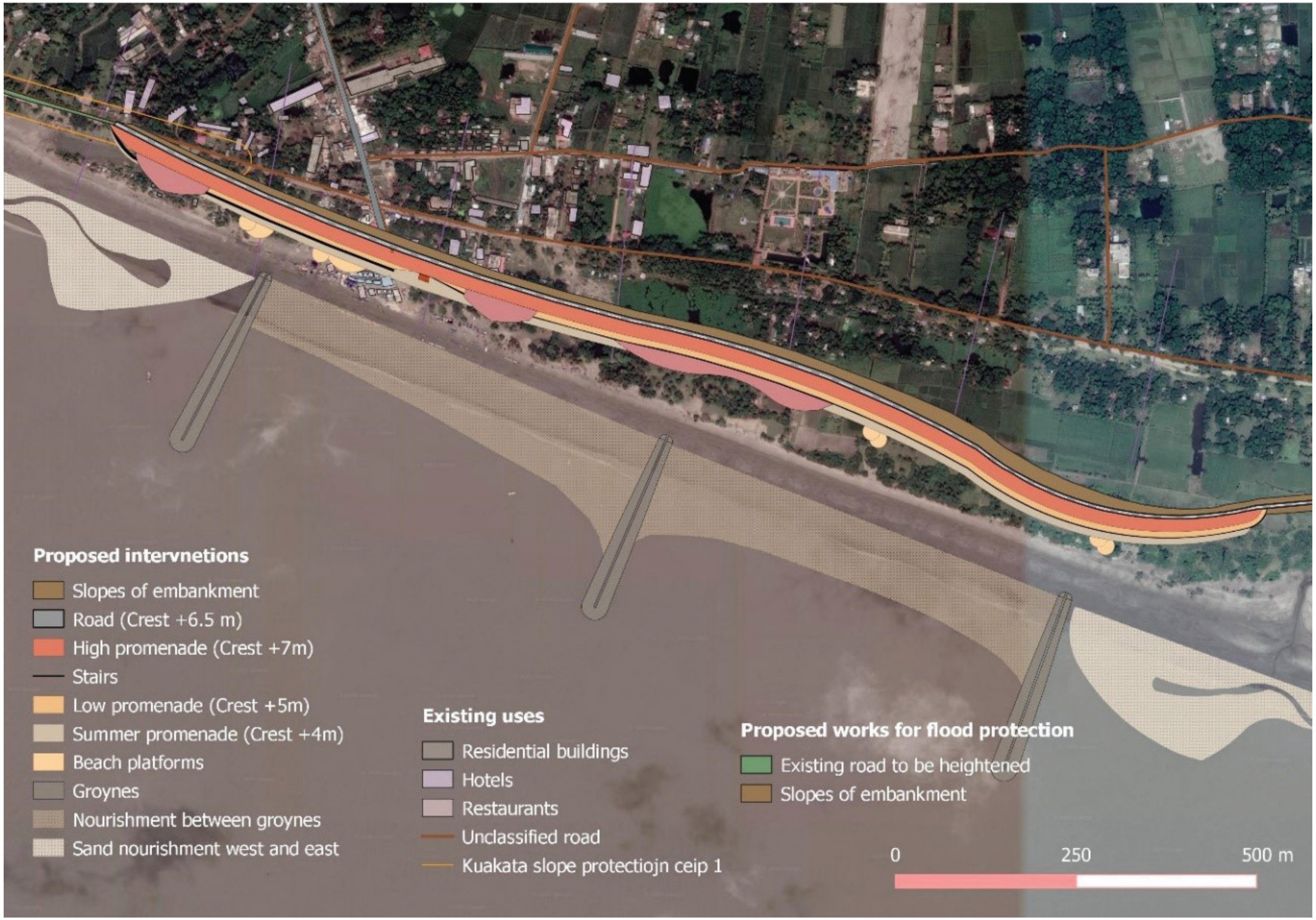
Source: World Bank 2021a.
Note: Analysis reveals that transport gradients and therefore erosion is largest during the SW monsoon and smaller during the NE monsoon. The coordinate system is Bangladesh Transverse Mercator (BTM) projection with X horizontal and Y vertical in kilometers.

6.2.3. A Hybrid Approach to Combat Coastal Erosion

As an alternative to traditional protection works, a hybrid solution is proposed, consisting of both hard and soft measures to maintain an attractive sea beach for both locals and tourists. A multifunctional embankment in combination with groynes and sand nourishments have been proposed to combat coastal erosion, reduce the area's vulnerability to flooding, and allow for the development of tourism and related economic activities (**Figure 6.13**).

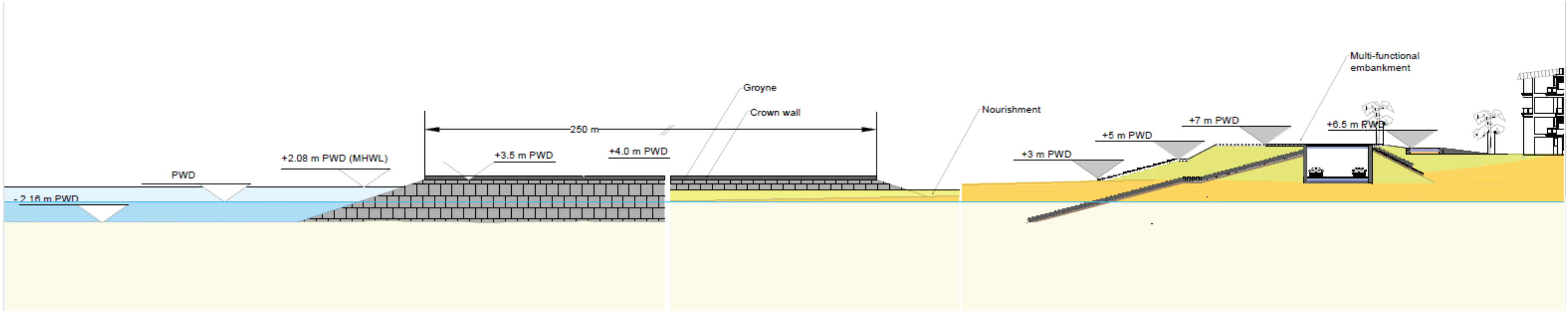
Groynes will keep the beach in place and additional sand nourishments will be added to the outer sides of the groyne-protected area to combat shoreline retreat caused by downdrift erosion. Economic activities can be facilitated by integrating the existing shops, restaurants, and fish markets that are currently located along the beach in the multifunctional embankment. Furthermore, sand nourishments in front of the embankment and between the groynes will attract recreational tourism and assist in maintaining the countryside character of Kuakata (**Figure 6.14 and Figure 6.15**).

Figure 6.13: Layout of Proposed Interventions at Polder 48, Kuakata Sea Beach



Source: World Bank 2021a.

Figure 6.14: Cross Section of Interventions at Polder 48, Kuakata Sea Beach: Multifunctional Embankment, Sand Nourishment, and Groynes



Source: World Bank 2021a.

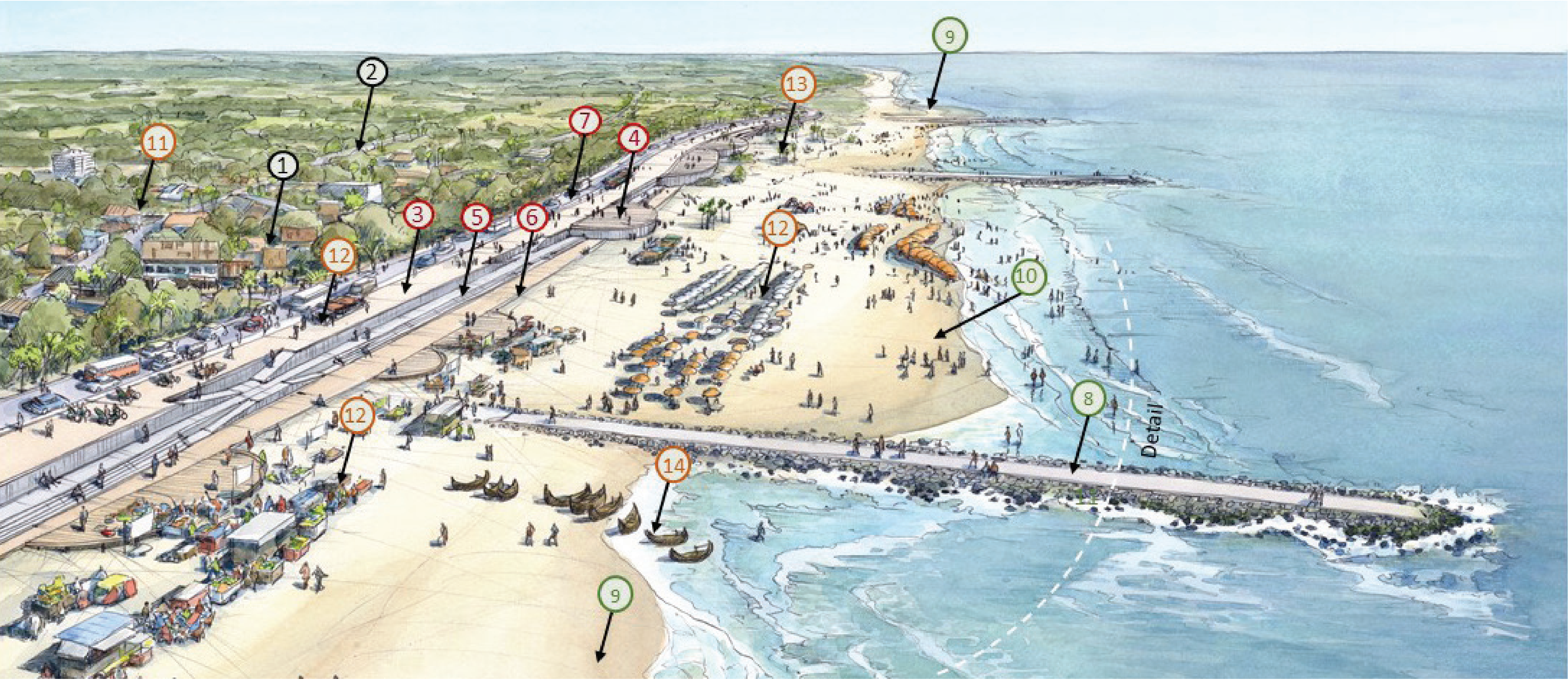
The optimal design of the hybrid solution consists of three groynes in combination with minor sand nourishments. Modeling of the erosion and sedimentation patterns of the upcoming two decades shows that, with the placement of the three groynes, the shoreline can be stabilized locally. Groynes 250 meters long spaced 600 meters apart were found to be effective to block the sediment transport. A possible source for the sediment to be nourished could be found east of Polder 48, or from ongoing dredging activities in the access channel for Payra Port.

After a quick reorientation of the beach in the first two years, the area between the groynes will stabilize for the following 20 years. During the first two years after construction, some 30 meters of sedimentation will occur on the western side of the middle groyne, and erosion on the eastern side of the middle groyne at a similar rate. Also, east of the most western groyne some erosion is predicted due to shoreline reorientation. Additional nourishments (~110,000 cubic meters) will be needed to counteract the erosion of the western part of the beach between the groynes due to the reorientation of the shoreline. After this, the area between the groynes will stabilize.

Outside the protected area, the retreat of the shoreline is expected to continue at a slightly higher pace compared to past decades. As the sub-hotspot of Kuakata Sea Beach is located at a divergence point in longshore transport, additional downdrift erosion is predicted to occur on both coastline sections adjacent to the proposed multifunctional embankment; locally up to 10 meters per year. Sand nourishments (with volumes up to 250,000 cubic meters) should be planned for both sides of the beach to mitigate the additional downdrift erosion for the first 20 years after construction.

The hybrid solution can therefore reduce coastal risks by stabilizing the shoreline at the erosion hotspot, while also providing significant opportunities for economic growth. A preliminary cost-benefit analysis found a positive benefit-cost ratio for the hybrid alternative. As the effects of SLR and the reduced probability of damage to critical infrastructure and intangible benefits (such as tourist income, employment, etc.) were not yet included in the preliminary analysis, it is strongly believed that the hybrid solution will provide a cost-effective alternative for increasing the coastal resilience of Kuakata Sea Beach. The additional benefits are, among others, the revitalization of the Kuakata waterfront, expanded economic opportunities, and increased attractions for tourists (**Figure 6.16**).

Figure 6.15: Artist Impression of Kuakata Sea Beach Design for Polder 48



Existing situation
1. Kuakata commercial area (hotels and restaurants)
2. Main road

Proposed interventions/multifunctional embankment
3. Crest of multifunctional embankment +7.5 m PWD
4. Balconies +7.0 m PWD
5. Lower promenade +5.0 m PWD
6. Beach level +4.0 m PWD
7. Road +6.5 m PWD

Proposed interventions/groyne field and nourishment
8. Groyne crest +4 PWD, width 3-5 m, length 250 m, spacing 600 m
9. Small-scale sand nourishments to avoid downdrift erosion
10. Small-scale sand nourishment to advance beach between groynes

Potential areas of development after implementation of interventions
11. Potential areas for development of tourist activities
12. Potential areas for development of beachfront tourist activities
13. Potential area for development of green areas (afforestation)
14. Potential areas for maintenance and development of fishing activities

Source: World Bank 2021a.

Figure 6.16: Artist Impression of a Street View, Kuakata Sea Beach Design for Polder 48

Source: World Bank 2021a.

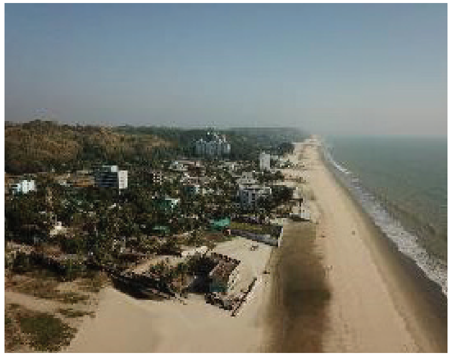
6.3. Cox's Bazar: A Hybrid, Nature-Based, and Multifunctional Solution for Combating Coastal Erosion, Preventing Flooding, and Enhancing Tourism

6.3.1. Polder Description, Social Context, and Coastal Dynamics

Cox's Bazar, located in the eastern part of the coastal zone, is the tourism capital of Bangladesh. With property development and an international airport, Cox's Bazar could become a billion-dollar income hub for the entire country. The latest developments in security, accommodation, and amusement have already prepared the town for hosting local and foreign tourists. At least 500 hotels, furnished flats, international standard resorts, and restaurants have been established in the area surrounding the beach. Currently, the number of foreign tourists coming to Bangladesh is small compared to the number of Bangladeshi outbound tourists; only 267,000 foreign tourists came to Bangladesh in 2018 (Deb and Nafi 2020). However, industry experts say that with improvements in infrastructure services and an adequate marketing policy, the number of tourists could increase drastically within the next few years.

Cox's Bazar attracts many domestic tourists. According to local sources, the number of domestic tourists rose to 15 million in 2019, from 10 million a year earlier, with tourists spending an average of BDT 25,000 each in Cox's Bazar, which translates to a total of BDT 375 billion yearly. This money circulates in the district's overall economy, creating as many as 2,414,400 jobs in the sector in 2018, a number that was expected to reach 3,155,300 jobs by 2019 (Ahmed 2019). As such, the service sector in Cox's Bazar (48 percent of the local GDP) proves the largest when compared with other sectors like agriculture (28 percent) and industry (24 percent) (Lemma et al. 2018).

Tourists at Inani beach, Marine Drive.



A view of Cox's Bazar beach.

The Cox's Bazar-Teknaf Marine Drive Road was built to facilitate tourism opportunities, develop the fishing industry, enhance regional connectivity, and improve the management of natural resources. It is an 80-kilometer-long road that goes from Cox's Bazar to Teknaf running close to the shoreline. Its construction started in 1993. In June 2008, the first phase of 24 kilometers, from Kolatali to Inani, was completed. The second phase, which started in July 2008, covered another 24 kilometers of road, from Inani to Shilkhali, and the third phase was 32 kilometers from Shilkhali to Teknaf. Construction was completed in 2018 by the Bangladesh Army, under the supervision of the Bangladesh Roads and Highways Department. The project components include road works, cross drainage structures, and coastline protection works.

Over the years, there has been severe erosion and damage to Marine Drive Road, mainly caused by wave action from the sea. The road is directly exposed to the Bay of Bengal and is vulnerable to tides, wave action, and cyclonic storm surges. Since the start of construction, several locations along the road have been damaged by wave action, reducing the width of the beach significantly. To protect these locations, the BWDB suggested protective measures, such as revetments. In some places, combined protection works have been implemented, comprising concrete blocks, tetrapods, and geotubes. Despite working well locally (at some locations the measures caused sedimentation), these measures remain temporary fixes that do not eliminate the need for a more permanent, long-term, solution for the entire road.

Marine Drive Road at Cox's Bazar (Himchori Beach), including its current erosion protection measures.

