# Susceptibility to Changes in Coastal Land Dynamics in Bangladesh

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The candidate declares that the work is original and solely accomplished by him. The contributions of individual supervisors are clearly indicated below. The candidate confirms that appropriate credits have been given to the authors where references have been cited from literature pertinent to the study.

The work in chapter 2 of the thesis has appeared in publication as follows:
Where is the coast? Monitoring coastal land dynamics in Bangladesh: An integrated management approach using GIS and remote sensing techniques. *Ocean and Coastal Management* (2018) 151, 10-24. **Asib Ahmed**, Frances Drake, Rizwan Nawaz, Clare Woulds.

Contributions: **Asib Ahmed** (AA) was responsible for literature review, collection, processing and analysis of Landsat satellite images, collecting data on management and policy issues, preparing figures and writing-up the draft paper. Frances Drake (FD) made significant contribution to identify site-specific factors of land dynamics in the study area and policy and management aspects where Rizwan Nawaz (RN) provided guidelines on the appropriateness of the satellite images. Clare Woulds (CW) made significant efforts on the structure of the paper and recommendations for further works. All authors provided valuable comments on the draft paper and made efforts to prepare the paper as final.

The work in chapter 3 of the thesis has appeared in publication as follows:
Modelling land susceptibility to erosion in the coastal area of Bangladesh: A geospatial approach. *Geomorphology* (2018) 320, 82-97. **Asib Ahmed**, Rizwan Nawaz, Frances Drake, Clare Woulds.

Contributions: AA was responsible for selecting the parameters and designing the LSCE model. AA conducted a literature survey for the study. AA was also responsible for collecting and analysing the data for the model and conducted the pre and post processing tasks of the raster surfaces. AA then run the model, conducted the validation works of the model results and prepared the draft paper based on the model outputs. RN provided significant guidelines for selecting the parameters and designing the model frame. FD made valuable efforts for validating the model results where CW was responsible for matching the consistency of the model results and supported to prepare the draft paper. All the authors provided their comments for finalising the paper.

The work in chapter 4 of the thesis currently submitted for publication as follows:
Modelling impacts of future climate on land susceptibility to erosion: A geospatial approach applied for the coastal area of Bangladesh. *Natural Hazards*. **Asib Ahmed**, Rizwan Nawaz, Clare Woulds, Frances Drake.

Contributions: AA was responsible for gathering data on future climate scenarios, prepared the raster surfaces and run the model scenarios. AA reviewed the available literature for the study. AA was also prepared the draft paper based on the model results. AA made necessary works for the justifications of the model results. RN provided significant guidelines in assessing the impacts of future hydro-climatic changes on land susceptibility to erosion. CW guided throughout the process of selecting appropriate numbers of model scenarios. FD made contributions to the justifications of the model scenarios. All the authors provided valuable comments on the paper.

The work in chapter 5 of the thesis has appeared in publication as follows:
Beyond the tradition: Using Fuzzy Cognitive Maps to elicit expert views on coastal susceptibility to erosion in Bangladesh. *Catena* (2018) 170, 36-50. **Asib Ahmed**, Clare Woulds, Frances Drake, Rizwan Nawaz.

Contributions: AA was responsible for conducting two consecutive workshops and prepared the fuzzy cognitive maps based on the contributions of the selected experts in the workshops. AA accomplished the review of relevant literature necessary for the study and prepared the draft paper. CW made contributions in drafting the structure of the paper. FD provided necessary guidelines for the design of the workshops where RN suggested selecting appropriate experts for the workshops. All the authors made significant contributions in writing the final paper.

## Thesis by Alternative Format (TAF) rationale

Having a general consensus on the research questions, objectives and methodology based on in-depth review of relevant literature, chapter 2 of the thesis has been prepared by the end of the first year of studentship. The works in chapter 2, chapter 3 and chapter 5 have appeared in publications by August 2018. The work in chapter 4 has been submitted for consideration for publication. The major parts of the research have already appeared in publications that include significant outcomes of the study. That means, TAF found as the most appropriate option for the thesis. Copied of the published papers are included in the submission. The candidate also attended relevant conferences held in UK, Bangladesh and USA and presented the methods and results of the study. Two papers prepared from the results of the study that appeared in conference proceedings but, only the papers considered for recognised journals are included herewith.

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# Abstract

Coastal areas of the world are physically dynamic in nature. The present study contributes new knowledge to studies on coastal land dynamics and land susceptibility to erosion. This study developed a raster GIS-based model namely, Land Susceptibility to Coastal Erosion (LSCE) to assess erosion susceptibility of coastal lands under hydro-climatic changes. The devised model was applied to the entire coastal area of Bangladesh. The model required the characterisation of the nature of land dynamics (i.e. erosion and accretion). The analysis showed a net gain of 237 $km^2$ of land over the past thirty years but, constant changes in land dynamics were observed in the area. The study then applied the LSCE model to measure the existing levels of land susceptibility of the coastal area to erosion. The validated model outputs were then used as a baseline for generating four possible scenarios of future land susceptibility to erosion in the coastal area. This allowed the model to ascertain the probable impacts of future hydro-climatic changes on land susceptibility to erosion in the area. Additionally, the study assessed seasonal variations of land susceptibility to erosion by using the same model. The model outputs showed that 276.33 $km^2$ of existing coastal lands classified as highly and very highly susceptible to erosion, would substantially increase in the future. Using a Fuzzy Cognitive Mapping (FCM) approach, the study elicited expert views to evaluate the model scenarios and to address uncertainties relevant to erosion susceptibility. This study could allow coastal managers and policymakers to develop effective measures in managing highly erosion susceptible coastal lands in the area.

**Acronyms used in this thesis**

| | |
|---|---|
| ANN | - Artificial Neural Network |
| ASTER-DEM | - Advanced Space-born Thermal Emission and Reflection Radiometer-Digital Elevation Model |
| BARC | - Bangladesh Agricultural Research Council |
| BIWTA | - Bangladesh Inland Water Transport Authority |
| BWDB | - Bangladesh Water Development Board |
| CDMP | - Comprehensive Disaster Management Plan |
| CDS | - Coastal Development Strategy |
| CDRI | - Climate Disaster Resilience Index |
| CEP | - Coastal Embankment Project |
| CORDEX | - Coordinated Regional Climate Downscaling Experiment |
| CRI | - Coastal Resilience Index |
| CVI | - Coastal Vulnerability Index |
| CZP | - Coastal Zone Policy |
| DF | - Degree of Fit |
| DCM | - Dynamic Computer Modelling |
| DESYCO | - Decision Support System for Coastal Climate Change |
| DIVA | - Data Interpolating Variation Analysis |
| DN | - Digital Number |
| DOS | - Dark Object Subtraction |
| DSS | - Decision Support Systems |
| ETM+ | - Enhanced Thematic Mapper Plus |
| FCM | - Fuzzy Cognitive Mapping/Maps |
| FGD | - Focus Group Discussion |
| GBM | - Ganges-Brahmaputra-Meghna |
| GCP | - Ground Control Points |
| GIS | - Geographical Information System |
| GMRT | - Global Multi-Resolution Topography |
| GoB | - Government of Bangladesh |
| GRASS | - Geographic Resources Analysis Support System |
| ICZM | - Integrated Coastal Zone Management |
| IDW | - Inverse Distance Weighting |
| IMF | - International Monetary Fund |

| | |
|---|---|
| IPCC | - Intergovernmental Panel on Climate Change |
| IWFM | - Institute of Water and Flood Management |
| LGED | - Local Government and Engineering Department |
| LRP | - Land Reclamation Project |
| LSCE | - Land Susceptibility to Coastal Erosion |
| LUP | - Land Use Policy |
| MNCH | - Maternal, New-born and Child Health |
| MoEF | - Ministry of Environment and Forest |
| MoWR | - Ministry of Water Resources |
| MoLGRDC | - Ministry of Local Government Rural Development and Cooperatives |
| m/s | - Metre per second |
| $m^3/s$ | - Cubic metre per second |
| MSL | - Mean Sea Level |
| NAPA | - National Adaptation Program of Action |
| NGO | - Non-Governmental Organization |
| NOAA | - National Oceanic and Atmospheric Administration |
| NWPo | - National Water Policy |
| NWRD | - National Water Resource Database |
| PDO-ICZMP | - Program Development Office- Integrated Coastal Zone Management Program |
| POLCOMS | - Proudman Oceanographic Laboratory Coastal Ocean Modelling System |
| PRSP | - Poverty Reduction Strategy Paper |
| PRECIS | - Providing Regional Climate for Impact Studies |
| PSMSL | - Permanent Solution for Mean Sea Level |
| RCP | - Representative Concentration Pathway |
| RMSE | - Root Mean Square Error |
| SRDI | - Soil Resources Development Institute |
| SoB | - Survey of Bangladesh |
| TM | - Thematic Mapper |
| TRM | - Tidal River Management |
| UHSLC | - University of Hawaii Sea Level Centre |
| UNDP | - United Nations Development Programme |
| USGS | - United States Geological Survey |
| WARPO | - Water Resources Planning Organization |

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## Chapter 1: Introduction

Coastal areas form a dynamic part of the world and exhibit as a multi-functional complex system (Ramieri et al., 2011). As a functional region, coastal areas are subject to several natural disturbances. Coastal erosion and accretion are natural processes that are key to understanding land dynamics in coastal areas. Coastal erosion is the physical process of removing materials from the coast (British Geological Survey [BGS], 2012) that causes a landward retreat of the shoreline. That is, coastal erosion is the encroachment of land by the sea (EUROSION, 2004) predominantly as a result of natural factors (Feng et al., 2009; van-Vliet, 2011). However, human actions and interventions bring into play substantial influences on the process of coastal erosion (i.e. Hallsands in Devon, England) (van-Vliet, 2011). In the past, coastal erosion was considered less threatening to human livelihood because of lower erosion rates than present and the affected areas were primarily used for recreational purposes (Furuseth and Ives, 1987). Currently, a considerable percentage of the world's population (i.e. nearly 37%) lives within 100 km distance from the coastline (United Nations [UN], 2017). The impacts of coastal erosion pose a threat to the communities living in these erosion-prone areas.

The term susceptibility indicates the degree of resistance capacity of a system in response to potential changes in the fundamental components of that system (Nunn et al., 2014). Susceptibility differs from hazard and vulnerability and hence, it is important to define the connotations of hazard and vulnerability in studying coastal land dynamics (i.e. erosion and accretion) and land susceptibility to erosion. A hazard is a phenomenon, condition, substance or human activity which has the potential to cause damage to life, property, livelihood etc. (United Nations International Strategy for Disaster Reduction [UNISDR], 2009, 2017; Sultana and Hussain, 2015). In the literature, coastal erosion is identified as a natural hazard event (Boruff et al., 2005, McLaughlin and Cooper, 2010; Mujabar and Chandrasekar, 2013; Islam et al., 2016). Vulnerability is a measure of the potential harm to a system due to a hazard (Cutter et al., 2000; Mujabar and Chandrasekar, 2013; Rashid and Paul, 2014) whereas, risk is the probability of harmful consequences that depends on hazard, vulnerability and coping capacity (Sotic and Rajic, 2015). However, the susceptibility of coastal lands to erosion determines the nature and level of resistance capacity of those lands to erosion (Ministry for Primary Industries [MPI], 2017). A low resistance capacity of a coastal system means that the coastal land is highly susceptible to erosion

(Alexandrakis et al., 2010). On the other hand, a high resistance capacity reduces erosion susceptibility of coastal lands and consequent risk originating from erosion (Figure 1a).

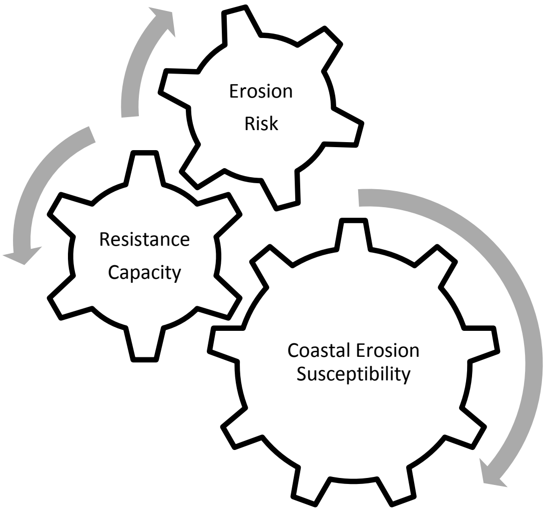

Figure 1a – Interrelationships of resistance capacity and erosion risk with erosion susceptibility within a coastal system. [Modified after: van Beek, 2006 and Balica et al., 2012]

Coastal erosion is a global problem (Feng et al., 2009). Coastal erosion is treated as a morpho-dynamic hazard (Addo et al., 2008) in different coastal zones of the world such as Wamberal of New South Wales, Santa Barbara of California and Holderness of Yorkshire. The geological controls, geomorphic processes and climatic drivers vary substantially from one coastal area to another (Naylor and Stephenson, 2010). Trends in coastal erosion are difficult to determine due to the interconnected coastal physical processes (e.g. changes in bathymetry, wave actions etc.) and climatic variables (e.g. rainfall, wind, water discharge etc.) (Gornitz, 1991). This dynamic nature of erosion considerably affect the development of, and changes in, coastal landscape (Dimou, 2014). The coastal area of Bangladesh is highly dynamic (Brammer, 2014). More specifically, the coastal lands are geomorphologically active due to the constant processes of erosion and accretion in the coastal area. The dynamic nature of the coastal area is closely associated with the formation process of the Bengal delta in the Ganges-Brahmaputra-Meghna (GBM) river basin area (Figure 1b). The formation of the coastal area of Bangladesh can be traced back 11,000 years within the large Bengal basin in Asia (Kuehl et al., 2005; Mikhailov and Dotsenko, 2007). However, the delta development process in the GBM basin was accelerated by the supply of huge sediments from the Himalayas through the Ganges and the Brahmaputra River during Holocene epoch with a subtle balance of sea level rise evidenced in the late Quaternary period (Umitsu, 1993; Goodbred and Kuehl, 2000a, b; Allison and Kepple, 2001). Currently, however, natural and human-induced forces are, responsible for the dynamic nature of land (i.e. erosion and accretion) in the coastal area of Bangladesh (Goodbred et al., 2003; Sarker et al., 2011; Brammer, 2014; Hussain et al., 2014a, b).

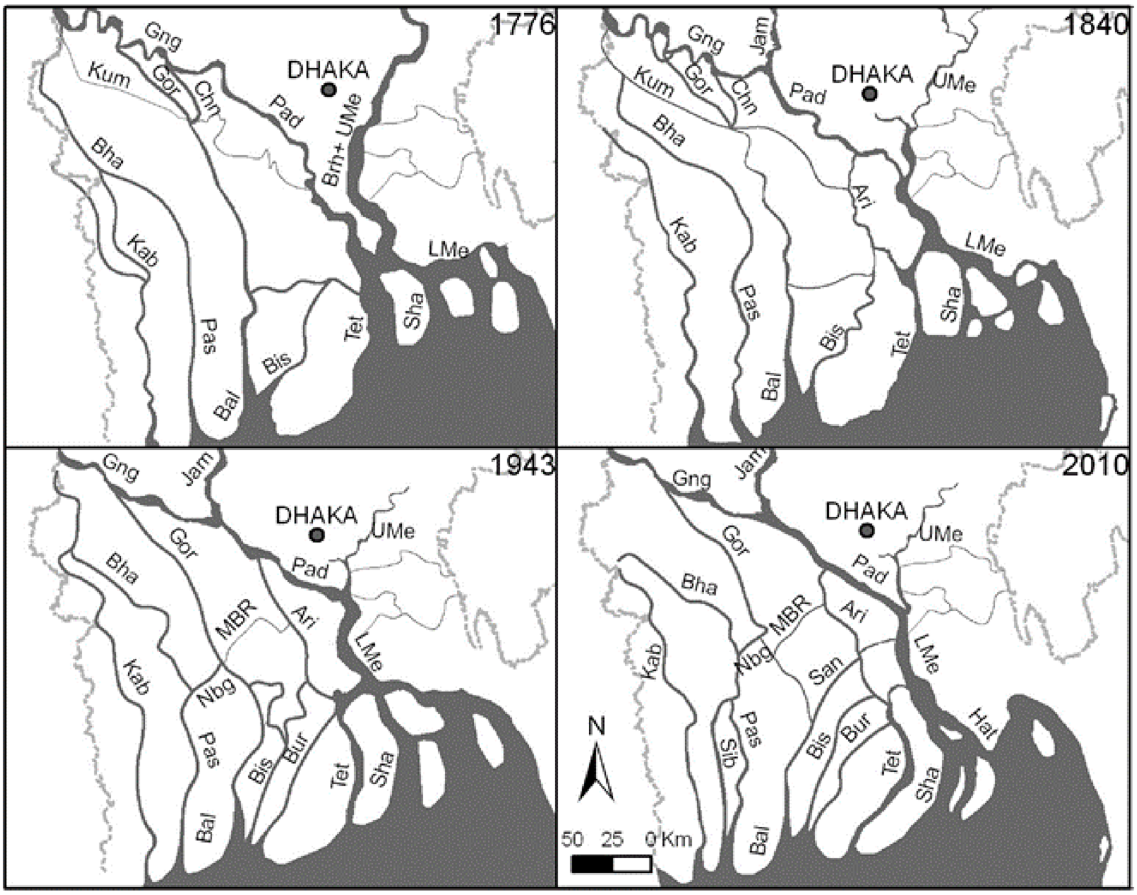

Figure 1b - The formation of the coastal area in Bangladesh along with the changes of river courses through time. During the last 250 years, major changes in the land have been observed in the central coastal zone of the area. [Source: Rennel, 1778; Sarker et al., 2015]

## 1.1 Theoretical underpinnings

Literature suggests several methodological approaches that are available to study coastal land dynamics (i.e. erosion and accretion) from different perspectives such as shoreline retreat, land loss and gain, susceptibility and exposure to erosion hazard. This section first outlines the geospatial approaches used to study coastal land dynamics before considering semi-quantitative approaches. It comprises of a review of the relevant approaches (i.e. an assessment of existing coastal land dynamics) to assess the suitability of the approaches to the present study and to ascertain specific knowledge gaps in assessing coastal land dynamics. Finally, this section considers how to construct future scenarios of coastal land dynamics. In each sub-section, a review of the current state of literature with regards to Bangladesh is given.

### 1.1.1 Assessment of existing coastal land dynamics

Previous studies suggest that land dynamics in coastal areas around the world were evaluated by using several geospatial methods and techniques. Moreover, the studies indicate the potentiality of using semi-quantitative methods to study coastal land dynamics. Hence, this section first discusses the theoretical aspects of several methods and techniques of geospatial approaches that were applied in previous studies. This section then identifies the relevant studies and methods that were used to assess land dynamics in the coastal area of Bangladesh. The various advantages and disadvantages of each geospatial technique are then discussed.

#### 1.1.1.1 Geospatial approach

The term ‘geospatial’ denotes geographically referenced data (e.g. latitude and longitude) that are associated with a particular location on earth (McCall and Verplanke, 2008). In recent years, technological advancements have brought substantial changes in geospatial science (United Nations Conference on Trade and Development [UNCTAD], 2012). Geospatial data are now enhanced by the use of Geographical Information System (GIS) and satellite images. The geospatial approach of studying coastal land dynamics comprises the methods and techniques that use geospatial science, technology and geographical data. Several studies assessed the issues of coastal land dynamics by applying different geospatial methods and techniques.

### *Empirical field study techniques*

Several empirical field study techniques were employed to assess coastal land dynamics. The field techniques include manual field survey, aerial photography and photogrammetry, GPS/GNSS (Global Positioning System/Global Navigation Satellite System), LiDAR (Light Detection and Ranging), Terrestrial Laser Scanner (TLS) and Structure from Motion (with Multi View Stereo) etc. For instance, Duc et al. (2012) conducted an empirical field survey along the Vietnam coast to observe the rate of coastal erosion. Using aerial photographs, Ferreira et al. (2006) developed an integrated method to determine set-back lines for coastal erosion hazard of a sandy shore of Portugal. By using GPS, Baptista et al. (2011) studied the rate of shoreline changes for the two sites in Portugal. In recent years, LiDAR (Kuhn and Prüfer, 2014; Earlie et al., 2015; Obu et al., 2016), Terrestrial Laser Scanner (TLS) (Montreuil et al., 2013; Feagin et al., 2014), Unmanned Aerial Vehicle (UAV) (Papakonstantinou et al., 2016) and Structure-from-Motion (Brunier et al., 2016; Westoby et al., 2018) techniques have been widely used to identify the coastal changes. The LiDAR is a survey method that emits laser lights from an airborne source (e.g. aircraft) and measures the reflected pulses of those lights by a sensor (Richter et al., 2013). Similarly, the TLS is a ground-based method of survey that uses the same procedure as LiDAR does. In combination with GPS, the LiDAR and TLS provide fully georeferenced data and are capable of capturing time-series measurement of topographical changes. The UAV uses vertical take-off and landing of an aerial vehicle to capture high resolution orthophotos (i.e. geometrically corrected aerial photograph). Unlike UAV, Structure from Motion is a ground-based photography technique to monitor the changes of shoreline position for different periods. The SfM-MVS is an advanced photogrammetry that uses overlapping images from cameras set at ground control points in identifying topographical changes (Smith et al., 2015; Carrivick et al., 2016). The study by Westoby et al. (2018) followed the SfM-MVS method to monitor the rate of erosion in the coastal area of Marsden Bay, England. However, the results of the study were more precise than the TLS-based study conducted for the same coastal segment (Westoby et al., 2018).

### *Index-based method*

Coastal land dynamics have been partially assessed using the framework of coastal vulnerability assessment. Several studies were devoted to analysing the influence of shoreline retreat on coastal vulnerability due to sea level rise in different coastal areas around the world. The studies however, used some indexes in the assessments such as Coastal Vulnerability Index (CVI), Coastal Sensitivity Index (CSI) and Coastal Cultural Resources Vulnerability (CRV) index (Ramieri et al., 2011). The Coastal Vulnerability Index (CVI) and Coastal Sensitivity Index (CSI) are the widely accepted methods for coastal researchers and coastal planners to study coastal vulnerability (Islam et al., 2016). The CVI is a mathematical approach of calculating the degree of harm by ranking the coastline into different levels of vulnerability to reflect the potential influences of various factors (both physical and human-induced) affecting vulnerability (Kunte et al., 2014). The first step of deriving a CVI is to identify the potential factors of coastal vulnerability followed by a quantification of the factors usually under five categories in which, 1 represents very low and 5 represents very high vulnerability. The categorised factors then need to aggregate into an index by using square root of the product mean algorithm (Islam et al., 2016). Gornitz (1990) first formulated the Coastal Vulnerability Index (CVI) based on physical parameters to assess the impacts of sea level rise on coastline vulnerability and applied it to the east coast of the USA. Later, the basic numerical algorithm of CVI was applied by different authors (e.g. Pendleton et al., 2004; Boruff et al., 2005; McLaughlin and Cooper, 2010; Le-Cozannet et al., 2013) to assess erosion-induced coastal vulnerability around the world. Studies on erosion-induced coastal vulnerability in South Asia using CVI are also evident in the literature (e.g. Kunte et al., 2014; Islam et al., 2016). The Coastal Sensitivity Index (CSI) in lieu of Coastal Vulnerability Index (CVI) is used in studies as an alternative for vulnerability only. For instance, Shaw et al. (1998) first used the term ‘sensitivity’ in their study. Abuodha and Woodroffe (2010) also used CSI in assessing erosion-induced coastal vulnerability. Moreover, the study by Reeder-Myers (2015) used Cultural Resources Vulnerability (CRV) index to assess erosion-induced vulnerability of coastal archaeological sites in the United States. However, similar to CVI, the Coastal Hazard Wheel (CHW) method was also used to identify the coastline vulnerability (United Nations Environment Programme [UNEP], 2012). For instance, the study of Stronkhorst et al. (2018) applied CHW method to identify the levels of erosion hazard for Colombian coastline in which, the influences of relevant factors on erosion hazard were evaluated by arranging them into a wheel.

*GIS and remote sensing techniques*

In recent years, the applications of GIS and remote sensing techniques are becoming popular in monitoring, mapping and analysing coastal land changes (Lan et al., 2013). The techniques are particularly useful to detect shoreline changes and to identify dynamic coastal land areas (Kumar and Jayappaa, 2010; Naji and Tawfeeq, 2011). The GIS and remote sensing techniques of studying shoreline and land changes make extensive use of satellite images (Table 1.1.1a). The changes in shoreline positions are possible to identify by using multi-temporal satellite images and aerial photographs covering a particular segment of coast (Saravanan et al., 2014). Digitizing the shoreline positions from the images provides the changing positions of the shoreline for different time-slices (Kumaravel et al, 2013). Similarly, the GIS and remote sensing techniques are useful to detect areal changes in lands by separating water bodies from multi-temporal satellite images and then by digitizing the changes in lands between the images (discussed in chapter 2: section 2.4). Several local-scale studies applied GIS and remote sensing approach of studying shoreline changes and land dynamics by using satellite images (Table 1.1.1a). Moreover, the studies on coastal land dynamics at large spatial scale (e.g. regional and global) by using GIS and remote sensing techniques are also available in literature (Table 1.1.1a).

Several types of GIS and remote sensing methods and techniques are available to assess coastal land dynamics. The DSAS (Digital Shoreline Analysis System) has been widely used as an extension of ArcGIS software to identify the changing rates of historical shoreline statistics (i.e. time-series of shoreline position) by using satellite images (Sheik and Chandrasekar, 2011; Oyedotun, 2014). The DSAS calculates the rate of changes by identifying historical polylines and placing the polylines into a set of transects. For instance, the works of Hashmi and Ahmad (2018) and Stanchev et al. (2018) identified the shoreline retreat in Sindh (Pakistan) and northeast Bulgaria respectively by using DSAS. The use of GIS is also evident in assessing cliff instability. The study by Andriani and Pellegrini (2014) applied Cliff Instability Susceptibility Assessment (CISA) method to assess the conditions of cliff instability in the Murgia coastline of Italy. The CISA method used 28 parameters affecting cliff instability including geomechanical, morphological, meteo-marine and anthropogenic parameters and segmented the coastline into five instability classes by using GIS. Combined with GIS, the use of process-based numerical models (e.g. Soft Cliff And Platform Erosion-SCAPE, Xbeach, multi-scale climate emulator-MUSCLE) (Brown et al., 2005; Antolinez et al., 2016; Ramakrishnan et al., 2018) and heuristic equilibrium models (i.e. static and dynamic equilibrium models) (Toimil et al., 2017) are also evident in the literature to assess shoreline evolution and shoreline instability. The process-based models include a set of small-scale coastal physical processes relevant to shoreline changes (Dean, 1995). On the other hand, the heuristic equilibrium models use beach evolving hypothesis to identify an equilibrium state under steady-state forcing conditions (Jara et al., 2015) by considering the Bruun Rule (i.e. response of shore profile to sea level rise) (Bruun, 1962).

Studies on erosion susceptibility and erosion risk using GIS and remote sensing techniques is very limited in the literature. The EUROSION (2004) study was conducted mainly to identify the levels of erosion risk for the entire European shoreline. Moreover, Sharples et al. (2013) prepared several maps based on shoreline erosion hazard bands of Tasmania by using secondary datasets on geological and geomorphological characteristics of the shoreline in GIS. Fitton et al. (2016) studied the coastal erosion susceptibility of Scotland by using Coastal Erosion Susceptibility Model (CESM). The CESM is a raster GIS-based model in which, the levels of underlying physical susceptibility of the area to erosion was assessed by interpreting the entire land area as a collection of cells (i.e. pixel) and identifying, weighing and classifying the ranges of cell values of the selected physical parameters in the model. The study used ground elevation, rockhead elevation, proximity to open coast and wave exposure as model parameters to assess underlying physical susceptibility of the coastal lands. Later, Fitton et al. (2018) modelled the risk of erosion in Scotland by combining the outputs of Coastal Erosion Susceptibility Model (CESM) and Coastal Erosion Vulnerability Index (CEVI). The final scores of erosion risk were then calculated by combining the exposure and vulnerability obtained from CESM and CEVI respectively.

Table 1.1.1a - Summary of methods relevant to the previous studies on coastal land dynamics by using GIS and remote sensing techniques. The table provides the spatial and temporal scales along with other important aspects such as the types of GIS approach (i.e. vector and raster), inclusion of hydro-climatic factors and the subjects of the studies. The list also includes some other literature that is discussed in the later part of this chapter (i.e. section 1.1.2.2).

| Study reference | Scale (local, regional, national, global) | Erosion [Yes (Y) or No (N)] | Accretion [Yes (Y) or No (N)] | Raster (R) or Vector (V) | Hydro-climatic factors included? [Yes (Y) or No (N)] | Temporal scale: Past (P); Current (C); Future (F) | Subject of study |
|---|---|---|---|---|---|---|---|
| Dolan et al. (1980) | Regional | Y | N | V | N | P, C | Shoreline |
| Li (1993) | Local | Y | N | V | N | P, C | Shoreline |
| White and El-Asmar (1999) | Regional | Y | N | V | N | P, C | Shoreline |
| Shifeng et al. (2002) | Regional | Y | Y | V | N | P, C | Shoreline |
| Azab and Noor (2003) | Regional | Y | N | V | N | P, C | Shoreline |
| Wang (2003) | Local | Y | N | V | N | P, C | Shoreline |
| EUROSION (2004) | Regional | Y | N | V | Y | C | Shoreline erosion risk |
| Brown et al. (2005) | Local | Y | N | V | Y | C | Shoreline |
| Ferreira et al. (2006) | Local | Y | Y | V | Y | C | Set-back line |
| Zoran and Anderson (2006) | Local | Y | Y | V | N | P, C | Erosion and accretion |
| Lantuit and Pollard (2008) | Regional | Y | N | V | N | P | Shoreline |
| Boori (2010) | Regional | Y | N | V | N | C | Shoreline |
| Jimmy (2010) | Regional | Y | N | V | N | P, C | Shoreline |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Prabaharan et al. (2010) | Local | Y | Y | V | N | P, C | Erosion and accretion |
| Duc et al. (2012) | Local | Y | N | V | N | C | Shoreline |
| Burkett and Davidson (2013) | Local | Y | N | V | Y | C | Shoreline erosion risk |
| Chowdhury and Tripathi (2013) | Local | Y | Y | V | N | P, C | Erosion and accretion |
| Hinkel et al. (2013) | Global | Y | N | V | N | F | Land loss |
| Sharples et al. (2013) | Regional | Y | N | V | N | C | Shoreline |
| Andriani and Pellegrini (2014) | Regional | Y | N | V | N | C | Cliff instability |
| Dissanayake and Karunarathna (2015) | Local | Y | N | V | Y | C | Beach erosion |
| Fitton et al. (2016) | National | Y | Y | R | N | C | Susceptibility |
| Fitton et al. (2018) | National | Y | Y | R | N | C | Risk |
| Luijendijk et al. (2018) | Global | Y | Y | V | Y | P | Beach erosion and accretion |
| Martínez et al. (2018) | Regional | Y | N | V | N | P | Shoreline |
| Mentaschi et al. (2018) | Global | Y | Y | V | N | P | Erosion and accretion |
| Stancioff et al. (2018) | Regional | Y | N | V | N | P, F | Shoreline |
| Stanchev et al. (2018) | Local | Y | N | V | N | P | Shoreline |

#### 1.1.1.2 Application of geospatial approach in Bangladesh

The geospatial approach has been extensively used to study land dynamics in the coastal area of Bangladesh. Studies mainly dealt with the analysis of shoreline changes and the loss and gain of coastal lands by applying GIS and remote sensing techniques. The use of empirical field study techniques is also evident in the literature. The geomorphological characteristics distinguish the coastal area of the country into three zones: western, central, and eastern (discussed in section 1.2.4) (MoEF, 2016). Hence, this section identifies the application of geospatial methods and techniques that were applied for the entire coastal area as well as for the three coastal zones of the country.

There is no comprehensive assessment of the dynamic nature of lands for the entire coastal area of Bangladesh. However, the work of Sarwar and Woodroffe (2013) is regarded as the only study that assessed the changing positions of shoreline along the coastal area of the country (Table 1.1.1b). The study analysed Landsat satellite images over a 20-year period from 1989 to 2009 and identified that the retreat rate is substantially high in the central coastal zone (i.e. up to 120 m/year) compared to the western and eastern coastal zones (i.e. up to 20 m/year). A very limited number of studies were conducted by using the geospatial approach to identify the morphological changes in the western coastal zone (Table 1.1.1b). Similar to the western coastal zone, the use of geospatial approach in studying shoreline retreat and morphological changes in the eastern coastal zone is also very limited (Table 1.1.1b). Studies were largely devoted to identifying shoreline changes and land dynamics (i.e. past rates of erosion and accretion) in the central coastal zone by using empirical field observation and GIS and remote sensing techniques (Table 1.1.1b). Morphological changes of the major offshore islands in the central coastal zone are also studied by applying field survey and GIS and remote sensing techniques. The studies suggest that morphological changes in the central coastal zone are comparatively much higher than the changes identified for the western and eastern coastal zones of the country.

Table 1.1.1b – Summary of geospatial methods and techniques used for the previous studies relevant to land dynamics in the coastal area of Bangladesh. The table indicates that most of the studies were conducted for the central coastal zone of the area. Most importantly, except for a few empirical field surveys, all other studies applied GIS and remote sensing techniques by using Landsat satellite images. The subjects of study varied from shoreline/ coastline change detection to sediment concentration and land dynamics (i.e. erosion and accretion) for the three coastal zones in which, the study on erosion susceptibility and risk was absent.

| Spatial limit | Study reference | Subject (and location) of study | Data used | Method/ technique | Vector (V)/ Raster (R)/Not Applicable (N/A) |
|---|---|---|---|---|---|
| Entire coast | Sarwar and Woodroffe (2013) | Shoreline change | Landsat satellite images | GIS and remote sensing | V |
| Western zone | Rahman et al. (2011) | Land dynamics | Landsat satellite images | GIS and remote sensing | V |
| | Rahman (2012) | Shoreline change | Landsat satellite images | GIS and remote sensing (Time-series analysis) | V |
| | Islam et al. (2013) | Shoreline change and land dynamics (Kuakata) | Landsat satellite images | GIS and remote sensing | V |
| | Rahman et al. (2013) | Shoreline change and land dynamics (Kuakata) | Landsat satellite images | GIS and remote sensing | V |
| Central zone | BWDB] (1997) | Sediment concentration (Meghna estuary) | Field observation | Empirical field survey | N/A |
| | Krantz (1999) | Erosion (Bhola Island) | Field observation | Empirical field survey | N/A |
| | BWDB] (2001) | Sediment concentration (Meghna estuary) | Field observation | Empirical field survey | N/A |
| | CEGIS (2009) | Land dynamics (Meghna estuary) | Landsat satellite | GIS and remote | V |

| | | | | | |
|---|---|---|---|---|---|
| | | | images | sensing | |
| | Alam and Uddin (2013) | Land dynamics (Offshore islands) | Landsat satellite images | GIS and remote sensing | V |
| | Taguchi et al. (2013) | Coastline changes (Urir Char) | PALSAR satellite images | GIS and remote sensing | V |
| | Brammer (2014) | Land dynamics | Landsat satellite images | GIS and remote sensing | V |
| | Hussain et al. (2014a) | Coastline changes (Offshore islands) | PALSAR and Landsat satellite images | GIS and remote sensing | V |
| | Uddin (2015) | Sedimentological Characteristics and erosion (Sandwip) | Landsat satellite images survey data | GIS, remote sensing and field survey | V |
| | Emran et al. (2016) | Shoreline changes and land dynamics (Sandwip) | Landsat satellite images | DSAS and<br>NDWI | V |
| | Hossain et al. (2016) | Land dynamics (Domar Char) | Landsat satellite images | GIS and remote sensing | V |
| | Hassan et al. (2017) | Land dynamics (Meghna estuary) | Landsat satellite images | GIS and remote sensing | V |
| Eastern zone | Islam et al. (1999) | Land loss estimation along the coastline | Scenario of sea level rise and field measurement | Bruun's Rule | N/A |
| | Islam et al. (2014) | Shoreline change (Kuakata) | Landsat satellite images | DSAS | V |
| | Rahman (2015) | Land dynamics (Kuakata) | Landsat satellite images | GIS and remote sensing | V |

### 1.1.1.3 Strength and weakness of geospatial approach

The different types of geospatial methods that are described in the preceding section (section 1.1.1) were applied to study several aspects of coastal land dynamics such as shoreline position, erosion and accretion, erosion susceptibility and erosion risk (Table 1.1.1a and Table 1.1.1b). However, the capabilities of all the methods are not equal in assessing coastal land dynamics; especially in assessing coastal erosion. Fotheringham and Rogerson (1993) described eight impediments that may arise in spatial analysis of a complex system of interest. The impediments are (1) modifiable areal unit, (2) boundary, (3) spatial interpolation, (4) spatial sampling, (5) spatial autocorrelation, (6) goodness-of-fit, (7) context-dependent results and non-stationarity and (8) spatial aggregation. The table (Table 1.1.1c) indicates the capabilities of different geospatial methods and techniques used to assess coastal land dynamics to overcome the impediments.

Table 1.1.1c – The strength of different geospatial methods and techniques to overcome impediments in spatial analysis of coastal erosion and accretion. Based on the literature reviewed in this section (section 1.1.1), it is identified that the raster GIS is the only method that enables with the capacity to address all the mentioned impediments.

| Category of approach | Specific methods and techniques | Capacity to overcome impediments<br>(The numbers are the impediments mentioned in section 1.1.1.3) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| GIS and Remote Sensing (RS) | Remote Sensing images (vector) | | ✓ | ✓ | ✓ | ✓ | | | |
| | DSAS (vector) | ✓ | ✓ | | ✓ | | ✓ | | |
| | CISA | ✓ | | | ✓ | | | | |
| | Process-based models | | ✓ | | | ✓ | | ✓ | |
| | Heuristic equilibrium models | | ✓ | | | | | ✓ | |
| | Raster GIS | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Empirical field study technique | Aerial photography and photogrammetry | | ✓ | ✓ | ✓ | ✓ | | | |
| | GPS/GNSS | ✓ | | | ✓ | | ✓ | | |
| | LiDAR | ✓ | | | | | ✓ | ✓ | |
| | Terrestrial Laser Scanner | | ✓ | ✓ | ✓ | ✓ | | | |
| | Unmanned Aerial Vehicle | | ✓ | ✓ | ✓ | ✓ | | | |
| | SfM-MVS | ✓ | ✓ | | ✓ | | ✓ | | |
| Index | Coastal Vulnerability Index | ✓ | ✓ | | ✓ | | | | ✓ |
| | Coastal Sensitivity Index | ✓ | ✓ | | ✓ | | | | ✓ |
| | Coastal Hazard Wheel | ✓ | ✓ | | ✓ | | | | ✓ |

The methods and techniques of geospatial approach have some advantages as well as some disadvantages in assessing different aspects of coastal land dynamics (i.e. erosion and accretion). The methods such as CVI, CSI and CRV are not capable of assessing land susceptibility to coastal erosion. This is because the basic structure of the indices was designed to assess coastal vulnerability by which, the impacts of shoreline erosion on coastal vulnerability are addressed only (Kunte et al., 2014). The CVI is particularly useful to identify the exposure of coastline to coastal hazards (Bevacqua et al., 2018) that does not necessarily assess the resistance capacity of coastal lands to erosion. Additionally, the use of CVI is effective and important for scoping 'first look' assessment of coastal erosion (Ramieri et al., 2011). Similarly, the CHW is only suitable to objectively identify the degree of shoreline erosion hazard in a situation where the availability of digital data is limited (Micallef et al., 2018). Moreover, the use of process-based and equilibrium numerical models are principally suitable to reconstruct the response of shoreline to climate change and coastal forcing (e.g. waves, storm surges, tides etc.). For instance, the numerical models used two types of approaches (i.e. deterministic and probabilistic) in which, the deterministic approach is useful to analyse the evolution of shoreline. Whereas, the probabilistic models are only suitable for predicting the likely outcomes of changes in shoreline morphology due to natural variability (Panzeri et al., 2012). Additionally, the empirical field study methods by using different techniques such as LiDAR, GPS/GNSS, SfM-MVS and UAV are only beneficial for identifying the changes in shoreline position and the rates of erosion and accretion in a coastal area. Moreover, the empirical field techniques were applied locally by which, analysis of erosion for a large segment of coastal area is impractical. In contrast, a raster GIS-based method is highly suitable to deal with the spatial aspects of land susceptibility for both offshore and inland conditions (Fitton et al., 2016). However, the use of a raster GIS-based method depends on the availability of sufficient spatial data. More specifically, a raster GIS-based modelling work largely relies on the model parameters and requires the validation of the model results (Burrough, 1996).

### 1.1.1.4 Semi-quantitative approach

A semi-quantitative approach is useful to understand a dynamic system and to clarify the possible solutions of a problem by disentangling and sharing group knowledge (Voinov and Bousquet, 2010). Semi-quantitative methods are becoming popular in a variety of fields such as environmental management, agricultural decision making and climate change perceptions (Cash et al., 2002; Seppelt et al., 2011). The methods are extensively used in the field of social-ecological systems (SES) (Lynam et al., 2007; Sandker et al. 2010) in a flexible manner because of their ability to establish feedback relationships between variables (Gray et al., 2015). This section discusses different types of semi-quantitative approaches along with their advantages and disadvantages so that the best semi-quantitative approach to studying coastal erosion and accretion is identified. Moreover, potentials of the approach in studying land dynamics in the coastal area of Bangladesh are also discussed in this section.

### 1.1.1.5 Types of semi-quantitative approach

Several semi-quantitative methods are evident in the literature (Börjeson, 2006). Depending on how knowledge is being collected, the semi-quantitative methods are categorised into two types: individual and participatory. The individual methods such as interview, questionnaire and Delphi are commonly used methods to evaluate a system of interest. Semi-quantitative data are obtained from individuals by way of conducting interviews. Alternatively, a questionnaire survey is useful to obtain the opinions of individuals. In contrast, the participatory approach of collecting knowledge is widely used by the scientific community due to its free association of knowledge (Gray et al., 2014). The participatory approaches are capable of converging both the perspectives of science and of practice (Bergold and Thomas, 2012).

### *Delphi*

Delphi is an indirect participatory method to elicit and synthesize experts' views on a particular topic of study (Raubitschek, 1988). The method comprises of a structured group of individual experts (i.e. the number of experts are pre-planned) which is more precise than those of an unstructured group of individuals (Rowe et al., 1991; Rowe and Wright, 1999). The Delphi method is highly suitable to reduce the possible influences of powerful members on the outcomes by way of maintaining anonymity in the process (Linstone and Turoff, 1975). However, due to the individual collection of feedbacks from a structured group of experts, this method takes comparatively more time than other methods (Jairath and Weinstein, 1994).

### *System Dynamics*

The System Dynamics (SD) method permits the involvement of potential experts in the process to understand dynamic systems and to define scenarios (Yu et al., 2011; Mavrommati et al., 2014). The method disentangles the causal relationships between different components of a system by using stocks, flows, causal loops and feedbacks (Ford, 1999; Schmitt-Olabisi et al., 2010). However, the method lacks rigour in ensuring the accuracy of the results in the event of faulty assumptions and lack of data for validation (Mallampalli et al., 2016). Further, the method is difficult for participants engaged in the study to learn due to its complex way of visualization (Caulfield and Maj, 2001).

### *Analytical Hierarchy Process*

The Analytical Hierarchy Process (AHP) is a method based on multi-criteria decision mapping which is suitable for integrating the opinions of experts in a more structured way (Malczewski, 2006; Chakar, 2006). The method uses a pairwise comparison of parameters selected for a particular topic (Barredo et al., 2000). The weighting of the parameters follows a rating system by using a scale proposed by Saaty (2008). The method has been tested by integrating expert's opinion in different fields of study such as hazard and risk zoning (Ayalew et al., 2005; Gorsevski et al., 2006; Yalcin, 2008; Ercanoglu et al., 2008), landslide susceptibility mapping (Barredo et al., 2000; Ayalew et al., 2005; Komac, 2006; Akgun and Bulut, 2007), soil erosion hazard mapping (Rahman et al., 2009), flood mapping (Nguyen-Mai et al., 2011; Chen et al., 2011) etc. However, the AHP method has its major drawbacks in terms of its inability to identify future possible system dynamics (Mallampalli et al., 2016). Due to the defined scale, the possibility of generating a free association of knowledge could also be hampered (Abildtrup et al., 2006).

### *Bayesian networks*

The Bayesian Networks (BN) method is capable of illustrating human reasoning graphically. The method was first formulated by Pearl (1985) to address the cognitive knowledge of experts (Marcot et al., 2001; Barton et al., 2012). A BN system is useful to identify influence diagrams to visualize the underlying interactions between different components of a system. The application of BN is substantive for a system with uncertainty (Russell, 2003). However, BN has a limitation in integrating feedbacks into the system (Jensen, 2001; van-Vliet et al., 2010).

### *Fuzzy sets*

Fuzzy sets is a translation method of human language by using mathematical functions (Mallampalli et al., 2016). The idea was first proposed by Zadeh (1965) and later on Goguen (1969) to use the knowledge from stakeholders and experts as a direct parameterization in the system. The method is also useful to generate policy choices and prospective actions. A similar kind of participatory method of integrating experts' views is qualitative probabilistic networks (QPNs). The QPN method is capable of visualizing experts' knowledge through networks (Kouwen et al., 2008). However, these fuzzy sets and QPN methods are limited only to being able to integrate quantifiable parameters and do not permit feedbacks in the systems (Mallampalli et al., 2016).

### *Focus group discussion*

A Focus Group Discussion (FGD) is regarded as a simple form of participatory method in which perceptions from a targeted group are obtained by designing carefully planned discussion on a subject of study (Krueger, 1998). The pioneer work on designing FGD was conducted by Merton and Kendall (1946). The advanced uses of FGD are categorised into two groups: focus groups as lay groups and focus groups as experts panels (Chioncel et al., 2003). The benefit of using FGD relies on its quick and easy way of collecting information from a group (Gorman and Clayton, 2005). However, it is difficult to gather all the desired participants at a time (Gibbs, 1997). Further, some vocal participants may dominate the whole process which then limits the scope for other members to participate in the discussion.

*Q-methodology*

The use of Q-methodology allows a semi-quantitative analysis to be formed from a subjective study on a particular topic in participatory research (Logo, 2013). It requires a participant to complete a Q-sort on the selected topic by ranking statements (McKeown and Thomas, 1988; Hagan and Williams, 2016). The method has been used in different fields of study such as global environmental change (Niemeyer et al., 2005), environmental problems (Ray, 2011), environmental awareness (Logo, 2013) and marine biodiversity conservation (Hagan and Williams, 2016). However, the method is extremely time-consuming (McKeown and Thomas, 1988). Moreover, generalization of information and bias in selecting responses by the researcher in the process of Q-sorting can limit the quality of a study (Logo, 2013).

#### 1.1.1.6 FCM as a participatory method

Fuzzy Cognitive Mapping (FCM) is becoming a popular participatory method since its ability to generate transparent graphical models of complex systems (Gray et al., 2015). Fuzzy cognitive mapping is regarded as a semi-quantitative model to identify variables of a system of study as well as to visualise the causal relationships between the identified variables (Özesmi and Özesmi, 2004) (discussed elaborately in chapter 5: section 5.3.2 and section 5.3.3). The pioneer works of Özesmi and Özesmi (2004) focused on ecological models where they investigated the perceptions of different stakeholders on an environmental conflict (i.e. dam project) through a multi-step fuzzy cognitive mapping. Fuzzy Cognitive Mapping has been widely used to study agricultural decision making and policy design (Markinos et al., 2007; Christen et al., 2015; Sacchelli and Sottini, 2016). The FCM method has been extensively applied to assess stakeholders' perceptions on climate change (Murungweni et al., 2011; Reckien et al., 2013; Reckien, 2014 Singh and Nair, 2014). For instance, Gray et al. (2014) conducted a study on assessing stakeholders' perception on coastal climatic vulnerability by using Fuzzy Cognitive Mapping. Moreover, Alvin and Petros (2015) studied on vulnerability and adaptation to flooding risk of a coastal river basin ecosystem in Nadi, Fiji Islands. The use of FCM faces two challenges (Kok, 2009): first, it requires a long time to carry out the study and second, there is a chance of comparing incomparable factors by the participants in the FCM process. However, available literature suggests that there is still a great scope for using FCM approach to generate participatory knowledge on different aspects of coastal erosion and accretion since, the method is highly efficient in eliciting experts' views on a complex system (Jetter and Kok, 2014). Jetter, and Schweinfort (2011) and Yilmaz (2013) identified several evaluation criteria of semi-quantitative and qualitative methods in which, FCM fulfils most of the criteria (Table 1.1.1d).

