Developing an automated open source system for coastal multi-hazard assessment and management of water resources in a changing climate

Based on the Coastal Hazard Wheel system

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Abstract

Bangladesh, a country formed by three mighty river systems, is home to the largest delta in the world. Deltas create favourable living conditions and have always attracted population centres all over the world. Bangladesh, with a population of over 160 million, is no exception. But inhabitants of deltas are also very vulnerable to the impacts of climate change and to natural disasters. Often referred to as the “Ground Zero of Climate Change”, and struggling with its immense population pressure, limited funds, institutional capacity and resources, the need for a solid and sustainable coastal water management plan in Bangladesh is evident. Current coastal water management strategies, often developed by foreign consultancies, are heavily criticized, mainly for being non-transparent and undermining the Bangladeshi vision to become self-sufficient in its development sectors. The Coastal Hazard Wheel is a system for performing coastal multi-hazard assessment and identifying possible water management solutions, especially designed to be applicable in developing countries with limited resources and data availability. Its transparent method enables capacity building of local institutions, and supports coastal planners by identifying an overview of the coastal hazards, and identifying a range of suitable management options.

The aim of this study is to identify if the essence of the CHW framework can be captured in a (semi-) automated model using global and publically available data only, while making sure that its strong points - simplicity and low data requirements - will be sustained. This would avoid the need of manual labour, and take care of the challenge of suitable input data, significantly increasing the potential and usability of the CHW. Based on a case study in Bangladesh, different data sources are evaluated, and the model’s potential to replace human interpretation in coastal decision making is critically reviewed. Both its potential as hazard assessment method as planning/management tool are investigated and a comparison is made with the Bangladesh Delta Plan 2100 which currently is in its final stage of formulation.

This research showed that (semi-)automated hazard classification does have potential. The user has to be aware that the CHW assessment only results in an inherent hazard estimation based on the physical system, and does not include the impacts of inland processes and human alterations to the natural system. It will never beat field observations or local knowledge, but when applied in environments where resources and data are limited, in hard-to-reach areas, or as a first exploration to get a better overview of a certain coastal region, it definitely has an added value. The potential of the CHW as a planning/management tool should be sought in the exploration phase, to select a range of suitable options which will be further investigated and optionally complemented with other measures. However, there is still need for improvement. A proper accuracy assessment of the CHW system, including field observations, is recommended. Furthermore, including land use or economic interest as an input layer of the CHW would significantly increase its potential for coastal policy making.

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Acronyms

BDP2100	Bangladesh Delta Plan 2100
BWDB	Bangladesh Water Development Board
CHW	Coastal Hazard Wheel
DEM	Digital Elevation Model

EKN	Embassy of the Kingdom of the Netherlands
ESRI	Environmental Systems Research Institute
EPWPDA	East Pakistan Water and Power Development Authority
GBM delta	Ganges-Brahmaputra-Meghna delta
GED	General Economics Division
GLiM	Global Lithology Map
IR	Infrared
ISRIC	International Soil Reference and Information Centre
MODIS	Moderate Resolution Imaging Spectroradiometer
MSL	Mean Sea Level
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
SRTM	Shuttle Radar Topography Mission
UNEP	United Nations Environmental Programme
WMO	Water Management Organizations

A boy looks how the river washes away the embankment and floods the polders – Khulna district
Photo courtesy: Carel de Groot

Part I

INTRODUCTION

Bangladesh, a country formed by three mighty river systems, is home to the largest delta in the world. Over 400 rivers run through Bangladesh, defining both its geography and its people's way of life. Fertile soils, high productivity and easy transportation along abundant waterways make deltas a favorable living environment. But deltas are also very dynamic areas and vulnerable to natural disasters. Proclaimed as the ground zero of climate change, a solid coping strategy for climate induced coastal hazards will be vital. Bangladesh is a young country, and though rapidly developing, institutional capacity, data availability and expertise remain problematic. The coastal hazard wheel, a low tech coastal hazard assessment- and planning tool, could be an outcome for dealing with climate change, and potentially contribute towards a safer, more sustainable and prosperous future for Bangladesh and coastal environments all over the world.

1. Country setting

Bangladesh, the largest deltaic floodplain in the world, consists for about 80% of rivers and their floodplains. Governed by three of the world's greatest river systems – the Ganges, the Brahmaputra and the Meghna – Bangladesh comprises a unique but vulnerable environment. The river systems and floodplains support the livelihoods of millions of people, and have been forming the basis of the country's economy (EKN, 2013). Fertile soils, high productivity, rich biodiversity and easy transportation along abundant waterways make deltas all over the world favourable living environments for human population, and Bangladesh is no exception (Overeem & Syvitski, 2009). With a population of about 160 million, and an average population density of over 1250 inhabitants per square kilometre, it is in fact one of the most crowded regions on earth (UN, 2016).

Located on the interface of rivers and the ocean, deltas are naturally shaped by the forces of rivers, waves and tides, and have very dynamic hydrological, morphological, landscape and ecological characteristics (Overeem & Syvitski, 2009; EKN, 2013). They are also highly sensitive to (both natural as anthropological) modifications in the environment (Overeem & Syvitski, 2009). It can be no surprise that the increasing population pressure and predicted climate change are therefore very important developments in Bangladesh, and it gives water management a vital role (Bucx *et al.*, 2010).

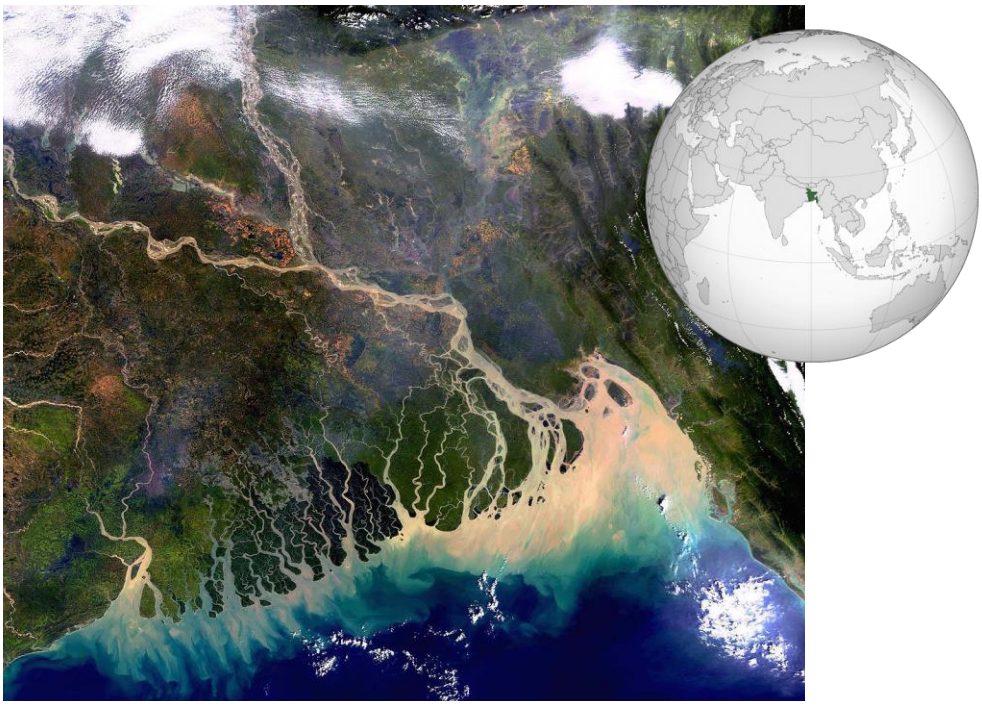

Figure 1: Satellite image of Bangladesh and the Ganges-Brahmaputra-Meghna delta (Seos, 2015).

1.1 Water management challenges in Bangladesh

Water is a natural resource of immense importance, and looking at the water sector, Bangladesh truly is a country of extremes (Chowdhury, 2010). On average about 20% of the country is flooded annually, and during extreme floods as much as 70% of the country can be inundated (Chowdhury *et al.*, 1996; Mirza, 2002). The river banks and the coastal region are highly dynamic areas where erosion and accretion processes affect millions of people (Shamsuddoha & Chowdhurry, 2007; Vidal, 2013). Fresh water supplies are threatened by the intrusion of saline water, arsenic pollution, and the ever increasing water requirements for agricultural-, industrial and domestic use (Hossain *et al.*, 2013; Hoque *et al.*, 2014). As a result of groundwater overexploitation in Dhaka, a 20 meter drop of the water table was observed in a single decade (Hoque *et al.*, 2007). Furthermore ecosystems are threatened by reductions of water quality and quantity (Chowdhury, 2010). Subsidence and sea level rise are expected to further increase these problems (CSE, 2012; Dasgupta, 2013).

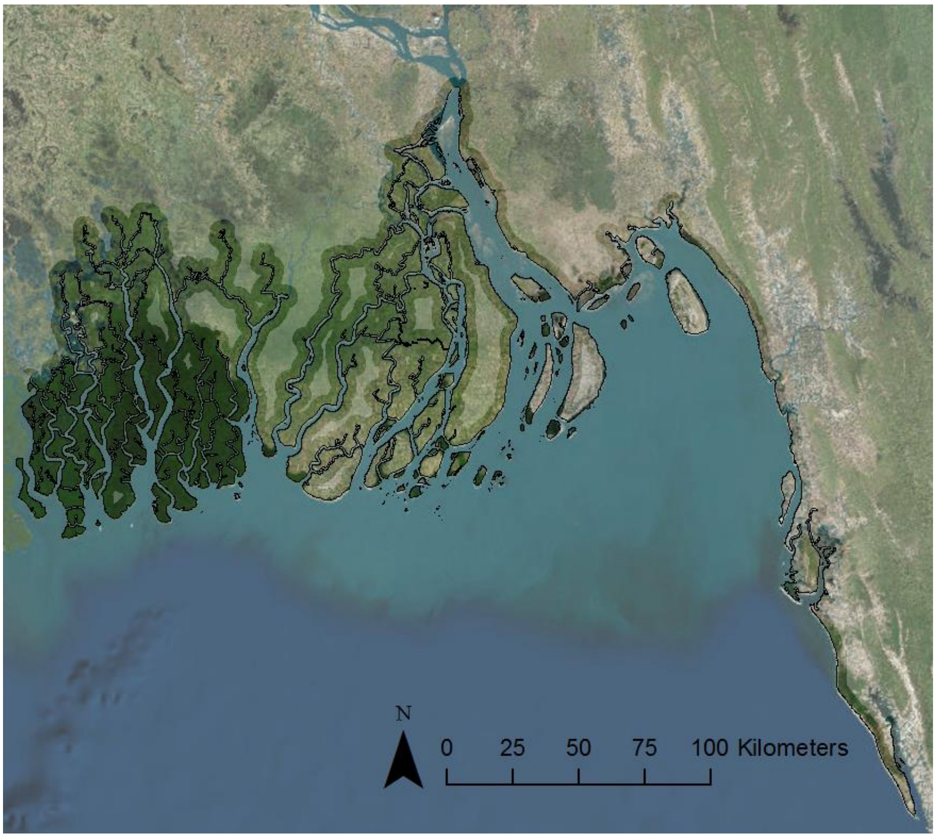

Figure 2: The coastal belt of Bangladesh, and coastline definition used in this research (black line)

The low-lying coastal zone of Bangladesh is a very disaster prone region. In the last decades, 60% of all deaths associated with cyclones worldwide occurred in Bangladesh, and the 1970's 'Bhola cyclone' which caused over 300.000 casualties still is one of the most deadly natural disasters ever recorded (Nicholls, 2007). Fresh water availability is highly seasonal, dominated by the monsoon climate, and both floods as droughts are occurring every year (Chowdhury, 2010; Khan *et al.*, 2014). Climate change is projected to increase this seasonality, with more extreme rainfall and temperatures, and a higher risk of cyclones (Dastagir, 2015; Miyan, 2015). Furthermore it decreases the land availability in the coastal belt (Figure 2) due to sea level rise, salinization, and more and longer periods of water logging (CSIRO, 2014). The impacts of climate change are extensively studied in Bangladesh, and it is globally recognised as one of the most vulnerable countries to global warming, often referred to as the "ground zero of climate change" (Sarwar & Wallman, 2005; Mirza, 2012; Pethick & Orford, 2013; Azzaman, 2014; Brammer, 2014; Rahman & Rahman, 2015). Climate refugees are arriving in Dhaka's slums every day, having lost their land in the coastal areas (Anwer, 2012; Penning-Rowsel *et al*, 2013), and the ones who stay appear to be fighting a losing battle (Arthus-Bertrand & Mikova, 2016). The coastal belt harbours millions of people, and is absolutely vital for the country's food production, making an effective hazard management an absolute necessity.

1.2 Rapidly developing coastal zones in a changing climate

Coastlines create favourable living conditions, and have always attracted human development and population centres all over the world. The urbanization of coastlines has increased dramatically, and deserves more attention from policy makers and planners (Wong *et al*., 2006). Coastlines are highly dynamic natural systems that undergo continuous changes as a result to interaction with terrestrial, marine and atmospheric processes. While these processes have been relatively stable and predictable in the last centuries, they are expected to change more rapidly and unpredictable due to climate change. Nowadays, this is rarely taken into account in coastal development. Especially in developing countries, where data availability, economic resources and expertise are limited and coastal populations are often growing rapidly (Appelquist, 2014). Past coastal trends cannot be directly projected into the future, and recognizing how different coastal environments will react to climate change is vital in order to deal with the expected coastal hazards in coastal planning processes.

2. Problem statement

2.1 Climate change impacts

While Bangladesh is well on its way to become a middle income country, having demonstrated an impressive stable economic growth of about 6% in the last two decades (World Bank, 2016), this development is threatened by its population pressure, climate change, and an insufficient water resource management. If no measures are taken, climate change impact could dislocate more than 35 million people in the coastal districts and make an additional 14% of the country extremely vulnerable for floods (BanDuDeltAS, 2014). This would push people back below the poverty line, and it is evident that coastal hazard management is vital for the country's welfare and proper measures should be taken as soon as possible.

And although the impacts of climate change are extensively studied (World Bank, 2010; Mirza, 2012; Lee, 2013; CSIRO, 2014; GED, 2016), the availability and access to accurate data needed for a proper water management strategy remains a big challenge (Centre of Policy Dialogues, 2014). Furthermore, the government is known for its cumbersome bureaucratic system, lack of man-power and funds, and has a bad reputation regarding corruption, limiting its institutional strength (IMF, 2013). The government of Bangladesh typically works with 5-year plans, which makes prioritizing essential (General Economics Division, 2015). This requires an objective and scientifically solid method to identify the coastal hazards and to determine appropriate measures to manage them.

2.2 Criticism on current management strategies

Current water management strategies are often developed by foreign consultancies, financed with development aid. But as Bangladesh approaches the status of a middle income country, this type of financing is slowly phasing out. In addition, it does not lead towards an increased capacity and ownership of the water management strategies by the government of Bangladesh. The Bangladesh Delta Plan 2100 (BDP2100) is a perfect example. While it is presented as a Bangladeshi project that, with support of the Netherlands, will enable Bangladesh to develop its own delta vision, it is mainly Netherlands-initiated, with over 87% of the financing coming from the Netherlands, and only 2 out of 10 consortium partners being Bangladeshi (EKN, 2013). Publically criticized for being non-transparent and undermining the Bangladeshi vision to become self-sufficient in its development sectors, it lacks the capacity building and Bangladeshi ownership to help the country to be able to develop her own management strategies in the future (Khalequzzaman, 2016). Therefore it is questionable if it really is a sustainable way to go, and it demonstrates the need for realistic and locally applicable policy tools.

2.3 Gap in existing coastal hazard assessment methods

Since coastal vulnerability to climate change is widely recognized, there is an abundance of existing risk assessment methods, all with their own strengths in limitations. However, an unfilled niche was identified by Appelquist (2014) for regions dealing with data scarcity and limited institutional capacity. GIS-based decision models and dynamic computer models are often not applicable due to their high input- and expertise requirements. Low-requirement models such as index-based or indicator-based methods are more realistic options, but while index-based methods cannot be used to identify a range of sector-specific hazards and lack transparency, indicator-based methods require relatively detailed input data. Furthermore they both cannot be used directly to identify management options (Appelquist, 2014).

The United Nations Environmental Programme, in cooperation with the Technical University of Denmark, developed the Coastal Hazard Wheel (CHW) system. This theoretical framework is a policy tool designed for exactly the circumstances described above: a vulnerable and rapidly developing coastal zone, with limited institutional capacity and resources. The CHW is a tool for coastal decision-makers that identifies both a complete overview of the expected coastal hazards as well as a range of management options, based on the projected climate change and the characteristics of the physical system. Specifically designed to target the needs of developing countries, it is a simple system that can be applied in areas with limited data availability and institutional capacity.

The CHW system was developed only recently, and currently is just a theoretical framework (Appelquist & Halnæs, 2015). It was applied in two case studies, in Djibouti and India, where the coastline was classified based on climate induced coastal hazard levels (Appelquist & Balstrøm, 2014; Appelquist & Balstrøm, 2015). They were both performed manually, meaning that based on a visual interpretation of maps and satellite imagery (mainly Google Earth), the coastal characteristics are assigned by hand, and this is repeated for approximately every 100 meters of coastline. This is an extremely time consuming and labour intensive process, especially looking at regional or national scales, and also requires a certain amount of expertise. Furthermore it results in a very subjective result, based on an individual judgement of the user. The CHW system could have a great potential for coastal management in developing areas, but as it is now, with the large amount of required manual labour, it is not suitable yet for large scale application.

3. The Coastal Hazard Wheel concept

The Coastal Hazard Wheel is a system that helps coastal planners and decision makers to cope with climate change related hazards. The hazard analysis is based purely on the physical characteristics of a coastal strip of a few hundred meters in width, combined with the expected trends in climate change. It should therefore be seen as a way to get insight in how climate change will affect a certain coastal stretch, and not necessarily as a tool that identifies all existing water management related problems. Until now, the Coastal Hazard Wheel has been applied two times, leading to the publication of a case study in Djibouti and a case study in India (Appelquist & Balstrøm, 2014; Appelquist & Balstrøm, 2015).

The foundation of the Coastal Hazard Wheel methodology is a classification system that is able to classify any coastline into one of its 131 unique categories. These categories are based on the bio-geophysical characteristics that are deemed most important in order to differentiate between different generic coastal environments, being the geological layout, the wave exposure, the tidal range, the flora/fauna, the sediment balance and the storm climate. The CHW framework combines these six different information layers, determines the coastal classification, and links this classification to a certain hazard profile and a range of potential measures (Figure 3). The definitions and assumptions for the different input layers and the classification method can be found in Chapter 7.1, based on Appelquist & Halnæs (2015).

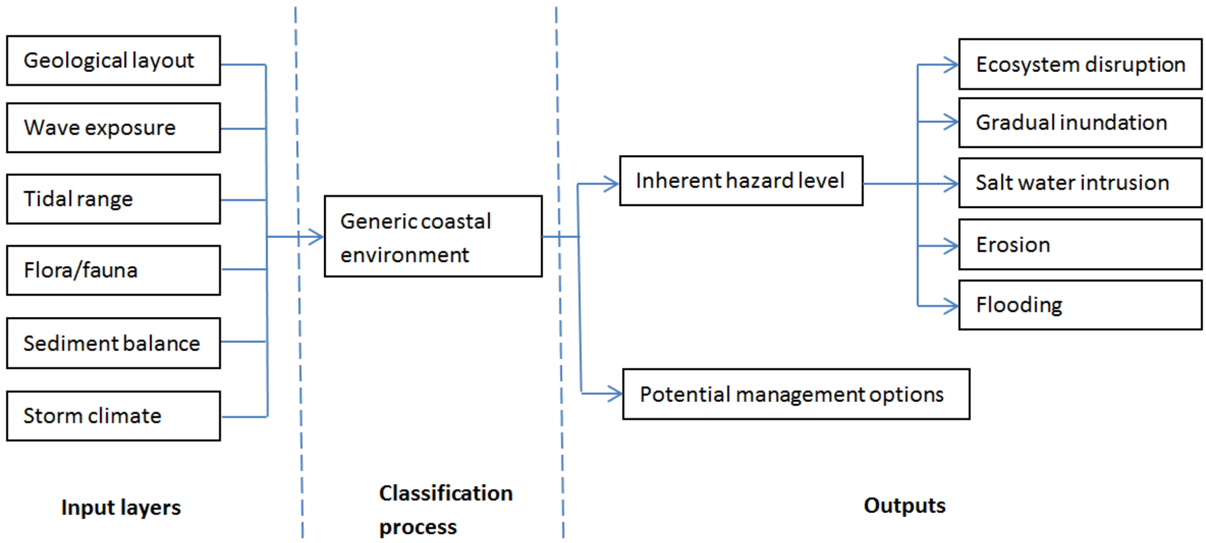

Figure 3: Schematic illustration of the functioning of the Coastal Hazard Wheel methodology

The inherent hazards covered by the CHW system are ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding, being defined as:

- Ecosystem disruption: the possibility of a disruption of the current state of the coastal ecosystems due to climate change.
- Gradual inundation: the possibility of a gradual submergence of a coastal environment due to climate change.

- Salt water intrusion: the possibility of salty sea water penetrating into coastal surface waters and groundwater aquifers under a changing climate.
- Erosion: the possibility of erosion processes leading to a loss of land surface under a changing climate.
- Flooding: the possibility of a sudden, abrupt and often dramatic inundation of a coastal environment caused by a short term increase in water level due to a storm surge or extreme tides, under a changing climate.

More detail of the different coastal hazards can be found in Chapter 7.2.

The potential management options consist of three types: hard protection measures, soft protection measures and accommodation approaches. A total overview of the methodology and very basic cost indication is provided in Chapter 7.3.

4. Research objective and research questions

The research objective of this study is to identify if the essence of the Coastal Hazard Wheel (CHW) framework can be captured in a (semi-)automated model using global and publically available data only, while making sure that its strong points - simplicity and low data requirements – and reliability of the outcome will be sustained. This would avoid the need of manual labour, and take care of the challenge of suitable input data, significantly increasing the potential and usability of the CHW. For this study, two objectives were formulated, that were further divided into six research questions.

To develop an objective (semi-)automated model, only requiring open source geo-data, which captures the theoretical framework of the Coastal Hazard Wheel and is capable of executing a coastal multi-hazard assessment.

I. *Are publically available ready-to-use datasets sufficient to execute a reliable coastal multi-hazard assessment?*
II. *Is it possible to improve this input data with remote sensing techniques and basic GIS-analyses, while maintaining the Coastal Hazard Wheel's simplicity?*
III. *Can the model satisfactorily replace human interpretation?*
IV. *Is the model applicable in other regions?*

To investigate the Coastal Hazards Wheel's potential as a planning and management tool for coastal regions in data scarce areas.

V. *Are the management options suggested by the Coastal Hazard Wheel in line with the coastal management projects of the last decades?*
VI. *How do the management options suggested by the Coastal Hazard Wheel compare with the management options suggested by the Bangladesh Delta Plan 2100, which is currently in the final stage of its formulation?*

The model is designed and evaluated based on a case study in Bangladesh, and further validated by reproducing the multi-hazard assessment for Djibouti, as previously performed manually by Appelquist & Balstrøm (2014).

4.1 Hypothesis

The expectation is that the Ganges-Brahmaputra-Meghna (GBM) delta will be a challenging region for a global hazard assessment methodology as the CHW. First of all it is a very dynamic area, impeding an easy combination of the different input layers. But furthermore, looking at a global scale, the GBM delta might look like a relatively uniform region. Therefore it is not certain whether the CHW can provide enough detail to be of any additional value for Bangladesh itself. If 95% of the country would be classified as being extremely vulnerable to a certain hazard, the applicability for prioritizing certain areas would be very minimal. The hypothesis is therefore that without an extra input layer including land use, infrastructure or economically essential areas, the functionality of the CHW will be limited. Furthermore, because the automated methodology will be based on the

Bangladeshi coastal zone, a quite unique area, problems may occur when applying the model in different coastal environments.

Looking at the CHW as planning and management tool, important to realise is that it only takes the physical characteristics of the coastline into account. Since most coastal masterplans will base their recommendations on a certain strategy, for example protecting economically interesting areas, capital or infrastructure, it is to be expected that the CHW will be less specific than measures suggested by for example the Bangladesh Delta Plan 2100.

4.2 Societal significance

Bangladesh is a country that could make use of the CHW methodology as a way to get an overview of the coastal hazards that climate change will bring, and the possible management options to deal with them. It does not automatically deliver a complete outlined strategy that will solve all the water management challenges, but it can serve as a tool for prioritizing certain regions and interventions, which then can be further developed into concrete designs. With the limited resources available in Bangladesh, and the long list of climate hazards, the niche of the CHW is evident.

Furthermore, with the simplicity and transparency of the CHW, it could be a way to increase the institutional capacity of local authorities and to come to measures that are properly owned and supported by the coastal managers. Bangladesh is a country that receives a lot of development aid, but the downside of this is that most projects are executed by foreign consultancies and companies, which are undermining the self-reliance of the government of Bangladesh. Too often these foreign consortia do not consult local skills, knowledge and experiences, and produce masterplans that are not supported by local authorities and in some cases even worsening the situation (Islam & Kibria, 2006; Rouillard *et al*., 2014).

4.3 Scientific significance

This case study would be a good possibility to critically review the CHW framework itself. Bangladesh is undoubtedly a region where climate change has major impacts on the coastal region, and perfectly fits the target group of the CHW system as being a country where data availability and institutional capacity are a challenge. Because climate change impacts have been studied quite extensively in Bangladesh, it offers a good opportunity to test whether the CHW framework is able to accurately predict the coastal hazards. Furthermore, during the execution of this study, the Bangladesh Delta Plan 2100 is in the last phase of its formulation. The BDP2100 is a holistic, long-term plan for the Bangladesh Delta that aims to ensure a safe living environment and a sustainable and sound economic development in the delta. This offers the opportunity to compare the management options given by the CHW framework with an extensive delta strategy. That will identify the strong points of the CHW framework and the points where it could still be improved.

5. Thesis structure

The automated CHW methodology consists out of two parts. One is to construct six input layers from open source data, combine these, and produce a combination of coastal hazard levels. The other one is to evaluate a range of management options, including hard – and soft measures and accommodation approaches, and to list the most suitable ones based on the physical characteristics. This structure is followed through the methodology and result parts.

First the study area will be introduced and the CHW concept will be further defined. Then the automated methodology for the construction of input layers and hazard assessment is discussed, followed by the method to evaluate the potential of the CHW as planning/management tool. The results chapter will separately discuss the construction of the input layers, the final hazard assessment and the applicability of the model outside the study area. The suggested coastal measures will be put in the context of both the coastal water management practices of the past as the coastal strategy as formulated in the Bangladesh Delta Plan 2100. The findings and potential of the CHW method will be critically evaluated in the discussion, from which conclusions and recommendations for future research will be made.

Sundarbans; the world's largest mangrove forest
Photo courtesy: Noor Ahmed Gelal

Part II

METHODOLOGY

Human capabilities of data interpretation and analysis set the bar high in terms of precision, adaptive abilities and overall quality. If technology could replace the manual labour of collecting and interpreting data in remote or developing areas, that would open up great possibilities for an effective coastal management. It could save time, man power and money, while providing objectivity and consistency exceeding human capabilities. The ultimate goal is to mimic the human interpretation skills, while adding the benefits of an objective automated assessment procedure. Technology still has a long way to go before it can rival with our own interpretation capabilities, but an automated CHW methodology could potentially show one of the directions to do so.

6. Study area

The Coastal Hazard Wheel bases its classification by looking at the physical characteristics of only a very narrow coastal strip of a few hundred meters. This simplicity is one of its strengths, but also brings along some challenges, since especially in a deltaic country as Bangladesh, inland processes are an extremely important factor for the coastal dynamics. Therefore this case study will be an interesting test case to see how well the different categories are defined and take into account inland developments.

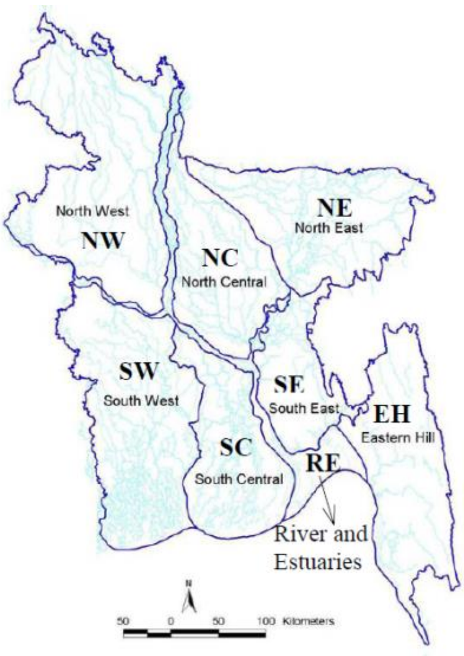

Figure 4: Coastal hydrological regions (CEGIS, 2013)

Even though Bangladesh is a relatively small country, with a coastal region of about 325km width from west to east and about 275 km north to south, due to its complex deltaic nature almost 8100 km of coastline was identified (Figure 2). The data analysis will be limited to the coastal strip along the entire Bangladeshi coastline. Most water related policy documents consistently use a division of eight different regions, based on their hydrological characteristics (CEGIS, 2003; MWR, 2004; GED, 2016). This document will apply the same division, allowing for a convenient comparison (Figure 4). Only the relevant coastal zones fill be described, being: South West, South Central, South East, River and Estuaries and Eastern Hills. Other regions will only be discussed if it is relevant in order to understand the system.

6.1 Topography

Bangladesh consists out of three major physiographic units: hills (12%), terraces (8%) and alluvial floodplains (80%). The hill areas are ridges positioned north to south in the NE and Eastern Hill regions, and range in elevation from about 300 – 1000 meters above mean sea level (MSL). The terraces can be found in the North West and North Central regions, and are formed by floodplain deposits related to the higher sea levels in the interglacial periods of the Pleistocene. The remaining regions are floodplains, crisscrossed by a network of over 400 rivers (GED, 2016). Relief is generally low in these areas, and mostly less than 10 meters above MSL (Figure 5).

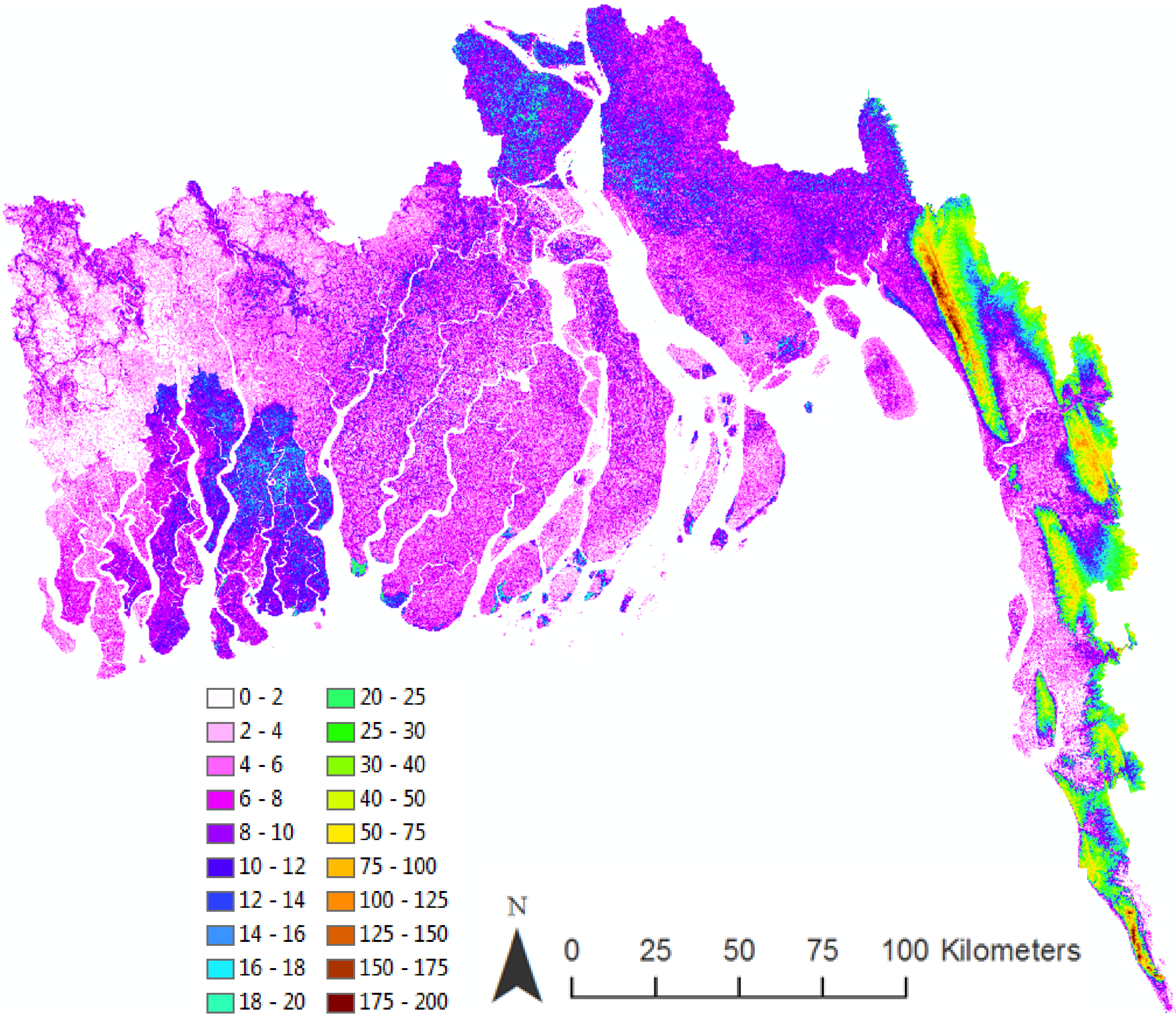

Figure 5: The elevation in meters above mean sea level – based on SRTM elevation data (USGS, 2007)

6.2 Climate

Bangladesh has a semi tropical, monsoon dominated climate (GED, 2016). Four seasons can be defined based on the rainfall distribution throughout the year (Chowdhury, 2010). Up to 80% of the total rainfall occurs during the monsoon, from June until September. The post-monsoon and winter period, respectively October-November and December-February are dry (about 10% of the annual rainfall) and relatively cold. The pre-monsoon period (March-May) can be very hot, up to 40 degrees, and can have a very unreliable rainfall pattern (Chowdhurry, 2010). Seasonable water shortages are no exception in the pre-monsoon, while early monsoon rains are also notorious to wash away seeds and destroy crops (CEGIS, 2003; Bijlmakers, 2016). The total annual precipitation ranges from 2000 mm in the west to 4000 mm in the North- and South-East (GED, 2016). While this geographic variation is rather large, the temporal pattern is quite uniform over the different regions, and follows the trend outlined in Figure 6.