6.3.2. Coastal Erosion Along Marine Drive Road

Satellite imagery shows variations in the erosion and sedimentation in space and time of the coast between Cox's Bazar and Inani. Several rivers and streams along the coast, of which Raju channel is the largest, deliver water and sediment from the hills. The amount is highly variable over time because of heavy rain showers during the wet southwest monsoon. Both wave action and cyclones add to the variations in the morphodynamics of the system, making this coast sensitive to shoreline instabilities. These shoreline instabilities are likely to be initiated near river mouths, where sand spits occur. During a severe event (such as a cyclone) or if the river breaks through a sand spit, the spit may become unstable and detach from the river mouth, after which it migrates along the coast, and gradually smooths out. This explains why alternating periods of accretion and erosion occur along this coastline.

Over the 30-year period that is covered by satellite imagery, the erosion rates along Marine Drive Road vary between 3 to 5 meters per year over the long term, and 0 to 10 meters per year over shorter periods. The difference in the short-term versus the long-term rates further substantiates the shoreline instabilities explained above. Vegetation at the dry beach just in front of the coastal protection measures also indicates that erosive and accretive periods alternate. A first order sediment budget estimate based on the average erosion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rates at the coast between Cox's Bazar and Inani shows that typical erosion and sedimentation volumes are in the order of 50,000 to 200,000 cubic meters per year. This indicates an important role for sediment input by rivers of at least the same order of magnitude.

This case study considered three erosion sub-hotspots: (1) Kolatoli beach; (2) Himchori beach; and (3) Inani beach (**Figure 6.17**). Kolatoli beach (**Figure 6.18** and **Figure 6.19**) is currently (as of 2020) quite wide, however, satellite images reveal a coastline retreat of about 3 to 5 meters per year. Here, attempts have already been made to combat coastal erosion by constructing small sea walls (**Figure 6.19**). Himchori beach, on the other hand, is very narrow. Temporary measures have been taken to combat ongoing erosion, including geotubes and tetrapods (**Figure 6.20**). Inani beach is the widest of all hotspots (**Figure 6.21**). Here, in the long term, erosion and accretion rates are quite low (0.2 to 1 meter per year), while for shorter time scales, there seems to be fluctuations in the coastline position. Currently, the aforementioned temporary measures work well in providing protection for Marine Drive Road. However, over the long term, more permanent measures will be needed to directly address the cause of the erosion.

6.3.3. A Hybrid Approach to Ensure Coastline Stability

A combination of a multifunctional embankment with large sand nourishments is proposed to reduce coastline retreat, minimize the impacts of flooding, and enhance tourism. The embankments would provide the necessary protection against flooding of the hinterland, while the sand nourishments would provide protection against coastal retreat. The proposed multifunctional embankment at Kolatoli **(Figure 6.22**) and Inani Beach is integrated into the surrounding area and includes space for housing functions such as local shops, restaurants, and (small) hotels. The multifunctional embankment would also aid in further developing the area around Himchori Beach (**Figure 6.23**) by providing space to locate several additional activities on the embankment. Green slopes with vegetation are included in its design to reduce the impact of waves on the embankment and attract recreational activities.

Figure 6.17: Location of the Three Sub-Hotspots at Cox's Bazar and along Marine Drive

Source: World Bank 2021a.

Figure 6.18: Sub-Hotspot 1: Kolatoli Beach, Cox's Bazar (during high tide on February 28, 2020)

Source: World Bank 2021a.

Figure 6.19: Coastal Protection Structures at Kolatoli Beach

Short seawall with mild slope and crest accessible by stairs.

Short seawall with steep slope.

Figure 6.20: Sub-Hotspot 2: Existing Coastal Protection at Himchori Beach

Birdseye view of coastal protection in Himchori: geotubes, randomly placed tetrapods, and a second series of geotubes along Marine Drive.
Source: World Bank 2021a.

Figure 6.21: Sub-Hotspot 3: Inani Beach

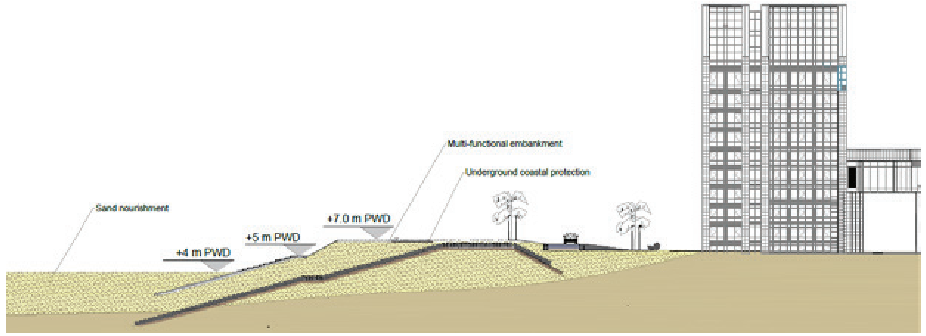
Source: World Bank 2021a.

The proposed sand nourishments directly mitigate coastline retreat and work well with the existing natural beaches. The three envisaged nourishments at each erosion hotspot are intended as a local buffer against ongoing longshore transport of sediment and as a natural sea defense during storms, preventing cross-shore erosion and the undermining of the multifunctional embankments. The sand that is placed at the beaches (and in the underwater section of the profile) would result in a considerable local seaward movement of the coastline, which will erode over time. For every location, a beach width of approximately 100 meters is proposed (**Figure 6.24**). The nourishment at Inani beach is split into two separate nourishments to avoid blocking the streams that drain water to the sea. **Figure 6.25** to **Figure 6.30** show further layouts and artist impressions of two of the three beach restoration projects.

After construction, the proposed nourishments would quickly change into a bell shape and be dispersed completely after 5 to 10 years at Kolatoli Beach and Himchori Beach, and 10 to 15 years at Inani Beach. The erosion would start at the edges of the nourishment and progress inward over time. These edges coincide with the peaks and troughs in the longshore transport rates. The nourishment at Kolatoli Beach (about 1 million cubic meters) would spread evenly over the coast in about five years, to a width of about 30 meters. The nourishment at Himchori Beach (about 1.4 million cubic meters) would follow a similar pattern, with a width of about 50 meters after five years (**Figure 6.31**). In comparison, the Inani nourishment (about 0.8 million cubic meters) is expected to evolve considerably slower due to the smaller transport rates locally (**Figure 6.32**). Here it is recommended to monitor the opening of the streams between both nourishments and if needed, create new openings if the mouths of the streams are getting blocked by sedimentation.

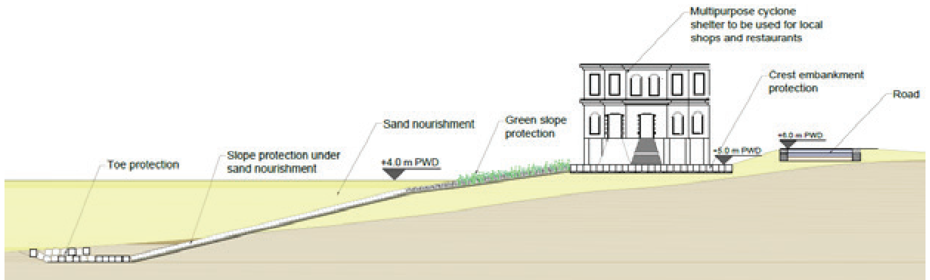
The proposed combination of sand nourishments with a multifunctional embankment will provide the necessary protection of Marine Drive Road while also creating opportunities for local economic development. As the hybrid solution provides protection for both the longshore and cross-shore transport of sand, it will protect the hinterland against both ongoing and event-driven erosion. By continuously monitoring the mobility of the initial nourishments, the ongoing erosion patterns can be better understood. This will make it possible

Figure 6.22: Cross Section of Proposed Multifunctional Embankment at Kolatoli Beach



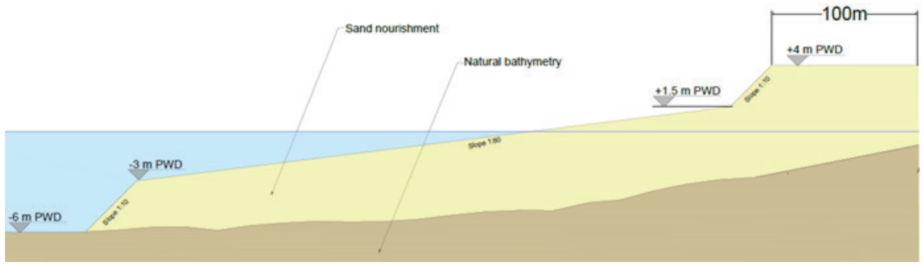
Source: World Bank 2021a.

Figure 6.23: Cross Section of Proposed Interventions at Himchori Beach



Source: World Bank 2021a.

Figure 6.24: Cross Section of Sand Nourishment Proposal at Cox's Bazar and Marine Drive



Source: World Bank 2021a.

Figure 6.25: Intervention Layout of Kolatoli Beach with Sand Nourishment and Multifunctional Embankment

Source: World Bank 2021a.

to establish whether additional nourishments are needed to further protect the area in the long term. Finally, as the area of Cox's Bazar is known for its sandy beaches, beach restoration through nourishments will benefit the local tourism sector and provide opportunities for economic development.

Figure 6.26: Artist Impression of a Bird's Eye View of the Design Proposal for Kolatoli Beach

Existing situation	**Proposed interventions/multifunctional embankment**	**Proposed interventions/sand nourishment**	**Potential areas of development after implementation of interventions**
1. Kolatoli commercial area (hotels and restaurants)	2. Crest of multifunctional embankment +7.0 m PWD and width 15 m 3. Balconies +7.0 m PWD 4. Lower promenade +5.0 m PWD 5. Road +6.5 m PWD	6. Sand nourishments with a width of 100 m and a length of 1 km 7. Beach level +4.0 PWD	8. Potential development of tourist activities 9. Potential area for development of beachfront tourist activities

Source: World Bank 2021a.

Figure 6.27: Street View Perspective of Multifunctional Embankment at Kolatoli

Source: World Bank 2021a.

Figure 6.28: Intervention Layout at Himchori Beach: Sand Nourishment and Beautification of Embankment

Source: World Bank 2021a.


J. H. Laboyrie

Figure 6.29: Artist Impression of a Bird's Eye View of the Design Proposal for Himchori Beach

Existing situation
1. Himchori hilly area
2. Existing residential houses
3. Road +6 m PWD

Proposed interventions/beautified embankment
4. Crest of beautified embankment +5.0 m PWD and width 10 m
5. Multipurpose shelter for safe development of tourist activities
6. Green slopes

Proposed interventions/sand nourishment
7. Sand nourishments with a width of 100 m and a length of 2 km, Beach level +4.0 PWD

Potential areas of development after implementation of interventions

8. Potential development of tourist activities

Source: World Bank 2021a.

Figure 6.30: Artist Impression of a Street View of Himchori Beach

Source: World Bank 2021a.

Figure 6.31: Nourishment Evolution at Kolatoli Beach (Himchori Beach Shows a Similar Evolution)

Source: World Bank 2021a.

Figure 6.32: Nourishment Evolution at Inani Beach

Source: World Bank 2021a.

6.4. Opportunities for Integrating Mangroves in Coastal Protection Strategies

6.4.1. Mangroves in the Coastal Zone

Mangroves are forest species located in intertidal zones, commonly seen along the sheltered muddy shorelines of most tropical and a few subtropical areas (especially deltas) such as the Bengal Delta. Situated between land and sea, mangrove species are adapted to wet soils, saline habitats, and periodic tidal submergence. There are three components of the protective function of mangrove forests: (1) wave attenuation, by mitigation of the hydraulic forces of storm surges; (2) storm protection by providing shelter from the wind; and (3) shoreline stabilization as they help with sediment retention and erosion control. Mangroves increase the soil volume as their roots grow and they can capture up to 1,000 tonnes of sediment per square kilometer (Ellison 2000), thereby elevating the land. An important precondition for the sediment capture is that the tidal movement of water in and out of the mangrove forest is not disturbed (such as by embankments or dams placed seawards from the mangroves). One of the best ways to use mangroves to enhance coastal resilience is to protect the existing forest. Protection of existing forests is far cheaper and easier than planting new mangrove forests. However, mangrove loss is continuing worldwide, including in Bangladesh, with conversion to aquaculture or agriculture being the most common cause (Thomas et al. 2017).

In 1966, Bangladesh's Forest Department launched a program of mangrove afforestation, as the existing Bangladesh Sundarbans mangrove forests provided significant protection against cyclone-induced hazards. While the initial objective of the afforestation program was to create a shelter belt to protect the lives and properties of the coastal communities, the success of the plantations further identified additional objectives for coastal afforestation (see **Box 6.3**), including to: (1) provide forest products for a range of uses; (2) develop forest shelter belts to protect life and property inland from tidal surges; (3) inject urgently needed resources into the national economy (that is, timber and land); (4) create employment opportunities in rural communities; (5) create an environment for wildlife, fish, and other estuarine and marine fauna; and (6) create forest carbon sequestration opportunities (see **Box 6.4**).

Over the last few decades, several cyclones have damaged large portions of the mangrove forests of the Sundarbans, which have not yet fully recovered. Cyclone Sidr (2007) caused significant damage to the mangroves in the Sundarbans forests, creating a loss of about 10 to 45 percent of the mangroves. The economic loss associated with mangrove degradation by Cyclone Sidr

Box 6.3: Ecosystem Services and Livelihoods Benefits from the Sundarbans Mangrove Forest – Opportunities as a Nature-Based Solution

Mangroves are among the most productive ecosystems on Earth and are critical in providing a large number of ecosystem services and benefits, including protection from flooding, cyclones, and tidal surges; carbon storage and sequestration; and support for local livelihoods through the provision of food, fuelwood, timber, and construction materials. As a result of their diverse benefits, mangroves are increasingly regarded as a cost-effective nature-based solution. Mangrove ecosystem services are worth US$33,000-57,000 per hectare per year (UNEP 2014). Mangroves can also help fight climate change and sequester carbon from the atmosphere faster than terrestrial ecosystems, such as tropical rainforests (Donato et al. 2011). A recent estimate suggests that global flood protection benefits of mangroves are worth nearly US$65 billion per year (Menéndez et al. 2020) and the cyclone protection value of mangroves is worth about US$1.8 million per square kilometer per year (Sun and Carson 2020). In Bangladesh, it is estimated that a strip of mangroves 100 meters wide can reduce storm surge velocity by up to 92 percent, saving embankment maintenance costs (Dasgupta et al. 2019).

Located on the active delta of the Ganges-Brahmaputra River system, the Sundarbans constitute the world's largest single tract of mangrove forest, covering an area of about 10,000 square kilometers (Mukul et al. 2020). This unique mangrove ecosystem plays an important role by acting as a bio-shield against cyclone and tidal surges originating in the Bay of Bengal, thereby reducing the vulnerability to such extreme climatic events (Halder et al. 2021). The Sundarbans region has experienced more than 20 major cyclones over the past two decades, and historically, eight out of the ten deadliest tropical cyclones have originated in the Bay of Bengal, where the Sundarbans is located.

The latest World Bank *The Changing Wealth of Nations: Managing Assets for the Future* (2021c) report finds that the mangrove asset value of Bangladesh is worth about US$10 billion, which is a four-fold increase from their 1995 value. The Sundarbans Forest of Bangladesh provides direct and indirect benefits to almost 3.5 million people. In the Sundarbans area, forest income contributed as much as 74 percent of total household income, mainly through non-timber forest products (Abdullah et al. 2016). The cyclone protection value of the Sundarbans during Cyclone Sidr was valued at about US$1,025 per household (Akber et al. 2018). The provisioning and cultural ecosystem services from the Sundarbans contributed to the revenue of the Bangladesh Forest Department an average of US$744,000 and US$42,000 per year, respectively, with increasing revenue from the tourism sector (Uddin et al. 2013). Therefore, the prospect of utilizing the Bangladesh Sundarbans as a nature-based solution is enormous and should be strengthened through scientific management incorporating local people's needs and aspirations.