Table 1.1.1d - Comparison of major semi-quantitative participatory methods in which, FCM fulfils most of the evaluation criteria. [Source: Delphi (Rowe and Wright, 1999; Linstone and Turoff, 2011); System dynamics (Schmitt-Olabisi et al., 2010); AHP (Abildtrup et al., 2006; Chakar, 2006); Bayesian Networks (van-Vliet et al., 2010); FGD (Chioncel et al., 2003; Gorman and Clayton, 2005); Q-methodology (Nijnik and Mather, 2008; Logo, 2013) and FCM (Jetter and Kok, 2014; Gray et al., 2014)]

| Evaluation criteria | Semi-quantitative approach | | | | | | |
|---|---|---|---|---|---|---|---|
| | Delphi | System dynamics | AHP | Bayesian networks | FGD | Q-methodology | FCM |
| Feedback | ✓ | ✓ | | | | | ✓ |
| Dealing with complex system | | ✓ | | ✓ | | | ✓ |
| High level of integration | | | | ✓ | | | ✓ |
| Communicability | ✓ | | | | ✓ | ✓ | ✓ |
| Linking with model | | ✓ | ✓ | | | | ✓ |
| Less time | | | | | ✓ | | |
| Easy with dynamic system | | ✓ | | ✓ | | | ✓ |
| Integration of experts | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Generation of scenario | ✓ | | ✓ | | | ✓ | ✓ |
| Identification of driving forces | ✓ | | | | | ✓ | ✓ |
| Ability to include new components | | | | | | | ✓ |
| General consensus | | | | | ✓ | ✓ | ✓ |

#### 1.1.1.7 Application of semi-quantitative approach in Bangladesh

The literature suggests that a study applying semi-quantitative approach to land dynamics is absent for the coastal area of Bangladesh. The semi-quantitative methods such as Delphi, FGD and Q-methodology have been used to assess residents' perceptions on community coping practices (Parvin et al., 2008), hazard perceptions (Kabir et al., 2016) and water scarcity (Rahman et al., 2017). The uses of FCM are evident to study food and agriculture system and crop intensification in the coastal area of the country. For instance, the study by Talukder and Palmer (2013) used FCM method to study food and agriculture system sustainability at Dumuria sub-district of Khulna. The study utilized fuzzy cognitive mapping to model the interaction among sustainability indicators of food and agriculture system. The work by Shahrin (2016) assessed farmers' perceptions on crop intensification in the western coastal zone of the country by using FCM method. However, there is scope for studying different aspects of land dynamics in the coastal area of Bangladesh by using semi- quantitative methods including FCM.

### 1.1.2 Future scenario of coastal land dynamics

Due to climate change, sea level rise and extreme weather events, coastal systems are continuously being affected by natural hazards and are responding in different ways (Balica et al., 2012). It is predicted that the future rate of erosion might be increased due to likely changes in hydro-climatic scenarios (Fitzgerald et al., 2008). Hence, the generation of future erosion scenarios is vital to comprehend the likely impacts of hydro-climatic changes on coastal lands. Scenario planning is highly suitable for climate change studies (Symstad et al., 2017) considering a wide variety of uncertainty with limited control (Peterson et al, 2003). Firstly, this section describes the basic methodological approaches of generating future scenarios, followed by previous studies and methods used to generate future scenarios relevant to coastal land dynamics. Finally, in this section, the need for addressing future coastal land dynamics of Bangladesh is evaluated.

#### 1.1.2.1 Scenario generation

Scenario generation is an emerging approach for a diverse number of study areas during the last few decades (Symstad et al., 2017). Scenario generation is a useful tool to plan for future uncertainties (Martelli, 2001). Scenario generation provides a set of possible, plausible, probable, preferable and justifiable future conditions (Figure 1.1.2a) (Symstad et al., 2017). However, literature suggests that the number of scenarios in scenario building process might range from at least two (van Der Heijden, 1996) to six (Durance and Godet, 2010). Several methodological approaches exist to develop future scenarios that can be segmented into two types: qualitative and quantitative (Varum and Melo, 2010). The methodological changes in scenario generation have emerged from a recent paradigm shift from a more quantitative approach to qualitative and process-oriented approach (Mietzner and Reger, 2005). The usefulness of the quantitative approach in generating near-future scenario relies on the fact that current conditions are very likely to change in future (Pillkahn, 2008). Relying heavily on quantitative data for generating future scenarios is often problematic because the data required is collected from historical observations and may not represent the uncertainties that are in a simple future trend (Gordon, 1994). However, instead of having some weak links between the approaches (i.e. qualitative, quantitative) (Kok and van Delden, 2009), they are complementary to each other (Symstad et al., 2017). Application of more than one approach might enable future scenarios to be created in a more robust way (Figure 1.1.2a). Further, the combination provides outputs that are highly suitable for future policy planning (Mallampalli et al., 2016). The application of mix methodological approach is not new for future studies (Alcamo, 2008) that is evident in a variety of fields including more recent uses in climate change studies (Byrd et al., 2015). However, the generation of scenarios by using GIS-based geospatial model is evident in the literature (Lwin et al., 2012). The vector GIS supports qualitative assessment where, there is a potential to develop quantitative models by applying raster GIS-based geospatial approach (Lwin et al., 2012).

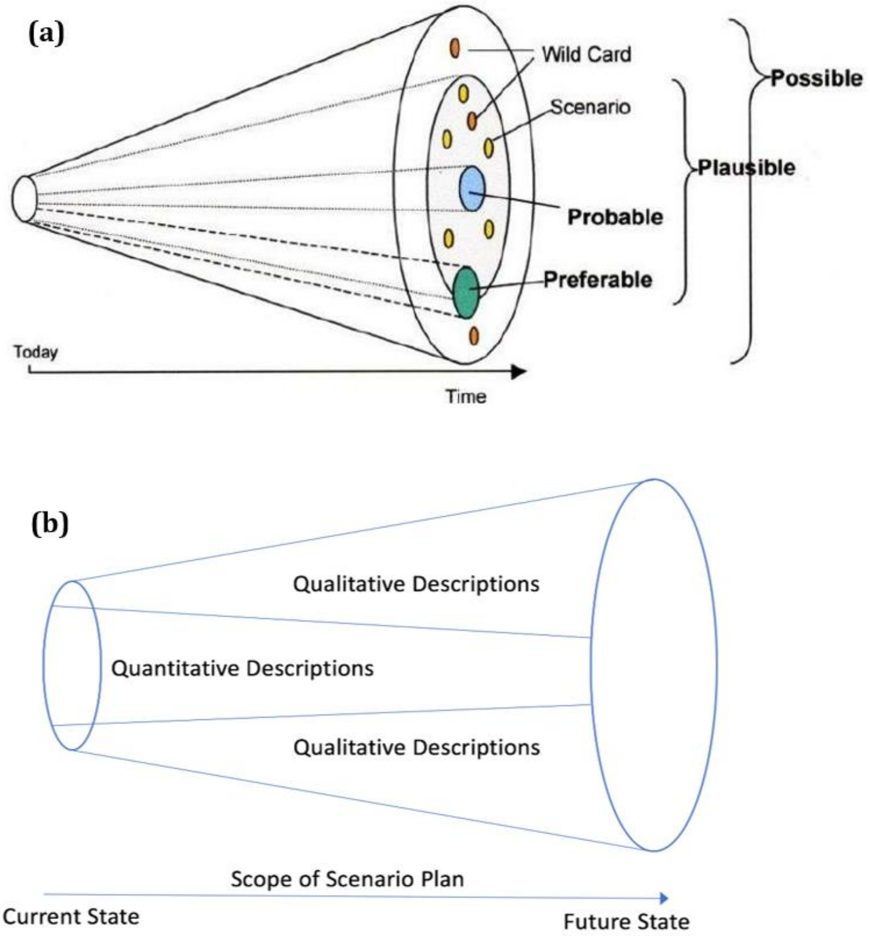

Figure 1.1.2a - A schematic representation of future scenario generation by using a future cone. The probable and preferable scenarios are more reliable for a short time period in the future whereas, the generation of plausible future scenarios might be suitable for a long time-period (Figure a). The quantitative descriptions are more applicable for current and near-future scenarios along with qualitative descriptions (Figure b) whereas, qualitative scenarios are more effective than quantitative scenarios for far-future. [Adapted from: Voros, 2003; Amer et al., 2013]

### 1.1.2.2 Studies on future coastal land dynamics

Studies of the potential impacts of future hydro-climatic changes on coastal land dynamics (i.e. erosion and accretion) are very limited in literature. The study by Nunes and Nearing (2011) theoretically discussed the overall likely impacts of future climate change on erosion. Moreover, some noticeable studies (Burkett and Davidson, 2013; Dissanayake and Karunarathna, 2015) did not consider land susceptibility to coastal erosion while assessing the likely impacts of climate change on the coastal areas. At the local spatial scale, Reinen-Hamill et al. (2006) assessed the probable impacts of sea level rise for the next 100 years on beach erosion susceptibility for selected beaches in Auckland coastal area of New Zealand. The global scale study by Hinkel et al. (2013) assessed the likely effects of future sea level rise on erosion of sandy beaches in the world by using the Dynamic Interactive Vulnerability Assessment (DIVA) as an extension in ArcGIS software. However, in practice, there is still a lack of understanding in the use of GIS-based modelling efforts in generating future scenarios of coastal land susceptibility to erosion. The work of Fitton et al. (2016) assessed the existing condition of coastal erosion susceptibility only by using a GIS-based model. The potential impacts of future hydro-climatic factors on erosion susceptibility were not addressed in the assessment. However, the assessment of future land susceptibility to erosion might allow coastal planners and coastal managers to better prepare for future coastal erosion. There is an opportunity to apply raster GIS-based quantitative modelling approach to generating future scenarios of land susceptibility to erosion (Table 1.1.1a) (Hinkel and Klein, 2007; 2009; 2010).

The semi-quantitative approaches to coastal land dynamics, however, are devised with the ability to reflect individuals' perceptions on future scenarios of environmental and human concerns. The literature review indicates that there is a potential for using FCM-based mental modelling approach to conduct a participatory study on future aspects of coastal erosion and accretion. Fuzzy Cognitive Mapping (FCM) is a suitable method to elicit expert's knowledge (Gray et al., 2014) that is convenient for predicting future aspects of a system (Jetter and Kok, 2014). The approach has already been used for some studies (Biloslavo and Dolinsek, 2010; van-Vliet, 2011; Salmeron et al., 2012; Soler et al., 2012) in assessing future aspects of climate change and natural disasters. Recently, Fuzzy Cognitive Mapping has been used to interpret future vulnerability, risk perception and scenario development for different hazardous events. For instance, the study of Erol et al. (2013) focused on participatory fuzzy cognitive mapping analysis to evaluate the future of water in the Seyhan Basin, Turkey. More recently, the study by O'Neill et al. (2015) used cognitive mapping to study stakeholders' perceptions on coastal flood risk in Ireland.

#### 1.1.2.3 Future coastal land dynamics in Bangladesh

Available literature (Table 1.1.1b) suggests that the study of future scenarios of land dynamics (i.e. erosion and accretion) in the coastal area of Bangladesh is absent. However, it is predicted that the coastal area of Bangladesh will be heavily impacted by the likely changes in future climate and associated sea level rise due to its flat and low terrain (Minar et al., 2013; Rawat et al., 2016; Davis et al., 2018). For instance, a 1.5 m rise of mean sea level may inundate approximately 22,000 $km^2$ of coastal lands of the country (Fitzgerald et al., 2008). The impacts of predicted sea level rise would worsen under changing rates of sediment supply in the coastal area (Sarker et al., 2015). Similarly, the amount of rainfall in the Ganges-Brahmaputra-Meghna (GBM) river basin area is projected to increase by 1%, 4% and 6% for 2030, 2050 and 2080 time-slices respectively (Yu et al., 2010). The predicted increases in rainfall may lead to increasing amounts of water discharge in the area. Mirza (2002) indicated a probability of 6.4% and 21.1% increases of river water discharge in the GBM basin area due to the increases of 10.2% and 13% rainfall respectively. These changes in mean sea level, rainfall and water discharge might exert substantial influences on future erosion susceptibility in the coastal area of the country. However, uncertainties associated with future changes in hydro-climatic forces and the likely impacts on land susceptibility to erosion in the coastal area remain unanswered. Uncertainties also exist on the extent of human interferences such as large-scale polderization, cross dam projects and their impacts on the fluvial and tidal characteristics in the area.

## 1.2 Research specifications

### 1.2.1 Research gaps

The review of literature contained in this chapter (section 1.1) provides a clear understanding of some considerable research gaps in which the present study aimed to contribute new knowledge:

- There is no previous study available globally that addressed hydro-climatic factors in assessing existing land susceptibility to coastal erosion.
- There is a lack of understanding on the likely impacts of hydro-climatic changes on future scenarios of land susceptibility to coastal erosion worldwide.
- There is no prior work in evaluating existing land susceptibility and generating future land susceptibility to erosion in the coastal area of Bangladesh.

### 1.2.2 Objectives

Based on the reviewed literature, conceptual background and impending research gaps, this study considered the following research questions in fixing specific objectives:

- What patterns of land dynamics exist in the coastal area of Bangladesh?
- How best to assess land susceptibility to coastal erosion?
- What are the current and possible future scenarios of land susceptibility to erosion in the coastal area of the country?
- How to address the compelling aspects of coastal erosion susceptibility in Bangladesh?

To find out the best possible answers to the identified research questions, the present study aimed to accomplish four specific objectives. The first objective was to analyse the pattern of land dynamics for the entire coastal area of Bangladesh by assessing historical trends of morphological changes observed in the area. The study then aimed to devise a best possible method of assessing land susceptibility to erosion in evaluating the impacts of hydro-climatic factors on erosion susceptibility. The study then decided to apply the devised method in the coastal area of Bangladesh as a case study to identify the existing land susceptibility of the coastal area to erosion and to generate future possible scenarios of erosion susceptibility in the area. Finally, the study aimed to elicit erosion susceptibility and associated uncertainties in the coastal area of the country from a humanistic point of view.

### 1.2.3 Methods

Depending on the appropriateness of the relevant approaches discussed in this chapter and the anticipated objectives, the present study applied a mix-method approach of studying land dynamics and land susceptibility to erosion in the coastal area of Bangladesh. The methods and techniques include both the geospatial and semi-quantitative approach. More specifically, the trends and pattern of land dynamics in the coastal area of the country were analysed by applying GIS and remote sensing techniques. To assess existing land susceptibility of the coastal area, this study developed a raster GIS-based model namely, Land Susceptibility to Coastal Erosion (LSCE) and applied the model in the coastal area of the country. The LSCE model is capable of integrating both underlying physical elements and hydro-climatic factors of land susceptibility to erosion in the model domain and hence, the same model was applied to generate future scenarios of land susceptibility to erosion in the area with an aim to address the probable impacts of future hydro-climatic changes on land susceptibility in the coastal area. Additionally, to address the broad aspects of land susceptibility to erosion in the coastal area, this study applied the FCM-based semi-quantitative participatory approach. The details on the rationale and application procedures of the methods are discussed in the consecutive sections followed by the details on the study area.

### 1.2.4 Study area

The entire coastal area of Bangladesh was selected for the present study that covers a total area of 47,200 km$^2$ including waterbody (Ministry of Environment and Forests [MoEF], 2016). As mentioned, based on geomorphological characteristics, the coastal area is divided into three zones: western (27,150 km$^2$), central (12,040 km$^2$) and eastern (8,010 km$^2$) (Pramanik, 1988; Program Development Office for Integrated Coastal Zone Management Plan [PDO-ICZMP], 2006; MoEF, 2016). However, on the basis of exposure to the Bay of Bengal, the coastal area is segmented into two parts: interior (23,265 km$^2$) and exposed (23,935 km$^2$) (Figure 1.2.4a) (Islam et al., 2006; MoEF, 2016). The motivation behind selecting the study area was due to the dynamic nature of coastal lands (Brammer, 2014) and likely impacts of hydro-climatic factors in the coastal area in future (Centre for Environmental and Geographic Information Services [CEGIS], 2014). This study included both offshore islands and inland areas attached to the shoreline. Since a coastal area is a physical entity, the landward limit of the coastal area was fixed on the basis of tidal movement, propagation of wave and the extent of delta development processes (Shibly and Takewaka, 2012; Brammer, 2014; MoEF, 2016). The inclusion of inland coastal areas under the present assessment provides scopes of generating future scenarios of land susceptibility to erosion in the coastal area. The relevant physical and human aspects of the study area along with maps are provided in the consecutive chapters in detail.

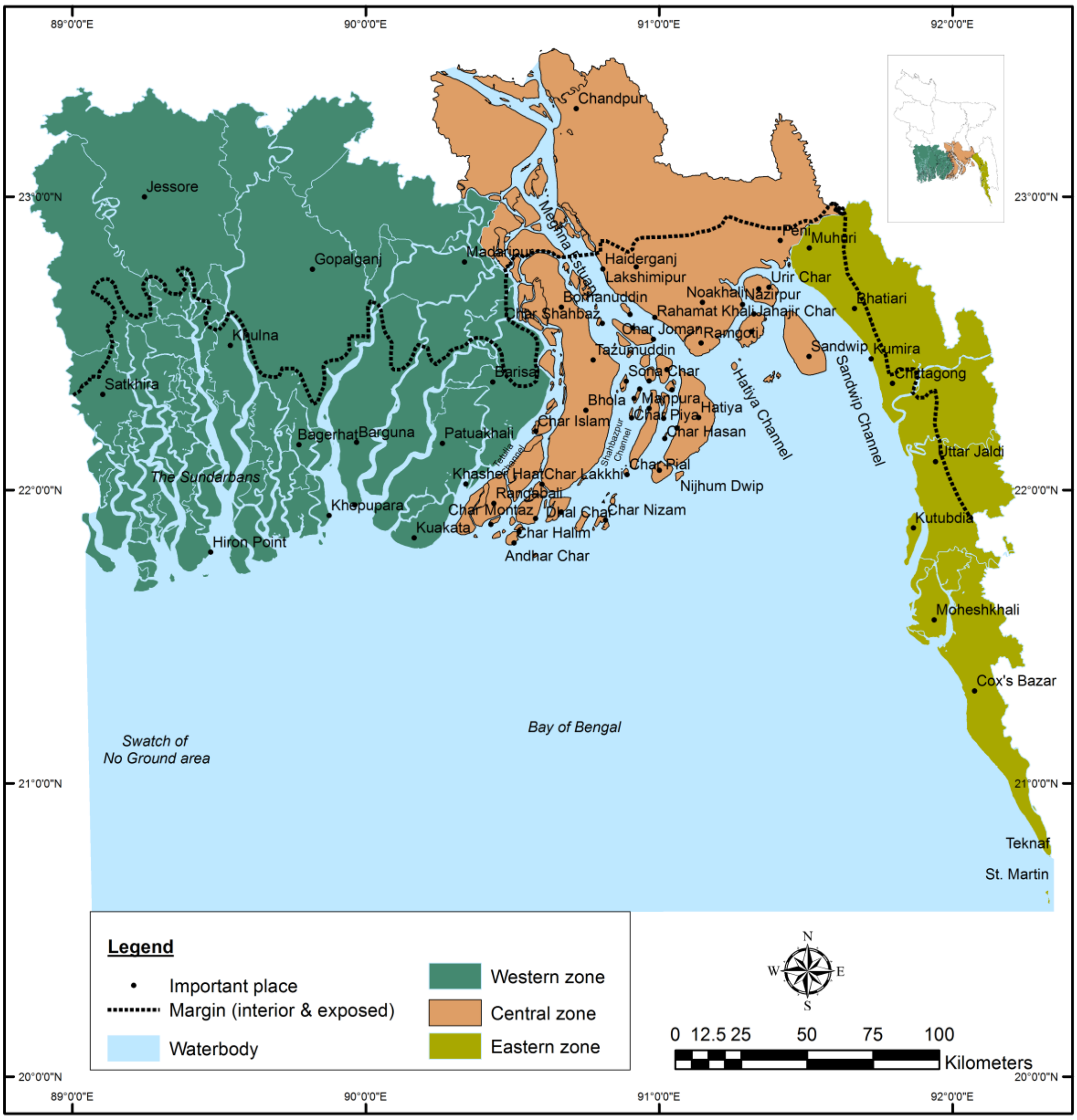

Figure 1.2.4a – The entire coastal area of Bangladesh that includes both interior and exposed coastal lands. The three coastal zones: western, central and eastern are marked by using different colours. A zoomed-in map (Figure 1.2.4b) is provided to identify most of the offshore islands and newly accreted lands in the central coastal area. [Data source: BBS, 2015 and BWDB, 2016 (important place); MoEF, 2016 (coastal zones and margin between interior and exposed coast)]

Figure 1.2.4b – The central coastal zone (zoomed-in) of Bangladesh. The map shows the locations of offshore islands and newly accreted lands in the Meghna estuary area. [Data source: BBS, 2015 and BWDB, 2016 (important place); MoEF, 2016 (central coastal zone and the margin between interior and exposed coast)]

### 1.2.5 Data availability

Bangladesh is recognised as a data-scarce country (Islam et al., 2016). The study aimed to identify the availability of data, which was indispensable for the intended methods. However, depending on the data available for the coastal area (Table 1.2.5a), this study identified alternative suitable methods where necessary to fulfil the objectives set for the present study.

Table 1.2.5a – Data availability for the study. The shortages of data in several areas were closely associated with the limitations of the present study (discussed in chapter 6). Moreover, the available data on defence structures required to check the validity by conducting ground-truthing survey before using the data in the model.

| Technical topic | Available data | Unavailable data |
|---|---|---|
| Land dynamics | 1. Landsat TM (1985, 1995)<br>2. Landsat ETM+ (2005, 2015) | 1. Landsat level 1 data product (early 2016) |
| Policy relevance | 1. Policy: Integrated Coastal Zone Management, Coastal Zone Policy, Land use policy, National water policy, National forest policy<br>2. Strategy: Coastal development strategy<br>3. Plan: Delta development plan 2100, National Adaptation Plan of Action, Priority Investment Plan<br>4. Project: National land zoning | 1. Policy on land dynamics<br>2. Plan of BWDB for 25 years<br>3. Detailed plan and program relevant to mangrove vegetation |
| Existing land susceptibility | Underlying physical element<br>Surface elevation, surface geology, bathymetry, soil permeability, shoreline distance<br>Hydro-climatic factors<br>Water discharge, rainfall, MSL, Wind speed and direction<br>Moderator<br>Accreted area<br>Hard defence structure<br>Soft defence structure (limited) | Underlying physical element<br>Soil consistency<br>Geomorphic features (partial)<br>Hydro-climatic factors<br>Longshore current<br>Wave height and propagation<br>Moderator<br>Rate of sedimentation<br>Areal extent of mangroves |
| Risk assessment | Administrative boundary-wise total number of population | 1. Location of each property/household/settlement<br>2. Location-specific population distribution |

| | | |
|---|---|---|
| Future land susceptibility | GHG trajectory based scenario (overall)<br>A1B, RCP2.6, RCP4.5, RCP8.5<br>GHG trajectory based scenario (seasonal)<br>A1B<br>GHG trajectory based scenario (temporal)<br>2020, 2050, 2080 | GHG trajectory based scenario (seasonal)<br>RCP2.6, RCP4.5, RCP8.5<br>GHG trajectory based scenario (temporal)<br>2025/2030/2100 |

### 1.2.6. Methodological rationale

This section discusses the rationale behind selecting specific methods and techniques to accomplish the aims of the study. However, the method details section (section 1.3) elaborates on how the particular methods were applied for each empirical part of the present study.

#### 1.2.6.1. Coastal land dynamics

Since land dynamics is a broad term, this study defines land dynamics as the changes in land areas by the processes of erosion and accretion. Previous studies suggest that comprehensive assessment of land dynamics for the entire coastal area of Bangladesh is absent (Table 1.1.1b). However, the assessments of land dynamics in different coastal areas around the world were efficiently conducted by using GIS and remote sensing techniques (Table 1.1.1a and Table 1.1.1b). Hence, depending on the availability of satellite images (Table 1.2.5a), this study aimed to identify the dynamic nature of lands for the selected coastal area by using GIS and remote sensing techniques. There were some considerable reasons for assessing the trends of land dynamics in the study area. First, it was vital to assess whether the coastal land area is highly dynamic or not since, the assessment of erosion susceptibility brings no results for a considerably less dynamic coastal area. Additionally, it was essential to check the consistency of independent historical datasets used for validating the model results on erosion susceptibility. This study analysed the pattern of land dynamics in the study area for the past 30 years from 1985 to 2015 by applying GIS and remote sensing techniques. Moreover, this study conducted an in-depth review of coastal land management and policy aspects that addressed human interventions on land dynamics in the area.

#### 1.2.6.2 Existing and future land susceptibility to coastal erosion

The land susceptibility to coastal erosion largely depends on the underlying physical elements (e.g. soil characteristics, geomorphic features etc.) and preparatory factors (e.g. defence structures, development activities etc.) of a coastal area (Sharples et al. 2013; MPI, 2017). Furthermore, the severity of land susceptibility to erosion relies on the triggering factors such as rainfall, sea level rise, wave action and discharge of water that are greatly influenced by the changes in hydro-climatic conditions (Saunders and Glassey, 2007; Prasad and Kumar, 2014; MPI, 2017). Moreover, the assessment of land susceptibility to coastal erosion requires both inland and offshore areas of the coast over time are included (Fitton et al., 2016). Therefore, the methodological implication is to incorporate both spatial and temporal aspects of erosion susceptibility (van Westen, 2000; Boori, 2010).

The review of available literature suggests that the methods of previous studies on coastal land dynamics (discussed in section 1.1.1) were mainly applied for assessing the changes in shoreline position, erosion exposure, and to identify the rate and extent of eroded and accreted lands for the selected coastal areas (Table 1.1.1a and Table 1.1.1b). Although methodological advancements are evident to assess coastline vulnerability (i.e. vulnerability indexes), the assessment of coastal erosion was limited, typically to analysing the changes in shoreline, coastal morphological changes and to some extent, susceptibility and exposure. The previous studies (Table 1.1.1a and Table 1.1.1b) also suggest that the assessment of land susceptibility to coastal erosion under hydro-climatic changes is absent. There is a clear knowledge gap that exists in developing a method to assess land susceptibility to coastal erosion by addressing the impacts of hydro-climatic factors in the assessment. The work of Fitton et al. (2016) studied coastal erosion susceptibility for Scotland but, without integrating hydro-climatic factors in the model. More specifically, the influences of hydro-climatic factors on the severity of erosion susceptibility were not evaluated in the assessment. In sum, the assessment of existing land susceptibility and generation of future scenarios of land susceptibility to erosion by evaluating hydro-climatic factors for the coastal areas around the world are absent in the literature.

Based on the availability of data (Table 1.2.5a), the present study developed the raster GIS-based LSCE model and applied it to the coastal area of Bangladesh to assess current condition and future scenarios of land susceptibility to erosion. There are important reasons justifying the use of raster GIS-based model in assessing land susceptibility to erosion. The vector-based GIS and remote sensing techniques such as DSAS and CISA are only effective for assessing the retreat of shoreline, cliff instability and morphological changes. In contrast, the framework of a raster GIS-based model is capable of assessing parameters quantitatively by representing them as pixel values (Boori, 2010). Hence, a raster GIS-based model provides a way of developing a quantitative geospatial model (Lwin et al., 2012). Compared to other available geospatial methods and techniques (discussed in section 1.1.1.3: strength and weakness of geospatial approach), the compatibility of a GIS-based method is highly efficient to analyse the spatio-temporal aspects of coastal erosion (Table 1.1.1c). Except for the study by Fitton et al. (2016), the practice of using raster (i.e. cell or pixel) GIS-based modelling approach to assess land susceptibility to coastal erosion is very rare (Table 1.1.1a). However, as a powerful tool, GIS is capable of addressing the consequences of hydro-climatic changes (Woodruff et al., 2018). GIS is highly useful for layering, querying, analysing and visualizing data relevant to climate change (Gemitzi and Tolikas, 2007). Hence, there is a potential scope of studying both offshore and inland erosion susceptibility of the coastal area by using raster GIS-based LSCE model. Moreover, along with underlying physical elements and preparatory factors, the possibility to integrate hydro-climatic factors in the LSCE model provides pathways in evaluating the existing and probable future impacts of hydro-climatic factors on erosion susceptibility in the coastal area.

The study performed a Sensitivity Analysis (SA) for the LSCE model to test the model validity and to make the recommendations based on the model results more credible. There is a growing trend of conducting SA to validate and communicate with the results of quantitative models in assessing environmental issues (Pianosi et al., 2016). SA is the process of investigating how the variation in the model input parameters impacts the outputs (Sarrazin et al., 2016). SA is essential to investigate the model behaviour by way of changing parameter values. The SA is an important task of modelling a system of analysis during its result processes. The SA provides insights into the relative importance of the inputs and these inputs have substantial impacts on the sources of uncertainty of the model outputs (Crosetto and Tarantola, 2001).

Moreover, SA is the most effective way of informing the validity of model results to decision makers (Pannell, 1997). However, the performance of SA in GIS-based modelling efforts reliant upon several decision-making processes which will determine the reliability of the model outputs (Crosetto and Tarantola, 2001). A GIS-based model requires a variety of spatial data that may produce a number of uncertainties originating from type, source, scale, collection methods and measurement errors (Crosetto et al., 2000). Hence, it was an essential task of the present study to conduct SA for the GIS-based LSCE model to validate and communicate the model results in a more effective way.

#### 1.2.6.3 Semi-quantitative assessment of erosion susceptibility

Several physical and human-induced factors are involved in coastal land susceptibility to erosion (EUROSION, 2004; Prasad and Kumar, 2014.). The scope of addressing qualitative aspects of coastal erosion in a quantitative geospatial approach is very difficult (Crosetto et al., 2000). Moreover, data unavailability is an added factor in dealing with the model (Table 1.2.5a). Hence, the integration of a large number of parameters in the LSCE model is limited in assessing the existing condition and future scenarios of land susceptibility to erosion in the coastal area of Bangladesh. However, as indicated in the preceding sections, the use of qualitative and/or semi-quantitative approach is highly suitable to address the data limitations and qualitative aspects of a system. Further, qualitative discussions enhance the model outputs with regards to future scenarios by addressing uncertainties relevant to the field of study (Jetter and Kok, 2014).

The review of literature on available semi-quantitative methods suggests that the broad aspects of coastal erosion is possible to address from humanistic viewpoints since, human value judgement is an important criterion for coastal studies (Green and McFadden, 2007). Expert opinion, as a reliable source of information, is useful for expanding knowledge on coastal erosion and its associated uncertainties (Hargreaves et al., 2003; Climate Change and Marine Ecosystem Research [CLAMER], 2011). Expert judgement is regarded as an important source of information when the system faces an uncertain future (Meyer and Bookeer, 1991; Durance and Godet, 2010). The evaluation of expert's views in parallel to the model outputs is vital to enhance the model results in a structured way (Fairbanks and Jakeways, 2006; Vinchon et al., 2009; Hanson et al., 2010). Moreover, the elicitation of experts' opinion along with the physical datasets of GIS is of great importance in establishing model parameters (Abdolmasov and Obradovic, 1997). Eliciting expert views thus is an efficient way to address the impacts of hydro-climatic changes on future land susceptibility to coastal erosion.

The FCM approach offers several advantages in eliciting experts' views on erosion susceptibility. FCM based study facilitates debates and dialogues among potential experts to understand the problem and to find out the best possible solutions (Soetanto et al., 2011). These debates and dialogues open up opportunities to realise future scenarios of erosion susceptibility in the area. The semi-quantification of the problem bridges the gap between storylines and models (van-Vliet, 2011). Moreover, the generation of future scenario by using FCMs is possible in an efficient manner by adding new components to, and removing existing component from, the steady state condition. The FCMs detect the future system states and system instabilities (Jetter and Kok, 2014). Considering the issue of model complexity and less-availability or unavailability of data, a multi-step FCM based modelling approach is capable of generating new knowledge which is based on perception and reasoning (Özesmi and Özesmi, 2004). Moreover, FCM has the potential to enhance the outputs of quantitative models. FCM based modelling approach is easy to understand, has a higher level of integrational ability and able to provide a system description in an effective manner (van-Vliet et al., 2010). Moreover, FCM is highly suitable to generate semi-quantitative scenario on environmental issues (Kok, 2009). The available literature discussed in the preceding section (section 1.1.1.6) clearly indicates that there is scope for using an FCM approach to elicit experts' perceptions on issues relevant to coastal erosion and climate change. Considering the advantages of the approach over other semi-quantitative participatory methods (Table 1.1.1d), the present study selected FCM to address broad aspects of erosion susceptibility in the coastal area of Bangladesh by eliciting experts' opinions.

## 1.3 Method details

### 1.3.1 Assessment of coastal land dynamics

#### 1.3.1.1 Landsat data analysis

The study used GIS and remote sensing techniques to identify the dynamic nature of land (i.e. erosion and accretion) for the past 30 years from 1985 to 2015 in the coastal area of Bangladesh (Table 1.3a). The study collected multi-temporal Landsat satellite images for the years 1985, 1995, 2005 and 2015 to identify the changes in the rate of erosion and accretion between the selected years. The satellite images were collected from United States Geological Survey (USGS) Global Visualization Viewer for the concerned years. Due to the unavailability of the required number of standard USGS Landsat level-1 images in early 2016, this study then pre-processed the available images by applying atmospheric, radiometric and geometric corrections (discussed in chapter 2). The reason behind the fact is that USGS started to compile the level-1 products in the year 2016 and made available for download at later times of the same year (USGS, 2018). The advantage of using level-1 products is that the industry standard geometric, atmospheric and radiometric corrections are already applied for the downloadable images and do not require further pre-processing tasks on the images. However, the present study applied Dark Object Subtraction (DOS) method for atmospheric corrections. DOS is an image-based method of removing atmospheric haze from satellite images (Chavez, 1996). It is assumed that there is a possibility of having some black pixels which are dark. These black pixels (% reflectance) are termed as dark objects in the images (Mustak, 2013). The dark objects are clear water, shadow etc. whose DN (Digital Number) values are zero (0) or close to zero. To check the consistency of the collected images with the real world, a geometric correction was performed by conducting a ground-truthing survey. By using Magellan Global Positioning System (GPS) data logger (model 320), the survey collected 16 Ground Control Points (GCPs) from the land areas which had previously experienced no erosion or accretion events. A Ground Control Point (GCP) denotes the horizontal (x, y) and vertical (z) measurements of a location in the real world (Kunapo, 2005) whereas, Root Mean Square Error (RMSE) is a measure of the differences between the calculated and observed values used for spatial analysis (e.g. identification of GCPs) (Shelly and Wade, 2006). To select the unchanged location on lands, previous reference maps collected from Survey of Bangladesh (SoB), Local Government Engineering Department (LGED) and Water Resources Planning Organization

(WARPO) were used. Finally, the demarcations between land and water for the images were performed by obtaining DN of band 4 (0.76–0.90μm) Near Infrared (NIR) images by Erdas Imagine remote sensing software. A DN indicates relative reflectance value of a raw satellite image (Eastman, 2001). The study used raw quantized calibrated DN values (Dewan et al., 2017; Ahmed et al., 2018) to identify land dynamics by separating the land areas from the water bodies. The study excluded mudflats from land areas because of their diurnal inundation and appearance during winter and complete inundation during monsoon season. Manual digitisation was performed to extract the separated land areas from the water bodies. The results on eroded and accreted lands obtained from the images were validated by calculating error matrix, overall accuracy and kappa coefficient.

While assessing land dynamics, the study identified a number of 'char' lands in the coastal area of the country. The term 'char' indicates a newly accreted land area that is formed by the deposition of sediments in the coastal area of the country (Sharmin, 2013). A number of *char* lands are evident in the central coastal zone such as Latar Char, Sona Char, Bodnar Char and Urir Char (Figure 1.2.4b). The study defines some terminologies such as land reclamation, polder and cross dam that are essential to discussing government interventions and policy implications of land dynamics in the coastal area. For instance, land reclamation is the activity of recuperating and improving a land area that is not accessible to use in its present form (Banglapedia, 2018). The present study defines land reclamation as a project that aims to acquire new lands from the coastal area by way of constructing engineering structures such as dam and embankment. Relevant to land reclamation activity, a polder is a low-lying tract of land enclosed by embankments (Consultative Group for International Agricultural Research [CGIAR], 2018). A cross dam is a hard engineering construction that builds across a channel or river to stop the free flowing of water in order to promote land reclamation in the area (Khan, 2008).

The principal causes of land dynamics in the area were analysed by conducting an in-depth review of relevant literature. The method in this regard was to find published articles, books and periodicals from national and international sources. Additionally, a number of unpublished documents from different departments of the government such as Bangladesh Water Development Board (BWDB), Water Resources Planning

Organization (WARPO) and Bangladesh Inland Water Transport Authority (BIWTA) were consulted. The reliability of the identified causes was cross-checked with the raw data on relevant parameters collected from BWDB, WARPO, BIWTA and Bangladesh Meteorological Department (BMD).

#### 1.3.1.2 Policy appraisal

To analyse the policy relevance of land dynamics in the coastal area of the country, a number of government policies, plans, strategies and projects were reviewed for the present study. In dealing with the policies from several ministries, agencies, institutes and departments of the government, the study followed the steps below:

- Identifying key sources
- Fixing the way of abstracting the documents (i.e. online or hard copy)
- Visiting the source if necessary
- Searching for relevant information
- Assessing the documents

To identify the key sources, the study selected five relevant ministries, their departments and affiliated institutions. The ministries are: Ministry of Planning, Ministry of Water Resources, Ministry of Land, Ministry of Environment and Forest and Ministry of Agriculture. The data and information regarding Coastal Zone Policy (CZP), Delta Plan 2100, National Adaptation Plan of Action (NAPA), Coastal Development Strategies (CDS) and Priority Investment Plan (PIP) were collected from the ministry of planning. The policies on Integrated Coastal Zone Management (ICZM), National Water Policy (NWP), cross-dam, polder, land reclamation projects and coastal defence structures were collected from BWDB, WARPO and BIWTA under the ministry of water resources. Comprehensive information on the national land use policy and national land zoning projects were collected from the ministry of land. Moreover, the data and information on national forest policy and the total area of mangrove forests were collected from the ministry of forest and agriculture whereas, data on national agricultural policy and plans (relevant to coastal land zoning project) were obtained from the ministry of agriculture.

### 1.3.2 Assessment of existing land susceptibility to erosion

The assessment of coastal land dynamics in the study indicates that the processes of erosion and accretion are constant phenomena in the coastal area of the country. Having explicit patterns of erosion and accretion, this study then aimed to analyse existing land susceptibility of the coastal area to erosion by developing the raster GIS-based Land Susceptibility to Coastal Erosion (LSCE) model and applying the model in the coastal area of Bangladesh (Figure 1.3a).

The LSCE model considered offshore islands and inland conditions of the coastal area in identifying the current levels of land susceptibility to erosion. A total number of nine parameters were selected by in-depth review of literature on site-specific factors of erosion susceptibility and then included in the model domain. Among the selected parameters, five are underlying physical elements (i.e. surface elevation, surface geology, bathymetry, soil permeability and distance from shoreline) and the remaining four are hydro-climatic triggering factors (drivers of change) (i.e. coastal river water discharge, mean sea level, rainfall and wind speed and direction). The justifications of selecting the mentioned parameters are discussed in chapter 3 (section 3.3.2: model parameters) in which the influences and interrelationships of the parameters on land susceptibility to erosion in the coastal area of the country are evaluated. However, to find out the existing shoreline, this study used the Normalised Difference Water Index (NDWI) method (Mcfeeters, 1996) in separating the land areas from the water bodies. The use of NDWI method was more convenient for OLI_TIRS sensor (Operational Land Imager_ Thermal Infrared Sensor) images (Li et al., 2013) than DN values.

The LSCE model required individual raster surfaces for each parameter to evaluate the impacts of the parameters on land susceptibility to erosion. Hence, the study prepared nine raster surfaces based on the data collected for each parameter (Figure 1.3a and Figure 1.3b). The raster surfaces of the five underlying physical elements were prepared by using raw raster surfaces and data collected from different sources. To prepare raster surfaces based on point data (i.e. location-specific four hydro-climatic parameters) the study applied two types of surface interpolation techniques: Inverse Distance Weighting (IDW) and Kriging. The IDW is a deterministic technique that uses measured values surrounding the prediction locations in which, the values of the measured location diminish with distance (ESRI, 2018). Kriging is a geostatistical interpolation technique that uses spatial autocorrelation in measuring the unknown values surrounding the measured locations (ESRI, 2018). The present study used the IDW technique to interpolate rainfall and wind speed and Kriging technique to interpolate water discharge and mean sea level. The reason for using two types of techniques for the parameters is that the data on water discharge and mean sea level are attached to spatially correlated distance and directional bias in which, Kriging is a suitable interpolation technique to address the spatial behaviour of the phenomenon by using Z-values (ESRI, 2018). The values of the raster surfaces then scaled into five susceptibility classes in which 1 represents very low susceptibility and 5 represents very high susceptibility to erosion. To classify the raster surfaces, the location-specific literature and opinions from local experts were consulted. The reason behind following this procedure is that the selected parameters are site-specific and hence, local experts should be familiar with the fundamental characteristics of the parameters and their impacts on erosion susceptibility in the area. The decision in this study to classify the levels of erosion susceptibility into five classes is based on other similar regional as well as global studies that were conducted for coastal vulnerability (Islam et al., 2016), risk (EUROSION, 2004) and susceptibility (Fitton et al., 2016) assessment. After classifying the raster surfaces, individual parameters were given weights by following experts' judgement. After having scaled and weighted parameters, the LSCE model was run by using model builder extension in ArcGIS (version 10.3) to obtain the results on land susceptibility to erosion under five susceptibility classes.

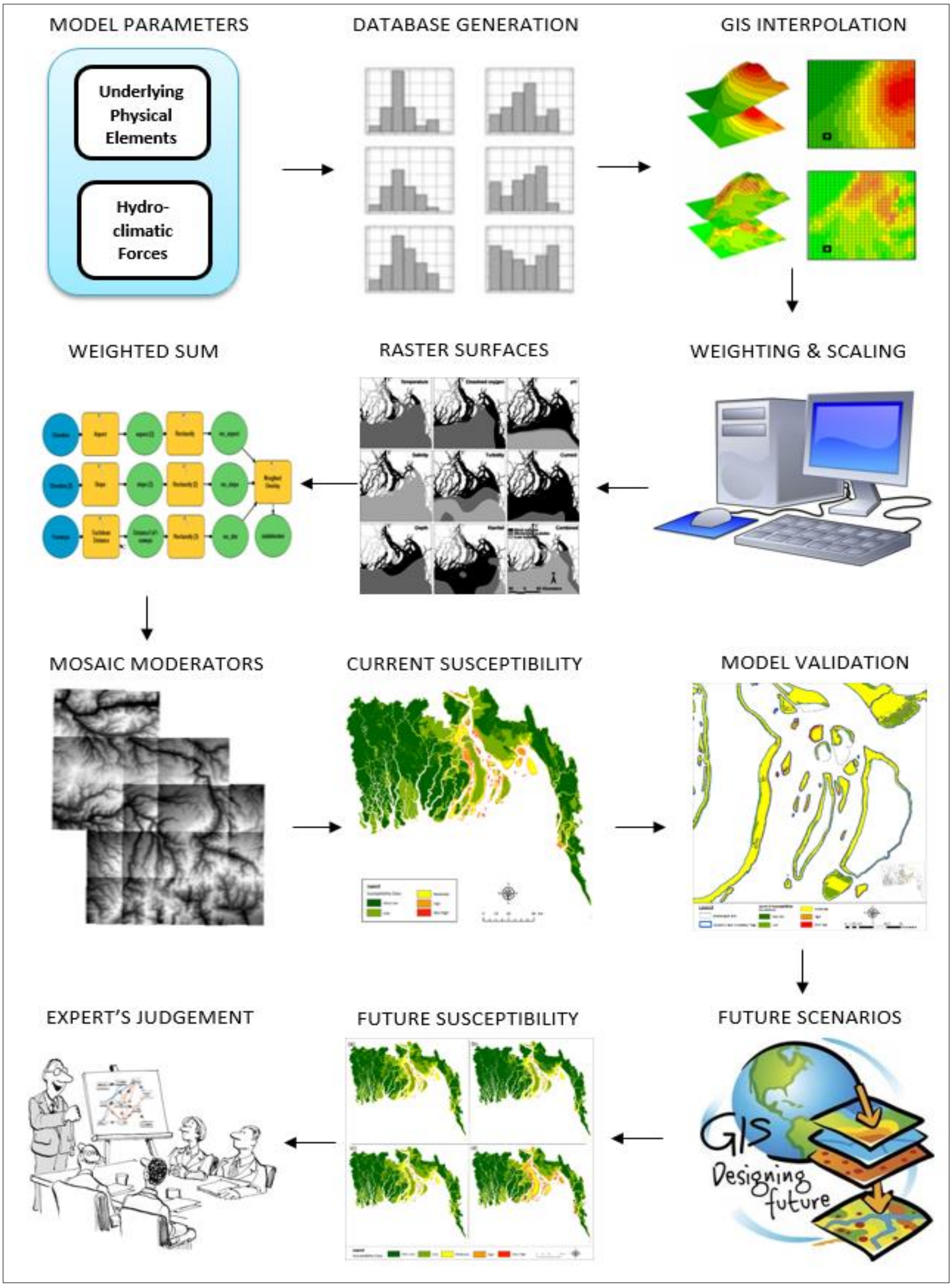

Figure 1.3a - Simplified workflow of the LSCE model that starts with selecting five underlying physical elements and four hydro-climatic factors. The generated databases were used to prepare raster surfaces for each parameter. The moderators (i.e. buffer zones for defence structures and accretion) were integrated with the nine weighted parameter values for baseline susceptibility assessment. The validated model outputs were the bases for future scenario generation following experts' judgement.

The LSCE model used two sets of moderators (i.e. buffer zones) to address the impacts of human interventions and sedimentation on erosion susceptibility: one for defence structures and another for accretion (sedimentation). The study followed a specific method of identifying the number and types of moderators and applied the moderators in the LSCE model. After collecting the data on the number of hard (i.e. sea wall, dykes) and soft (i.e. polder, dam) defence structures from BWDB, WARPO and BIWTA under the ministry of water resources, the study conducted a number of field visits in the three coastal zones to identify the existence and current conditions of the structures. To match the locational data obtained from the said sources, the study conducted a ground-truthing survey by collecting real-world locations of 5 hard defence and 10 soft defence structures. The study found an exact match of the secondary data on hard defence structures with the real world. However, the study found about an 80% match of the secondary data on sample soft defence structures with the real world. The probable reason of 20% mismatch might be due to the regular maintenance of the polders and embankments that is required after having considerable damages during monsoon seasons. The study finally selected a total number of 26 hard defence structures (from 30 recorded structures) and 60 polders and embankments (from 117 recorded structures) in the three coastal zones for the LSCE model on the basis of their existence and effectiveness as coastal defence structure. However, to identify the moderators for sedimentation, the study used the results of land dynamics for the last ten years from 2005 to 2015 and identified 38 accreted areas in the three coastal zones of the country.

The study identified the seasonal variation of land susceptibility of the coastal area to erosion. This was done because the selected hydro-climatic factors varied for most of the prevailing seasons in the coastal area. Assessment of land susceptibility by segmenting the overall susceptibility into four seasons (i.e. winter, pre-monsoon, monsoon and post-monsoon) provides insights into the seasonal influences of the hydro-climatic factors in the coastal area. However, an inventory map of land dynamics was prepared to validate the outputs of the LSCE model for current land susceptibility to erosion in the coastal area (discussed in chapter 3).

The study conducted a SA to identify the importance and influences of the individual parameters in the LSCE model and to analyse the regional variability of the input variables. However, the study applied the moderators in the SA followed by a similar method as for the general (overall) assessment. The results of the SA were compared with the results obtained for the general assessment of existing land susceptibility to erosion. Several methodological approaches of SA are available such as local versus global, qualitative versus quantitative and One-At-a-Time (OAT) versus All-At-a-Time (AAT) (Pianosi et al., 2016). Depending on the nature of the LSCE model, this GIS-based spatial modelling study designed the SA into three types and applied for overall baseline conditions of existing land susceptibility to erosion:

- Weightings between parameters
- Distribution of parameter values
- General vs regional models

The details of the methods, results and interpretations of the results obtained from the SA are discussed and placed as an annex in the third chapter of the thesis.

### 1.3.3 Generation of future scenarios on land susceptibility to erosion

The study used validated outputs of the LSCE model as a baseline condition of land susceptibility to erosion in generating future scenarios by using the same model frame. The aim was to address the impacts of probable changes in hydro-climate factors on future land susceptibility to erosion in the area. The study used scenario data for the selected hydro-climatic drivers of the LSCE model obtained from secondary sources. The source data were based on four Greenhouse Gas (GHG) concentration trajectories (i.e. A1B, RCP2.6, RCP4.5 and RCP8.5). The GHG concentration trajectories are pathways adopted by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Emissions Scenarios (SRES) in 2000 (Nakicenovic et al., 2000). The IPCC adopted four pathways such as A1B, A2, B1, and B2 as a first instance. The pathways describe possible future climate depending on the probable amount of GHG that will be emitted in future (O'Neill and Oppenheimer, 2004). Later, IPCC adopted four Representative Concentration Pathways (RCPs) such as RCP2.6, RCP4.5, RCP6, and RCP8.5 in their fifth Assessment Report (AR5) in 2014 (IPCC, 2014). The new pathways (i.e. RCPs) supersede the SRES pathways adopted in 2000. The four pathways used in this study are, A1B represents business-as-usual, RCP2.6 represents low scenario, RCP4.5 represents moderate scenario and RCP8.5 represents high scenario. The study generated both RCP-based low, moderate and high scenarios and SRES A1B-based moderate scenario of erosion susceptibility by applying secondary data in the LSCE model. This enables the study to compare A1B-based results with the latest RCP4.5-based results. The scenarios were segmented into three time-slices: near future (2020), future (2050) and far future (2080). Due to data scarcity, this study generated seasonal variation of erosion susceptibility based only on A1B trajectory. The scenarios of land susceptibility to erosion are named as the four Greenhouse Gas (GHG) concentration trajectories selected for the present study.