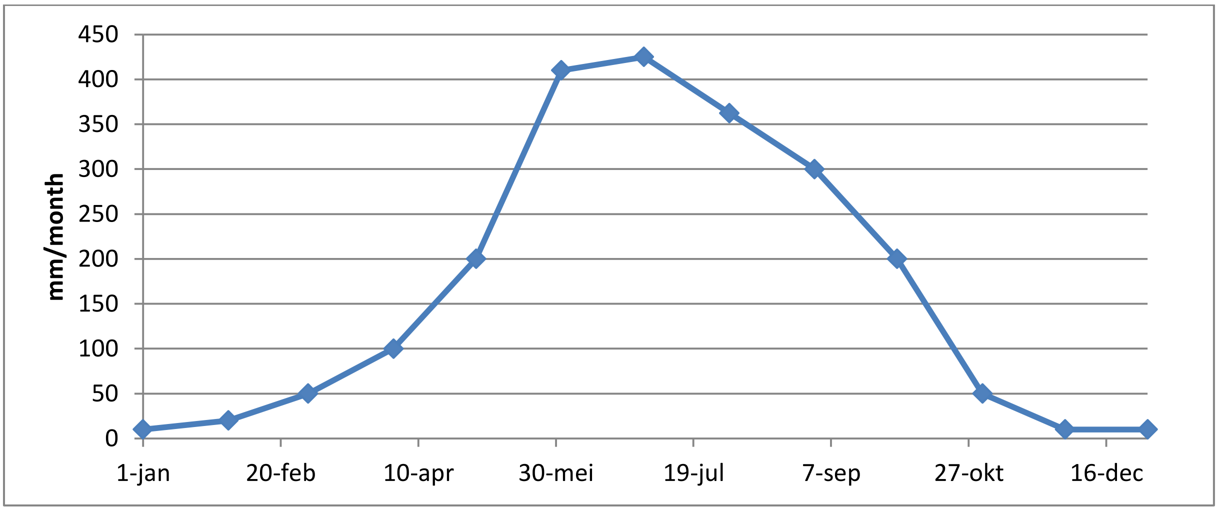

Figure 6: The mean annual rainfall pattern of Bangladesh (GED, 2016)

6.3 Coastal regions

South West: the coastal region is dominated by the Sundarbans, the biggest contiguous tidal mangrove forest in the world (10,000 km^2) and best known for its Royal Bengal Tiger population (Figure 7). The western part is located in India, while the eastern part (about two-third of the total area) is located in Bangladesh (Uddin *et al.*, 2013). A large part of the Sundarbans is a protected UNESCO nature area, and though it is very sparsely populated, the forest is estimated to provide livelihoods for several millions of people (Chowdhury, 2010).

Figure 7: The Sundarbans, the largest mangrove forest in the world

South Central and South East: very densely populated and important agricultural (rice) areas. *Aman* (rain-fed, monsoon period) is the leading rice crop (56%), followed by *boro* (irrigated, winter) rice (27%) (Chowdhury, 2010). In some areas, a third harvest with *aus* (pre-monsoon) rice or cash crops are cultivated if water logging can be prevented.

River and Estuaries: Bangladesh is a downstream country and makes up only 7-8% if the total catchment area of the GBM-river system, which is about 1.72 million km^2 (Chowdhury, 2010). The Jamuna (Brahmaputra), Ganges and upper Meghna rivers come together in the lower Meghna, which reaches the Bay of Bengal. The lower Meghna experiences a wide variation of discharge throughout the year, ranging from 8,000 m^3/s in February/March to 100,000 m^3/s in July-September, while the peak discharge exceeds 120,000 m^3/s (Kamal *et al.*, 2013). It is an extremely dynamic area with rapid erosion and sedimentation processes and seasonal flood events.

Eastern Hills: Home to Chittagong, the second city and largest port of Bangladesh. This region is the hilliest area of the country, and though the inland is quite remote and forested, the coastal zone is densely populated. Its coastal fringe is particularly exposed to cyclones, and flash floods are notorious during extreme precipitation events (Ministry of Water Resources, 2004).

7. Coastal Hazard Wheel methodology: definitions and assumptions

Based on the six different input layers, the CHW distinguishes between 131 unique coastal environments (Figure 8). The user starts in the centre of the CHW (the geological layout) and then moves outwards, ending with the inherent hazard evaluations in the outermost circles.

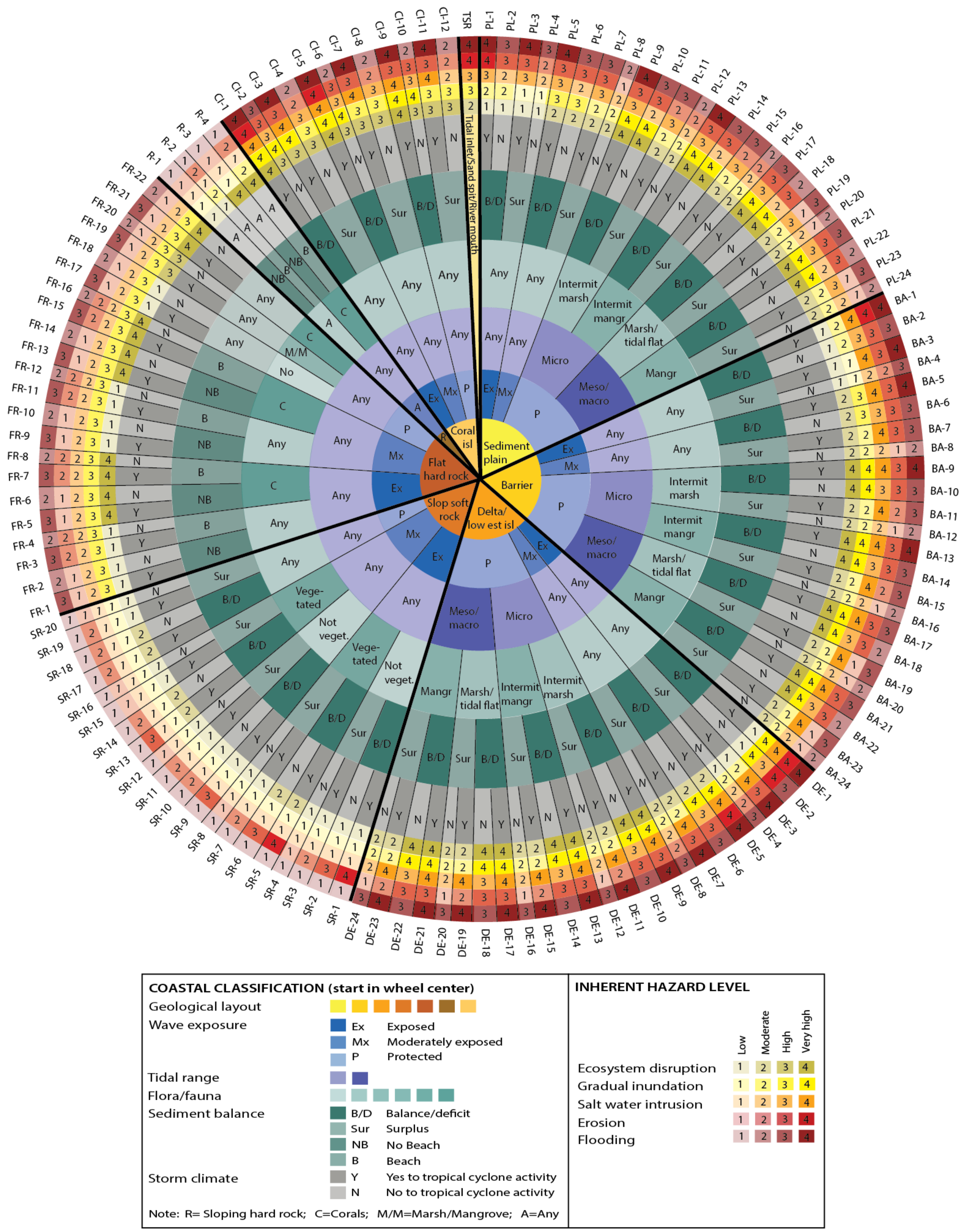

Figure 8: Decision structure of the Coastal Hazard Wheel methodology (Appelquist & Halaes, 2015)

In Chapter 7.1, 7.2 and 7.3 the input layers, coastal hazards and water management options of the CHW will be defined, summarizing the concept developed by the UNEP (Appelquist. 2012; Appelquist, 2014; Appelquist & Halnæs, 2015)

7.1 Input layers

Geological layout

Created by tectonic, fluvial, marine, volcanic and sometimes glacial processes, the geological layout can be seen as the basis on which all coastal processes act. In an effort to capture the major geological coast types, Appelquist & Halnæs framed the world's coastal environments into the following categories: sedimentary plain; barriers; deltas/low estuary islands, sloping soft rock coasts; flat hard rock coasts; sloping hard rock coasts; coral islands; and tidal inlets/sand spits/river mouths. Their exact definitions are outlined below.

The sedimentary plain category is defined as coasts composed of sedimentary deposits, with an average slope of less than 3-4% at least 200 meters inland of the MSL. The deposits typically consist of clay, silt, sand or gravel, and are usually formed by fluvial or glacial processes.

Barriers are low lying sedimentary bodies that are formed parallel to the shoreline. While their cross distance typically ranges from less than 100 meters to several kilometres, their length can be a multitude of this. The seaward side of a barrier is usually wave dominated, while the protected landward side often consist of lagoons or estuaries.

Deltas/low estuary islands are defined as the coastal areas composed of fluvial sediments, situated where river systems reach the coast. Dominated by the river system's flows and sediment transport and marine processes such as waves, tides and currents, deltas/low estuary islands are typically very dynamic areas.

Sloping soft rock coasts are comprised of soft rock materials with an average slope of more than 3-4% in the first 200 meters land inwards. Coastal cliffs with a steep gradient combined with a flat shore platform land inwards also fall into this category. Deposits such as chalk, clay, silt, sand and till with larger pebbles all fall into the soft rock category.

Flat hard rock coasts are consisting of igneous, sedimentary or metamorphic rocks. The same slope threshold of less than 3-4% 200 meters land inwards is used to differentiate between flat and sloping hard rock coasts. Igneous rock is formed by magma, and can be composed out of a large range of different minerals and grain sizes. Sedimentary rock is heavily compacted or cemented sediment that formed a solid rock structure under high pressure and temperatures. Metamorphic rock can be formed of both igneous and sedimentary rock, when undergone recrystallization under extremely high temperatures and pressures. While these different rock types can have very different chemical and physical properties, they are considered a uniform group looking at the impact on the different coastal hazards outlined in Figure 3.

Sloping hard rock coasts are igneous, sedimentary or metamorphic rocks, and have a slope of more than 3-4% in the first 200 meters land inwards. They typically occur in coastal mountain ranges and archipelagos.

The coral island category is defined as low-lying coral islands, atolls or cays. Atolls are typically round shaped islands resting on a volcanic foundation. Cays are younger islands formed on top or adjacent to reefs due to the accumulation of reef-derived sediments as result of wave action.

The tidal inlets/sand spits/river mouths category is a collection of highly morphologically active environments. Tidal inlets are found along barrier coastlines and connect the protected lagoons with the open coast. Sand spits are locations where sediment is depositing rapidly, forming elongate sand bodies, usually formed by longshore currents. River mouths are the locations where a river meets the coast. In the case of tidal inlets and river mouths, a zone of one kilometre on each side of the inlet/river mouth is included in the classification.

Wave exposure

Waves are a dominant energy source in nearshore environments, generating nearshore currents and sediment transport, making it an important driver of morphological change. Waves are generated by wind stress on the ocean's surface together with the earth's gravity force. The wave climate is composed of sea- and swell waves. Sea waves are formed under direct influence of the wind, and have peaked crests and broad troughs. Swell waves have a sinusoidal shape with a long wavelength and low wave height, and develop outside wind areas.

The CHW differentiates three different classes, being exposed, moderately exposed and protected, based on the significant wave height and geographic location**.** All coastlines within the protected and swell areas (Figure 9) are automatically classified as respectively protected and moderately exposed.

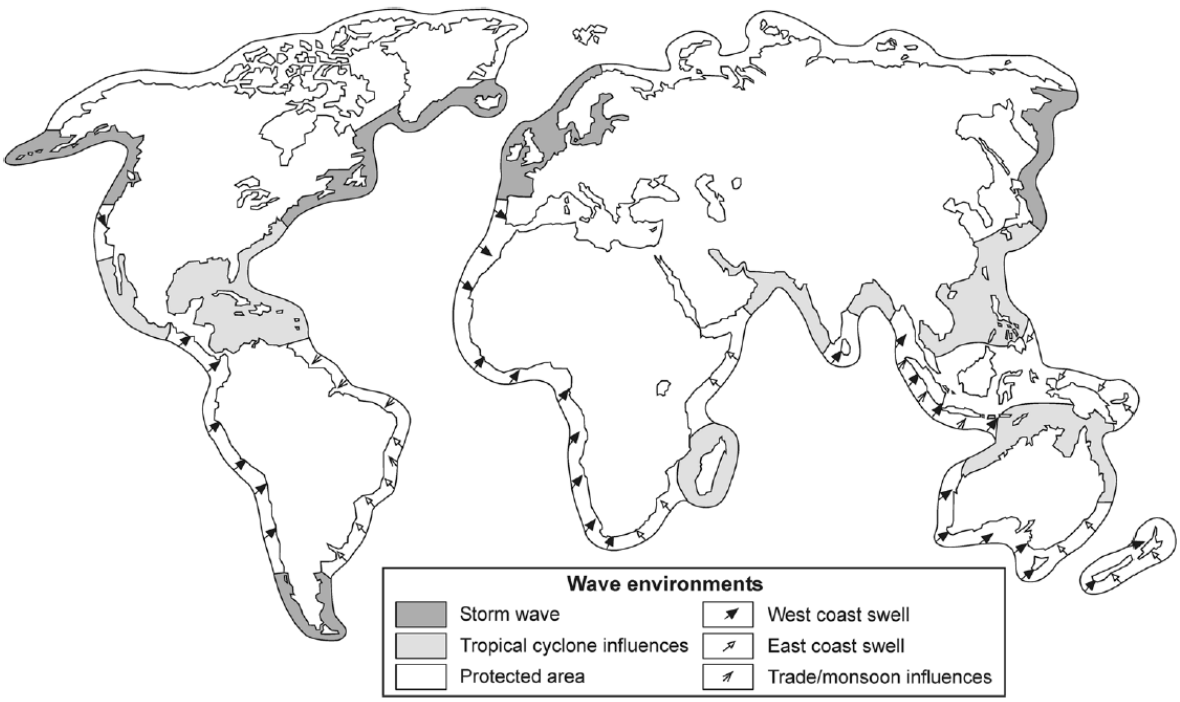

Figure 9: Global wave climates (as in Masselink *et al*., 2003)

For other coastal areas, the significant wave height should be determined, ideally with the S-B-M method (Mangor, 2004). This method uses a nomogram to predict the significant wave height based on the wind speed, wind duration and fetch length. The wave exposure is considered **exposed** when the significant wave height is more than 3 meters, **moderately exposed** if it is 1-3 meters, and **protected** if it is less than 1 meter. When this data is not available, the free fetch can be used as an indication. Free fetch is defined as the distance of uninterrupted open sea in a certain direction. For the free fetch indication, the classes are respectively over 100 km, 10-100 km, and under 10 km.

Tidal range

The tides are caused by the gravitational forces of the moon and the sun acting on the oceans. Basically tides are big oceanic waves with a wavelength of thousands of kilometers, resulting in periodic fluctuations in water levels (Davis & Fitzgerald, 2004). The amplitude of the tides are determined by several factors including the local bathymetry, shape of the coastline and the distance from an oceanic amphidromic point – a point with no sea level change during a harmonic constituent of the tide (Desplanque & Mossman, 2004; Haslett 2009).

The CHW differentiates between **macro-tidal** environments where the tidal range exceeds 4 meters, **meso-tidal** where it is within 2-4 meters, and **micro-tidal** where it does not exceed 2 meters. The global distribution of the different tide-environments is shown in Figure 10**.**

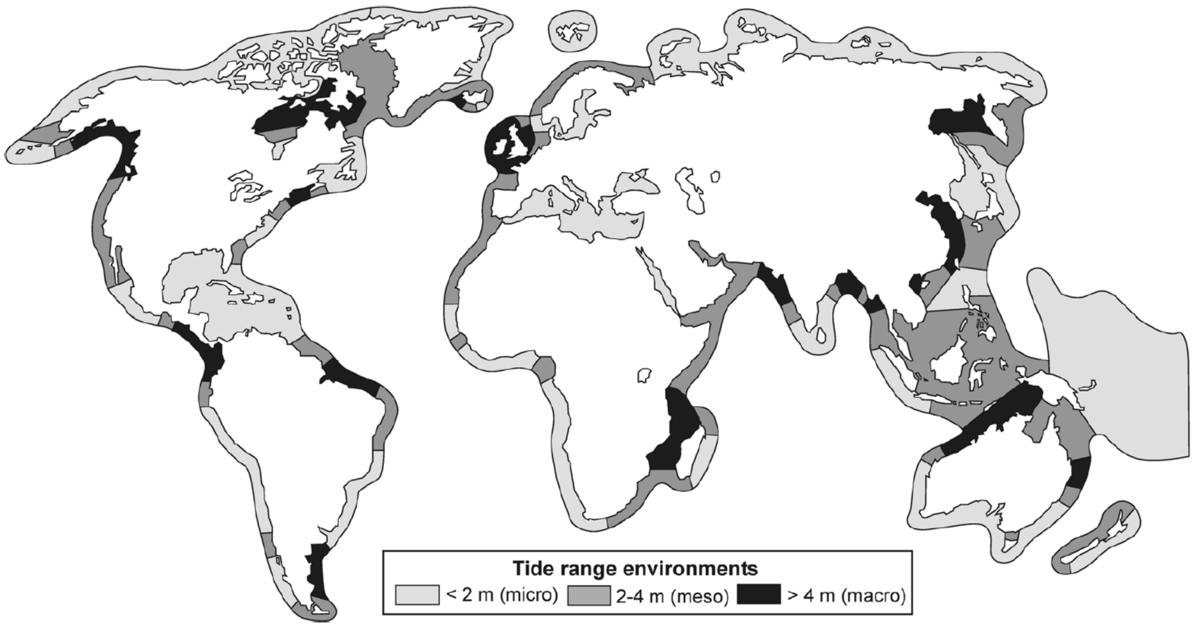

Figure 10: Global variations in tidal range (as in Masselink *et al*., 2003)

Looking at morphological processes, the effect of the tides is significantly influenced by wave action. Therefore the factor essential for calculating the hazard levels should be the relative size of the tides and waves, rather than just the tidal range. This is incorporated in the decision-tree of the CHW (Figure 8).

Flora/fauna

In general, vegetation will have a stabilizing effect on a soil or coastline, but some types of ecosystems can have a high impact to certain processes. The CHW differentiates between the following nine different flora/fauna classes:

Marsh areas are formed by continuous flooding and subsequent sediment deposition along low energy coastlines. This results in a grass-like salt resistant vegetation. Depending on the tidal range, marshes are classified as '**intermittent marsh**' in areas with micro-tidal conditions and '**marsh/tidal flat**' in areas with either meso- or macro-tidal conditions.

Mangroves are woody shrub/tree species that grow in salty water along protected coasts. Their extensive root systems act as an efficient trap for sediment, and reduce the wave impact on the coast. The CHW differentiates between three different mangrove types: the '**intermittent mangrove**' and '**mangrove**' classes occur in sedimentary plains, delta/low estuary islands and barriers with respectively micro-tidal and meso/macro-tidal conditions, the '**marsh/mangrove**' class occurs where mangroves grow along protected, flat hard rock coasts.

The '**vegetated**' and '**not vegetated**' classes are applied to sloping soft rock coasts. In some cases the distinction between these two classes might be arbitrary, but a threshold value of about 25% vegetation cover is used to define vegetated areas.

The '**coral**' category is applied to coral reefs. Areas where the local flora/fauna is not considered very influential for the hazard calculation will fall into the flora fauna class '**any**'.

Sediment balance

The sediment balance is an important morphodynamic parameter, determining whether there is a net accumulation, removal or balance of sediment. Non-cohesive, sand-sized sediment plays an essential role in exposed and moderately exposed coastlines, where it is transported along the coastline, mainly due to the wave height and incidence angle. The finer cohesive sediment goes into suspension in these environments and only plays a role in protected coasts, generally vegetated with mangrove or marsh vegetation (Mangor, 2004).

The system only differentiates between '**balance/deficit**' and '**surplus**'. The rationale behind this simplification is that taking into account the expected sea level rise, both areas with a sediment balance as a deficit are likely to suffer from retreating coastlines unless new sediment sources emerge.

Storm climate

Tropical cyclones include extreme wind-, wave- and precipitation conditions that can have a significant impact on the coastal dynamics and the inherent hazard levels. Whether tropical cyclones can occur is merely based on geographical location, they can only develop over tropical seas where the water temperature exceeds 27 ℃. Figure 9 gives an overview of the areas where tropical cyclones can occur. The CHW only differentiates between two possibilities: '**yes**' and '**no**'. The frequency of tropical cyclones is not incorporated.

7.2 Inherent hazard definitions

Ecosystem disruption

The ecosystem disruption hazard is based on the complexity, sensitivity and expected response to climate change of a particular ecosystem associated with a certain generic coastal environment.

Littoral coastal environments with an exposed or moderately exposed wave climate will generally have a low hazard level as these environments are often hostile environments for biota. These coastlines have a limited flora, while fauna is mainly composed of micro- and meiofauna living beneath the sand surface. This makes them relatively protected from changes in sea level rise and increasing water temperatures, though they may be, to some degree, be sensitive to beach erosion.

Protected coastal environments usually have more diverse and complex ecosystems such as marshes, mangroves or tidal flats, especially in environments with a large tidal range. Tidal flats and marshes often provide nursing grounds for a range of animal species, and often harbour large bird populations. Furthermore marshes are characterized by a high primary production and species diversity. Mangroves are highly complex ecosystems and among the most productive in the world, and provide organic matter that forms an important energy source for marine live. This complexity, with all its interspecies relations and linkages, makes these environments more susceptible to changes since every alteration triggers other processes to change as well.

Coral reefs are among the most diverse ecosystems on the planet, and also among the most vulnerable. Though there is no general consensus on the exact reason, increasing ocean temperatures correlate to large scale coral bleaching and mortality. Furthermore, acidification of oceans due to an increased CO_2 uptake reduces the calcification rates of marine organisms, limiting coral growth.

Gradual inundation

The gradual inundation hazard reflects the possibility of submergence of a coastal environment due to climate change. Contrary to flooding it is a gradual process, that occurs when the sediment deposition cannot keep up with sea level rise.

The sediment balance is a crucial factor for the gradual inundation hazard assessment. If enough sediment is available, marshes, mangroves and tidal flats are expected to keep up with sea level rise through vertical accretion. Delta environments are more sensitive to inundation processes. A lot of deltas have decreased sediment supplies due to upstream damming activities and are subsiding. Other human activities such as the abstraction of groundwater and fossil fuels enhance the subsidence rates, creating environments that would even be problematic without sea level rise.

Though coral reefs have a vertical growth rate of about 1-10 mm/y, rapid sea level rise can lead to drowning of corals, and especially corral atolls are at risk of submerging. Exposed littoral coastlines are expected to respond to sea level rise through a different equilibrium profile. If no additional sediment is supplied, this new equilibrium will be land inwards, causing erosion rather than inundation. Sloping coastlines are for obvious reasons not at high risk of inundating.

Salt water intrusion

The hazard of salt water intrusion reflects the possibility of salty sea water penetrating into coastal surface waters and groundwater aquifers. The intrusion of saline water can pose a big threat to the fresh water availability, agriculture and ecosystems. While the salt water intrusion of coastal surface waters and the intrusion of groundwater aquifers are two different processes, and furthermore are largely related to human water abstraction, the CHW combines both of them in a single hazard evaluation based solely on the natural characteristics of a coastline.

The risk of salt water intrusion depends on different factors such as coastal geology, aquifer dimensions, groundwater withdrawal, surface water recharge, submarine groundwater discharge and local precipitation. Flat coasts are typically more susceptible for salt water intrusion as inundation, erosion and retreating shorelines increase the land inwards effect that high sea levels and waves have, and reduce the area available for groundwater recharge. Deltas and estuaries are extra at risk, due to changing hydrological regimes with more extremes and subsidence processes. Especially areas with a sediment deficit will be at risk. Small islands are expected to face increased problems due to depleting fresh water lenses, caused by groundwater extraction, sea level rise and limited recharge.

This being said, saltwater intrusion is a complex process, strongly related to human water extraction and interventions in the natural system, which are not included in the CHW.

Erosion

Coastline erosion depends on multiple natural factors, with geological layout, coastal slope, wave energy and presence of vegetation being the most important ones. Geological layouts of sedimentary origin have a higher erodibility than hard rock coastlines. Coastlines with a low slope generally retreat faster than steeper coastlines, although soft rock cliffs are expected to face increased erosion rates in the future due to a rising sea level, higher groundwater levels and possibly more extreme precipitation events.

Barrier coastlines might migrate landwards due to sea level rise, and can even breach due to overwash and sediment loss. Since barriers form an important protection for the lagoon or coast behind it, this would have major impacts for the erosion and flooding hazards.

In exposed littoral environments, erosion is a key parameter for sediment transport. High wave energy causes large quantities of offshore and longshore sediment transport, and in case of a sediment deficit, this will lead to a retreating coastline. Sea level rise will increase the required amount of sediment to sustain the location of the coastline, and an increased frequency of extreme weather events will lead to more episodic erosion events. In protected coastal environments, the erosion processes are dominated by the tides and presence of vegetation. Marsh and mangrove vegetation can trap sediment and protects the soil during extreme events. Vegetation also plays an important role on sloping coasts, decreasing runoff, and reducing the wave impact.

Reduced calcification rates may lead to a reduced coral stability, which may lead to more wave energy reaching the shore. The expectation is that rising sea levels combined with increased storm intensity will lead to significant erosion of coral islands.

Flooding

The inherent flood hazard reflects the possibility of a sudden and often dramatic inundation of a coastal environment due to a short term increase in water level. For a large part, this is determined by the geological layout, especially the elevation. Low lying areas such as coastal plains, barriers, deltas and coral islands have a relatively high vulnerability. Especially deltas, where the high water levels can come from both the sea as from extreme peak river flows, have a high flooding hazard.

The tidal range also influences the flooding hazard. In general, the flooding risks will increase with decreasing tidal ranges. Because the probability that a storm will occur exactly during high tide is relatively low, macro tidal often have a larger buffer zone before the water level will exceed the normal high tide level. In micro tidal environments there usually is very little space to intercept the increased water level. Since tropical cyclone intensity is predicted to increase, this will increase the flooding hazards.

Marshes and mangroves are often flooded as part of their natural dynamics, and have a well-known protective function for the hinterland. Degradation of these systems, due to natural or human induced processes, will create a more vulnerable situation.

7.3 Hazard management options

The CHW evaluates the applicability of 16 coastal management options frequently used all over the world, based on the physical characteristics of a certain generic coastal environment. Figure 11 gives a matrix that provides the management options for each of the 131 coastal environments and which hazard type they primarily address. By combining this matrix with the hazard maps, or any specific area of interest, the most suitable coastal management options can be identified. Another essential parameter in the design of a coastal management strategy is the financial aspect. The costs of certain measures can vary significantly for different locations, due to differences in local labour costs, material costs and construction techniques. Therefore a reliable cost estimation is not possible to include. Only a rough, quantitative indication is given in the section below. Among the coastal management options are hard protection measures, soft protection measures and accommodation approaches, which are defined as follows:

Ecosystem disruption	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
PL/BA/DE-1														X		X
PL/BA/DE-2														X		X
PL/BA/DE-3														X		X
PL/BA/DE-4														X		X
PL/BA/DE-5														X		X
PL/BA/DE-6														X		X
PL/BA/DE-7														X		X
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PL/BA/DE-10											X			X		X
PL/BA/DE-11											X			X		X
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CI-11											X			X		
CI-12											X			X		
TSR											X			X		X

Gradual inundation	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
PL/BA/DE-1						X		X								X
PL/BA/DE-2						X		X								X
PL/BA/DE-3						X		X								X
PL/BA/DE-4						X		X								X
PL/BA/DE-5						X		X								X
PL/BA/DE-6						X		X								X
PL/BA/DE-7						X		X								X
PL/BA/DE-8						X		X								X
PL/BA/DE-9						X					X					X
PL/BA/DE-10						X					X					X
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CI-12						X					X					
TSR								X								

Salt water intrusion	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
PL/BA/DE-1						X			X						X	X
PL/BA/DE-2						X			X						X	X
PL/BA/DE-3						X			X						X	X
PL/BA/DE-4						X			X						X	X
PL/BA/DE-5						X			X						X	X
PL/BA/DE-6						X			X						X	X
PL/BA/DE-7						X			X						X	X
PL/BA/DE-8						X			X						X	X
PL/BA/DE-9						X					X				X	X
PL/BA/DE-10						X					X				X	X
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TSR							X								X	

Erosion	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
PL/BA/DE-1	X	X		X	X			X	X							X
PL/BA/DE-2	X	X		X	X			X	X							X
PL/BA/DE-3	X	X		X	X			X	X							X
PL/BA/DE-4	X	X		X	X			X	X							X
PL/BA/DE-5	X	X		X	X			X	X							X
PL/BA/DE-6	X	X		X	X			X	X							X
PL/BA/DE-7	X	X		X	X			X	X							X
PL/BA/DE-8	X	X		X	X			X	X							X
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SR-5	X	X		X	X			X		X					X	
SR-6	X	X		X	X			X		X					X	
SR-7	X	X		X	X			X		X					X	
SR-8	X	X		X	X			X		X					X	
SR-9	X	X		X	X			X		X					X	
SR-10	X	X		X	X			X		X					X	
SR-11	X	X		X	X			X		X					X	
SR-12	X	X		X	X			X		X					X	
SR-13	X	X		X	X			X		X					X	
SR-14	X	X		X	X			X		X					X	
SR-15	X	X		X	X			X		X					X	
SR-16	X	X		X	X			X		X					X	
SR-17										X					X	
SR-18										X					X	
SR-19										X					X	
SR-20										X					X	
FR-1																
FR-2																
FR-3	X	X						X								
FR-4	X	X						X								
FR-5																
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FR-7	X	X						X								
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R-2	X	X						X								
R-3																
R-4	X	X						X								
CI-1	X	X		X	X			X								
CI-2	X	X		X	X			X								
CI-3	X	X		X	X			X								
CI-4	X	X		X	X			X								
CI-5	X	X		X	X			X								
CI-6	X	X		X	X			X								
CI-7	X	X		X	X			X								
CI-8	X	X		X	X			X								
CI-9				X	X						X					
CI-10				X	X						X					
CI-11				X	X						X					
CI-12				X	X						X					
TSR			X					X			X					X

Flooding	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
PL/BA/DE-1						X			X			X	X			X
PL/BA/DE-2						X			X			X	X			X
PL/BA/DE-3						X			X			X	X			X
PL/BA/DE-4						X			X			X	X			X
PL/BA/DE-5						X			X			X	X			X
PL/BA/DE-6						X			X			X	X			X
PL/BA/DE-7						X			X			X	X			X
PL/BA/DE-8						X			X			X	X			X
PL/BA/DE-9						X					X	X	X			X
PL/BA/DE-10						X					X	X	X			X
PL/BA/DE-11						X					X	X	X			X
PL/BA/DE-12						X					X	X	X			X
PL/BA/DE-13						X					X	X	X			X
PL/BA/DE-14						X					X	X	X			X
PL/BA/DE-15						X					X	X	X			X
PL/BA/DE-16						X					X	X	X			X
PL/BA/DE-17						X					X	X	X			X
PL/BA/DE-18						X					X	X	X			X
PL/BA/DE-19						X					X	X	X			X
PL/BA/DE-20						X					X	X	X			X
PL/BA/DE-21						X					X	X	X			X
PL/BA/DE-22						X					X	X	X			X
PL/BA/DE-23						X					X	X	X			X
PL/BA/DE-24						X					X	X	X			X
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FR-10						X						X	X			
FR-11						X						X	X			
FR-12						X						X	X			
FR-13						X						X	X			
FR-14						X						X	X			
FR-15						X						X	X			
FR-16						X						X	X			
FR-17						X						X	X			
FR-18						X						X	X			
FR-19						X					X	X	X			
FR-20						X					X	X	X			
FR-21						X						X	X			
FR-22						X						X	X			
R-1																
R-2																
R-3																
R-4																
CI-1						X						X	X			
CI-2						X						X	X			
CI-3						X						X	X			
CI-4						X						X	X			
CI-5						X						X	X			
CI-6						X						X	X			
CI-7						X						X	X			
CI-8						X						X	X			
CI-9						X					X	X	X			
CI-10						X					X	X	X			
CI-11						X					X	X	X			
CI-12						X					X	X	X			
TSR						X	X				X	X				

Figure 11: Matrix of hazard management options for all coastal environments of the CHW, as in Appelquist & Halaes (2015)

Hard protection measures

The traditional "engineering" approach. The use of hard structures to create a solid barrier that resists wave and tide energy and limit the land-sea interaction.