Box 6.4: Forest Carbon Sequestration Opportunities in Coastal Bangladesh

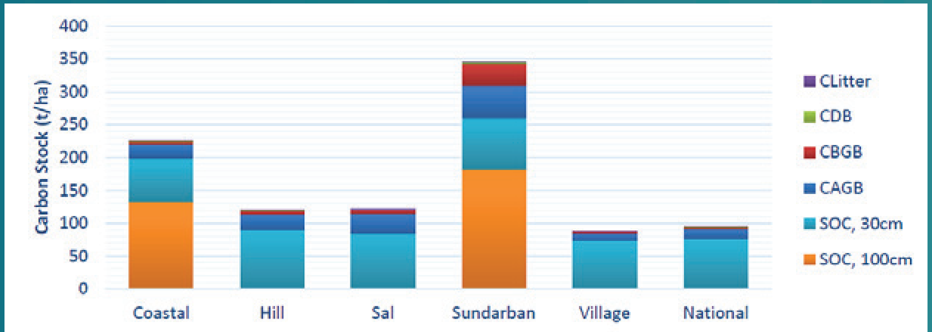
Forests play a crucial role in the global carbon cycle, and increasing emphasis is now put on forestry activities, including forest and landscape restoration, as an effective tool for climate change mitigation (Houghton 2013). Forests can reduce GHG from the atmosphere in two ways: (1) by avoiding emissions from deforestation and degradation; and (2) by letting them grow to sequester more carbon from the atmosphere. Forest carbon can be stored in five different pools: (1) aboveground biomass; (2) belowground biomass; (3) litter; (4) deadwood/ woody debris; and (5) soil (Mukul, Halim, and Herbohn 2021). However, the capacity of different forests to sequester carbon varies. Tropical mangrove forests, for example, have a higher carbon density than tropical rainforests, and they are also highly regarded for their capacity to sequester carbon faster than any other terrestrial ecosystem (Donato et al. 2011).

About 20 percent of Bangladesh's GHG emissions are estimated to derive from land-use, land-use change, and forestry activities, although the country's contribution to global GHG emissions is rather low. Per capita CO2 emissions are also low and were estimated at 0.51 metric tons in 2018 (World Bank 2021b).

According to the latest Bangladesh National Forest Inventory, forest areas hold 21.5 percent of the total carbon stock in the country (GoB 2020). A large variability exists, however, in the national-level estimates of forest carbon density, which is mainly attributable to differences in methods and sampling strategies (Mukul et al. 2014). The density of carbon in aboveground, belowground, and dead biomass is highest in the Sundarbans mangrove forest followed by coastal mangrove plantations (**Figure 6.33**). Carbon density in belowground biomass is 9.6 times higher in the Sundarbans compared to the national average. Nationally, most of the carbon stock is contained in the top 30 centimeters of soil (80 percent), followed by the aboveground biomass (15 percent). In the Sundarbans and coastal mangrove plantations, the soil carbon density at a 100-centimeter depth is more than double that at a 30-centimeter depth.

The spatial distribution of forests is not uniform across the country, they are scattered mainly in the few districts of southern, central, and coastal Bangladesh

Figure 6.33: Carbon Stock Densities in the Major Pools by the Forest Zones of Bangladesh



Source: GoB 2020.

Note: CLitter – carbon in litter; CDB – carbon in dead biomass; CBGB – carbon in belowground biomass; CAGB – carbon in aboveground biomass; SOC – soil organic carbon for 0-30 cm depth soil layer and 30-100 cm depth soil layer.

(Mukul et al. 2014). Over the past few decades, the quality and extent of forests have deteriorated in most parts of the country. Given the high population pressure and high demand for land for competing uses, extending forest cover in most parts of the country is quite difficult. The coastal regions of the country can be effectively used for this, where plantations under social forestry arrangements can be raised for carbon sequestration, coastal protection, and local livelihoods benefits. Restoration of degraded mangrove and other forests using suitable species and coastal land stabilization for soil carbon benefits are also crucial.

Global forest carbon credits are valued at over US$100 billion per year and are an emerging, growing sector. Tackling deforestation is the cheapest option for reducing human-induced GHG emissions, and thereby addressing climate change. To fully capture this opportunity, the carbon sequestration potential of Bangladesh's forestry sector needs to integrate a high-quality forest monitoring and reporting mechanism with REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and other voluntary carbon payment schemes.

alone was estimated to be approximately US$142.9 million (Khan et al. 2021). After Cyclone Sidr, subsequent storms (**Figure 6.34**) continued to damage the mangrove forests, which is why Bangladesh is looking into active interventions for restoration. While restoration and afforestation are not always needed to recover mangrove forests, natural recovery takes time. As of 2018, about 48 percent of the areas affected by Cyclone Sidr had not yet recovered, highlighting the need for active interventions.

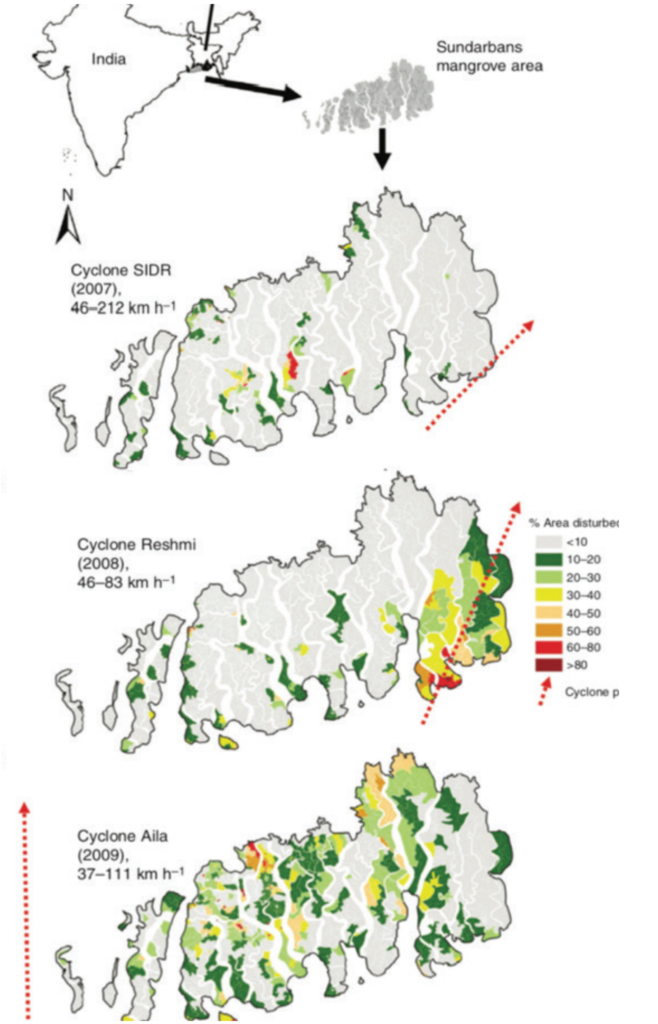
6.4.2. Restoration of Mangrove Forests for Coastal Protection

Mangrove forests can be restored for coastal protection purposes (for wave attenuation and surge velocity reduction), for their ecological functions (such as being a breeding and nursery habitat) and/or for economic reasons (such as wood harvesting). Defining the specific aim of the restoration effort is an important first step in the design of an afforestation project since the type of mangrove and the required size of the forest varies by function. Different mangrove restoration techniques (**Figure 6.35**) could be implemented depending on the reason for the lack of mangroves. In this case study, mangrove afforestation for coastal protection purposes, specifically wave attenuation, was considered.

The effectiveness of mangroves for wave attenuation is assessed by evaluating their impact on required embankment heights. A mangrove belt of a few hundred meters will have a small impact on the surge height, but can significantly reduce wave run-up, and with that, the amount of overtopping over an embankment. Wave attenuation rates range from 5 to 100 percent over 100 meters of mangrove forest (**Figure 6.36**), depending on incoming wave heights and periods, but also as a function of the tree species, tree geometry, and total vegetation extent (Mazda et al. 1997; Bao et al. 2011). Assuming a conservative wave height reduction of 8 percent over 100 meters of mangroves, and a mangrove belt of 500 meters, a 40 percent reduction of the wave height could be the result. By reevaluating the crest height of the embankment based on the design overtopping volume (5 liters per meter per second) for Polder 56/57, such a mangrove forest would reduce the required crest height of the embankment by almost 10 percent (from 6.1 meters to 5.5 meters) (**Figure 6.37**). This reduction in crest height would decrease the direct costs of raising the embankment and reduce the required footprint of the embankment, and thus the indirect costs in the polder itself (such as for land acquisition).

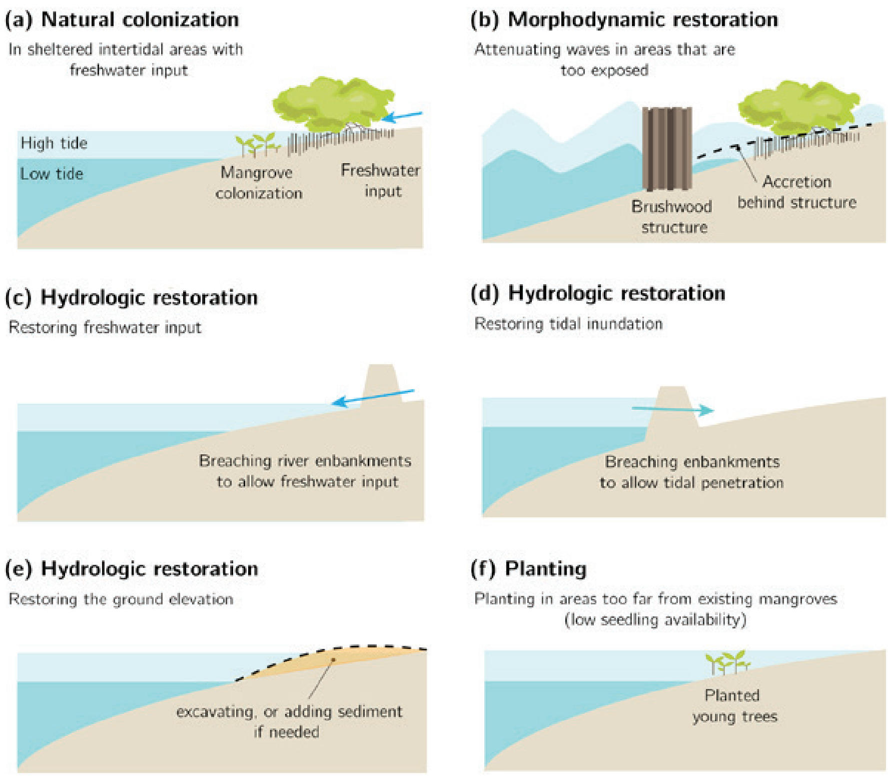
Ultimately, the wave attenuation obtained from a mangrove belt depends on the bathymetry, the characteristics of the planted (or native) mangrove species, and the local wave climate. Furthermore,

Figure 6.34: Spatial Distribution of Damage (percentage of area disturbed) Caused by Three Tropical Cyclones (SIDR, Rashmi, and Aila) Affecting the Sundarbans from 2007 to 2009



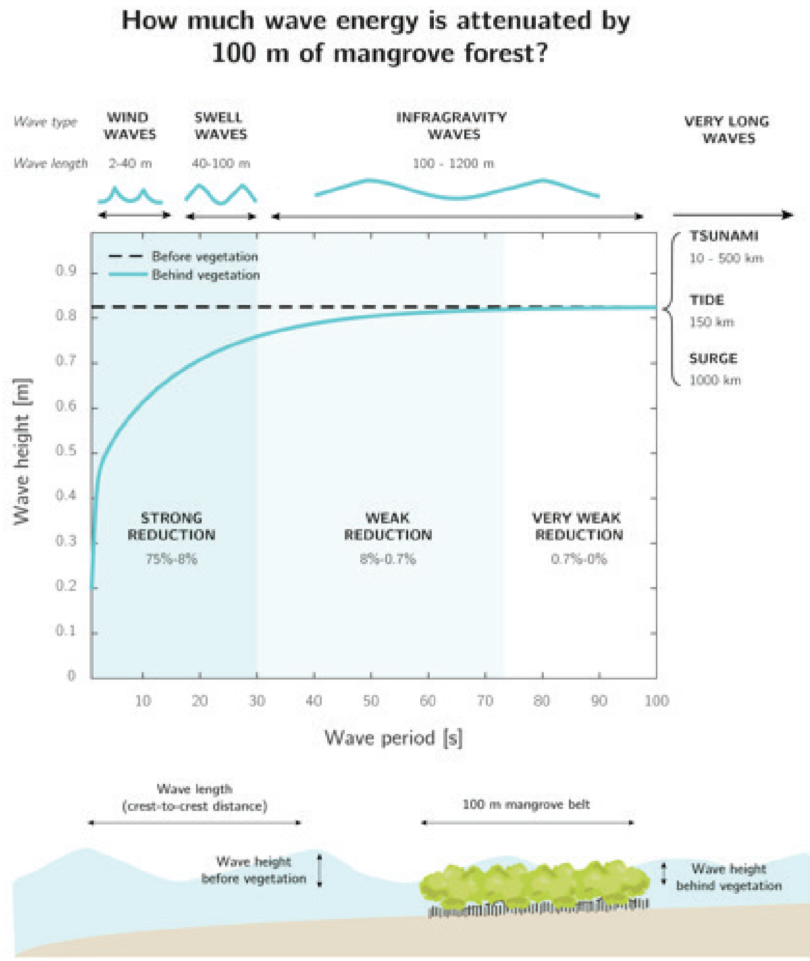
Source: Kraus and Osland 2019.
Note: Red-dashed arrows indicate approximate storm tracks.

Figure 6.35: Illustration of Several Mangrove Restoration Techniques



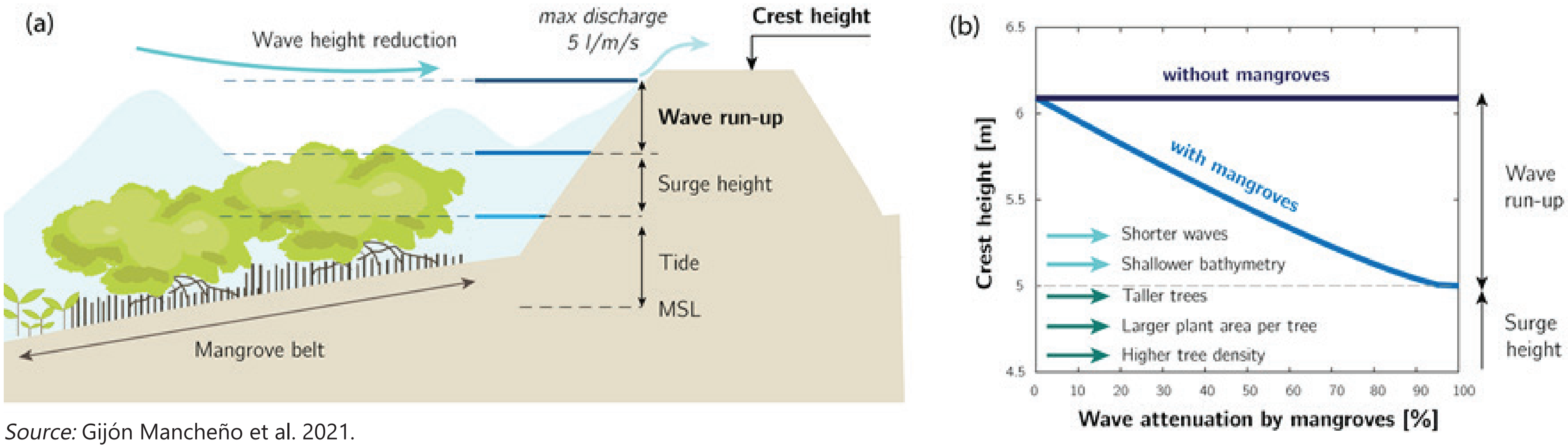
Source: Gijón Mancheño et al. 2021.

Figure 6.36: Wave Reduction through a 100 m-wide Mangrove Belt, Dependent on Incoming Wave Height and Periods



Source: Gijón Mancheño et al. 2021.

Figure 6.37: Design Water Levels (left) and Required Embankment Height (right) with and without Wave Attenuation by a Mangrove Belt (Polder 56/57)



Source: Gijón Mancheño et al. 2021.

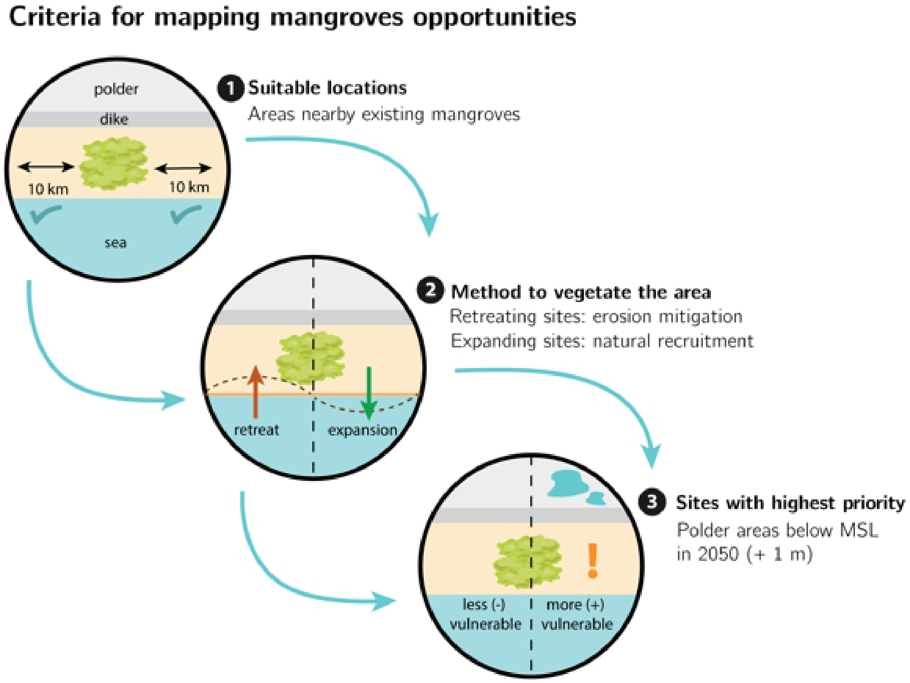
the effectiveness of a combination of mangrove forests in front of embankments also strongly depends on the local morphological conditions. This can be analyzed using a hydrodynamic model that includes the effect of the vegetation and evaluates if and how the bathymetry (and the rate of wave attenuation) will change over time. To identify locations for mangrove afforestation, the current and expected future wave climates (influenced by interventions and climate change) and resulting sedimentological conditions must be analyzed carefully.