### 1.3.4 Addressing the broad aspects of coastal land susceptibility

The present study applied Fuzzy Cognitive Mapping (FCM)-based semi-quantitative approach to justify the LSCE model outputs, to evaluate other relevant factors that were not possible to address by the LSCE model and to apprehend uncertainties relevant to future land susceptibility to coastal erosion by eliciting experts' views (Figure 1.3b and Table 1.3a).

The study identified four challenges while conducting FCM based study on land susceptibility to erosion in the coastal area. These were:

- The number of experts needed for the workshops
- Selection criteria of the experts
- The way of generating and disentangling their knowledge
- Methods of validating the FCMs

As literature suggests (Morgan and Keith, 1995), there is no defined rule of selecting a particular number of experts for a particular study (discussed in chapter 5). However, it is imperative to select experts from relevant fields to capture diverse knowledge on the topic of study. Considering the nature of the topic, the study identified 15 experts from several relevant fields. To identify the suitable experts, this study used the following selection criteria. First, the study decided to generate FCM based knowledge on coastal erosion susceptibility from traditional experts. The distinction between traditional and non-traditional experts is discussed in chapter 5. The involvement of non-traditional experts (e.g. stakeholders) in the FCM might be more suitable for participatory planning purposes. However, the reason behind selecting traditional experts is that they have conceptual and technical expertise on the issues of land susceptibility to coastal erosion. Moreover, the traditional experts easily capture the idea of generating new knowledge by way of using the FCM-based approach. Second, the study prioritised the fields of study of the potential experts that matched with the present study topic. Hence, this study classified the fields of expertise into two broad categories: coastal physical processes and coastal human aspects. For instance, the fields of study of the selected experts include coastal geomorphology, coastal sedimentation, meteorology, climate change, soil science, land use policy, land management etc. Third, after selecting the fields of study, the study focused on 'threshold experience' of the experts to be selected for the workshops. This study defines threshold experience as the minimum satisfaction level of expertise the experts need to be hold. The present study fulfilled such level of satisfaction by accounting their total year of expertise and by reviewing their publications. In case of years of expertise, this study assumed 5-years as a minimum requirement.

After selecting a total number of 15 relevant experts, the study faced the challenge of generating and disentangling FCM based knowledge from the experts by way of arranging workshops (as a participatory method). The first workshop was segmented into three interfaces: concept mapping, matrix and scenario. Before starting the interfaces for future erosion susceptibility, the experts were provided with the scenarios of hydro-climatic factors used in the LSCE model along with other relevant data and information (discussed in chapter 5). The aim was to provide an overview of future scenarios that guided them to identify the interrelationships of the future components of erosion susceptibility. Furthermore, based on the given information, the experts were provided with several 'what-if' situations to facilitate the discussions on each interface. In concept mapping interface, the experts identified several physical and human-induced factors of erosion susceptibility as concepts. In matrix interface, the experts identified the positive and negative interrelationships between the components by assigning values in an adjacency matrix ranging from (-1) to (1). The adjacency matrix is a matrix table for the directed graphs (links between the components of the FCMs) in which, in-degree of a vertex (i.e. connection) is computed by summing the corresponding column and the out-degree is computed by summing the corresponding row for each of the components. In scenario interface, the experts identified future components and their interrelationships. As mentioned, the experts were selected from a number of relevant fields and hence, it was certain that their participation for the three interfaces of generating FCMs were varied in nature. For instance, in concept mapping interface, relevant concepts (i.e. factors) were provided by the relevant experts in the workshop based on their field of expertise. By this way, it was possible in the workshop to check the inclusion of irrelevant components in the FCMs from irrelevant experts. The same procedure was followed for the matrix and scenario interfaces of the workshops. In sum, the experts identified the current and potential future components of land susceptibility to erosion and mapped the causal relations between the factors by considering the impacts of hydro-climatic changes in the study area throughout the entire process. Moreover, the uncertainties in giving the degree of relationships between the components were also addressed by the experts by providing their confidence ratings in the FCM process.

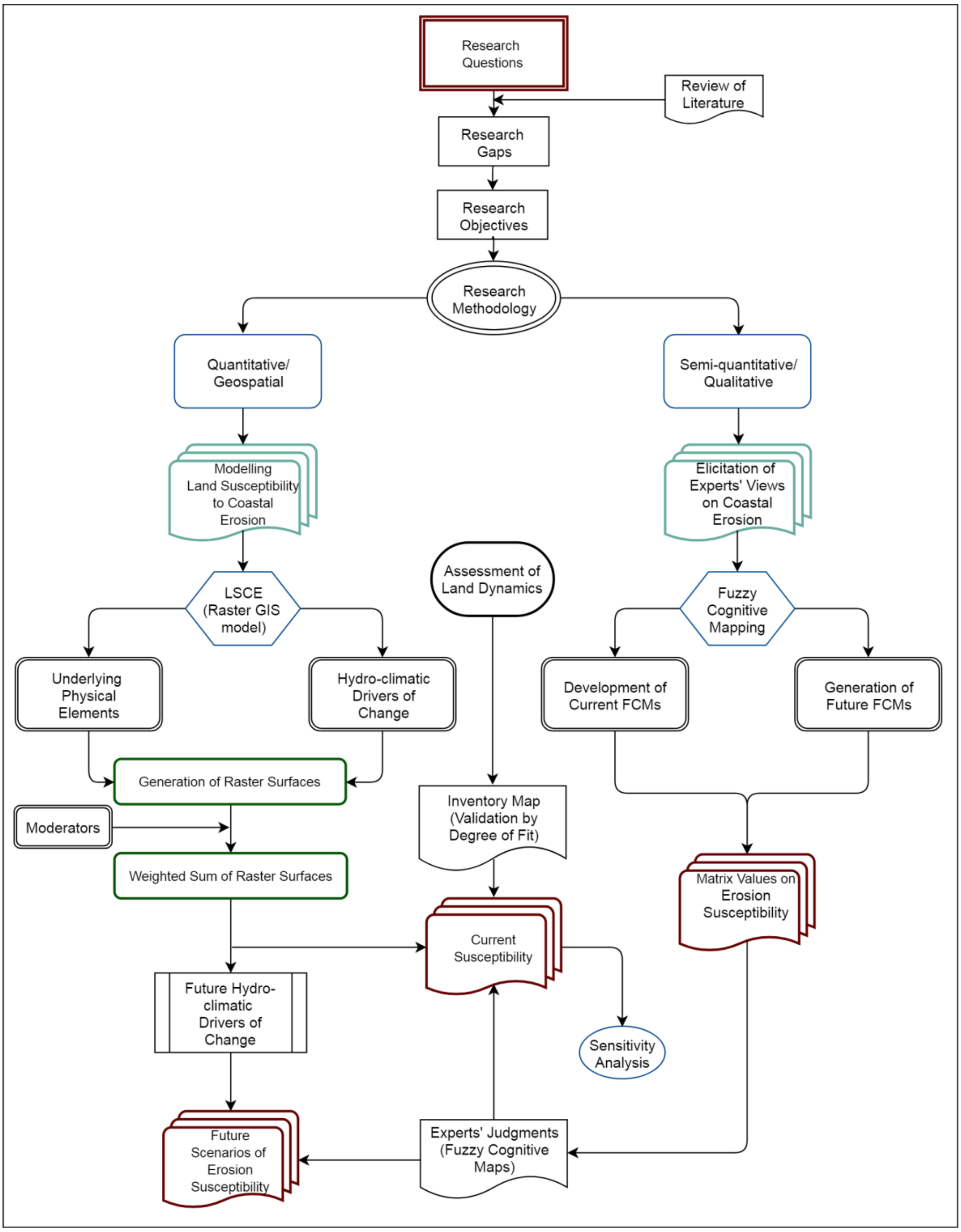

Figure 1.3b - Overview of the research frame applied for the current study. The entire process of assessing land susceptibility to erosion was segmented into two types of methodological approaches: quantitative (geospatial) and semi-quantitative. Additionally, the assessment of land dynamics in the coastal area was accomplished to prepare the inventory map. Both the quantitative and semi-quantitative methods were used to provide a consistent and justifiable assessment on land susceptibility to erosion in the coastal area.

Table 1.3a - Matrix of research methods. Based on the research questions, the study aimed at fulfilling the research objectives. To accomplish, the study followed several sequential steps: fixing initial purposes, searching for data availability and identifying suitable methods.

| Research question | Initial purpose | Data | Method | Initial output | Final output |
|---|---|---|---|---|---|
| What patterns of land dynamics exist in the coastal area of Bangladesh? | Analyzing the trend of erosion and accretion (land dynamics) | Landsat Satellite Images | Image analysis by GIS and Remote Sensing software | 1. Rates of erosion and accretion<br>2. Cross-check for inventory map | Assessment of land dynamics |
| How best to assess land susceptibility to coastal erosion?<br>And<br>What are the current conditions of land susceptibility to erosion in the coastal area of Bangladesh? | Identifying factors responsible for land susceptibility to erosion | Published materials | In-depth literature survey | Model parameters | Development of LSCE model and assessment of current land susceptibility to coastal erosion in Bangladesh |
| | Developing cell based GIS model and applying in the coastal area of Bangladesh | A. Underlying physical elements<br>B. Drivers of change<br>C. Moderators | Land Susceptibility to Coastal Erosion (LSCE) model | 1. Scaling and weighting model parameters (raster surfaces)<br>2. Analysing and mapping existing land susceptibility to coastal erosion | |
| | Validating the outputs of LSCE model for current physical susceptibility to erosion | Current erosion inventory map prepared from historical datasets | ‘Degree of fit’ curves | Validation of current land susceptibility to coastal erosion in Bangladesh | |

| | | | | | |
|---|---|---|---|---|---|
| What are the possible future scenarios of land susceptibility to erosion in the coastal area of Bangladesh? | Generating future scenarios of land susceptibility to coastal erosion | IPCC and other RCM model based projection data on driving forces of erosion | LSCE model | Future scenarios of the model parameters | Generation of possible future scenarios of land susceptibility to erosion |
| | Justifying the model outputs and addressing uncertainties | Fuzzy Cognitive Mapping (FCMs) | Expert's opinion by arranging workshops | Justification of future land susceptibility to coastal erosion | |
| How to address the compelling aspects of coastal erosion susceptibility in Bangladesh? | Eliciting experts' views | LSCE model outputs<br>Hydro-climatic factors | Fuzzy Cognitive Mapping (FCM) | Matrix of relationship tables | Factors of erosion susceptibility<br>Cognitive maps of erosion susceptibility |

Finally, the generated FCMs in the first workshop were validated by arranging a second workshop comprising of 4 remaining experts from the list (combination of both physical and humanistic fields of expertise). This second group of experts were provided with none of the data that were provided to the first group of experts. This was purposively designed with an aim to conduct an unbiased assessment by the second group of experts. The design of the two consecutive workshops was in such a manner that saved time. The first workshop started in the morning and took about 6 hours to accomplish. The second workshop started in late afternoon, after having the outputs of the first workshop. The first group of experts had some time for refreshment during the time of the second workshop. The modifications of the FCMs by the second group of experts were accomplished and the validated outputs were presented to all the 15 experts for further modifications and final concluding remarks.

### 1.4 Chapter plan

The present study organised the full thesis under seven chapters that are logically connected to each other (Figure 1.4a). The introductory chapter (chapter 1) includes the review of relevant literature and knowledge gaps. Moreover, the first chapter provides an overview of methodological considerations relevant to the objectives of the study. The analysis of land dynamics in the coastal area of the country is presented in the second chapter. Chapter 3 of the thesis includes the assessment of existing land susceptibility to erosion in the coastal area of the country. Chapter 4 contains the third objective of the study (i.e. generation of future land susceptibility to erosion). The fifth chapter comprises the fourth objective of the study that includes the experts' elicitation on erosion susceptibility by applying Fuzzy Cognitive Mapping (FCM) approach. The sixth chapter contains the synthesis of the results and the limitations of the study together with some cross-cutting issues of land susceptibility to erosion in the coastal area. The concluding chapter (chapter 7) provides further recommendations and delivers the key messages of the study for policymakers (i.e. policy deliverables) and local people along with future research needs for the academic community.

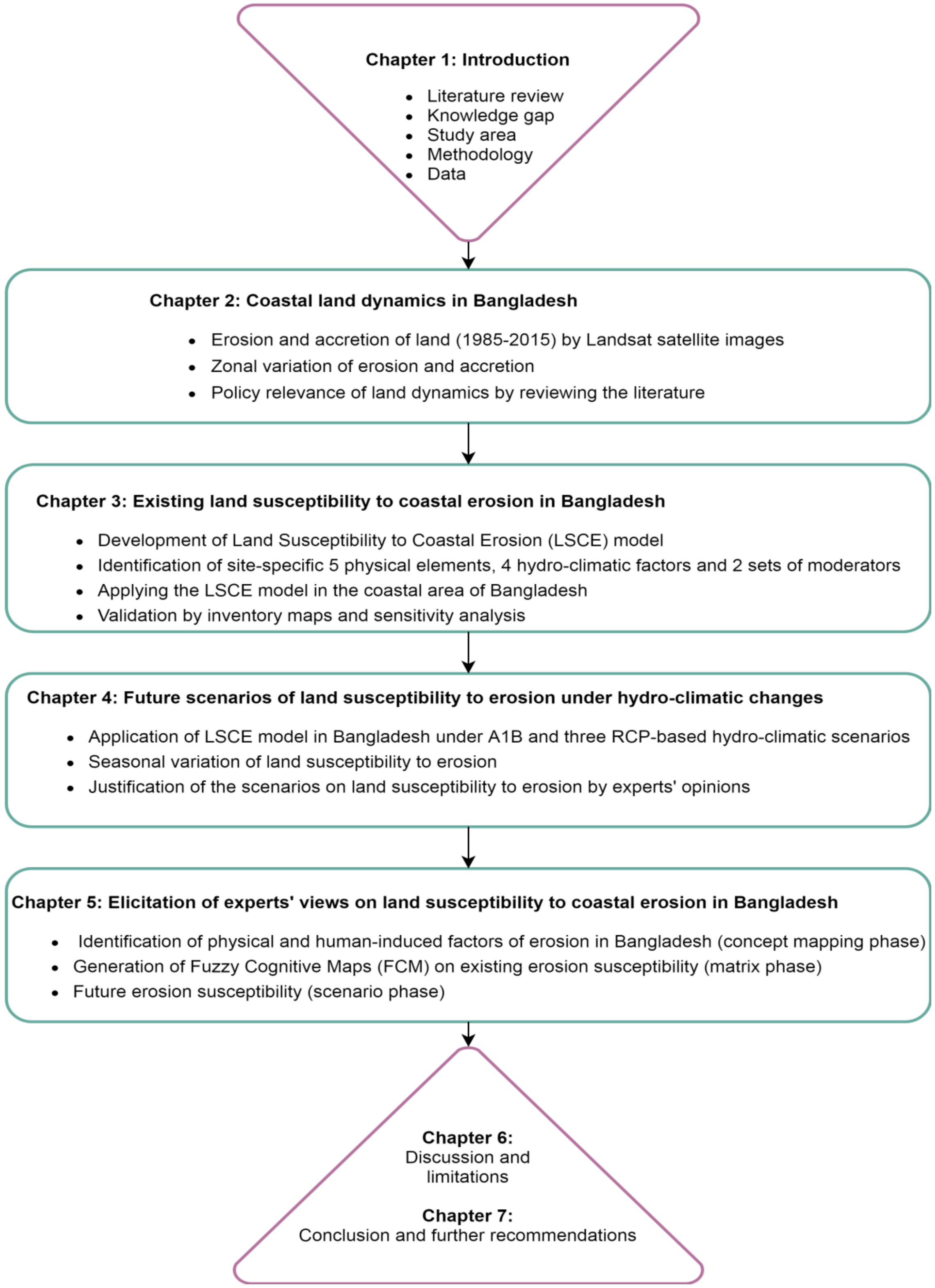

Figure 1.4a – Chapter plan of the thesis in fulfilling the aims of the present study. The titles of the chapters are summarised here in the figure. The full titles of the chapters are given in the relevant papers. The major part of introduction (i.e. chapter 1) contains the review of literature to justify the rationale of the present study. The major objectives of the study were articulated in the next four chapters (i.e. chapter 2, 3, 4 and 5).

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# Chapter 2: Where is the coast? Monitoring coastal land dynamics in Bangladesh: An integrated management approach using GIS and remote sensing techniques

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## 2.1 Abstract

This paper draws upon the application of GIS and remote sensing techniques to investigate the dynamic nature and management aspects of land in the coastal area of Bangladesh. The geomorphological characteristic of the coastal area is highly dynamic where land erosion and accretion with different rates remain a constant phenomenon. This study focuses on three coastal zones: western, central and eastern that comprise the entire coastal area of the country. At its core, this study used the past 30 years' Landsat satellite images. This is the first time that the entire coastal area of Bangladesh has been considered for assessment. This research reveals that the rate of accretion in the study area is slightly higher than the rate of erosion. Overall land dynamics indicate a net gain of 237 $km^2$ (7.9 $km^2$ annual average) of land in the area for the whole period from 1985 to 2015. The results also demonstrate that the rates of both erosion and accretion are higher in the central zone compared to the western and the eastern zones of the coastal area. This study has highlighted some causes of land dynamics associated with the coastal zones. River water discharge in the Meghna estuary, prevailing monsoon wind and wave actions, tidal variation, anti-clockwise tidal circulation, cross dam and development projects are considered as major drivers of land dynamics in the central coastal zone. Moreover, wave actions, mangrove vegetation, storm surges and polders are the most important factors of land dynamics for the western coastal zone whereas, soft and unconsolidated soils, rainfall, development activities and deforestation are key physical and human-induced causes of land dynamics in the eastern coastal zone. This study recommends that coastal managers, planners and policymakers consider the identified dynamic trends of coastal land before opting for any specific measure. The nature and pattern of land dynamics and the associated causes identified by the present study might be useful to identify the nature of interventions needs to be taken for each zone. Regular monitoring (e.g. seasonally or yearly) using GIS and remote sensing techniques would be a viable management option for this purpose.

## 2.2 Introduction

The coasts of the world are dynamic systems (Balica et al., 2012) since coastal areas exhibit constant morpho-dynamic processes as a result of the geomorphological and oceanographic factors (Cowell et al., 2003a, b). They are also prone to a large number of hazards (Torresan et al., 2008). Coastal land dynamics, particularly coastal erosion is seen to pose serious morpho-dynamic hazards in coastal areas around the world (Addo et al., 2008). Coastal land dynamics includes the process of erosion (removal of materials from shoreline) that results in the loss of coastal land and the retreat of coastline. The deposition of materials removed through the process of erosion leads to the accretion of land in another place (Gibb, 1978).

Instant and reliable techniques are key to address the dynamic nature of coastal lands (Ghosh et al., 2015). Although empirical field studies and aerial photos are generally used to address the issue (Papakonstantinou et al., 2016), the techniques are not cost-effective and take a long time to accomplish. However, remote sensing and GIS techniques provide the opportunity to monitor the dynamic nature of coastal land in a cost-effective manner (Ghosh et al., 2015). The monitoring of coastal land dynamics around the world by using GIS and remote sensing techniques is not new. In fact, there are numerous studies conducted for different coastal areas using aerial photographs, GIS and remote sensing techniques (discussed in chapter 1). For instance, Wang (2003) used Landsat 7 satellite imagery to detect changes in the shoreline of Delaware inland bays. A study by Chowdhury and Tripathi (2013) identified coastal erosion and accretion in Pak Phanang, Thailand between 1973 and 2003 using GIS analysis of maps and satellite imagery. Study on shoreline change detection also conducted by Zoran and Anderson (2006) and Prabaharan et al. (2010) for the Romanian Black Sea coastal zone and Vedaranniyam coast of India respectively. Depending on the nature of the coast, a number of approaches based on numerical models (Ferreira et al., 2006; Zoran and Anderson, 2006) have been used where dynamic stability, erosion and accretion of the shores have been assessed. Empirical field studies (Prabaharan et al., 2010; Duc et al., 2012) and different computer-based approaches (Shifeng et al., 2002; Brown et al., 2005) have also been conducted to assess coastal erosion.

From geomorphological point of view, the coastal area of Bangladesh is highly dynamic where land erosion and accretion are taking place at different rates (Brammer, 2014). The Bengal delta encompasses a large part of the coastal area and is the largest delta in the world (Goodbred et al., 2003; Hori and Saito, 2007) which covers approximately 100,000 km$^2$ in area. The Bengal delta is driven by the hydrologic discharges of the Ganges-Brahmaputra-Meghna (GBM) river system which carries sediments from upstream (Umitsu, 1993; Allison and Kepple, 2001; Sarker et al., 2015). These three rivers, via the lower Meghna river channel (Sarker et al., 2015) carry close to one trillion m$^3$ of water and one billion tons of sediment annually. For the past 100 years, considerable changes have been observed in the courses of major rivers in Ganges-Brahmaputra-Meghna (GBM) basin. The changes of the river courses together with the tidal influence from the Bay of Bengal were the major driving forces in shaping the coastal area of Bangladesh (Goodbred and Kuehl, 2000a, b; Sarker et al., 2015) and are still considered as the active agents of changes in the coastal area of the country.

In-depth regional study on coastal land dynamics is crucial for effective management of coastal lands (Naji and Tawfeeq, 2011; Jayson-Quashigah et al., 2013). This is especially true for the coastal area of Bangladesh where a comprehensive and detailed study is essential to address the potential loss of land and to take effective measures to minimize that loss. The changes in lands are very rapid in the coastal area of the country which is home to 44.8 million people (Ahmed, 2011). Monitoring dynamic nature of coastal land, particularly in the coastal area of Bangladesh is important because it affects the livelihoods of the people living in that area. Although several studies have been conducted using GIS and remote sensing techniques on morphological changes in the coastal areas of Bangladesh (de Wilde, 2011; Shibly and Takewaka, 2012; Islam et al., 2013), the studies were limited to deal with the retreat of shorelines. Some studies identified erosion and accretion of lands in the coastal area but, these studies were conducted only for specific coastal islands, sections and zones (discussed in chapter 1). For instance, the study by Ali et al. (2013) identified the pattern of erosion and accretion of the Manpura Island located in the central coastal zone of the country. The study identified the land dynamics for the period from 1973 to 2010 and found that the total area of the island has gradually decreased from 148 km$^2$ to 114 km$^2$ of land during the 37 years. The work of Brammer (2014) identified the general pattern of erosion and accretion in the Meghna estuary area with lesser details for the western coastal zone and no analysis for the eastern coastal zone of the country. The work was primarily based on topographical survey maps and empirical field tests where, Landsat satellite images were employed for two years (i.e. 1984 and

2007) to compare the rate of erosion and accretion between the mentioned years. Ghosh et al. (2015) identified the changes in coastline of Hatiya Island for the period from 1989 to 2010. The study used Thematic Mapper (TM) for the years 1989 and 2010 and Enhanced Thematic Mapper (ETM) for the year 2000. To demarcate the boundary between land and water, the study used modified normalized difference water index (MNDWI) algorithm for the selected years. The study identified land gains in the northern and western pasts and land lost in the southern and eastern parts of the island. Overall, the study identified a total amount of 64.76 km$^2$ of eroded land in comparison with 99.16 km$^2$ of accreted land. Some previous studies (Sarwar and Woodroffe, 2013; Islam et al., 2016) identified the rates of coastal erosion and accretion by way of analysing the retreat of shoreline only.

This research contributes new knowledge to study on land dynamics in the coastal area of Bangladesh from several perspectives. The current study aimed to identify the long-term trend (past thirty years from 1985 to 2015) of the dynamic nature of land for the entire coastal area of the country. This study considered the total land area of the coast which has the threshold limit of tidal movement and has both direct and indirect influences of the Bay of Bengal. As such, this research aimed to offer a more comprehensive picture on the dynamic nature of lands for the entire coastal area of the country. As far as the authors are aware, there is no complete study on the comparison of the dynamic nature of land among and between the three coastal zones. Hence, the present study emphasised on the identification and comparison of rates of erosion and accretion among the three coastal zones. This study also evaluated the underlying causes of the variation of rates of erosion and accretion among the zones. The study carries essence from the methodological point of view. This study used multi-temporal satellite images in the assessment where, the uses of such images are more advantageous to delineate land areas from existing water bodies more accurately. Moreover, the study addressed the existing policy relevance and management aspects of the dynamic nature of land and suggested some measures options for coastal managers and policymakers to deal with the issue.

## 2.3 Study area and data

### 2.3.1 The study area

The reason for choosing the study area lies on its diverse coastal characteristics as identified by IPCC (2007a, b) that brings in most of the natural coastal systems, namely the beaches, deltas, estuaries, lagoons and mangroves. Moreover, the assessment of rapid morphological changes in the densely populated coastal area (about 949 persons/ km$^2$) is important for the people living in the area (Bangladesh Bureau of Statistics [BBS], 2015). On the basis of geomorphological characteristics, Pramanik (1988) first divided the coastal area of Bangladesh into three zones: western, central and eastern that covers approximately 27,150 km$^2$, 12,040 km$^2$ and 8,010 km$^2$ of coastal land area respectively (Figure 2.3.1a). These have been used in this study. The total area of the identified coastal zones is 47,200 km$^2$ (MoEF, 2007; MoEF, 2016) that includes the land areas and water bodies. This study groups the land areas into three different categories: eroded, accreted, and unchanged land. The assessment of land dynamics for this research considered the dynamic land areas only that found from 1985 to 2015 while, the total areas of water bodies were excluded from the analysis. The inland boundary of the coastal area from the shoreline was fixed to the threshold limit of tidal movement that has both direct and indirect influences of the Bay of Bengal. Based on the exposure to the Bay, the coastal area can also be marked as interior coast (23,265 km$^2$), and exposed coast (23,935 km$^2$) (Figure 2.3.1a) (PDO-ICZMP, 2006 and Islam et al., 2006; MoEF, 2016). The exposed coast meets directly with the Bay and lower estuary (Ministry of Water Resources [MoWR], 2005; MoEF, 2016), of which this has met the maximum limit of tidal movement, salinity, cyclone risk etc. (PDO-ICZMP, 2006).

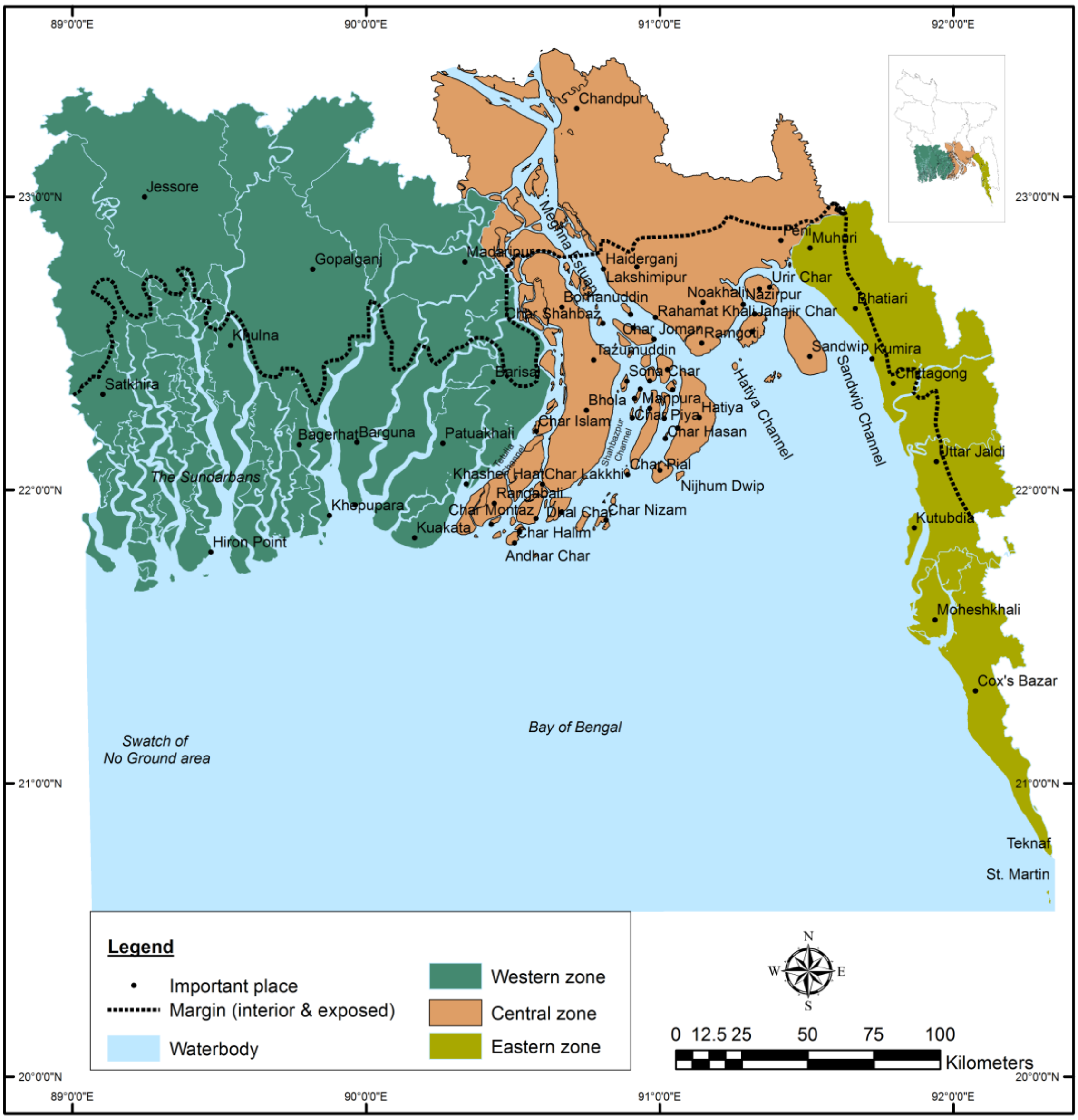

Figure 2.3.1a - The three coastal zone of Bangladesh comprise the entire coastal area of the country were selected for the present study. [Data sources: BBS, 2015 and BWDB, 2016 (important place); MoEF, 2016 (coastal zones and margin between interior and exposed coast)].

### 2.3.2 Satellite images

The study analysed multi-temporal Landsat satellite images (Table 2.3.2a) to acquire current and past rates of erosion and accretion in order to assess the dynamic nature of coastal land in the selected area. This study used multiple images of the same scene acquired at different times of selected months for specific years. In discussing the temporal changes in land dynamics, the past 30 years images were split into four periods and hence, images of 1985, 1995, 2005 and 2015 were gathered for analysis. Landsat Thematic Mapper (TM) images were used for the years 1985 and 1995 which are multispectral data obtained from Landsat 4 and 5 missions. Landsat Enhanced Thematic Mapper Plus (ETM+) images were used for the years 2005 and 2015 which are high resolution multispectral data obtained from Landsat 7 mission (Appendix A). The acquired images for those periods were downloaded using the USGS Global Visualization Viewer which are freely available in 30×30 m pixel resolution (USGS, 2016). The selection of such pixel resolution is essential considering the spatial extent of the study area. The TM comprises seven bands whereas ETM+ contains eight bands (one additional panchromatic band with 15 m resolution). Both the bands include the visible (red: 0.63-0.69 μm; green: 0.52-0.60 μm; blue: 0.45-0.52 μm), near infrared (0.76-0.90 μm), mid infrared (1.55-1.75 μm) regions as well as the thermal infrared (10.4-12.5 μm) region of the electromagnetic spectrum (United States Geological Survey [USGS], 2013).

Table 2.3.2a - Landsat satellite images used for the study. The study acquired satellite images having same spatial resolution. The acquisition periods of the images were the months of January and December during winter seasons. [Source: USGS, 2016]

| Year | Sensor | Resolution | Month of image acquisition |
|---|---|---|---|
| 1985 | TM | 30x30 m | January |
| 1995 | TM | 30x30 m | January |
| 2005 | ETM+ | 30x30 m | December |
| 2015 | ETM+ | 30x30 m | January |

### 2.3.3 Policy and management issues

This study made extensive use of secondary materials to build up and support the objective of identifying policy relevance and management issues of land dynamics in the coastal area of the country. To analyse the policy implications in managing coastal land dynamics, this study reviewed the available coastal policies along with the relevant plans, strategies and projects of the government (discussed in chapter 1). The study also evaluated the impacts of the policies on coastal land dynamics as well as the gaps in formulating policies to address the issues of coastal morphological changes.

## 2.4 Methods

### 2.4.1 Pre-processing of satellite images

To analyse the trends and rates of erosion and accretion in the selected area, the collected raw satellite images went through some pre-processing works such as atmospheric, radiometric and geometric corrections. These processes are discussed in turn as follows. First, the images were atmospherically corrected by using Dark Object Subtraction (DOS) method (Chavez, 1996) to cancel out the presence of dust, smoke and haze in the images. Second, a normalized radiometric correction was performed for the images to achieve the real reflectance values of the images and to remove sensor noise. Next, individual shapefiles were generated for analysis. Finally, all the images were then geo-rectified using the sixteen Ground Control Points (GCPs) with a view to acquiring geometrically correct images. By this way, the GCPs yielded an average value of 0.0013054 metre Root Mean Square Error (RMSE) that demonstrates a good agreement of the selected images with the corresponding locations in the real world.

### 2.4.2 Delineation of land-water boundary

The amplitude of tides in the coastal area of Bangladesh is an important factor in detecting land and water that vary substantially for the three coastal zones (Islam et al., 2016). For example, the Ganges deltaic coastal area experiences both micro-tidal (<2 m) and meso-tidal (2 m to 4 m), the Sundarbans area receives only micro-tidal amplitudes whereas, the coastal areas of Barguna, Patuakhali and Noakhali receive a mix-tidal characteristics having both meso and micro tides (Islam et al., 2016). The situation, however, is different for the central (Meghna estuary) and eastern zones of the coast whereby these vary from 0.5 m to 3.5 m (Ghosh et al., 2015). The variations are also visible during monsoon and winter seasons. For this, pre-processed images were further analysed to separate water bodies from landmasses as a pre-requisite to detect land dynamics. Considering the drawbacks pertaining to the delineation of the foreshore (between high tide and low tide) associated with tidal variations, spectral signatures from multi-temporal satellite images were used to demarcate the common boundary between land and water. Band 4 (0.76 to 0.90 μm) with Near Infrared (NIR) images were used to achieve this, as this band is notably suitable for separating landmass from water body (Sarker et al., 2013). These separations were performed by using the Erdas Imagine software with a simple algorithm (Equation 1). A DN (Digital

Number) value 35 identified from the histograms of the images, was then applied in the equation (Equation 1). This number can vary from 0 to 50 and indicates the threshold value for separating the water body from other land covers.

*Either (Landsat ETM+) IF (Band 4<36) or 0 otherwise* (1)

### 2.4.3 Detection of land dynamics

To determine the dynamic nature of erosion and accretion, the pre-processed images were resampled to 30×30 m pixel size. To do this, the nearest neighbour resampling method was applied by using an algorithm for first-order polynomial transformation. To detect the land dynamics, manual digitization was conducted for each image. The digitised shapefiles for each year were then superimposed on the shapefiles for the subsequent years to group the coastal land areas into three categories: eroded, accreted, and unchanged. The results were then quantified and analysed in ArcMap. Next, the rates of these changes were calculated by using the equation (Equation 2).

$$r = A \div t \qquad (2)$$

Here, r= rate of erosion/accretion
A= Area eroded/ accreted
t= time period

### 2.4.4 Method of validation

To validate the eroded and accreted landmass obtained for the selected years, these data were compared to the referenced data. For reference data, topographical maps for 1985 and 2005 obtained from Survey of Bangladesh (SoB) were used. The reference map of 1995 was collected from Local Government Engineering Department (LGED) of Bangladesh, while a reference map collected from National Water Resource Database (NWRD) of Water Resources Planning Organization (WARPO), Bangladesh was used to validate the results of 2015. The comparisons were performed using the error matrix (Equation 3). The final assessment was done by calculating overall accuracy (Equation 4) and kappa coefficient (Equation 5). In equations 3, 4, and 5: $n$ indicates the total number of samples, $i$ indicates the number of rows and columns, $N$ indicates the total number of observations and $nii$ indicates the diagonal elements in the error matrix. Likewise, $nij$ indicates the major diagonal element of class $i$ where

'$ni$' indicates the total number of observations in row $i$ and '$nj$' indicates the total number of observations in column $j$. A total number of 150 sample pixels were selected from each image to validate the results with reference data.

$$\text{Error matrix, } n = \sum_{i=1}^{k} X \sum_{j=1}^{k} nij \tag{3}$$

$$\text{Overall accuracy} = \frac{\sum_{i=1}^{k} nii}{n} \tag{4}$$

$$\text{Kappa coefficient, } K = \frac{n\sum_{i=1}^{k} nii - \sum_{i=1}^{k} ni + nj}{N2 - \sum_{i=1}^{k} ni + ni} \tag{5}$$

This study conducted an in-depth literature survey to identify the relevant causes associated with the dynamic nature of lands in different coastal zones of the area studied.

## 2.5 Results

### 2.5.1 Erosion and accretion (1985 - 1995)

A total of 987 km$^2$ of eroded lands and 1115 km$^2$ of accreted lands were identified for the period from 1985 to 1995. It is observed that the rate of accretion was slightly higher than the rate of erosion during this period where the rate of accretion was 111.50 km$^2$/year and the rate of erosion was 98.7 km$^2$/year respectively. The net gain of land identified during this period is 128 km$^2$. It is important to note that these rates did not vary substantially, only to an extent of 12.8 km$^2$/year. Major erosion and accretion occurred in the central zone of the area for this period (Figure 2.3.1a and Figure 2.5.1a).

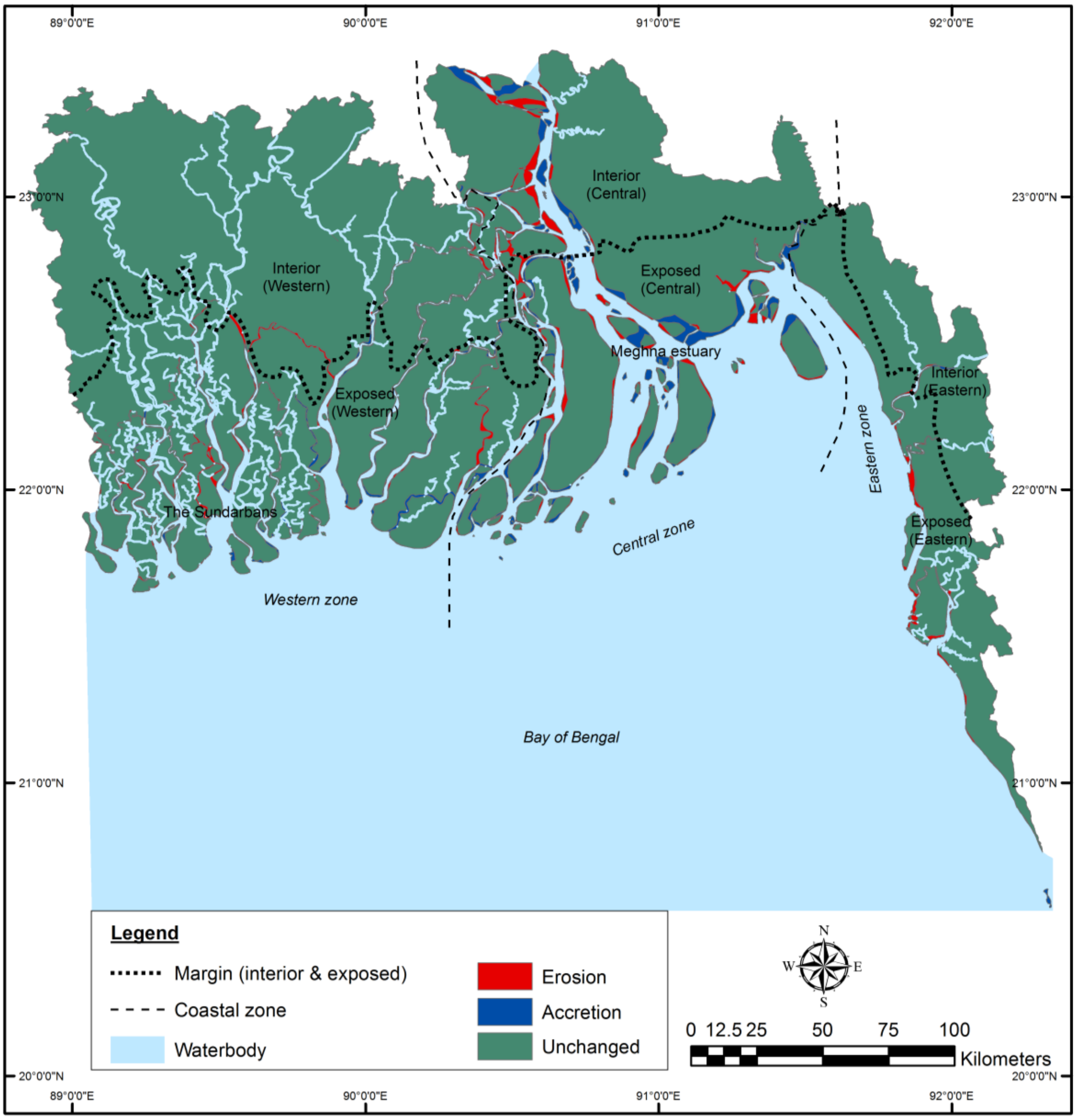

Figure 2.5.1a - Areas of erosion and accretion from 1985 to 1995 in the area studied. The figure shows that land dynamics were mainly observed in the interior (near Chandpur) and exposed (lower reach of the Meghna estuary) central coastal area.

### 2.5.2 Erosion and accretion (1995 - 2005)

The rates of erosion and accretion do not vary remarkably during the period ranging from 1995 to 2005 in comparison with the previous period. Nevertheless, the results confirmed that the rate of erosion was lower than the rate of accretion during this period. A total of 1183 km$^2$ of land was eroded as compared with 1284 km$^2$ of accreted land (Figure 2.5.2a). The rate of erosion was 118.3 km$^2$/year whereas, the rate of accretion was 128.4 km$^2$/year. The net gain of land for this period was 101 km$^2$

of coastal land (10.1 km$^2$ per annum) which is slightly 27 km$^2$ less than the previous period. Major erosion events occurred in the areas of Meghna estuary and along the coasts of major islands such as the eastern coast of Bhola, the northern coast of Hatiya and the south-western coast of Sandwip whereas, major accretions identified at Noakhali district, Urir Char, Jahajir Char and some small islands in the Meghna estuary (Figure 2.3.1a and Figure 2.5.2a).

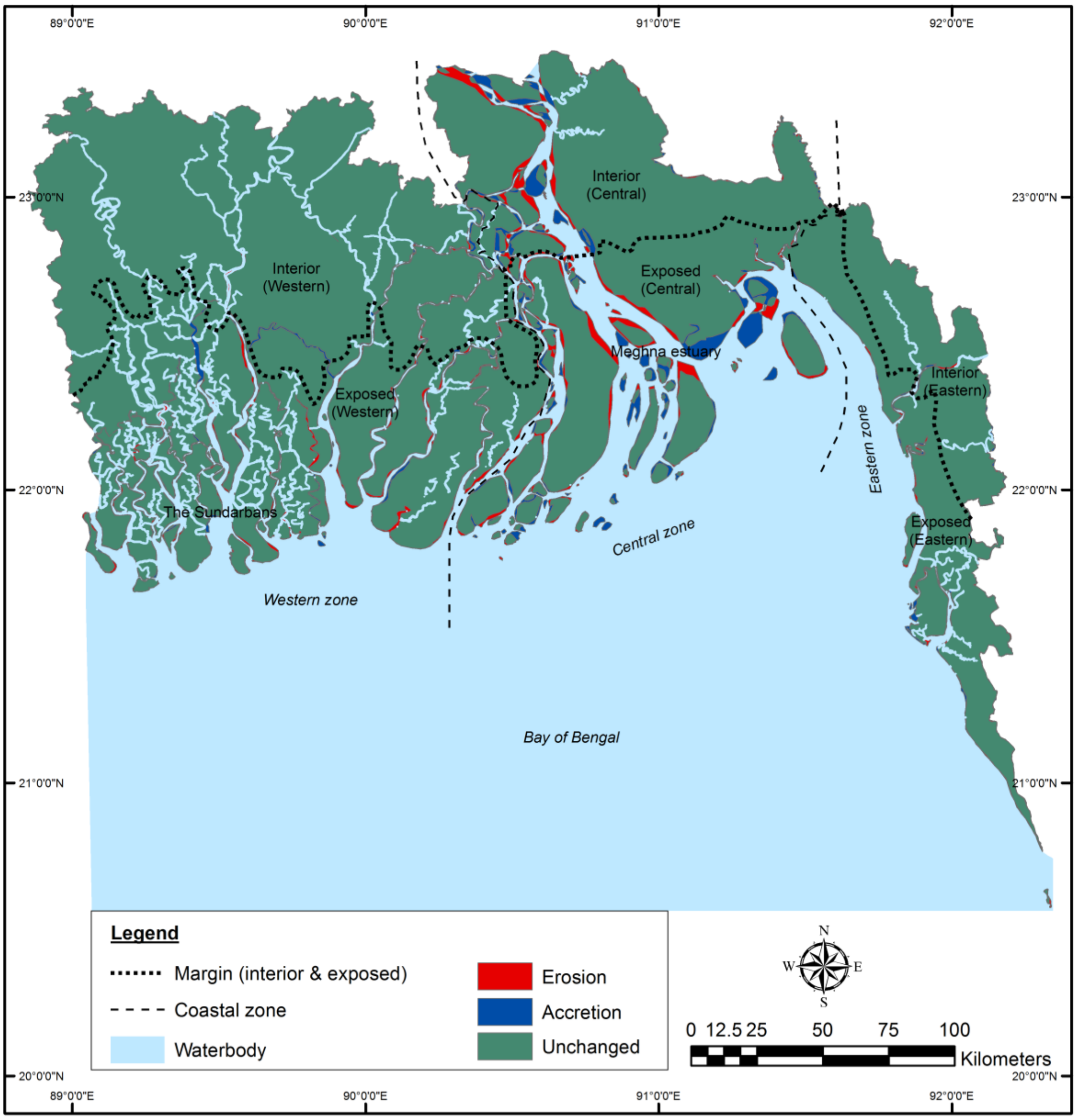

Figure 2.5.2a - Areas of erosion and accretion from 1995 to 2005 in the area studied. The figure shows that the central coastal zone was highly dynamics than the western and eastern coastal zones during that period.

### 2.5.3 Erosion and accretion (2005 - 2015)

For the period ranging from 2005 to 2015, a higher rate of erosion of land was observed. A total 1194 km$^2$ of land was eroded for the period as compared with a total 1175 km$^2$ of accreted land (Figure 2.5.3a). The net balance of land lost is estimated to cover an area of 19 km$^2$ (1.9 km$^2$ annual average) during this period. The probable reason for this could be due to the higher rate of erosion as compared to the rate of accretion during this period. Most of the accretions of land were detected in the Meghna estuary areas, while most of the erosions of land occurred along the coast of Noakhali district (Figure 2.3.1a and Figure 2.5.3a).

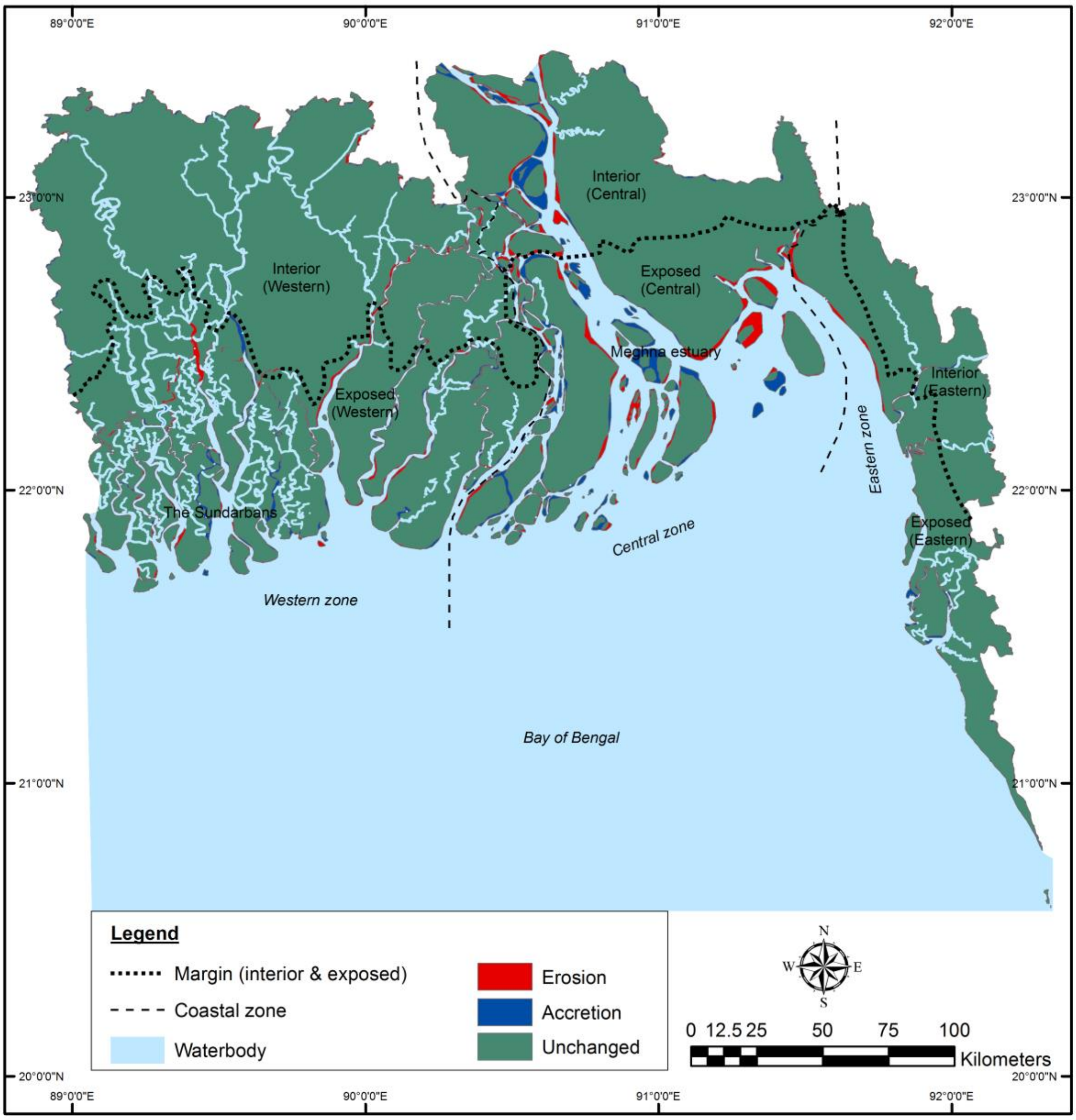

Figure 2.5.3a - Areas of erosion and accretion from 2005 to 2015 in the area studied. The figure indicates that the major erosion events occurred in the exposed area of the central coastal zone.