Breakwaters: shore-parallel structures positioned just offshore the surf zone to intercept incoming waves. By reducing incoming wave energy, they mainly address the erosion hazard and to a lesser extent the flooding hazard. They can lead to sand deposition in the lee-side of the structure, but they to be relatively large and robust, and may lead to erosion further downstream the littoral drift.

Groynes: hard structures perpendicular to the coast to trap longshore sediment transport to address erosion. The downsides are the possibility on sediment starvation downstream, and the formation of rip currents adjacent to the groynes that can lead to sediment loss and dangerous situations for swimmers.

Jetties: Very comparable to groynes, but constructed at river mouths to stabilize one or both sides from shifting position and prevent sand from blocking the inlet. Usually bigger in dimensions than groynes, the can lead to major setbacks in the coastline downstream.

Revetments: shore-parallel, sloping structures constructed landwards of the beach in order to protect the coast against wave impact. They address the erosion hazard, and depending on the design also the inundation and flooding hazards.

Sea walls: Vertical or sloping, shore-parallel structures designed to address erosion and flooding hazards. Vertical designs cause more reflection of incoming wave energy and may lead to scouring of the beach in front of the wall, while sloping designs are more capable of disseminating the incoming energy.

Dikes: Shore-parallel features, often build of unconsolidated material, mainly to address the flooding hazard in low lying areas. They might be combined with harder protection structures such as revetments to prevent erosion.

Storm surge barriers: Large scale, movable or fixed structures in river mouths, tidal inlets and harbours which can be closed during extreme water levels to prevent coastal flooding. They can be easily integrated with other defence structures but have very high construction costs.

Figure 12 Different types of hard coastal protection measures.

Not only are the costs of measures highly depended on their dimensions, design and physical context, they also vary highly between different countries. Hillen *et al*. (2010) compared the costs of sea dikes in different countries around the globe, and estimated the total engineering costs between €4 – €21,6 million/km for every meter of dike height in the Netherlands, and €0,75 - €1,2 million/km in Vietnam. In general it can be stated that hard constructions require both relatively high investment costs and operation and maintenance costs.

Often projects executed by international companies can be 10-50% more costly in developing countries because they are regarded as having a higher business risk.

Soft protection measures

Soft protection measures provide a more holistic approach than the ad hoc hard protection measures, and are designed to fit in the landscape without intervening in the natural dynamics of the system that may cause problems downstream.

Beach nourishments: the artificial deposition of sediment on the beach or in the nearshore zone. The natural dynamics will cause the sediment to spread gradually over the coastline, addressing erosion, gradual inundation and flooding hazards. A well-known form of building with nature.

Dune construction/rehabilitation: The use of fences or vegetation to trap aeolian sediment transport, and to stabilize the soil from washing and blowing away to reinforce dune formation.

Cliff stabilization: reducing cliff erosion due to precipitation, groundwater seeping and wave impacts. By planting vegetation, improving the drainage of precipitation and groundwater, and possibly terracing, cliffs can be reinforced and erosion hazards decrease.

It is difficult to compare the cost of soft protection measures with hard protection measures, since they do not result in the same reduction in hazards. They work in different ways, but since soft protection measures generally use local building materials and use the natural dynamics to do a large part of the "work" (building with nature), they are generally at lower costs than the hard engineering approaches.

Accommodation approaches

Measures that do not reduce the inherent hazard itself, but increase the society's resilience and ability to cope with the effects of extreme events are called accommodation approaches. Since the very diverse natures of the different accommodation approaches, it is not possible to give a proper cost estimation.

Wetland restoration: By intercepting wave and tidal energy and trapping sediment, wetlands, marshes and mangroves can form an important first defence line during extreme events. A very cost-effective way to mitigate ecosystem disruption, erosion and flooding hazards.

Flood warning system: Early detection and preparation of flood events. These systems allow the public and relevant institutions to take appropriate measures and therefore reduce the exposure to flood events.

Flood proofing: Reducing the impacts of flood events on physical structures. The "wet-approach" is to allow flood water to easily access and exit a structure in order to minimize damage, to use water resistant or floating materials and to elevate crucial components. The "dry-approach" is to make structures water tight or impermeable.

Coastal zoning: Depending on local conditions, a coastal area is divided in different zones where certain activities can be allowed, allowed with permission, or forbidden. Coastal zoning can be used in relation to economic development, tourism and conservation.

Two other management strategies that are included in the CHW but that cannot be captured in the categories above are groundwater management and fluvial sediment management. Groundwater management, which can be both enhancing (artificial) groundwater recharge or regulating the groundwater abstraction, is vital to address the salt water intrusion of groundwater aquifers. Managing fluvial sediment deals with silted up rivers and reinforces river banks, coastlines and deltas, and therefore reducing the erosion, inundation and flooding hazards.

8. Choice of Geo-Information software

While the CHW methodology is designed to be applicable in developing countries where resources and knowledge can be very limited, both previous case studies in Djibouti and India were still performed manually with ArcGIS, commercial Geo-Information software. This requires both a license as expertise, and comes with certain restrictions which could pose obstacles for a successful and convenient application of the CHW. A lot of free and open source Geo-Information (GI) software alternatives exist, which come with several user benefits besides the gain of not having to pay license fees (Steiniger & Bocher, 2009). An automated version of the CHW system should be able to work with different data sources, and be capable of executing terrain analysis, image classification, interpolation- and overlay tools, and raster calculations. Furthermore it should be relatively user friendly and able to process large datasets.

Quantum GIS (QGIS) is generally considered as one of the most promising open source alternatives for commercial software, offering a broad spectrum of analysis and visualization capabilities (Steiniger & Hay, 2009; Neteler *et al*., 2010; Blake & Morse, 2016). Furthermore it has the advantage of a robust network of developers, continuing to improve the applications and keeping up with new developments (Blake & Morse, 2016). QGIS provides an effective interface for the GRASS GIS package, can be coupled with the statistic software R, offers customization options such as Python scripting, and has one of the largest user communities (Steiniger & Hay, 2009). This makes it technically capable to do the job, and makes it one of the best documented and user-friendlier options in the field of GI-software. All the data sources and geo-analysis tools used in this research are compatible with QGIS, improving its potential compared with the commercial ArcGIS software.

The newest development in the field of satellite imagery analysis has to be the emerging cloud platforms. The enormous growth in satellite data created more demands in storage and computation possibilities, in order to enable analysis of planetary-scale data (Donchyts *et al*., 2016). The leading initiative in this field is the Google Earth Engine, a platform for scientific analysis and visualization of geospatial datasets, both for public benefit and for business and government users. Earth Engine stores satellite imagery, organizes it, and makes it available for the first time for global-scale data mining. The public data archive includes historical earth imagery going back more than forty years, and new imagery is collected every day (Google Earth Engine Team, 2015). Earth Engine also provides APIs in JavaScript and Python, as well as other tools, to enable the analysis of large datasets (Mclnerney & Kempeneers, 2015). The huge advantage is that all data is stored and processed on Google's servers. Users only need an internet connection and a Google account. No data storage or GI-software is required, the analysis could even be run from a tablet or smartphone.

The CHW methodology was captured in a GI model. When improvement of input layers required the analysis of primary satellite imagery products, the Google Earth Engine was used to create the desired input layers, which were then imported in the model.

9. Automated multi-hazard assessment

The process of investigating the potential of the Coastal Hazard Wheel as an objective (semi-) automated model consists out of three phases. First the usability of existing, ready-to-use datasets which require no or very limited corrections or adjustments will be investigated. For each input layer, the most used suitable data sources will be presented, and their main limitations will be discussed. Flow charts of the model's decision tree for the construction of the different input layers can be found in Appendix A. The second phase investigates possible remote sensing techniques to minimize or overcome the limitations discovered in phase one. Both the effect on individual input layers as the effect on the hazard assessment will be evaluated. The final phase is to check whether the model is applicable and accurate outside Bangladesh. Being globally applicable is one of the strong features of the Coastal Hazard Wheel, and the model should therefore be tested in different environments. Therefore Appelquist's case study in Djibouti (2014) will be replicated

9.1 Input layers

In line with the CHW principles, only open source data is used. An overview of all used data and their sources can be found in Table 1 (page 33). The data collection and processing necessary for improving the input layers was done in the Google Earth Engine. Results of this analysis can directly be exported and included in the QGIS model. Different circumstances might require a different use of model parameters, but all model components were designed in a way that the user only has to change a few basic threshold values. The Google Earth Engine enables a very user friendly programming interface, and any changes in threshold values can directly be visualized. In this way, the amount of required expertise remains very low.

Geological Layout

The basis of this input layer has to be a geological/soil map. The Global Lithology Map (GLiM) from the Environmental Systems Research Institute (ESRI) and Soilgrids from the International Soil Reference and Information Centre (ISRIC) provide global maps of the rock and sediment types with a spatial resolution of 250m. Looking at geological layers, this resolution provides sufficient detail, and these layers can be used to differentiate between the "hard- and soft rock" classes of the CHW.

To differentiate between flat and sloping coasts, a Digital Elevation Model (DEM) is required. The Shuttle Radar Topography Mission (SRTM) produced an unrivalled dataset of global elevations with a spatial resolution of 30m (USGS, 2007). Though the standard vertical uncertainty can vary up to 16 meters, an accuracy assessment proved that the average absolute vertical errors are significantly lower (Gorokhovich & Voustianiouk, 2006). Furthermore errors mainly occur on slopes steeper than 10 degrees, caused by the diffuse nature of the reflected radar waves. Since the CHW methodology distinguishes between flat and sloping areas around 3-4% (corresponds with a 1,4-1,8 degree slope), most of the errors will fall outside the areas of interest and are not expected to significantly influence the classification.

Areas of interest, such as river mouths, coral reefs and estuaries are identified using separate datasets. USGS HydroSHEDS offers a global dataset of hydrographic information including rivers networks. Locations where the rivers meet the coastline are defined as river mouth. The most comprehensive global dataset of coral reefs to date originates from the United Nations Environmental Program (UNEP), with a spatial resolution of about 500m (UNEP-WCMC, 2010). UNEP also supplies the Global Estuary Database, including all major delta- and lagoon systems (Alder, 2003).

Limitations

Some of the more specific geological characteristics; barriers, tidal inlets and sand spits, could not be recovered from open source datasets. Therefore they cannot be included in the automated classification. These characteristics form generally dynamic landscape features, and the fact that they cannot be included will lead to an underestimation of the hazard assessment. But since they generally only make up a small share of the coastline, this underestimation will be limited.

A second limitation is caused by the nature of the SRTM. The radar waves used to measure the elevation cannot penetrate through dense canopy cover, causing it to be a surface model rather than an elevation/terrain model (Figure 13 left). Because a large part of the coastal zone of Bangladesh has very small elevation differences, this problem becomes very evident (Figure 13 right). Errors due to closed tree canopies are a recognized problem, but not easy to correct (Baugh *et al*., 2013).

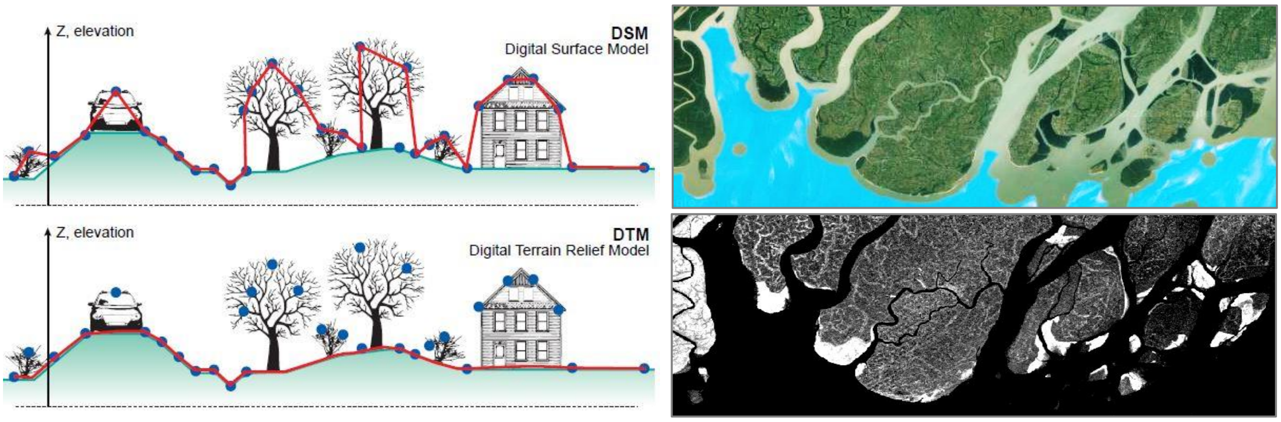


Figure 13: **Left**: The difference between a surface- and an elevation/terrain model (ACP-EU). **Upper right**: Satellite imagery of a typical coastal environment, showing patches of mangroves and agricultural areas. **Lower right**: SRTM derived elevation map of the same area in greyscale: black resembles MSL, lighter colors indicate relative height

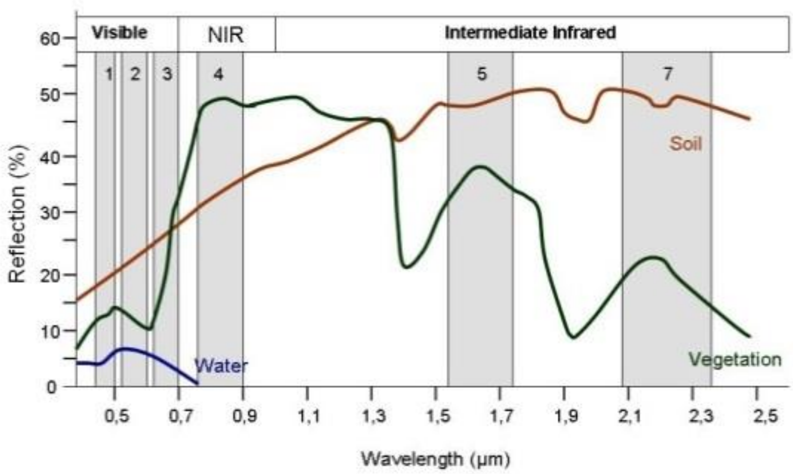
SRTM vegetation removal

Following from the CHW class definitions, coasts that reach an elevation of 8m above MSL in within a 200m coastal zone are classified as sloping. Therefore the vegetation height errors in the DEM cause a lot of regions to be incorrectly classified as sloping coasts. This will happen only in the areas where trees occur on or around MSL.

Two interesting DEM-correction efforts were found. Lefsky (2010) created a global forest canopy height map from moderate resolution imaging spectroradiometer (MODIS) and the Geoscience Laser Altimeter System data. It predicts the 90th percentile height of tree patches. The aim of this effort was to map carbon pools, but Baugh *et al*. (2013) investigated its potential for DEM-correction. In this research, conducting hydrodynamic modelling in the Amazon, it was suggested that subtracting 50-60% of the estimated canopy height would significantly improve the SRTM DEM performance

(Baugh *et al*., 2013). Pengra *et al*. (2015) validated a Landsat derived global reference database for tree cover with an impressive 30m spatial resolution (Sexton *et al*., 2013). For each raster cell, the percentage of tree cover is estimated. Pengra concluded an overall accuracy of 90,6% based on a case study in South America.

Besides evaluating these two existing datasets, an effort was made to derive the areas that were falsely classified as elevated due to tree cover directly from primary open source imagery. A lot of research on tree detection is being conducted, and high density LIDAR data is generally accepted as the most state of the art and accurate data source (Eysn *et al*., 2015; Ferraz *et al*., 2016; Paris *et al*, 2016). Unfortunately this is not a viable option for most data scarce areas. Looking at optical-based imagery instead, texture- or object based analysis would be the best alternative method, having the advantage to not only look at pixel based reflection values but also at the spatial context (Hay & Castilla, 2008; Jakubowski *et al*, 2013; Lui & Coomes, 2015). The options for object based analysis are however limited in open source GI-software, most research in this field is conducted using specialized commercial software packages such as eCognition (Jakubowski *et al*., 2013). Therefore the focus was on the use of vegetation indices. Every surface type has its own unique reflection 'signature' that can be captured by multispectral sensors (Figure 14). Spectral indices make use of the specific characteristics of these signatures, and are an easy and commonly used tool to differentiate between different surface types. The normalized difference vegetation index (NDVI) makes use of the chlorophyll's relatively low reflection of 'red' visible wavelengths (400-700 nm) and high reflection of the near infrared (NIR) wavelengths (700-1100 nm). The NDVI is a value between -1 and 1, with higher values indicating a higher vegetation density. Currently the NDVI is mainly applied in precision agriculture (Wu *et al*., 2009; Pena-Yewtukhiw, 2016).



$$NDVI = \frac{(\mathrm{NIR} - \mathrm{red})}{(\mathrm{NIR} + \mathrm{red})}$$

$$NDWI = \frac{(\mathrm{NIR} - \mathrm{IR})}{(\mathrm{NIR} + \mathrm{IR})}$$

Figure 14: Spectral signatures for Soil, water and vegetation (Seos, 2015), the 7 bandwidths measured by Landsat 7, and the formulas for the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI)

Landsat7 ETM+ imagery was used to derive the NDVI values. In order to account for data gaps due to cloud cover and shades, the Landsat 7's infamous striping errors, and to reduce the impact of seasons, weather, and extreme events, data from 135 images between 2010 and 2016 were included in the NDVI analysis. The derived NDVI value corresponds with the amount of chlorophyll/productive biomass on the surface, and can be used to distinguish between trees, low vegetation, and bare soils/water. The large amount of images considered should also be sufficient to account for errors caused by high productivity agricultural fields during the growing season. Since trees in Bangladesh are evergreen, and the crops (mainly rice) have very distinct growing seasons, it is relatively easy to make this distinction. A tree mask is derived from the NDVI data using a threshold value.

In situations where trees occur on slopes or elevated surfaces, the elevation should still be included in the slope calculations. Most hills and ridges will not be completely covered by trees, and will therefore still be detected. But to minimize any potential errors, all surfaces above 25 meters elevation are not included in the tree mask, regardless of the NDVI value. Most tree canopies occurring in areas on or close to MSL will be less than 25 meters high, while most trees on elevated surfaces will be more.

This adapted tree mask is then used to correct the DEM. Areas that fall within the tree mask are not included in the slope calculations and will be given the classification 'flat'. This will not completely fix the DEM, but should at least contribute to a better approximation of respectively the steep and flat coasts. The alternative was to fill these uncertain areas in de DEM by interpolating neighbouring cells, but some forest patches were simply too big to do this accurately. Especially in the Sundarban areas in the South West this would have been impossible.

The three options outlined above are compared in Figure 15. Lefsky's global forest canopy height dataset (13.2) proved to be too coarse and inaccurate to use for the DEM-correction. Sexton's global tree cover dataset has a suitable spatial resolution, but struggles to detect all patches of trees. Either these tree patches fall below the threshold value, or agricultural fields start to be classified as trees (13.3). As indicated by the red circles, the NDVI is able to detect all tree cover, while ignoring the highly productive agricultural fields (13.4). The NDVI-based method was therefore selected for the DEM-correction.

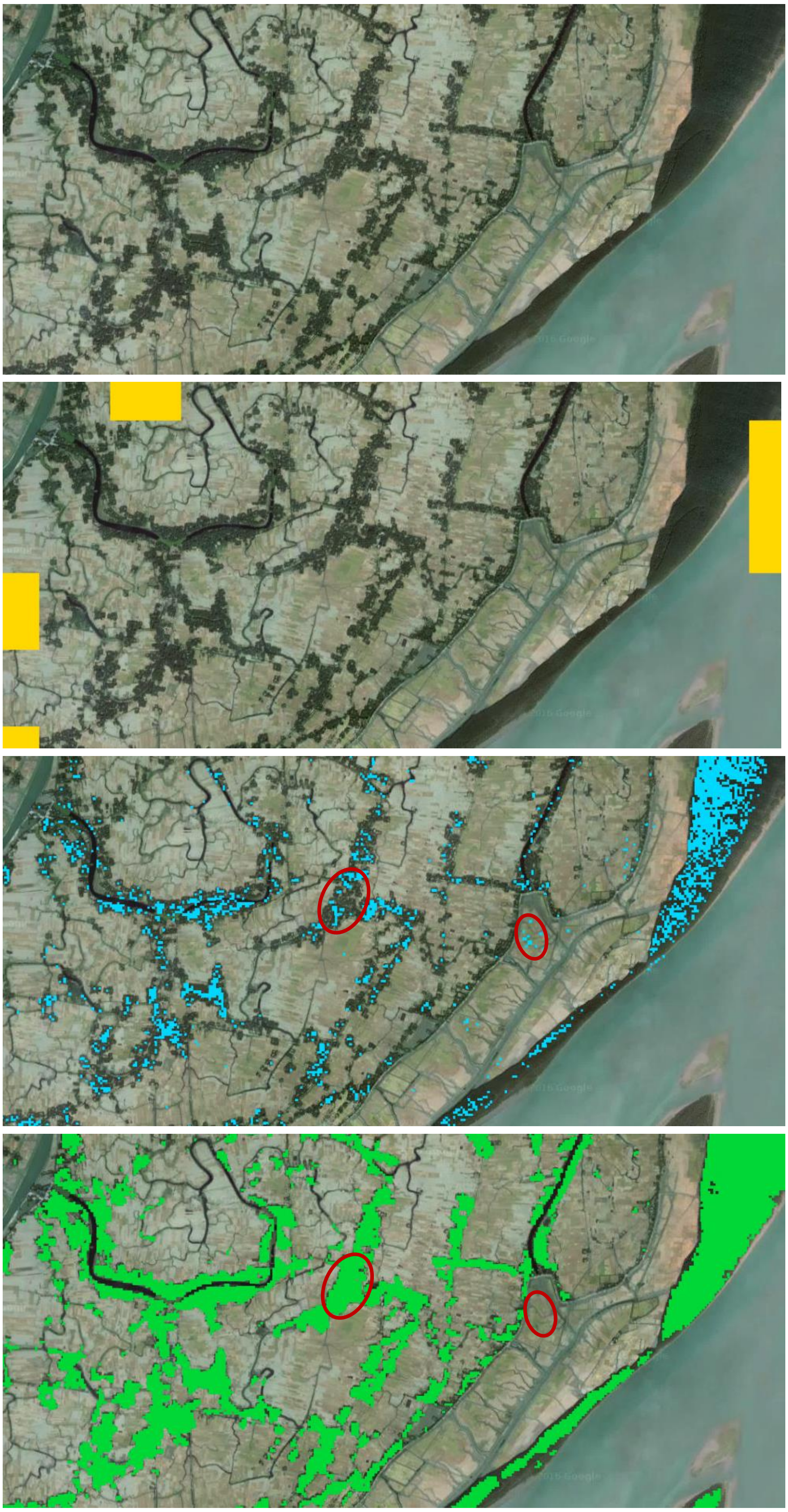


Figure 15: From top to bottom: 1) satellite imagery of a coastal polder (Rangabali) in the SC region; 2) Global forest canopy height map (Lefsky *et al*., 2010); 3) Global tree cover map (Sexton *et al*., 2013); 4) NDVI-based tree detection method, created in Google Earth Engine. The red circles indicate that the NDVI-based method (4) is able to differentiate between tree cover and high-productivity agricultural fields, while the Global tree cover map is not (3).

Wave exposure

The leading producer of open source oceanic data is the National Oceanic and Atmospheric Administration (NOAA) (Hibbets, 2011). Since the CHW classification system is based on the significant wave height, determined with the S-B-M method (Mangor, 2004), the required data for this input layer consist out of wind speed, wind duration and free fetch length. Wind duration is not globally available and therefore proofs to be a limiting factor. It would be possible to compute the significant wave height by doing a statistical analysis on NOAA's wave data, but this would require a thorough analysis, specialized software and expertise, and is beyond the scope of this research.

The model includes a digital version of Figure 9. Some protected wave environments are indicated, and all swell-and trade/monsoon areas are classified as moderately exposed. The remaining areas have to be determined by the free fetch method, as described by Appelquist & Halnaes (2015) and as applied in previous case studies.

Limitations

Using the free fetch method to estimate the wave exposure involves some manual work. The three different zones; with respectively a < 10 km, < 100km and >100 km free fetch distance, need to be assigned by hand. This is however a minor task, that does not require any extensive knowledge of coastal dynamics or GI-software other than drawing polygons.

Automated free fetch estimation

An effort was made to automate the free fetch estimation, avoiding any manual labour. Only the coastline features are necessary as input. The model verifies the distance between different land features, and when they are within a specified range, they will be connected to form one new land feature. Based on the CHW classes, these distances are defined as 10 km (protected coasts), 100 km (moderately exposed coasts) and remaining areas (exposed coasts). In this way the model creates 3 new polygons, based on the wave environments (Figure 16).

Default, once different land features are 'aggregated' together as being protected of moderately exposed, its coastline will also be classified as respectively protected or moderately exposed. The model recognizes this and will assign the coastline to a 'higher' wave environment. The island appointed by the arrow in Figure 16.2 is aggregated as protected land feature, but its west coast still is assigned as moderately exposed. This approaches a sense of direction, though it is not yet perfect.

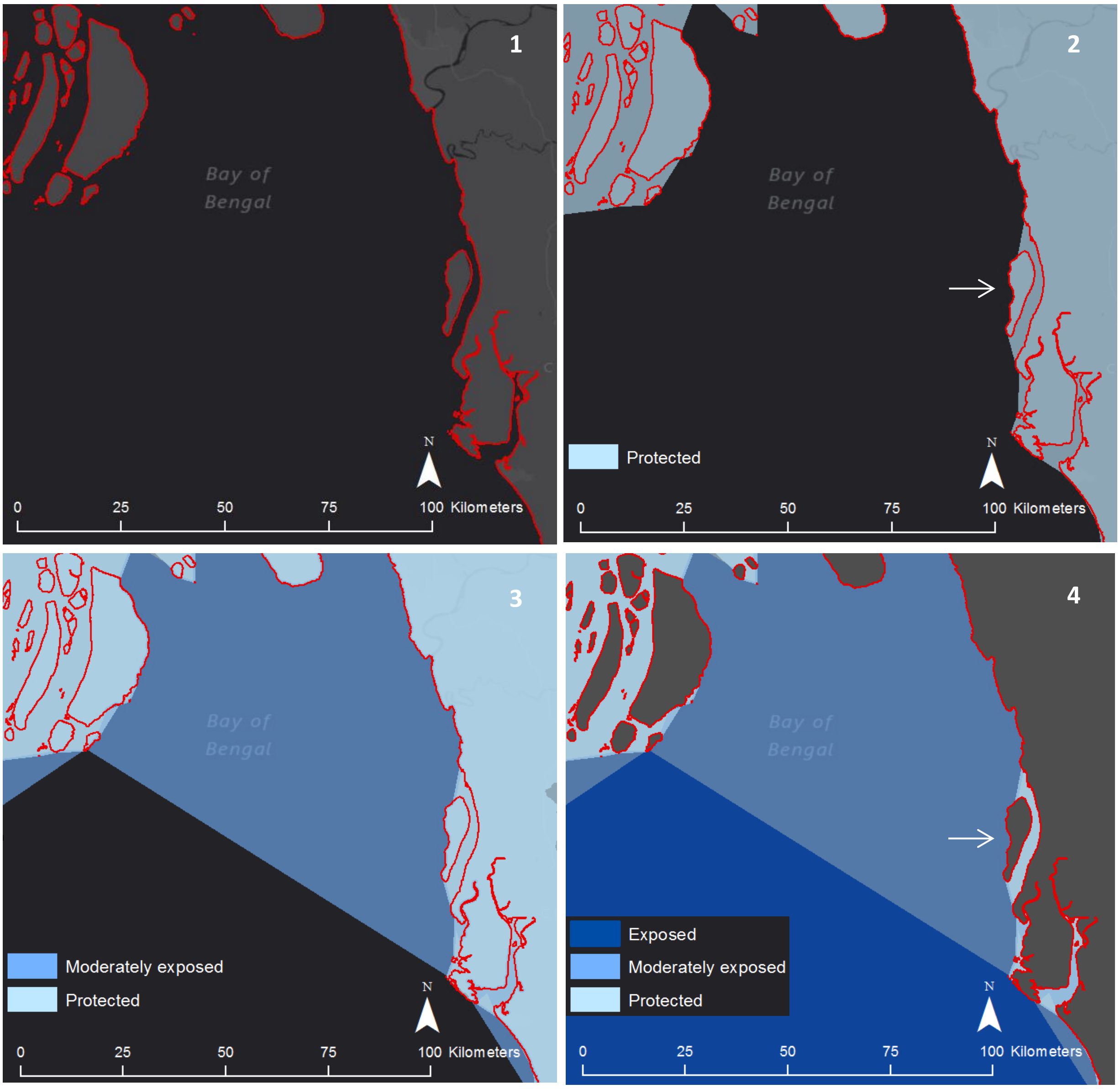


Figure 16: The intermediate steps of the automated free fetch estimation. 1) Original land features. 2) Land features within 10 km distance are connected. 3) Land features within 100 km distance are connected. 4) The final classification

Tidal range

No global datasets indicating tidal ranges were found. Again, it could theoretically be derived from NOAA's tide gauges, but it would require a lot of data, expertize, programming and a computation time that is beyond the scope of this research. Therefore, the CHW system comes with a map indicating global variation in tidal ranges (Figure 10). The model contains a digitized version of this map, preventing the need of manual actions.

Limitations: In regions where several tidal environments occur, there will be no distinctive boundary. A search for tide tables from local harbors might be a solution in order to estimate this boundary.