6.4.3. Potential Sites for Mangrove Restoration and Afforestation

Analyses of the conditions necessary for mangrove growth have helped identify potential mangrove habitats in Bangladesh's coastal zone. Information from satellite imagery was used (Gijón Mancheño et al. 2021). Firstly, sites within 10 kilometers of existing mangrove forests were selected along the coastline (10 kilometers being the distance needed for colonization based on the dispersal distance of mangroves). A nearby mangrove presence is considered an indicator of suitability as mangrove habitat and suggests that there is a natural supply of seeds. Secondly, the selected stretches were classified as accreting (expanding seaward) or eroding (retreating landward), to determine which type of afforestation methods would be needed. "Natural colonization" and "Planting" approaches (**Figure 6.35**) could be suitable afforestation techniques in accreting sections, while erosion mitigation measures would also be needed at eroding sites. Lastly, afforestation was prioritized seawards from the polder areas with the lowest ground elevation, as these are most at risk from flooding. The steps to identify potential sites for mangrove afforestation are illustrated in **Figure 6.38**.

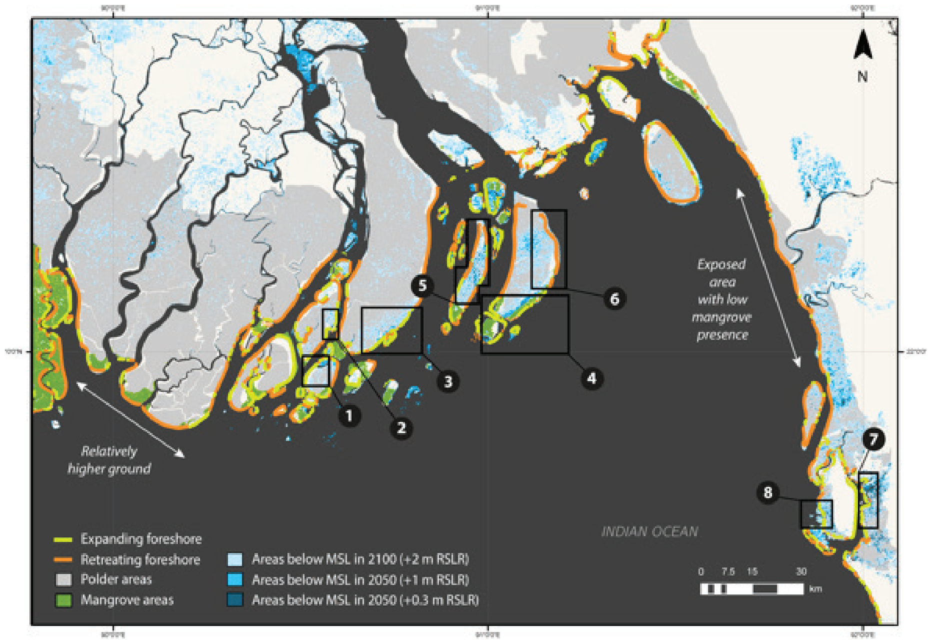
Several mangrove afforestation locations with high potential and priority (in terms of flood risk) were thus identified in Bangladesh **(Figure 6.39**[26]). These sites are highlighted in green if the coastline is expanding and orange if the coastline is eroding (in that case the sites would need more detailed assessments, and investments in erosion mitigation techniques). While natural

Figure 6.38: Steps to Find Potential Sites for Mangrove Afforestation



Source: Gijón Mancheño et al. 2021.

Figure 6.39: Mangrove Establishment Opportunities Along the Coastline of Bangladesh



Source: Gijón Mancheño et al. 2021.
Note: Existing mangroves are shown in dark green, and new potential afforestation sites are enclosed by black rectangles. The coastline is highlighted in light green at locations where it is expanding (moving seawards) and in orange at locations where it is retreating (moving landwards). Natural colonization and planting are possible afforestation techniques at expanding locations, whereas erosion mitigation measures are needed at eroding sites.

colonization (if there is seedling availability in the area) is likely to take place in multiple locations indicated in green (such as at Barguna and Patuakhali, Bhola and Noakhali, along the coastline of Chandnandi, and at Cox's Bazar), planting must be considered if natural colonization is too slow for coastal protection purposes. In total, approximately 600 kilometers of coastal stretches are located within 10 kilometers of existing mangrove patches. Multiple potential restoration locations were identified (enclosed by black boxes), mostly centered in the Meghna Estuary and along the eastern shoreline. The sites in the Meghna Estuary have potential to help reduce flood risk and can benefit from easy restoration on accreting lands, although for other places (such as Bhola island), mangrove restoration should be combined with erosion mitigation measures. The east coast locations are close to existing mangrove forests, making natural recruitment or planting relatively easy.

The analysis shows that a significant area in the coastal zone has the potential for mangrove afforestation. Mangroves could be a low-cost alternative to hard flood and riverbank erosion protection works. Also, mangroves can be combined with embankments to lower the required elevation (and thus footprint) of the embankments. The fact that mangroves require little O&M could be a considerable advantage considering the O&M challenges in Bangladesh's coastal zone. Also, mangrove afforestation programs could help restore damaged ecosystems, benefiting both the natural environment and local communities. This mapping exercise provides a systematic insight into where potential opportunities of combined solutions that include mangroves are possible along the entire coastal zone. This is vital input for enhancing combinations of green and grey infrastructure in the planning and programming of future investments in the coastal zone. The mapping methodology could also be applicable for projects in other countries, while lessons learned from projects elsewhere can help identify best practices for the development of such a project in Bangladesh (**Box 6.5**).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Box 6.5: Mangrove Afforestation in Indonesia

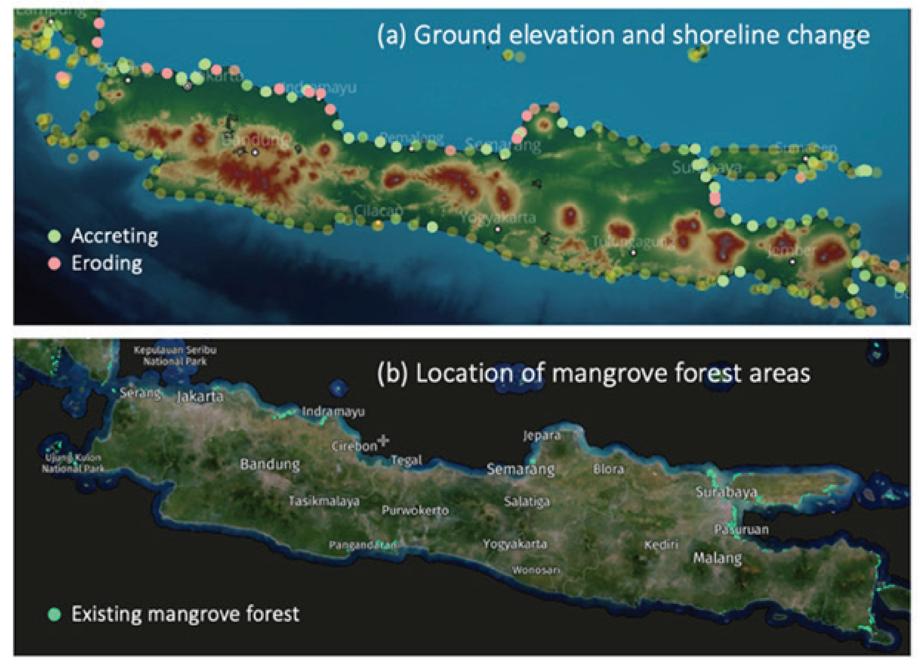
Indonesia has 23 percent of the mangrove areas in the world, and the greatest richness in terms of mangrove species. However, it also has one of the highest mangrove deforestation rates, having lost 40 percent of its forests to aquaculture over the last three decades. Mangrove loss has exposed coastal areas to the effects of extreme events and RSLR. By restoring mangroves, vulnerable coastal communities can increase their resilience and recover these natural flood defenses.

The methodology to identify potential mangrove afforestation sites presented in Section 6.4. could also help highlight sites with high mangrove suitability in Indonesia. In order to provide an indication of its mangrove potential, the mangrove cover, ground elevation, and shoreline behavior data of Java, the most populated island in Indonesia, are shown in **Figure 6.40.**

The north coastline of Java is shallower and has more areas exposed to large coastline retreat compared to the south. Moreover, several urban areas along the north coast experience land subsidence due to groundwater extraction. However, Java also has regions with considerable mangrove presence, such as the area east of Jakarta, and the areas of Indramayu, Semarang, Surabaya, and Pasuruan. The specific sites to be restored could be assessed resorting to more detailed flood risk and infrastructure data, in combination with the ground elevation and shoreline behavior data shown in the figure above. Since the island of Java is densely populated, mangrove restoration at these sites has a large potential for flood risk reduction.

The Building with Nature Indonesia project was carried out between 2014-2020 with the aim to restore mangroves along the eroding coastline of Demak, in north Java. Mangrove deforestation in combination with land subsidence due to groundwater extraction had caused coastline retreat rates of up to 100 meters per year in Demak. The loss of mangrove vegetation left coastal areas exposed to the effect of waves and removed their natural sediment trapping mechanism. The project aimed to stop this retreat and create new habitat for mangrove colonization, while providing economic alternatives for the local communities.

Figure 6.40: (a) Ground Elevation of Java (Indonesia); (b) Map of Mangrove Presence in Indonesia



Source: Elevation and shoreline data: https://blueearthdata.org; mangrove cover data: https://globalforestwatch.org.
Note: The ground elevation is shown, with dark green corresponding to lower ground elevations and yellow and brown corresponding to higher ground elevations. The behavior of the shoreline is shown by dots, with light green dots corresponding to expanding coastlines (moving seawards) and pink dots corresponding to eroding coastlines (moving landwards).

Bamboo and brushwood structures were built along the coastal system to attenuate waves and enhance sediment trapping near the shoreline. This accumulation of sediment provided new ground for mangrove establishment. The project also included a line of research on sustainable aquaculture techniques, to develop farming techniques that were compatible with the protection of the mangrove forest. The project was developed in collaboration between the local communities, nongovernmental organizations (NGOs), research institutes, and engineering companies (for further information see: https://www.ecoshape.org/en/pilots/building-with-nature-indonesia/).

Bamboo and brushwood structures built in Demak (north Java, Indonesia) to enhance mangrove restoration along the coast.

6.5. Notes

24. More information on multifunctional embankments is available at: https://www.flooddefences.org.

25. Bogi is a village in Polder 35/1 in Southkhali Union, Sharankhola Upazila, Bagerhat District.

26. A full description of the methodology and detailed maps showing mangrove afforestation opportunities can be found in the following article: https://www.mdpi.com/2071-1050/13/15/8212.

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A WAY FORWARD: SEVEN RECOMMENDATIONS FOR A MORE RESILIENT COAST

7

CHAPTER 7: A WAY FORWARD: SEVEN RECOMMENDATIONS FOR A MORE RESILIENT COAST

So far, this report has shown that Bangladesh has already made significant steps in enhancing coastal resilience and many achievements and milestones illustrate this. Addressing climate change and improving the resilience of the coastal zone is a national priority for Bangladesh; since Independence, the country has invested more than US$10 billion (Government of Bangladesh 2018) in climate resilience actions. An investment portfolio of a wide variety of structural and non-structural interventions has been implemented, alongside efforts to increase the capacity of government agencies to respond to emergencies and enhance the resilience of local communities. The country has implemented structural interventions, such as constructing and strengthening river embankments and coastal polders, building multipurpose disaster shelters and resilient houses, adapting rural households' farming systems to better cope with environmental stressors, and taking measures to reduce saline water intrusion (such as building water management infrastructure). These have been complemented with a variety of non-structural measures such as strengthening hydrometeorological services, implementing EWS, awareness-raising systems, emergency management systems, and enhancing community-based disaster preparedness programs. Altogether, these investments have significantly reduced damages and losses from extreme events over the years, especially in terms of deaths and injuries. In Chapter 4, a detailed evaluation of the effectiveness of some of these interventions is provided.

Bangladesh's ambition to become an upper middle-income country by 2030 is subject to significant challenges; alongside rapid socioeconomic development there are increasing adverse impacts from climate change. A recent report (PwC 2017) forecasts that Bangladesh will become the 23rd largest economy in the world by 2050, advancing from 41st place in 2020, as a result of steady projected economic growth. The time frame of this economic transition, however, coincides with a rapidly changing climate and its associated potential increase in the intensity and frequency of climate-induced disasters, expected rapid urbanization, loss of agricultural land, uncertainty in water availability from upstream, and an accelerated rise in sea levels along the coast. This could all result in more frequent floods, permanent inundation, increased salinity, and changing sediment dynamics. Therefore, to achieve Bangladesh's aspiration to become a safe, sustainable, and resilient delta, specific medium- and long-term goals have been set to ensure protection from the devastating impacts of climate change, build an integrated and sustainable estuary management strategy, preserve and properly utilize valuable ecosystems, and ensure an optimum level of integrated use of land and water resources.

This chapter explores seven key recommendations (listed below) to move towards a more resilient coast. They are as specific as possible, grounded in the work presented in this report and based on global best practices, with strategic actions proposed for implementation of each recommendation.

1. Strengthen O&M to extract maximum benefits from investments and nurture sustainable interventions.
2. Embrace the uniqueness of the Bangladesh coast, recognize local knowledge, strengthen the application of state-of-the art modeling tools and systems, and cultivate knowledge sharing.
3. Apply risk as the guiding principle for adaptive delta management.
4. Complement infrastructure interventions with nature-based solutions to enhance resilience and effectiveness.
5. Incorporate risk-sensitive land-use planning to guide appropriate activities based on integrated coastal zone management practices.
6. Support inclusive community participation, local institutions, and livelihoods adaptation for sustainable resilience.
7. Establish an integrated framework of performance criteria of interventions that goes beyond risk reduction and includes growth, wellbeing, and sustainable development at its core.


J. H. Laboyrie

7.1. Recommendation 1: Strengthen O&M to extract maximum benefits from investments and nurture sustainable interventions

Key message: *Solid O&M of all existing natural and human-made structural and non-structural assets (that is, forests, embankments, drainage systems, shelters, EWS) is the foundation of coastal resilience. Investments in O&M activities alongside clear organizational responsibilities should be prioritized to ensure that existing key assets provide their essential services to coastal communities.*

The coast of Bangladesh has a vast and varied system of natural and human-made structural and non-structural assets providing essential services to coastal communities, such as flood and erosion protection, and livelihoods opportunities. Examples of these systems are tidal river and coastal ecosystems (for example, forests, embankments, polder drainage systems, riverbank protection works, shelters, and EWS. On the one hand, the Bengal delta system, with its abundant sediment and mangroves, is part of the largest natural delta ecosystem in the world. On the other hand, it has extensive human-made systems: over 6,000 kilometers of embankments, approximately 5,000 multipurpose disaster shelters, 8,000 kilometers of canals, more than 2,000 drainage/flushing structures, and 1,000 regulators (see Chapter 2 for more details).

Good O&M of all these assets is the foundation for coastal resilience, but as in many places around the world, sound O&M is challenging. In Bangladesh, the O&M activities vary depending on the asset category, with each having their own distinctive characteristics. For example, the maintenance of embankment systems requires regular checks to ensure that design dimensions (such as height or width) are maintained, and the embankments are in acceptable condition, and to identify any deviations from the original design that need maintenance (e.g. emerging cracks). Regular maintenance activities of human-made structures include grass cutting and cleaning, while post-disaster event activities often consist of repairs to damaged roofs or bank protection works. From an operational perspective, activities include the opening and closing of drainage/flushing structures or the management of shelters during cyclone and non-cyclone situations. Global examples show that good O&M will pay off in several ways, including adequate functioning of the assets, postponement of large rehabilitation works, and the ability to be more proactive in the planning and implementation of asset upgrades. "Getting the basics right" is crucial to reaping these benefits. At least three limiting factors were derived from the evaluation of past projects in Chapter 4 and other reviews, for which specific recommendations have been formulated to help overcome them.