### 2.5.4 Overall erosion and accretion (1985 – 2015)

Overall, table (Table 2.5.4a) shows that slightly less erosion took place compared to accretion for the whole period between 1985 and 2015 (Figure 2.5.4a and Figure 2.5.4b). A total of 1576 km$^2$ of land has been eroded for the whole period from 1985 to 1995, compared to a total 1813 km$^2$ of land accreted for the same period. The rate of erosion observed stood at 52.5 km$^2$ as compared with the rate of 60.4 km$^2$ accretion annually. The net balance of land demonstrated a gain of 237 km$^2$ (7.9 km$^2$ annual average) of coastal land for the past thirty years period ranging from 1985 to 2015.

Table 2.5.4a - The overall area and rate of erosion and accretion for the period from 1985 to 2015. The increasing rates of erosion were identified for all three periods. Except for the period from 2005 to 2015, the net balance shows a gain of lands in the coastal area.

| Duration | Erosion | | Accretion | | Net Balance | Annual Average |
|---|---|---|---|---|---|---|
| | Total (km$^2$) | Rate (km$^2$/y) | Total (km$^2$) | Rate (km$^2$/y) | Land (km$^2$) | Land (km$^2$) |
| 1985-1995 | 987 | 98.7 | 1115 | 111.5 | (+) 128 | (+) 12.8 |
| 1995-2005 | 1183 | 118.3 | 1284 | 128.4 | (+) 101 | (+) 10.1 |
| 2005-2015 | 1194 | 119.4 | 1175 | 117.5 | (-) 19 | (-) 1.9 |
| 1985-2015 | 1576 | 52.5 | 1813 | 60.4 | (+) 237 | (+) 7.9 |

Note: (+) indicates the gain and (-) indicates the loss of land

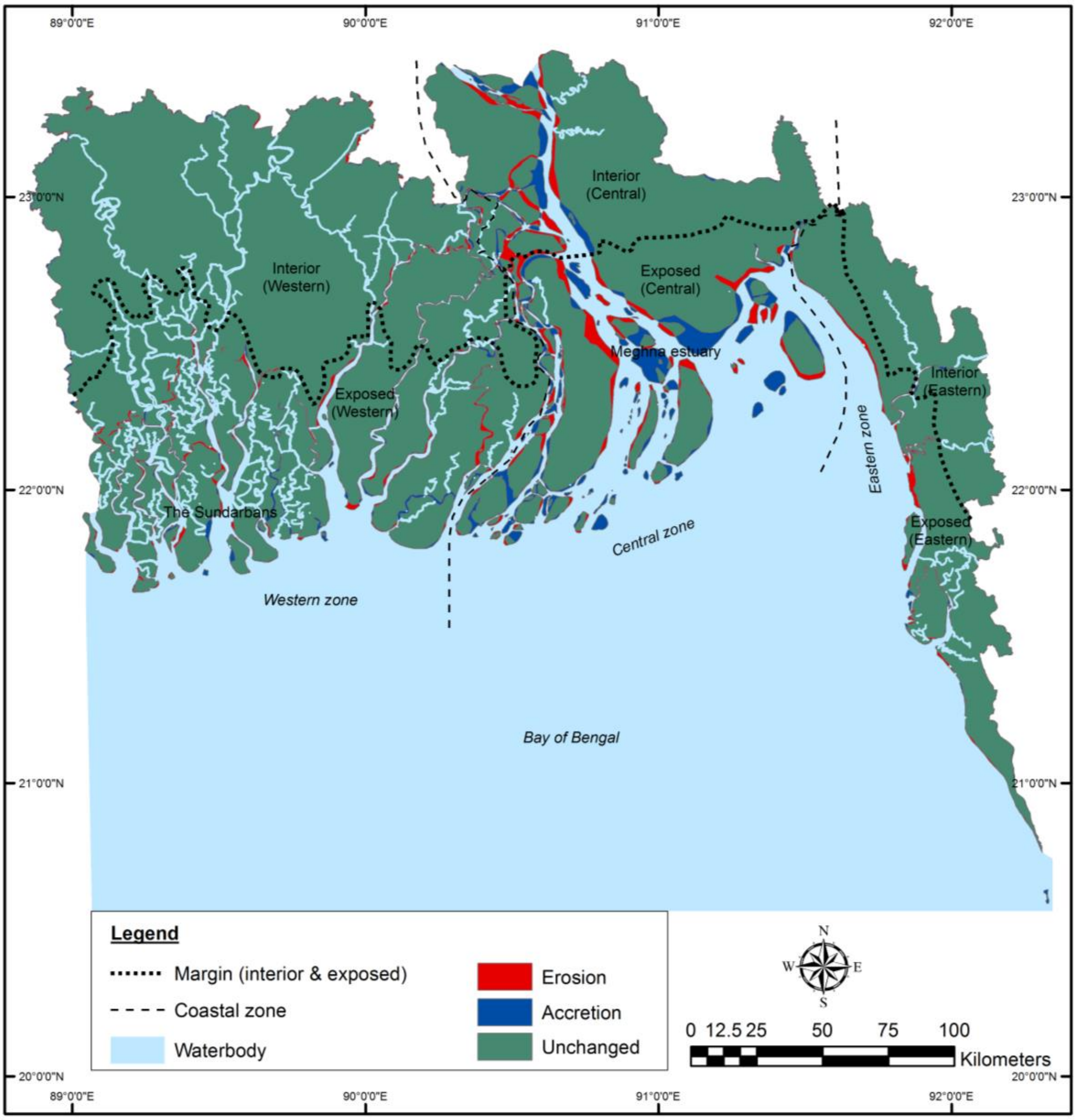

Figure 2.5.4a - Areas of erosion and accretion from 1985 to 2015 in the area studied. The pattern of land dynamics for the entire period indicates that the interior areas of the western and eastern coastal zone were less dynamic than the exposed coastal areas. Moreover, both the interior and exposed areas of the central coastal zone were highly dynamic in comparison with the western and eastern coastal zones.

### 2.5.5 Zone-wise erosion and accretion

This study identified the variation of land changes for the three coastal zones. For the period from 1985 to 1995, the analysis exhibits that both the rates of erosion and accretion were lower in the western zone of the coast, with a reading 36.9 km$^2$/year and 32.5 km$^2$/year respectively compared to the central and eastern coastal zones. These rates, however, varied for the remaining periods where the rate of erosion increased to 37.6 km$^2$/year for the period from 1995 to 2005 and 45.2 km$^2$/year for the period from 2005 to 2015. In contrast, the rate of accretion increased slightly to 33.8 $km^2$/year for the period from 1995 to 2005 and 34.6 $km^2$/year for the period from 2005 to 2015. The net balance of land for this coastal zone indicates the losses of 44 $km^2$ and 38 $km^2$ of land for the periods from 1985 to1995 and 1995 to 2005 respectively. This study shows a loss of 106 $km^2$ of land for the period from 2005 to 2015. The important outcome of the analysis shows a loss of 150 $km^2$ of land (5 $km^2$ annual average) in this zone for the total period from 1985 to 2015.

The rates of both erosion and accretion were found as higher for the three periods in the central zone of the coast (Table 2.5.5a) than the western and eastern coastal zones. However, the rates did not vary extensively for the three periods. The variations of the amount of annual average land gained were much lesser, where the results showed 14.7 $km^2$, 14.1 $km^2$ and 12.3 $km^2$ of land lost for these periods: 1985 to 1995, 1995 to 2005 and 2005 to 2015 respectively. This analysis found a net 13.7 $km^2$ annual average gain of land in the central zone for the total period from 1985 to 2015.

Table 2.5.5a - Patterns of erosion and accretion in the central coastal zone. The net balance shows a constant gain of land that was mounted to 411 $km^2$ of land for the total period from 1985 to 2015.

| Duration | Erosion | | Accretion | | Net Balance | Annual Average |
|---|---|---|---|---|---|---|
| | Total ($km^2$) | Rate ($km^2$/y) | Total ($km^2$) | Rate ($km^2$/y) | Land ($km^2$) | Land ($km^2$) |
| 1985-1995 | 555 | 55.5 | 702 | 70.2 | (+) 147 | (+) 14.7 |
| 1995-2005 | 709 | 70.9 | 850 | 85.0 | (+) 141 | (+) 14.1 |
| 2005-2015 | 623 | 62.3 | 746 | 74.6 | (+) 123 | (+) 12.3 |
| 1985-2015 | 885 | 29.5 | 1296 | 43.2 | (+) 411 | (+) 13.7 |

Note: (+) indicates the gain and (-) indicates the loss of land

The rate of erosion in the eastern coastal zone was 6.3 $km^2$/year for the period ranging from 1985 to 1995 in comparison with the rate of 8.8 $km^2$/year of accreted area for the same period. That means, the net balance of land was a gain of 25 $km^2$ of land (2.5 $km^2$ annual average) for the mentioned period. The rate of erosion for the period from 1995 to 2005 was 3.5 $km^2$/year higher than the previous period which was higher than the rate of accretion (9.6 $km^2$/y) for the same period. The results display a sharp margin of 2 km² net loss of land (0.2 km² annual average) for the period ranging from 1995 to 2005. The rate of erosion (11.4 km²/y) was higher for the period ranging from 2005 to 2015 than the previous periods. The ultimate result was the loss of 36 km² of land in this zone of the coast for the same period. The net balance shows a loss of 24 km² of land (0.8 km² annual average) for the total period from 1985 to 2015 in this eastern coastal zone of the country.

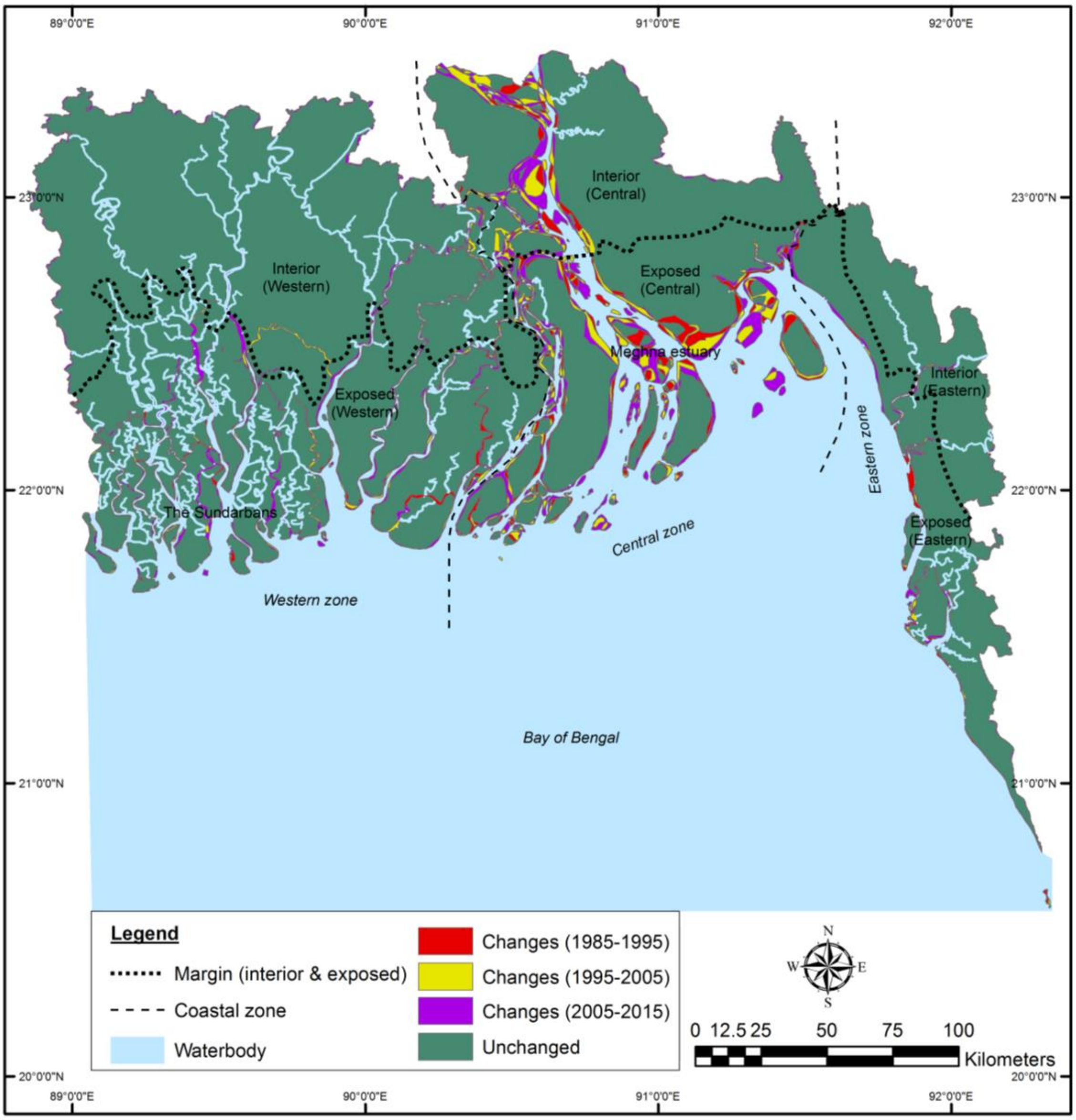

Figure 2.5.4b - Periodic changes of lands from 1985- 2015 in the coastal area of the country. The changes in the map indicated both erosion and accretion for the total period.

An overall representation of the rates of erosion and accretion for the periods can be found in the figures (Figure 2.5.4b and Figure 2.5.5a), where higher rates of both erosion and accretion in the central zone of the coast were observed in comparison with other zones. Both the rates of erosion and accretion did not consistently exhibit an increase or decrease, instead, they varied over different time periods. This indicates a dynamic nature of land existed in the coastal area of the country.

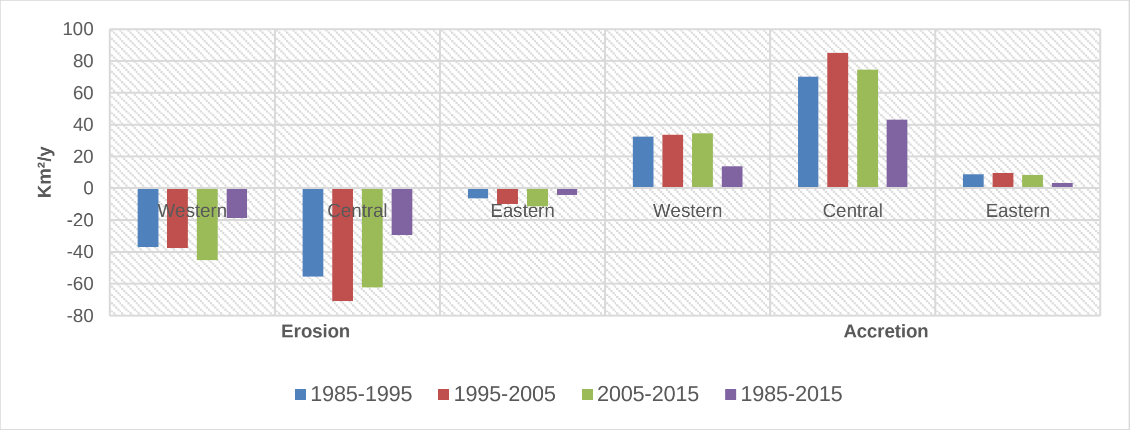

Figure 2.5.5a - Zone-wise rates of erosion and accretion for different periods in the coastal area of the country. The figure indicates high rates of both erosion and accretion in the central coastal zone. Moreover, the changes in land in the western coastal zone were comparatively higher than the eastern coastal zone.

### 2.5.6 Accuracy of satellite images

The identified categories of eroded and accreted lands were matched with the reference data. While matching with the topographical maps collected from Survey of Bangladesh, an overall accuracy of 0.873 (87%) was found for 1985. An almost similar accuracy of 0.894 (89%) was obtained for 1995 that matched with the maps collected from the Local Government and Engineering Department (LGED) of Bangladesh. Overall, an accuracy of 0.961 (96%) and 0.982 (98%) were acquired for 2005 and 2015 respectively, both these were much more accurate as compared with those obtained for 1985 and 1995. All the results have met the minimum standard of 85% accuracy as suggested by the U.S. Geological Survey (Anderson, 1976).

### 2.5.7 Policy relevance of coastal land dynamics

Since 1970s, the Government of Bangladesh (GoB) has been concerned on the issues of coastal land dynamics and has formulated many policies that are relevant to the management of dynamic coastal lands in Bangladesh (Figure 2.5.7a). Because of the lack of an integrated coastal policy, a number of area-specific plans and initiatives relevant to coastal land dynamics such as Off-Shore Islands Development Board (1977–1982), UN/ESCAP-GoB Coastal Environment Management Plan for Bangladesh (1987) and National Capacity Building Plan for ICZM (1997) were implemented during different periods. The aforementioned plans and initiatives were acted as the foundation of an Integrated Coastal Zone Management (ICZM) plan initiated in 1999. The principles of ICZM approach have managed to reinforce the coastal development and coastal defence strategy of the Government of Bangladesh (MoWR, 2005; Water Resources Planning Organization [WARPO], 2005). Before the adoption of ICZM in 1999 as a separate policy approach, the Government made several efforts to protect the coastal area from erosion and to rehabilitate the victims of erosion under the framework of Comprehensive Disaster Management Plan (CDMP) (Iftekhar, 2006).

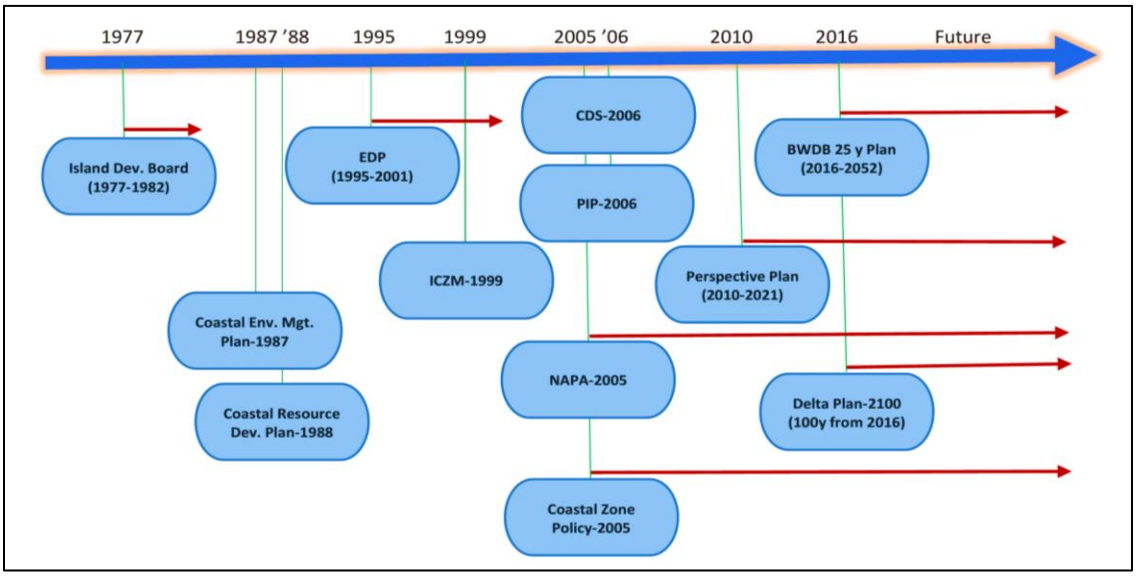

Figure 2.5.7a - Development of coastal policy framework in Bangladesh. Except for Delta Plan 2100 and BWDB 25 years plan, all other previous plans of the government relevant to coastal management were executed for short-time periods. [Data source: MoWR, 2006; CEGIS, 2009; BWDB, 2016; MoEF, 2016]

The formulation and adoption of Coastal Zone Policy (CZP) in 2005 has been a major step forward towards the proper implementation of ICZM plan for coastal land dynamics. In the Coastal Zone Policy, coastal erosion is being regarded as a combined natural and human-induced hazard along with other disasters, which has adverse effects on the lives and livelihood of people living in the area. The framework of the coastal zone policy includes different issues under eight broad headings where the issues relevant to coastal land dynamics such as erosion, accretion, land reclamation, rehabilitation, afforestation, land re-distribution have been outlined. Along with the policy, the formulation of Coastal Development Strategies (CDS) in 2006 can be regarded as a linking pin (PDO-ICZM, 2006) between the goals of Coastal Zone Policy and the concrete interventions. The CDS has prioritised different issues of land dynamics in the coastal areas. The optimum use of coastal land, balanced reclamation of new lands and planned and proper distribution of newly emerged lands to the landless and marginal people under existing land use policy have been emphasized in the CDS. However, the issues of land dynamics have also been given priority in the existing 20 concept notes prepared for the Priority Investment Program (PIP) of the government.

Along with different coastal policies, the issues of coastal land dynamics are being emphasized in different sectoral policies formulated by different ministries of the government. The country's Forest Policy (1994), National Fish Policy (1998), National Water Policy (NWPo) in 1999 (Mustafa, 2002; Islam and Koudstaal, 2003), National Land Use Policy (NLUPo) in 2001 (Islam, 2006), Draft Shrimp Strategy (2004), Agricultural Strategic Plan (2002-2006), National Agriculture Policy (2013) and resettlement and rehabilitation policy (Mainuddin et al., 2011; Ishtiaque and Chhetri, 2016) have been prepared for different periods to address the issues related to coastal land dynamics of the country. The issues of coastal land dynamics have also been reflected in different plans and strategies of the government. Coastal issues are emphasized in the revised 'National Strategy for Accelerated Poverty Reduction' in 2009. Under four strategic goals, the strategic paper identified erosion control, water resource management, land reclamation, *char* (newly accreted land) development, afforestation and land zoning for the coastal areas of the country.

Currently, the government is trying to address the issues of coastal land erosion and land management under different long-term strategies and plans. The 'Perspective Plan of Bangladesh' (2010-2021) is prepared for the articulation of development visions of the government where long-term strategies relevant to coastal development have been given emphasis. The strategies include coastal water resources management, operation and maintenance of embankments and polders along with the issues of land reclamation. The 'Delta Plan 2100' is a long-term plan covering the duration between 50 to 100 years. Special emphasis pertaining to the issues of coastal land erosion, coastal agricultural land use and polder management along with other 16 thematic areas of concern has been placed under this plan.

## 2.6 Discussion

The dynamic nature of coastal land identified by this study for different time-periods might be the results of a number of causes. These causes can be grouped into two broad headings: natural causes (such as sea level rise, variability in sediment supply, excessive rainfall, wave actions, prevailing south-western monsoon wind), and human-induced causes (such as removal of subsurface resources, deforestation, reduction of sediment supplies to the littoral zone) (Krantz, 1999). A simplified relationship of the causes of land dynamics for the periods studied is presented in the figure (Figure 2.6a).

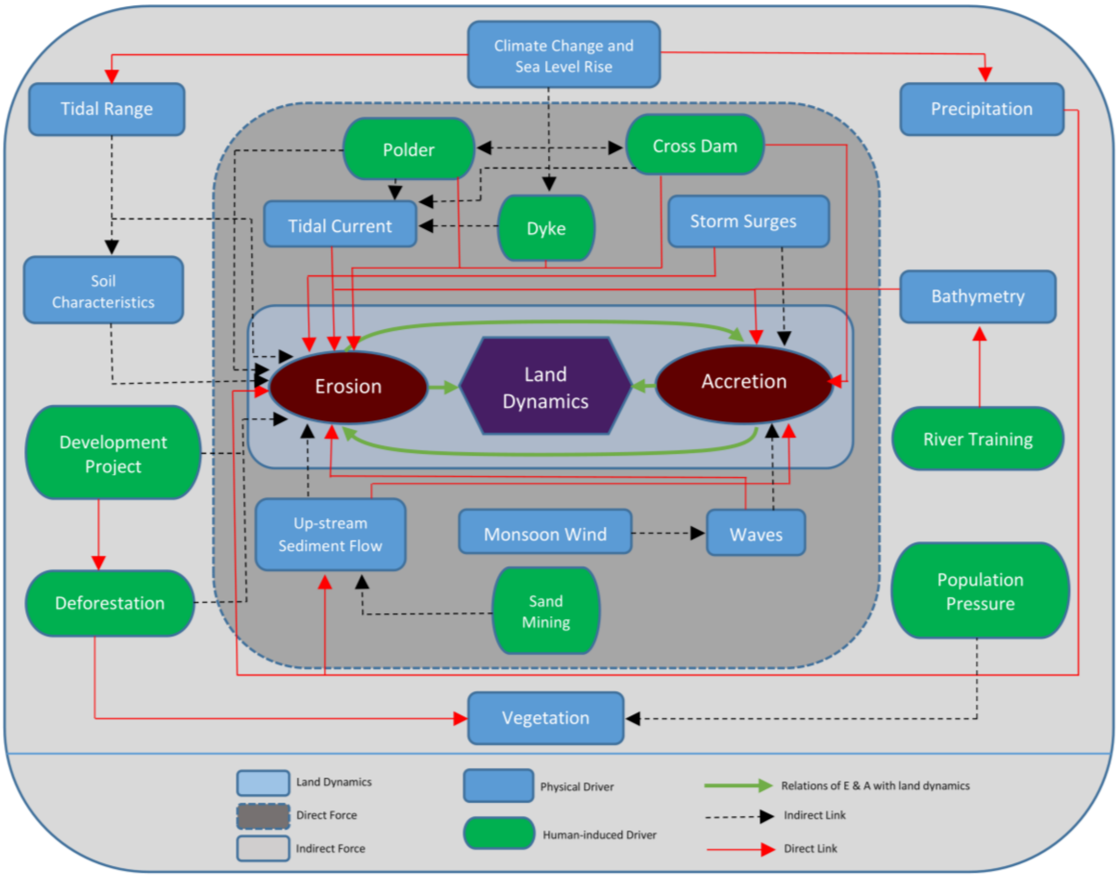

Figure 2.6a - Influence and relationships of the drivers of coastal land dynamics in Bangladesh. Several human-induced factors such as polder, cross-dam and dyke have direct influences to reduce erosion whereas, tidal currents, storm surges and waves are key direct drivers of erosion in the area. Moreover, the indirect impacts of climate change exert considerable influences on the dynamic nature of land in the coastal area.

The variation in magnitude of erosion and accretion in different parts of the coastal area depends on the different grades of vegetation cover, the variation of forces of ebb-tide currents, tidal bores, variation in amount of water discharges from upstream rivers, beach slope gradient, soil compaction and the extent of human interventions (Krantz, 1999). Hence, this study attempted to identify the causes of land dynamics based on the three coastal zones of the area studied (Table 2.6a). The study found very less morphological changes (except some small amounts of local erosion) in the western zone as compared to the estuarine part of the coast (Figure 2.5.4a). The reason behind this comparative lower rate of erosion in this zone could be due to the existence of mangrove vegetation that has acted as an active force of accretion through a strong interrelationship with the tide and river flow (Warrick and Ahmad, 1996). It has also created barriers to storm surges originated from tropical cyclones, and these barriers also acted as effective fences against the actions of waves (Umitsu, 1997). The likely causes of lower rates of changes in the western zone during the period from 1985 to 1995 were due to the lesser occurrences of tropical cyclones in the Bay of Bengal region and consequent lower degree of wave actions in the zone. On the contrary, an explanation on the rising rate of erosion in this coastal zone might be the devastating impact of the tropical cyclone ‘Sidr’ in 2007 that surpassed the rate of accretion during recent times (Sarwar and Woodroffe, 2013).

The analysis shows that the central coastal area of the country was comparatively more dynamic (Table 2.5.5a) than other coastal zones. The reason behind this higher rate of erosion and accretion could be the results of high rate of sediment supply (Barua, 1997), ebb-tide currents (Brammer, 2014), bathymetry (Mikhailov and Dotsenko 2007), high rate of river water discharges (Ali, 1999; Shamsuddoha and Chowdhury, 2007), soft and unconsolidated soils, wave actions etc. (Parvin et al., 2008; Masatomo, 2009; Hossain, 2012). The force of ebb-tide currents in estuarine channels was the dominating factor (Brammer, 2014) that affected in the higher rate of land dynamics in this zone. Tidal motions have also greatly influenced the movements of water in this central coastal zone which was affected by the refraction of the incoming tidal wave from the Bay of Bengal (Barua, 1997). The swatch of no ground (submarine canyon) (Figure 2.3.1a) stimulated the refraction which has resulted in high tidal ranges on both sides of the canyon and low tidal ranges at the head of the canyon. In the Sandwip and Hatiya Channel tides, the funnelling effect was highly visible. During spring tides, tidal current is observed around 3 m/sec in

Sandwip and Hatiya channels (Barua, 1997), created tidal bores in areas north of Sandwip Island which then merged with Hatiya channel resulting in high rate of erosion in both the islands. With these, the Bay of Bengal drained a combined discharge of the Ganges, Bhramaputra and Meghna rivers amounting an average of up to 35,000 $m^3/s$ which accelerated the rate of erosion and accretion in the central coastal zone (Krantz, 1999).

A crucial assessment was found for the central coastal zone where constant gains of lands were observed for the three periods. Brammer (2014) identified a net gain of 451 $km^2$ of land (19.6 $km^2$ annual average) for the Meghna estuary area by comparing two satellite images collected for 1984 and 2007. Similarly, the present study demonstrates a net gain of 411 $km^2$ of land (13.7 $km^2$ annual average) in the central Meghna estuarine coast. Although the results of the present study for the central zone are very close to the results found by Brammer (2014), the present study used multi-temporal satellite images and hence obtained results which are thought to be more precise and very much closer to the actual net gain. One of the important reasons contributing to this highly dynamic nature of land can be observed in the central coastal zone, which could be due to the frequent occurrences of tropical cyclones that hit these islands at the first instance, followed by the mainland. The funnel-shaped Bay of Bengal intensified cyclones and associated storm surges in the coastal area (Rabbani et al., 2010). During the period from 1584 to 2009, 157 recorded cyclones and cyclone induced storm surges passed over the coastal area of Bangladesh (Khan, 2012). The Meghna estuary suffered from most severe tropical cyclones and storm surges (Parvin et al., 2008) which has substantially influenced on the changing shapes of the islands located in the central coastal zone during the periods studied. Another reason behind these high rates of both erosion and accretion found in the central zone could be the action of tidal waves. The tidal waves from the Indian Ocean travel fast through the depth of the Bay of Bengal and the shallow area in front of the delta (Krantz, 1999), which continuously hit the land areas and cause erosion in one place and subsequent accretion in another place of the central coastal zone.

Table 2.6a - Major drivers of land dynamics in the coastal zones (including the islands). The table was prepared based on an in-depth review of literature discussed in this section. This gives an overview of major drivers of land dynamics that identified both physical and human-induced drivers in the three coastal zones of the country.

| Major Drivers of change | | Coastal Zone | | |
|---|---|---|---|---|
| | | Western | Central | Eastern |
| Physical drivers of change | Astronomical tides | ⬜ | 🟨 | 🟥 |
| | Wave action | 🟥 | 🟥 | ⬜ |
| | Variation in tidal range | 🟥 | 🟥 | ⬜ |
| | River discharge | 🟦 | 🟥 | ⬜ |
| | Mangrove vegetation | 🟦 | ⬜ | ⬜ |
| | Monsoon wind | 🟥 | 🟥 | ⬜ |
| | Bathymetry | 🟨 | 🟨 | ⬜ |
| | Circulation of residual flow | ⬜ | 🟨 | ⬜ |
| | Soil characteristics | 🟨 | 🟨 | 🟨 |
| | Storm surges | 🟥 | 🟥 | 🟥 |
| | Rainfall | 🟥 | 🟥 | 🟥 |
| Human induced drivers of change | Polder | 🟥 | ⬜ | ⬜ |
| | Destruction of forest | 🟥 | 🟥 | ⬜ |
| | Dykes | ⬜ | 🟨 | ⬜ |
| | Cross dam | ⬜ | 🟨 | ⬜ |
| | River training | 🟥 | 🟨 | ⬜ |
| | Sand mining | ⬜ | 🟨 | ⬜ |
| | Development projects | 🟨 | 🟨 | ⬜ |

Legend: Erosion 🟥 Accretion 🟦 Both Ero. & Acc. 🟨 No impact ⬜

The islands were found as extremely dynamic, particularly in the Meghna estuary coastal area. Although there is a substantial amount of land gained, there is also a considerable amount of land lost in the islands of the estuary. These could be the results of the dynamic nature of the estuarine and offshore islands in the central coastal zone due to the high rate of water discharge from the rivers and the anti-clockwise circulation of tides in the estuary (Sarwar and Woodroffe, 2013). The present study shows that the existing islands such as Sandwip, Hatiya and Bhola exhibited a significant rate of erosion, which then contributed to the development of new islands such as Urir Char, Jahajir char and other small islands in the estuary (Figure 2.3.1a). A large mass of land named Jahajir Char has developed during recent times between 2007 and 2013. Rapid and considerable changes in land areas were observed for the case of Sandwip, Hatiya and Bhola islands. Another dynamic island observed was Hatiya, situated in the Meghna estuary, where the rate of erosion has been reported at 400 metres/year. The reason behind the rapid changes of land areas in the estuarine islands could be the soft and unconsolidated silt and clay sediment (Masatomo, 2009) of the islands.

The present study shows that the eastern coastal zone is comparatively less dynamic (i.e. a rate of 6.0 $km^2$ erosion and 3.3 $km^2$ accretion per year from 1985 to 2015) than the central (i.e. a rate of 29.5 $km^2$ erosion and 43.2 $km^2$ accretion per year from 1985 to 2015) and western (i.e. a rate of 18.8 $km^2$ erosion and 13.8 $km^2$ accretion per year from 1985 to 2015) coastal zones. The probable reason could be due to the flat and unbroken coast (Huq et al., 1999) and the northerly transportation of sediments along this coastal zone (Barua et al., 1994). Although the rates of changes were very low in comparison with the other zones, the rates of erosion were higher than the rate of accretion in the zone for all of the periods except from 1985 to 1995 (Figure 2.5.5a). The process of erosion could be accelerated in this coastal zone by the anti-clockwise circulation of tidal current that passes through the Sandwip channel. The excessive amount of rainfall due to rising temperature could also be the probable reason for erosion in this zone whereby the mean annual rainfall ranges between 1750 mm in the north-western coast and >3000 mm in the south-eastern coast of the country (Krantz, 1999). The net balance of land for this coastal zone showed a loss of 24 $km^2$ of land (0.8 $km^2$ annual average) during the total period from 1985 to 2015.

To protect newly accreted lands in the coastal area from erosion, government initiated a number of projects and schemes such as coastal afforestation and polder project (1966), Char Development and Resettlement Project (1994), Coastal Embankment Rehabilitation Project (1995), land reclamation projects, Meghna Estuary Study (1986 to 1994), and Estuary Development Programme (1995 to 2001) (Islam, 2006; MoWR, 2006; Ali et al., 2007; Parvin et al., 2008). Although the goals of the policies, plans, strategies and projects regarding coastal land dynamics are not fully implemented, both positive and negative impacts are visible in the coastal area of the country. For instance, the results of this study demonstrate a slightly higher rate of 111.5 $km^2$/year accretion for the period from 1985 to 1995 in comparison with the erosion of 98.7 $km^2$/year for the entire coastal area of the country. The likely cause of this higher rate of accretion could be the reclamation of a considerable portion of landmass at the lower Meghna estuary. This might be the implication of the coastal policy under which a number of cross dams were being built in the Meghna river near Laksmipur, Noakhali and Feni districts by Bangladesh Water Development Board (BWDB). The

Meghna-1 cross dam project in 1957 and the Meghna-2 cross dam project (Figure 6.3c) in 1964 reclaimed a total 300 km$^2$ and 600 km$^2$ land areas that have connected Ramgoti island with the mainland of Noakhali district (Figure 2.3.1a). The Muhuri river cross dam project also yielded a total of 500 km$^2$ of land near Feni district (Khan, 2008). The polder project initiated by the government during the 1970s and 1980s can be also treated as equally important human intervention in land dynamics in the coastal area. Several new offshore islands have emerged during that period, namely the Dhal Char, Char Jonak, Nijhum Dwip and Sona Char and some other unnamed small islands (Figure 2.3.1a). As a probable consequence of the cross dam project, a substantial amount of lands accreted (i.e. 88 km$^2$ of land accreted) during 1985 to 1995 time period in the eastern coastal zone of the country. In contrast, the changes in land areas in the western zone were very low during that period (i.e. 44 km$^2$ net loss of land during 1985 to 1995 period) as compared with the central zone (i.e. 147 km$^2$ net gain of land during 1985 to 1995 period). However, followed by the implementation of the cross dams and polders, a noticeable portion of lands were eroded as well at Bhatiari, Uttar Jaldi and Moheshkhali in the eastern coast during the period from 1985 to 1995 (Figure 2.3.1a). The northern and eastern coasts of Hatiya Island also showed a considerable amount of erosion during this period. Similarly, the eastern coast of Bhola Island showed erosion of land in the areas of Borhanuddin and Tazumuddin sub-districts (Figure 2.3.1a). A sporadic situation was also observed in the Sandwip Island during that period, where, a gain of land was identified in the northern front and a loss of land was detected in the southern front of the island.

The policies and strategies also emphasized on regular maintenance of sea dykes as the first line of defence from storm surges under the existing policy framework. This intervention had great implications for the protection of coastal lands for the period from 1995 to 2005, identical to the previous period from 1985 to 1995. Like before, more erosion and accretion were observed in the central coastal area during the period from 1995 to 2005 yet, the net balance of land yielded 101 km$^2$ of land (10.1 km$^2$ annual average) during the same period. Additionally, during this period, the policy encouraged the inhabitants to engage in social forestry and other forms of plantations in existing and newly accreted coastal lands (Char Development and Settlement Project [CDSP], 2005). This policy guideline of social forestry could ultimately be beneficial for the protection of coastal lands from erosion and the settlement of newly accreted lands in the coastal area. The coastal afforestation project of the government with a view to protecting coastal lands from erosion brought effective results. Forest department claimed 142,835 hectares of mangroves during the period from 1960 to 2000 through implementing a number of afforestation projects (MoEF, 2007). The pilot mangrove afforestation project afforested 192,395.24 hectares of mangrove, 8689.53 hectares of non-mangrove, 2872.88 hectares Nipa, 10.0 hectares Coconut, 40.0 hectares Arica Palm, 280.0 hectares Bamboo and Cane and 12,127.13 km of strip plantations in Chittagong, Cox's Bazar (south) and Feni areas of the coastal zones.

The coastal zone policy formulated in 2005, but most of the goals still remain incomplete. The Coastal Zone Policy (CZP) emphasized the reclamation of new lands in the coastal area. The ultimate result of land reclamation plan has yielded about 100,000 hectares of land in the Meghna estuary area during the last half century (GoB, 2006). However, this study found an increasing rate of erosion over accretion for the period covering 2005 to 2015. Currently, the government plans to conduct another major land reclamation project in the Meghna estuary by connecting Sandwip Island and Urir Char with Noakhali mainland. Moreover, Bangladesh Water Development Board (BWDB) aimed at attaining its 25 years future plan from 2016 that includes strategies to reclaim new lands in the coastal area (BWDB, 2016).

Instead of having a sound number of coastal policies, strategies, plans and projects of the government, this research identified some considerable gaps in the existing policies in managing coastal land dynamics (erosion and accretion) of the country. First and foremost, the policies, strategies and plans formulated were made without any detailed and comprehensive study on the dynamic nature of land for the entire coastal area. A study named Meghna Estuary Study (1986-1994) that has been conducted by the government, only covers a specific local area and does not include the entire coastal area of the country. In relation to this, the government of Bangladesh needs to pay closer attention to the proper implementation of land reclamation projects. For instance, the current study identified that the implementation of Cross Dam 1 and Cross Dam 2 projects by the government has yielded a substantial amount of land near Ramgoti and Noakhali coastal areas (Figure 2.3.1a), nevertheless the government should also be held responsible for the extensive erosion that has occurred in Hatiya and Bhola islands. This is due to the fact that the two cross dam projects were conducted by way of shifting the flows of water from the eastern to the western Meghna and Shahbazpur channels (Figure 2.5.1a and Figure 2.5.2a), which has brought to the massive erosion in the two islands mentioned. Moreover, most of the coastal policies are suitable for a ‘static’ system rather than a complex coastal system that exhibits a dynamic interplay between physical and human forces of change. Since the changes in land areas in one coastal zone could affect the other, land reclamation projects of the government need to be implemented based on a complete feasibility study for the entire coastal area. To address this shift of channels, coastal managers and policymakers need to address the physical behaviour of the coast before implementing any land reclamation projects in the coastal area of the country.

Different ministries such as Ministry of Water Resources (MoWR), Ministry of Environment and Forest (MoEF), Ministry of Local Government Rural Development and Cooperatives (MoLGRDC) have identified different issues of coastal land dynamics from different perspectives (Parvin et al., 2008). However, a proper integration of activities among and between ministries is vital for a better management of dynamic coastal land of the country and hence, the current research suggests an indicative institutional arrangement which is shown in the figure (Figure 2.6b). The current research suggests that the ministries, in particular, Ministry of Water Resources, Ministry of Land, Ministry of Environment and Forest and Ministry of Agriculture might implement specific policies through different departments, agencies and NGOs followed by the guidelines of the Ministry of Planning. Constant monitoring of the dynamic nature of land by applying GIS and remote sensing techniques could be a viable management approach for this purpose.

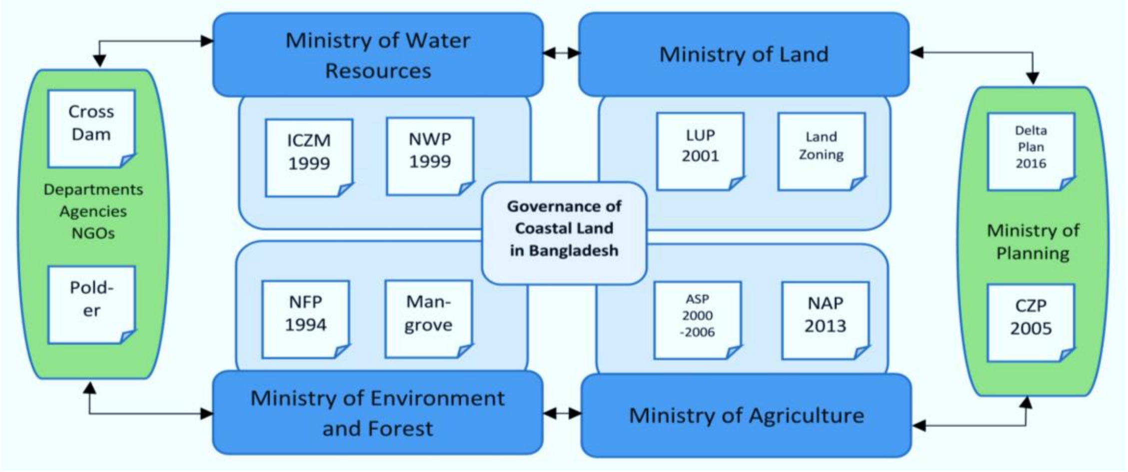

Figure 2.6b – An indicative institutional arrangement in implementing coastal policies in Bangladesh. The ministries and their affiliated departments and institutions can play a major role to implement the policies and plans formulated by the ministry of planning in which, a proper coordination between the ministries is vital to formulate these policies and plans.

Beside the mentioned issues, the policies lack in integrating the probable effects of climate change and associated sea level rise on coastal land dynamics properly, which overwhelmed the other issues. More importantly, the policies need to incorporate the likely impacts of future scenarios of water discharge, wave dynamics, and rainfall etc. into its current policy framework to better manage coastal land dynamics. Given that the increase of sea level remains one of the main driving forces of land dynamics in coastal areas of Bangladesh, any increase in sea level could change the horizontal configuration of any coastline through the process of erosion and accretion (Warrick and Ahmad, 1996). This may lead to long-term erosion of coastal lands, and a counterbalance to the previous erosion might be achieved with the new accretion (Fitzgerald et al., 2008). For instance, a 1.5 metre rise in sea level may inundate 22,000 km$^2$ of coastal land in Bangladesh (Fitzgerald et al., 2008). These newly inundated lands would be highly affected by future wave actions. Moreover, the coastlines and the river mouths have already been pushed in by the rise of mean sea level. This might result in the alteration of flow of discharge and consequent erosion in the coastal areas. Additionally, the frequent occurrence of tropical cyclones as a probable result of climate change in the Bay of Bengal is a common phenomenon which creates storm surges in the coastal area. This phenomenon in the coastal area could further be increased by climate change, global warming and associated sea level rise (Huq et al., 1999; Davis et al., 2018).

## 2.7 Conclusion and recommendations for further work

This study has shed light on the application of GIS and remote sensing techniques for assessing the dynamic nature of land in the coastal area of the country and hence, analysed the changing pattern of coastal land in an efficient manner. The current research emphasises on the spatial (three coastal zones) and temporal (past thirty years from 1985 to 2015) patterns of erosion and accretion which evaluate multi-temporal satellite images that cover the entire coastal area of the country. Both the erosion and accretion rates do not produce a consistent increase or decrease but varied over different time periods which indicates the dynamic nature of land in the coastal area of the country. Annual average rates of 98.7 $km^2$, 118.3 $km^2$ and 119.4 $km^2$ erosion were observed for 1985-1995, 1995-2005 and 2005-2015 time-periods respectively. Similarly, the annual average rates of accretion for the same periods were very close to the rates of erosion: 111.5 $km^2$, 128.4 $km^2$ and 117.5 $km^2$ respectively. However, several factors are associated with the dynamic nature of land in the area among which river water discharge in the Meghna estuary, prevailing monsoon wind and associated actions of waves, soft and unconsolidated soils, cross-dams, polders, deforestation are key physical and human-induced causes. The results demonstrate that both these rates are higher in the central zone of the coast, as compared with the western and eastern zones.

Because of the changes in natural morphological pattern, coastal planning and coastal land management have received attention by the Government of Bangladesh. A number of policies, strategies and, plans have so far been adopted by the government. The adoption of the Land Use Policy (2001), Coastal Zone Policy (2005), Coastal Development Strategy (2006) and the Delta Plan 2100 (under formulation) are some of the milestone achievements. In recent years, various NGOs have also been engaged in erosion induced vulnerability work. Nonetheless, the policies, strategies, plans and projects have some noticeable shortcomings which need to be reviewed by the government. Both physical and human-induced drivers of coastal land dynamics need to be addressed for a viable policy framework. The priority, however, needs to be given on understanding the physical susceptibility of the coast before formulating any further policies. Hence, the study recommends the consideration of the trends of physical behaviour of the coastal lands for taking specific measures options. For instance, the soft defence measures such as polder might be effective for the eastern and western coastal zones but not highly suitable for the most dynamic central coastal zone of the country. Instead, some hard defence structures, such as embankment, dyke etc. might be suitable for that zone.

In conclusion, this study recommends the integration of future policy issues along with the future scenarios of hydrodynamics, sea levels, coupled with the GIS and remote sensing techniques for further analysis of land dynamics and land management in the area. Future scenarios of land susceptibility to erosion also need to be generated for the coastal area. This will require a proper assessment of likely impacts of hydro-climatic changes on erosion susceptibility in the area in future. Population changes, environmental pollution and future infrastructural development are additional factors to be considered when devising new policy relevant to coastal land dynamics of the country. The current research offers a comprehensive analysis of the dynamic nature of land for the past thirty years that could be used by the coastal managers and policymakers for taking effective measures to address the issues. The results of this study could also be a vital input for the policy on rehabilitation and resettlement of erosion victims. The assessment could be supportive to formulate century-long Delta Plan-2100 as well as to update the existing coastal zone policy formulated by the government in 2005.

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# Chapter 3: Modelling land susceptibility to erosion in the coastal area of Bangladesh: A geospatial approach

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Key words: coast; erosion; LSCE; susceptibility.