Interpolation of local tide data

To improve the tidal range input layer, tide charts from 12 ports in the Bay of Bengal have been imported, analyzed and interpolated in QGIS. This included some ports outside Bangladesh itself, to ensure a sensible interpolation near Bangladesh's borders (Figure 17). Spline was used as interpolation tool, creating a smooth surface while minimizing the overall surface curvatures to simulate the tidal sinusoidal.

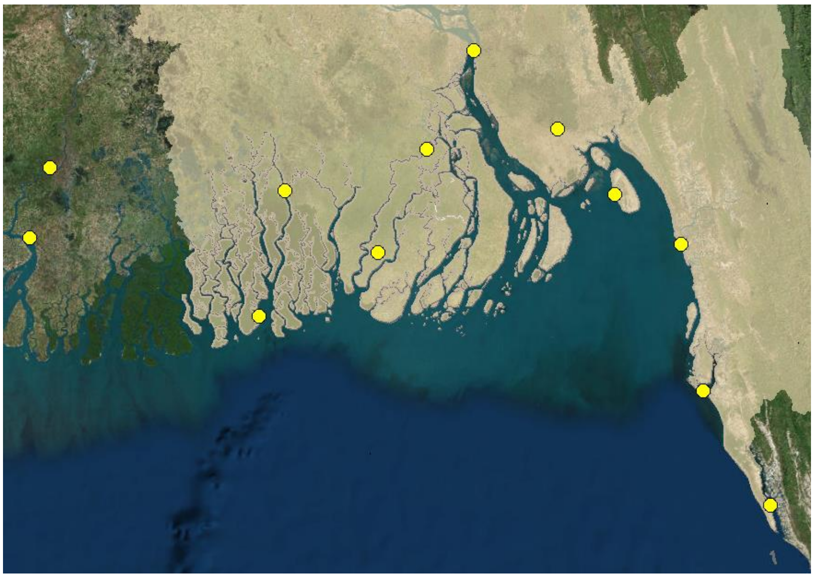


Figure 17: Locations of the interpolation points used to compute the tidal range

Flora Fauna

Global land cover and vegetation classification entered a new era whit the development of moderate resolution spectroradiometers in the early 2000's (Friedl *et al*., 2002). Several data sources were developed, with especially MODIS, SPOT VEGETATION and MERIS being worth mentioning (Friedl *et al*., 2010). These three satellites have provided valuable global land cover datasets, each with their own characteristics. Comparison shows general agreement between the different classification efforts, though spatial and temporal resolution differs slightly (Giri *et al*., 2005; Bontemps *et al*., 2009; Friedl *et al*., 2010). The datasets 'Global Land Cover', 'GLOBCOVER' and MODIS were reviewed, and although GLOBCOVER has a slightly better spatial resolution, MODIS was selected because of its high accuracy, most recent algorithm refinements and better temporal resolution (Friedl *et al*., 2010). This dataset has a spatial resolution of 500m, and differentiates between 16 different vegetation classes (excluding water and unclassified areas) (Friedl *et al*., 2010; Channan *et al*., 2014). By combining this dataset with the coral-, mangrove-, geological- and tidal data (Table 1), all the information required for the CHW classification is accounted for.

Limitations

Looking at land cover dynamics on a global or national scale, a spatial resolution of 500m provides enough detail, but looking at a small coastal strip such as the CHW system does, it results in problems. A lot of raster cells that fall partially in the ocean and partially on land will be classified as water, causing big data gaps in the coastline. Not all coastal categories of the CHW require information about the flora/fauna, but nonetheless it is a big limitation.

Filling data gaps with satellite imagery analysis

The main limitation of the Flora/Fauna input layer is the data gaps caused by the coarse resolution of the MODIS dataset. Looking at the different flora/fauna classes defined by the CHW system, the only required information to fill the data gaps is whether there is land or not, and whether this land is vegetated or not. With help of the mangrove dataset and geological-, wave-, and tidal input layers the final classification can be determined. A similar approach as the DEM-correction method is chosen. Just as chlorophyll, water and bare soil also have their own spectral signatures (Figure 14). Using Landsat 7 ETM+ imagery, the Normalized Difference Water Index (NDWI) was derived to differentiate between water and land, and the NDVI was derived to identify the vegetated areas. The wavelengths used for the NDWI are respectively 860 nm for the Near-Infrared (NIR) and 1240 for the Infrared (IR).

This results again in values ranging from -1 to 1, with higher values representing water surfaces. A threshold value will be set to differentiate between land and water surfaces. Taking a similar approach as the SRTM vegetation removal, the spectral indices were derived from a large quantity of satellite images. Besides the removal of clouds and striping, it is necessary to compensate for fluctuations in water levels. However, wet mud and tidal flats can remain challenging areas to define the land-water boundary.

Sediment balance

The GBM river complex transports huge amounts of sediment. But within the system, local shortages and erosion spots occur. Predicting local erosion and sedimentation hotspots requires extensive knowledge of the system, and is not a feasible option in data scarce areas. The CHW methodology suggests looking at past coastline trends using Google Earth and its timeline function. For each coastal section, the timeline function can be used to visually evaluate satellite imagery from different moments in time. This is an extremely labour intensive method to detect coastline movements, and furthermore Google Earth's timeline function has a very limited temporal resolution. For some locations, only a few images of varying quality are available. This gives the method a very high uncertainty due to the relatively high impact of different tide- and wave conditions, seasons, and water levels. Therefore this was not included in this case study. Because there are no datasets to support a reasonable assumption, all areas were classified as having a sediment balance/deficit, the 'worst case scenario'. This will result in an overestimation of the erosion- and flooding hazards.

Mapping coastline developments

The mapping of coastline developments was automated with use of the Google Earth Engine. By making multiple surface water masks of different moments in time, major coastline movements can be easily observed. The coastline developments were determined by comparing a surface water mask based on data from 2000 with a surface water mask of data from 2009, both derived from Landsat 7 ETM+. These years were selected because they were the years with the most cloud-free images of the coastal districts of Bangladesh. Precautions need to be taken when determining the coastline based on imagery, since waves, tide- and weather conditions can have big influence on the horizontal location of the sea-land boundary, especially on flat coasts (Donchyts *et al*, 2016). To deal for this uncertainty, the surface water masks of both 2000 and 2009 were constructed from 22 different images. The temporal resolution of these images is 16 days, spread over the whole year, making it safe to assume that they contain different tide- and weather conditions and filter out extreme events. The GBM is a very dynamic area, which makes it possible to detect significant coastal developments over a 9-year period.

The CHW-methodology only differentiates between a sediment surplus and a sediment balance/deficit. Therefore it is sufficient to identify the areas that convert from water to land, and define these as sediment surplus. All other areas automatically fall in the balance/deficit category. A minimum area-threshold was used to make sure that only the significant coastline changes were included in the input layers. In this way, small errors due to minor water table fluctuations or georeferencing are filtered out.

Storm climate

The model determines the storm climate by using Figure 9. The main simplification of this method is that it only identifies areas where tropical cyclones can occur, but it does not include the intensity and frequency of tropical storm events. However, doing so would require a whole new hazard-methodology, which is beyond the scope of this research. Therefore this is not included in this case study.

Validation

The advantage of being proclaimed "the ground zero of climate change" is that it opens a lot of funds for environmental research. Numerous efforts have been made to understand the impact that climate change will have on the coastal zone of Bangladesh. Rarely are these reports leading to any concrete implementations, but nonetheless they are a useful means to validate our multi-hazard assessment. Though different site visits have been made, time constraints and the security situation did not allow for a field campaign as a way to validate the hazard assessment. Therefore the validation will be based on an extensive literature review for each of the hazards. Additionally, the model performance will be tested on Djibouti's coastline. This case study will compare the model's accuracy with a manual classification done by Appelquist (2014), and test the model in a different coastal environment.

Table 1: An overview of the different input layers, their data requirements and the main available open source datasets

CHW classes	Data requirements	Available open source datasets*
Geological Layout		
Sedimentary plain	Geology map	GLiM (ESRI, 2013)
Flat hard rock coast	Soil map	Soilgrids (ISRIC, 2016)
Sloping soft rock coast	Elevation map	SRTM GDEM2 (USGS, 2007)
Sloping hard rock coast		
Tidal inlets/sand spits/river mouths	River dataset	USGS HydroSHEDS (Lehner *et al.*, 2006)
Delta/low estuaries	Delta dataset	Global Estuary Database (UNEP-WCMC, 2003)
Barrier islands	Coral dataset	Global Distribution of Coral Reefs, (UNEP-WCMC, 2010)
Coral islands		
Wave exposure		
Exposed coastlines	Wind speed	National Oceanic and Atmospheric Administration (NOAA)
Moderately exposed coastlines	Wind duration	
Protected coastlines	Free fetch	
Tidal range		
Macro/meso tidal ranges	Tidal information	Map provided by Appelquist (2015)
Micro tidal ranges		
Flora/fauna		
Intermittent marsh	Land cover	MCD12Q1 MODIS land cover (USGS, 2012)
Intermittent mangrove	Mangrove dataset	World Mangrove atlas (UNEP-WCMC, 2010)
Marsh/tidal flat		
Mangrove	Tidal information	Map provided by Appelquist (2015), no global datasets available
Marsh/mangrove		
Vegetated	Coral dataset	Global Distribution of Coral Reefs, (UNEP-WCMC, 2010)
Non-vegetated		
Corals		
Any		
Sediment balance		
Surplus	Coastline movements	No global datasets available
Balance/deficit		
Storm climate		
Yes	Geographic location	Map provided by Appelquist (2015)
No		

9.2 Model performance in a different coastal environment

One of the big advantages of the Coastal Hazard Wheel methodology is that it is applicable in any coastal environment around the world. Even though the model makes use of globally available datasets only, the design is based on a case study in Bangladesh. Validating the model's performance in Bangladesh only is not sufficient to evaluate its potential as a globally applicable coastal multi-hazard assessment method. The coastline of Djibouti was selected to test the applicability and performance of the model, for a number of reasons.

The most important motivation to select the coast of Djibouti is that it was subjected to an earlier case study of the Coastal Hazard Wheel, in which the author classified the coast manually based on visual interpretation of different maps and datasets. This offers the possibility of objectively comparing the model's classification with a manually performed classification. Based on this comparison, conclusions can be drawn about the model's potential for replacing the manual mapping process. An additional advantage is that it prevents the necessity of an extensive literature study, which would have been impossible within the time frame of this research. Furthermore, Djibouti is a country with a completely different coastal environment than Bangladesh. This approach will show whether the model is applicable under different circumstances. A case study of the coastline of Karnataka, India, was an alternative, but the contrast with the coastal environment of Bangladesh would have been less.

10. The CHW as coastal planning tool

10.1 The fit with local water management practices

A good start to evaluate the measures proposed by the Coastal Hazard Wheel is to compare them with the traditional water management practices in Bangladesh. Building upon local knowledge and experiences is vital for successful projects. Furthermore, water resources management and water safety are collective issues that should involve local communities and be complementary to their way of life (Dungumaro *et al*., 2003). If measure do not respect or fit in the people's livelihoods or culture, they will probably not bring resilient and sustainable solutions (Varghese *et al*., 2006). But the discussion about top-down versus bottom-up water management solutions is a touchy one, also in the coastal belt of Bangladesh (Dewan *et al*., 2014). Integrated approaches and involving local communities can be both a source of success as of failure (Rouillard *et al*., 2014; Dewan *et al*., 2015). But in any case, knowledge of the social environment and lessons learnt from successful and failed former coastal management projects are an indispensable part of any successful masterplan.

The main developments and traditions in water management in the coastal belt of Bangladesh will be analyzed based on literature, experiences of the Embassy of the Kingdom of the Netherlands in the field of water management and consultations with local experts. This will give a valuable context that will help to evaluate the measures suggested by the Coastal Hazard Wheel.

10.2 Similarities and differences with the Bangladesh Delta Plan 2100

The Bangladesh Delta Plan 2100 is currently in the final stage of its formulation. Although it is not completely uncontroversial, it is arguably the most elaborate, topical and holistic analysis of the impact of climate change on Bangladesh and provides an elaborate masterplan with several short- and long term strategies. In no sense is it the aim of this research to come to an analysis or management strategy that is in any way the equivalent of the BDP2100. The comparison is made solely in order to see how the suggestions based on a low tech tool as the Coastal Hazard Wheel relate to a multi-sectoral masterplan developed by 10 different (international) consultancies, at the cost of millions of euros, having all possible expertise and research facilities to their disposal.

Furthermore, since the BDP2100 is an official project of the General Economics Division of the government of Bangladesh and comes with an elaborate investing plan, it is reasonably likely that it will at least to some degree outline the direction the coastal management in Bangladesh will move in. This provides a unique opportunity to really evaluate the potential of the Coastal Hazard Wheel as management and planning tool.

Since the BDP2100 plan accounts for the entire country, and involves different sectors and scenarios, only the relevant water management strategies for the coastal region will be discussed. This is only a (small) component of the entire BDP2100.

Green lush rice fields, as far the eye can see – Satkhira district
Photo courtesy: Carel de Groot

Part III

RESULTS

The automated CHW methodology consists out of two parts. One is to construct six input layers from open source data, combine these, and produce a combination of coastal hazard levels. The other one is to evaluate a range of management options, including hard and soft measures and accommodation approaches, and to list the most suitable ones based on the physical characteristics. As such, a complete overview of the climate induced coastal hazards and their management options is given in an objective and reproducible manner.

11. Automated multi-hazard assessment

This chapter consists out of three different sections. First the constructed input layers of the CHW will be described. Besides the general layout, the focus will be on how the limitations of the datasets affect the input layers, and whether these limitations could be overcome. Maps of all input layers can be found in Appendix B. Secondly, the five computed hazard maps will be described, and evaluated with a literature study on each of the hazards. Finally, the model's hazard classification for Djibouti's coastline is compared with the manual classification done by Appelquist (2014). This will enlighten the ability of the model to mimic human interpretation and how well it performs for different coastline types.

11.1 Input layers

Geology Layout

The GBM delta dominates the coastal belt of Bangladesh. The delta covers the entire South West, South Central, South East and Estuary and River regions, and due to its complex coastline and many islands it covers over 92% of the total coastline. Only the Eastern Hill region falls outside the delta/estuary island category. This region has a sandy coast, only intersected by river mouths. It is a palette of sedimentary plains (4,9%) and sloping soft rock (1,56%), depending on the slope. The third category in the Eastern Hill region is the tidal inlet/sand spit/river mouth category (1,3%). A noteworthy feature is St. Martin's Island, in the far south. It is Bangladesh's only coral island, and makes up for 0,11% of the entire coastline.

The correction of the Digital Elevation Model, the removal of errors due to tree canopies, only had a very minor impact on the final classification (Table 2). In fact, the method was quite effective, with about 76% of the areas originally classified as *sloping* being corrected to *flat*. But because the correction occurred almost entirely within the delta region, where the classification system does not differentiates between different slopes, this is not reflected in the final classification. In the Eastern Hill region, where due to its topology relatively few areas occur where trees grow on or around sea level, the difference was minimal.

Table 2: Occurrence of coastline categories in the geological layout input layer

Coastline categories	Ready-to-use input dataset		Improved classification	
	Coastline length (km)	% of total coastline	Coastline length (km)	% of total coastline
Coral Island	9	0,1	9	0,1
Delta/low estuary island	7526	92,1	7580	93,6
Sedimentary plain	400	4,9	325	4,0
Sloping soft rock	127	1,6	83	1,0
Tidal inlet/sand spit/river mouth	107	1,3	101	1,2

Wave exposure

Due to the complex layout of the delta, with its many islands and chars, the vast majority of the coastline falls under the protected category (Table 3). Only the far south of the delta, directly facing the Bay of Bengal, and parts of the Eastern Hill region are classified as having an exposed wave climate. Moderately exposed wave conditions are mainly found in the ER area, where the chars and islands are relatively sheltered from the Bay of Bengal, but still face large patches of open water.

The process of automating the process of the free fetch estimation proved challenging. While the identification of protected coastlines is relatively simple, the exposed coastlines require more finesse. While the model recognizes whether other land features are within a certain range or not, including a sense of direction is more difficult. This is illustrated in Figure 18. Even though the islands are well within a range of hundred kilometres of other land features and are therefore classified by the model as moderately exposed, certain parts of the island still face the open Bay of Bengal, stretching for hundreds of kilometres. Also, since India's and Myanmar's land features were not included in the input data, some errors were observed near the borders.

Table 3: Occurrence of the coastline categories in the wave exposure input layer

Coastline categories	Ready-to-use input dataset		Improved classification	
	Coastline length (km)	% of total coastline	Coastline length (km)	% of total coastline
Exposed	493	6,1	128	1,6
Moderately exposed	1114	13,7	515	6,4
Protected	6502	80,2	7466	92,1

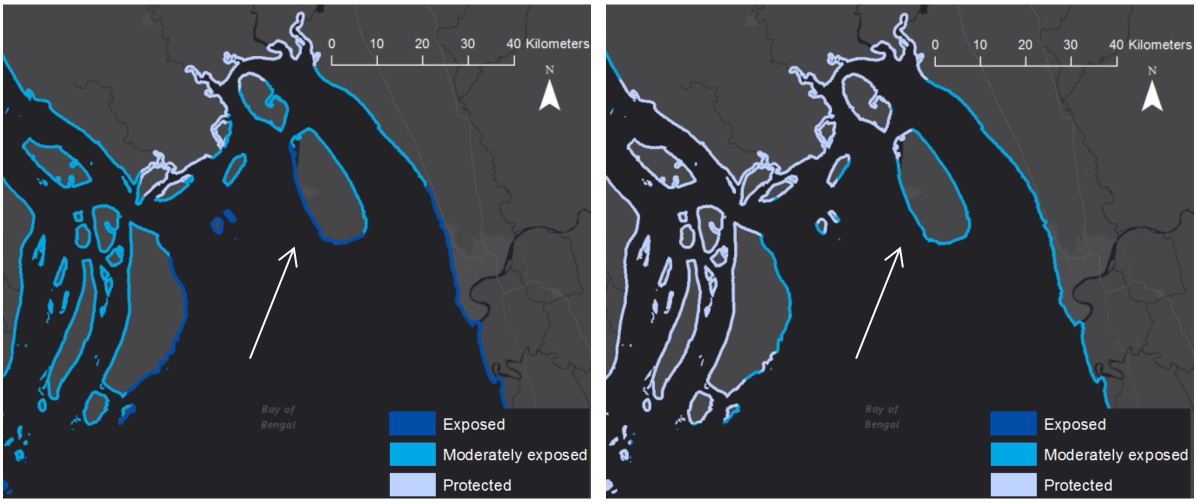


Figure 18: The manual (left) and automated (right) free fetch estimation. The white arrows indicates a possible wave direction

Tidal range

According to the map provided by Appelquist (2015), the entire coast of Bangladesh is classified as macro-tidal, which given the topological layout of the Bay of Bengal is to be expected. But within the delta, the influence of the tide will decrease when going up north due to the topology and opposing river flows. Interpolating tidal data of all main ports of the country led to some contradicting observations. First of all, according to the port data only a minor part of the coastline would fall into the category macro tidal (Table 4). Furthermore, these macro tidal areas were not located at the open coast, but were observed in the Sundarbans, over 50km away from the Bay of Bengal and upstream the Meghna river. The tidal range is influenced by a lot of factors, such as river discharge, bathymetry, river width and many more. Also the method of analysing the tide data from port measurements (extreme events versus long term averages/quartiles, return periods) is not described in the CHW methodology. Properly investigating these observations would require an amount of data collection and modelling beyond the scope of this research, and therefore no satisfactory explanation of these observations can be given at this point.

Table 4: Occurrence of the coastline categories in the tidal range input layer

Coastline categories	Ready-to-use input dataset		Improved classification	
	Coastline length (km)	% of total coastline	Coastline length (km)	% of total coastline
Macro tidal	8110	100,0	964	11,9
Meso tidal	0	0,0	7053	87,0
Micro tidal	0	0,0	94	1,2

Flora/Fauna

The coastal belt shows some very distinct vegetation zones, the most remarkable being the mangroves of the Sundarbans in the South West region. The South Central, Rivers and Estuaries and South East regions show a relatively consistent image of marshes and tidal flats, with patches of mangrove forests occurring on the southern islands. The sandier Eastern Hill coast deviates from this image, with a mosaic of vegetated and non-vegetated areas. The flora/fauna layer has relatively many data gaps. Especially the Rivers and Estuary region, where most morphological dynamics take place, proofs to be a difficult area (Figure 19), but also the Eastern Hill shows significant data gaps. The coarse resolution of the MODIS land cover dataset, and the fact that datasets of different ages do not overlap properly in dynamic regions lead to a total of almost 18% of coastline that could not be classified.

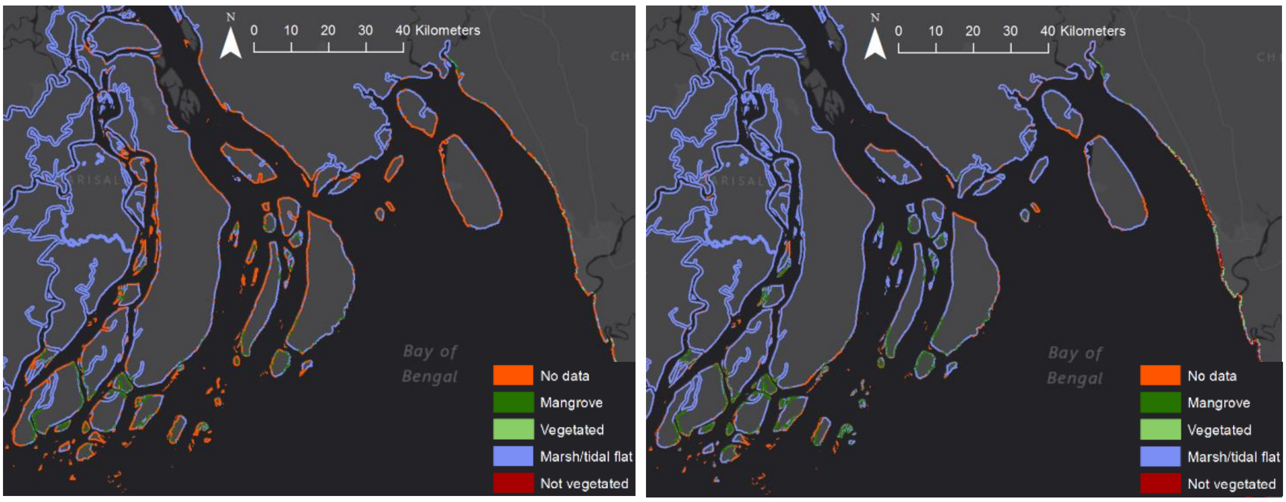


Figure 19: The majority of the data gaps in the first attempt (left) were reclassified with use of Landsat 7 ETM+ data (right)

The Landsat analysis was able to recover information for 65% of the data gaps, leaving a total of 6,3% still unclassified. Despite this significant improvement, it still is the input layer with the most classification problems (Table 5). Coastal stretches that miss necessary information to complete the decision structure of the CHW (Figure 8) will be classified as no data in the final hazard assessment. Most of the previously unknown areas were reclassified as *marsh/tidal flat*. Since these areas usually occurred in morphologically active areas this seems very plausible. But these dynamic areas remain very challenging for remote sensing, especially when different data sources need to be combined.

Table 5: Occurrence of the coastline categories in the flora/Fauna input layer

Coastline categories	Ready-to-use input dataset		Improved classification	
	Coastline length (km)	% of total coastline	Coastline length (km)	% of total coastline
No data	1457	18,0	511	6,3
Mangrove	2459	30,3	2676	33,0
Vegetated	44	0,5	62	0,76
Marsh/tidal flat	4050	49,8	4705	58,0
Not vegetated	6	0,1	157	1,9

Sediment balance

Since no reliable open source sediment datasets were available, the 'ready-to-use' dataset was simply assuming the worst case scenario. A lot of improvements could be made using land masks derived from Landsat 7 ETM+ data. The South West, South Central and Eastern Hill coastlines were classified as relatively stable, while a lot of land dynamics seem to occur in the Rivers and Esturaries- and South East regions (Figure 20). Large stretches of riverbanks of the Meghna are subject to erosion, while chars and islands appear in the river itself and in front of its river mouth. Over time the chars seem to be moving downstream, eroding on their upstream side and growing on their downstream end. The high sediment load of the Meghna creates high potential for land reclamation, and the project area of the Dutch funded Char Development and Settlement Project is clearly visible (marked by the 1).

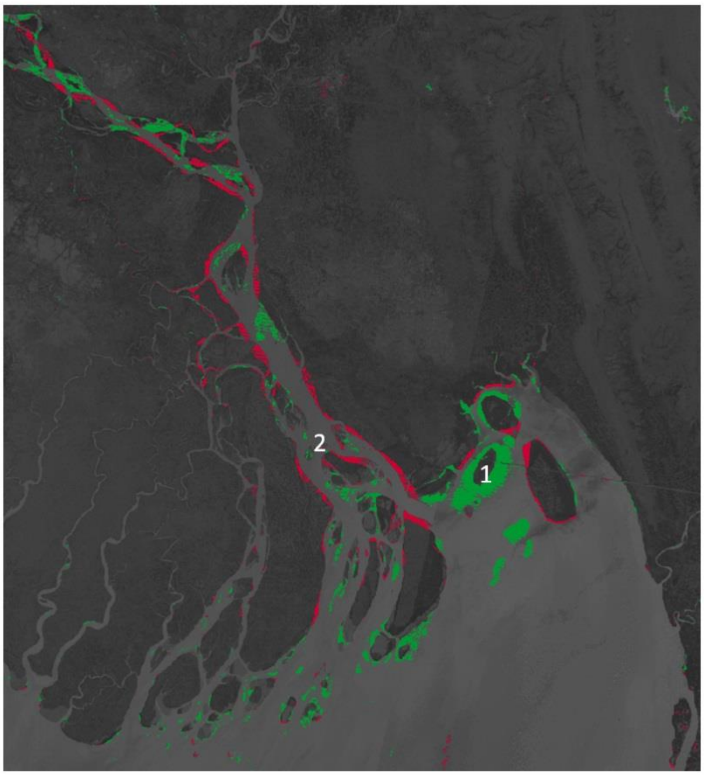


Figure 20: Land developments in the river mouth of the Meghna. Red indicates a conversion from land to water, green from water to land. 1) Area with Land reclamation projects. 2) Chars are observed moving down-stream

Table 6: Occurrence of the coastline categories in the sediment balance input layer

Coastline categories	Ready-to-use input dataset Coastline length (km)	% of total coastline	Improved classification Coastline length (km)	% of total coastline
Balance/deficit	8110	100,0	3358	41,4
Surplus	0	0,0	4753	58,6

Storm climate

As explained in the methodology, no improvements have been made to the storm climate input layer. The entire country is subjected to cyclone activity, and frequency and intensity are not included in the hazard classification.

A total of 37 coastal types were observed in the Bangladesh, out of a 131 possible CHW categories. The 10 most occurring classes can be found in Table 7. Together they make up for 93.3% of the total coastline.

Table 7: The top 10 most occurring coastal environments in Bangladesh

Geology	Wave exposure	Tidal range	Flora/fauna	Sediment balance	Storm climate	CHW class	Length (km)	% of coastline
Delta/estuary island	Protected	Meso/ macro	Marsh/ tidal flat	Balance/ deficit	Yes	DE-17	2329	28,8
Delta/estuary island	Protected	Meso/ macro	Mangrove	Balance/ deficit	Yes	DE-21	2115	26,1
Delta/estuary island	Protected	Meso/ macro	Marsh/ tidal flat	Surplus	Yes	DE-19	1237	15,3
Delta/estuary island	Moderately exposed	Any	Any	Surplus	Yes	DE-7	527	6,5
Delta/estuary island	Moderately exposed	Any	Any	Balance/ deficit	Yes	DE-5	517	6,4
-	-	-	-	-	Yes	No data	266	3,3
Delta/estuary island	Protected	Meso/ macro	Mangrove	Surplus	Yes	DE-23	176	2,2
Delta/estuary island	Exposed	Any	Any	Surplus	Yes	DE-3	153	1,9
Sedimentary plain	Protected	Meso/ macro	Marsh/ tidal flat	Surplus	Yes	PL-19	129	1,6
Sedimentary plain	Exposed	Any	Any	Surplus	Yes	PL-3	103	1,3

11.2 Hazard evaluation

This chapter describes the five different hazard assessments, discusses how the improved input layers changed the final hazard classification, and evaluates the hazard maps with findings in literature. Only the improved hazard assessment maps are displayed, maps of the initial hazard assessment (based on primary data only) can be found in Appendix C. This Appendix also gives the improved assessments and accompanying change tables, providing more insight in how the improved datasets changed the final hazard classification.

Ecosystem disruption

A clear distinction is visible between the delta area and the Eastern Hill region (Figure 21). Almost the entire delta is classified as having a very high hazard for ecosystem disruption, with only the sea facing southern edges of the delta having 'only' a moderate hazard. These southern edges and islands are typically marsh/tidal flat coasts in combination with a sediment surplus. This environment is capable of keeping up with the SLR. During each flooding event, a new layer of fine sediment is deposited, causing the marsh/tidal flat to rise together with the sea level. Vegetation is usually salt resistant, making these relatively stable coastal ecosystems. The more inland parts of the delta on the other hand does not have clear expanding land features, and was therefore classified as having a sediment balance/deficit. This hinders the wetlands to rise at an equal rate as the SLR. Enormous stretches of wetlands and mangrove forests are therefore in danger of slowly disappearing, giving them a high ecosystem disruption hazard. The sandy Eastern Hill coast is classified as a quite stable environment, with mainly low or moderate ecosystem disruption hazards. Only river mouths are classified as vulnerable.

The improvements of the input datasets mainly reduced the *no data* and very *high hazard* areas. In general these areas were reclassified as having a moderate hazard level (Table 8). The reduced data gaps in the flora/fauna layer and the improved sediment balance were responsible for these changes. Remarkable is that even in the improved classification, the Sundarbans remain almost entirely classified as very vulnerable to ecosystem disruption due to climate change (Figure 21).

Table 8: The distribution of ecosystem disruption hazard levels

Hazard level for ecosystem disruption	Ready-to-use input dataset		Improved classification	
	Coastline length (km)	% of total coastline	Coastline length (km)	% of total coastline
No data	1413	17,6	266	3,3
Low	204	2,6	497	6,1
Moderate	752	9,3	2816	34,8
High	0	0,0	0	0,0
Very high	5730	70,6	4520	55,8

This image is reflected by the scientific literature on environmental issues in Bangladesh. Most of the attention goes out to the Sundarbans. Partially because it is a unique area in the world and a global priority for biodiversity conservation, but also because it simply is very vulnerable (Payo *et al*., 2016). Salinity has severely threatened the health of the mangrove forests, and is directly linked to the top dying disease (Rahman *et al*., 2010; Mahadevia & Vikas, 2012). Sea level rise, subsidence and erosion cause wetlands to slowly disappear, and erratic monsoon raining patterns are damaging the ecology

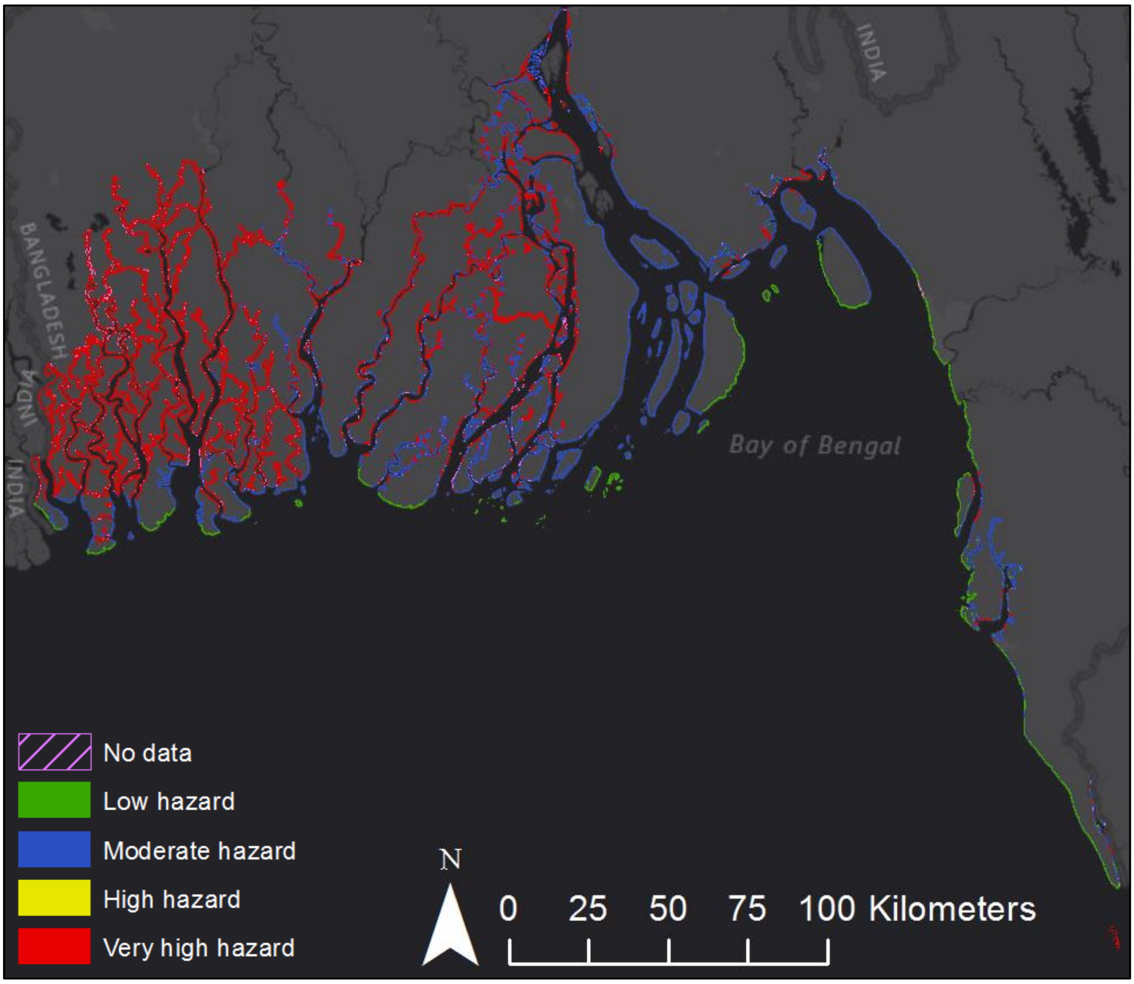


Figure 21: The spatial distribution of the ecosystem disruption hazard levels

(Mahadevia & Vikas, 2012; Payo *et al.*, 2016). These are worrying observations since mangroves form an important defense system during cyclones and storm surges, events also predicted to increase due to climate change (Englart, 2013).