First, Bangladesh needs to shift its trajectory towards ensuring that assets reach their intended lifetime by implementing sound O&M practices. This reduces the need for ad hoc infrastructure investments and enables the country to move away from a mindset of "build, neglect, rebuild" towards more sustainable and long-term solutions. Proper O&M of assets is often limited because of budgetary constraints in Bangladesh. Insufficient funding for O&M is a major concern and has complex social, institutional, and financial dimensions. For example, the BWDB, the main authority in Bangladesh responsible for water management infrastructure (such as embankments, drainage sluices, and canals), does not have sufficient budget or manpower to carry out proper monitoring of the polders; often only a small fraction of the actual required O&M budget is approved. In the past, inadequate O&M has led to damaged hydraulic structures, deteriorating embankments, and the silting up of drainage canals, leading to reduced operability and reliability of these infrastructure systems. The lack of funding for O&M leads to the approach of implementing temporary and emergency protection works in locations where a failure or breach has been identified after extreme conditions. The impact of Super Cyclone Amphan (May 2020) is a recent example of the application of such temporary emergency protection works, which were used in locations where the impacts of erosion were significant and the stability of the previously implemented emergency works required further strengthening given the cyclone event. Had there been sufficient investments in the needed protection works and adequate O&M, such ad hoc emergency works may not have been required. A global analysis highlighted that poor maintenance could increase the infrastructure investment needs by 50 to 60 percent for transport and water infrastructure (Hallegatte, Rentschler, and Rozenberg 2019), while in the United Kingdom, it was found that every dollar spent on the maintenance of flood protection works limits capital expenditure by seven dollars (JBA 2021). Given the size of investments in Bangladesh, these benefits could be substantial and would free up capital for alternative investments.

Second, technological advances should be embraced to systematically monitor the vast number of assets in the coastal zone. Systematic monitoring of asset data for O&M and establishing detailed O&M procedures is another challenge in Bangladesh. Up-to-date knowledge of the status of the assets is the premise for planning O&M activities and identifying the human and financial resources required to perform such O&M activities. A review of past projects in Chapter 4 showed that systematic monitoring of coastal protection works is often not in place. However, this monitoring is essential to move away from ad hoc emergency works and to be able to plan for regular maintenance and the potential upgrading of assets. As an example, within the recent CEIP-I, all available information on embankments and structures for the entire polder system is being collected and stored in one geoportal for relevant stakeholders to access (with the necessary approvals). Similar databases should be developed for other structural and non-structural assets in the coastal zone in collaboration with the relevant asset owners. Technology can help in monitoring a large number of assets, for instance using satellite imagery to detect trends in forest cover, InSAR satellites to detect ground displacement around assets, and remote sensing to detect riverbank erosion. This can help in continuously monitoring assets in space and time and can provide the necessary information to determine where to prioritize in-depth O&M inspections. On top of that, budget and staffing should be appropriated to manage these data systems continuously. In addition, an O&M planning system should be set up to decide when (and where) appropriate actions need to be taken.

Lastly, local involvement in O&M activities should be fostered and embraced in large-scale infrastructure investments. Historically, O&M was mainly carried out by the responsible agency, although it was often limited because of budget constraints, and did not incorporate forward-looking practices regarding monitoring and O&M procedures. As outlined above, adequate resources, staffing, and implementation of good practices will improve the current O&M activities of these agencies. However, the organization of O&M activities should not take a solely top-down approach but should actively involve local communities throughout the O&M cycle. Local communities often have better knowledge of the local conditions, which is essential for the O&M process. Good initiatives to enhance community participation in O&M have been piloted by projects such as the CEIP-I and the Blue Gold Program. For example, the CEIP-I is implementing a participatory scheme for O&M management, by involving local communities at all stages of project planning, implementation, and monitoring (see Chapter 4). WMOs have engaged women in their communities as members as well as in leadership positions to improve the uptake of good O&M practices across gender and social groups. As per the national Participatory Water Management Rules, women must form 30 percent of the WMO constituency, and should be given encouragement to join WMOs and be provided with training on gender and leadership. Such initiatives can be further upscaled and mainstreamed into other O&M initiatives.

Strengthening these O&M factors is an essential first step in enhancing coastal resilience to safeguard the functionality of existing natural and human-made assets and to ensure that investments in assets will continue to provide the essential services throughout their envisioned lifetime. Specific recommendations to enhance O&M in Bangladesh are to:

- Allocate more funding for O&M alongside exploring new revenue streams for financing O&M. The BDP 2100 recommends that 0.5 percent of GDP be allocated for the O&M of water management infrastructure. The present level of the O&M budget is estimated to be about 0.1 percent of GDP. These resources are required to increase staffing, develop systematic management systems, and provide funding for regular maintenance activities. A thorough analysis of existing O&M funding and how it is currently spent is necessary, which can help set specific recommendations on how to increase and make better use of this budget

- Further strengthen the use of technology, tools, and data for solid asset management and embed these systems in the O&M organization of the relevant agencies. Existing database systems, such as the disaster shelter database maintained by the LGED and the initiative now under development within the CEIP-I for the entire polder system, could be a good starting point for an asset management system of the BWDB and enhancement of mangrove mapping and management for Bangladesh Forest Department. The use of recent advances in technology, in particular remote sensing, should be incorporated into O&M as it can provide a low-cost solution for monitoring a large number of assets in space and time, and aid in the prioritization of in-depth inspections.

- Enhance the governance structure of structural assets with further streamlining and upscaling of community involvement and engagement. Project initiatives should be developed to ensure continuity after project lifetimes, with clearly defined roles and responsibilities, and funding sources for O&M for local communities.

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7.2. Recommendation 2: Embrace the uniqueness of the Bangladesh coast, recognize local knowledge, strengthen the application of state-of-the-art modeling tools and systems, and cultivate knowledge sharing

Key message: *In-depth knowledge of the coast and the interaction with the structural interventions is another foundation for coastal resilience. The unique landscape and dynamics of coastal Bangladesh requires a thorough understanding of how the present system functions and its inherent uncertainties in order to predict how future scenarios of the coastal environmental conditions might change the system as a whole and what that means in terms of the design of interventions. Continuous development of knowledge and the application of state-of-the-art tools and guidelines should be prioritized, including knowledge transfer of these developments.*

The coastal landscape of Bangladesh is predominantly shaped by the GBM river systems that drain an enormous amount of water and sediment from the Himalayan Mountain range into the Bay of Bengal, with tides and waves redistributing this sediment along the coast. The interactions between the sediment, fresh and saline water, and underlying geology of the area provide the building blocks for the unique delta landscape and its productive, diverse, and dynamic ecosystems that are host to an abundance of flora and fauna. For instance, while the western and central parts of the coastal zone are low-lying with numerous tidal channels and creeks, the southeast has steep topography with small rivers draining from the hills. Refer to Chapter 2 for an extensive overview of the coastal landscape and its characteristics.

Given the uniqueness of the Bangladesh coastal zone, local knowledge and research is essential for sustainable coastal zone management, which can also add to the knowledge base of delta dynamics globally. Understanding the key processes that shape the system dynamics is critical to the ability to predict changes in the system in the near and long-term future, especially in view of climate change. Tidal riverbank erosion is a practical example of why insights into coastal system behavior are a necessity for management purposes. This phenomenon results in the loss of valuable land and undermines the integrity of coastal structures such as embankments and drainage structures (see Chapter 3). The dynamic tidal riverbanks change as a result of tidal motion, waves, and seasonally varying river discharge and sediment supply. To date, however, the understanding of and predictive capability about this phenomenon is limited in Bangladesh and in practice, bank erosion needs are mainly based only on experts' judgement—the use of tools and models can provide complementary information to better guide planning. SLR, changes in cyclone intensity, and shifts in the fresh water and sediment supply from upstream play an important role in longer time scales and will add to the complexity of predicting system behavior in the future.

Bangladesh has successfully built up a knowledge base of the coastal system, resulting in more resilience for its communities. A good example is the development and implementation of community based EWS in Bangladesh (see Chapter 4). An integrated approach consisting of coastal embankments as a first line of defense, complemented by advanced cyclone forecasting, sufficient warning of the local communities, and a network of cyclone shelters and access roads along with a systematic mobilization of volunteers to conduct cyclone preparedness and awareness-raising campaigns, has resulted in a steep decrease in the number of casualties in the coastal zone over the past couple of decades. This would not have been possible without the development of data and modeling tools to better predict cyclone characteristics in advance and during landfall. These knowledge and modeling capabilities are also embedded in various research institutes and universities in Bangladesh. The successful application of knowledge to increase resilience should inspire the relevant stakeholders to further intensify investments in knowledge development. Three areas of attention are specifically highlighted based on the presented analytics.

First, systematic data collection, storage, and analysis of the natural environment, including monitoring for changes in the system, should be prioritized. Essential physical, chemical, and biological data to be collected are, among others, bathymetry, water levels, waves, currents, river discharge, salinity, temperature, sediment concentration, sediment grain size distribution, nutrients, and heavy metals. Remote sensing data is an additional powerful data source for understanding coastal systems. For example, recent research has demonstrated that large-scale analysis of bank movements from space is now feasible (Jarriel et al. 2020). The collection and analysis of satellite imagery can thus complement ground observations to better understand the spatial movement of riverbanks. Currently, such data sources are often collected as part of individual projects but are not collected in a systematic way. As outlined above, changes in the system often happen at multiple scales both spatially and temporally. A systematic and continuous system-wide survey and monitoring system will help detect trends and anomalies at the various spatial and temporal scales, which can complement modeling studies and help identify drivers of change.

Second, numerical models should be treated in a similar way as data collection, meaning that they should be continuously developed and applied in practice as part of the overall management of the system rather than on a project-specific basis only. In the past, a variety of numerical models have been developed for the coast of Bangladesh, often as part of large investment projects. For example, various one-dimensional models have been set up describing the distribution of water flows in the Bangladesh delta. The next step is to develop, maintain, and apply a structured hierarchy of numerical models to cover all spatial and temporal scales of the system, including regarding the hydrodynamic, sediment, morphological, and ecological behavior of the system. There are now innovative modeling techniques available to achieve a

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much higher spatial and temporal resolution, providing much more detail on the governing physical and ecological processes, resulting in a more accurate representation of reality. Both ground and remotely sensed observations are essential ingredients feeding into these numerical models in order to generate and update model schematizations and validate the model outputs.

Third, open data sharing platforms should be established to make knowledge widely available and allow consistent use of input parameters and scenarios across projects. Knowledge transfer and data sharing between agencies but also with the public are essential ingredients for successful cooperation within government and to help create awareness among and inform the general public. The data needed for coastal resilience interventions are multidimensional, with data variables covering the natural environment, local economy, and social-demographic characteristics. Although such data is often collected for specific projects, data sharing mechanisms are not always in place, or need extensive knowledge transfer. As such, collective data platforms, such as the Geospatial Data Sharing Platform (known as GeoDash),[27] are essential to ensure that the most up-to-date and accurate resources are used in projects. The inclusion of readable and clear metadata is key for reproducibility and for understanding the underlying model assumptions or data limitations associated with a dataset. Effective data sharing can free up resources and facilitate dialogue between stakeholders. Universities and research institutes are key stakeholders in this. Apart from data sharing and knowledge transfer, it is essential to maintain the consistency of certain key variables (such as the expected rate of SLR) and scenarios (such as future socioeconomic scenarios) across projects. In some cases, inconsistencies are present within different projects, which can result in regional discrepancies in terms of project outcomes. Therefore, it is important to create consistent baseline variables and future scenarios across projects. Within the CEIP-I's Long-Term Monitoring and Research Program, for instance, consistent climate change scenarios are prescribed for the different polders based on various model outcomes and assumptions.

Enhancing in-depth knowledge and embedding the use of state-of-the-art tools and scenarios into the planning and design of coastal interventions is paramount for Bangladesh. Specific recommendations are to:

- Expand and intensify coastal monitoring through more systematic collection, storage, and analysis of relevant ground observations and remote-sensing data. The data should be updated and maintained via a data sharing platform within the government and also with the wider public, with necessary protocols established.

- Develop and maintain a hierarchy of flow and sediment models with high resolution for the coastal zone to better predict changes in the system (such as storm surge levels, waves, bank erosion, large-scale erosion, and sedimentation patterns). These models should be coupled with observed data and continuously finetuned and adopted for practical applications to improve EWS, and the design and maintenance of interventions.

- Create a better knowledge sharing and training environment for young professionals in collaboration with universities. The data sharing and modeling initiatives can be the basis of this collaboration. This could be further stimulated by defining regular challenges for students around coastal topics and/or creating positions for students to join ongoing programs and bring in innovative ideas and applications of state-of-the-art knowledge.

The current Long-Term Monitoring and Research Program within the CEIP-I is an ideal catalyst for making progress in this field of knowledge development and numerical tools (see **Box 7.1**). This initiative has already collected a large amount of system data, generated a hierarchy of models, and provided recommendations on improving design guidelines. It is recommended that the relevant agencies (in this case the BWDB) take the results of this program forward to ensure that dedicated personnel within the organization can further develop and adopt this knowledge and the numerical tools for management applications. With the support of this knowledge and the associated tools, proactive planning of interventions, optimization of designs, and improved maintenance are within reach, resulting in more efficient use of available budgets.

Box 7.1: Progress within the CEIP-I Long-Term Monitoring and Research Program

The dynamic coast of Bangladesh is subject to a multitude of complex natural phenomena, human intervention, and climate change, most of which are not yet well understood. In addition, there is limited systematic monitoring of the coastal region, which is needed to generate data, information, and new knowledge to assess the effects of the multiple drivers on the coastal environment to guide future design, rehabilitation, and improvement of investment requirements.

To bridge this knowledge gap, the CEIP-I is supporting a comprehensive monitoring and morphological assessment of the Bangladesh Delta, known as the Long-Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics) Program. Through this initiative, the CEIP-I is developing a framework for polder design and an investment plan based on an improved understanding of, and new insights into, the large-scale dynamics of the delta. Comprehensive data collection and analysis in combination with state-of-the art numerical modeling (2D and 3D) are performed with regards to aspects such as bank erosion, tidal river management, and long-term and large-scale morphodynamic behavior of the delta. All results feed into the future planning and design of the polder system.

Moreover, the program's analytics have been designed to enrich the empirical evidence of multiple key coastal processes and issues. Notable among these are geomorphological attributes, the process of land subsidence, the impact of tectonic effects, erosion rates, SLR, changes in tidal dynamics, river cross-section changes, meander migration, shoreline changes, and the increase in salinity and its impacts. Key outputs of the study include macro, micro, and mesoscale modeling of the long-term processes in the coastal zone, finalization of approaches for rehabilitation of the polders, including their phasing and construction program, updated design parameters and specifications for planning and design works, review of approaches for the management of polders, and an investment plan for the entire coastal zone. The initiative is also undertaking activities for the capacity building of relevant professionals in the planning, design, and sustainable management of polders.

Source: CEIP-I project documents.

7.3. Recommendation 3: Apply risk as the guiding principle for adaptative delta management

Key message: *Given the changing climate and dynamic coastal processes of Bangladesh's coastal zone, ADM should be the cornerstone of any approach to achieving coastal resilience. ADM is about flexible decision-making in view of the uncertainties related to present and future risks. International experience shows that a risk management approach is well suited for informing decisions about public safety given large uncertainties. Adopting such a risk-based approach could help tie together strategic planning, design, and O&M, further improving the efficiency and effectiveness of coastal interventions in Bangladesh.*

Past disruptive catastrophic events such as Cyclones Bhola (1970), Gorky (1991), and Sidr (2007) have highlighted the vulnerability of the coast and its communities. These events have caused billions of dollars' worth of damage to assets and livelihoods and wiped out achieved development gains. Managing these risks is one of the cornerstones of ADM. Investments made over the past few decades to reduce risk in the coastal zone have clearly paid off. For example, Chapter 4 shows that investments in EWS and disaster preparedness have drastically reduced loss of life from cyclones, and an economic analysis of past projects on strengthening polder systems repeatedly showed a positive benefit-cost ratio, confirming that these investments pay off in terms of risk reduction. This fact aligns with the global observation that investments in climate-resilient infrastructure have a very solid economic justification (**Box 7.2**).

Despite the achievements in risk reduction in Bangladesh, the risk profile of the coastal zone is still high and will further deteriorate under a no-action scenario. The system-wide risk analysis of Chapter 3 shows that the current expected annual damage from cyclone-induced storm surges is still very significant at about US$300 million. From climate change alone, this risk will increase by 90 percent in the coming 50 years. Other coastal risks prevalent in the coastal zone are salinity intrusion, erosion, and waterlogging. The damage associated with these risks is more difficult to quantify since they are more slow-moving threats to the coastal zone. Overall, evidence clearly highlights the magnitude of the current risks and how these risks will continue to evolve in time and space as a result of ongoing climate change trends and socioeconomic developments. These insights are indispensable for the adaptation strategies of the Bangladesh coastal zone.