## 3.1 Abstract

This research aimed to develop a widely applicable raster GIS-based model for analysing susceptibility of coastal lands to erosion. The model, Land Susceptibility to Coastal Erosion (LSCE), was applied to the coastal area of Bangladesh as a case study. This study included three coastal zones (western, central and eastern) that cover the entire coastal area of the country. The outputs of the model comprised physical susceptibility of the coastal lands to erosion according to five susceptibility classes. The overall results demonstrate that out of the entire coastal area about 0.59% (266.32 km$^2$) and 0.02% (10.01 km$^2$) of the coastal lands exhibit high and very high susceptibility to erosion, respectively. These make 276.33 km$^2$ in total as being highly susceptible to erosion, which is noteworthy for the densely populated coastal area of the country. The remaining 5.49%, 20.56% and 73.34% of lands were identified as having moderate, low and very low susceptibility to erosion, respectively. The developed model is highly suitable for addressing the impacts of hydro-climatic parameters on susceptibility to coastal erosion. The influences of hydro-climatic parameters on seasonal variation of erosion susceptibility in the coastal area were identified and mapped in the present study under seasonal assessment of land susceptibility to erosion. The outputs were then validated by developing an inventory map and analysing the independent historical observations by using 'degree of fit' curves. The LSCE model could be useful for coastal researchers in assessing erosion susceptibility of dynamic coastal lands around the world.

## 3.2 Introduction

Coastal areas form a dynamic part of the world and act as a multi-functional complex system (Ramieri et al., 2011). Due to climate change, sea-level rise and extreme weather events, coastal systems are continuously being affected by natural hazards and respond in different ways (Balica et al., 2012). Coastal erosion is being treated as a serious morpho-dynamic hazard in coastal areas around the world (Addo et al., 2008). The coastal area of Bangladesh is particularly dynamic having high rates of erosion and accretion of lands (Ahmed et al., 2018). However, the assessment of physical susceptibility to erosion is of substantial importance in managing coastal land and formulating policies and mitigation plans (Cai et al., 2016).

Global (Gornitz, 1990; Klein and Nicholls, 1999), as well as regional (Bryan et al., 2001; Dawson et al., 2009) approaches, have been used widely for assessing coastal erosion (McLaughlin and Cooper, 2010). These approaches can be grouped into three main categories (Ramieri et al., 2011): Geographic Information System (GIS) based Decision Support Systems (e.g. DESYCO, DITTY-DSS), Dynamic Computer Modelling (e.g. DIVA, RACE, Delft3D, RegIS, SimCLIM), and index- or indicator-based methods (e.g. CVI, Composite Vulnerability Index, Multi-scale Coastal Vulnerability Index). Moreover, satellite images have been used that are convenient in identifying the pattern of land dynamics (area and rate of eroded and accreted lands) and useful for extracting information that can be of value in assessing coastal erosion. However, the approaches do not provide readily available information for erosion susceptibility and are not suitable for assessing the level of physical susceptibility of coastal lands to erosion (Ahmed et al., 2018) (discussed in chapter 1: section 1.2.5). Hence, it is imperative to develop models that incorporate both spatial and temporal aspects of land susceptibility to erosion (van Westen, 2000; Boori, 2010). The use of GIS in developing susceptibility models has already received much attention (Van Westen, 2000; Chung and Fabbri, 2003) and hence can be regarded as an important tool for such analysis (Chung and Fabbri, 2003). GIS can be an efficient way of analysing coastal land susceptibility by way of selecting parameters, assigning parameter weights, interpolating pixels and presenting maps under a model domain (Boori, 2010).

Assessment of erosion susceptibility at large spatial scales (global) is quite ineffective since coastal processes are complex, being highly influenced by local factors and requires a large amount of data in GIS-based models (Fitton et al., 2016). There are several GIS-based studies conducted on coastal erosion at regional and local scales (discussed in chapter 1: section 1.1.1; table 1.1.1a, b). For instance, White and El-Asmar (1999) used Thematic Mapper imagery to monitor the changing position of the shoreline of Nile delta. Shifeng et al. (2002) conducted a study on the dynamic nature of eight outlets in Pearl River estuary by using remote sensing techniques. The work of Azab and Noor (2003) identified the changes of shoreline for North Sinai coast by using remote sensing and Geographic Information System. Most of the studies, however, identified coastal erosion by lines in vector-based GIS model (Harvey and Woodroffe, 2008; Lins-de-Barros and Muehe, 2011). For example, the work of Lins-de-Barros and Muehe (2011) applied ‘smartline’ approach to identifying the shoreline erosion as a part of vulnerability assessment of a coastal segment of Rio de Janeiro state, Brazil. Similarly, the study by Fernandez-Nunez et al. (2015) used 'multipurpose' lines to identify the changes in the shoreline of the Andalusian coast of Spain. The problem of dealing with vector-based outputs of coastal erosion is that the vector lines only represent the shorelines and exclude information on offshore and inland conditions (Fitton et al., 2016). Inland conditions are essential in assessing coastal susceptibility to erosion (Fitton et al., 2016). However, the assessment of both offshore and inland conditions of coastal land susceptibility to erosion is convenient to interpret by using a pixel (or cell) based GIS model.

The evaluation of physical elements (e.g. surface elevation, bathymetry, soil characteristics, geomorphic features etc.) is important in assessing erosion susceptibility (MPI, 2017). Additionally, hydro-climatic factors (e.g. water discharge, mean sea level, rainfall etc.) have substantial impacts on physical susceptibility to erosion and their influences are likely to increase in future (Warrick and Ahmad, 1996; Fitzgerald et al., 2008). However, existing physical conditions of any coastal system might exert substantial control over the impacts of hydro-climatic factors. For instance, geomorphic characteristics have a considerable influence on rapid runoff generation and movement of water through the drainage network in a coastal area (Naylor et al., 2017). Moreover, human interventions such as the construction of defence structures (e.g. revetment, polder), land reclamation and afforestation (e.g. mangrove plantation) have extensive impacts on the overall susceptibility of coastal lands to erosion (Hegde, 2010). As far as the authors are aware, a raster GIS-based study on assessing inland and offshore (i.e. islands) conditions of erosion susceptibility by addressing both physical elements and hydro-climatic conditions has not been done before. The studies conducted by McLaughlin and Cooper (2010) and Alves et al. (2011) emphasised tidal and wave heights as coastal forcing in classifying vulnerability of coastal lands by applying an index-based approach. The study of Fitton et al. (2016) dealt with a pixel-based GIS model in assessing coastal erosion susceptibility at a regional scale, but the study did not incorporate the impacts of hydro-climatic triggering factors in the assessment. However, considering the shortcomings of the above-mentioned literature, this study formulated the research question: how best to address the compelling factors in assessing land susceptibility to coastal erosion?

This research described herein developed a widely applicable raster GIS-based model, namely Land Susceptibility to Coastal Erosion (LSCE), to analyse coastal physical susceptibility to erosion. The current research is an improvement on previous methods in assessing land susceptibility to coastal erosion because of its inclusion of both physical elements and hydro-climatic factors in the assessment. Moreover, the developed model is highly suitable for addressing the impacts of hydro-climatic parameters on physical susceptibility to erosion and broadens the opportunity for predicting future land susceptibility to coastal erosion around the world by incorporating future scenarios of hydro-climatic factors in the model. The LSCE model is applied here for the coastal area of Bangladesh as a case study. Previous GIS-based studies have assessed shoreline retreat and the rate of erosion and accretion in the coastal area of Bangladesh and the Bay of Bengal region (discussed in chapter 1 and chapter 2). For instance, Shibly and Takewaka (2012) emphasized the estimation of land loss in the western coastal zone for the period from 1989 to 2010 by using remote sensing images. The work of Islam et al. (2013) focused on the stability of Kuakata coast of Bangladesh by using multi-temporal remote sensing images. However, the present research analysed the spatial (i.e. inland and offshore islands) and temporal (i.e. seasonal variations) aspects of existing land susceptibility to erosion in the study area. The research is also unique for the area in that it includes the seasonal impacts of hydro-climatic factors on physical susceptibility to erosion.

## 3.3 Methodology

### 3.3.1 Study area

To apply the LSCE model, this research considered the entire coastal lands of Bangladesh as a study area (Figure 3.3.1a). The total area is 47,200 km$^2$ (MoEF, 2007) that includes the lands (including islands), internal rivers, estuarine and nearshore water bodies. It accounts for 32% of the total area of the country (Islam, 2004). The coastal area can be divided into three zones: the western (27,150 km$^2$), central (12,040 km$^2$) and eastern (8,010 km$^2$) based on geomorphological characteristics (Shibly and Takewaka, 2012; MoEF, 2016). This study identified a total 45,220 km$^2$ of land area for assessment and excluded all types of water bodies from the analysis. Since the coastal area is a physical entity, the inland boundary was fixed based on both direct and indirect influences of water discharge from coastal rivers, wave actions, tidal movement and sea level rise (PDO-ICZMP, 2006; MoEF, 2016).

The physical and hydro-climatic settings of the coastal area are highly diverse. Most of the areas in the western and central coastal zones are low-lying, being at altitudes between 0 and 6 m, but the elevations in the eastern coastal zone range from 0 to 327 m above mean sea level (USGS, 2017). The average nearshore bathymetric depths vary from 0 to -45 m for the three coastal zones (Marine Geoscience Data System [MGDS], 2017). The Meghna estuary area, however, represents higher bathymetric depths comparing to other areas in the central coastal zone (Appendix C). Furthermore, the types of surface geology and geomorphic features are not uniform for the entire coastal area. The interior part is mostly formed by Pleistocene and Pliocene formations, deltaic silt and marsh clay and peat. The areas close to the Bay of Bengal are formed by estuarine deposits, Pleistocene and Neogene formations, tidal deltaic deposits and tidal muds. Most of the coastal soils (i.e. about 63%) are moderate to highly permeable. However, the hydro-climatic features of the area substantially vary between the zones and the seasons. The average discharge of 29.07 $m^3/s$ water from the coastal rivers during winter season reached as high as 65,396.12 $m^3/s$ during the monsoon season in 2015 (BWDB, 2016). In addition, seasonal variation in mean sea level in the coastal area is noticeable that ranges from 1.61 m during winter to 2.76 m during monsoon season (Bangladesh Inland Water Transport Authority [BIWTA], 2017; Permanent Solution for Mean Sea Level [PSMSL], 2017; University of Hawaii Sea Level Centre [UHSLC], 2017). The average rainfall in the area was recorded as 123 to 301 mm in 2015 but this amount of rainfall fluctuates between seasons (Bangladesh Meteorological Department [BMD], 2016). Seasonally, the lowest rainfall recorded during winter ranges from 10.22 to 16.79 mm, whereas highest rainfall occurred during monsoon ranges from 300 to 896 mm on average. The average wind speed in the area varied from 0.36 m/s during the post-monsoon to 3.84 m/s during the monsoon in 2015 (BMD, 2016). The south-asian monsoon winds dominate in the area in which approximately 37% and 31% (68% in total) winds blow from southwest and south directions respectively (BMD, 2016). Remaining 32% annual average winds blow from north, northwest and southeast directions. For instance, 45%, 54% and 53% of annual average winds blown over the Khulna, Barisal and Chittagong coastal areas, respectively, from south, southwest and southeast directions in 2015 (BMD, 2016; Global Wind Atlas [GWA], 2017). During pre-monsoon and monsoon seasons, strong winds blow from southwest and south directions respectively whereas, weak winds blow from north direction during winter season (Institute of Water and Flood Management [IWFM], 2012). Wind speeds during post-monsoon period are moderate and blow from lands (i.e. from northwest direction). Tides in this area are semi-diurnal (Islam et al., 2016). Tidal currents can be as fast as 3 m/s, as observed in Sandwip and Hatiya channels (Barua, 1997). However, the longshore currents travel anti-clockwise in the area and are influenced by tidal bores and waves (Krantz, 1999).

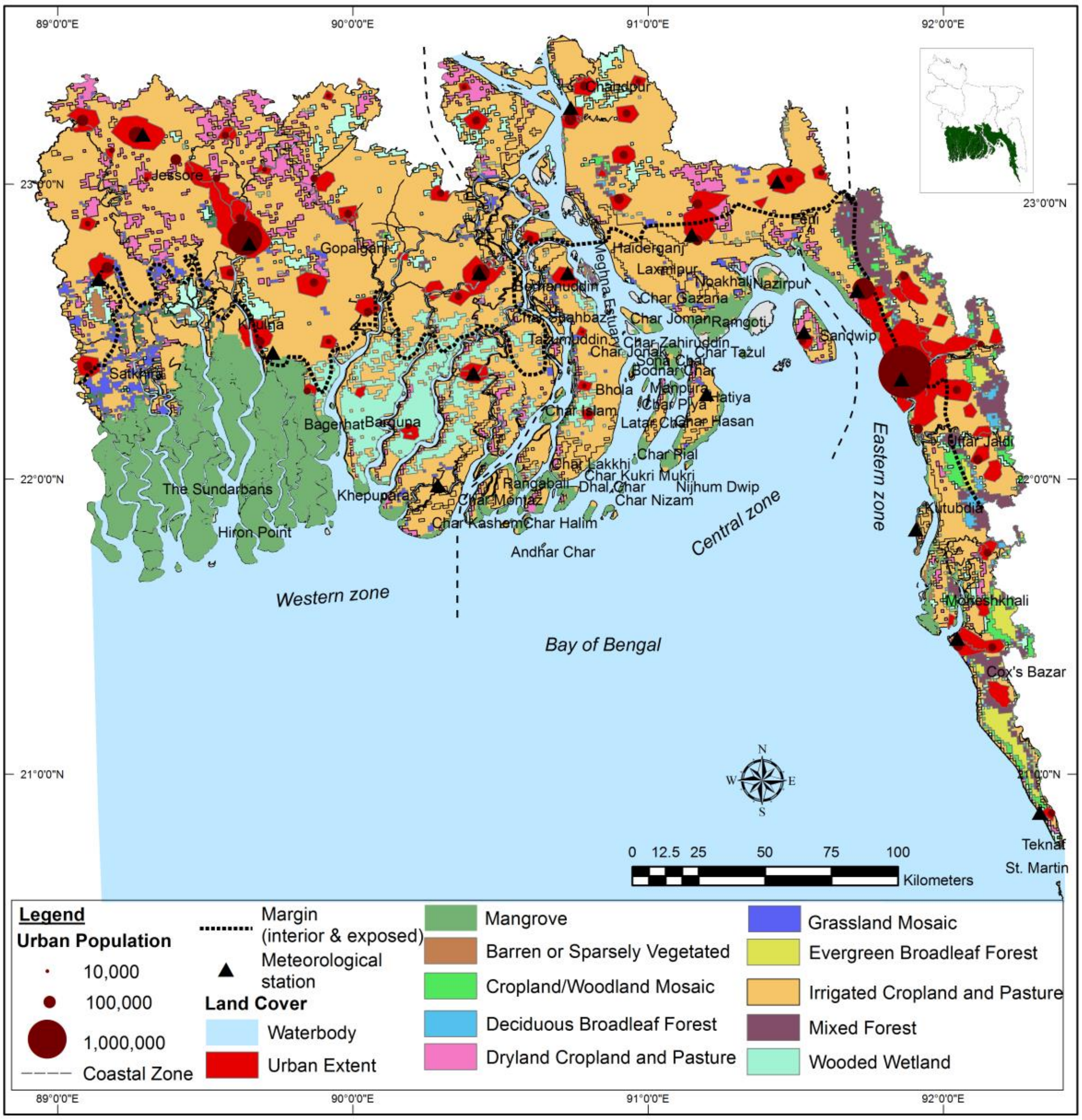

Figure 3.3.1a - The study area (coastal area of Bangladesh). The figure shows the presence of major land cover categories in the area. A large part of the western coastal zone is covered by mangrove vegetation. However, the urban areas and their population are noteworthy in the coastal area. [Data sources: BBS, 2015 (Urban population and urban extent); BMD, 2016 (meteorological station); MoEF, 2016 (coastal zones and margin between interior and exposed coast); FAO, 2018 (land cover)]

The selection of the study area is important from a risk management perspective. The population in the coastal area comprises about one-third of the total population of the country (Bangladesh Bureau of Statistics [BBS], 2015). The population in the area has increased from only 8.1 million a century earlier (WARPO, 2004) to about 50 million during recent times (BBS, 2015). Due to fertile lands and the abundance of livelihood options, this number is expected to be around 57.9 million by 2050 (Minar et al., 2013). The density of population varies between the coastal zones. The density varies from 688 to 1935 people/km$^2$ for the districts such as Chittagong, Feni, Chandpur, Cox's Bazar, Laxmipur and Noakhali located in the eastern and central coastal zones whereas, the western zone contains about 87 - 687 people/km$^2$ (Figure 3.3.1a) (BBS, 2011).

### 3.3.2 Model parameters

Since land susceptibility to coastal erosion is largely determined by predispositions, preparatory and triggering factors (Saunders and Glassey, 2007; MPI, 2017), this study identified nine parameters among which five are the underlying physical elements (which can be considered as predispositions): surface elevation, surface geology, bathymetry, soil permeability and distance from shoreline. The remaining four parameters are the hydro-climatic triggering factors: discharge of coastal river water, mean sea level, rainfall and wind speed and direction (Figure 3.3.2a). Moreover, this study addressed the role of preparatory factors on land susceptibility to coastal erosion. The preparatory factors are the actions and interventions that may place a land unit at a higher or lower likelihood of erosion (MPI, 2017). The study addressed two types of preparatory factors: natural (i.e. sedimentation) and human-induced (i.e. defence structures).

The model parameters were identified and selected through an in-depth review of relevant literature available for the study area. However, to select the model parameters, the present study justified the influence and interrelationships of the factors of land susceptibility to erosion in the coastal area. To do this, the study reviewed literature that is discussed in this section. It is recognised that higher surface elevations along with solid rock formations (Huq et al., 1999) and unbroken coast (Karim and Mimura, 2006) in the eastern coastal zone are less likely to erode compared to the western and central coastal zones. Previous studies (Sarker et al., 2011; Islam et al., 2016) suggest that the nearshore bathymetric depths have substantial influences on the pattern and rate of erosion in the coastal area. The pattern of sediment distribution in the area is largely influenced by the bathymetry and the forces of tides and waves (Palinkas et al., 2006; Bird, 2008). The study considered all the types of surface geology in which, major types of geomorphic features (e.g. sand dunes, tidal floodplains, estuarine floodplains, coastal plains, beaches, lagoons, inter-tidal wetlands etc.) and their influences on erosion susceptibility are evaluated (Table 3.3.2a). It is evident that the soft and unconsolidated silt and clay sediments quickly respond to the forces of coastal river water discharge in the area (Masatomo, 2009; SDC, 2010). The offshore islands in the coastal area are mostly formed of this type of sediments (Umitsu, 1997; Rabbani et al., 2010). Moreover, the permeability of water into the coastal soils is high. About 63 % of the coastal soils are inclined to moderate and rapid permeability classes among which about 94 % of the entire Meghna estuary area fall under moderate to rapid permeability classes (Bangladesh Agricultural Research Council [BARC], 2016).

The influences of hydro-climatic factors on erosion potential in the coastal area are noteworthy (Huq et al., 1999; Khan, 2012). For instance, discharge of water from the coastal rivers can be considered as an active driving force of erosion in the area (Ali et al., 2007; Islam, 2008; Taguchi et al., 2013). Besides, continuous wave action is one of the most important factors of erosion susceptibility especially, in the central coastal zone (Ahmed, 1999; Ali, 1999; Parvin et al., 2008). The prevailing southern and southwestern monsoon winds generate waves that largely affect the offshore islands located in the central coastal zone. This study evaluated the speed and directions of winds as a proxy for wave actions in the coastal area. Moreover, the rise of mean sea level in the Bay of Bengal region is evident (Regional Resources Centre for Asia and the Pacific [RRCAP], 2001; Unnikrishnan and Shankar, 2007; Smith, 2012; Brammer, 2014) that inundates new coastal lands and thus affects the lands by wave actions. The Ganges floodplains and islands in the Meghna estuary have the high potential to be affected by rising sea level in the coastal area (Shamsuddoha and Chowdhury, 2007; Brammer, 2014). Together with water discharge, wave actions and mean sea level rise, an excessive amount of rainfall triggers the rate of erosion in the coastal area (Krantz, 1999; BMD, 2016). Moreover, noticeable seasonal variations were observed for the hydro-climatic triggering factors (Karntz, 1999; Hossain, 2012; Chowdhury, 2013; BWDB, 2016) in the coastal area and hence, the daily average data were segmented into four seasons (BMD, 2016) and applied in the model domain. In assessing seasonal variations, the effects of underlying physical elements and the preparatory factors were considered as static.

It is reported that the high volume of sediment supply accelerates the accretion process in the Meghna estuary (Mikhailov and Dotsenko, 2007). During the monsoon season when the sediment fluxes from the rivers are high, the process of accretion dominates in the Meghna estuary (Sokolewiczand-Louters, 2007). Like sedimentation, the impacts of defence structures such as polder, dyke, embankment and land reclamation projects (discussed in chapter 2) are evident in the coastal area (Meghna Estuary Study II [MES II], 2001; Khan, 2008).

### 3.3.3 Methods

The study addressed the impacts of predispositions, preparatory and triggering factors on land susceptibility to erosion in the coastal area by using the LSCE raster GIS model (Figure 3.3.2a). The model evaluated the individual contributions of the parameters by preparing, scaling, weighting and overlaying raster surfaces on the selected parameters. The preparation of raster surfaces involved some pre-processing tasks on the collected images used for surface elevation, bathymetry and shoreline detection. The tasks included geometric (i.e. geo-referencing), radiometric (i.e. conversion of DN to radiance and then to Top of Atmosphere-TOA reflectance for shoreline detection) and atmospheric corrections (i.e. Dark Object Subtraction-DOS). The pixel values of the processed raster surfaces were then classified into five different susceptibility categories (discussed in chapter 1) by using a scale ranging from 1 to 5 (where 1 represents very low and 5 represents very high susceptibility) (Table 3.3.2a). To prepare the scale, this study assumed that the higher the values of surface elevation, bathymetric depths and distance from the shoreline, the lower the susceptibility and vice versa. On the other hand, the higher the values of river water discharge, mean sea level, rainfall and wind speed, the higher the susceptibility to erosion and vice versa. However, scale values for surface geology were assigned to five susceptibility classes based on their resistance capacity to erosion supported by relevant literature (Hossain, 2012; Chowdhury, 2013; Brammer, 2014). Similarly, the types of soil permeability (BARC, 2016) were segmented into five susceptibility classes in which, slow permeability designates low erosion susceptibility and vice versa. Based on the source area (i.e. land or water), the south-western and southern winds were assumed to be highly effective for generating waves and the northern and north-western winds have less influence on waves. However, the south-eastern wind has moderate effects in generating waves in the central coastal zone. Hence, this study categorised the susceptibility classes of wind directions as: Northern (N) = 1; North-western (NW) =2; South-eastern (SE) = 3; South-western (SW) = 4 and South (S) = 5. The aggregated susceptibility scores (i.e. score for wind speed and score for wind direction) were then averaged and applied in the model.

Table 3.3.2a - Scales used for the LSCE model to categorise the cell values of raster surfaces into five susceptibility classes. To classify the numerical model parameters such as surface elevation, bathymetry, distance from the shoreline, river water discharge, mean sea level, rainfall and wind speed this classification followed equal interval classification method. As indicated, to classify the categorical values for surface geology, soil permeability and wind direction, the study followed experts' opinion and relevant literature.

| Parameter | Time period | Susceptibility category | | | | |
|---|---|---|---|---|---|---|
| | | Very low (1) | Low (2) | Moderate (3) | High (4) | Very high (5) |
| Surface elevation (m) | Average and all seasons | >12 | 9-12 | 6-9 | 3-6 | 0-3 |
| Surface geology (type) | Average and all seasons | Dihing and DupiTiila formation, Girujan Clay, Bhuban formation, BokaBil formation, Tipam Sandstone | Valley alluvium and colluvium, Tidal mud, Marsh clay and peat, Mangrove swamp deposits, Lakes | Estuarine deposits, Alluvial silt and clay, Chandina alluvium | Alluvial silt, Deltaic silt, Tidal deltaic deposits | Newly formed ocean and riverine deposits, Tidal sand, Deltaic sand, Beach and sand dune, Alluvial sand |
| Bathymetry (m) | Average and all seasons | > -20 | (-15)- (-20) | (-10)- (-15) | (-5) – (-10) | < -5 |
| Soil permeability | Average and all seasons | Very slow | Slow | Mixed | Moderate | Rapid |

| | | | | | | |
|---|---|---|---|---|---|---|
| (class) | | | | | | |
| Distance from the shoreline (m) | Average and all seasons | > 400 | 300-400 | 200-300 | 100-200 | < 100 |
| River water discharge ($m^3/s$) | Average | 13- 6152 | 6152-12290 | 12290-18429 | 18429-24567 | 24567-30706 |
| | Winter | 4- 1766 | 1766-3529 | 3529-5291 | 5291-7054 | 7054-8816 |
| | Pre-monsoon | 4- 2806 | 2806-5608 | 5608-8410 | 8410-11212 | 11212-14013 |
| | Monsoon | 29- 13102 | 13102-26175 | 26175-39249 | 39249-52322 | 52322-65396 |
| | Post-monsoon | 16- 6868 | 6868-13721 | 13721-20574 | 20574-27427 | 27427-34280 |
| Mean Sea Level (m) | Average | 1.84- 2.17 | 2.17- 2.50 | 2.50-2.83 | 2.83-3.20 | 3.20-3.50 |
| | Winter | 1.61- 1.93 | 1.93- 2.25 | 2.25-2.57 | 2.57-2.89 | 2.89-3.20 |
| | Pre-monsoon | 1.72- 2.10 | 2.10- 2.40 | 2.40-2.73 | 2.73-3.10 | 3.10-3.41 |
| | Monsoon | 2.12- 2.44 | 2.44- 2.77 | 2.77-3.11 | 3.11-3.44 | 3.44-3.78 |
| | Post-monsoon | 1.95- 2.26 | 2.26- 2.58 | 2.58-2.89 | 2.89-3.21 | 3.21-3.53 |
| Rainfall (mm) | Average | 123- 158 | 158- 194 | 194- 230 | 230- 265 | 265- 301 |
| | Winter | 10.22-11.53 | 11.53-12.85 | 12.85-14.16 | 14.16-15.48 | 15.48-16.79 |
| | Pre-monsoon | 90- 109 | 109- 128 | 128- 147 | 147- 167 | 167- 186 |
| | Monsoon | 303-421 | 421- 540 | 540- 659 | 659- 777 | 777- 896 |
| | Post-monsoon | 86- 104 | 104- 122 | 122- 140 | 140- 158 | 158- 176 |
| Wind speed (m/s) and direction | Average | 0.76- 1.16 | 1.16- 1.57 | 1.57-1.98 | 1.98-2.39 | 2.39-2.79 |
| | Winter | 0.52- 0.81<br>N | 0.81- 1.12<br>N | 1.12-1.40<br>N | 1.40-1.69<br>N | 1.69-1.99<br>N |
| | Pre-monsoon | 1.15- 1.62<br>SW | 1.62- 2.09<br>SW | 2.09-2.56<br>SW/SE | 2.56-3.03<br>SW | 3.03-3.49<br>SW |
| | Monsoon | 0.96- 1.54<br>S | 1.54- 2.11<br>S | 2.11-2.69<br>S | 2.69-3.26<br>S | 3.26-3.84<br>S |
| | Post-monsoon | 0.36- 0.66<br>NW | 0.66- 0.96<br>NW | 0.96-1.26<br>NW | 1.26-1.56<br>NW | 1.56-1.86<br>NW |

It was necessary to assign weights of individual parameters for the LSCE model in ArcMap. This study incorporated ratings of relevant experts in assigning weights of the model parameters. To accomplish this, the study organised a workshop inviting 11 experts having in-depth local knowledge on land susceptibility to coastal erosion. The experts were asked to rate the parameters on a scale of 0 to 1 where 0 indicates the least weight and 1 indicates the most weight of the parameters. The experts agreed on assigning the full weight (1 in a range of 0 to 1) for the underlying physical elements. However, the assigned weights for the drivers of change varied due to the diversified nature of influences of the hydro-climatic factors in the area. The final weights of the parameters yielded as 0.84 weight for discharge of river water, 0.79 for mean sea level, 0.71 for rainfall and 0.65 for wind speed and direction by averaging the weights given by individual experts.

This study incorporated the impacts of preparatory factors in the model domain by generating two sets of buffer zones: one for defence structures and another for sedimentation. These buffer zones are enclosed areas and termed as 'moderators' in the LSCE model. Since the moderators (i.e. defence structures and sedimentation) reduce erosion susceptibility of coastal lands, the buffer zones were assigned negative values followed by experts' opinions, on a range from 1 to 5 based on their nature of impacts. A negative value (-3) was assigned for the accreted buffer zones that are within 200 m landward from the coastline. Negative values (-2) and (-1) were assigned for the two buffers (i.e. 100 m and 50 m) consecutively next to the first buffer zone. However, two sets of buffer zone were applied for the coastal defences. A negative value (-5) was assigned to the buffer zones for hard defence (i.e. sea-wall, dyke) whereas, a negative value (-3) was set for soft defences (i.e. polder, dam). The pixels of the raster surfaces that overlapped with the buffer zones were then identified and the values were recalculated by using 'raster calculator' tool in ArcMap. The re-calculated pixels were finally mosaicked with the generated raster surfaces to obtain final susceptibility scores.

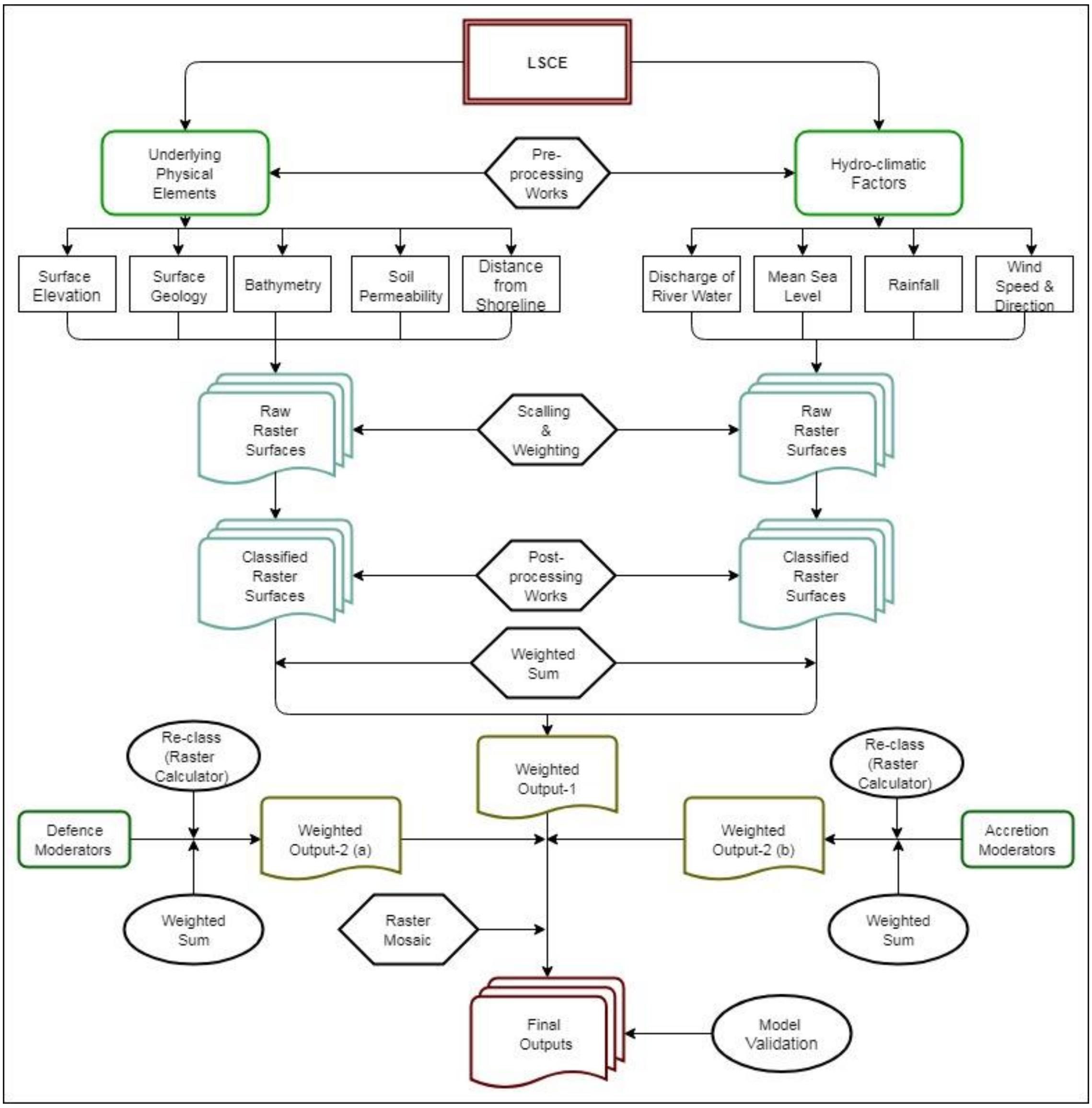

Figure 3.3.2a - A simplified representation of the processes involved in the LSCE model. The figure shows the inclusion of hydro-climate forces together with underlying physical elements in the model domain to obtain final outputs on erosion susceptibility.

Immediately after scaling and weighting of the raster surfaces and then mosaicking the moderators, the model was run by using ‘Model Builder’ extension of ArcMap (version 10.4). To run the model, the ‘weighted Sum’ operation of ArcMap was used that overlaid the raster surfaces where each were multiplied by their given weights; finally summing them together. The weighted sum scores of the raster surfaces were converted to a non-dimensional scale ranging from 0 to 100 by using the following equation (Equation 1):

$$\frac{\text{Aggregated Score} - \text{lowest score}}{\text{Range (difference between highest and lowest score)}} \times 100 \qquad (1)$$

The yielded scores were then presented under five susceptibility classes ranging from 1 to 5 where, 0-20 = 1 (very low), 20-40 = 2 (low), 40-60 = 3 (moderate), 60-80 = 4 (high) and 80-100 = 5 (very high). The same procedure was applied for the four identified seasons: winter (December to February), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October to November) with a view to addressing the seasonal variations of hydro-climatic factors on land susceptibility to coastal erosion in the area.

### 3.3.4 Data sources

The spatial data for the underlying physical elements were collected from available secondary sources. Data on surface elevation were downloaded as ASTER-DEM (Advanced Space-born Thermal Emission and Reflection Radiometer-Digital Elevation Model) from the United States Geological Survey (USGS) Global Visualization Viewer for the areal extent of study. The images having 30 m spatial resolution were used for further processing and analysis. Similarly, data on nearshore bathymetry for the entire coastal area were gathered from Global Multi-Resolution Topography (GMRT) synthesis by using 'GeoMapApp' (version 3.6.3) software tool. These data were cross-referenced with the data collected from the Bangladesh Naval Force (BN, 2010; GMRT, 2017). Spatial datasets (i.e. shapefiles) on surface geology and associated geomorphic features were collected from the United States Geological Survey (USGS, 2001), originally developed by Geological Survey of Bangladesh. The spatial dataset on soil permeability was collected from Bangladesh Agricultural Research Council (BARC, 2016). However, this study identified the existing shoreline with a view to measure the distances of each pixel from the shoreline. Hence, tide-synchronous Landsat (i.e. Landsat 8) satellite images were used to obtain the shoreline for the area. The use of satellite images to obtain shoreline is now well established (Boak and Turner, 2005). The benefit of using satellite images in identifying shoreline is that there is no need of fixing traditional benchmarks (known as proxies) such as high water line, datum based mean high water etc. (Boak and Turner, 2005). While using satellite images, the proxies depend on the definition of the shoreline and the image acquisition time. This study considered Mean High Water Level (MHWL) as the shoreline (line of demarcation between land and water). Only those images were selected that clearly represent MHWL in the images. Using OLI_TIRS sensor (Operational Land Imager_ Thermal Infrared Sensor), a total number of six images were collected to cover the entire coastal area (between path: 136-138 and row: 44-45). The acquisition date of the images was on 28 January 2016. Since Landsat satellite pass time over Bangladesh is between 10:00-10:30 (Islam, et al., 2016), all the images were selected based on the synchronization of satellite pass-time and high tide level. The images were collected on specific dates during the winter season (December to February) when most parts of the coastal lands were flood free. Hence, the shoreline during this season can clearly be discernible compared to the pre-monsoon, monsoon and post-monsoon seasons. The collected images were then mosaicked into a single image, georeferenced in the World Geodetic System (WGS84) datum and projected using the Universal Transverse Mercator system (zone UTM 46 North). The McFeeters's Normalized Difference Water Index (NDWI) (McFeeters, 1996) was used to separate the land areas from the water bodies. The demarcated line between land and water was then digitised to identify the desired shoreline.

Data on mean sea level, rainfall and wind speed and direction were collected for the past thirty years from 1986 to 2015 (BMD, 2016; BIWTA, 2017; PSMSL, 2017; UHSLC, 2017) whereas, data obtained for the discharge of coastal river water were available for past twenty years from 1996 to 2015 (BWDB, 2016). The average values of these data were used as existing conditions of the selected drivers. This study considered data for mean sea level that were collected from six stations located at Char Chenga, Chittagong, Cox's Bazar, Hiron Point, Khepupara and Sandwip in the coastal area of the country (Appendix C). These data were obtained from Bangladesh Inland Water Transport Authority (BIWTA), Permanent Solution for Mean Sea Level (PSMSL) and University of Hawaii Sea Level Centre (UHSLC). For rainfall and wind speed, this study analysed the data obtained from all 18 meteorological stations of the Bangladesh Meteorological Department (BMD) located in the coastal area of the country (Figure 3.3.1a). A total of eleven stations of the Bangladesh Water Development Board (BWDB) were considered for river discharge data that cover the major rivers, tributaries and distributaries in the coastal area (Appendix C).

### 3.3.5 Data processing and generation of raster surfaces

Considering the spatial extent of the area, the resolution of the raster surfaces was resampled to a 30×30 m (1 arc second) dimension. It took 16 individual scenes of ASTER-DEM (60×60 km) to cover surface elevations for the entire coastal area of the country. The initial vertical accuracy of the raw surface was ± 3.62 m. However, the mosaicked scene was first processed to remove artificial heights such as rooftops, construction works etc. (known as artifacts) from the original values by using the 'Majority Filter' in ArcMap. The Root Mean Square Error (RMSE) of the surface was then found to be ±0.28 m. The artifact-free raster surface went through consistency checks with observed ground data. Hence, a total number of 90 sample spot heights were taken for the coastal area arbitrarily from 1,711 vertical control points measured by Survey of Bangladesh (SoB, 2016). The correlation coefficient of Pearson's *r* between the sample heights and the corresponding elevations of the ASTER-DEM was found as 0.94 (p= 0.001 at 0.01 level of significance). The processed data showed surface elevations ranging from 0 to 327 m for the area studied (Figure 3.3.5a). To evaluate the role of geomorphic features, the entire coastal land was segmented into 21 types of areas.

The shallow depths are the areas where the wave actions are highly effective for potential erosion (Mazaheri and Ghaderi, 2011). In contrast, wave orbitals in deep water have less effects on erosion since the orbitals do not touch the bed. Hence, this study considered shallow depths as high susceptibility to erosion and vice versa. The categorical values of nearshore bathymetric depths were transferred to the associated land areas to reflect the impact of bathymetric depths on that lands. The transformation process was accomplished by using 'Zonal Statistics' tool of ArcMap through creating 1000×1000 m fishnets for the whole coastal area attached to the waterbody. The use of zonal statistics is identical with the work of Islam et al. (2016) where statistics for target zones were calculated by a set of input zones (i.e. in this case, the land zones were considered as the target and the bathymetric zones were as the input zones). The reason for choosing 1000 $m^2$ fishnet was based on the conventional use (i.e. considered by governmental and nongovernmental organizations but, not approved officially until recently) of 500 $m^2$ set-back distance from the shoreline for the study area. Since wave actions at nearshore bathymetric zone are most likely to impact on associated lands (not essentially over the whole coastal area), the bathymetric values of input zones (i.e. 500 $m^2$ water body) were transferred to the target zones (i.e. 500 $m^2$ land area). However, to generate a raster surface on soil permeability, vector layers obtained from Bangladesh Agricultural Research Council (BARC) were converted into raster format using ArcMap. Likewise, raster surfaces for four the hydro-climatic parameters were generated from point data by applying polynomial surface interpolation techniques in ArcMap. For instance, raster surfaces for river discharges and mean sea levels were generated by using kriging interpolation technique, whereas raster surfaces for rainfall and wind speed were generated by using Inverse Distance Weighting (IDW) interpolation technique in ArcMap. Like bathymetry, the values of river water discharge and wind speed and direction were transferred to the associated land areas attached to the rivers by following the same method. However, generated raster surfaces for elevation and bathymetry went through some post-processing tasks by using 'rescale by function' and 'fill' operation in ArcMap to generalise the values of 'sinks' and 'peaks' by rounding nearest integer values.

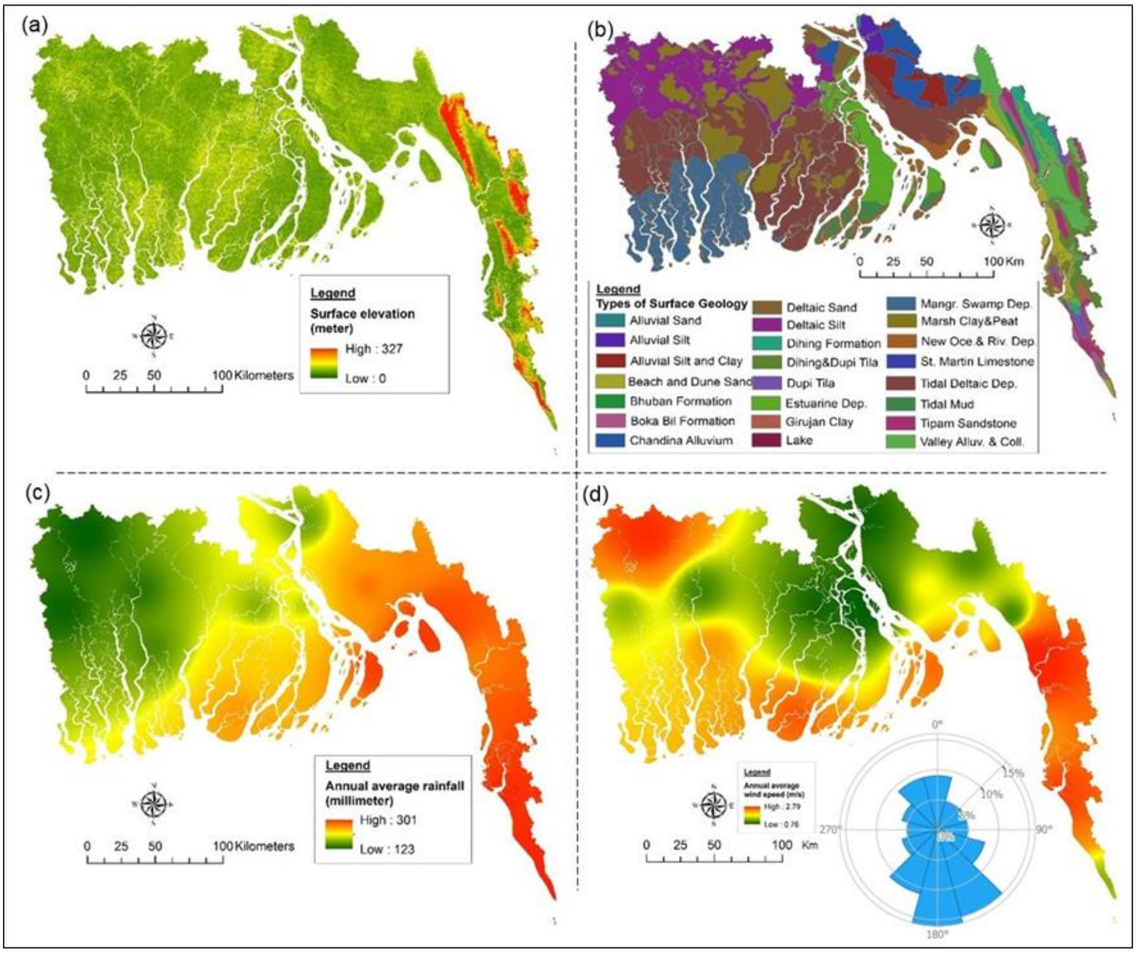

Figure 3.3.5a – Example of some raster surfaces used for further processing in the LSCE model in which (a) represents the surface elevation, (b) types of surface geology, (c) annual average rainfall, and (d) annual average wind speed and direction (wind rose) in the area. All other raw raster surfaces for the overall baseline susceptibility are provided in the appendix (Appendix C).

### 3.3.6 Model validation

The validation of the outcomes of the LSCE model was performed by using an inventory map of land erosion and accretion prepared from independent datasets. To prepare the inventory map, historical data collected from Water Resources Planning Organisation (WARPO) of Bangladesh and Landsat satellite images were used (Ahmed et al., 2018). The collected data from WARPO provided the areas of eroded and accreted lands for the past thirty years from 1985 to 2015. Moreover, the study used multi-temporal Landsat satellite images for the years 1985 (TM), 1995 (TM), 2005 (ETM+) and 2015 (ETM+) for the same time period (i.e. 1985 to 2015) to check the consistency of the data collected from WARPO. The satellite images were collected for the months of December and January considering the cloud cover, visibility and availability of images. The study followed raw quantized calibrated pixel values (DN) (Dewan et al., 2017) to identify the eroded and accreted land areas by separating the land areas from the water bodies. The inventory map identified a total of 2693.80 km$^2$ of coastal lands that experienced erosion and/or accretion (or both erosion and accretion) over the past thirty years from 1985 to 2015. This time period corresponds to the datasets used for hydro-climatic parameters (except river discharge for which data for the past twenty years were used) of the LSCE model. The areas of change identified by the inventory map cover 5.96% of the entire coastal area. The outputs of the LSCE model were then overlaid on the inventory map and the overlapped areas under five susceptibility classes of the model were used for generating 'Degree of Fit' (DF) curves. The Degree of Fit (DF) curve indicates the association between the values of inventory and susceptibility maps (Jimenez-Peralvarez, et al., 2009). The study considered 5% degrees of freedom and assumed that the higher the percentages of high and very high susceptibility areas of the model results that overlap on the dynamic area identified by the inventory map, the greater the validity of the model and vice-versa. This method has been applied to different studies (Fernandez et al., 2003; Irigaray et al., 2007; Jimenez-Peralvarez et al., 2009). The following equation (Equation 2) was used to generate the degree of fit curves for this study:

$$DF_i = \frac{m_i/\, t_i}{\sum m_i/\, t_i} \qquad (2)$$

where,

$m_i$= area occupied by the source areas (inventory map) at each susceptibility level

$t_i$ = total area covered by that susceptibility level

## 3.4 Results

### 3.4.1 Overall susceptibility to erosion

The raster-based LSCE model generated comprehensive maps by which, the levels of overall (annual average) land susceptibility of the coastal area to erosion are presented under five susceptibility classes (Figure 3.4.1a). The model identified 0.59% (266.32 km$^2$) and 0.02% (10.01 km$^2$) of the coastal lands as high and very high susceptibility to erosion respectively, which makes 276.33 km$^2$ in total that is noteworthy for the densely populated coastal area of the country. Remaining 5.49%, 20.56% and 73.34% of lands were identified by the model as moderate, low and very low susceptibility to erosion respectively (Appendix D).

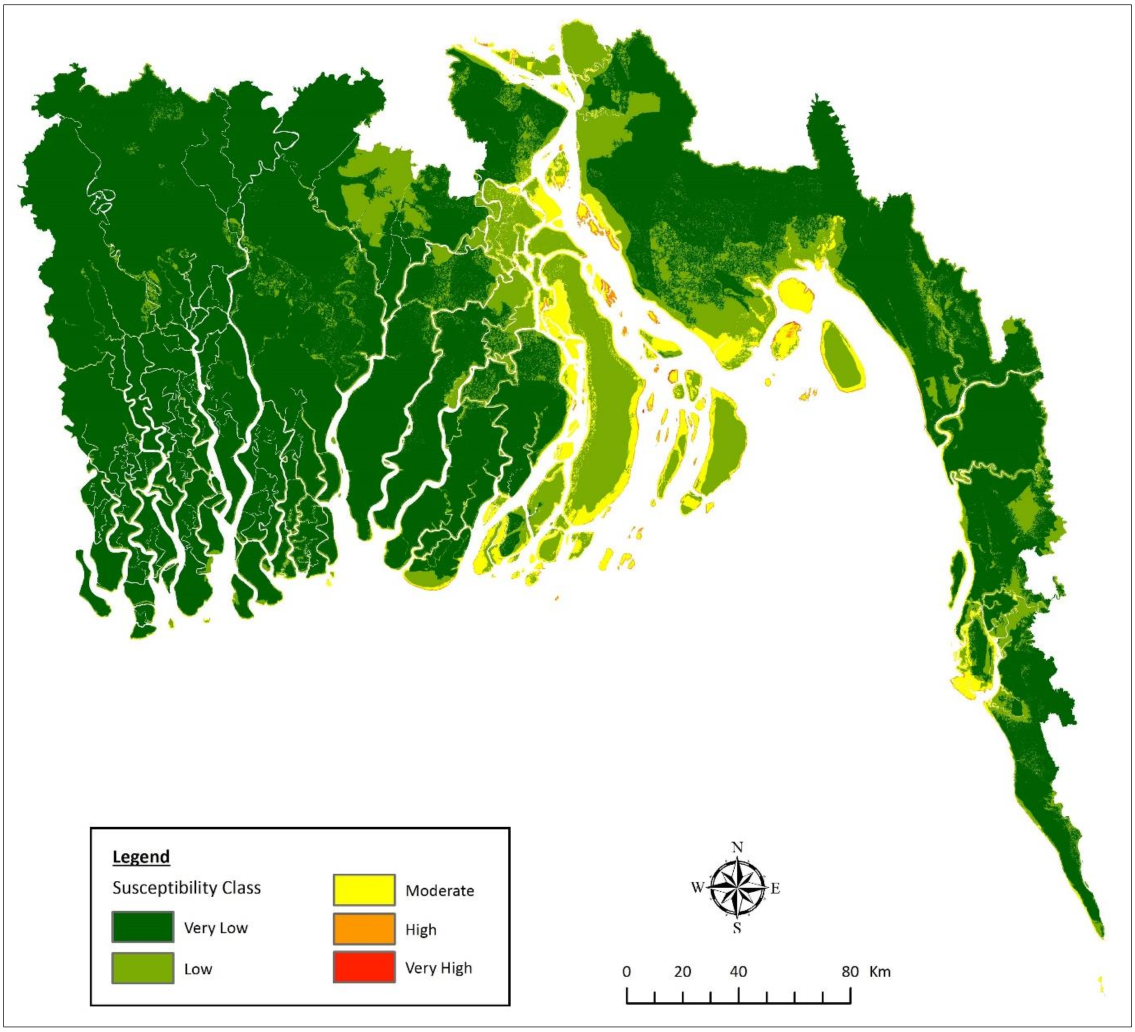

Figure 3.4.1a - Overall land susceptibility to erosion in the coastal area of Bangladesh. The outputs of the model indicate significant spatial variations in susceptibility to erosion. Most of the interior coastal lands were modelled as very low susceptibility class whereas, the exterior areas showed a mix of low, moderate, high and very high susceptibility to erosion.