This being said, another important observation from scientific literature is that even though climate change is indeed a factor of biodiversity loss, other factors are likely to play a more important role (Mamun *et al.*, 2016). Especially anthropogenic developments such as deforestation, encroachment of agricultural fields, pollution, industrialization and ineffective institutions are expected to put severe pressure on the ecosystems. Mainly driven by population pressure, industrial development, high economic interests and limited biological knowledge, these threats are not expected to decrease in the (near) future (Islam, 2005; Rahman *et al*, 2010).

Gradual inundation

As to be expected (Figure 22), the low lying delta itself is very vulnerable to gradual inundation, especially in areas with a sediment deficit, while the more elevated Eastern Hill region is considered more robust. This hazard classification shows a lot of similarities with the ecosystem disruption hazard. This is because inundation is considered one of the biggest threats to the wetland ecosystems, and is in fact the main cause of the high hazard level. Therefore they are both very interlinked, and have similar hazard maps (Figure 22). This similarity is also reflected by the changes due to the improved input layers. Areas identified as having a sediment surplus cause the inundation hazard to decrease from very high to moderate, and likewise reduced data gaps in the flora/fauna layer cause a lot of no data areas to be classified as having a moderate hazard (Table 9).

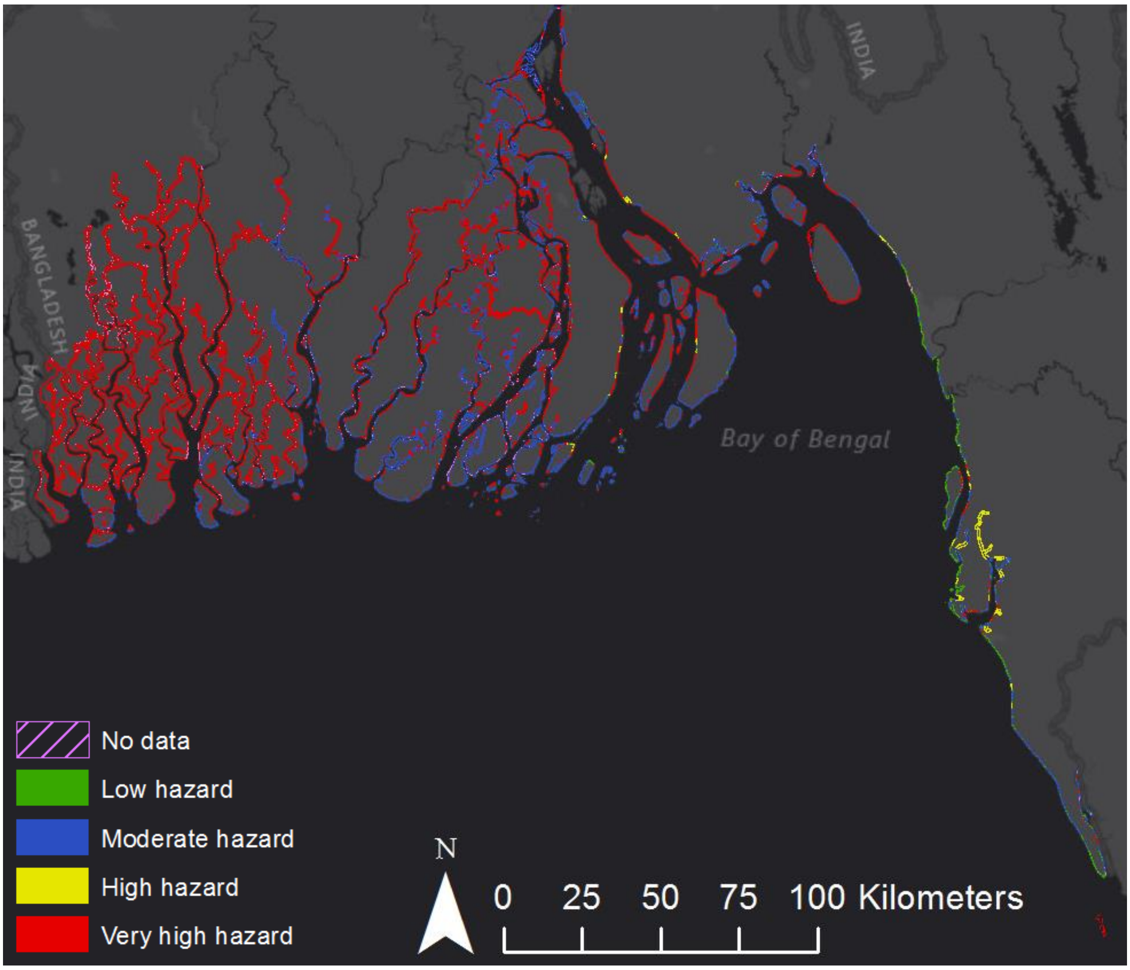


Figure 22: The spatial distribution of the gradual inundation hazard levels

Table 9: The distribution of gradual inundation hazard levels

Hazard level for gradual inundation	Ready-to-use input dataset		Improved classification	
	Coastline length (km)	% of total coastline	Coastline length (km)	% of total coastline
No data	1413	17,6	266	3,3
Low	61	0,8	208	2,6
Moderate	69	0,9	2377	29,3
High	112	1,4	128	1,6
Very high	6445	79,4	5121	63,2

Several processes increase the inundation risk, with river bed siltation and a back water effect due to sea level rise being the most important ones (Awal, 2014). The drainage problems due to siltation increased since the late 1980's, mainly due to badly designed water infrastructure, cross dams and a decreased river flow (De Die, 2013; GED, 2016). The areas that are most vulnerable to long periods of water logging are the areas adjacent to the main rivers, the haors in the north east, and the Satkhira and Khulna districts, directly north of the Sundarbans (Islam *et al*., 2010, CSIRO, 2014; GED, 2016). The direct coast area is less sensitive, possibly due to a higher sediment load from the Meghna. The hazard map shows a similar pattern, though the predicted hazard level in the inland of the South Central region seems to be slightly overestimated. Existing river embankments could be a reason why this area does not show severe inundation events in flood maps and literature, since human interference in the natural system is not included in the CHW.

Salt water intrusion

Bangladesh is a country very vulnerable for salt water intrusion. The hazard map is more homogeneous than the previous hazard classification, with roughly the entire South West, South Central, Rivers and Estuaries and South East regions classified as having a very high hazard, and the Eastern Hill as having a high hazard for salt water intrusion (Figure 23). Remarkable is that the improved input data did not change any of the hazard classifications but only filled in the data gaps (Table 10; Appendix C). Though it convincingly shows the vulnerability of Bangladesh to salt water intrusion, it is not a very useful hazard classification in terms of prioritizing certain areas.

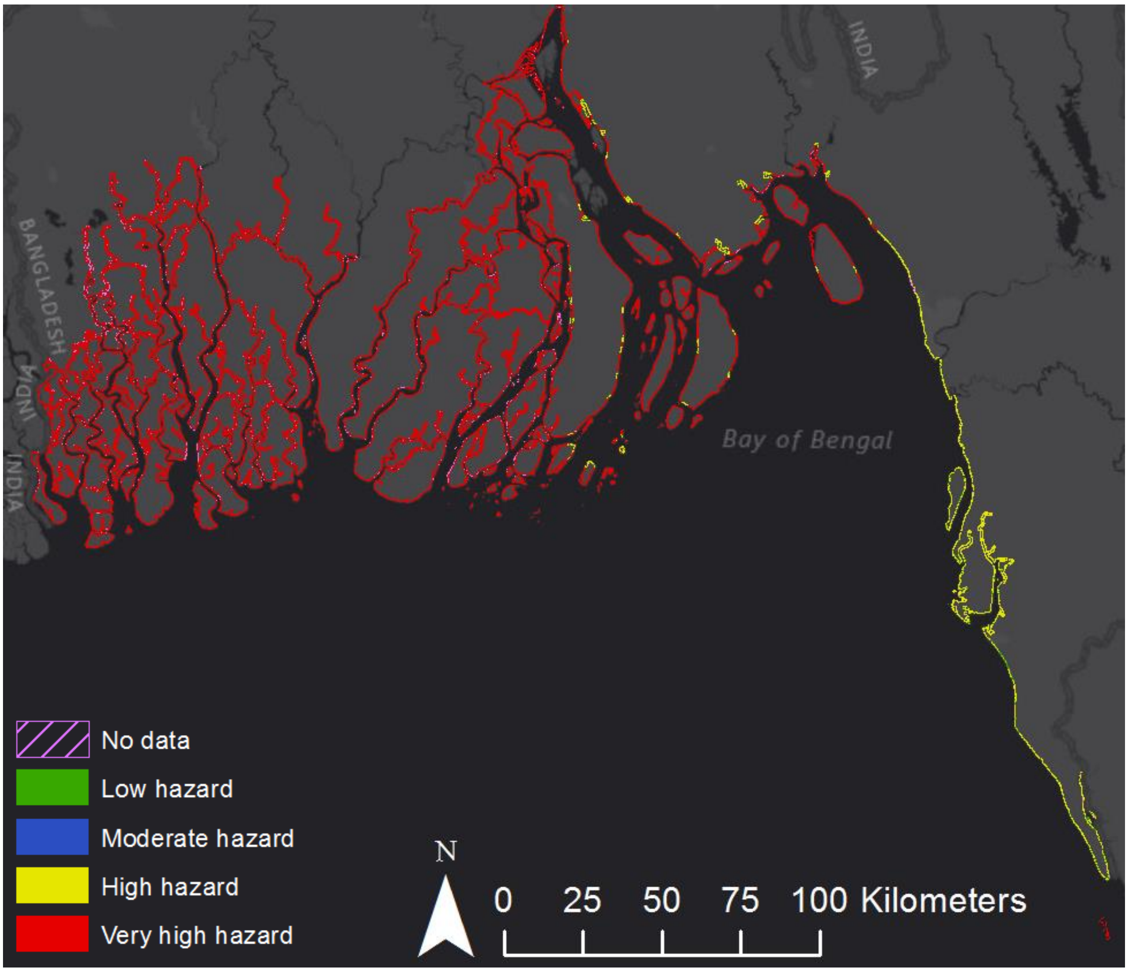


Figure 23: The spatial distribution of the salt water intrusion hazard levels

Table 10: The distribution of salt water intrusion hazard levels

Hazard level for salt water intrusion	Ready-to-use input dataset		Improved classification	
	Coastline length (km)	% of total coastline	Coastline length (km)	% of total coastline
No data	1413	17,6	266	3,3
Low	61	0,8	105	1,3
Moderate	0	0,0	0	0,0
High	267	3,3	534	6,6
Very high	6358	78,3	7194	88,8

The homogeneity of the salinity hazard is contradicting findings in literature. Practically all models identify a higher salt water intrusion in the South West region than in other regions (Figure 24) (Bashar& Hossein; Mohal *et al*.; Bhuiyan & Dutta,2012; CSIRO, 2014; GED, 2016). Obviously, SLR would have a big impact on the salt water intrusion, but other factors such as decreased river flows, land conversion to shrimp farming and groundwater exploitation cannot be disregarded. Salinization in the South West is directly linked to the river flows, and the relatively high salt water intrusion in the South West seems to be contributed to the decreased dry season flow of the Ganges (Bashar & Hossein). While other regions also receive water from the Brahmaputra and Meghna catchment areas, the South West is fed by the Ganges only. Increasing water demands in the Ganges tributaries therefore lead to an increased vulnerability in the South West.

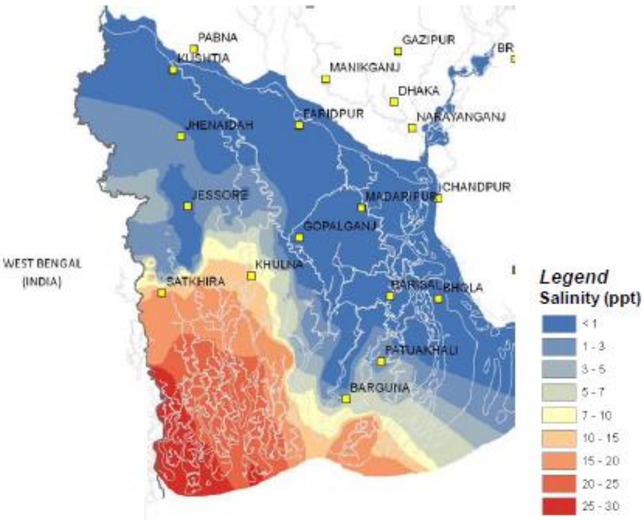


Figure 24: Salinity intrusion in south-west Bangladesh (CSIRO, 2014)

While the climate change driven SLR and more extreme drought periods are taken into account in the CHW methodology, and could very well be homogenous within the delta, it misses anthropogenic factors such as upstream water use and land use conversions. Therefore the CHW does not differentiate between the Ganges-fed South West and for example mainly Meghna-fed South East regions.

Erosion

The erosion hazard has a different geographical pattern than the other hazards, which typically have a very high classification in the delta and a low classification in the Eastern Hill region. The erosion hazard is the highest in the river mouth of the Meghna river, and along the exposed southern coastline of the Eastern Hill region. Large parts of the delta have a moderate to high erosion hazard, and only the protected coastlines along the Eastern Hill region are classified as not vulnerable (Figure 25). The improved input data led to a shift from a high to a moderate erosion hazard, mainly in the South Central region (Table 11). These are the areas where a sediment surplus was observed, obviously decreasing the erosion hazard.

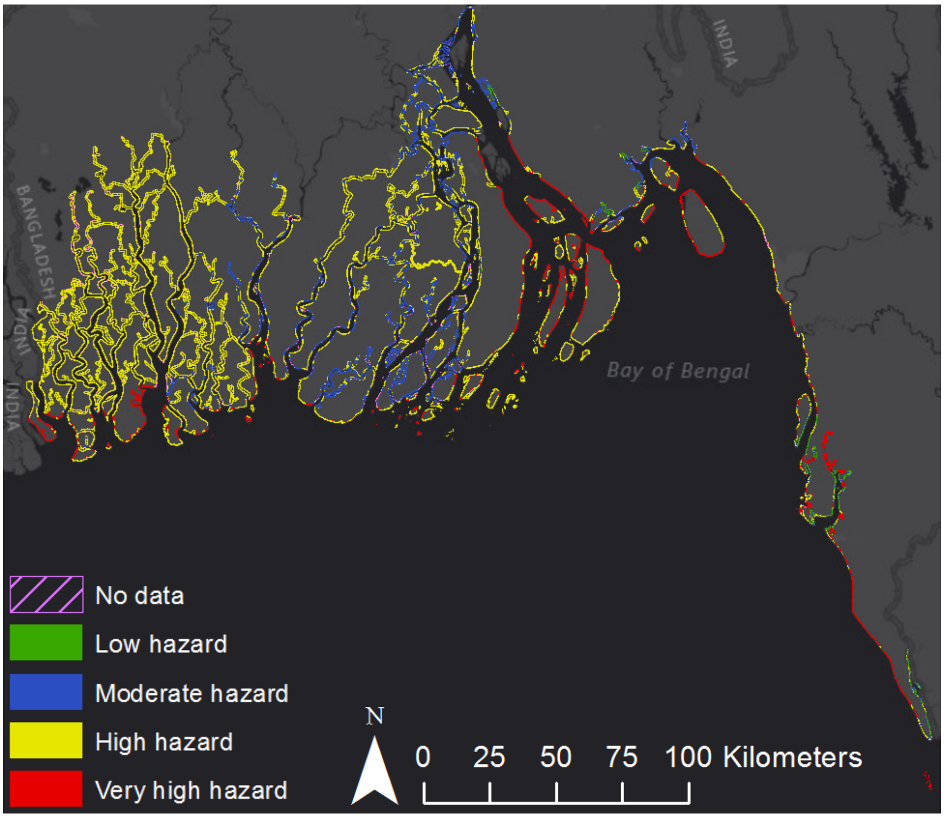


Figure 25: The spatial distribution of the Erosion hazard levels

Table 11: The distribution of erosion hazard levels

Hazard level for erosion	Ready-to-use input dataset		Improved classification	
	Coastline length (km)	% of total coastline	Coastline length (km)	% of total coastline
No data	1413	17,6	266	3,3
Low	0	0,0	144	1,8
Moderate	32	0,4	1520	18,8
High	5727	70,5	5356	66,1
Very high	928	11,5	813	10,0

Scientific literature confirms the high erosion processes in the River and Estuary region (Figure 26). Note that the net land erosion is illustrated in blue, not red. There is no general consensus on the erosion rates, with maximum estimations ranging from 120 – 200 m/y (Sarwar & Woodroffe, 2013; Vidal, 2013; Brammer, 2014). The erosion locations found in Figure 26 correspond with the hazard assessment, with vulnerable areas on the east coast of the Bhola island, north side of the Hatia island and large parts of Sandwip island. Other parts of the delta appear to be more stable, with some exceptions along the southern edge of the Sundarbans. This was also concluded from the hazard classification. It is important to note that despite these high erosion rates, a net accretion is observed in the Bay of Bengal, partially due to land reclamation projects in the South East and South Central region (Sarwar & Woodroffe, 2013, Brammer, 2014). Along the riverbanks however, erosion rates significantly outpace the accretion rates (GED, 2016).

No solid literature evidence was found for erosion rates along the southern Eastern Hill coastline, implying that erosion is not a very large problem. The hazard assessment identified the high hazard because of the exposed wave climate combined with no clear sediment surplus, a combination likely to cause erosion due to wave impact, especially during extreme events. This however cannot be confirmed by literature.

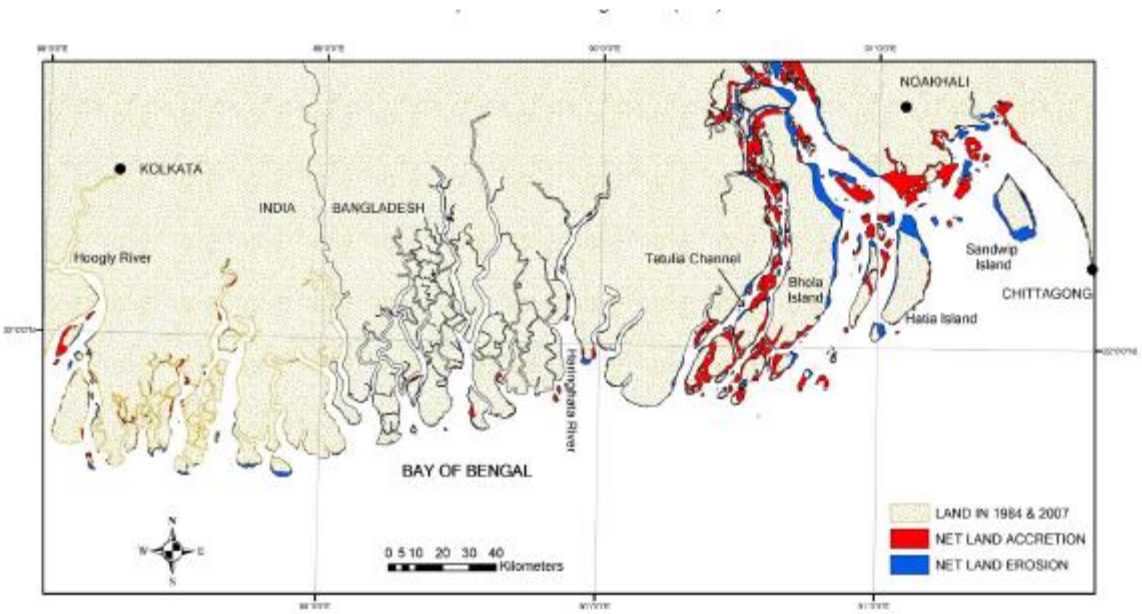


Figure 26: Gains and losses of land in the Bengal Bay (Brammer, 2014)

Flooding

Of all assessed hazards, Bangladesh is the most vulnerable for flooding and storm surges, with 92,7% classified as very vulnerable. Not only the delta but also almost the entire Eastern Hill region was given a very high hazard level (Figure 27). The combination of its low elevation with major river systems and a cyclone climate proof to be a dangerous combination. Even though the Eastern Hill coast is located outside the delta, its exposed coast and occurrence of cyclones cause it to be very vulnerable to storm surges. The improved input data did not significantly changed the hazard assessment but mainly filled the no data gaps (Table 12; Appendix C).

Table 12: The distribution of flooding and storm surges hazard levels

Hazard level for flooding and storm surges	Ready-to-use input dataset		Improved classification	
	Coastline length (km)	% of total coastline	Coastline length (km)	% of total coastline
No data	1429	17,6	266	3,3
Low	61	0,8	105	1,3
Moderate	0	0,0	0	0,0
High	87	1,1	222	2,7
Very high	6542	80,6	7507	92,7

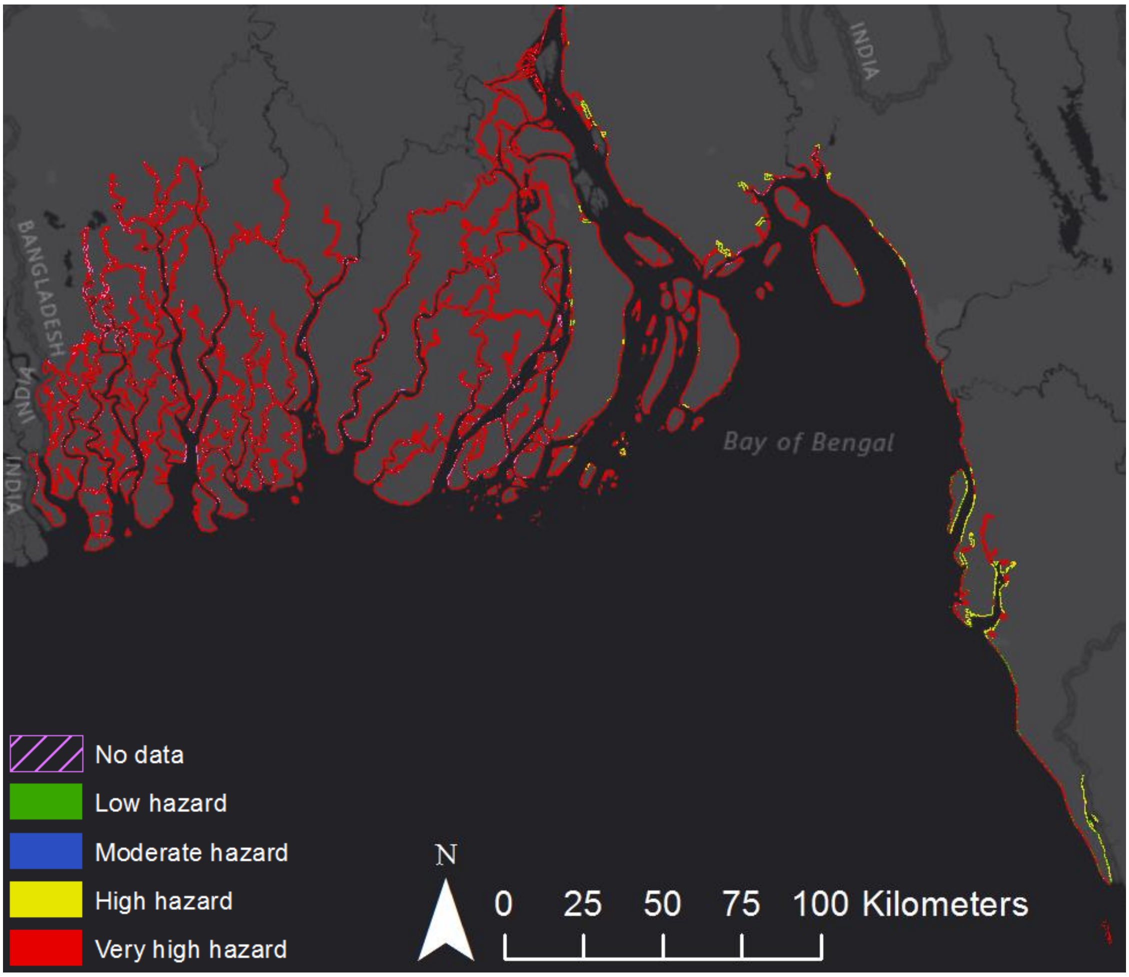


Figure 27: The spatial distribution of flooding and storm surge hazard levels

Other than the case of the homogenous salinity intrusion hazard, this classification is actually largely reflected by literature. It is beyond doubt that the coastal belt of Bangladesh is vulnerable to storm surges and that climate change is likely to further increase this vulnerability (Karim & Mimura, 2008; Mirza, 2012; Lee, 2013; GED, 2016). Actually a lot of recent research is dedicated to strategies to cope with this reality, rather than confirming the high vulnerability (Sarwar & Wallman, 2005; Ahamed, 2013; Ahmed *et al*., 2015; Hossain *et al*., 2015; Hossain, 2015; Lu *et al*., 2016). One aspect however was not recognized by the hazard assessment: the protective effect of the Sundarbans against cyclones and storm surges (Figure 28). Mangrove forests form a barrier between the coast and the inland, stabilize the soil, and increase resilience and protection from storm surges (Alongi, 2008). The area north of the Sundarbans is therefore less vulnerable than the other coastal regions.

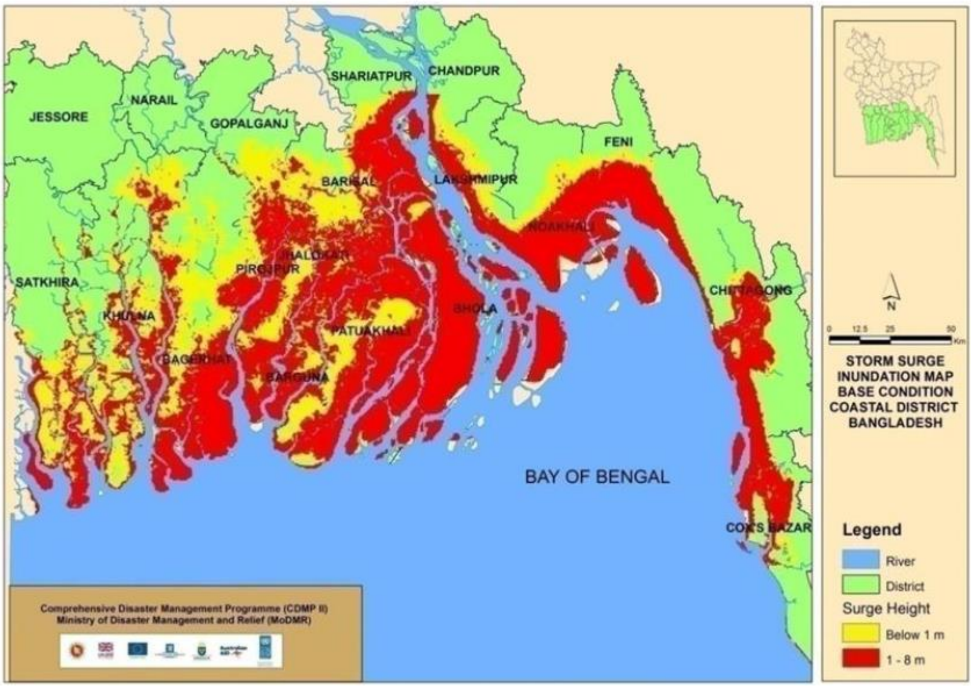


Figure 28: Storm surge hazard map (expected inundation depth at changed climate in 2050)

11.3 Model performance in a different coastal environment

The multi-hazard assessment of Djibouti serves two goals. It checks whether the model is applicable in a different environment than Bangladesh, and secondly, thanks to a previous case study (Appelquist, 2014) it provides a possibility to check to what extent the model can replace human interpretation. Unfortunately, no digital data from the previous case study was available for this thesis. Therefore the only way to validate the model's performance is through a visual comparison with the hazard maps made by Appelquist.

Hazard analysis

Figure 29 compares the manual ecosystem disruption hazard assessment with the automated assessment created by the model. Even though some differences are observed, the main high and low risk areas correspond quite well. Looking into the classification result, large parts of Djibouti's coastline have a very high hazard for ecosystem disruption. This is mainly caused by the extensive coral reef systems in the high north and the coastal stretch between Obock and the southern border.

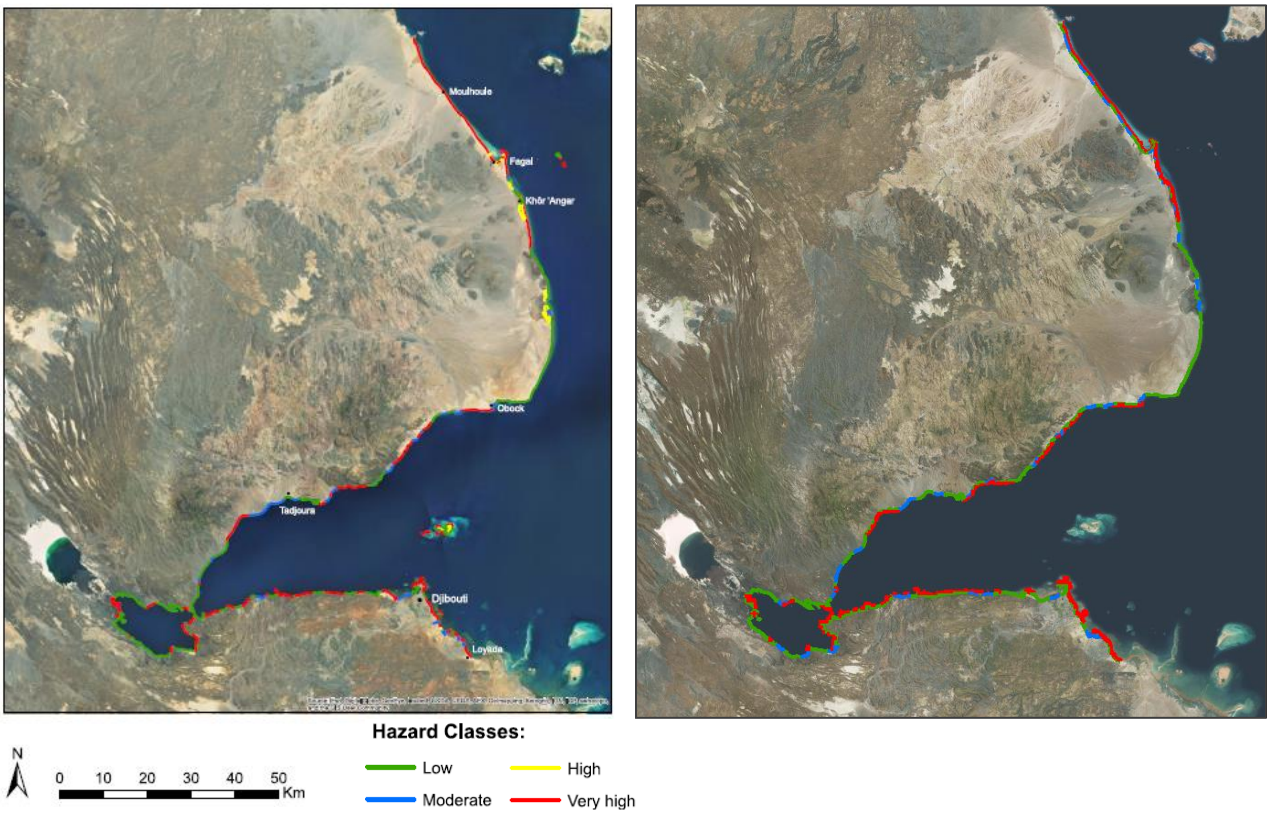


Figure 29: Manually classified (**left**) versus automated classified (**right**) ecosystem disruption hazard levels for the coastline of Djibouti

These coral systems become interesting when looking at the other hazard classifications. Figure 28 compares the manual and automated hazard assessments for gradual inundation.