ADM is an "approach to deal with uncertainties in a transparent and sensible way to support decision making with regard to water policy, planning and infrastructural investments. It links current decision making to future choices" (Deltares 2014). It thus emphasizes a forward-looking approach of dealing with uncertainties in a flexible manner, with risk as the guiding principle. The potential of using risk as a basis for ADM has been further evaluated in Chapter 5. Risk management approaches have proven highly successful in other countries and industries in controlling hazard, vulnerability, and exposure in an integrated and continuous manner. Three key issues were identified when comparing international best practices to current risk management practices in Bangladesh, which form the basis of the recommendations below.

First, an integrated risk management framework should be developed for Bangladesh that would allow for continuously improving coastal resilience. Successful risk management is a cyclical process that involves strategic planning, design, and O&M. These activities are carried out by different entities. A risk management framework ties these activities together. The absence of an overarching scheme for directing and controlling organizations with respect to risk complicates the alignment of climate change and disaster risk management programs in Bangladesh and makes it more difficult to exploit synergies between multiple risk management projects (such as building disaster shelters, restoring embankments, combating erosion). A fuller understanding of the potential synergies between programs may lead to the use of scarce resources in more cost-effective ways. For instance, investments in shelters, EWS, coastal embankments, and mangrove afforestation all impact the risk of flooding in Bangladesh's coastal zone, albeit in different ways. Also, it would allow a more proactive approach to coastal resilience envisaged by the BDP 2100 and the Second Perspective Plan of Bangladesh 2021-2041, in which strategic investments are less post-disaster driven and more forward looking, making sure that development gains are not lost from inadequate O&M. Such a risk management framework includes clear roles and responsibilities for the different components of the risk management framework and the time dimensions of such a framework (such as for renewal of standards).

Second, uniform tolerable risk guidelines for supporting climate change and disaster risk management decisions should be developed and applied consistently across projects and industries. Tolerable risk levels are currently established on a case-by-case or project-by-project basis. The same applies to the choice of performance criteria for the design of climate change and disaster risk management solutions, such as the flood protection standards adopted for the design of coastal embankments. The inconsistent use of risk thresholds and design standards result in the inefficient use of resources and make it harder to evaluate which areas need additional investments as a result of climate change. Using a uniform set of tolerable risk guidelines throughout

Box 7.2: The Economic Case for Investments in Climate-Resilient Infrastructure

Multiple initiatives have demonstrated that investing in climate-resilient infrastructure will pay off. For instance, on the 2019 International Day for Disaster Risk Reduction (13 October 2019), UN Secretary António Guterres mentioned that "for every dollar invested in climate-resilient infrastructure, six dollars are saved." This statement is backed up by other recent reports stating similar numbers, such as the 2019 Global Commission on Adaptation's report *Adapt Now* claim that investment in resilient critical infrastructure has a benefit-cost ratio of 4:1 and can contribute to the Triple Dividend of Resilience (see Section 7.8 for further details) in action by avoiding losses and stimulating economic development, and if implemented well, can have social and environmental benefits (GCA 2019). Similarly, the 2019 *Lifelines* report by the World Bank showed that the extra cost of building resilience into infrastructure systems is about 3 percent of the overall investment needs and could unlock approximately US$4.2 trillion in economic benefits in developing countries over the lifetime of infrastructure investments (Hallegatte, Rentschler, and Rozenberg 2019).

the entire risk management process will ensure that the decisions and actions of the organizations involved in the different parts of the risk management cycle remain closely aligned. Moreover, in numerous countries and sectors worldwide, risk has proven to be a useful tool for establishing and communicating the urgency of life safety interventions. Clear tolerable risk guidelines can facilitate evaluations of investment opportunities and further improve the transparency of investment decisions.

Third, improving and updating technical guidelines for the design of coastal interventions is necessary in Bangladesh. For example, the current design guidelines were introduced in the 1980s, with new knowledge and best practices developed in the meantime in Bangladesh and abroad, for example, the probabilistic design of flood defense systems. Improved design standards should utilize the available morphological models and new data that is being collected in order to support the technical guidance of structural designs given the local environmental conditions. Also, as the current technical guidelines mainly focus on hard structures, there is a potential to develop guidelines for the design of complementary soft and hybrid solutions for the coastal zone in Bangladesh (for example, a combination of mangroves, embankments, and nourishments as identified in Chapter 6). Knowledge sharing across countries is essential for this, as many countries intend to develop such guidelines in line with international calls to embed natural and hybrid solutions in design (see Recommendation 4).

Given the potential benefits of implementing a risk management framework that is tailored to the challenges facing Bangladesh's coastal zone, specific recommendations are to:

- Develop a risk management framework for the coastal zone, including a clear set of roles, responsibilities, and time horizons per action. The framework should tie together planning, design, and O&M in a continuous and cyclical manner.

- Develop a set of tolerable risk guidelines for supporting risk-informed decision-making by the different entities that are involved in coastal zone management in Bangladesh. The BDP 2100 lists several general principles that could be used as the starting point for this endeavor.

- Mainstream a risk-based approach in the entire planning process of coastal interventions, taking present and future uncertainties into consideration. This approach should apply state-of-the-art techniques to quantify risk, including the use of robust decision-making tools and methods that account for present and future natural and socioeconomic uncertainties to ensure that selected interventions are effective under a wide range of scenarios.

- Update and refine technical guidelines for coastal interventions with state-of-the-art techniques, including extending the guidelines to new types of interventions (such as nature-based, hybrid, and soft solutions).


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7.4. Recommendation 4: Complement infrastructure interventions with nature-based solutions to enhance resilience and effectiveness

Key message: *Acknowledging that the coast is highly dynamic but also very rich in terms of natural resources and assets is essential. The natural environment provides a great opportunity to reduce risk while providing additional services to society. Smart hybrid combinations of traditional infrastructure with nature-based solutions like sediment solutions (such as nourishments) and mangrove restoration for protection against cyclones and erosion should be pursued in future programs. However, developing and monitoring pilot projects are key to learning from best practices and establishing guidelines for the implementation of such solutions in different parts of the coastal zone.*

Bangladesh's coastal zone has a dynamic and rich portfolio of natural assets. Despite their dynamic nature, coastal ecosystems have the potential to reduce risk to lives, livelihoods, and infrastructure. For instance, the tidal sedimentary systems with mangroves scattered across the coast provide natural buffers against hazard impacts such as cyclones. Traditionally, a range of grey infrastructure has been implemented to combat flooding and erosion. If designed well, these flood protection interventions with extensive bank and slope protections (such as revetments and breakwaters) perform well under extreme conditions, which for the highly vulnerable Bangladesh coastal zone is a necessity to protect lives and livelihoods, but these are often quite expensive. For example, 25 percent of the total budget of the recent CEIP-I of US$400 million is being spent on bank and slope protections alone. High costs are the result of, among others, the necessity to produce, transport, and place a large number of concrete blocks for these types of protection works. Grey infrastructure solutions are not always flexible or adaptable to changing boundary conditions (which hinder Recommendation 3 on ADM). For example, bank and slope protections are usually designed for a specific design wave load. If these loads increase, larger blocks will be necessary, with substantial associated costs. In at-risk settings, such as Bangladesh and other highly vulnerable coastal regions, grey infrastructure is essential, although there are opportunities to strengthen resilience by supplementing this infrastructure with softer approaches.

There is vast potential to use nature-based solutions, specifically, combinations of nature-based and grey infrastructure solutions or hybrid solutions (see also Chapter 6) in the Bangladesh coastal zone. Given the high level of risk in Bangladesh, nature-based solutions can effectively complement existing or new structural interventions. Sand nourishments and mangrove forests have the potential to reduce the acting forces on the riverbanks, thereby reducing the length of bank protection works needed, while also reducing the required level of embankment crest height and design overtopping volume. In addition, there is substantial evidence that natural infrastructure and combinations of natural and built infrastructure enhance coastal resilience by providing essential services (such as flood protection), while also providing important co-benefits (such as economic growth, fish habitat, carbon capture). Social forestry projects, for instance, provide important revenue streams for those involved in planting and maintenance. Moreover, sand nourishments may provide opportunities for economic growth via tourism, as nourishments provide space for allocating multiple functions along the coastline while sustaining the attractiveness of the waterfront (de Schipper et al. 2021). Although several projects have demonstrated the potential for incorporating nature-based solutions in design (see **Box 7.3**), their implementation is still in its infancy, and several challenges remain.

First, the benefits and costs of nature-based solutions should be quantified and the opportunities and barriers to scale up interventions identified and documented. As mentioned, complementary nature-based solutions can lower the investment needs of structural solutions. For instance, sand nourishments can often be constructed with locally available materials, as was shown in the case study of the Bogi area in Polder 35/1. As such, the necessary maintenance costs associated with the proposed solutions can also be reduced. However, before nature-based solutions can be widely adopted, the costs and benefits should be quantified, which are often more uncertain than conventional hard infrastructure solutions. Studies have shown that planting mangrove forests can have larger benefit-cost ratios than conventual infrastructure systems when it comes to risk reduction (Narayan et al. 2016). However, it is hard to say how universal this is and what the reliability of such interventions is under different extreme loads. For instance, it is unclear how well a mangrove forest could reduce wave heights during a cyclone if extreme winds wash away part of the mangrove forest. Detailed project evaluations to understand what works, and under which conditions, are needed to move to a widespread adoption of using nature in design. These best practices should also be incorporated into design guidelines (for example, the type of mangrove given local conditions, sediment composition for nourishments, and dredging strategy). The same holds true for the various co-benefits of hybrid solutions, although these are often more difficult to quantify.

Second, establishing monitoring systems to evaluate the performance of nature-based designs is imperative. A significant additional benefit of nature-based or hybrid solutions is their flexibility and/or adaptability to changing conditions along the coast. Nature-based solutions are less intrusive and can be adapted to changes caused by morphological behavior and/or climate change. However, to do this, regular monitoring is needed. For example, at Himchori beach (Chapter 6), large sand nourishments are proposed to counteract coastal erosion. For this case study, it is not entirely clear how the nourishments will develop in time as a result of continued coastal transport that may block the opening of streams beside the beach. If needed, additional dredging or nourishments can be performed to account for changes in the predicted behavior of the solution and prevent the river mouths from closing. Moreover, the potential for mangrove reforestation along the coastline (Chapter 6) is critically dependent on the erosion rates, SLR, and salinity levels, which are all uncertain. Hence, the implementation of nature-based and hybrid solutions should go hand in hand with the establishment of monitoring systems to evaluate the performance of the interventions over the project lifetime.

Third, suitability maps should be developed that identify the potential for incorporating nature-based solutions into the design. To understand the scale and potential for nature-based solutions, and identify places with the largest benefits, mapping exercises with suitability indicators should be established. For instance, in Chapter 6, the suitability of mangrove reforestation was identified based on the rates of erosion, the expected SLR, and the existence of natural mangrove forests for natural colonization. Thus, places where the mangrove forest has been degraded over the years could be reforested more efficiently such that ecosystems could be restored. Such suitability criteria can be combined with other indicators, such as, among others, the potential for risk reduction, proximity to settlements, proximity to coastal embankments, biodiversity indices, and salinity levels. Similarly, such suitability proxies can be developed for other hybrid solutions, such as beach restoration. In this way, the areas with the highest potential can be prioritized, and co-benefits maximized. Large-scale feasibility maps also help in deriving a long-term strategy for the

Box 7.3: Putting Nature-Based Solutions into Practice as Part of the CEIP-I

The CEIP-I incorporates a nature-based solution initiative through the afforestation component, embedding social forestry as part of an overall integrated protection program. In the CEIP-I, afforestation provides an additional layer of protection to embankments and the livelihoods of communities, as it potentially reduces the impact of waves, tidal flooding, and storm surges, and creates income-generating opportunities. Plantations of selected species, including mangrove and other saline tolerant species, are being undertaken to play the important role of a protective belt at the tidal inundation zone on the river side of the embankment. The species are carefully selected considering the location, the level of protection provided, and co-benefits to the local population, including a range of commercial wood, fruit, and other shallow rooting tree species. The afforestation component is embedded within a social forestry approach by engaging local communities to ensure benefit sharing and achieve social, environmental, and economic sustainability. The component includes efforts to increase community awareness of the protective and productive functions of trees and build the capacity of local institutions and communities in secondary maintenance schemes of the foreshore and embankment afforestation, and protection of the embankment against toe erosion. Key lessons from past embankment afforestation projects have been taken into account in the implementation of this component. This includes lessons in participatory planning, selection of forest types and species, selection of beneficiaries, post-planting O&M, plantation protection, harvesting of wood and non-wood forest products, and benefit sharing.

Source: CEIP-I project documents.

scaling up of nature-based solutions, as they prevent initiatives happening in isolation, and help to set suitable targets for widespread adoption of nature-based solutions.

Embracing nature-based solutions in the design of new interventions along the coastal zone is therefore recommended to further increase coastal resilience while also providing opportunities for economic growth and other social and environmental benefits. Specific recommendations about nature-based solutions are to:

- Set up and implement pilot projects with nature-based and hybrid solutions. Pilots will support knowledge development and help to mainstream these solutions. Chapter 6 provides several conceptual solutions which could be an excellent starting point for potential pilots (Cox's Bazar and Kuakata Sea Beach).

- Develop knowledge, tools, and guidelines through these pilot projects about the implementation of nature-based and hybrid solutions in Bangladesh based on national and international experiences. This will aid in understanding where these solutions have been successfully implemented and identifying factors that determined their effectiveness, which can help in setting guidelines for design.

- Establish a monitoring framework to track the performance and evolution of hybrid solutions over space and time. This not only allows for ongoing knowledge improvement on the functioning of hybrid solutions, but it also provides flexibility to adapt the interventions over time if required.

- Create coastal-zone-wide suitability maps for various nature-based solutions based on a number of proxy indicators. Such suitability maps can then be used for the prioritization of initiatives and to help in creating a shared vision and suitable targets for the implementation of nature-based solutions over time.

7.5. Recommendation 5: Incorporate risk-sensitive land-use planning to guide appropriate activities based on integrated coastal zone management practices

Key message: *Changes in land use and socioeconomic characteristics will shape the inherent composition of the coastal zone in terms of what is at risk, where, and how. Given the longevity of investment horizons, and the often complex interactions between society and the natural and human-made assets, risk-sensitive land-use planning should be at the core of coastal zoning policies. Risk-sensitive land-use planning can take place on different scales and should be based on various plausible land-use and socioeconomic scenarios, contingent on the changing environmental conditions. Such scenarios not only help in testing the robustness of interventions but can also inform expected migration patterns and policies to cope with this, as well as zoning policies for the spatial allocation of present and future economic activity.*

Changes in the social and economic demographics of the coastal zone will determine what is at risk, and where and who is impacted, which is often a larger uncertainty than uncertainties around changes in hazards as a result of climate change. Over the last couple of decades, major land-use transformations have taken place, such as the expansion of shrimp farming, the ongoing degradation of natural ecosystems, and the growth of urban areas and infrastructure. Moreover, socioeconomic changes have transpired, such as the decline in poverty, increasing employment in the manufacturing and service sectors, changing migration patterns, more varied housing types, and more options in access to finance. All these developments shape the spatial location of economic activities, the interaction of society with natural and human-made assets, and the risk profile of those inhabiting the coastal zone.

Since most investments have long-term horizons, it cannot be assumed that the current occupation and household characteristics will stay constant over that time frame, especially in rapidly developing areas such as coastal Bangladesh. Far too often, changes in the vulnerability and exposure of people and assets are not fully explored, and the associated effectiveness of interventions might be over or underestimated. In the BDP 2100, the emphasis is on an integrated

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and multisectoral approach to natural resource management. Through four plausible scenarios, investment strategies can be evaluated in terms of their performance and suitability. Although these scenarios are a step in the right direction when it comes to the exploration of future scenarios and the ability to evaluate the robustness of interventions, they are only indicative and considered the "end points" of the many plausible futures. Moreover, although the BDP 2100 envisions an integrated coastal zone planning framework, which refines the rather land-centric view of the 2005 CZP, institutional limitations in coastal planning should be addressed first before such realizations can be made in practice. In particular, a clear land-use planning policy is needed, which addresses questions like: (1) Who lives where given the expected change in local environmental conditions? (2) Where will economic activity take place? and (3) What do different futures mean for migration patterns in the coastal zone? To accommodate this, there are three areas to take into consideration.