Spatially, the model identified a total 99.41% of the lands in the western coastal zone as very low and low susceptibility to erosion (Appendix F: Table 2). Exceptions were found for the Kuakata coastal area under the Patuakhali district where a substantial portion of lands (i.e. 28.34%) were marked as moderate to high and very high susceptibility to erosion (Figure 3.3.1a and Figure 3.4.1a). The model outcomes for the eastern coastal zone are slightly different than the western zone for overall susceptibility to erosion. Although most of the areas in the eastern zone (i.e. 90.84%) were identified as very low and low susceptibility classes, some areas such as Kumira and Bhatiari of the Chittagong district, Kutubdia Island, the southern part of Moheshkhali sub-district and St. Martin Island (Figure 3.3.1a) showed moderate to high and very high susceptibility to erosion (Figure 3.4.1a). In contrast, the most diverse erosion susceptibility was found for the central estuarine coastal area of the country that comprised all the susceptibility classes. Low erosion susceptibility (i.e. 55.77%) was identified for the interior parts of this central zone whereas, most of the small islands were identified as moderate to high and very high susceptibility to erosion.

### 3.4.2 Seasonal variation

#### 3.4.2.1 Winter

The percentages of land area under very high, high, moderate and very low susceptibility classes for winter season were identified as lower than the percentages obtained for annual average (overall) erosion susceptibility of the area (Figure 3.4.2a). For instance, the high and very high susceptibility classes were identified as 0.34% (155.16 km$^2$) and 0.01% (3.02 km$^2$) of the total land area respectively, for this season. Moreover, the total land area identified as moderate susceptibility during this season was 1.48% less than the overall annual susceptibility (Figure 3.4.2b). The results showed 70.65% of the total land area as very low susceptibility to erosion which was 2.69% less than the overall susceptibility. However, the area for low susceptibility showed 24.99% land which is 4.43% higher than the overall susceptibility assessment. Spatially, most of the interior lands (i.e. 94.51% land of the zone) in the central coastal zone exhibited low and very low susceptibility to erosion during this season (Figure 3.4.2a). However, some small islands in the central coastal zone were identified as very high susceptibility to erosion during this season. Except for some moderate erosion susceptibility areas in Moheshkhali and the St. Martin Islands (Figure 3.3.1a), 96.32% of the areas in the eastern coastal zone were modelled as very low and low erosion susceptibility (Figure 3.4.2a). However, almost the entire western zone (i.e. 98.41 %) was identified as very low to moderate erosion susceptibility during this season.

#### 3.4.2.2 Pre-monsoon

The model identified 0.33% (150.71 km$^2$) and 0.01% (3.88 km$^2$) of land areas as high and very high susceptibility to erosion respectively, for the pre-monsoon season. These amounts are lower than the overall annual susceptibility values but are almost similar to those for the winter season. On the other hand, about 83.8% of the land was modelled as very low erosion susceptibility for this season, which is 10.46% and 13.15% higher than overall and winter susceptibility to erosion respectively. Differences were also found for low and moderate susceptibility classes that are much lower (6.57% and 3.63% subsequently) than the average susceptibility to erosion. The western coastal zone showed a very low susceptibility to erosion during this season except for some areas in Kuakata and some small islands located in the exposed western coastal zone (Figure 3.3.1a and Figure 3.4.2a). In contrast, the central coastal zone was mostly identified as low erosion susceptibility during this season, having 12.31% of moderate, high and very high susceptibility areas (Figure 3.4.2a). The southern parts of the islands in this zone were modelled as very low susceptibility compared to other areas. However, the newly developed small islands and the shorelines of comparatively bigger islands in the central zone were identified as moderate to high and very high susceptibility to erosion during this season. A highly exceptional case was found for Urir Char and Char Piya islands in the central coastal zone (Figure 3.3.1a). A considerable amount of lands of these newly accreted islands were modelled as moderately susceptible but, some areas were classified as high and very high susceptibility to erosion. About 95.22% land in the eastern coastal zone exhibited very low to low erosion susceptibility during this season. About 28.41% of the total 362.2 km$^2$ lands in Moheshkhali Island (Figure 3.3.1a and Figure 3.4.2a) were identified as moderate susceptibility to erosion as an exception in this zone.

#### 3.4.2.3 Monsoon

The LSCE model identified the monsoon as the most susceptible season to land erosion when considerable amounts of high (i.e. 441.8 km$^2$) and very high (i.e. 21.14 km$^2$) susceptibility areas were noticed. A total 1680.98 km$^2$ land area was identified as moderate susceptibility during this season, which is lower than winter and pre-monsoon seasons. A total 451.43 km$^2$ of land area in the central coastal area was found as high and very high susceptibility to erosion. The lands attached to the northern, eastern and southern shorelines of most of the comparatively larger islands in the exposed central coastal zone, namely Bhola, Hatiya, Urir Char, Jahajir Char, Char Piya, Sandwip and Monpura, (Figure 3.3.1a) were modelled as high and very high susceptibility to erosion (Figure 3.4.2a). The southern shoreline areas of the mentioned islands showed comparatively less susceptibility to erosion in this zone. All other small islands in the exposed central coastal zone mostly exhibited high and very high susceptibility to erosion during this season. In general, the eastern coastal zone showed comparatively lower levels of susceptibility than the central zone but, indicates higher susceptibility than the western zone during this season (Figure 3.4.2a). However, the Moheshkhali and St. Martin islands in the eastern zone (Figure 3.3.1a) showed higher susceptibility to erosion than other areas during this season.

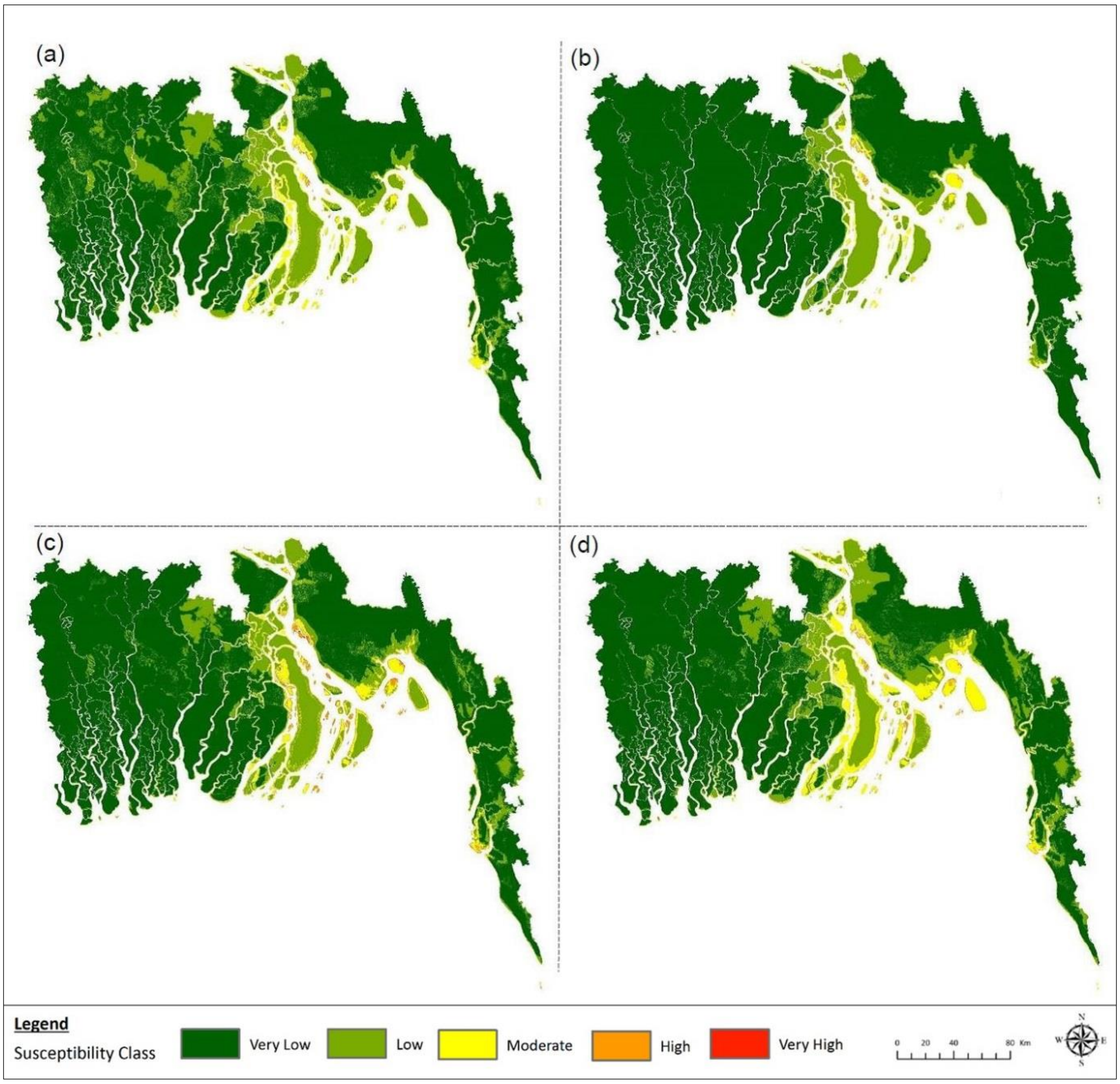

Figure 3.4.2a - Susceptibility to erosion during (a) winter, (b) pre-monsoon, (c) monsoon and (d) post-monsoon seasons in the coastal area of Bangladesh. The figure indicates spatial variations of erosion susceptibility for the seasons that are mostly governed by the varied nature of influences of the hydro-climatic forces in the area.

### 3.4.2.4 Post-monsoon

Susceptibility to erosion during the post-monsoon season showed a very similar result to those for average susceptibility. During this period, very high, high and moderate susceptibility classes showed slightly higher amounts of land compared to average susceptibility to erosion. However, very low susceptibility land area was only 3% less than the average susceptibility whereas, low susceptibility land area was 1.29% more than the average erosion susceptibility. About 97.32% lands of the western coastal zone were identified as very low and low erosion susceptibility for the post-monsoon season. A similarity with overall susceptibility was found for the Kuakata coastal area that showed moderate to high susceptibility to erosion. Several islands and newly accreted lands such as Sandwip, Urir Char, Jahajir Char, Monpura, Char Piya, Char Shahbaz, Char Gazaria, Char Zahiruddin, Dhal Char, Char Joman, Latar Char, Char Tazul, Sona Char and some other unnamed small islands in the central coastal zone (Figure 3.3.1a) showed moderate, high and very high susceptibility to erosion during this season. Like the monsoon season, the coastal areas of Moheshkhali and St. Martin islands located in the exposed eastern coastal zone (Figure 3.3.1a) were modelled as moderate to high and very high susceptibility to erosion during the post-monsoon season (Figure 3.4.2a).

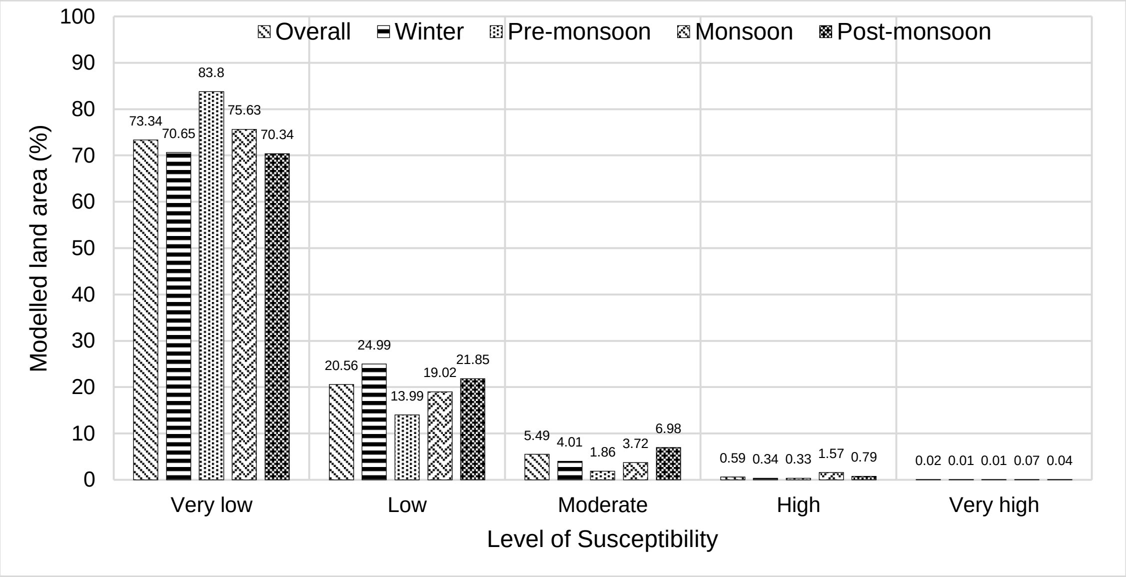

Figure 3.4.2b - Comparison of the percentages of land areas for overall and seasonal susceptibility under five susceptibility classes. The figure demonstrates high percentages of land for high (1.57%) and very high (0.07%) susceptibility classes during the monsoon season. However, this situation is different for winter, pre-

monsoon and post-monsoon seasons. These variations in seasonal susceptibility compared to the overall conditions indicate the influence and interactions of hydro-climatic factors on erosion susceptibility in the area.

Table 3.4a - Estimated number of populations exposed to high risk for overall and seasonal periods. The estimation was calculated by multiplying the total amount of high and very high susceptibility lands by the average density of 949/km$^2$ population (BBS, 2015) in the area.

| Time/ season | Total amount of high and very high susceptible land (km$^2$) | Total number population at risk (estimated) |
|---|---|---|
| Overall | 276.33 | 2,62,237 |
| Winter | 158.18 | 1,50,112 |
| Pre-monsoon | 154.59 | 1,46,705 |
| Monsoon | 739.27 | 7,01,567 |
| Post-monsoon | 375.72 | 3,56,558 |

## 3.5 Discussion

### 3.5.1 Validation of the results

The LSCE model outputs demonstrate a strong match with the areas of coastal change identified on the inventory map. The degree of fit curves (Figure 3.5.1a) and map (Figure 3.5.1b) show that 95.7%, 96.36%, 95.05%, 95.79% and 95.06% of very high susceptibility class of the modelled areas for annual average, winter, pre-monsoon, monsoon and post-monsoon periods respectively, overlapped with the dynamic area identified on the inventory map. Although the very high erosion susceptibility class covers 0.02%, 0.01%, 0.01%, 0.07 % and 0.04 % of the total modelled area for average, winter, pre-monsoon, monsoon and post-monsoon periods respectively (Figure 3.4.2b), most of the areas in that class (above 95%) overlapped within the area identified similarly on the inventory map (Figure 3.5.1b). On the other hand, only 0.48%, 0.47%, 0.92%, 0.51% and 0.46% of very low erosion susceptibility class of the modelled areas for overall, winter, pre-monsoon, monsoon and post-monsoon periods respectively, overlapped with the areas identified on the inventory map. These two opposite overlapping conditions of modelled areas with the inventory map meet the assumptions previously set for the validation of the model. The validation also fulfils the assumptions set for low and high erosion susceptibility areas of the model for the annual average and for all the four seasons. As expected, the overlapped areas for moderate susceptibility class ranging from 52.89% to 66.36% for overall and all other seasons except pre-monsoon (86.93%). These overlapped areas of moderate susceptibility class for most of the seasons also indicate the validity of the model results.

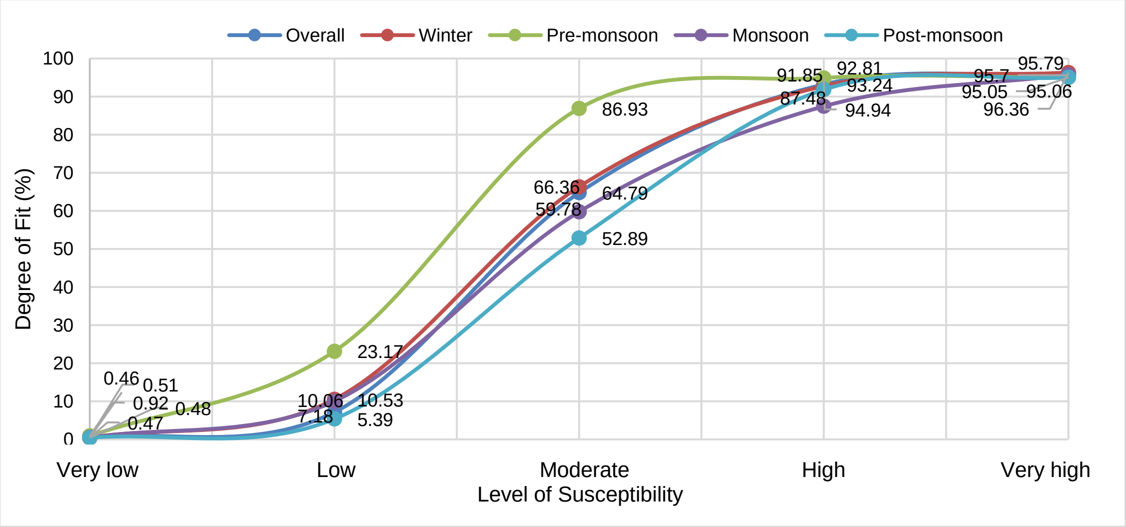

Figure 3.5.1a - Degree of fit curves used for the validation of LSCE model results. The vertical axis shows the relative frequency of the degree of fit (%) to independent observations of coastal change whereas the horizontal axis indicates the levels of susceptibility identified by the LSCE model. The lines show the percentages of modelled lands that overlapped with the dynamic lands identified on the inventory map.

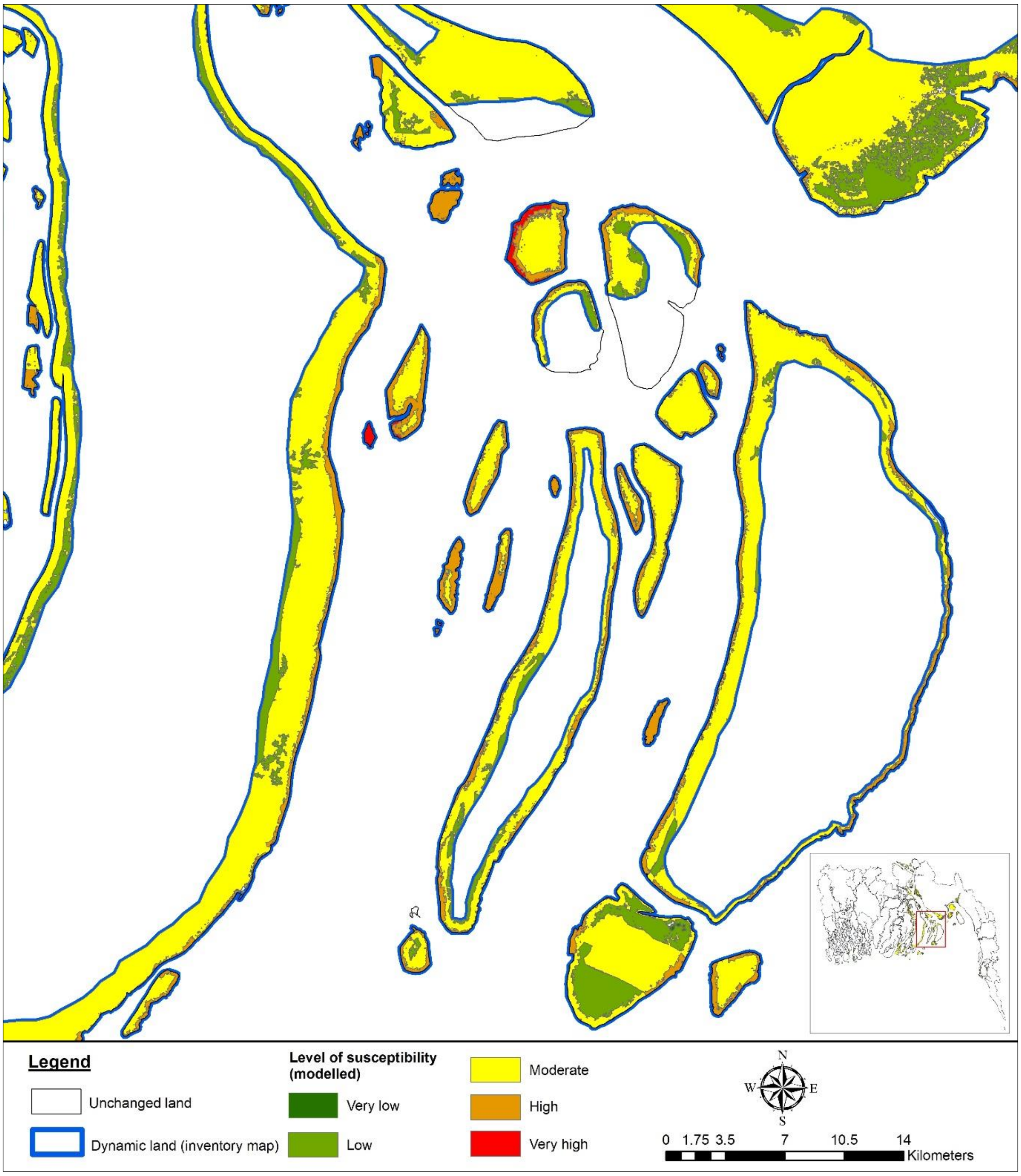

Figure 3.5.1b - Example of a zoomed-in area of the full inventory map (inset) used for validating the outputs of the LSCE model on erosion susceptibility. The figure shows the dynamic lands identified on the inventory map that experienced changes (erosion and/or accretion or the both) for different times from 1985 to 2015. The different levels of susceptibility to erosion show only the portions of land that overlapped with the dynamic land identified on the inventory map.

### 3.5.2 Impacts of hydro-climatic factors

The model results indicate substantial influences of the selected hydro-climatic factors (i.e. discharge of coastal river water, mean sea level, rainfall and wind speed) on land susceptibility of the coastal area to erosion. More specifically, variations in erosion susceptibility for the three coastal zones were the probable results of the spatial and seasonal variations of hydro-climatic parameters in the area. For instance, whilst having almost similar physical conditions (i.e. surface elevation, surface geology, soil permeability) to the central zone, most of the areas in the western coastal zone were identified as having lower susceptibility to erosion. The average discharge of river water in this western zone vary from a low 13 $m^3/s$ to a highest 6,152 $m^3/s$ only. This low river discharge has substantially less influences on the level of susceptibility to erosion in this zone that the model identified. Similarly, the mean sea-level data for the years from 1985 to 2015 show comparatively less variation in the western zone than other zones. However, the variation ranges from a low of 1.61 m during winter to a high of 2.77 m during the monsoon season. These situations of water discharge and mean sea level have likely impacts on the seasonal variations of erosion susceptibility in the western zone. Likewise, the pattern of rainfall that ranges from a low 90 mm to a high 421 mm during pre-monsoon and monsoon seasons in the western zone that has potential impacts on seasonal variations of erosion susceptibility. The effects of wind speeds in generating waves in this coastal zone are minimal for most of the times in a year. However, this zone experienced 3.26 m/s winds during monsoon season when the winds blow from south-western direction. This south-western direction of winds along with shallow water depths consequently increase the impacts of wave actions, the ultimate result of which initiate erosion in this exposed western coastal zone.

The probable impacts of hydro-climatic drivers were noteworthy for higher erosion susceptibility in the central coastal zone compared to the western and eastern coastal zones. The high river discharges, high rate of sediment supply, varied bathymetric depths, varied mean sea level and continuous wave actions seemed to have an influence on the model results for the identified higher erosion susceptibility in this zone. The data for the past twenty years show that the Meghna estuary area of both the interior and exposed parts of the central coastal zone experience discharge values as low as 3529 $m^3/s$ during winter to as high as of 65,396 $m^3/s$ during the monsoon season by the combined flow of the Padma (part of Ganges), the Meghna and the Jamuna (lower part of the Brahmaputra) river. Further, the varied mean sea levels (vary from a low of 1.61 m during winter to a high of 3.44 m during monsoon) in the estuarine areas inundate substantive portions (i.e. about 10 %) of the land area (Centre for Environmental and Geographic Information Services [CEGIS], 2014). This higher variation of mean sea levels combined with the huge volume of river discharge contributes to the high rate of erosion that is evident at the Sandwip channel, Urir Char and Jahajir Char areas located in the central coastal zone (Figure 3.3.1a and Appendix C).

Heavy rainfall during monsoon season along with high river discharge and south-westerly winds increase the water level in the Meghna estuary and south-eastern parts of the central coastal zone, which accelerated the rate of erosion for most of the islands located in the central coastal zone. Although the interior coastal area of the country experienced moderate to high range of rainfall (i.e. from a low of 122 mm to a high of 186 mm) during pre-monsoon and post-monsoon seasons but, the exposed coastal area in the eastern coastal zone experienced a range of 540 to 659 mm of rainfall on average for the years from 1985 to 2015. The model identified a higher level of erosion susceptibility for Patharghata and Meghna estuary areas and moderate susceptibility for the Barguna and Patuakhali coastal districts (Figure 3.3.1a and Figure 3.4.1a) that correspond with previous research (Hossain, 2012; Sarwar and Woodroffe, 2013).

The analysis infers that the influence of wind speed varies for the three coastal zones in accordance with the seasons and directions. The central coastal zone exhibits moderate wind speed that ranges from 0.36 m/s during the post-monsoon season to 2.69 m/s during the monsoon season. Due to southern and south-western directions of winds during pre-monsoon and monsoon seasons respectively, the islands and shoreline areas of the central coastal zone experiences significant wave actions. The exposed western zone exhibits wave actions mostly due to the southern wind during pre-monsoon season. In contrast, the strong southern winds blow over the land areas of the eastern coastal zone of the country and hence, have less considerable impacts on erosion in this zone. Moreover, the generated waves from south-western winds also seem to have a lower influence in the eastern coastal zone due to favourable geomorphic features. The northern and north-western winds have less potentials to generate waves in the three coastal zones due to their direction from land to the Bay. However, the combined effects of the prevailing south and south-western winds, river discharge and high tidal level are thought to be responsible for higher erosion susceptibility in this central coastal zone than the western and eastern zones. The case of Urir Char is a perfect example, which is an offshore island in the Meghna estuary (Figure 3.3.1a) (Hussain et al., 2014). Sediments from river discharges that enter into Hatiya channel (Figure 1.2.4a) are trapped by that counter-clockwise circulation before settling in or being transported out of the Meghna estuary (Ali et al., 2007). However, the data indicate that the effects of hydro-climatic drivers on erosion susceptibility are less in the eastern coastal zone than the western and central zones. This is because of the presence of higher surface elevations, solid geomorphic features and very slow permeability of soils in the eastern zone. The shallow bathymetric depths generate waves in this zone but, due to the aforementioned reasons, the waves actions are less effective for erosion.

### 3.5.3 Controls of underlying physical elements

The spatial and seasonal variability of the model outputs discussed relies highly on how the hydro-climatic factors interact with the underlying physical characteristics of the area. For instance, the study identified the eastern coastal zone as having a lower susceptibility to erosion than the central coastal zone. Except for winds and associated wave actions, the influences of all other hydro-climatic factors are less substantial in the eastern zone than the central and western coastal zone. The higher surface elevations along with hard and consolidated rock, flat and unbroken coast and the longest natural beach make the zone as a most stable part of the coast (Brammer, 2014). However, some areas in the exposed eastern zone, such as Kutubdia and Moheshkhali islands and the northern part of Cox's Bazar district (Figure 3.3.1a) showed moderate to high and very high susceptibility to erosion (Figure 3.4.1a) probably due to the presence of alluvial silt and clay and the Chandina alluvium formation. The areas of Kutubdia, Moheshkhali and Cox's Bazar that are below 3 m above mean sea level (Appendix C) were identified as moderate to highly susceptible to erosion. The bathymetric depths of this zone vary from high to very high susceptibility class (<-5 to -10 m). Although the impacts of river discharge are very low, wave actions are thought to have important roles to initiate erosion due to shallow nearshore depths in this zone. Additionally, the slow to moderate permeability of soils in the eastern coastal zone has considerable impacts on the low erosion susceptibility of the zone.

The central coastal zone is the most active and dynamic zone compared to other zones (Karim and Mimura, 2006) that correspond with the outputs of the LSCE model. Although the surface elevation of this zone ranges from 3 to 12 m for the coast of this zone, this value ranges from 1 to 3 m only for most of the islands and newly accreted lands. Together with surface elevations, the geomorphic features such as the estuarine silt and clay deposits, newly formed ocean and riverine deposits, tidal sands, deltaic sands, beach and sand dunes and alluvial sands (Appendix C) contribute to high erosion susceptibility of the islands and newly developed lands in the exposed central coastal zone. The islands are highly susceptible to erosion due to silt and clay dominated soft unconsolidated sediments. An example can be cited of Hatiya Island which is composed of Quaternary alluvial deposits of silt, sand and clay. The morphology of the island is changing rapidly due to its alluvial lithology which is very sensitive to river discharge, tides and waves (Ghosh et al., 2015). Along with geomorphic features and soil characteristics, the varied bathymetry of the zone (Appendix C) is thought to be favourable to erosion due to the high volume of river discharge. Moreover, the bathymetric depths of the central zone vary from a higher depth in the interior coast (i.e. up to -44.84 m near the upper portion of the Sandwip island and in the Meghna river channels) to a lower depth (i.e. -10 m) in the exposed coast. The high depths belong to the interior Meghna estuarine area that created thalwegs along the shoreline of small islands in the area (MES II, 2001; BN, 2010; GMRT, 2017). However, the exposed coast of the central zone experiences higher wave actions due to lower bathymetric depths, comparing to the internal coast.

The hydro-climatic parameters act differently in the western coastal zone than in the central and eastern zones. This situation is highly influenced by the existence of Mangrove vegetation in the area. Although the surface elevation of this zone shows a mixed range of 0 to 6 m above mean sea level, mangrove vegetation acts as an active agent of protection for the area from erosion and plays a vital role for accretion in this zone (Aziz and Paul, 2015; Islam and Rahman, 2015). Mangrove vegetation (Figure 3.3.1a) also creates a barrier against wave action (Umitsu, 1997). The exposed western zone (e.g. the Sundarbans Mangrove) is composed of valley alluvium and colluvium, tidal mud, marsh clay and peat and mangrove swamp deposits. Along with geomorphic features, the presence of fine sand and silt in the beds of this coastal zone (Sarker, et al., 2011) indicates a high rate of siltation (MES II, 2001) which substantially reduce erosion susceptibility of this zone. Additionally, the soils in this zone are characterised as having very slow to moderate permeability and are highly resistant to erosion that reduces the erosion susceptibility in this zone. Due to the excessive amount of siltation near the shoreline, most of the areas in this zone belong to the very low (<-5 m) to low (-5 to -10 m) nearshore bathymetric depths. The depths of the rivers in the interior part of this zone are higher than the exposed coast (i.e. -10 to more than -20 metres in some places). Moreover, the interior coastal land is not highly influenced by wave actions, and hence resembles lower susceptibility to erosion. However, the lower depths in areas such as Barguna, Patuakhali and Bhola generate waves that substantially contribute to erosion in that exposed coastal areas (Figure 3.3.1a and Figure 3.4.1a).

### 3.5.4 Roles of preparatory factors

Although very little is evident on the specific preparatory factors responsible for the susceptibility to erosion in the coastal area, this study addressed the influence of accretion (sedimentation) and defence structures on the susceptibility to erosion. A total number of 38 enclosed areas on accretion moderator were used for the LSCE model that substantially reduced the susceptibility scores in the model for different areas of the coast. For example, the accretion moderator used in the model for Ramgati, Rangabali and Khaser Haat (Figure 3.3.1a and Figure 6.1a) that noticeably reduced the level of erosion susceptibility from very high to high and moderate classes for those areas. Moreover, the accretion moderator applied for Nujhum Dwip, Char Gazaria, Char Shahbaz, Char Halim and Char Kukri Mukri located in the central coastal zone (Figure 3.3.1a) reduced the susceptibility scores for those areas. Similarly, the LSCE model addressed the issue of defence structures constructed by the government of Bangladesh from time to time, by generating accretion moderators in the model domain especially for the central coastal zone. It is reported that more than one billion tons of sediments are carried by the Ganges, the Brahmaputra and the Meghna each year, of which a considerable portion deposits on the tidal plain of the coast (Goodbred and Kuehl, 2000). The concentration of suspended sediments in the lower reaches of Shahbajpur channel is very high (about 2,000 ppm) (MES II, 2001; Sokolewicz and Louters, 2007). Consequently, the high rate of sedimentation remarkably reduces the levels of erosion susceptibility in this area of the exposed central coastal zone.

### 3.6 Conclusion

The study modelled the interior part of the coast as very low to low susceptibility to erosion and the exposed part of the coast as moderate to high and very high susceptibility to erosion. Based on the zones, the central estuarine zone (includes both interior and exposed) was identified as highly susceptible to erosion whereas the eastern and western zones of the coast were comparatively identified as very low to low erosion susceptibility. The results demonstrate that overall 276.33 km$^2$ land area is highly susceptible to erosion. The approximate population living in areas at high risk of erosion (Table 3.4a) is noteworthy for the country's socio-economic and demographic context. However, the modelled results strongly rely on the availability of data, the use of model parameters, the definition of class values and the given weights for the parameters (discussed in the annex of chapter 3: sensitivity analysis). Hence, the emphasis was given in choosing model parameters, classifying the data and assigning them weights before the model was run. Moreover, the framework of the model was designed to facilitate the analysis of prevailing impacts of hydro-climatic factors on erosion susceptibility. However, the LSCE model framework provides a new insight on assessing future erosion susceptibility, which may be applied to any coastal lands around the world that are prone to likely changes in future hydro-climatic factors.

The present assessment identified dominant regional as well as seasonal drivers of susceptibility to erosion. In the western coastal zone, along with a low impact of hydro-climatic drivers such as coastal river discharge, rainfall, mean sea level, wind speed and direction and wave action, other drivers such as slow permeability of soils, fine and silt deposits and varied bathymetry are thought to have substantial influences on land susceptibility to erosion. In contrast, low surface elevations, newly formed alluvial deposits, high permeability of soils, wave actions, varied bathymetry, high river discharge, variations in mean sea level, heavy rainfall, high rate of sedimentation and embankments (defence structure) are considered as probable active drivers of susceptibility to erosion in the central coastal zone. In case of eastern zone, high surface elevations, hard and consolidated rocks, beach and sand dune, lower bathymetric depths, heavy rainfall and development works (e.g. marine drive) are indicated as the main drivers of susceptibility to erosion. For instance, the construction of Cox's Bazar-Teknaf marine drive (which is 80 km long road from Cox's Bazar to Teknaf) (Figure 3.3.1a) in the eastern coastal zone of the country (Dhaka Tribune, 2017) is serving as a coastal defence in the eastern coastal zone. The effects of these drivers vary for the four seasons in which, winter is characterised by the low flow of coastal river water, less rainfall, low wind speeds and less wave action. The drivers are nearly similar for the pre-monsoon and post-monsoon seasons, whereas the monsoon season is characterised by high river discharge, continuous wave action, heavy rainfall and substantial variation in mean sea level.

The outputs of the LSCE model offer coastal managers and policymakers vital inputs in assessing erosion susceptibility of dynamic coastal areas, which in principle can be applied around the world. This assessment could offer insights into the underlying causes and the impacts of hydro-climatic factors on land susceptibility to coastal erosion in the area. This research is important for the coastal managers to take initiatives in protecting coastal lands and preventing the shoreline from potential erosion. Moreover, the LSCE model offers a new modelling approach by which the likely impacts of hydro-climatic changes on future land susceptibility to erosion can be assessed for the coastal areas around the world.

### 3.7 Acknowledgement

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## Annex of chapter 3

## 3.9 Sensitivity of the LSCE model

The following section discusses the methods, results and interpretation of the sensitivity analysis performed for the LSCE model.

### 3.9.1 Methods of sensitivity analysis

#### 3.9.1.1 Weightings between parameters

The first set of sensitivity analysis (SA) was based on the weightings between the model parameters. In assessing overall (general) land susceptibility to erosion, the model considered the full (1) weights for the underlying physical elements whereas, the weights for the hydro-climatic forces were varied between 0 and 1 on the basis of experts' opinions. The weights for the hydro-climatic factors were assigned as 0.84, 0.79, 0.71 and 0.65 for water discharge, mean sea level, rainfall and wind speed and direction respectively. To investigate the potential changes in outputs under the changes in given weights of the parameters, this study derived four sorts of test:

- Test 1: All the parameters having full (1) weight
- Test 2: A 10% decrease in weights for underlying physical elements and no changes in weights for hydro-climatic parameters
- Test 3: A 10% decrease in weights for underlying physical elements and a 10% increase in weights for hydro-climatic parameters
- Test 4: A 10% decrease in weights for all the parameters

The aim of the first three tests was to identify whether the given weights of the parameters are sensitive to erosion susceptibility in the LSCE model or not. The first test was designed to give full weight to all the parameters whereas, the second and third tests were to reduce the gaps of weights between physical elements and hydro-climatic factors in the model. However, the fourth test aimed at identifying if any similarities in the results existed when under an equal decrease of weights for all the parameters. The conditions (i.e. tests) were applied to the model parameters and the new weights of the parameters are shown in the table (Table 3.9.1.1a).

Table 3.9.1.1a - The assigned weights of the model parameters to perform sensitivity analysis under changing situations of weights. Due to the full (1) weight assigned for general assessment, it was not necessary to increase the weights of the underlying physical elements in the current SA. Except for the first test, the weights of the underlying physical elements for test 2, 3 and 4 were decreased. Except for the second test, the weights of the hydro-climatic factors were changed under test 1, 3 and 4.

| Model parameter | Weight | | | |
|---|---|---|---|---|
| | Test 1 | Test 2 | Test 3 | Test 4 |
| Surface elevation | 1 | 0.90 | 0.90 | 0.90 |
| Surface geology | 1 | 0.90 | 0.90 | 0.90 |
| Bathymetry | 1 | 0.90 | 0.90 | 0.90 |
| Soil permeability | 1 | 0.90 | 0.90 | 0.90 |
| Distance from shoreline | 1 | 0.90 | 0.90 | 0.90 |
| Water discharge | 1 | 0.84 | 0.92 | 0.76 |
| Mean sea level | 1 | 0.79 | 0.87 | 0.71 |
| Rainfall | 1 | 0.71 | 0.78 | 0.64 |
| Wind speed and direction | 1 | 0.65 | 0.71 | 0.58 |

### 3.9.1.2 Distribution of parameter values

The second set of SA was based on the changes in the distribution of class values (i.e. levels of susceptibility) of the model parameters. The overall erosion susceptibility was assessed based on the equal interval classification method in which, the values of the parameters were equally segmented into five susceptibility classes based on their ranges (i.e. highest and lowest). Due to the nature of data (i.e. categorical areas), the susceptibility classes for surface geology and soil permeability were assigned by using the literature and experts' opinion. The distances of each pixel from the shoreline were classified into five susceptibility classes for the general assessment followed by experts' opinion and relevant literature (Fitton et al., 2016).

To assess the distributional sensitivity of the parameter values in the LSCE model, a new classification method was applied to the model. This has given new class values for each susceptibility class. The study first aimed to distribute the parameter values into five susceptibility classes by using the exponential growth of the dataset. Due to the diverse nature of location-based data, no homogeneity was found between the data ranges for each location. It was not possible to calculate the succeeding growth rate (*r*) of the location-based data and hence, this study did not follow an exponential way of classifying the data for the new susceptibility classes. However, the study reviewed the possible classification methods in ArcGIS environment in which, seven types of methods (i.e. geometric interval, natural breaks [Jenks], quantile, manual, defined interval, equal interval, and standard deviation) are available to classify raster surfaces. The geometric interval method is suitable for continuous data but, makes relatively small class intervals in areas where there is a high frequency of occurrences (Environmental Systems Research Institute [ESRI], 2018) and hence, the data with high spatial variability used in this study are not suitable to classify by using this method. The Jenks natural breaks classification method minimizes within class variance (i.e. the sum of squared difference) but, maximizes variance between the groups. Therefore, this method is not recommended for spatial analysis that uses multiple datasets of the same geographical area (e.g. different types of raster surfaces) (de Smith et al., 2018). The quantile classification method assigns an equal number of features into each class and not suitable to include outliers (distant observation than others) within upper or lower quantile (ESRI, 2018). As a result, this method is not suitable for seasonally varied nature of data used in this study. Moreover, the defined interval method is not completely free from human bias in classifying data. However, based on the nature of spatial data used for the present study (i.e. mostly location-specific data), the standard deviation method was found as highly suitable for the present sensitivity analysis. In this classification method, the class values can be the proportions of one-half, one-third, or one-fourth standard deviations from the mean. By using this method, it is possible to distribute the location-specific values that are above and below the mean. This study followed the standard deviation (1σ) classification method to compare how the distribution of parameter values from the mean differs from the equal interval classification method, previously conducted for the study. Based on the data ranges, the following distributions of parameter-wise values were assigned for the five susceptibility classes (Table 3.9.1.2a). However, this new classification method for categorical values (i.e. surface geology, soil permeability and wind direction) followed experts' opinion and relevant literature previously applied for the general assessment. Due to the unavailability of relevant literature, the distance from shoreline under the new classification was classified as an experimental basis in which, classification started from 50 m distance from the existing shoreline. Moreover, the new classification used cut-off values for surface elevation and bathymetry due to the considerable variation in surface elevation for some areas in the eastern coastal zone and bathymetric depths in the central coastal zone (Table 3.9.1.2a).

Table 3.9.1.2a – Redistribution of parameter values under five susceptibility classes for the second set of sensitivity analysis. Since most of the raster values for surface elevation fall between 0 and 6 meters, the distribution was performed for the mentioned range. Values beyond 6 meters were classified as very low susceptibility to erosion. A similar procedure was also applied for bathymetric data in which, > -15 m was used as a cut-off value for very low susceptibility level.

| Model parameter | Time period | Susceptibility level | | | | |
|---|---|---|---|---|---|---|
| | | Very low (1) | Low (2) | Moderate (3) | High (4) | Very high (5) |
| Surface elevation (m) | Present | > 6 | 3.7-6 | 2.8-3.7 | 1.5-2.8 | 0-1.5 |
| Surface geology (type) | Present | Dihing and DupiTiila formation, Girujan Clay, Bhuban formation, BokaBil formation, Tipam Sandstone | Valley alluvium and colluvium, Tidal mud, Marsh clay and peat, Mangrove swamp deposits, Lakes | Estuarine deposits, Alluvial silt and clay, Chandina alluvium | Alluvial silt, Deltaic silt, Tidal deltaic deposits | Newly formed ocean and riverine deposits, Tidal sand, Deltaic sand, Beach and sand dune, Alluvial sand |
| Bathymetry (m) | Present | > -15 | (-11.4)- (-15) | (-5.6)- (-11.4) | (-1) – (-5.6) | < -1 |
| Soil permeability (class) | Present | Very slow | Slow | Mixed | Moderate | Rapid |
| Distance from the shoreline (m) | Present | > 350 | 250-350 | 150-250 | 50-150 | < 50 |
| River water discharge ($m^3/s$) | Yearly average | 13-3,629 | 3,629-8,816 | 8,816-14,003 | 14,003-19,190 | 19,190-30,706 |
| Mean Sea Level (m) | Yearly average | 1.84-2.21 | 2.21-2.45 | 2.45-2.72 | 2.72-3.10 | 3.10-3.50 |
| Rainfall (mm) | Yearly average | 123-159 | 159-195 | 195-230 | 230-266 | 266-301 |
| Wind speed (m/s) | Yearly average | 0.76-1.26 | 1.26-1.53 | 1.53-1.81 | 1.81-2.14 | 2.14-2.79 |

### 3.9.1.3 General versus regional models

The third set of SA was devoted to comparing and analysing the outputs of the general assessment with the regional model outputs applied for the three zones separately (i.e. western, central and eastern coastal zones). The regional assessment is important since the three coastal zones possess different physical and hydro-climatic characteristics. The general assessment was carried-out by averaging the parameter values and applied for the entire coastal area followed by the equal interval method. However, the regional SA classified the data based on the region-specific ranges (i.e. lowest and highest values of each parameter for each region). This was necessary since the data ranges among the selected parameters are different from each other for the three coastal zones. For instance, the surface elevation for the central and western coastal zones range from 0 to 6 metre above mean sea level. However, the surface elevation of some areas in the eastern coastal zone reaches to 327 metres. Similarly, the influences of hydro-climatic factors are different for the three coastal zones (discussed in chapter 3 and chapter 5). Hence, the scale of the levels of susceptibility was reclassified by applying equal interval method for the region-specific data ranges of each parameter (Table 3.9.1.3a).

Table 3.9.1.3a – The scale applied for the SA to analyse regional land susceptibility to erosion in the coastal area. Based on the regional ranges of the parameters, the values were reclassified into five susceptibility classes by following the equal interval method of classification. However, the scales of the categorical values (i.e. surface geology, soil permeability and wind direction) were redistributed to the five susceptibility classes following the literature and experts' suggestions previously used for the general assessment.

| Model parameter | Coastal zone | Susceptibility category | | | | |
|---|---|---|---|---|---|---|
| | | Very low (1) | Low (2) | Moderate (3) | High (4) | Very high (5) |
| Surface elevation (m) | Western | > 4 | 3-4 | 2-3 | 1-2 | 0-1 |
| | Central | > 2 | 1.5-2 | 1-1.5 | 0.5-1 | 0-0.5 |
| | Eastern | > 16 | 12-16 | 8-12 | 4-8 | 0-4 |
| Surface geology (type) | Western | BokaBil formation | Chandina alluvium,<br>Mangrove swamp deposits,<br>Lakes | Alluvial silt and clay | Tidal deltaic deposits | Beach and sand dune,<br>Alluvial sand |
| | | Valley alluvium and | Tidal | Alluvial | Tidal | Newly formed ocean and |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Central | colluvium | mud, Estuarine deposits, Marsh clay and peat | silt, Deltaic silt | sand, Deltaic sand | riverine deposits, Beach and sand dune, Alluvial sand |
| | Eastern | Dihing and DupiTiila formation, Girujan Clay, Bhuban formation | Tipam Sandstone | Tidal deltaic deposits | Beach and sand dune, Alluvial sand | Beach and sand dune, Alluvial sand |
| Bathymetry (m) | Western | > -7 | (-5)- (-7) | (-3)- (-5) | (-1) – (-3) | < -1 |
| | Central | > -16 | (-12)- (-16) | (-8)- (-12) | (-4) – (-8) | < -4 |
| | Eastern | > -6 | (-4.5)- (-6) | (-3)- (-4.5) | (-1.5) – (-3) | < -1.5 |
| Soil permeability (class) | Western | Very slow | Slow | Mixed | Moderate | Rapid |
| | Central | Very slow | Slow | Mixed | Moderate | Rapid |
| | Eastern | Very slow | Slow | Mixed | Moderate | Rapid |
| Distance from the shoreline (m) | Western | > 800 | 600-800 | 400-600 | 200-400 | < 200 |
| | Central | > 400 | 300-400 | 200-300 | 100-200 | < 100 |
| | Eastern | > 400 | 300-400 | 200-300 | 100-200 | < 100 |
| River water discharge ($m^3/s$) | Western | 13-252 | 252-491 | 491-730 | 730-969 | 969-1207 |
| | Central | 4,543-9,776 | 9,776-15,009 | 15,009-20,242 | 20,242-25,475 | 25,475-30,706 |
| | Eastern | 25-36 | 36-47 | 47-58 | 58-69 | 69-79 |
| Mean Sea Level (m) | Western | 1.84-1.94 | 1.94-2.03 | 2.03-2.13 | 2.13-2.22 | 2.22-2.32 |
| | Central | 2.21-2.36 | 2.36-2.51 | 2.51-2.67 | 2.67-2.82 | 2.82-2.97 |
| | Eastern | 2.16-2.43 | 2.43-2.69 | 2.69-2.96 | 2.96-3.23 | 3.23-3.50 |
| Rainfall (mm) | Western | 123-140 | 140-157 | 157-173 | 173-190 | 190-207 |
| | Central | 145-166 | 166-186 | 186-207 | 207-227 | 227-248 |
| | Eastern | 216-233 | 233-250 | 250-267 | 267-284 | 284-301 |
| Wind speed (m/s) | Western | 1.0-1.25 | 1.25-1.5 | 1.5-1.75 | 1.75-2 | 2-2.25 |
| | Central | 0.76-0.96 | 0.96-1.16 | 1.16-1.36 | 1.36-1.56 | 1.56-1.76 |
| | Eastern | 1.18-1.60 | 1.60-2.02 | 2.02-2.47 | 2.47-2.87 | 2.87-3.29 |

### 3.9.2 Results of sensitivity analysis

#### 3.9.2.1 Weightings of the parameters

The assignment of full (1) weight to all the nine parameters in the LSCE model shows that the current levels of erosion susceptibility slightly increased for very high, high and moderate classes (Figure 3.9.2.1a and Figure 3.9.2.1b). For instance, the sensitivity analysis shows an additional 3.56 km$^2$ of lands highly susceptible than the general assessment. Similarly, the amounts of 68.32 km$^2$ and 324.49 km$^2$ lands added to high and moderate susceptibility classes respectively under the sensitivity analysis compared to the general assessment. However, the SA shows a decreasing condition of susceptibility for low (i.e. 80.77 km$^2$ less) and very low (315.6 km$^2$ less) susceptibility classes in comparison with the general assessment.