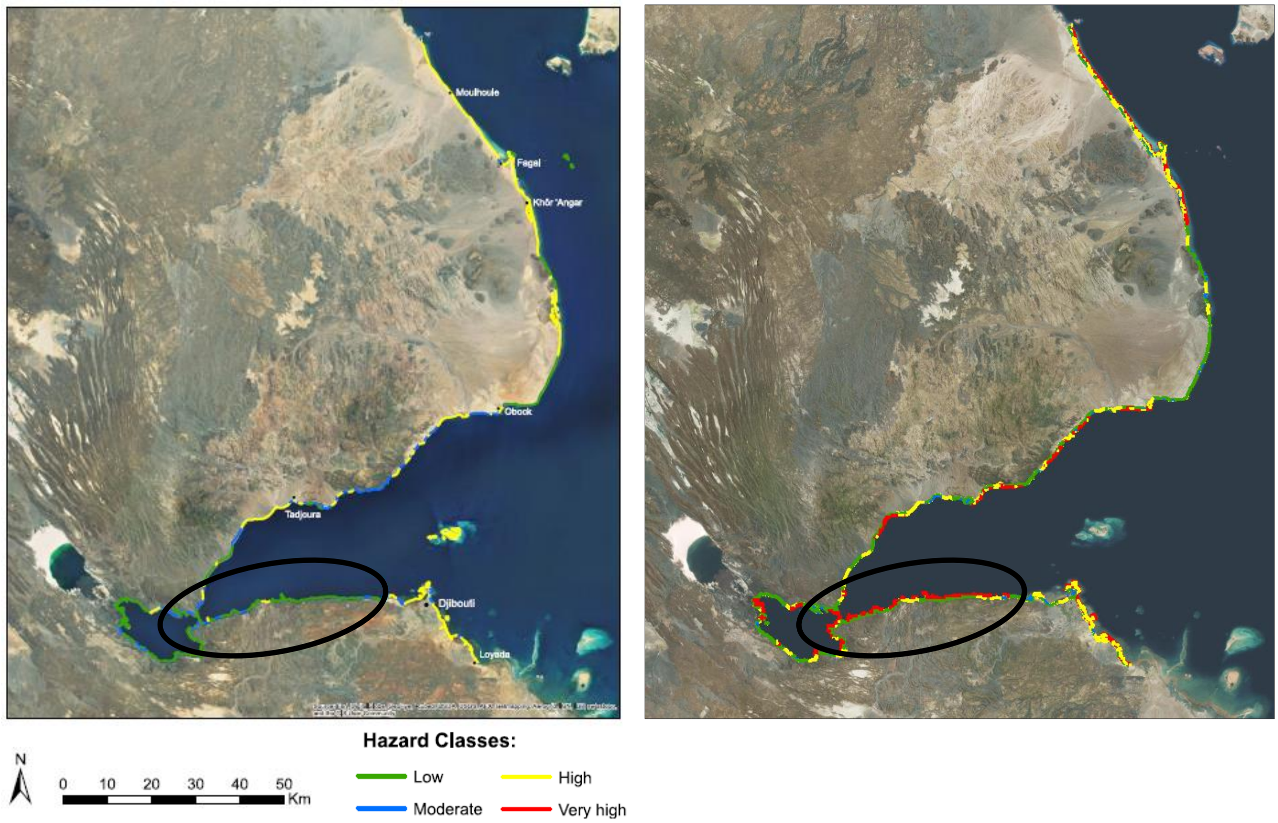


Figure 30: Manually classified (**left**) versus automated classified (**right**) gradual inundation hazard levels for the coastline of Djibouti

The same coral systems now cause big differences in the hazard classification, for example in the highlighted area. According to the CHW methodology (Figure 8), all types of coral coasts have a high or very high gradual inundation hazard, mainly based on tropical atolls and coral islands which are in danger of being submerged by SLR. In this case, the author of the manual classification recognized that this coral coast is not relevant for the inundation hazard of Djibouti because the land behind the coral reefs consists out of hard rocky mountains. The automated approach does not take this spatial context in account and gives it a high hazard. According to the CHW methodology, coral coasts are relatively vulnerable to most hazards, and therefore this has major implications for the overall hazard assessment. Therefore the model was designed in a way that if it detects a coral coast, it also assigns a hazard for the land behind it. Zooming in to the highlighted areas shows that the inland areas correspond reasonably well with the manual interpretation (Figure 31). In the manual

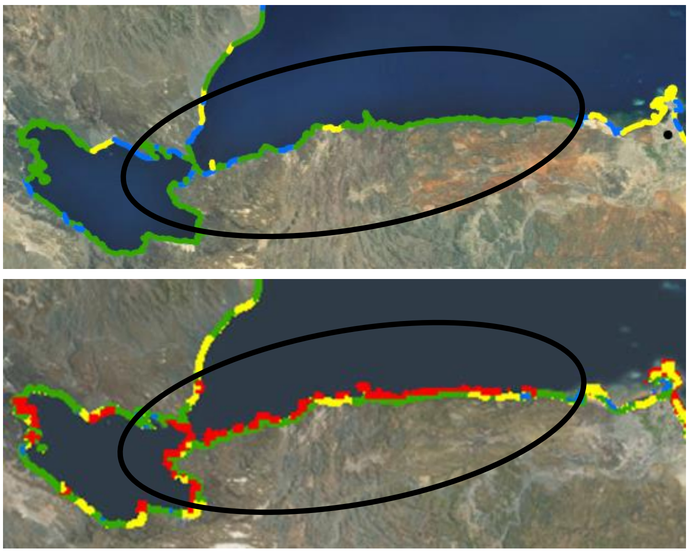


Figure 31: Impact of coral reefs on manual (**above**) and automated (**below**) gradual inundation hazard assessments

interpretation, the coral system was disregarded for all hazard assessment but ecosystem disruption. Therefore, when comparing the remaining hazard maps in Figure 32 & 33, being salt water intrusion, erosion and flooding, the coral reef areas were masked for displaying purposes. In this way the coral system does not distract from the automated classification of the inland, which is the classification that should be compared with the manual classification.

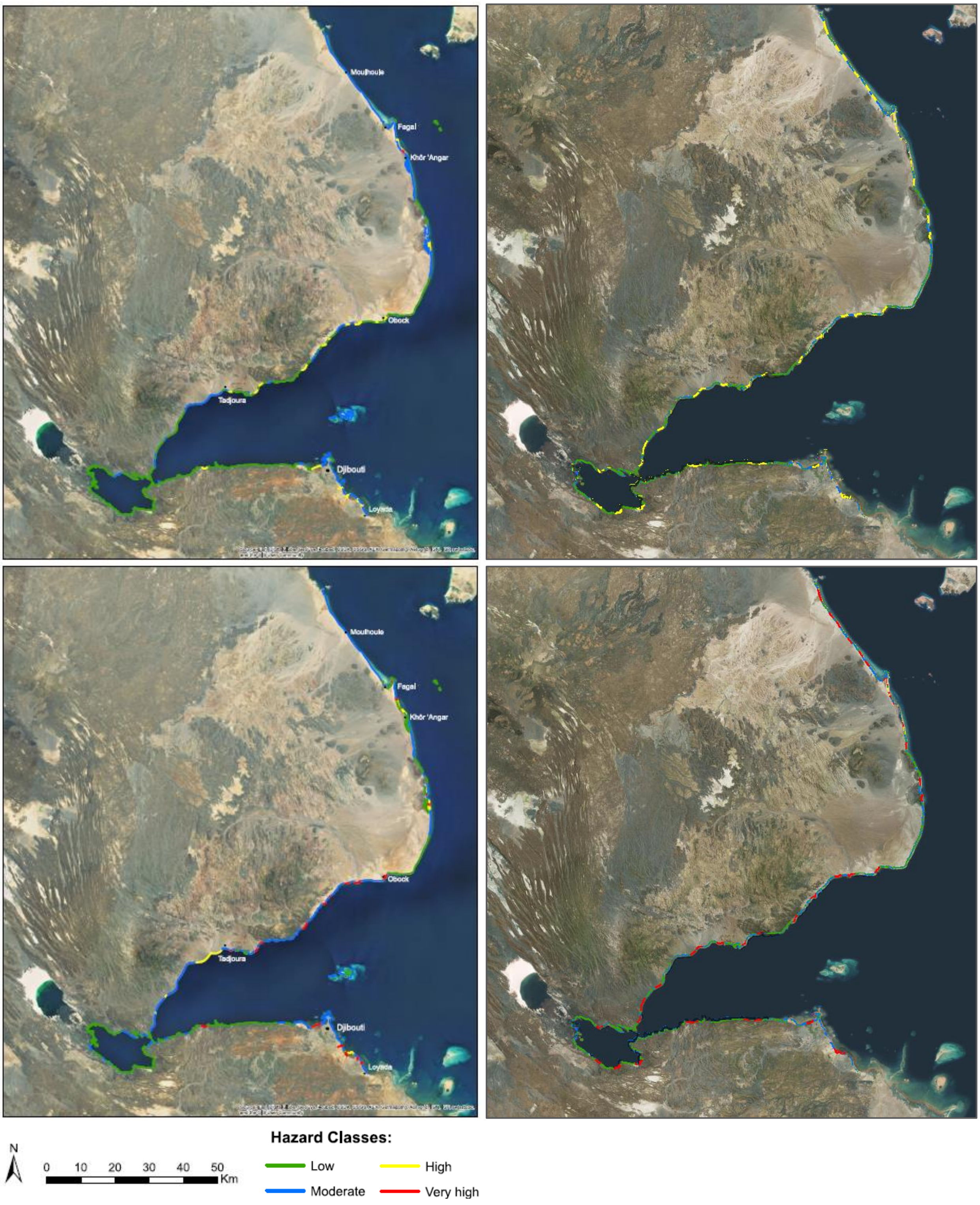


Figure 32: Manually classified (**left**) versus automated classified (**right**) salt water intrusion hazard levels (**top**) and erosion hazard levels (**bottom**) for the coastline of Djibouti

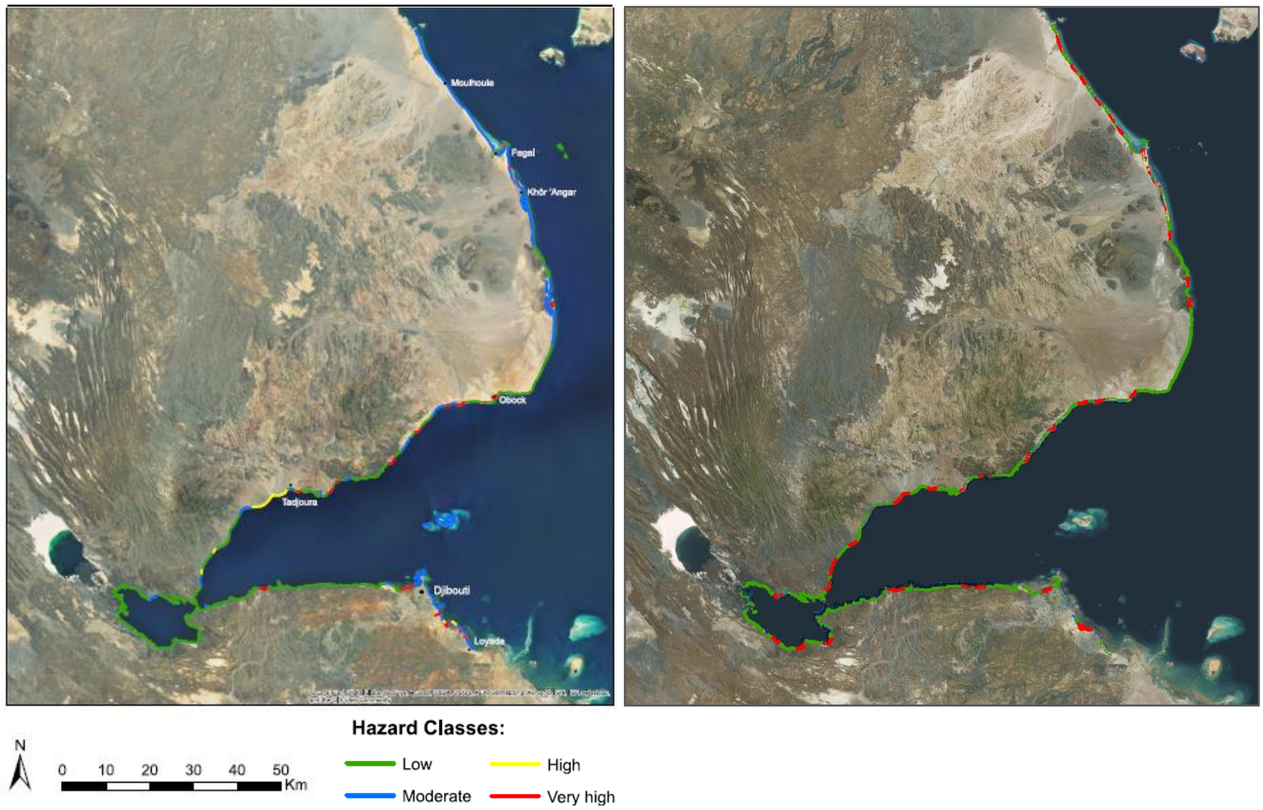


Figure 33: Manually classified (**left**) versus automated classified (**right**) flooding hazard levels for the coastline of Djibouti

The manual and automated hazard assessments correspond quite well, besides in one coastal environment: river mouths. A lot of Djibouti's rivers are very dry for a large time of the year. Therefore most of them were not assigned the relatively high river mouth hazards by Appelquist. The model however does, leading to several overestimated areas spread over the coastline. This overestimation comes back in all of the hazard assessments, but disregarding the dry river mouths, the automated approach seems capable of approaching the manual interpretation.

12. The CHW as coastal planning tool

12.1 History of water management in Bangladesh

The human race is very capable to adapt to and influence their surroundings, and in the biggest delta in the world, water is a way of life. The history of water management in Bangladesh goes back to the ancient period. This short overview is written based on the work of Dewan *et al.*, 2015 and the BDP2100, and an interview with dr. ir. Alamgir Chowdhury (2016).

From ancient/colonial traditions to post-colonial governmental water authorities

As far back as during the reign of the Sultans and Mughal emperors, overflow irrigation systems were already used, canals, embankments and water basins were constructed, and flood free homesteads were built (GED, 2016[b]). These practices continued throughout the colonial period (1757-1947), when the *zamindars* or landlords rose into prominence. These landlords had the right to collect revenue, and were also responsible for the water management. Communities took part in construction through compulsory labor, while the *zamindars* supervised and provided capital when necessary (Dewan *et al.*, 2015). The water management system consisted mainly out of temporary embankments, which prevented salinity in the dry season and were swept away by the river during the monsoon, enabling fertile silt to deposit on the fields and flood plains. This was a very flexible system, adapted to the dynamic erosion and sedimentation processes of the delta.

In 1950, after the partition of India, the zamindari system was abolished. The uncertainty following the partition, and a gap in water management responsibility coincided with a number of disastrous flood events in 1954, 1955 and 1956 (Dewan *et al.*, 2015). The United Nations took action through the Krug mission, which recommended a governmental intervention in flood protection. Following from this recommendation, the East Pakistan Water and Power Development Authority (EPWPDA) was created in 1959, and the first governmental water authority was born. After Bangladesh's independence in 1971 the Bangladesh Water Development Board (BWDB) was installed, which is still active today. Looking at water management in the post-colonial period, three different periods can be observed (Chowdhury, 2016).

The 1960s and early 1970s: the engineering approach

This period was characterized by mega-infrastructure projects, initiated top-down from the EPWPDA. Infrastructure and big constructions were seen as a solution to most water related issues, and with the help of international funding, over 4000 kilometers of embankments were constructed. These years marked an important transition from the local traditionally flexible systems to large scale polders, inspired by the Dutch system (Chowdhury, 2010; Dewan *et al.*, 2015).

Noteworthy are the Coastal Embankment Project, which created 136 polders across the entire coastal belt, the Ganges-Kobadak Irrigation Project, and the Brahmaputra Right Flood Embankment Project. These were typically Flood Control, Drainage and Irrigation projects (FCDI-projects), aimed at increasing agricultural production (Chowdhury, 2010; GED, 2016[b]). This had positive results, enabling farmers to harvest two to three crops per year instead of one. Furthermore it provided more stability, which led to a rapid rise in population (Dewan *et al*., 2015). But it also had downsides, disrupting the river-floodplain connectivity, silting up the rivers and opposing the delta's dynamic nature. This led to major maintenance requirements.

The late 1970s and 1980s: Small scale, and attention for empowerment/equity issues

It was concluded that mega projects in a delta as dynamic as the GBM delta are not a perfect solution, and furthermore require huge investments resulting in a very long time to derive benefits (Dewan *et al*., 2015; GED, 2016[b]). Therefore a shift was made towards small and medium scale projects in flood control, designed as nonstructural and low cost solutions. Early flag ship projects demonstrated that the benefits were not reaching the poor, and more attention for social equity was required. Together with the Green Revolution, participatory water management became a hot topic. Members would contribute to a central fund, and get access to subsidized fertilizers and pesticides (Dewan *et al*., 2015).

1990s – Present: Water Management Organizations – a sustainable solution?

The distribution of the costs and benefits was still problematic, and community based natural resource management was introduced. Water Management Organizations (WMOs) were formed as a way of depoliticizing participation and decentralizing water management responsibilities. WMOs are also included in the National Water Policy which was formulated in 1998 (Dewan *et al*., 2015; GED, 2016[b]). It became a donor requirement to include community participation through WMOs, leading to many 'overnight-created' WMOs in order to comply for funding. Too often these WMOs turn out to disappear when projects end, and therefore long term maintenance of projects still is a big problem (Dewan *et al*., 2015).

12.2 CHW measures

The CHW gives the suitability for a range of coastal management options for each of the 131 generic coastal environments. Based on the final classification, 16 different measures seem to be applicable in the physical context of Bangladesh (Table 13). Looking at the trends in coastal water management in Bangladesh, small scale, flexible and easy to maintain measures seem to be most adapted to the GBM-delta. Based on this knowledge and on some very basic knowledge of the characteristics of the coastal belt, not exceeding the brief description of coastal zones in Chapter 5.3 the following measures are proposed.

Table 13: Overview of the suggested measures by the CHW, the hazards they target and the regions where they could be applied

Measure	Target	Applicable regions
Wetland restoration	All hazards	Entire delta
Fluvial sediment management	All hazards	Entire coastal belt
Dikes	Gradual inundation, salt water intrusion, flooding	Entire coastal belt with exception of mangrove coasts
Dune construction	Salt water intrusion, erosion, flooding	Exposed coast of the Southern delta, entire Eastern Hill region
Beach nourishment	Gradual inundation, erosion	Exposed coast of the Southern delta, large part of Eastern Hill region
Groundwater management	Salt water intrusion, erosion	Entire coastal belt
Coastal zoning	Ecosystem disruption	Entire coastal belt
Storm surge barrier	Salt water intrusion	River mouths of Eastern Hill region
Breakwaters	Erosion	Exposed coast of the Southern delta, large part of Eastern Hill region
Groynes	Erosion	Exposed coast of the Southern delta, large part of Eastern Hill region
Jetties	Erosion	River mouths
Revetments	Erosion	Exposed coast of the Southern delta, entire Eastern Hill region
Sea walls	Erosion	Exposed coast of the Southern delta, entire Eastern Hill region
Cliff stabilisation	Erosion	Very sporadic in Eastern Hill region
Flood warning system	Flooding	Entire coast
Flood proofing	Flooding	Entire coast

Nationwide measures:

- Flood warning system
- Flood proving
- Coastal zoning
- Groundwater management
- Fluvial sediment management

Regional measures:

South West: Since this region is dominated by the Sundarbans, dikes and hard measures are not deemed very useful. Efforts should go out to wetland restoration and coastal zoning.

South Central, South East and River and Estuary: Besides the nationwide measures, focus should be on earthen dikes/embankments to provide a relatively flexible and easy to maintain measure that enables a high agricultural production and a safe living environment.

Eastern Coast: Areas of high economic interest such as the Chittagong port and city could be protected with hard measures such as a sea wall or breakwaters to limit the damage done by erosion and storm surges. Given the long stretches of sandy coasts, beach nourishments and dune construction should be preferred above expensive hard constructions.

12.3 Comparison with the Bangladesh Delta Plan 2100[1]

Based on the ambitions of Bangladesh to reach the status of a middle-income nation by 2021, and to consolidate its growth and reach the status of developed country by 2041, the following Delta Vision was formulated in the Delta Plan 2100:

"*Ensure long term water and food security, economic growth and environmental sustainability while effectively coping with natural disasters, climate change and other delta issues through robust, adaptive and integrated strategies, and equitable water governance.*"

Water is central to sustain life and livelihoods, especially in Bangladesh. To support the sustainable development of water resources as outlined in the Delta Vision, six Delta Goals were identified:

1. Ensure safety from floods and climate change related disasters
2. Enhance water security and efficiency of water usage
3. Ensure sustainable and integrated river systems and estuaries management
4. Conserve and preserve wetlands and ecosystems and promote their wise use
5. Develop effective institutions and equitable governance for in-country and trans-boundary water resources management
6. Achieve optimal and integrated use of land and water resources

These goals go beyond the measures suggested by the CHW, which are purely based on the physical system of the coastal region, and do not involve institutional aspects or trans-boundary issues. Zooming in to the concrete measures that the BDP2100 proposes in the coastal belt, the following projects are listed (projects that correspond with the measures suggested by the CHW are highlighted in a bold font):

1. **Floodplain Zoning** corresponding to various levels of risk (differentiated safety levels), including a communication strategy for the new zoning and safety levels
2. Planning and design of **flood control structures** and river training works for rivers and Khals (canals). Soil and water conservation measures are included for (flash) flood attenuation
3. Rationalize management of existing sea and river facing polders and **extend soft coastal defence and shelters against extreme floods, including elevated flood resilient housing**
4. **Revision of flood warning systems** and establish disaster management social groups and community based early warning and forecasting systems for people and livelihoods
5. Modernise Flood Control, Drainage and Irrigation projects
6. Stimulate sustainable and compact urban **development on higher grounds**
7. Feasibility study of a new mega-Special Economic Zone in the dynamic Meghna Estuary
8. Open space to store rainwater in urban areas, where possible combined with public urban, green or blue spaces, integrated in city planning
9. Enlarged share of surface water sources, including (additional) water treatment plants
10. **Aquifer recharge** in the agricultural sector, and a shift towards water-efficient crops

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[1] *This chapter is based on the October draft version of the Bangladesh Delta Plan 2100 (GED, 2016[a]). This draft document is meant for discussion purposes only, and no rights can be derived from it.*

11. Extensive long-term **sediment management plan**, including tidal river management program
12. Land reclamation and estuary development embedded in river basin management plans and sediment management plan in a sustainable way tuned with sediment balance
13. Integrated erosion management, watershed protection and development in the hills (around Chittagong and in the North East)
14. Impact studies of long-term effects of river channelization and river engineering on river bed morphology and discharge capacity
15. Innovative city development, capitalising on the meandering wide rivers as a strong characteristic of Bangladesh
16. **River, wetland and nature protection and restoration**
17. Promotion of sustainable cultivation practices and regeneration of degraded areas. This includes creating awareness on role of ecosystems in water management, replace mono-plantation and promote agroforestry with native (fruit) trees in support of livelihoods and water availability (around Chittagong and in the North East/North West)
18. **Protect unique wetlands, the Sundarbans in particular**, by (inter-)national laws and programmes and align water management to maintain their unique characteristics.
19. Sustainable integral **wetland development** and protection of green spaces in and near high density urban and peri-urban areas (e.g Gazipur forest areas)
20. Establishment of flow control and water reservation structures for water availability in dry season, including small scale (cross)dams and reservoirs for irrigation, livestock and aquaculture
21. Enhancement of freshwater flows in coastal rivers through Tidal River Management, and of dry-season flows in urban rivers

The measures suggested by the CHW seem to fit quite well within the BDP2100. Five out of the six nationwide measures derived from the CHW, being coastal zoning, flood proving, flood warning system, sediment management and wetland/floodplain restoration are included in the Delta Plan 2100 measures as well. The focus on flood control structures and embankments is also reflected in both management plans.

Measures that are missed by the CHW but included in the Delta Plan are partially measures that take place in the inland, such as watershed management in the hills, enhanced dry season water flows and water flow control structures. Furthermore, large scale land reclamation is more emphasized in the BDP2100. There are also measures suggested by the CHW that do not come back in the BDP2100. This mainly consists out of measures along the Eastern Hill coast, such as sea walls or breakwaters. While this area is apparently suitable for certain (hard) measures, it is not seen as a priority in the BDP2100.

13. Discussion

13.1 Review CHW system

The results of Chapter 10 and 11 show that it is possible to automate the CHW to do a coastal multi-hazard assessment and to use it as exploring planning tool. Strong points are its simplicity, transparent and nicely visualized decision framework, and low data- and expertize requirements. But its simplicity also comes with a price. First of all it only takes the natural characteristics and one climate scenario into account. Obviously many other factors such as economic development and human interventions in the natural system will have its effect on the coastal zone. Adding to this, because the framework only focusses on a small coastal strip, it overlooks inland processes that could alter the coastal dynamics. Especially in a delta such as Bangladesh, upstream developments can have significant impacts on the coastal belt. Only imagine what Bangladesh would look like if India really sets through its mega-project to divert the Ganges and Brahmaputra rivers to central and south India to solve its internal water crisis (Doshi, 2016). Maybe an extreme and rare example, but inland developments definitely play a role in the coastal dynamics. The CHW may try to capture these based on global trends and assumptions, but the framework does not offer the possibility to include or emphasize any upstream developments or human interventions. Furthermore it is not possible to quantify how far land inwards a certain hazard – think of salt water intrusion, inundation or storm surges – is expected to have an impact. These are serious limitations for its potential for policy makers, but very difficult to include in the methodology while keeping the existing framework. A relatively simple improvement, including an extra layer with land use information, would enable the system to give an actual indication of the risks instead of only the hazards. At this point, the CHW is a useful tool as initial exploration of a certain area, but not yet a complete decision-making tool.

13.2 Review research methodology

For the hazard assessment, input layers were constructed from open source geo-spatial data and combined to classify the generic coastal environments of the CHW. These generic coastal environments are linked to a specific combination of hazards. Only the hazard classification was validated with a literature study, the constructed input layers were not. A validation with stratified random sampling points and field visits to check both the input layers as any potential hazards would have strengthened the validation process. Another option would be specific geo-spatial data from specialized field studies. Both options were not possible within the scope and time frame of this research. The validation of the automated hazard classification of Djibouti's coastline also could be improved. No digital data of the manual constructed input layers or hazard assessment were available, making any kind of statistical comparison between the manual and automated approach impossible. This makes the validation the weakest aspect of this research.

It is important to note that both previous case studies, performed by the author of the CHW, were not validated by any kind of field observations either. In fact, in both publications there is no mentioning of expected accuracy or any kind of quality assessment at all (Appelquist 2014; Appelquist, 2015). This of course will have to change before the CHW can claim to be a well-functioning hazard assessment method.

13.3 Review input data

The hazard assessment starts with collecting the different datasets for the coastline of Bangladesh. This immediately poses a dilemma: what do you define as coastline? The CHW methodology is based solely on the first few hundred meters land inwards. But since datasets originate from different years, and coastline movements up to 200 meters a year are reported, chances are that datasets will not properly overlap. The main issue with this is not that some areas may receive a wrong classification – the methodology is designed for regional to national scale, not for very detailed assessments - but it can lead to significant data gaps, especially with datasets with relatively coarse resolutions. The MODIS land cover dataset is a good example of this. This was the biggest challenge for the automated method, and though partially solved by the Landsat imagery analysis, still a cause of errors. But Bangladesh is also an extreme case; problems are expected to be less in more stable coastal environments, also demonstrated by the Djibouti case which had a significantly lower percentage of data gaps.

Looking at data availability, the wave exposure and sediment balance layers were the most problematic. No user friendly data is available, and though the sediment balance layer was constructed with reasonable accuracy, the automated free fetch estimation still requires improvements. Besides these two layers, the geological input missed some of the more specific land features. This limits the amount of coastal categories that can be classified, and therefore the functionality of the CHW method. However, earth observation techniques are rapidly developing, and furthermore a trend of making data publically available is emerging. This creates more opportunities for automated remote sensing options.

13.4 Review of the results

The results corresponded reasonably well with scientific literature, although especially the hazards for salt water intrusion and flooding showed some deviations from previous studies. These could be explained by the inland characteristics that were not included by the CHW, in this case the decreased water flows in the Ganges and the buffering capacity of a large area of mangroves in the Sundarbans, and were born out of simplifications of the CHW methodology. In Bangladesh, a country that is subjected to a large amount of climate related research, these errors can be easily identified, but for regions that are given less attention it might be more problematic.

Critically reviewing the applicability of the hazard maps demonstrates its added value for coastal decision making, but also its limitations. Figure 27 and table 12 show that 92,7% of the coastline (over 7500 km) has a very high vulnerability for flooding events and storm surges. Though this is probably a reasonable estimation, it does not give policy makers any support in decision making or to prioritize areas. Again, Bangladesh might be an extreme case in this sense, and in a lot of other coastal regions this will be less problematic. But it does show the need to include land use information or economical value of areas to improve the identification of high priority areas.

13.5 Emerging technologies

While NASA’s Landsat program has been the leading source of global satellite data for over 4 decades, ESA’s recently launched Copernicus program is very likely to take over this position. The program launched four Sentinel satellites over the last three years, and three more are already announced. The spatial resolution of the Sentinel data is 300% higher than Landsat data, and more spectral bands are measured, enabling more possibilities for optical remote sensing. The main advantage that Landsat has over Sentinel is a 40 year data archive, enabling to observe trends and changes over time. But it will be a matter of time before Sentinel takes over, increasing the potential of automated remote sensing techniques.

Another breakthrough is the emergence of cloud platforms for analyzing and visualizing geo-spatial data, such as the Google Earth Engine. The possibility of visualizing data through the Earth Engine catalogue, accessing ready to use scripts and visualizing your analysis on the fly offers great potential for the automated CHW method and other geo-spatial analysis initiatives. A nice example is the Deltares Aqua Monitor, a tool supported by the Google Earth Engine that visualizes land-water and water-land conversions that occurred in the last 30 years (Donchyts, 2016). This tool can only be used for visualisation, the data is not available for downloading or to use as input for any GI analysis, and was therefore no part of this study. As the amount, quality and accessibility of data increases, the potential of automated GI analysis will grow.

14. Conclusion

More and more geospatial data is gathered and publically shared, and emerging technologies such as the cloud platforms like Google Earth Engine where dataset and analysis methods are made accessible to the public will only accelerate this process. Software packages are also freely available, ensuring a bright future for the GI-society.

14.1 CHW methodology for automated coastal multi-hazard classification

A large variety of data sources is available, enabling to construct most of the input layers with reasonable accuracy. If available, local or national datasets can be easily included in the model, and basic remote sensing techniques are able to cover for most of the data gaps (Figure 18 & 19). Open source software packages offer sufficient GI-tools to analyze the data, so the possibilities for automated hazard analyses are definitely there. A successful (semi-)automated hazard assessment of two different coastal environments is far from sufficient to claim a proper global applicability, but it at least shows a certain potential. But while models are able to combine different data sources and derive conclusions from them, they still cannot rival with human interpretation. The overestimation of hazards in the dry river mouths in the Djibouti case study (Figure 30-33) is a good illustration of this.