First, scenarios of future socioeconomic development should be considered more explicitly in design. Many complex feedback and interactions exist between adaptation interventions and socioeconomic development. In fact, many adaptation interventions, such as rural accessibility or financial inclusion, have implications for development, whether or not the climate-related risk will change, and are heavily influenced by the development pathway and transition of local communities (Jafino, Hallegatte, and Rozenberg 2021). The transformation of local economies, for instance, depends on how they benefit from local infrastructure (such as drainage systems) and natural resources (such as fisheries) and hence, the interventions that improve them. Moreover, interventions in themselves can lock in a certain development pattern. For instance, the hybrid coastal protection schemes (for Kuakata Sea Beach and Kolatoli Beach, see Chapter 6) could promote tourism and accelerate the movement of people from traditional employment into the service sector. To fully capture these uncertainties, plausible scenarios of land-use change (for


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example, transition out of agriculture, rural-urban migration) and socioeconomic characteristics (such as housing types, financial access) should be developed. These scenarios can then be used to compare alternative designs in terms of their feasibility and effectiveness, and better assess how portfolios of hard and soft interventions should be balanced. In the end, interventions should be robust under a large variety of scenarios in order to perform well, especially if planning horizons are long. There are many tools available today to perform such a robustness analysis that have clearly demonstrated the added value of performing such analysis for large investment decisions with long time spans (Marchau et al 2019). The four development scenarios in the BDP 2100 are a good starting point for this but should be tailored to the local scale and combined with narratives of how households will further develop as a result of changes in the economy and the natural environment, as done in other projects in Bangladesh (Lázár et al. 2020).

Second, although migration is often seen as a negative outcome, zero migration should not be seen as a desirable policy objective. When people are unable to cope or adapt, migration (either temporal or permanent) is a suitable adaptive strategy (Ayeb-Karlsson et al. 2016). In the rural areas of coastal Bangladesh, 30 percent of households already have migrant members, of which half of them have left the coastal zone (Lázár et al. 2020). Hence, migration is prevalent and arises from the interaction of social, economic, and environmental push and pull factors. Climate change may cause some areas to become uninhabitable, making adapting livelihoods in such areas undesirable, as it may prevent some workers from finding more secure and higher-wage jobs elsewhere. Therefore, depending on the local context and the expected changes in the local environmental setting, a decision should be made whether to support migration or promote livelihood transformation. For instance, for poor households near to the Sundarbans, it was found that improving rural accessibility to local markets (as some isolated communities travel 14 hours


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to reach market centers) combined with microfinance could help enhance resilience, as it would allow them to sell their products at markets or pursue eco-friendly livelihoods (Dasgupta et al. 2021). Moreover, as the spatial location of economic activity is expected to change, for instance, the partial transition out of agriculture into the service sector and manufacturing and the expected growth of tourism, migration is inevitable. Some studies predict a net in-migration of the coastal zone, even under scenarios of SLR-induced flooding (Bell et al. 2021), emphasizing that coastal cities need to prepare for a potential influx of migrant workers as economic amenities improve. Hence, both sending and receiving areas can help influence migration by protecting coastlines, but also by providing income credits and housing subsidies for inevitable migration. Migrant-friendly cities (some of which are in the coastal zone) could potentially be established through the development of smaller peripheral towns into migrant-friendly and climate-resilient cities (Khan et al. 2021). These envisioned migrant-friendly cities could have potential to absorb some of the climate migration but would require supportive mechanisms to provide livelihoods and skills development opportunities, low-cost housing, and resilient infrastructure services to new settlers, as well as the legal, policy, and institutional capacities to promote internal migration (Khan et al. 2021).

Third, land-use zoning policies should be developed that are coherent with the aforementioned socioeconomic scenarios and integrated into the proposed risk management framework. Land-use planning helps with the allocation of economic activities and can guide the spatial direction of development. If combined with an integrated risk management framework, considerable cost savings could be achieved, as different activities need different types of interventions for adaptation and different levels of optimum protection standards. For example, the four polder configurations highlighted in Chapter 5 underline that effective land-use planning in polder areas can effectively save costs, as locations with higher economic value will require higher protection standards, whereas areas with lower values of economic activity require lower protection standards. For instance, areas that will continue to experience an expansion of shrimp farming will need alternative adaptation options compared to regions with a continuous expansion of agricultural production. Further, land-use planning can help to avoid conflict and tensions between households engaged in different land-use practices, as is prevalent in some polder systems. Similarly, zoning policies should be established that cover larger-scale land-use allocation, which can help allocate resources when decisions have to be made about which areas to protect and which areas to retreat from if climate


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change makes it too costly to protect the entire populated zone. Enforcement of such zoning policies would also be required and would need to be backed by the right institutions. Moreover, land-use zoning policies can help guide the spatial development of economic activities and urban development. The GoB has outlined plans to invest in several SEZs in the coastal zone. These SEZs are major drivers of employment and local economic growth, as they often go hand in hand with infrastructure development, the growth of settlements, and indirect employment opportunities (**Box 7.4**). Making sure these developments take place within a coherent coastal zoning framework, instead of happening in silos, is important to understanding how such developments need to be accounted for in large-scale investment decisions, and to understanding the spatial drivers of economic change.

To facilitate better land-use planning, specific recommendations are to:

- Include socioeconomic development pathways more explicitly in the design process of coastal resilience interventions to identify complex feedback between development and the effectiveness of interventions. In the end, designs should be robust against uncertainties associated with both climate change (such as the amount of SLR) and socioeconomic development (such as access to finance, improved housing types), with the latter often having larger inherent uncertainties.

- Accommodate internal migration by the development of policies and mechanisms that remove the barriers of out-migration from high-risk areas. The envisioned migrant-friendly cities in the coastal zone, which could potentially absorb half a million migrants each, need to be integrated into the wider land-use planning of the coastal zone so as not to counteract existing development plans, and hence, be able to prioritize and allocate resilience investments accordingly.

- Establish coastal-wide zoning policies on different spatial scales. Large-scale zoning policies can help identify areas that are potentially becoming uninhabitable and areas that are suitable for promoting economic growth. On a polder level, land-use planning can help guide investment needs if aligned with the development of an integrated risk management framework that establishes optimum protection levels for different areas within a polder.

Box 7.4: Special Economic Zones and Improved Logistics Services

SEZs and export processing zones have been proposed as a viable solution to promote economic growth, create jobs, and support the industrial transformation of the country given the increase in agricultural productivity. After the Bangladesh Economic Zones Act was passed in 2010, the Bangladesh Economic Zones Authority was established to oversee the establishment of economic zones in the country. With support from the World Bank, through the Private Sector Development Support Project, US$3.9 billion in direct private investment has been generated in the economic zones across 1,500 acres of land, which helped create jobs for 41,000 people and 21,000 trainees (World Bank 2021). However, SEZs rely on resilient infrastructure as an enabling factor for growth. Hence, alongside the creation of land, the project created roads, embankments, bridges, electricity substations, and water reservoirs to support industrial activity. The current and proposed SEZ zones are strategic assets for the future economic development of the coastal zone. The SEZs, near economic hubs close to rivers and seaports, can employ millions of workers, including those that have to migrate away from at-risk coastal areas (Khan et al. 2021).

Apart from the SEZs, improved transport connectivity and logistics services are key to unlocking the economic growth potential of the coastal zone. At the moment, both the logistics performance within the country and between Bangladesh and neighboring countries is low. Congestion on roads and highways, and the inadequate capacity of the main economic transport corridor between Dhaka and Chattogram has led to poor reliability of services, resulting in high transport costs and the need for inventories. Analysis by the World Bank showed that improving logistics services could increase exports by 19 percent and generate employment opportunities across the country (Herrera Dappe et al. 2019). On top of that, another study showed that removing existing trade barriers between India and Bangladesh could increase income in Bangladesh by 16.6 percent, with higher overall benefits in the logistic hubs of Chattogram (Herrera Dappe and Kunaka 2021)

7.6. Recommendation 6: Support inclusive community participation, local institutions, and livelihoods adaptation for sustainable resilience

Key message: *Natural hazards and climate change impacts can directly alter the habitability and productivity of coastal areas. Strengthening the adaptive capacity of coastal livelihoods ensures that coastal inhabitants have the ability and means to make a living under the various shocks and stressors they face. However, before such efforts can be scaled up and mainstreamed into national adaptation plans, a systematic framework should be developed that can track the development of adaptation efforts in communities and investigate drivers of and barriers to success. On top of that, local institutions with a diverse representation of social groups, upgraded capacity, sufficient resources, and clear roles and responsibilities should be established or strengthened to make sure scaling efforts are sustainable.*

Communities in the coastal zone of Bangladesh are at the forefront of coastal hazard and climate-related impacts, particularly the low-income groups within these communities. The impact of natural hazards can influence human development by destabilizing the livelihoods of coastal communities, in particular for those livelihoods that are critically dependent on the natural environment (such as farming, fisheries, forestry). Strengthening the adaptive capacity of coastal livelihoods ensures that coastal inhabitants have the capabilities and assets (physical assets, rights) to make a living under the various shocks and stressors they face. Community livelihoods adaptation is at the heart of this, which is defined as the adjustment of livelihoods activities to mitigate harm or exploit benefits from changing conditions (Kulsum et al. 2021). Livelihoods can be improved on an individual level (diversification of income sources), the community level (basic infrastructure, utilities, healthcare, digital solutions), and the regional level (improved market access, polder construction). In order to design sustainable solutions, no matter the scale, interventions should be aligned with the needs and aspirations of local communities, and communities should be actively involved throughout the design process (Mfitumukiza et al. 2020). It has been recognized that local communities have the skills, local knowledge, experience, and networks to self-organize and undertake actions to increase their resilience and reduce their vulnerability to multiple coastal and climate risks (Forsyth 2013). Moreover, local involvement in the design, implementation, and O&M of large-scale interventions have the potential to make such interventions more sustainable and in line with local needs.

Bangladesh is an initiator globally with respect to bottom-up adaptation planning taking place through locally-led coordination, mobilization, and learning (Mfitumukiza et al. 2020). Key to the success of adaptation efforts is the involvement of local communities in the planning, implementation, and monitoring process (see **Box 7.5**). In particular, engagement with poorer and more vulnerable people in the community is essential to identifying the challenges posed by climate-related risks and suitable responses (Forsyth 2013). Such participatory approaches also help in understanding the needs and aspirations of these groups. Bangladesh is actively trying to scale up its best practices and lessons learned from local adaptation plans into its NAPAs and national long-term sustainable development plans (such as the Draft Mujib Climate Prosperity Plan). For instance, within the Draft Mujib Climate Prosperity Plan, the GoB has outlined its ambition to mainstream locally-led adaptation plans into national adaptation planning by establishing "Locally-Led Adaptation Hubs" throughout the coastal zone (by 2030 all vulnerable areas will be covered) that will act as the focal points for projects and serve as the venue for discussions and consultations. Despite the successful initiatives, a number of challenges have been identified that have to be overcome to help scale up and accelerate community livelihoods adaptation.

First, community involvement in design and implementation should be mandated in projects. The foundation of community livelihoods adaptation efforts is the utilization of local knowledge and aligning the project design with the aspirations of social groups within the community. There are a variety of factors that can prevent the most marginalized from successfully adapting, such as unequal power structures, unjust market incentives, top-down planning that clashes with local realities, insecure land tenure, or the incorrect interpretation of local norms and values (Mfitumukiza et al. 2020). Hence, identifying and considering these varied factors can help improve the inclusivity, uptake, and sustainability of these solutions, while also creating a sense of ownership by

Box 7.5: Examples of Successful Community-Led Bottom-Up Adaptation Projects

Two examples of successful community-led bottom-up adaptation projects are the Community Climate Change Project and the Char Development and Resettlement Project (CDSP). The Community Climate Change Project, a project initiated by the GoB and supported by the World Bank and the Bangladesh Climate Change Resilience Fund, a multi-donor trust fund, aimed to enhance the capacity of selected communities to increase their resilience to the impacts of climate change, including implementing community-driven climate change adaptation projects in the saline-prone areas of the coastal zone. For instance, in highly saline zones, where conventional crops could not be grown successfully, mud crab farming was introduced, which is tolerant of high salinity levels and for which there is growing demand on international markets. In addition, rainwater harvesting, and small-scale desalination plants were constructed to provide reliable water sources to the local communities. Capacity building was performed throughout to raise the awareness of local communities about the climate risks that they face and ways to better manage adaptation activities.

CDSP is a multiagency project led by the BWDB and has the Ministry of Land, the LGED, the Department of Agricultural Extension, the Forest Department, and the Department of Public Health Engineering as implementing partners, The grant support from the Government of the Netherlands and the contribution from the GoB financed the first three phases of the CDSP. In the fourth phase, the United Nations International Fund for Agriculture Development also provided credit support to the GoB (see CDSP, n. d. for an overview of the different phases).

Starting from 1994, the CDSP strived to improve the economic situation for people living on newly accreted chars in coastal Bangladesh, which are often vulnerable and exposed to flooding and other coastal hazards. Participation of local communities and a bottom-up approach was a core element of the CDSP's design. The CDSP effectively managed water resources to protect the land from tidal and storm surges, improved drainage, and enhanced accretion. These reduced crop damage and improved farming practices, which led to enriched cropping density. Upgraded road communication reduced the cost of transporting agricultural products. Tubewell water and hygienic latrines are now easily accessible to the community. Key to the project's design is that it established multiple gender-balanced Field Level Institutions (FLIs) to ensure community engagement and adaptation in all stages of the project cycle. These are locally-led community-based organizations consisting of representatives of the settlers in the chars. The FLIs make it possible for community members to participate in the planning, implementation, monitoring, evaluation, and sustainability of the project activities through O&M. The FLIs ensure that they address the local needs and interests in planning, execution, and maintenance, which stimulates a sense of ownership of the project.

the community. Within the CDSP, gender equality in public participation was emphasized. Most of the FLIs consist exclusively or predominantly of women to make sure solutions are acceptable to the wider community and tackle multiple gender barriers. For instance, care was taken that women-headed households, which often have insecure land rights, get possession of land and the associated ownership rights. Within the CEIP-I, extensive community involvement through stakeholder consultations helped identify the needs and aspirations of polder inhabitants. For instance, in many polders, communities expressed that the coastal embankments brought a sense of permanence to the community, with a recognition that the embankments are their lifeline with the development perspective of the communities centered around them (Rahman et al. 2021). The same holds for the road construction on top of the embankments that are perceived as the precondition to development, as they facilitate connectivity with cities (Rahman et al. 2021). These two examples illustrate that public participation and the involvement of various social groups early on in, and throughout, the process is essential to empowering local communities and ensuring gender equality. Such mandates for community involvement and incorporation of gender requirements, although through various degrees of intensity, can help stimulate community-led development and promote inclusive practices.

Second, communities should be involved in the O&M of livelihoods adaptation solutions to enable the sustainability of project outcomes. Past projects have demonstrated that the sustainability of interventions over time is determined by the transfer of roles and responsibilities for O&M from the NGO or other development agency to the local community. For instance, under the Blue Gold Program (see Chapter 4), the community-led agricultural WMOs were scaled up from a pilot study to a total of 71 schemes. Key to this scaling up was the willingness of local communities to co-finance the initiative, of local farmers to take on the responsibility of improving agricultural production management and


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teaching other farmers, and of the local WMO to take on the role of managing conflict and the construction of small-scale infrastructure. This ensured that the adaptation initiative was fully operational without continuous involvement of the organization that provided the initial intervention (referred to as "hands-off scaling"). Hence, strengthening local institutions by building capacity, providing resources and skills, and specifying the roles and responsibilities for scaling up the initiative is essential. To make the envisioned Locally-Led Adaptation Hubs work, it is imperative that the right type of mechanisms are put in place to facilitate this transition and to make sure that continuous learning is embedded within the planning and implementation process (Reid and Huq 2014).

Third, tracking the success of livelihood adaptation efforts by evaluating the reduction of vulnerability over time is key to learning from best practices and channeling funds to those areas that are lagging behind in their vulnerability reduction. In most NGO-funded adaptation projects, there are project-specific outcomes and evaluation criteria, which makes it hard to compare outcomes across projects and generate generalized insights given the large variation in community characteristics. For instance, a study that compared community-level resilience indicators across communities in nine countries (including Bangladesh) found that communities could be clustered according to some guiding socioeconomic characteristics that predict their level of community resilience (Laurien et al. 2020). Establishing such an indicator framework using mixed-method solutions (such as surveys, discussion groups, secondary data) that can be regularly updated could create a typology of coastal resilience, which could help target suitable community-level adaptation options. This not only allows tracking of the progress of adaptation over time, but also helps with exploring the enabling factors for successful adaptation. A coordinated effort is required among NGOs, development agencies, and local and national governments to ensure consistency of implementation.

Bangladesh has been successful in designing and implementing locally-led adaptation interventions and has the ambition to mainstream this into national policies. However, before such ambitions can be achieved, a number of necessary steps need to be taken to reach its full potential. Specific recommendations are to:

- Establish mechanisms through which various social groups are included in the design, implementation, monitoring, and maintenance of interventions to create acceptable, inclusive, gender-just, and equitable interventions, and ensure that the development aspirations of all members of the community are achieved. Past projects have illustrated that emphasis on such wider participation results in more sustainable solutions.

- Build a knowledge base of good practices for scaling community-based adaptation measures, resulting in hands-off scaling that relies on the self-organization of communities. Experience has shown that setting up local institutions with sufficient capacity, resources, and clear roles and responsibilities is necessary to achieve this. Community participation throughout the process is key to enabling this.