A 10% decrease in weights for underlying physical elements and no changes in weights for hydro-climatic factors indicate very similar but, not identical results compared to the first test of SA. Although the amount of very high susceptible land is similar to the first SA test, the amount of high susceptibility land decreased to 325.59 km$^2$ (9.05 km$^2$ less than the first test). However, the second test shows increases of 58.79 km$^2$ and 54.27 km$^2$ lands for moderate and low susceptibility classes respectively compared to the first SA test (Figure 3.9.2.1a and Figure 3.9.2.1b). Consequently, the second test shows a decrease of 104.01 km$^2$ very low susceptible lands decreased compared to the first SA test.

The third sort of changes in weights for SA results in substantial increases in the amounts of very high, high and moderate susceptible lands in the coastal area. The amounts of very high, high and moderate susceptible lands in the SA test show additional 8.07 km$^2$, 109.02 km$^2$ and 518.94 km$^2$ lands respectively than the general assessment (Figure 3.9.2.1a and Figure 3.9.2.1b). The changes were not substantive for the low and very low susceptible lands under this SA test compared to the general assessment. However, it was expected that the fourth sort of weighting would produce similar results to the general assessment. Consequently, a 10% decrease in weights for all the parameters produces similar results compared to the general assessment.

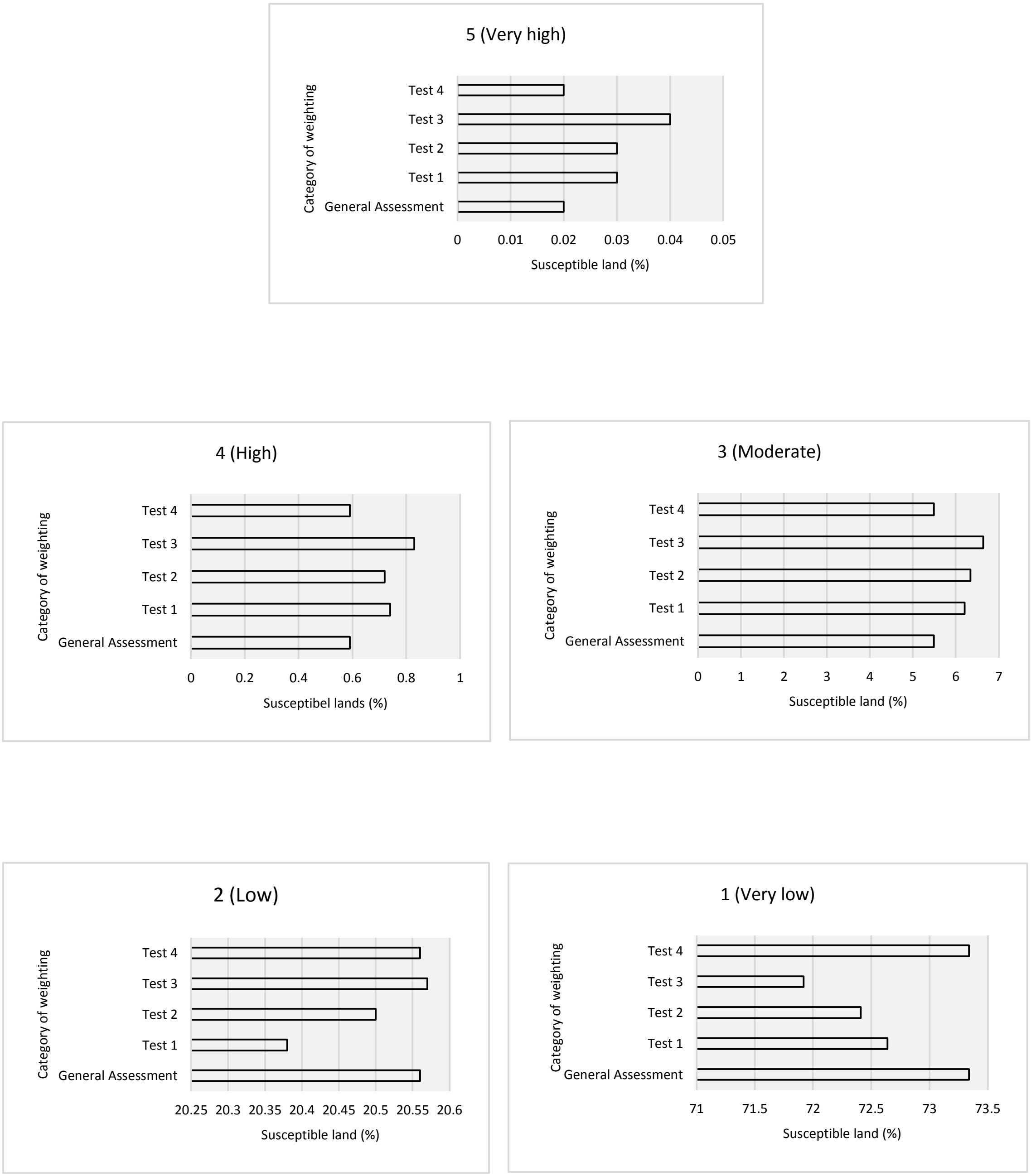

Figure 3.9.2.1a – Comparison of the results obtained for the four sorts of changes in the weights with the results of the general assessment. The figure scales for the susceptible lands are not identical due to the varied range of percentages between the susceptibility classes. Except for the fourth test, the amounts of susceptible lands under five susceptibility classes were slightly varied but, very close to the general assessment.

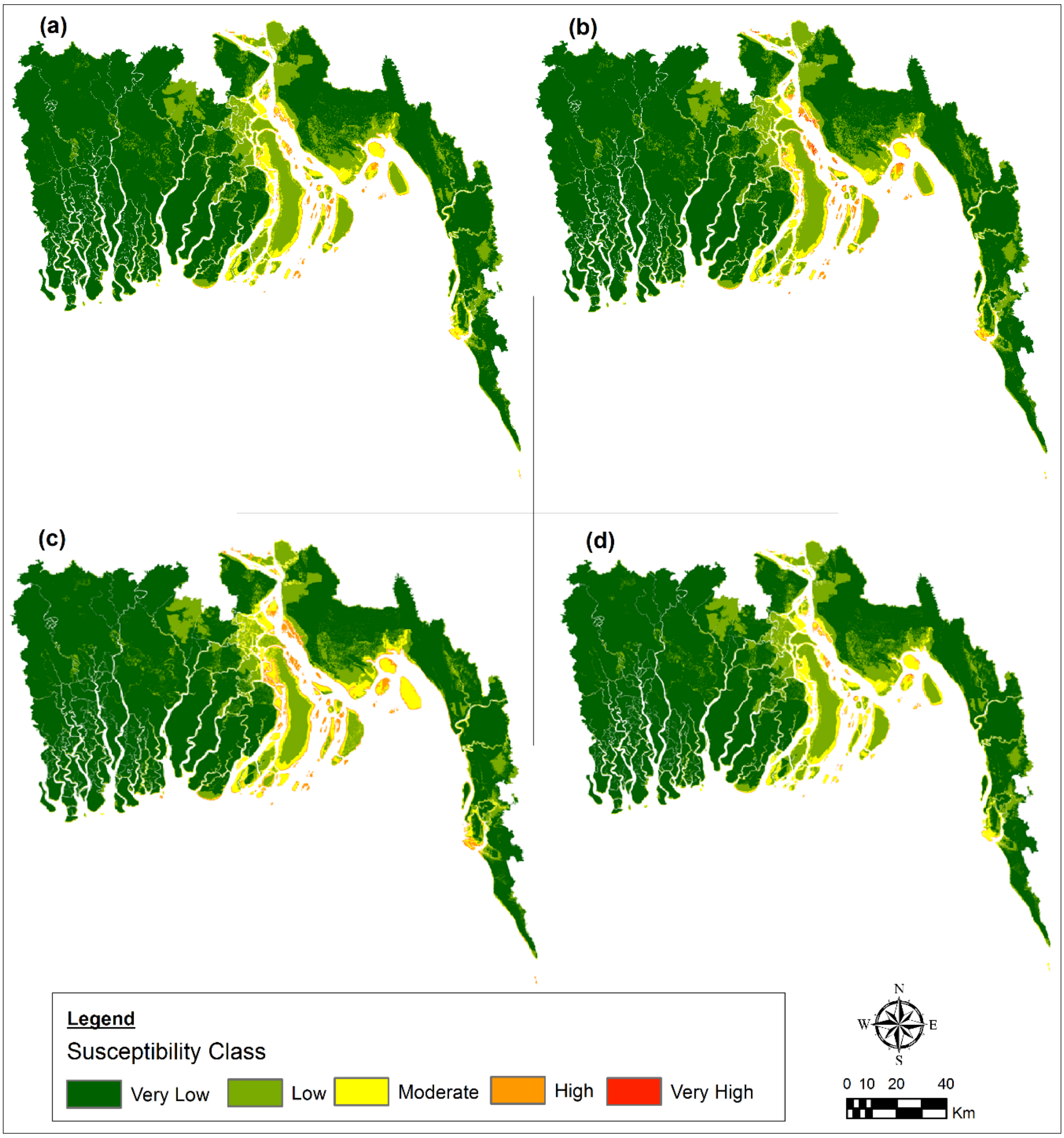

Figure 3.9.2.1b – The spatial variation of the results identified for the four sorts of weightings of the model parameters: (a) test 1, (b) test 2, (c) test 3 and (d) test 4. The maps indicate a minor amount of changes in the susceptibility classes for the western and eastern coastal zones. However, noticeable changes were identified for the central coastal zone under the third sort of SA test (map c). The zoomed-in view of the central coastal zone for the third SA test (c) is given in the figure (Figure 3.9.2.1c).

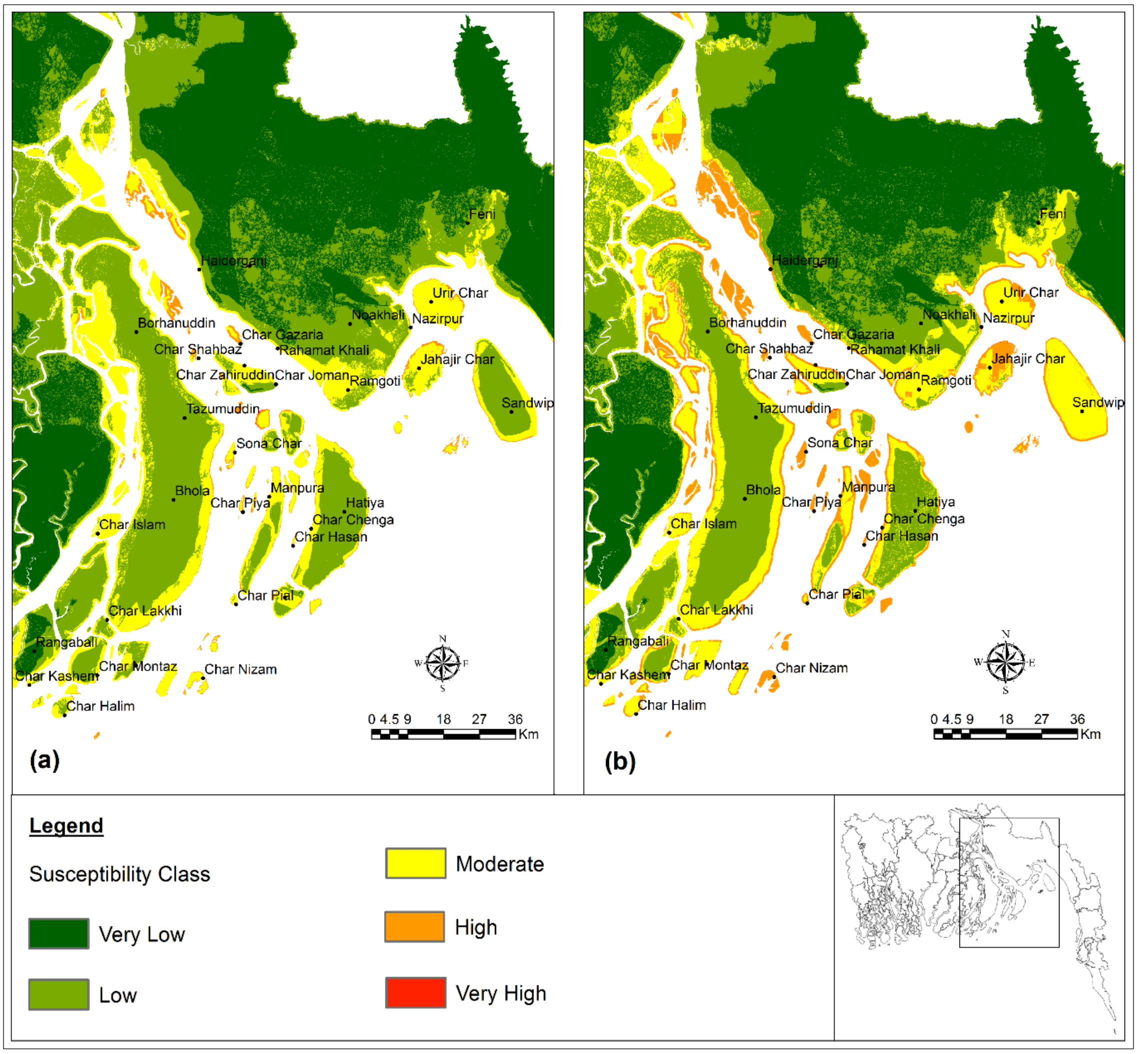

Figure 3.9.2.1c – Comparison of spatial variation in existing land susceptibility to erosion between the (a) general assessment and (b) third SA test for the central coastal zone of the country. Substantial changes were visible for the offshore islands such as Sandwip, Urir Char, Jahajir Char and Manpura in which, very low susceptible lands were turned into moderately susceptible to erosion. Moreover, considerable areas of high and very high susceptible lands were increased in the third SA test compared to the general assessment (Appendix F).

### 3.9.2.2 Distribution of parameter values

The redistribution of parameter values in the model by the using standard deviation classification method for the five susceptibility classes shows far less changes compared to the equal interval method of general assessment. For instance, only 0.39 km$^2$ and 53.17 km$^2$ of very high and moderate susceptible lands were increased respectively for the SA compared to the general assessment. Similarly, the SA showed only 12.18 km$^2$ less amount of high susceptible lands in comparison with the general assessment (Table 3.9.2.2a). A slight decrease in the amounts of low and very low susceptible lands was identified for the SA under new distribution. As a result, the spatial variation of susceptibility for the redistribution was almost similar to the general assessment (Figure 3.9.2.2a).

Table 3.9.2.2a – Comparison of the results obtained for general assessment and sensitivity analysis. The results indicate very similar amounts of susceptible lands for the coastal area obtained by performing the equal interval and standard deviation (1 σ) classification methods.

| Susceptibility class | Method of distribution | | | |
|---|---|---|---|---|
| | Equal interval (General assessment) | | Standard deviation (1 σ) (Sensitivity analysis) | |
| | Area | % | Area | % |
| 1 (very low) | 33163.79 | 73.34 | 33133.08 | 73.27 |
| 2 (low) | 9296.71 | 20.56 | 9286.04 | 20.535 |
| 3 (moderate) | 2483.70 | 5.49 | 2536.87 | 5.61 |
| 4 (high) | 266.32 | 0.59 | 254.14 | 0.562 |
| 5 (very high) | 10.01 | 0.02 | 10.40 | 0.023 |
| Total | 45220.53 | 100 | 45220.53 | 100 |

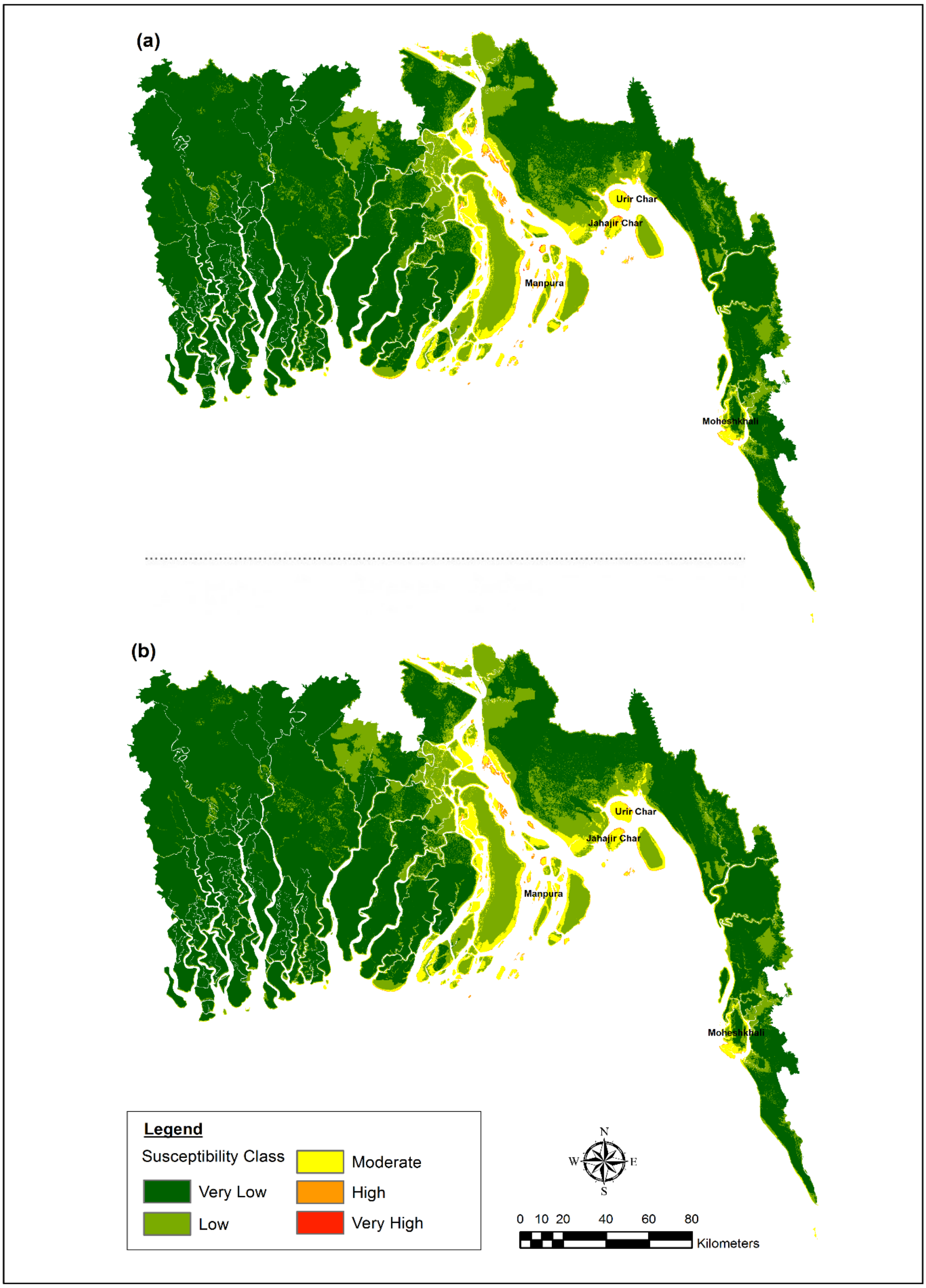

Figure 3.9.2.2a – Spatial variation between the results for (a) general assessment and (b) sensitivity analysis. Minor changes were identified for some offshore islands such as Urir Char, Jahajir Char and Manpura in the central coastal zone. Similarly, changes were visible for Moheshkhali area in the eastern coastal zone of the country.

### 3.9.2.3 General (overall) versus regional (zone) model

The zonal assessment of coastal land susceptibility indicates minor changes for the western and eastern zones but, considerable changes were identified for the central coastal zone in comparison with the general assessment. In the case of very high susceptibility, the central coastal zone resulted in an increase of 6.1 km$^2$ very high susceptible lands to erosion than the lands obtained by general assessment (Appendix F). Moderate changes were identified in the western and eastern coastal zones for very high susceptibility class. Similarly, the SA for regional assessment showed the increases of 6.23 km$^2$ and 144.56 km$^2$ of high susceptible lands for the western and central coastal zones respectively and a very sharp decrease of high susceptible lands (0.96 km$^2$) for the eastern coastal zone of the country (Figure 3.9.2.3a). The western coastal zone saw a substantial increase in moderate susceptibility of land (3.21% of lands) compared to the general (overall) assessment. However, changes in low and very low susceptible classes were minimal in comparison with the general assessment (Table 3.9.2.3a).

Table 3.9.2.3a - Comparison of area and percentages between general (overall) and regional model of land susceptibility to erosion. The combined results for the three zones show that the major changes occurred for very high and high susceptibility classes.

| Susceptibility class | Area | | Percentage | |
|---|---|---|---|---|
| | Overall | Zone-wise | Overall | Zone-wise |
| 1 (very low) | 33163.79 | 31374.91 | 73.34 | 69.38 |
| 2 (low) | 9296.71 | 9635.98 | 20.56 | 21.31 |
| 3 (moderate) | 2483.70 | 3774.84 | 5.49 | 8.35 |
| 4 (high) | 266.32 | 416.15 | 0.59 | 0.92 |
| 5 (very high) | 10.01 | 18.65 | 0.02 | 0.04 |
| Total | 45220.53 | 45220.53 | 100 | 100 |

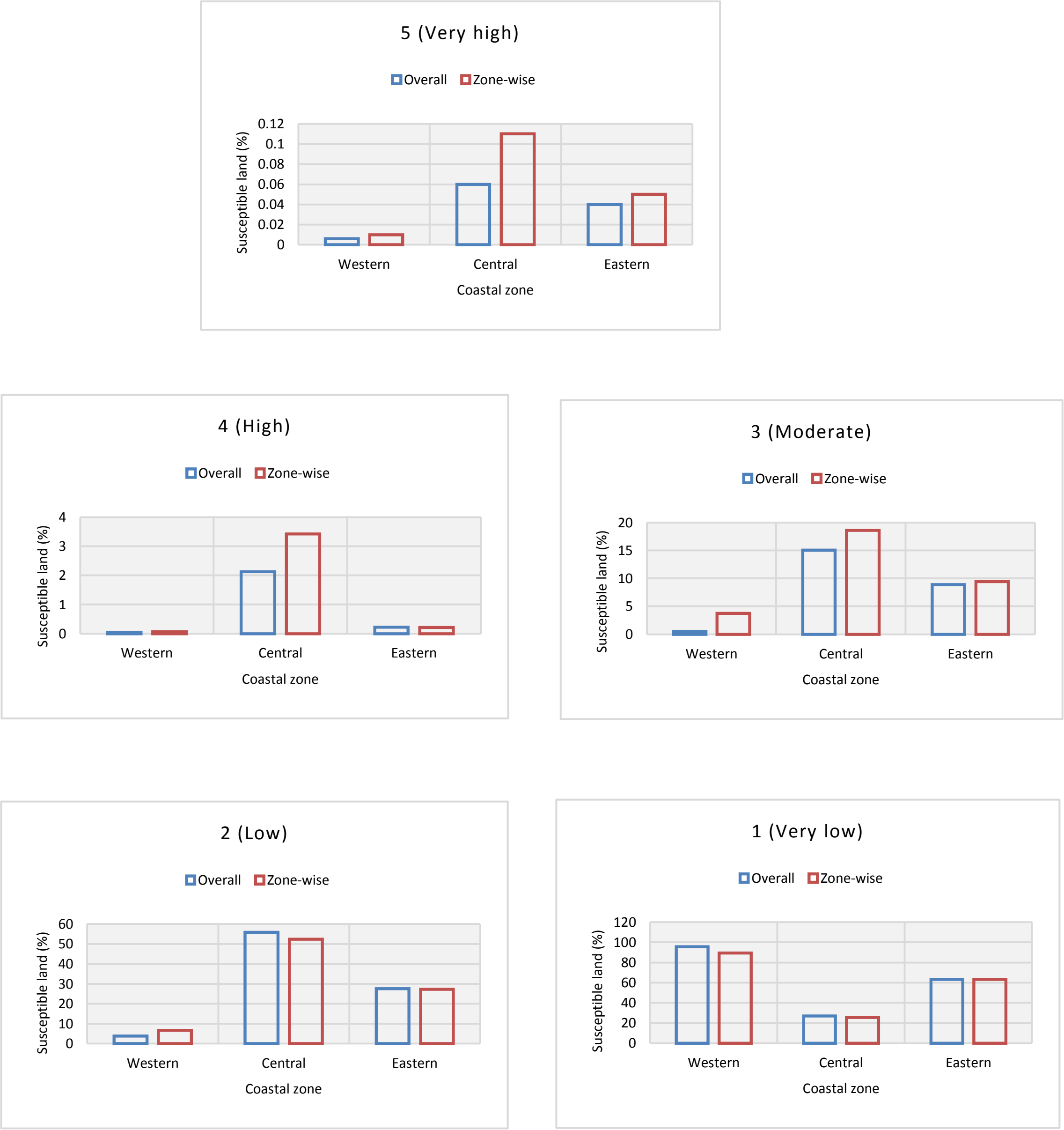

Figure 3.9.2.3a – Comparison of the levels of susceptibility between general (overall) and zone-wise (regional) assessment for the three coastal zones. Minor changes were identified for all of the susceptibility classes in the eastern coastal zone compared to the central and western coastal zones.

Spatially, Khepupara, Kuakata, Khasher Haat, Baufal, Dashmina, Charmonai, and Shibchar areas in the western coastal zone showed changes in the levels of erosion susceptibility under this zonal assessment (Figure 3.9.2.3b). Other areas such as Jessore, Satkhira, Gopalganj, Khulan, Bagerhat, Hiron Point and Alfadanga produced similar results as for the general assessment. Substantial changes were identified for the central coastal zone in which, low susceptible lands at Urir Char, Jahajir Char and Sandwip areas were turned into moderate susceptibility to erosion (Figure 3.9.2.3c). Further, the high susceptible lands at Borhanuddin and Haiderganj areas were converted to very high susceptibility to erosion. A substantial amount of low erosion susceptible area at the newly accreted lands was also turned into moderate erosion susceptibility in the central coastal zone. However, less changes in the levels of susceptibility were detected for the entire eastern coastal zone, except some increased amounts of moderate susceptible lands at Moheshkhali area of the zone (Figure 3.9.2.3d).

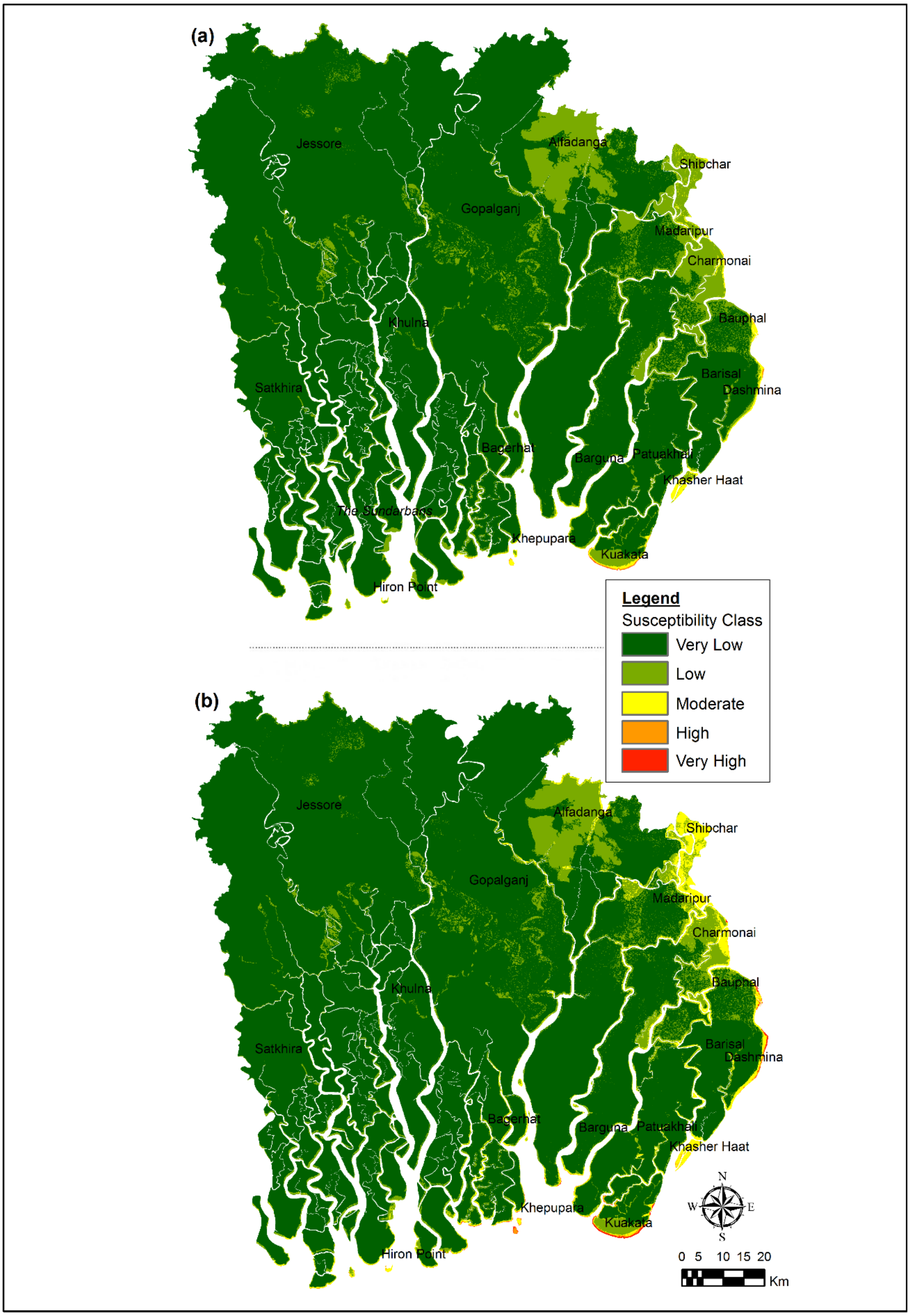

Figure 3.9.2.3b – Spatial changes in the levels of existing land susceptibility to erosion for the western coastal zone under (a) general assessment and (b) zonal assessment. Considerable changes in land area from low susceptibility to moderate susceptibility class were visible under the zonal assessment.

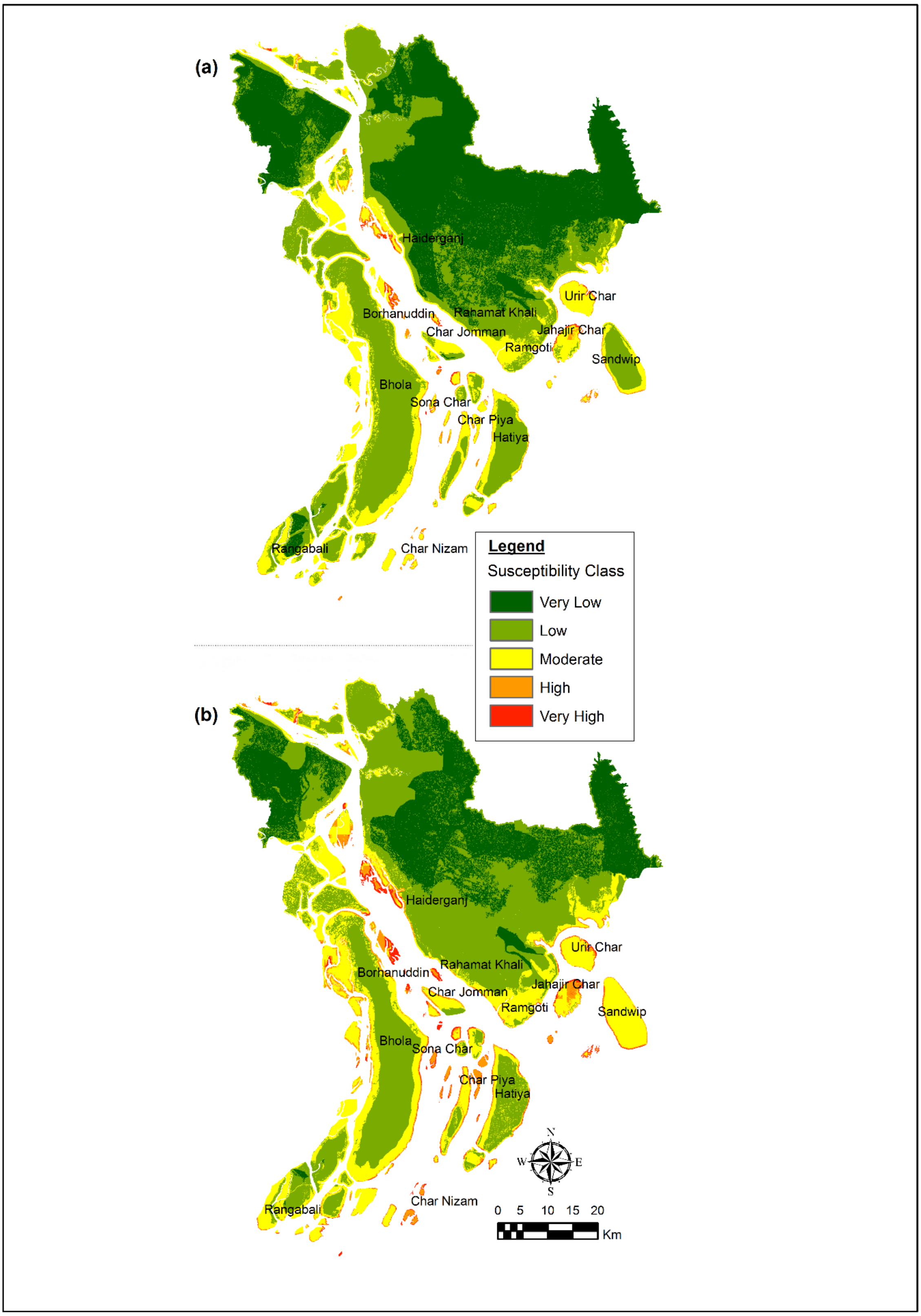

Figure 3.9.2.3c – Comparison of spatial changes in existing land susceptibility to erosion for the central coastal zone under (a) general assessment and (b) zonal assessment. Changes in very low, moderate and high susceptibility were noticeable for the entire area of the central coastal zone.

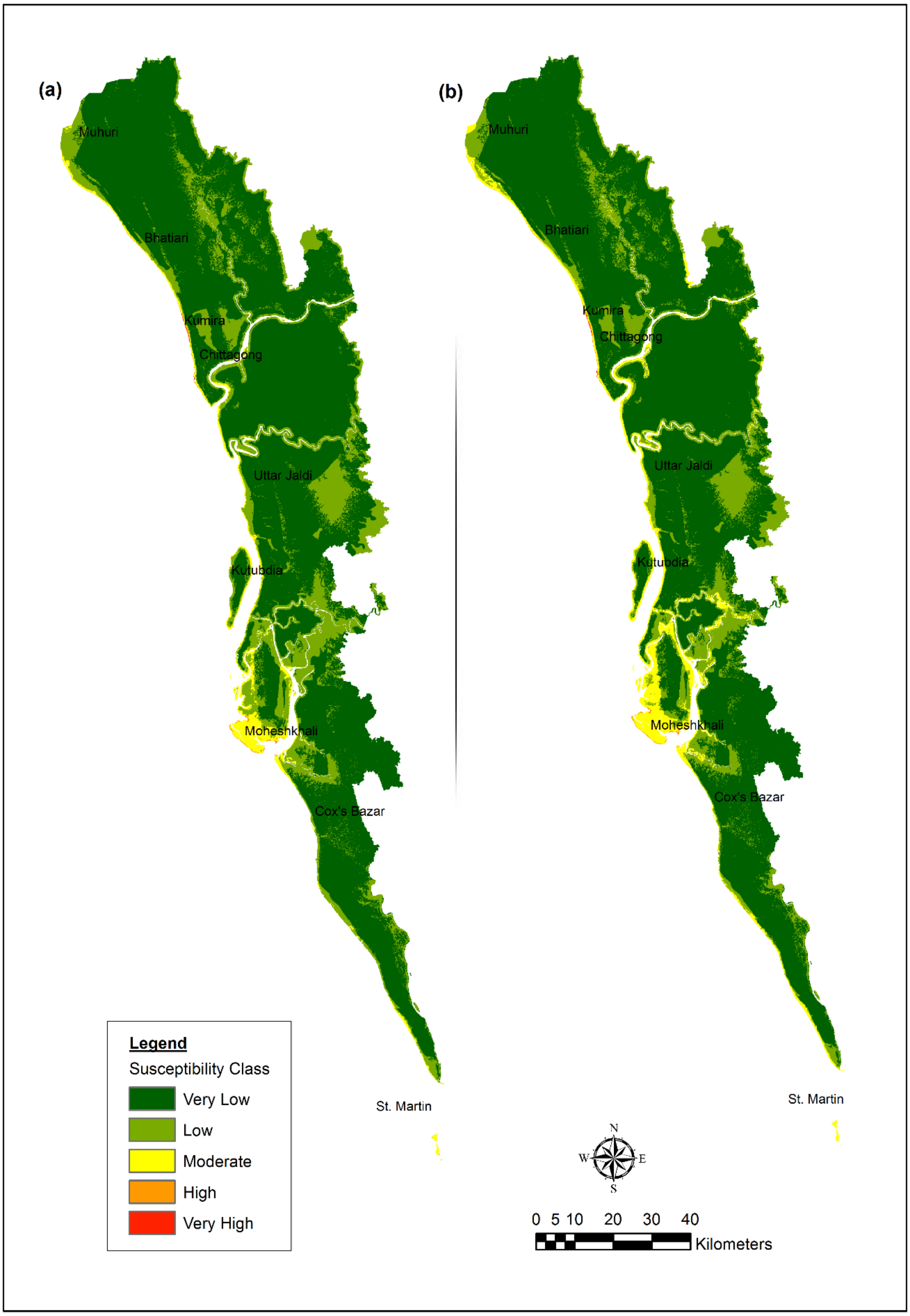

Figure 3.9.2.3d – Comparison of changes between (a) general and (b) regional model of land susceptibility for the eastern coastal zone of the country. The islands such as Moheshkahli and St. Martin showed noticeable changes in land susceptibility to erosion.

### 3.9.3 Discussion on sensitivity analysis

The sensitivity analysis (SA) by way of changing the weights of the model parameters indicates small changes for the first and second tests and considerable changes for the third test compared to the general assessment. As expected, the fourth test resulted in no changes in the levels of susceptibility to erosion. The probable reason behind the slight change in the levels of susceptibility under test 1 could be due to the impacts of hydro-climatic factors (i.e. increases of 10% weights). The assignment of full (1) weights for the hydro-climatic factors made 13.44%, 16.59%, 20.59% and 22.75% increases of weights in the model for water discharge, mean sea level, rainfall and wind speed and directions respectively from the previously assigned weights of 0.84, 0.79, 0.71 and 0.65 for the same parameters by the experts. Since there is a substantial influence of hydro-climatic factors in the central coastal zone (discussed in chapter 3), the changes were reflected in the offshore islands and newly accreted coastal lands (Ahmed et al., 2018). The probable controls of underlying physical conditions on erosion susceptibility were visible under the second test of weighting in which a 10% decrease in the underlying physical elements resulted in almost similar kind of changes in the levels of erosion susceptibility as obtained for the first test. The impacts of hydro-climatic factors were highly visible for the third test under the situation of a 10% decrease in weights for underlying physical elements and a 10% increase for hydro-climatic parameters. However, the SA produced no changes in the level of susceptibility under the fourth test. This similar result with the general assessment indicates that the weightings of the parameters in the LSCE model are sensitive. The current sensitivity analysis by changing 10% weights indicates that both the underlying physical conditions and hydro-climatic factors are sensitive for the model but, very less changes were observed for the SA in comparison with the general assessment. The present study assumes that further variations in the weights of the parameters (e.g. 15%, 20% and so on) might change the levels of erosion susceptibility in the LSCE model.

The SA by way of redistributing the parameter values into five susceptibility classes indicates less substantial changes in the levels of land susceptibility to erosion for the current study. The assessment infers that redistributing the ranges of susceptibility classes are not substantially sensitive for the present study area. The probable reason behind these minor changes might be due to several possible reasons. Firstly, the parameter values for surface geology and soil permeability were similar to the general assessment. Secondly, the data ranges of susceptibility classes for underlying physical elements were reduced under this new classification method but, these changes in the data ranges were balanced by the increases of data ranges for the susceptibility classes of hydro-climatic factors. However, the redistribution of the distances from the shoreline is thought to be an influential reason for minor changes observed in the assessment.

The regional (i.e. coastal zones) SA shows the probable impacts of the varied nature of underlying physical elements and hydro-climatic factors in the area more precisely than the other two methods. For instance, due to the probable impacts of hydro-climatic factors along with low surface elevations and low bathymetric depths in the exposed central coastal zone, the regional model identified comparatively more high and very high susceptible lands in the central coastal zone than the western and eastern zones. The lowest average water discharge of 13.70 $m^3/s$ for the Dakatia and 25.70 $m^3/s$ for the Bogkhali river in the western and eastern coastal zones respectively during winter season were much lower than the lowest discharge (i.e. 4543.15 $m^3/s$) recorded for the Meghna river in the central coastal zone (BWDB, 2016). During monsoon season, this lowest discharge in the central coastal zone amounted to 31,120.14 $m^3/s$. Moreover, the lowest average mean sea level in the central coastal zone for the years from 1986 to 2015 was recorded as 2.21 metre at Char Chenga, that was higher than the western (i.e. 1.85 metres at Hiron Point) and eastern (i.e. 2.16 at Cox's Bazar) coastal zones (BIWTA, 2017; PSMSL, 2017; UHSLC, 2017). The highest average mean sea level in the central coastal zone for the same time-period was also higher (i.e. 2.97 metre at Sandwip) than the western coastal zone (i.e. 2.32 metre at Khepupara) but, less than the eastern coastal zone (i.e. 3.48 metre at Chittagong) (Appendix F). Moreover, the amount of annual average rainfall in the central coastal area was higher (i.e. lowest 145.68 mm at Chandpur and highest 247.97 mm at Sandwip) than the western coastal zone (i.e. lowest 123.36 mm at Jessore and highest 206.5 mm at Khepupara) (BMD, 2017). However, the amount of rainfall in the central coastal zone was lower than the eastern coastal zone (i.e. lowest 216.84 mm at Chittagong and highest 301.4 mm at Teknaf). The impacts of low surface elevation and bathymetric depths on the levels of erosion susceptibility for the western and eastern zones were reflected in the sensitivity analysis. Comparatively low water discharges, low mean sea level and less amount of rainfall in the western coastal zone were the probable reasons for less changes in the levels of erosion susceptibility compared to the central coastal zone. Further, the probable impacts of hydro-climatic factors were compensated for by the favourable types of surface geology and low permeability of soils in the eastern coastal zone under this regional sensitivity analysis.

The three types of sensitivity analysis in the present study infer that the model parameters are less sensitive in respect of weightings (except the third test) and redistribution of parameter values but, considerably sensitive for regional analysis (especially for the central coastal zone). Moreover, the applicability of the LSCE model needs to consider carefully the assignment of weights for the parameters. One way of assessing parameter weights might be by relying upon the experts' comments that the current study followed for the general assessment. Distribution of parameter values for the susceptibility classes might be important for seasonal analysis in which, variation in the data range is large but, not substantial for the general assessment that the present SA indicates. However, the regional or site-specific parameters need to be considered as the most important factors of erosion susceptibility for the coastal area in a situation where the physical settings and hydro-dynamic conditions vary considerably (e.g. central coastal zone of the country).

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# Chapter 4: Modelling impacts of future climate on land susceptibility to erosion: A geospatial approach applied for the coastal area of Bangladesh

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## 4.1 Abstract

This study envisaged the likely impacts of future hydro-climatic changes on coastal land susceptibility to erosion by developing Geographical Information System (GIS) based raster model namely, Land Susceptibility to Coastal Erosion (LSCE). The model was applied to the coastal area of Bangladesh to assess future erosion susceptibility under four Greenhouse Gas (GHG) concentration trajectories: A1B, RCP2.6, RCP4.5 and RCP8.5. The results indicate considerable changes in future scenarios of coastal land susceptibility to erosion in the area compared to current baseline conditions. The current area of 276.33 km$^2$ (0.61%) high and very high susceptible lands would be substantially increased to 1019.13 km$^2$ (2.25% of land), 799.16 km$^2$ (1.77%), 1181.38 km$^2$ (2.61%) and 4040.71 km$^2$ (8.96%) by 2080 under A1B, RCP2.6, RCP4.5 and RCP8.5 scenarios respectively. Spatially, the western and eastern coastal zones would have low to moderate susceptibility to erosion whereas, the central coastal zone would have moderate to high/very high susceptibility to erosion. Seasonally, the model predicted the high erosion susceptibility during the monsoon seasons and very low erosion susceptibility during the winter seasons in future. The model outputs were enhanced by integrating experts' judgements through Fuzzy Cognitive Mapping (FCM) approach. The LSCE model might be indispensable for coastal researchers in generating future scenarios of physical susceptibility to erosion for highly dynamic coastal areas around the world.

## 4.2 Introduction

Along with a number of coastal hazards (such as tidal surge, cyclone, flooding etc.), the excessive rate of coastal erosion considerably increased coastal vulnerability at national, regional and global levels (Ramieri et al., 2011). Coastal erosion is the result of natural factors (e.g. sea level rise, wave actions etc.) and human actions (e.g. engineering works, land reclamation, deforestation etc.) (Alexandrakis et al., 2010; Van, 2011). Coastal susceptibility to erosion however, designates the degree of physical resistance of coastal lands to erosion hazard. Susceptibility to erosion essentially derives from physical forces and often can largely be treated as independent of human influences (United Nations Development Programme [UNDP], 2004). Along with a number of predispositions and preparatory factors (discussed in chapter 3), a range of triggering factors such as heavy rainfall, sea level rise, prevailing winds and discharge of water govern the likelihood and severity of erosion susceptibility (Saunders and Glassey, 2007; MPI, 2017). These triggering factors are closely associated with the changes in climatic conditions. However, there is a growing interest in the scientific community about the response of shoreline to the changes in future climate (Naylor et al., 2010). The likely changes in future climate might have substantial influences on the triggering factors (MPI, 2017), the consequent results of which would convert a considerable amount of coastal lands into high susceptibility to erosion. For instance, future scenarios of sea level rise might change the horizontal configuration of any coastline (Warrick and Ahmad, 1996; Huq et al., 1999) that may lead to a long-term erosion of coastal lands (Fitzgerald et al., 2008). However, coastal responses to climate change are strongly determined by the site-specific factors (Masselink and Russell, 2013) and hence, it is important to address the ways how underlying physical elements of any coastal system react with, and control on, the changes of hydro-climatic drivers.

The changes in hydro-climatic triggering factors due to global warming and consequent sea level rise are visible in the coastal area of Bangladesh (Mahmood, 2012; Brown et al., 2018). Hence, it is essential for coastal researchers to synthesise the likely influences of future hydro-climatic changes on erosion susceptibility in the coastal area of the country. It is also crucial to consider the probable responses of physical settings of the coastal area to the future scenarios of those changes. Considering the mentioned situations, the current study focused on the research question: how exactly the levels of future erosion susceptibility in the coastal area of Bangladesh will undergo changes due to likely changes in hydro-climatic triggering factors in the area? This study aimed to generate future scenarios of erosion susceptibility in the coastal area by applying Land Susceptibility to Coastal Erosion (LSCE) model (Ahmed et al., 2018b) under the four Greenhouse Gases emission trajectories: A1B, RCP2.6, RCP4.5 and RCP8.5 for the three time-slices (i.e. 2020, 2050 and 2080). This is the first study to address the future impacts of hydro-climatic changes on erosion susceptibility for both the offshore and inland coastal areas of the country. The study also identified the extent of seasonal variations compared to the overall scenarios of physical susceptibility to erosion. The findings reported here for Bangladesh provide insights into how erosion along similar dynamic coastal systems around the world may respond to future hydro-climatic changes.