However, most inaccuracies were born out of simplifications that are part of the CHW framework itself. Being able to determine a multi-hazard assessment on a global scale with a very basic amount of data is arguably the strongest feature of the CHW, but inevitably results in certain inaccuracies. The hazard classifications (Figure 23 & 27) emphasize that the exclusion of inland developments or characteristics can potentially have a big impact on the classification quality. Furthermore, a lot of drivers for processes as ecosystem disruption or erosion have very strong anthropogenic causes, which are not included in the CHW methodology.

Main shortcomings:

- Incomplete datasets: Due to data limitations it was not possible to include land features such as barriers, tidal inlets and sand spits in the automated hazard classification.
- Simplifications of CHW methodology: Every model is a simplification of the reality, and there will always be the trade-off between model complexity and output quality. The CHW is a simple and effective way to classify coastal hazards, but by not including inland processes and human alterations in the system there will always be uncertainties in the output.

The objective was to develop an objective (semi-)automated model of the CHW methodology that was able to do a multi-hazard assessment based purely on open source data. This research showed that (semi-)automated hazard classification is definitely possible. The user has to be aware that it only creates an inherent hazard estimation based on the physical system, and does not include the influence of inland processes and human alterations to the natural system. It will also never beat field observations or local knowledge. But when applied in environments where resources and data are limited, in hard-to-reach areas, or as a first exploration to get a better overview of a certain coastal region, it definitely has an added value.

14.2 CHW as a potential coastal planning and management tool

The CHW evaluates a number of coastal management measures based on the physical characteristics of the system. A total of the 16 most commonly used hazard management options is reviewed, and covers three different types: hard protection measures, soft protection measures and accommodation approaches.

Looking at the coastal management practices of the last decades, there was no fixed way of doing it or a certain successful approach. Several trends were observed, shifting from local flexible measures to large scale hard infrastructures, and then back to smaller scale, low cost projects. Over time, emphasis has been on flexibility, on top-down engineering solutions and on community participation and social equity. Because the CHW comes with a large range of options, the user can fit its suggestions into the local socio-economic and cultural context.

Even though the BDP2100 has an aim reaching way beyond the aim of the CHW, comparing the overlapping fields, proposed measures against several climate change induced coastal hazards in Bangladesh, they correspond quite well. Most management options suggested by the CHW were also proposed by the BDP2100, showing that the categories and decision structure of the CHW cover an extensive analysis of coastal environments. It also illustrated its weakness. Not only its input is solely focused on a narrow coastal strip, it also only provides management options directly applied in the coastal zone. Inland solutions such as augmented river flows or improved groundwater management safeguarding fresh groundwater resources, which are included in the BDP2100, are missed.

Therefore the potential of the CHW as management tool should be sought in the exploration phase to select a range of suitable options, which will be further investigated and optionally complemented with other measures.

14.3 Recommendations

Two main recommendations can be made based on the analysis above. First of all, both the constructed input layers as the hazard classification require a proper accuracy assessment, which was not available for previous case studies. Secondly, the need to include land-use, infrastructure or areas with economic interests arose in order to be of real value as a decision-support tool for policy makers. It would not influence the inherent hazard assessment, making sure the existing CHW framework can be sustained, and it would enable the user to prioritize areas in the coastal planning process. Further research should prioritize these two subjects, which would significantly strengthen the potential and added value of the CHW.

Furthermore it is recommended to include the missing input categories *barrier*, *tidal inlet* and *sand spit*, and to test the automated classification process in more coastal environments. This will be necessary in order to get a full impression of its potential as globally applicable coastal hazard analysis tool. Additionally, a more standardized approach for the remote sensing techniques would increase the usability for users with limited expertise.

Including human interventions in the natural system, such as overexploitation of natural resources or pollution, would be another major improvement, but not easy to include and quantify since rather detailed data and knowledge about the system is required.

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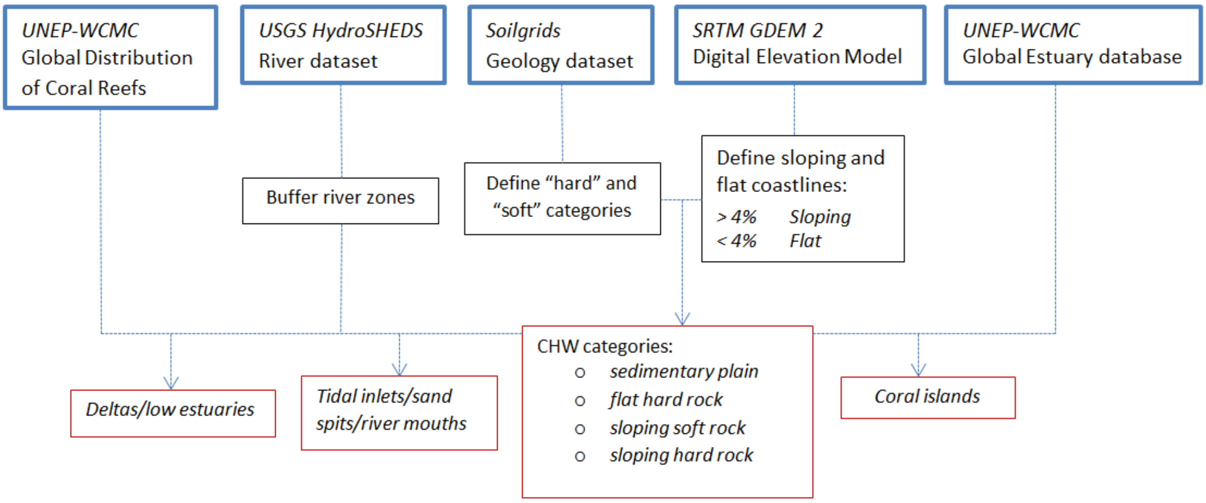
Polders in the coastal belt during the monsoon period
Photo: Snapshot from the documentary "Climate Change in Bangladesh – a film by Arthus-Betrand and Anastasia Mikova"

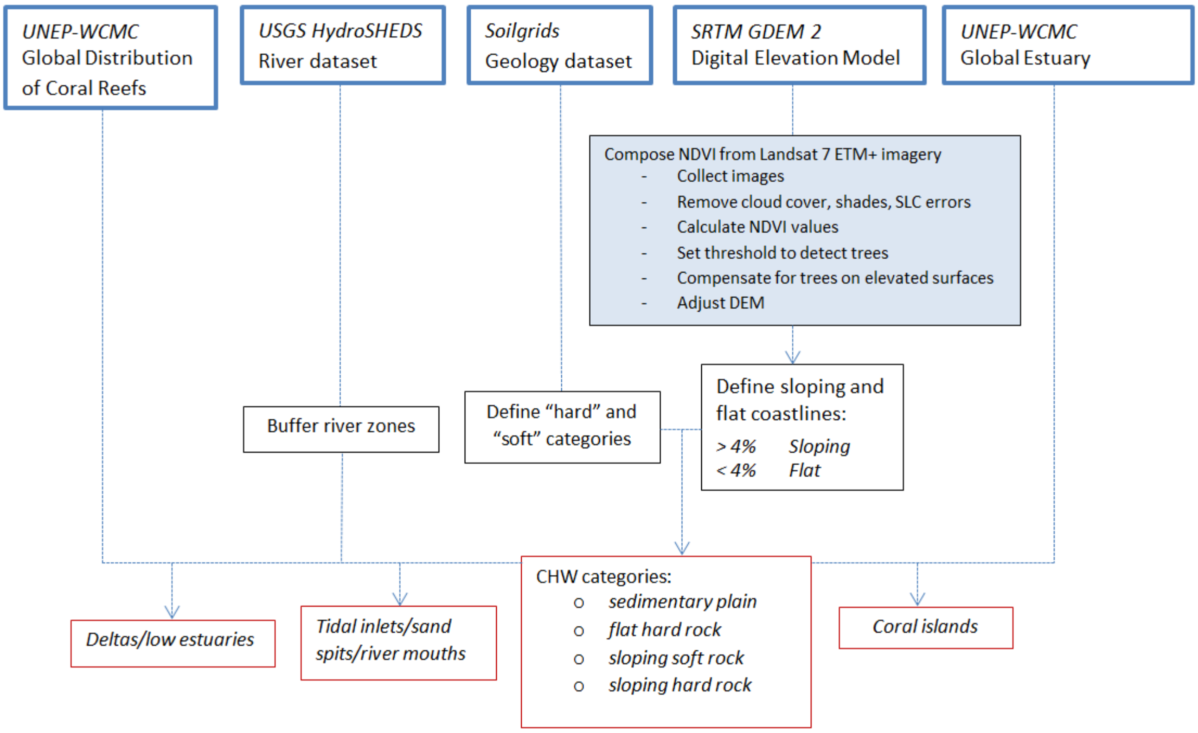
Part IV

APPENDIX

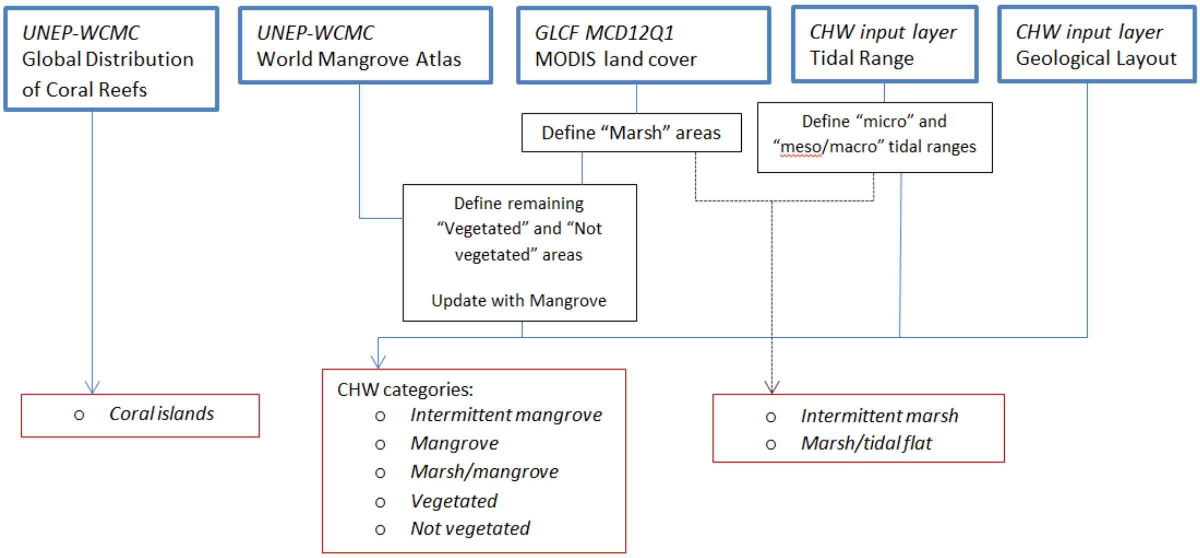
A. Appendix Flowcharts

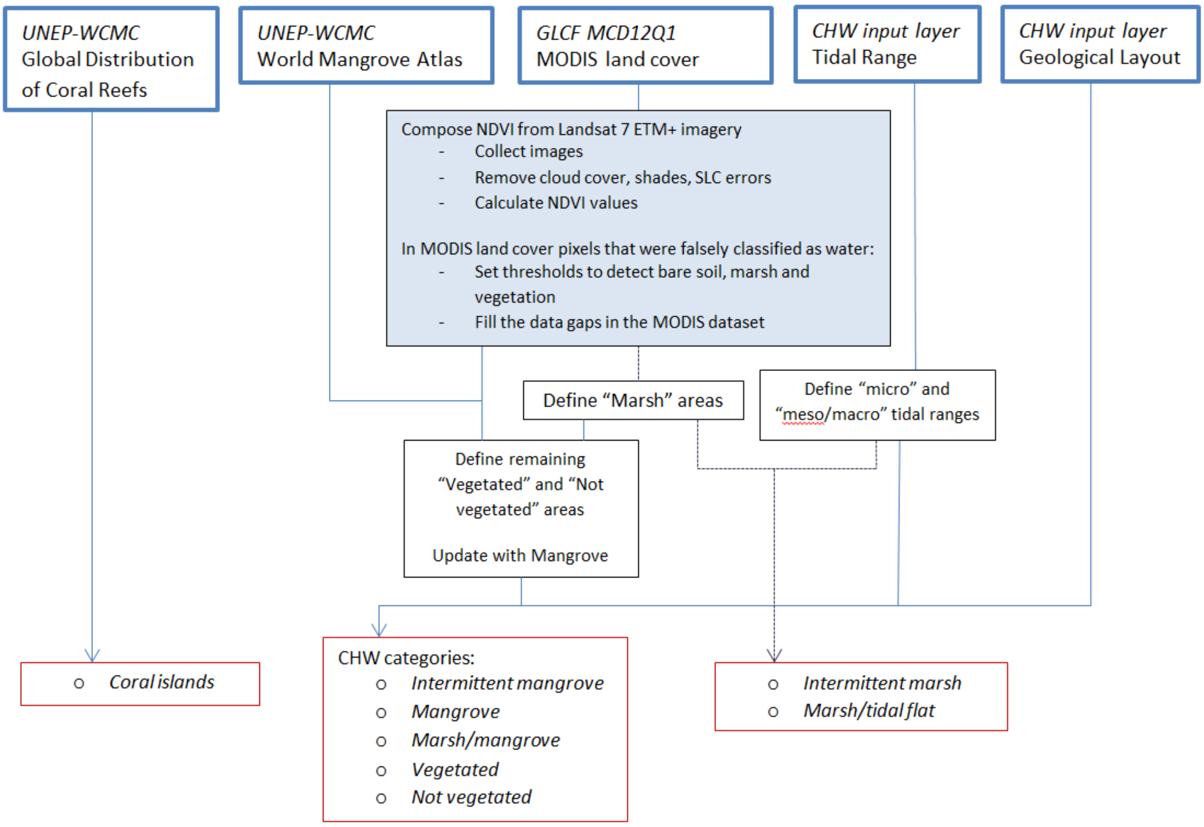
Flowcharts of the original and improved construction of the geological layout input layer





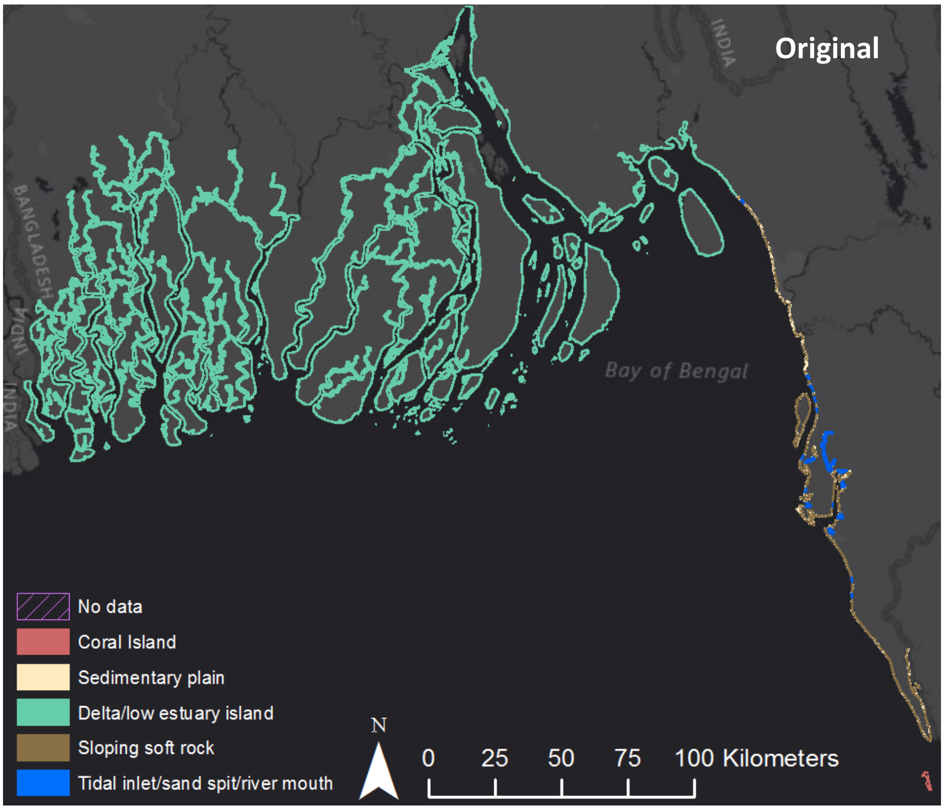
Flowcharts of the original and improved construction of the flora/fauna input layer

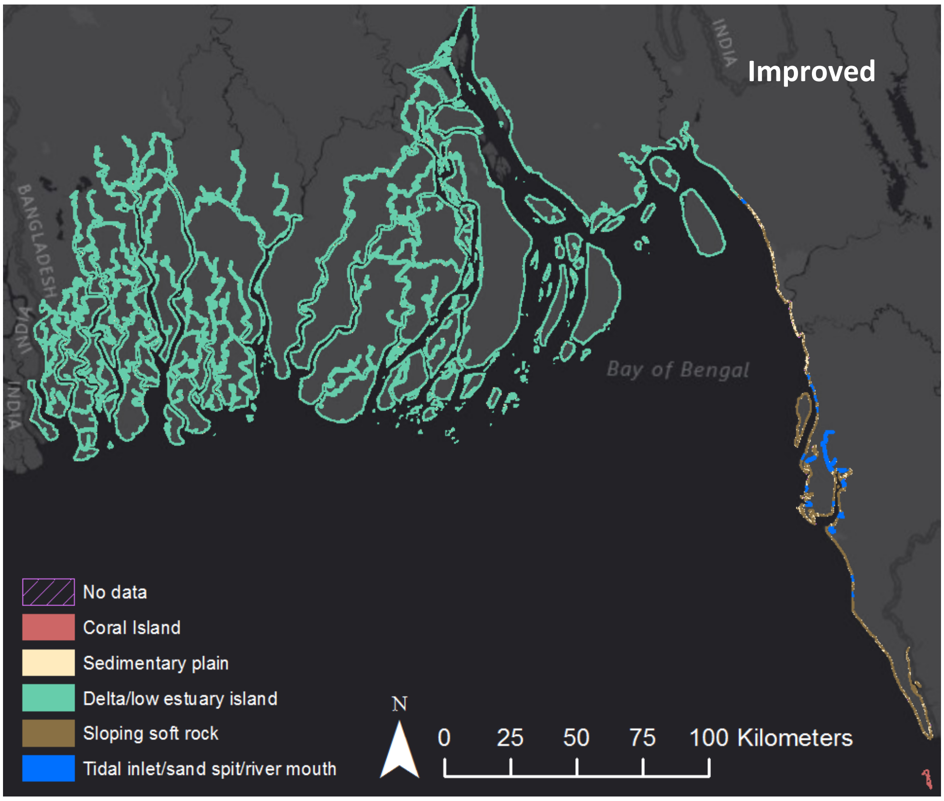




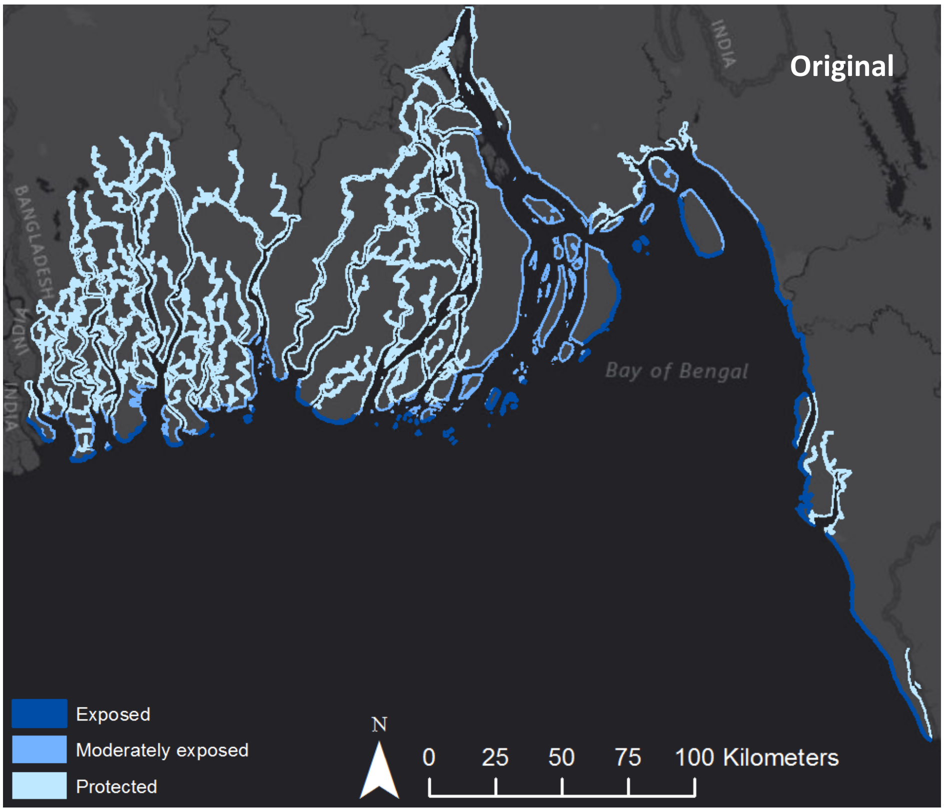
B. Appendix Input layers Bangladesh

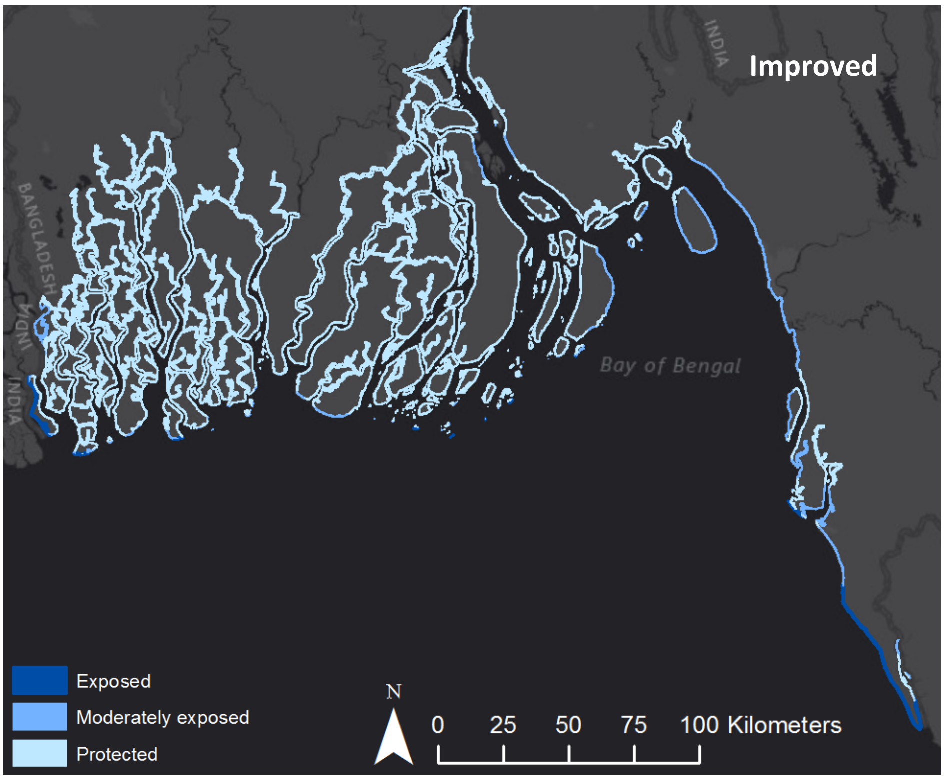
Geological layout



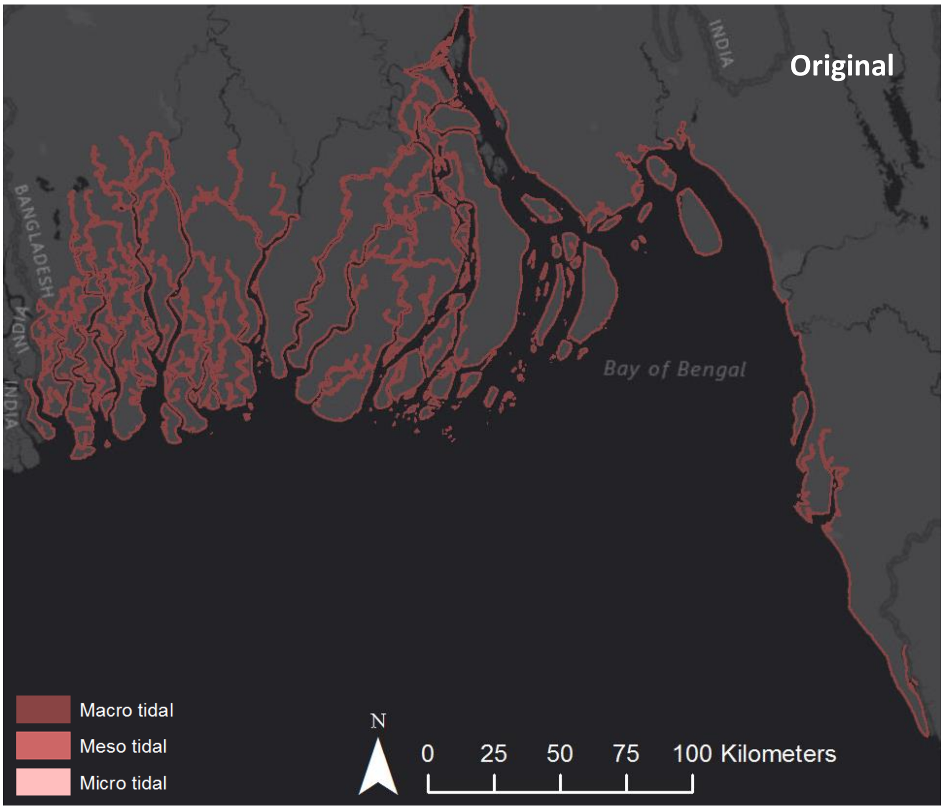


Wave exposure

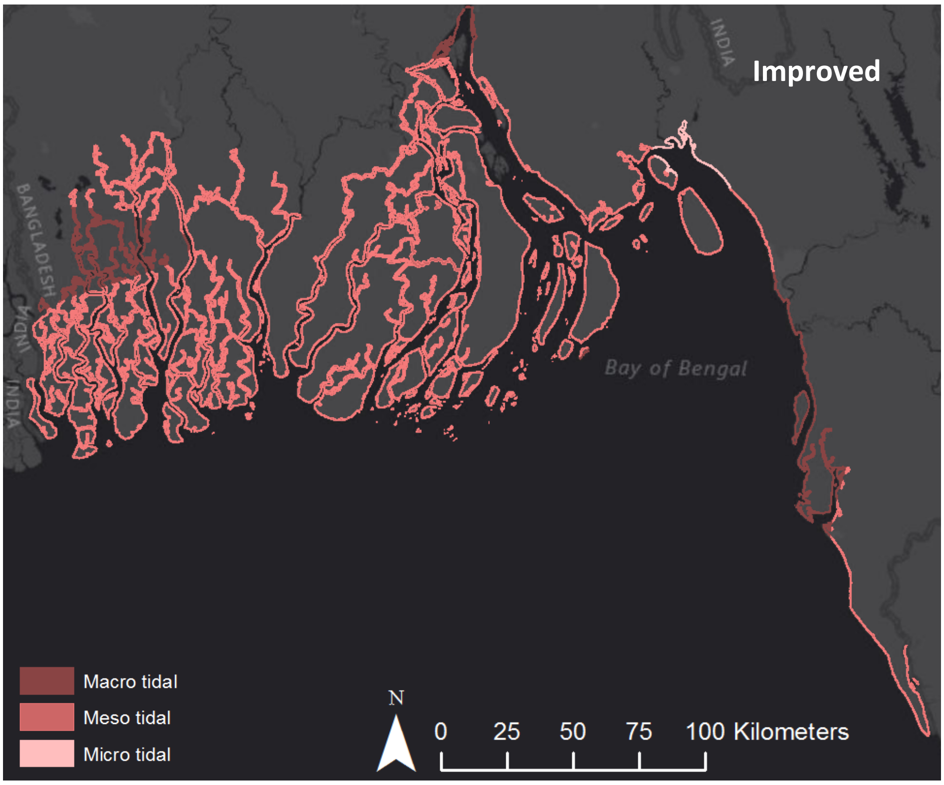




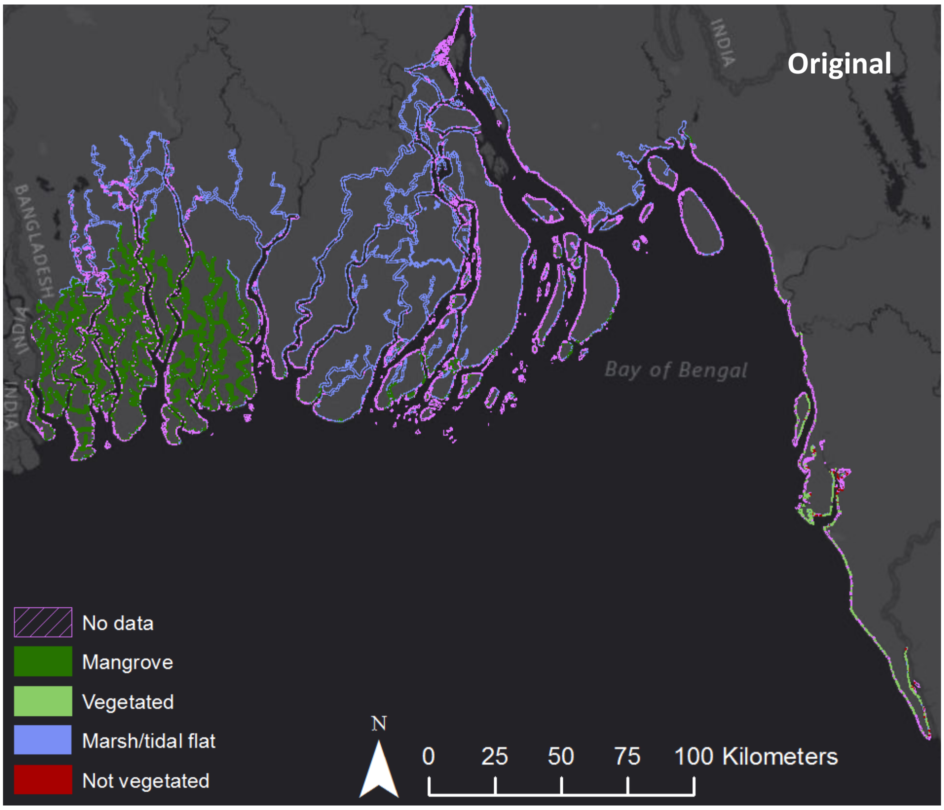
Tidal range

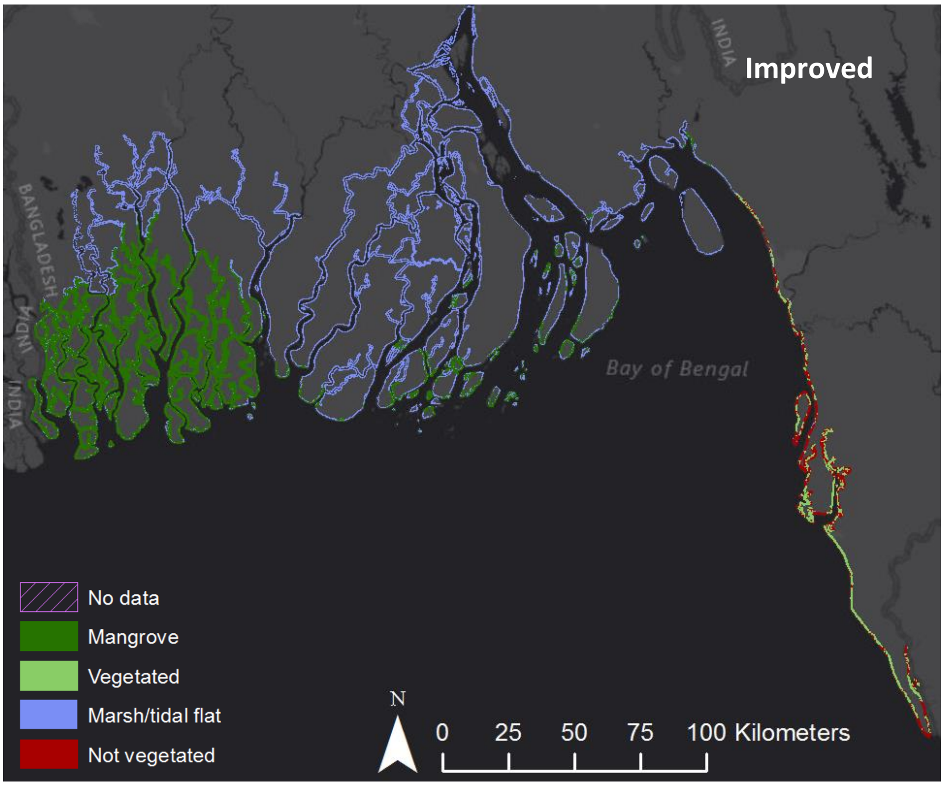


Original
INDIA
BANGLADESH
INDIA
Bay of Bengal
Macro tidal
Meso tidal
Micro tidal
N
0 25 50 75 100 Kilometers