- Set up a monitoring framework that allows the tracking of adaptation over time and the allocation of funds to those communities that are outperforming or those that need additional support. Suitable indicators to track progress, which can be generalized across areas and are easy to measure, should be identified. These indicators can be aligned with other initiatives, such as the SDG indicators, and should be complemented with data on the communities' social, economic, and ecological characteristics to investigate the barriers and enabling factors for successful adaptation.


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7.7. Recommendation 7: Establish an integrated framework of performance criteria of interventions that goes beyond risk reduction and includes growth, wellbeing, and sustainable development at its core

Key message: *Coastal resilience efforts take place in and around coastal communities and are often aligned with ongoing development efforts. Therefore, it is important to ensure that development objectives are well integrated into these efforts to reap the large gains that can be made to adapt to a changing climate while achieving sustainable development goals. Alternative policy evaluation frameworks should be developed that explicitly take development objectives into consideration alongside wider planning efforts to align different program objectives across sectors in order to benefit from positive cross-sectoral spillovers.*

Development and DRR are intrinsically linked to one another in the coastal zone. The natural and engineered assets in the coastal region are enablers of economic growth, as most households derive income from the services that these assets deliver (such as agriculture, fisheries, aquaculture, tourism). On the one hand, the interdependency of assets and development means that risk from natural hazards can directly impede development efforts. For instance, Cyclone Aila (2009) increased unemployment from 11 percent to 60 percent in surveyed coastal communities in the southwest (Akter and Mallick 2013). Moreover, faced with chronic risk, households may save or invest less, preventing them from accumulating wealth, or they may make the decision to migrate away from risk-prone areas. On the other hand, development influences DRR, as the accumulation of assets, transition of livelihoods, and land-use changes all affect the risk profile of households.

Traditional tools to evaluate the costs and benefits of risk reduction measures are not always capable of capturing the development gains and the wider wellbeing implications of those households that benefit from interventions. Ignoring the wider wellbeing impacts of interventions might mean that the prioritization of investments is not targeted to those that need it or are misaligned with other development objectives (such as poverty reduction). Moreover, as mentioned


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before, DRR efforts, and nature-based and hybrid interventions (for example, mangrove restoration) have wider co-benefits for local communities and other sectors (as discussed in Chapter 6). These co-benefits need to be identified early in the design process to maximize their potential and build capacity and complementary interventions to fully utilize them (for example, designing in community involvement in mangrove restoration and conservation). Three areas have been identified that serve as focal points for the prioritization and design of future interventions.

First, the prioritization of interventions, such as the new embankment upgrades under a next generation of coastal resilience investments should include a wider set of evaluation criteria compared to the narrow framing of benefits in terms of risk reduction only. A growing body of work has indeed shown that the traditional evaluation criteria, which express risk reduction in terms of the prevented damage to physical assets, are inherently biased towards richer households as they own by definition more assets (Hallegatte, Bangalore, and Vogt-schilb 2016; Markhvida et al. 2020; Verschuur et al. 2020). On the contrary, low-income households often have limited capacity to cope with the adverse effects of shocks, and hence take longer to recover. For instance, multiple studies in Bangladesh have illustrated that the poor are relatively more exposed to natural hazards and lose a larger percentage of their income or assets as a result of hazard impacts (Hallegatte et al. 2020). Therefore, bringing granularity into the risk management framework, which allows for the estimation of risk for different socioeconomic groups (by for example, income types), and developing alterative risk metrics that better capture welfare impacts can help identify where investments can have the highest development gain.

Second, the widening of the evaluation framework should be supported by empirical evidence on who is benefiting from such interventions, through which mechanisms, and whether complementary interventions are needed. For instance, increasing the elevation of the embankments, thereby reducing the frequency of flood impacts, can help farmers to start investing in productive assets (such as fertilizer, improved seeds) in order to boost agricultural income. Complementary measures, such as improving accessibility through improvements to the road network on top of the embankments can further reduce the transportation costs to sell products at local markets. Although evidence exists that past interventions have significantly boosted agricultural production and income, and roads have increased accessibility to markets, such wider economic benefits are often not included in cost-benefit analyses. To explore who might benefit from interventions and to target specific socioeconomic groups, detailed information on the location and characteristics of households is needed, which is often not available or if available, is not regularly updated. Innovations such as remote sensing to map settlements and downscaling of aggregated household survey data are a good starting point for identifying potential beneficiaries of interventions. Moreover, it allows for the evaluation of whether and how past interventions have had a positive effect on targeted communities. Building up the knowledge base on what works, and under which conditions, is essential to avoiding maladaptation (that is, the potential for adaptation measures to cause further inequalities) and identifying complementary measures for success (see **Box 7.6**). This will help unlock the potential for the Triple Dividend of Resilience (see Section 7.8 for further details).

Third, a framework to evaluate co-benefits and trade-offs between different development objectives should be established in order to identify the most suitable interventions and to optimize budget allocation. Bangladesh is considered a frontrunner in achieving the SDGs. Despite this, the impacts of climate change have the potential to slow down progress. Recent work has illustrated that climate change adaptation can benefit multiple SDGs simultaneously if such co-benefits are identified in the early stages of design (Fuldauer et al. 2021). However, planning for the SDGs often happens in silos, making for misaligned planning and ineffective budget spending. Given the major tasks at hand in adapting coastal Bangladesh to climate change and achieving the sustainable development agenda, any targeted action to align adaptation spending with the SDGs will pay off. Doing this should start by identifying how different adaptation measures are contributing to the various SDGs, and whether such interventions can partly substitute for investment made in the interrelated sectors. For instance, mangrove restoration can reduce wave impact and coastal erosion, but also promote the diversification of income streams (by providing habitat for flora and fauna and providing non-

Box 7.6: Example of Complementary Measures to Make an Intervention Work

A good example of the use of complementary measures is the recent upgrades of the multipurpose disaster shelters that have added complementary inclusive features to their design, such as a place for livestock, separates spaces for women and nursing mothers, sanitary facilities, provision of rainwater harvesting, solar panels, and improved accessibility, such as the provision of ramps, to try to avoid the possibility that those already more vulnerable to disaster impact will decide not to evacuate. Moreover, the construction and renovation of cyclone shelters is combined with the construction of rural access and evacuation roads to reduce the travel time to reach a shelter. These cyclone shelters are also a good example of positive cross-sectoral spillovers because of their multipurpose uses. Most of the shelters are used as schools and community centers throughout the year, thereby contributing positively to the development of local communities

timber forest products) and the capture of carbon, which can reduce additional investments needed in other sectors. Such a universal cross-sectoral framework thus helps to allocate budgets across sectors in order to maximize the overall gain.

Bangladesh has made significant steps in achieving coastal resilience and promoting sustainable development. Given the interdependency between coastal resilience and development, and the fact that climate change has the potential to slow down progress, development objectives should be more tightly coupled to coastal resilience efforts. Specific recommendations are to:

- Develop a wider evaluation framework that can capture not only the effectiveness of interventions in terms of risk reduction but also the broader wellbeing implications of coastal hazard impacts and climate change. In this way, the prioritization of interventions is targeted to those that really need it.
- Advance the knowledge base and approach to identifying beneficiaries of adaptation interventions and their socioeconomic characteristics. Innovative data solutions, such as high-resolution population mapping, can support this development by providing quantitative proxies for how various socioeconomic groups can benefit from interventions.
- Better align coastal resilience efforts with cross-sectoral planning to achieve the SDGs. Given the large interdependencies between the two and, hence, the cross-sectoral gains that can be made from improved resilience, the potential for positive spillovers should be identified early on in the design and planning process to align objectives of various stakeholders, optimize budget allocation, and discuss trade-offs. To do this, a framework should be developed that first maps all the interactions between the different SDGs, which can be combined with the current and future plans of different sectors (such as water, energy, forestry).


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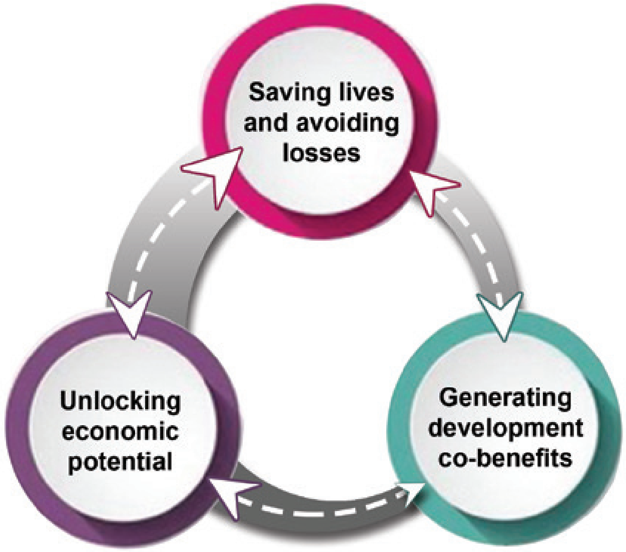
7.8. Coastal Resilience will Support Delta Prosperity

The evidence presented in this report makes it clear that Bangladesh is at a crossroads. The do-nothing scenario results in increasing risks to coastal communities that exceed the coping capacity of those exposed. However, with concerted action, many opportunities lie ahead; the review and corresponding recommendations clearly indicate that investing in coastal resilience will bring multiple benefits in terms of avoided losses, wider economic benefits, and social and environmental benefits, that is, a triple dividend.

The way forward for Bangladesh is to encompass the fundamentals of the Triple Dividend of Resilience concept (Tanner et al. 2015) in its development plans and policies, which will enable a proactive and informed approach to maximize the co-benefits of the coastal resilience process (**Figure 7.1**). The first dividend is the basic rationale and common motivation for DRR investments—to save lives, reduce losses, and promote effective recovery from disasters. While it is the most obvious of the benefits from coastal resilience investments, it is not easy to measure given the unpredictability of the dynamics of any disaster event and other factors that influence both its impact and successful recovery.

Figure 7.1: The Triple Dividend of Resilience



Source: Tanner et al. 2015.

The second dividend is the unlocking of the short- and long-term economic potential of disaster-prone regions by providing a higher sense of safety and security. There is strong evidence that the mere possibility of a future disaster has a real impact on present-day decisions and economic growth. The risk of extreme weather events and disasters looms as an ever-present background risk. As a consequence, risk-averse households and private firms avoid long-term investments in productive assets, entrepreneurship is restricted, and planning horizons are shortened, leading to lost development opportunities. Coastal resilience measures that reduce this background risk can have immediate and significant economic benefits to households, the private sector and more broadly, at the macroeconomic level. For instance, there is evidence that reduced background risk and effective risk management allow poor households to build up savings, invest in productive assets, and improve their livelihoods. More generally, increased resilience enables forward-looking planning, long-term capital investments, and entrepreneurship—even if disasters do not occur for a long time.

The third dividend is the generation of significant development co-benefits by pursuing the path of coastal resilience. Most investments in coastal resilience serve multiple purposes and are not solely designed to mitigate disaster impacts. Strengthened embankments can act as walkways, leisure areas, or roads; strengthened disaster EWS often also strengthen weather forecasting capacity, which can be used by farmers to know when to plant and harvest; and multipurpose cyclone shelters can be used as schools or community spaces when not being used as a shelter. Improved communications systems not only ensure better outreach in the event of a disaster but also support the commercial activities of local households and businesses. Integrating multipurpose designs into coastal resilience investments can save money and spur economic activities. These multiple uses of coastal resilience infrastructure, as well as the associated cost savings, can be classified as development co-benefits.

When developing plans and designing interventions towards coastal resilience, it is important to incorporate the concept of the Triple Dividend of Resilience, as this will help make the business case in favor of resilience-enhancing investments. Moreover, it will lead to plans and interventions becoming more inclusive and contributing to social and economic growth. Thus, coastal resilience can act as both a trigger and a tool for achieving sustainable development.

As such, following the Triple Dividend of Resilience is essentially enhancing coastal resilience, creating a wider discourse and understanding of the concept at multiple levels and across sectors. This enables the reimagination of resilience in a more holistic and integrated manner. Such an approach is compatible, and in fact, embedded within the NPDM 2021-2025, which seeks to integrate disaster risk resilience in consonance with the Sendai Framework for Disaster Risk Reduction 2015-30, the SDGs, and the Paris Climate Agreement. Moreover, enhancing investments in vulnerable sectors are a key component of Bangladesh's NDC as part of the climate change agreement at the UNFCCC Conference of the Parties in Paris in December 2015, and reflected in the updated NDC of August 2021.

Further, the concept of coastal resilience is in harmony with the Draft Mujib Climate Prosperity Plan, which will facilitate Bangladesh to build forward by charting a decade of robust socioeconomic development that fully integrates climate resilience and leverages opportunities within low carbon economic growth for optimized prosperity outcomes and partnerships. This perspective of coastal resilience in Bangladesh embeds the vision of the Mujib Climate Prosperity Plan, shifting Bangladesh's trajectory from one of vulnerability to one of resilience and prosperity. Based on the recommendations provided, it is envisioned that the actions put forth here will be the newly inspired steps taken to further enhance coastal resilience and thus, move towards the delta's prosperity.

7.9. Notes

27. https://geodash.gov.bd/.

7.10. References

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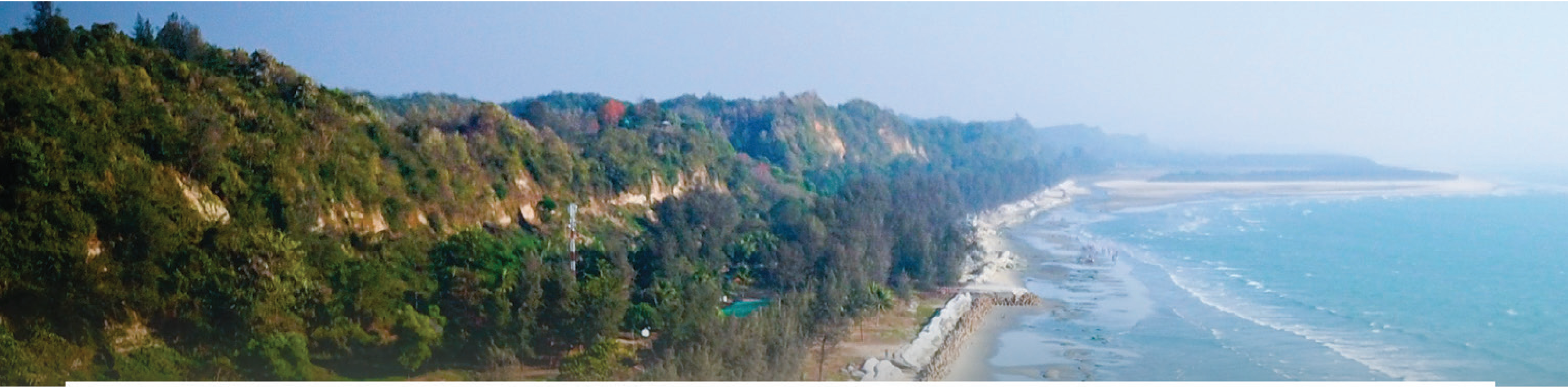

BANGLADESH:
ENHANCING COASTAL RESILIENCE IN A CHANGING CLIMATE

Coastal Bangladesh, home to over 40 million people, is a dynamic, unique, and thriving environment full of opportunities and multiple risks. Sitting on the frontlines in the battle against climate change, Bangladesh is among the most climate-vulnerable and disaster-prone countries in the world. The coastal zone of Bangladesh is experiencing setbacks in its development because of natural hazard impacts. Tropical cyclones and riverine floods are frequently recurring events, while coastal and riverine erosion and saline intrusion are chronic phenomena affecting millions of people each year. Protecting lives, livelihoods, and assets from disasters has been central to Bangladesh's development strategy, with the Government of Bangladesh headlining impressive progress in making the coastal zone safer over the last several decades, highlighted by a hundred-fold decline in fatalities from cyclonic events. Although significant development progress has been made, as the coastal population and economy is expected to grow and the intensity and magnitude of extreme events is projected to increase due to climate change, and hazard impacts still poses a great threat to the development ambitions of the country, further actions are needed to improve resilience of the coastal zone. The ability to continue the ongoing rapid economic growth hinges critically on how hazard impacts are managed, and resilience is built into the economy and natural environment.

The "Bangladesh: Enhancing Coastal Resilience in a Changing Climate" report seeks to provide actionable guidance for enhancing coastal resilience based on in-depth analytical work. The work included extensive stakeholder consultations, field visits, data analysis and modeling, with the aim of contributing to the design of sustainable climate-resilient coastal investments. The report provides evidence of the drivers of risks in Bangladesh's coastal region, what has been achieved so far in reducing these risks, and the lessons learned from these achievements. The report explores innovative solutions illustrated with artist impressions and puts forward seven key cross-cutting recommendations to move towards a more resilient coast, offering an opportunity to strengthen the resilience of the coastal zone in the changing climate and build shared prosperity for decades to come.

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