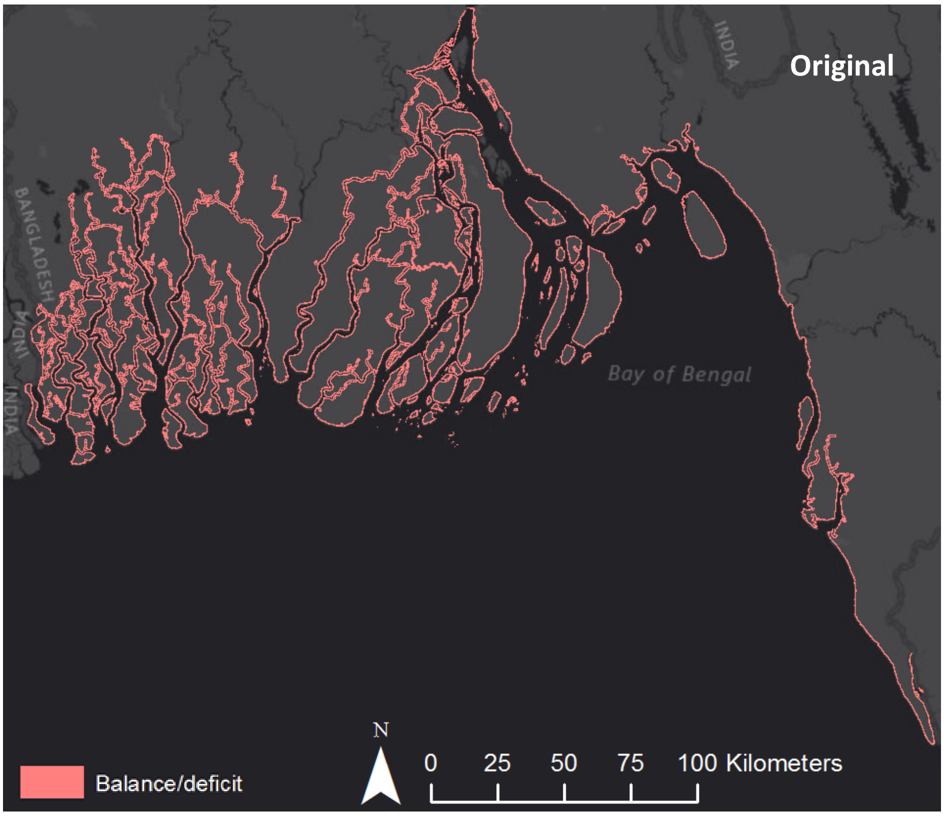


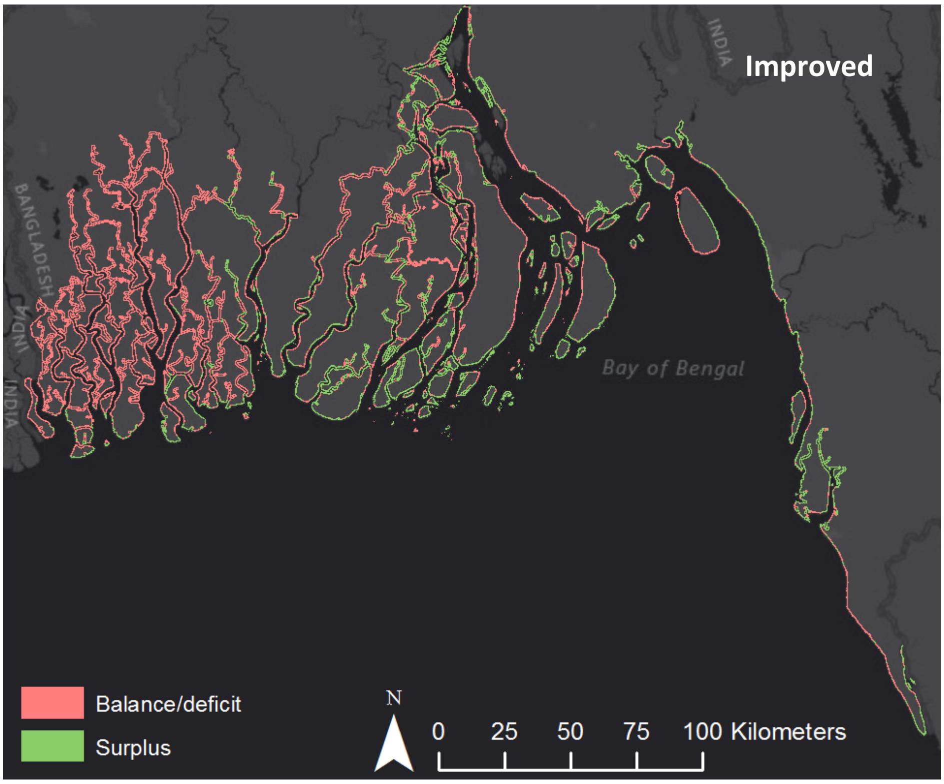
Improved
INDIA
BANGLADESH
INDIA
Bay of Bengal
Macro tidal
Meso tidal
Micro tidal
N
0 25 50 75 100 Kilometers


Original
INDIA
BANGLADESH
INDIA
Bay of Bengal
No data
Mangrove
Vegetated
Marsh/tidal flat
Not vegetated
N
0 25 50 75 100 Kilometers

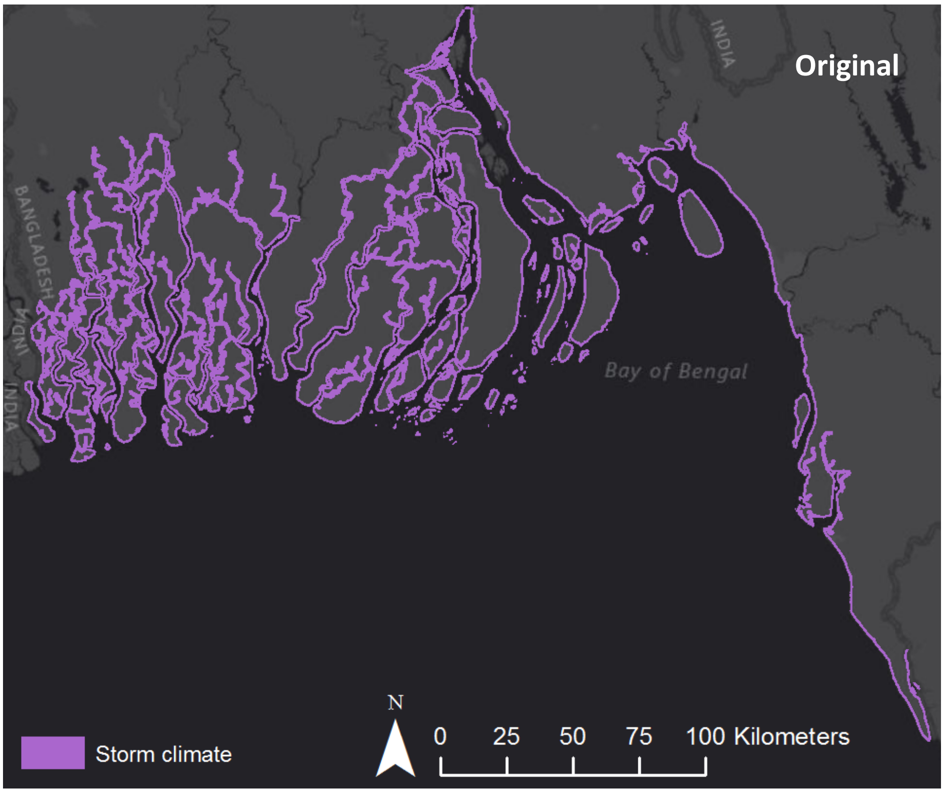

Improved
INDIA
BANGLADESH
INDIA
Bay of Bengal
No data
Mangrove
Vegetated
Marsh/tidal flat
Not vegetated
N
0 25 50 75 100 Kilometers

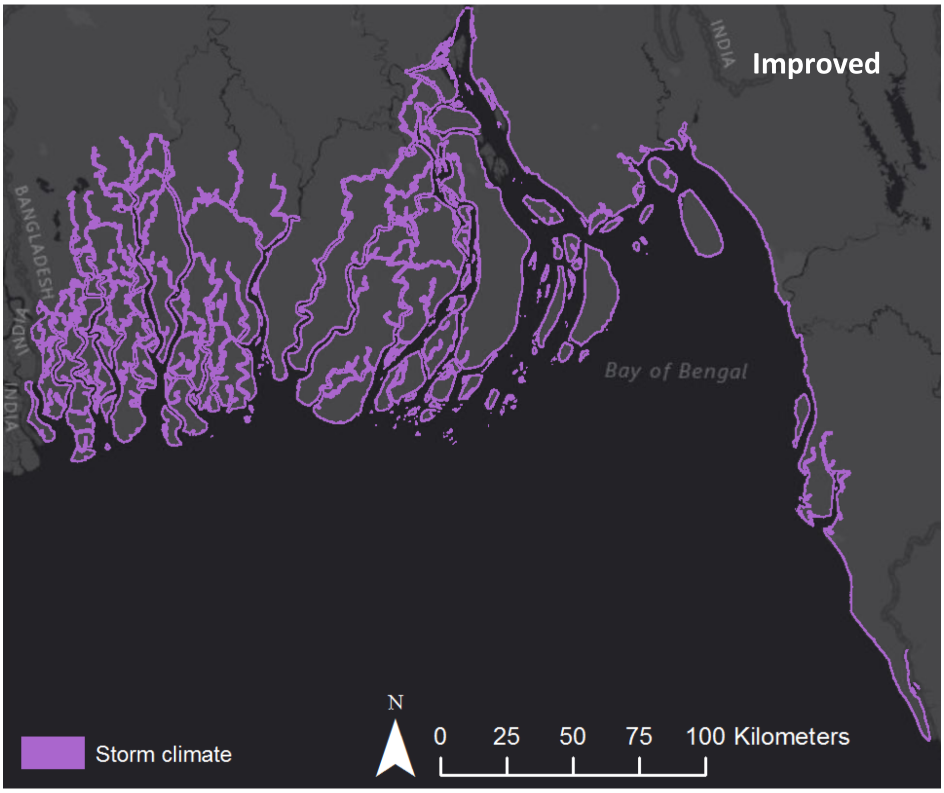
Sediment balance





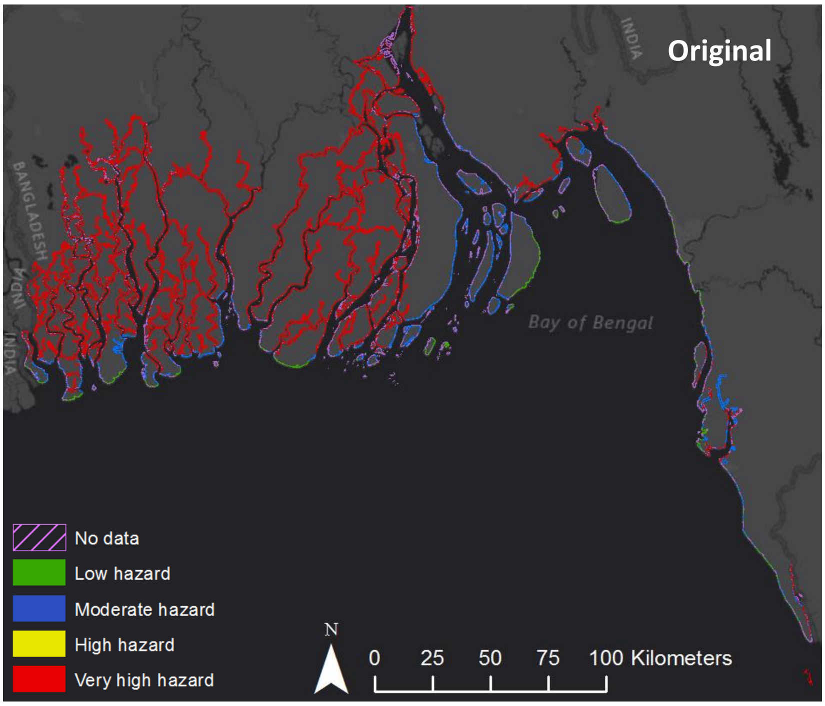
Storm Climate

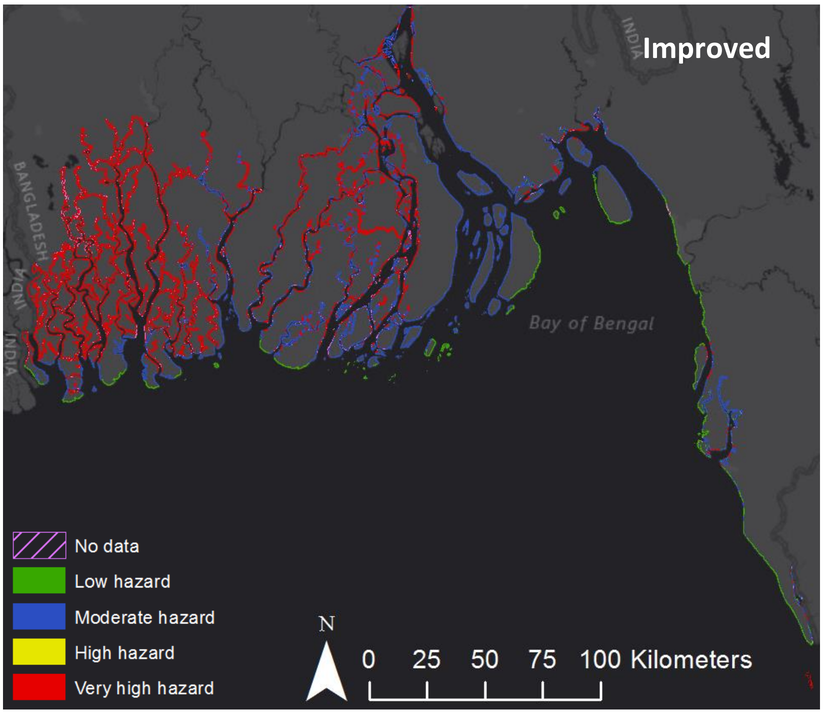




C. Appendix multi-hazard assessment Bangladesh

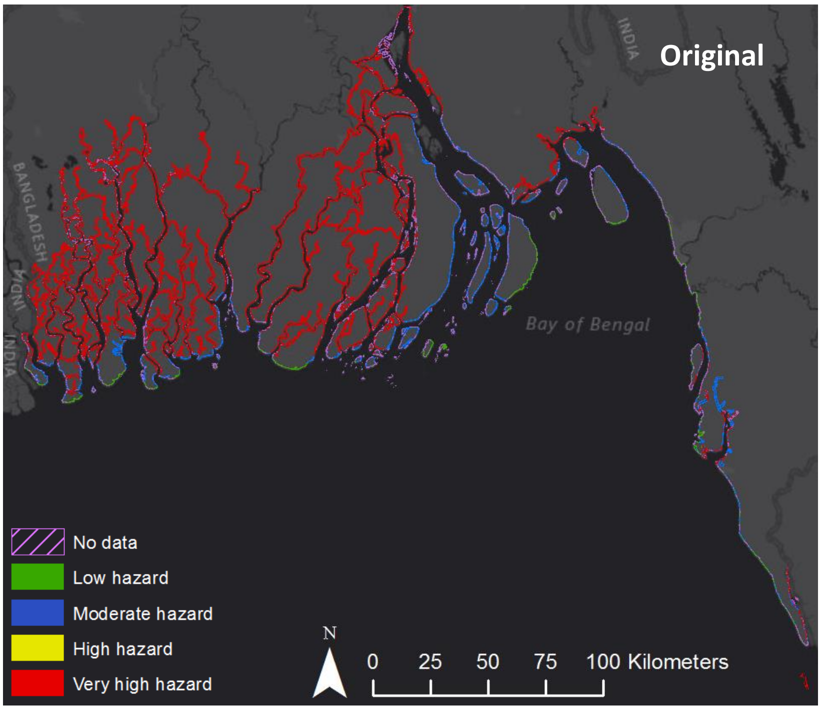
Ecosystem disruption

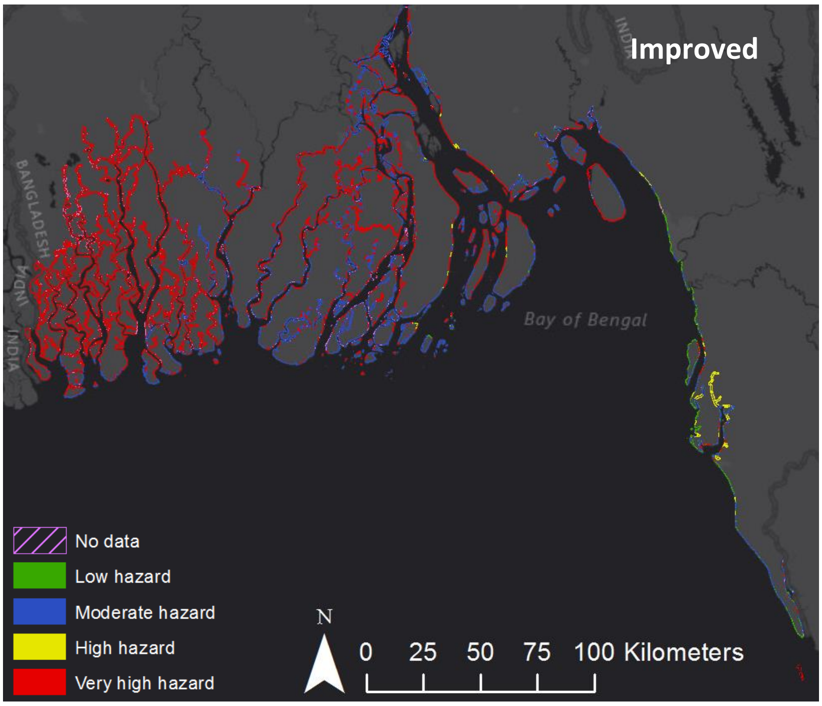




		Improved					
		No data	Low hazard	Moderate hazard	High hazard	Very high hazard	Total
Original	No Data	84,86	234,78	757,34	0	335,58	1413
	Low hazard	0,06	203,26	0,6	0	0	204
	Moderate hazard	1,28	47,22	699,08	0	4,44	752
	High hazard	0	0	0	0	0	0
	Very high hazard	179,54	11,56	1358,9	0	4180,32	5730
	Total	266	497	2816	0	4520	

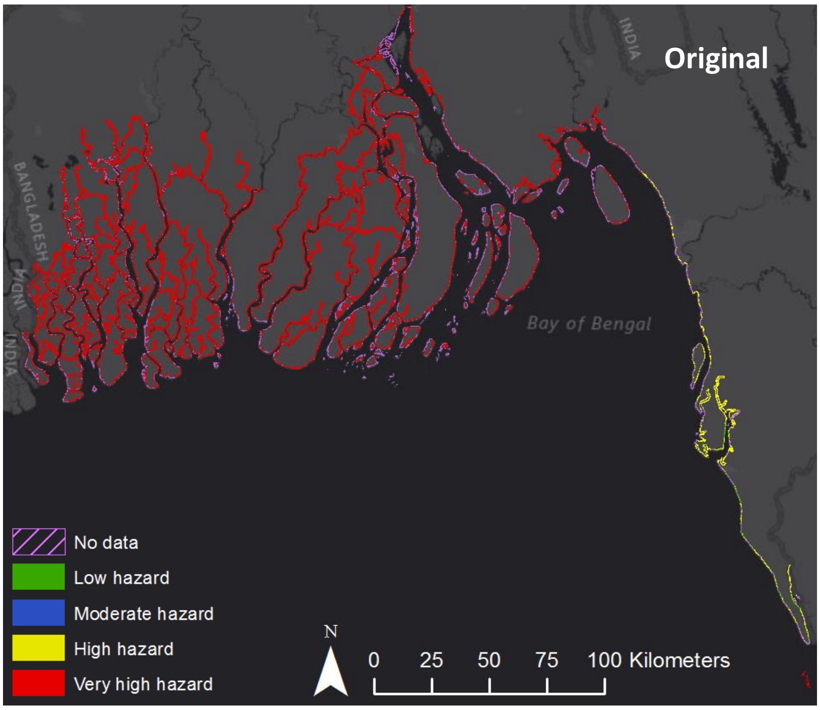
Gradual inundation

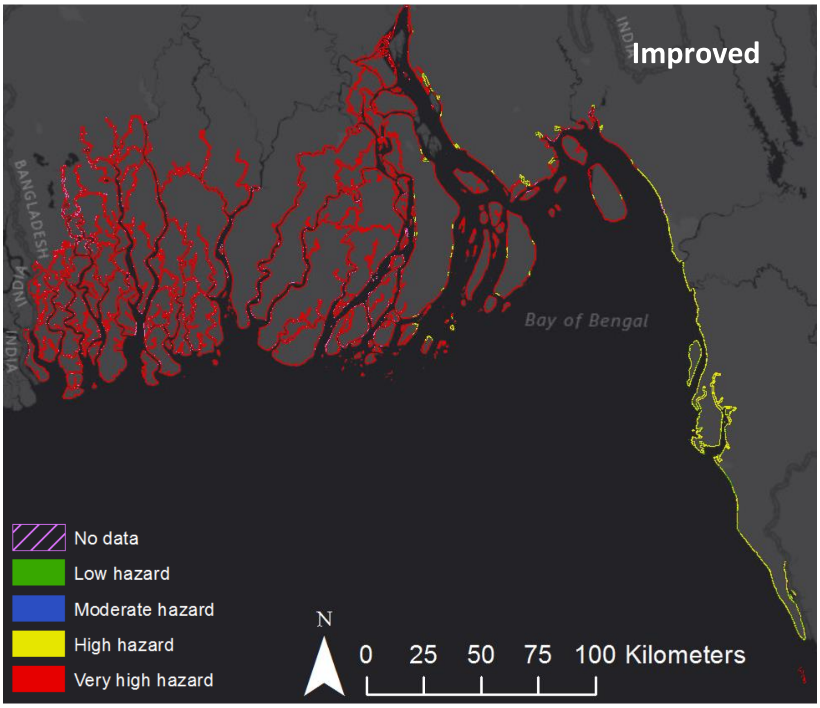




		Improved					
		No data	Low hazard	Moderate hazard	High hazard	Very high hazard	Total
Original	No Data	84,86	100,6	596,9	11,04	619,16	1413
	Low hazard	0,88	42,98	13,02	0	4,12	61
	Moderate hazard	0	36,7	32,18	0	0	69
	High hazard	0,12	3,32	5,08	102,88	0,2	112
	Very high hazard	179,88	24,14	1729,82	13,82	4497,12	6445
	Total	266	208	2377	128	5121	

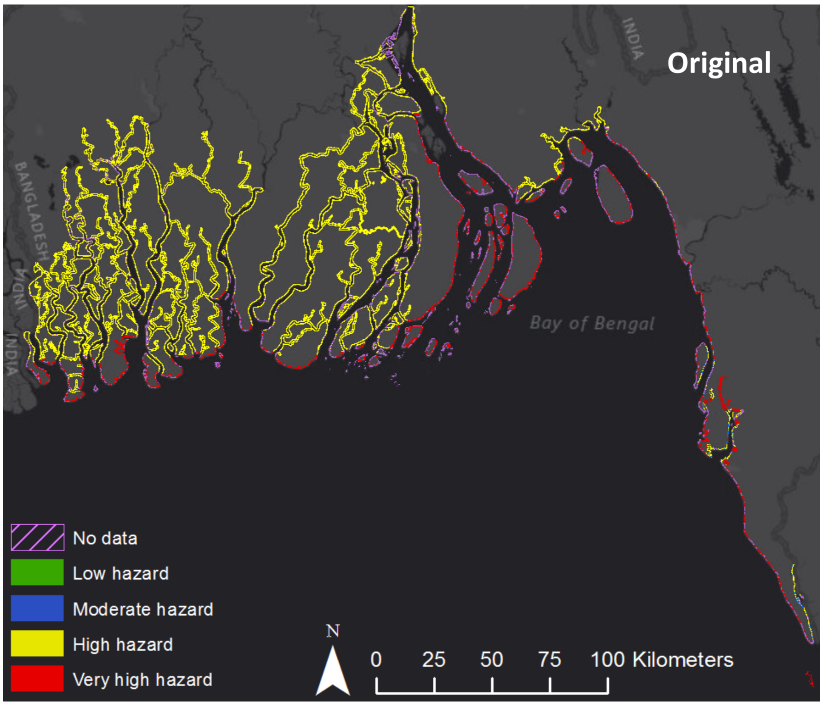
Salt water intrusion

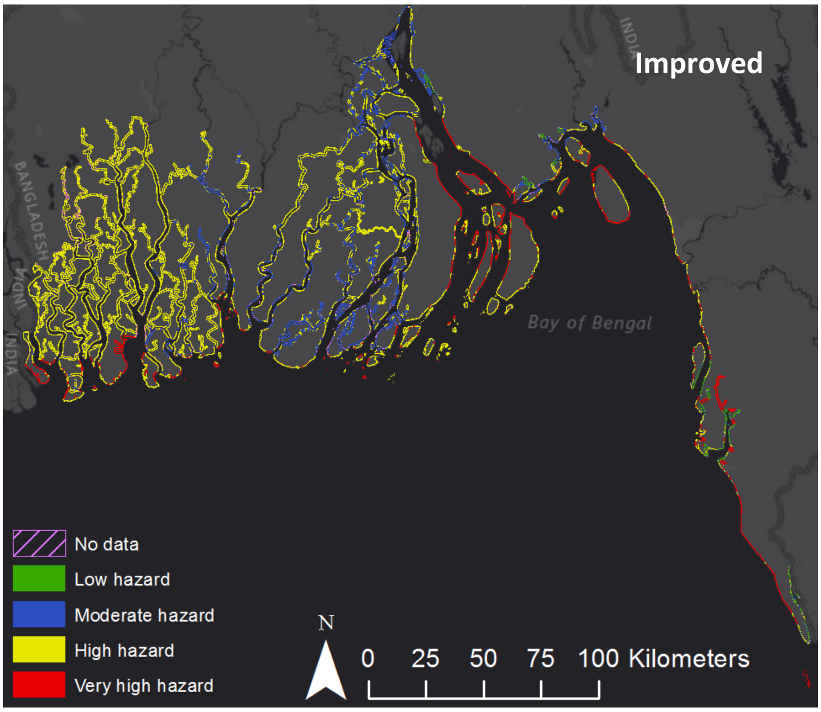




		Improved					
		No data	Low hazard	Moderate hazard	High hazard	Very high hazard	Total
Original	No Data	84,86	40,38	0	167,06	1120,26	1413
	Low hazard	0,88	42,18	0	17,94	0	61
	Moderate hazard	0	0	0	0	0	0
	High hazard	2,42	1,02	0	263,82	0	267
	Very high hazard	177,58	21,22	0	85,66	6073,54	6358
	Total	266	105	0	534	7194	

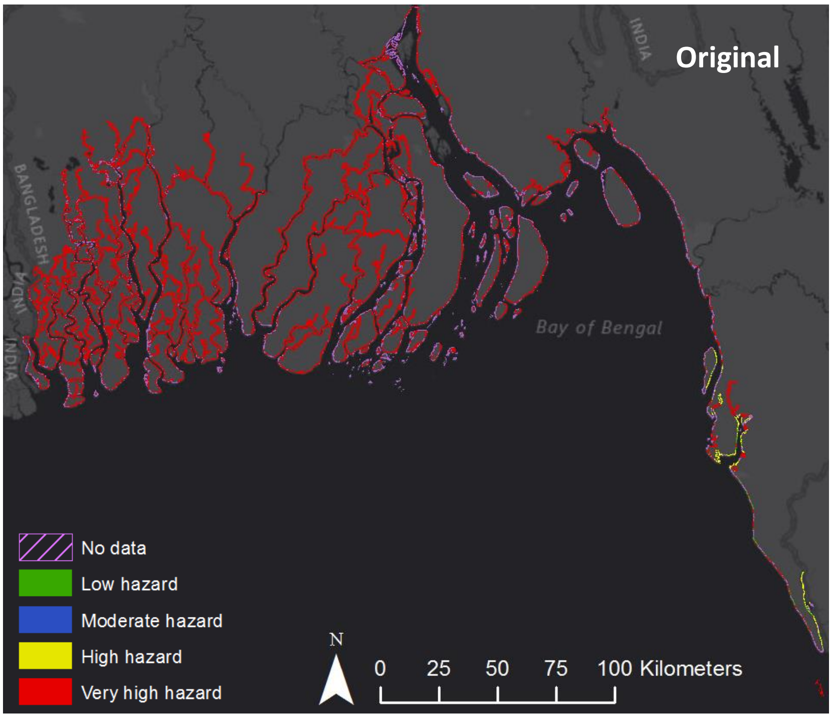
Erosion

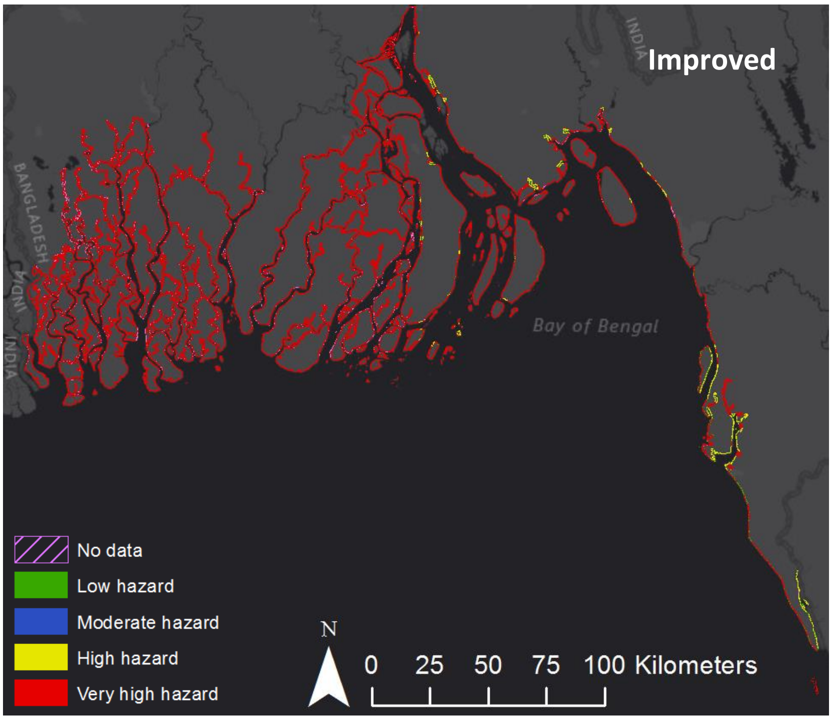




		Improved					
		No data	Low hazard	Moderate hazard	High hazard	Very high hazard	Total
Original	No Data	84,86	31,4	223,22	744,56	328,52	1413
	Low hazard	0	0	0	0	0	0
	Moderate hazard	0,02	3,26	24,64	4,12	0	32
	High hazard	179,56	106,32	1264,18	4176,48	0,12	5727
	Very high hazard	1,3	2,92	7,5	431,28	484,56	928
	Total	266	144	1520	5356	813	

Flooding





		Improved					
		No data	Low hazard	Moderate hazard	High hazard	Very high hazard	Total
Original	No Data	84,86	40,38	0	60	1227,32	1413
	Low hazard	0,88	42,18	0	7,4	10,54	61
	Moderate hazard	0	0	0	0	0	0
	High hazard	2,3	0	0	84,48	0	87
	Very high hazard	177,7	22,24	0	69,78	6268,76	6538
	Total	266	105	0	222	7507	