## 4.3 Methodology

### 4.3.1 Study area

Both inland and offshore coastal areas of Bangladesh were selected to apply the LSCE model in assessing future erosion susceptibility that cover a total 45,220 km$^2$ of lands. The inland coastal limit was based on tidal movements in the area that varies between three geomorphologically distinct coastal zones: western, central and eastern (MoEF, 2007; Shibly and Takewaka, 2012) (Figure 4.3.1a). The variations in tidal movements are visible during different seasons. Considering the settings, this research used spectral signatures obtained from multi-temporal satellite images as a common boundary between land and water (Ahmed et al., 2018a).

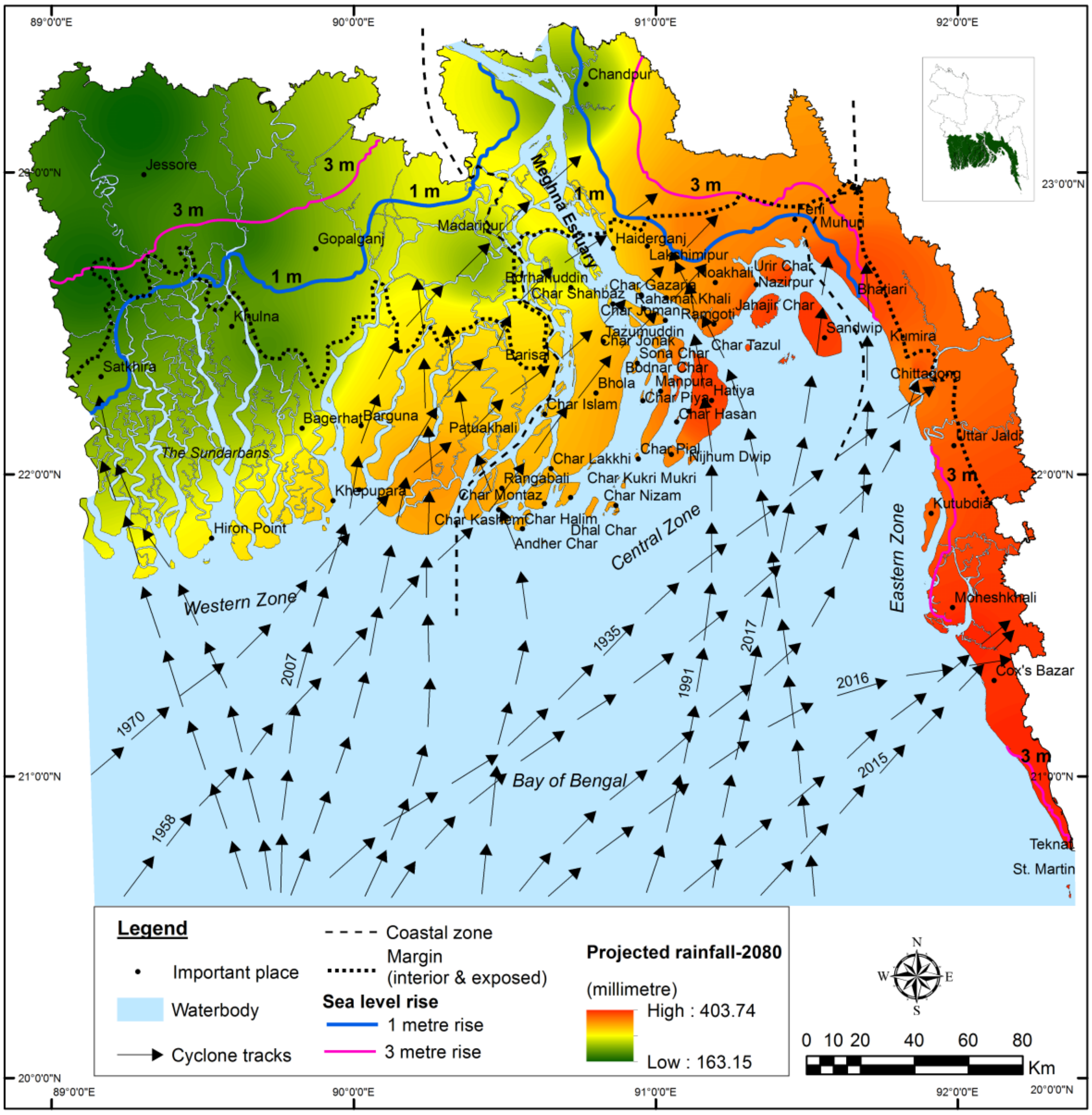

Figure 4.3.1a - The extent of the coastal area of Bangladesh selected for the present study. The figure shows the projected amount of rainfall by 2080 and the likely

propagation of mean sea level under 1 metre and 3 metres rises. The projections of mean sea level rise show the substantial extent of land inundation in the area. Moreover, the figure shows the historical cyclone tracts in the Bay of Bengal and the landfall places in the coastal area. [Data sources: BBS, 2015 and BWDB, 2016 (important place); CEGIS, 2014 (sea level rise); CCKP, 2016 (projected rainfall); MoEF, 2016 (coastal zones and margin between interior and exposed coast)]

This study considered the probable changes in future hydro-climatic conditions a key reason in choosing the highly dynamic coastal area of Bangladesh (Ahmed et al., 2018a) as a case to generate future land susceptibility to erosion by applying the LSCE model. The coastal area is likely to be affected severely by the future changes in hydro-climatic conditions (Centre for Environmental and Geographic Information Services [CEGIS], 2014; BMD, 2016; Climate Change Knowledge Portal [CCKP], 2016). The impacts are already visible in the coastal area of the country (Ali et al., 2007; Islam, 2008). The figure (Figure 4.3.1a) illustrates the likely impacts of future hydro-climatic changes in the area. The RCP4.5 rainfall scenario for monsoon season indicates a considerable increase in the total amount of rainfall in the central and eastern coastal areas of the country by 2080 (CCKP, 2016). Whereas, a 1 metre rise in mean sea level may inundate almost the entire exposed coastal area of the country (23,935 km$^2$) (CEGIS, 2014). The funnel-shaped coastal area is also exposed to future cyclonic storms that already affected by a number of historic tropical cyclones and strong winds (e.g. up to 260 km/h during cyclone SIDR in 2007) and storm surges (BMD, 2016; Banglapedia, 2018). It is predicted that the shoreline and river mouths might be pushed inland by the rising trends of Mean Sea Level (MSL) that would alter the amounts of river water discharge in the coastal area. Furthermore, the tidal range might be increased by the non-linear effect of inundation through rising sea level that could accelerate the rate of erosion in future (Huq et al., 1999; BWDB, 2016; BIWTA, 2017). Additionally, the occurrences of cyclones might increase in the area due to the probable changes in future climate (BMD, 2016). Moreover, the predicted rise in monsoon rainfall might increase the runoff and sediment loads in the Ganges-Brahmaputra-Meghna (GBM) river catchment area (Brammer, 2014). With this, the behaviour of waves in the Bay of Bengal will affect the net landward transport of sediments (Viles and Spencer, 1995). The mentioned scenarios might make the coastal area more dynamic in future.

### 4.3.2 Methods

This study assumed that there would be significant influences of hydro-climatic changes on future land susceptibility to erosion in the coastal area. A raster GIS-based model namely, Land Susceptibility to Coastal erosion (LSCE) has been developed (Ahmed et al., 2018b) to assess existing susceptibility to erosion in the coastal area of Bangladesh. However, the assumption of the present study is supported by the LSCE model in which five underlying physical elements (i.e. surface elevation, surface geology, bathymetry, soil permeability and distance from shoreline) and four hydro-climatic triggering factors (i.e. discharge of coastal river water, mean sea level (MSL), rainfall and wind speed and direction) were considered as model parameters. The parameters were identified by conducting an in-depth review of the literature for the study area. Additionally, to address the positive effects of sedimentation (accretion) and defence structures on erosion susceptibility, this study used two sets of buffer zones known as moderators. The existing underlying physical elements were assumed as static parameters in the model for generating future scenarios of erosion susceptibility. However, future changes in the four hydro-climatic triggering factors were calculated by applying the changes in percentages of future hydro-climatic scenarios obtained from secondary sources. The validated outputs of existing conditions (Ahmed et al., 2018b) were used as a baseline to generate future scenarios of erosion susceptibility by applying 10-year average model projections under four emission trajectories: A1B (business-as-usual scenario), RCP2.6 (Representative Concentration Pathway-low scenario), RCP4.5 (moderate scenario) and RCP8.5 (high scenario) for three time-slices: 2020 (2015~2025), 2050 (2045~2055) and 2080 (2075~2085). By using 'Model Builder' extension of ArcMap (version 10.3) the final outline of the model was designed. The 'weighted sum' operation in ArcMap was used to overlay the generated hydro-climatic raster surfaces on the raster surfaces prepared for existing underlying physical elements.

To assign weights to individual parameters, this study incorporated the opinions and ratings of 11 relevant experts having in-depth local knowledge on the selected parameters by arranging a workshop (Ahmed et al., 2018b). The weights ranged from 0 to 1 where 0 indicates no weight and 1 indicates the full weight of any parameter. The experts suggested full weights to the underlying physical elements (1 in a range of 0 to 1) for both baseline and future scenarios of the parameters. On the other hand, the weights of the hydro-climatic drivers varied: 0.84 for discharge of coastal river water;

0.79 for mean sea level; 0.71 for rainfall and 0.65 for wind speed and direction that were applied for baseline conditions and assumed to be same for future scenarios. The raster surfaces were multiplied by their given weights and finally summed together (Figure 4.3.5a). The weighted sum scores of each scenario were then converted into five different categories starting from 0 to 100 (where, 0-20= very low (1); 21-40= low (2); 41-60= moderate (3); 61-80= high (4) and 81-100= very high (5) susceptibility to erosion). The study area embraces four prevailing seasons: winter (December to February), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October to November) (BMD, 2016). Due to the scarcity of seasonal hydro-climatic scenario data, this study used only A1B trajectory-based data to generate scenarios of seasonal variation of erosion susceptibility in the coastal area. The outputs of the future scenarios were justified by incorporating experts' opinions through Fuzzy Cognitive Mapping (FCM).

### 4.3.3 Data sources

The baseline data for underlying physical elements were obtained from different sources (Ahmed et al., 2018b) such as ASTER-DEM (Advanced Space-born Thermal Emission and Reflection Radiometer-Digital Elevation Model) from United States Geological Survey (USGS, 2017) for surface elevation, near-shore bathymetry from Global Multi-Resolution Topography (GMRT, 2017), surface geology from United States Geological Survey (USGS, 2001) and soil permeability from Bangladesh Agricultural Research Council (BARC, 2017). Tide-synchronous Landsat satellite images (OLI_TIRS sensor) were collected in 2016 and used to identify the existing shoreline (considered as a mark of mean high water line) for measuring distances of each pixel from the shoreline (Ahmed et al., 2018b). However, hydro-climatic data for baseline conditions were collected from different sources (BMD, 2016; BWDB, 2016; BIWTA, 2017; PSMSL, 2017; UHSLC, 2017) in which, long-term averages of past datasets (i.e. 1985 to 2015 for MSL, rainfall and wind speed and direction and 1995 to 2015 for water discharge) were considered. Except for water discharge, the ranges of baseline data (i.e. long-term averages) were similar to the baseline data used for hydro-climatic scenarios in the present study. Data on mean sea level were collected from six coastal stations located at Char Chenga, Chittagong, Cox's Bazar, Hiron Point, Khepupara and Sandwip (Appendix C). A total number of 18 coastal stations were considered for the data on rainfall and wind speed and direction (the average values collected from Chittagong-IPA and Chittagong-Ambagan stations were considered as

Chittagong station) whereas, 11 stations were considered for the data on discharge of coastal river water (Appendix C).

Table 4.3.3a - The nature and sources of future hydro-climatic scenario data used for the LSCE model. The areal extent of the data for mean sea level, rainfall and wind speed and directions were for the coastal area of the country whereas, the data for water discharge derived by the sources were for the Ganges-Brahmaputra-Meghna basin area.

| LSCE model parameter | Climate trajectory | Model used | Area | Source |
|---|---|---|---|---|
| Water discharge | A1B, RCPs | Artificial Neural Network (ANN) | Ganges-Brahmaputra-Meghna basin | Kamal et al., 2013 |
| Mean sea level | A1B | POLCOMS (Proudman Oceanographic Laboratory Coastal Ocean Modelling System) | Coastal and shelf areas in Bangladesh | Kay et al., 2015 |
|  | RCPs | CMIP5 | Haldia station in Bay of Bengal region | IPCC's AR5 report (IPCC, 2014c) |
| Rainfall | A1B | PRECIS (Providing Regional Climate for Impact Studies) HadCM3Q regional climate model | Coastal area of Bangladesh | Institute of Water and Flood Management (IWFM, 2012) |
|  | RCPs | cesm1_cam5 | Coastal area of Bangladesh | Climate Change Knowledge Portal of World Bank Group (CCKP, 2016) |
| Wind speed and direction | A1B | PRECIS HadCM3Q regional climate model | Coastal area of Bangladesh | Institute of Water and Flood Management (IWFM, 2012) |
|  | RCPs | REM02009 (MPI) | Coastal area of Bangladesh | Centre for Climate Change Research (CCCR, 2016) |

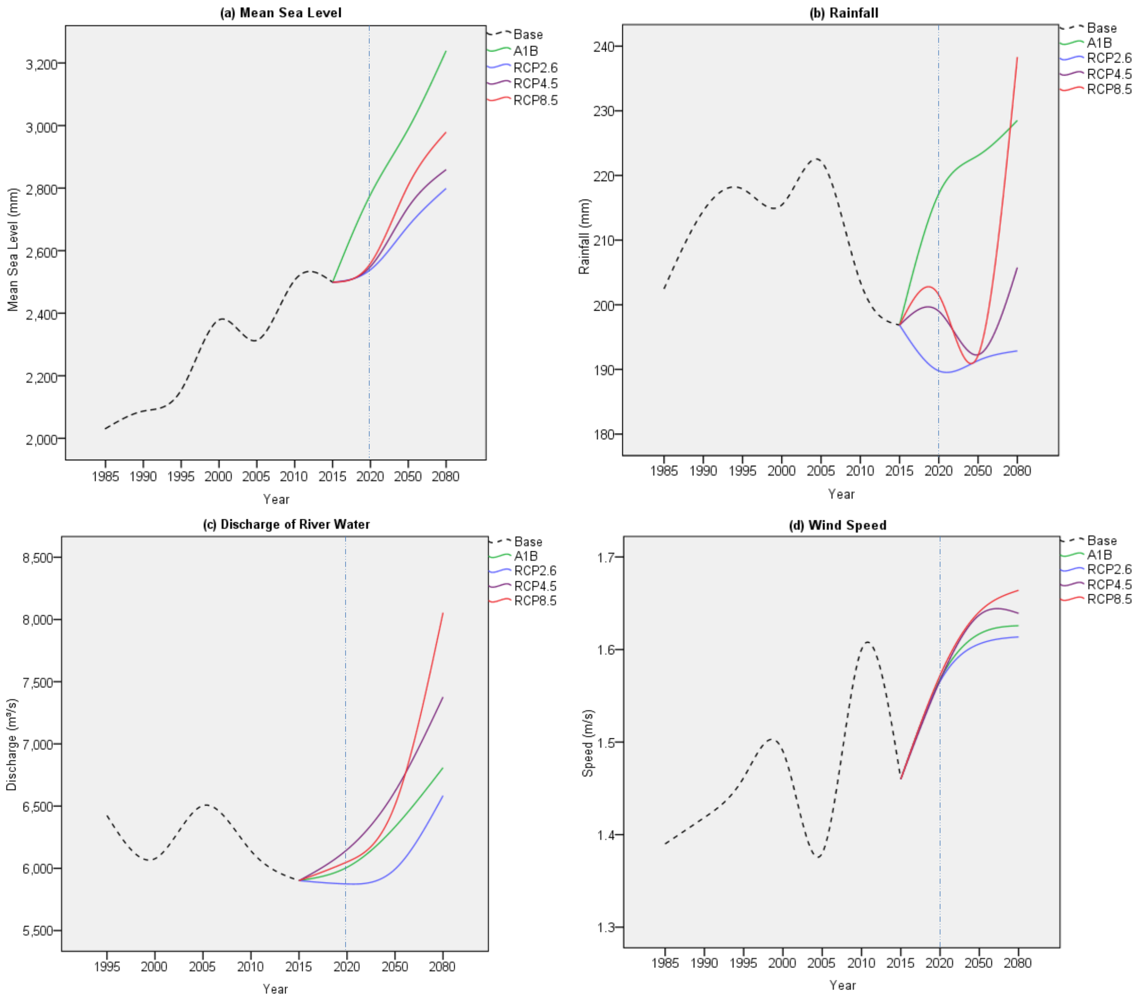

Figure 4.3.3a - Future drivers of change: (a) Mean Sea Level; (b) Rainfall; (c) Discharge of river water and (d) Wind speed obtained from different model results. The horizontal axis represents both short-term (i.e. 5 years from 1985/1995 to 2020) and long-term (i.e. 30 years from 2020 to 2080) changes. [Source: BMD, 2016; BWDB, 2016; BIWTA, 2017; PSMSL, 2017; UHSLC, 2017 (baseline data); Table 4.3.3a (future projections)]

This study applied A1B, RCP2.6, RCP4.5 and RCP8.5 trajectory-based (IPCC, 2007 a, b; IPCC, 2014c) hydro-climatic scenario data collected from different sources (Table 4.3.3a) to generate four future scenarios of land susceptibility to erosion in the coastal area. To prepare model data on future scenarios of hydro-climatic parameters, the baseline data were recalculated by using the percentage changes of parameters obtained from the model scenarios for the three time-slices. The overviews of annual average hydro-climatic data used for generating future scenarios of erosion susceptibility are presented in the figure (Figure 4.3.3a) and the table (Table 4.3.3b).

Table 4.3.3b – Projected wind directions in the coastal area of Bangladesh based on A1B trajectory. Substantial variation in the percentages of likely wind directions are projected for winter, pre-monsoon and post-monsoon seasons whereas, less variations are projected for monsoon seasons. [Source: IWFM, 2012]

| Time-slice | Winter | Pre-monsoon | Monsoon | Post-monsoon |
|---|---|---|---|---|
| 2020 | N (21%) | SW (29%) | S (33%) | NE (19%) |
| 2050 | N (16%) | SW (23%) | S (33%) | N (14%) |
| 2080 | N (18%) | S (31%) | S (31%) | NE (12%) |

### 4.3.4 Data processing and scaling of raster surfaces

To prepare raster surfaces, the raw data obtained for the underlying physical elements went through some pre-processing as well as some post-processing works by using ArcMap and Erdas Imagine software (Figure 4.3.5a). Likewise, raster surfaces for baseline and future scenarios of the four hydro-climatic triggering factors were generated from the collected point data by applying suitable polynomial surface interpolation techniques such as Inverse Distance Weighting (IDW) and Kriging in ArcMap. However, three sets of accretion moderators were generated for baseline conditions in which a negative value (-3) was applied for the first set considering 200 m landward from the shoreline, followed by (-2) and (-1) value for 100 m and 50 m landward respectively next to the first buffer zone. For defence moderators, (-5) was assigned to hard defence such as sea-wall, dyke etc. whereas, a negative value (-3) was set for soft defences such as polder, embankment etc. The values of the related pixels were then recalculated using 'raster calculator' tool in ArcMap that substantially reduced the previous values of the relevant pixels. Due to uncertainties pertaining to the future areas for sedimentation and defence structures, the future moderators were applied for the same areas as used for baseline conditions. The 'ready to run' raster surfaces were used for scaling, weighting and generating baseline conditions and future scenarios of land susceptibility to erosion. To identify the levels of future susceptibility, the pixel values of the raster surfaces were scaled and categorised into five different susceptibility classes ranging from 1 to 5 (where 1 represents very low and 5 represents very high susceptibility). The table (Table 3.3.2a in chapter 3) represents the scales of the baseline susceptibility as a basis for generating future scenarios whereas, the figure (Figure 4.3.3a) indicates the changes of percentages applied for scaling future hydro-climatic drivers. Due to data scarcity, A1B trajectory-based projections were considered as an average scenario of wind directions in the coastal area (Table 4.3.3b).

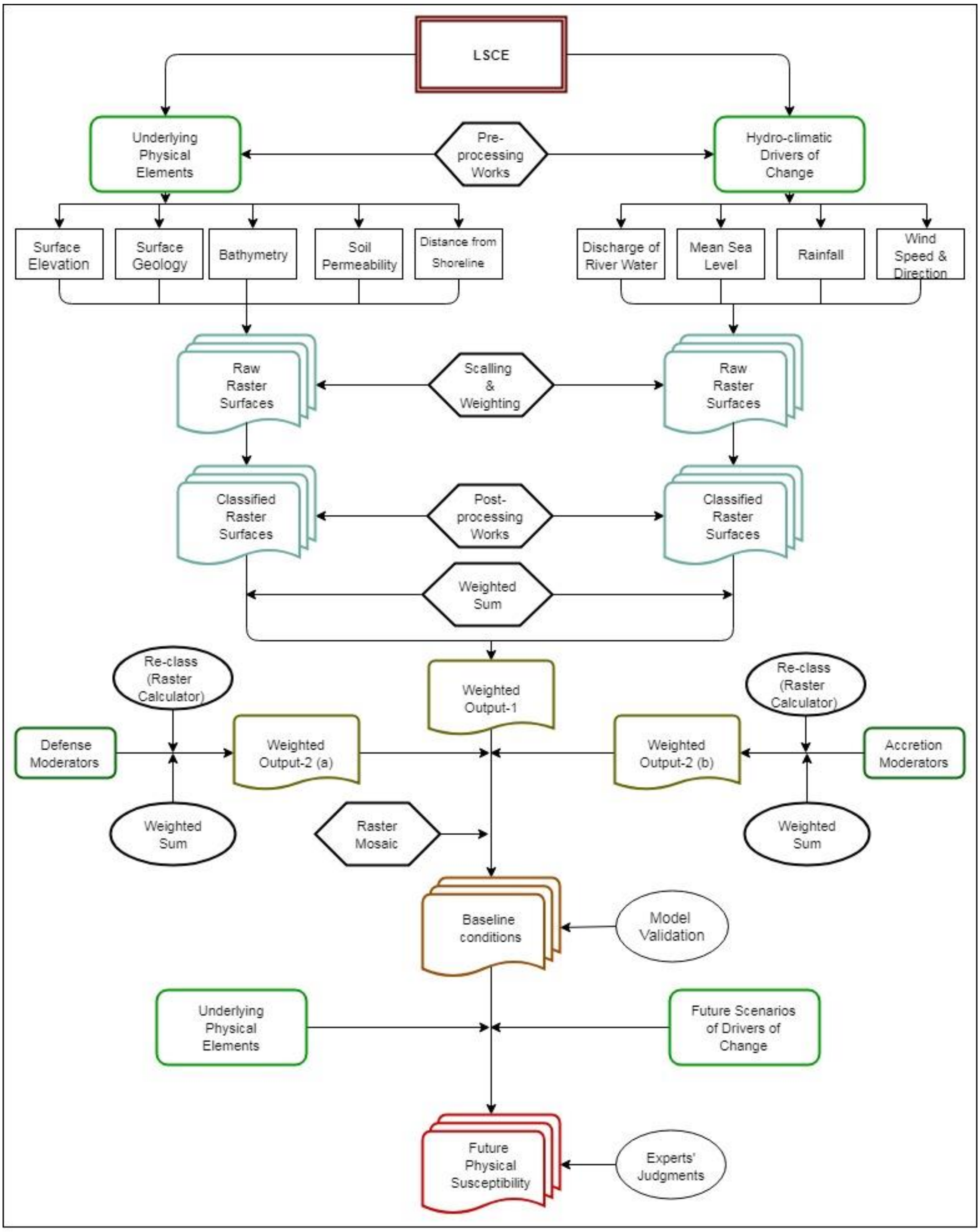

Figure 4.3.5a - A simplified schematic representation of the processes involved in the LSCE model to generate future erosion susceptibility. The pre-processing tasks included geometric, radiometric and atmospheric corrections of DEM, adjustment of vertical accuracy of DEM, making fishnet and conducting zonal statistics for bathymetric and water discharge data whereas, post-processing works included

‘rescale by function’ and ‘fill’ operations. Baseline hydro-climatic parameters were recalculated by the future scenarios and overlaid with existing physical parameters to generate future erosion susceptibility.

### 4.3.5 Process of justification

Although the study considered validated baseline erosion susceptibility (Ahmed et al., 2018b), it was uncertain as to how precisely the selected parameters of the LSCE model incorporated the future physical susceptibility of the coastal area to erosion. Considering the issue, this study applied a semi-quantitative approach to justify and enhance the model outputs on future scenarios of land susceptibility to erosion. The justification was accomplished by addressing the degree of importance of individual parameters of the model on future susceptibility. To do this, a Fuzzy Cognitive Mapping (FCM) approach was adopted to elicit experts’ judgement by using ‘Mental Modeler’ software (Ahmed et al., 2018c, discussed in chapter 5). The experts identified current and future drivers of erosion susceptibility in the coastal area and rated the relationships between the identified drivers in two separate workshops. The final ranking of the identified drivers was based on the centrality scores (i.e. the sum of in-degree and out-degree) yielded. To comprehend uncertainties, the experts were also asked to rate the levels of confidence for the established relationships between the drivers in a seven points rating scale where 1 represents very low and 7 represents very high confidence.

## 4.4 Results

### 4.4.1 Overall susceptibility to erosion

The results indicate substantial changes in future scenarios of land susceptibility to erosion in the coastal area compared to current baseline conditions (Figure 4.4.1a). As expected, the outputs of RCP4.5 scenario are quite similar to the results obtained for A1B scenario. The outputs of both RCP2.6 and RCP8.5 scenarios are, however, substantially differ from A1B and RCP4.5 scenarios (Appendix E). The A1B and RCP4.5 scenarios modelled moderate changes for future time-slices but, RCP2.6 identified less changes and RCP8.5 showed substantial changes in the amount of lands highly susceptible to erosion in future. For instance, RCP2.6 modelled only 0.02%, 0.17% and 0.35% of lands as very high susceptibility to erosion for 2020, 2050 and 2080 time-slices respectively. In contrast, RCP8.5 modelled 0.13%, 1.25% and 2.23% of very high susceptible lands for the same time-slices respectively. In summary, all the four scenarios designate that the amount of very low susceptible lands would be reduced substantially for different time-slices that would turn more lands into high susceptibility in far future.

Spatially, about 98.41% of the lands in the western coastal zone were identified as very low and low susceptibility to erosion for baseline conditions (Figure 4.4.1b). Kuakata and Rangabali areas in the exposed western zone showed moderate to high susceptibility to erosion. The future scenario of these areas, however, would be almost similar to baseline conditions by near future (2020) (Figure 4.4.1c). By 2050, the level of erosion susceptibility at Kuakata and some small islands in the western coastal area would be significantly higher than previous times (Figure 4.3.1a and Figure 4.4.1d). These areas would turn into high and very high susceptibility to erosion by 2080 (Figure 4.4.1e).

The baseline conditions identified about 90.87% of the lands in the eastern coastal zone as very low and low susceptibility to erosion. However, additional 3.54 km$^2$ of existing very low and low erosion susceptible lands at Moheshkhali, Kutubdia and St. Martine islands in the eastern coastal zone (Figure 4.3.1a) would be turned into moderate to high erosion susceptible by 2020. Noticeably, a substantial amount of lands at Chittagong, Cox's Bazar and Noakhali in the exposed eastern coastal zone (Figure 4.3.1a) would be turned into high susceptibility to erosion by 2050 (Figure 4.4.1b). By 2080, high erosion susceptible lands of these areas would be turned into very highly susceptible to erosion.

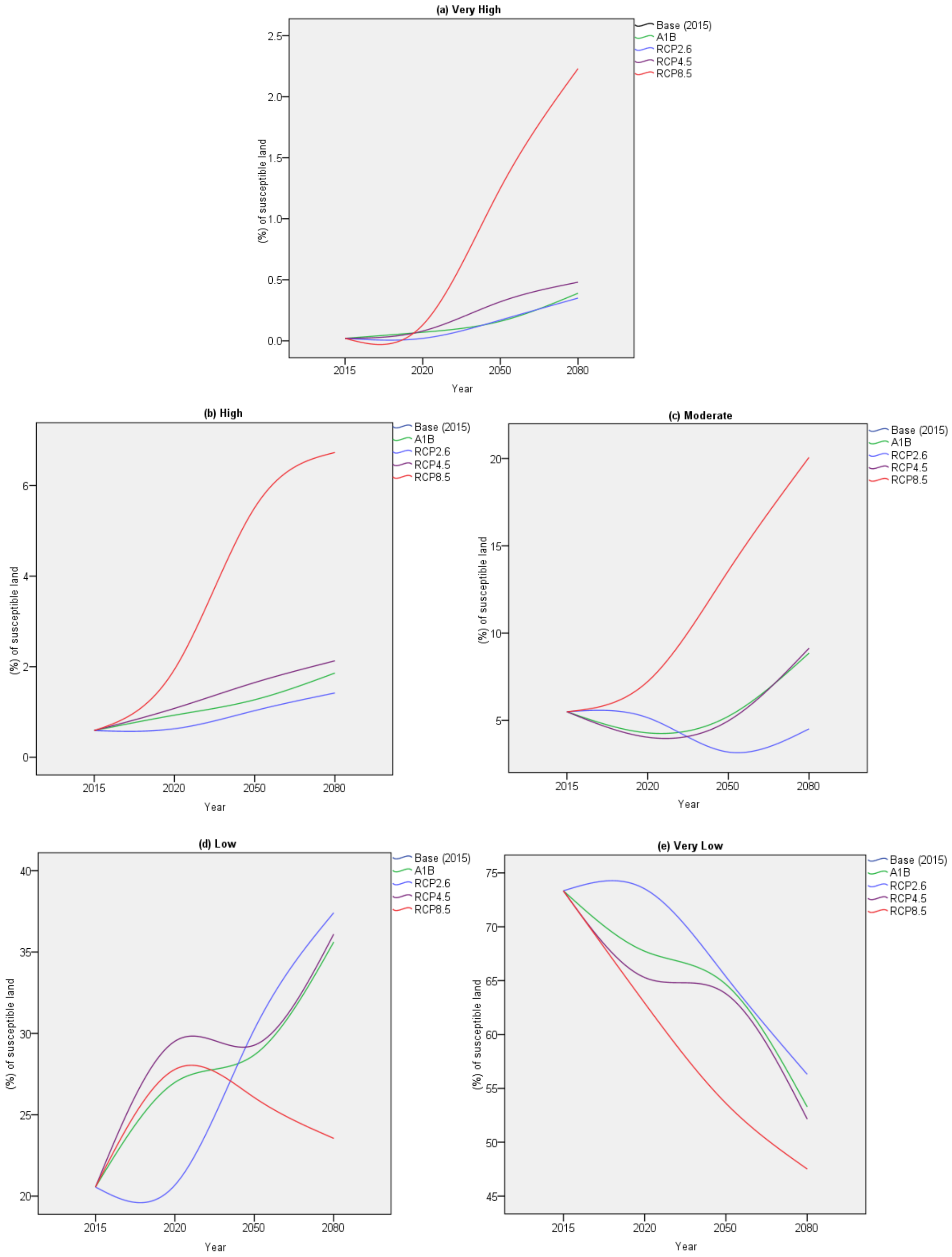

Figure 4.4.1a - Percent changes for future land susceptibility to erosion in the coastal area identified by the model under four climate trajectories for three time-slices (vertical scales are different due to varied data ranges). The total amount of 276.33 km$^2$ (0.61% of land) existing high and very high susceptible lands would be substantially increased to 1019.13 km$^2$ (2.25% of land), 799.16 km$^2$ (1.77% of land), 1181.38 km$^2$ (2.61% of land) and 4040.71 km$^2$ (8.96% of land) by 2080 under the A1B, RCP2.6, RCP4.5 and RCP8.5 scenarios respectively.

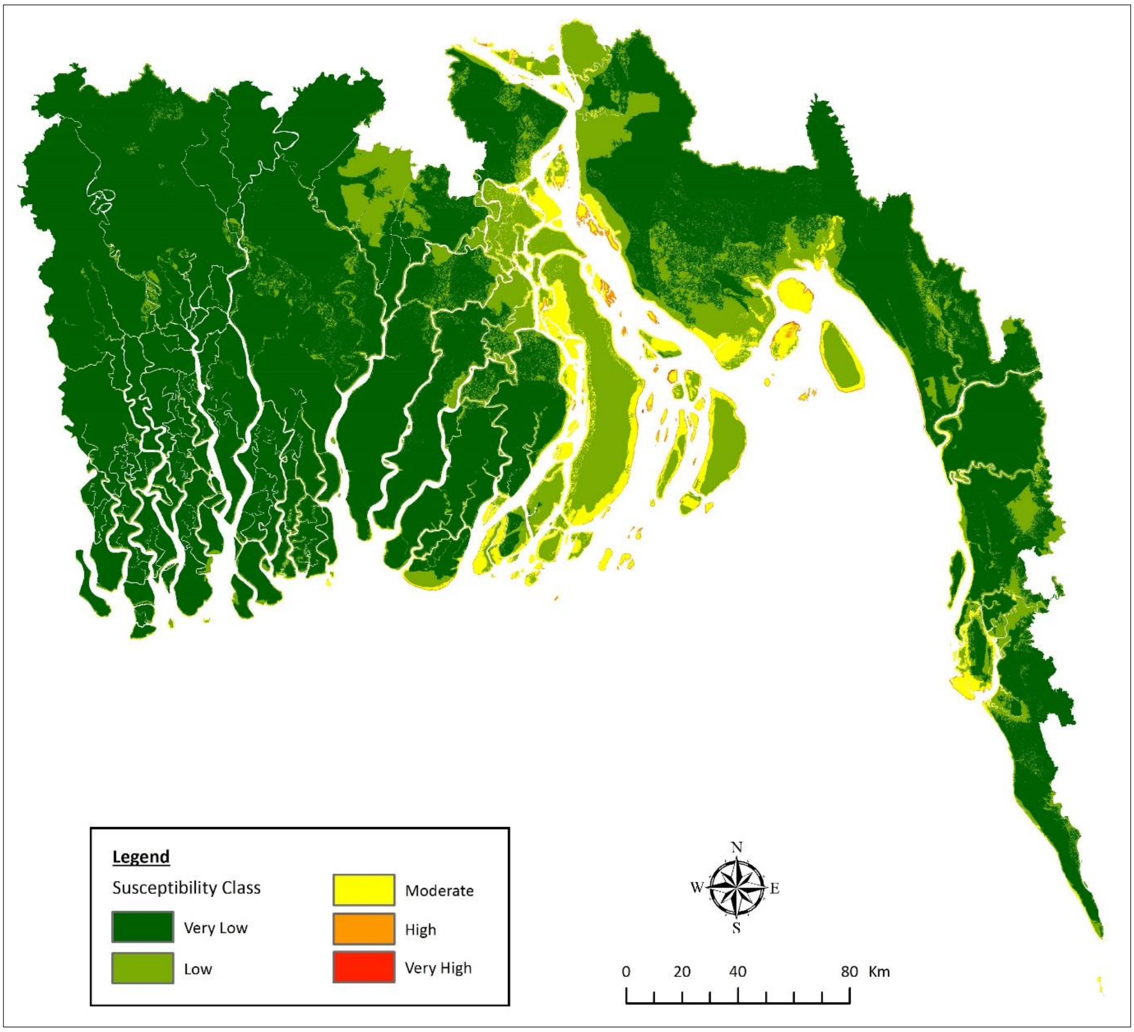

Figure 4.4.1b - Overall land susceptibility of the coastal area to erosion for baseline (2015) conditions (Ahmed et al., 2018b). The LSCE model shows the outputs in the raster map where each pixel represents a unique level of susceptibility among the five classes of erosion susceptibility.

The central coastal zone was identified as the most diversified zone of susceptibility to erosion for baseline conditions as well as for future scenarios. Along with low and moderate erosion susceptibility, some interior coastal areas in the Meghna estuary, newly accreted small islands and banks of the large islands in the exposed coastal area of the central zone were identified as highly susceptible to erosion as well. These areas would be almost similar to baseline conditions by 2020 but, would be turned into highly susceptible to erosion by 2050. For instance, all of the four scenarios for 2020 time-slice identified inland areas of Noakhali, north of Monpura, Char Jonak, Bodnar Char, Dhal Char and some unnamed small islands in this zone (Figure 4.3.1a) as highly susceptible to erosion. The RCP4.5 and RCP8.5 scenarios show that the lands attached to the shoreline and comparatively large islands in the central zone such as Bhola, Hatiya, Sandwip, Char Zahiruddin and Char Gazaria would be highly susceptible to erosion by 2020 (Figure 4.4.1f). A considerable amount of currently moderate susceptible lands at Urir Char, Jahajir Char and Char Piya in the central coastal zone (Figure 4.3.1a) would also be turned into highly susceptible to erosion by the same time. However, these inland and offshore island areas would be more susceptible to erosion under RCP8.5 scenario by 2050 than previous times (Figure 4.4.1d). The areas close to upper Meghna river (e.g. Chandpur) and the central estuarine areas (e.g. Haiderganj) (Figure 4.3.1a and Figure 4.4.1d) would be turned into very high susceptibility to erosion by that time. By 2080, the erosion susceptibility of the mentioned areas in this zone would be higher than the scenario generated for 2050. However, most of the existing very low and low susceptible inland areas in this zone would be turned into moderately susceptible to erosion under RCP8.5 scenario by 2080 (Figure 4.4.1e).

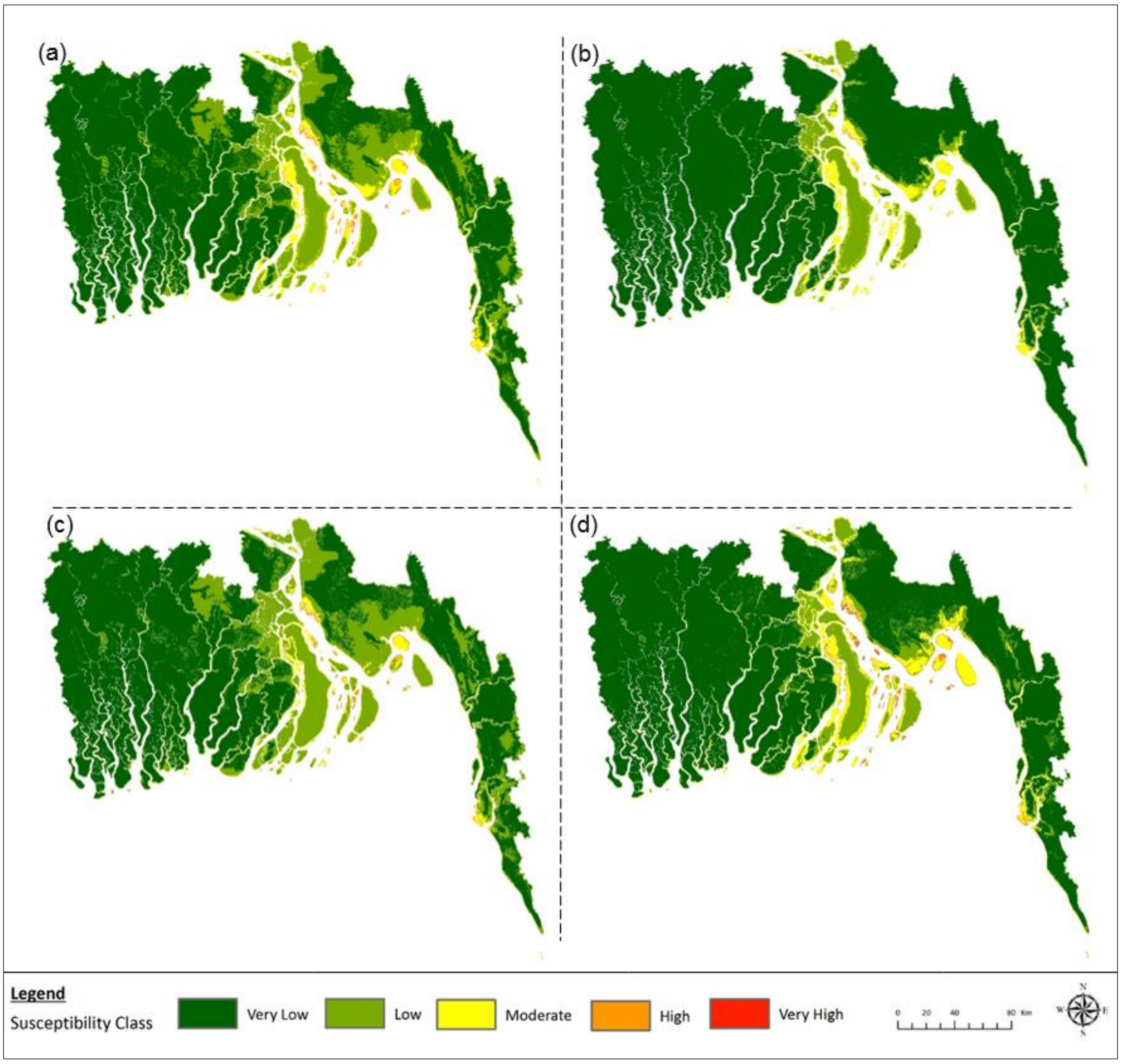

Figure 4.4.1c - Susceptibility of the coastal area to erosion by 2020 for (a) A1B; (b) RCP2.6; (c) RCP4.5 and (d) RCP8.5 scenarios. The susceptibility maps indicate that the

variation in land susceptibility under A1B and RCP4.5 are less. On the other hand, the variation in the levels of susceptibility under RCP2.6 and RCP8.5 are clearly reflected in the maps.

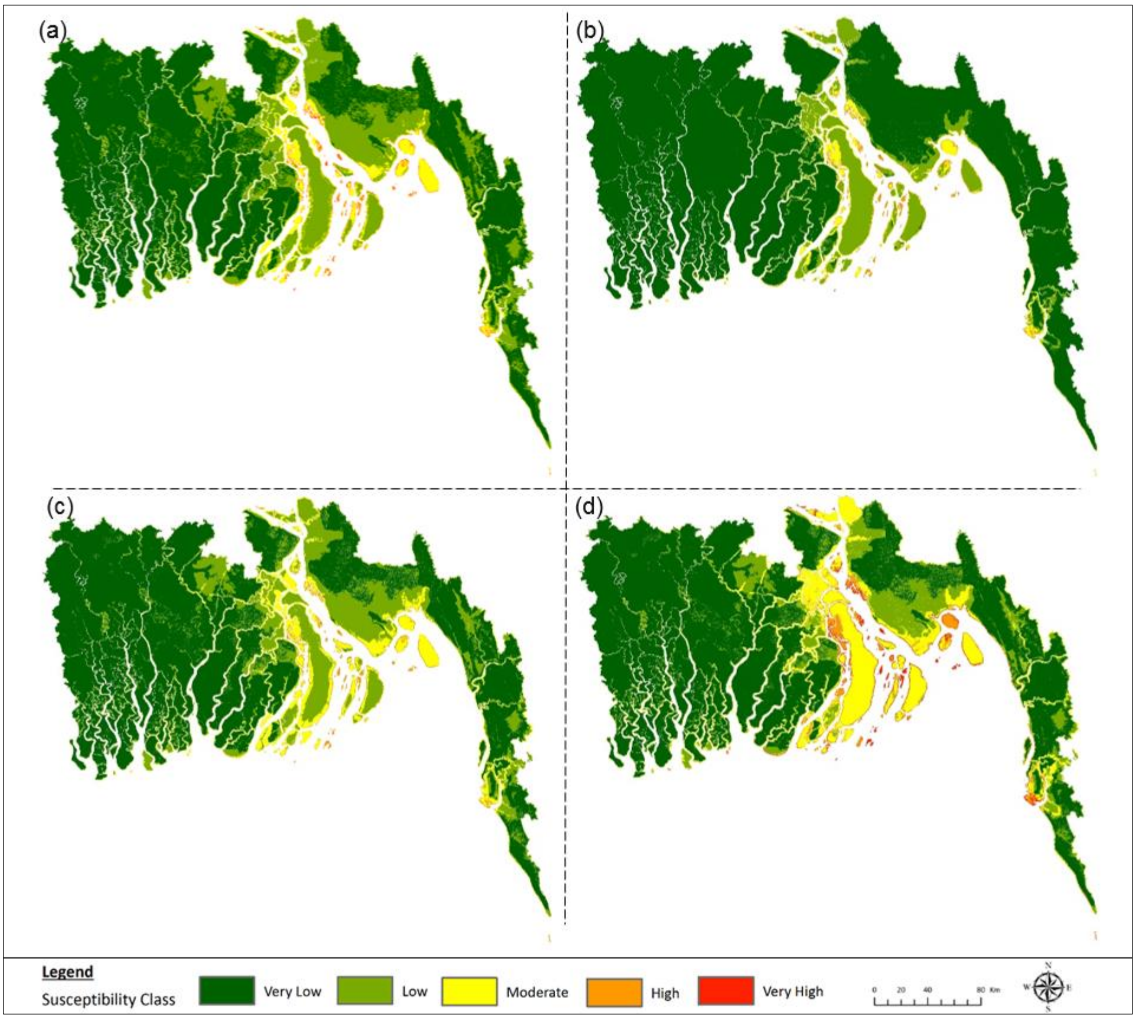

Figure 4.4.1d - Susceptibility of the coastal area to erosion by 2050 for (a) A1B; (b) RCP2.6; (c) RCP4.5 and (d) RCP8.5 scenarios. The likely changes in the levels of land susceptibility to erosion are highly discernible by 2080 under the RCP8.5 scenario.

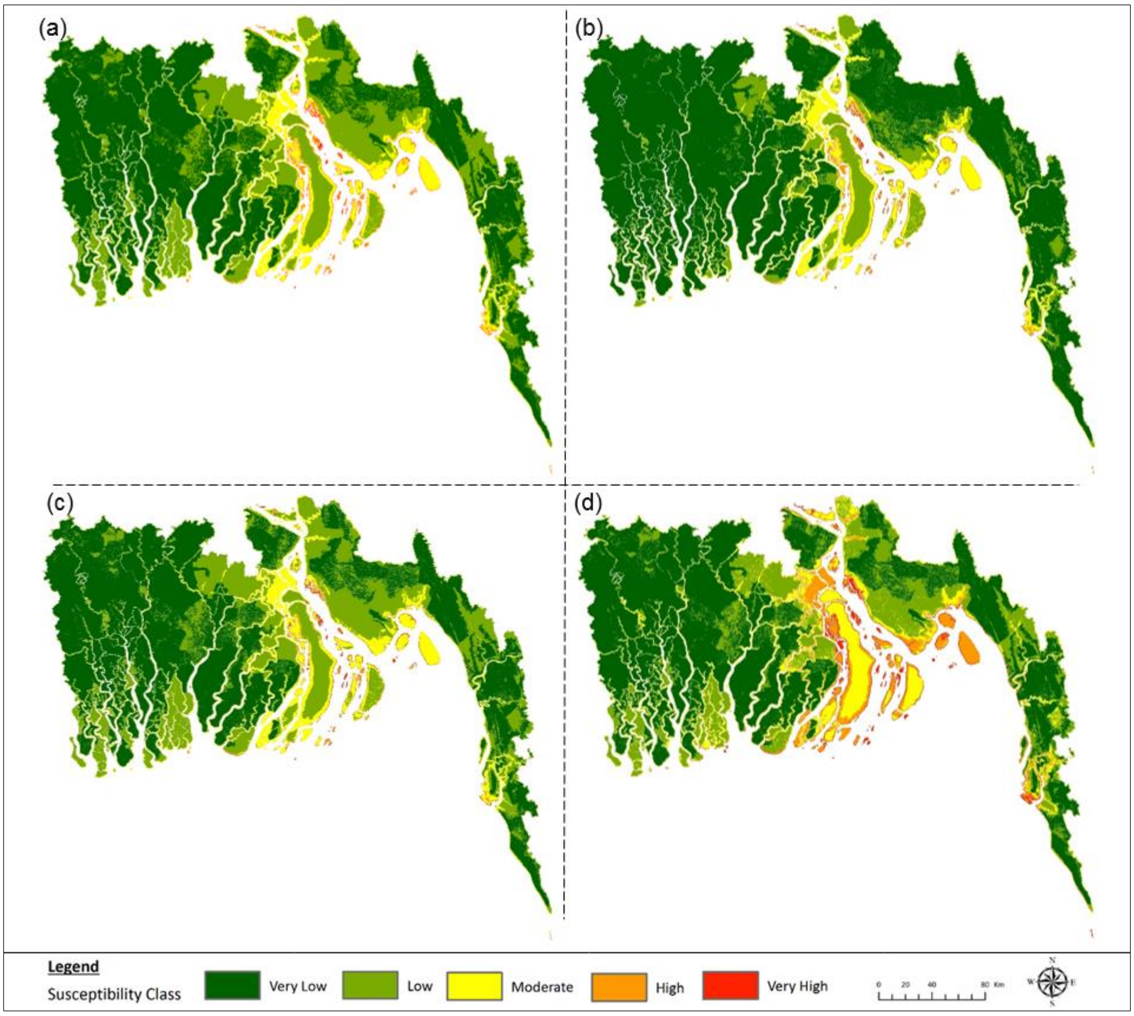

Figure 4.4.1e - Susceptibility of the coastal area to erosion by 2080 for (a) A1B; (b) RCP2.6; (c) RCP4.5 and (d) RCP8.5 scenarios. Although the changes in the levels of land susceptibility to erosion show substantial variations among the four scenarios, major changes are projected under the RCP8.5 scenario.

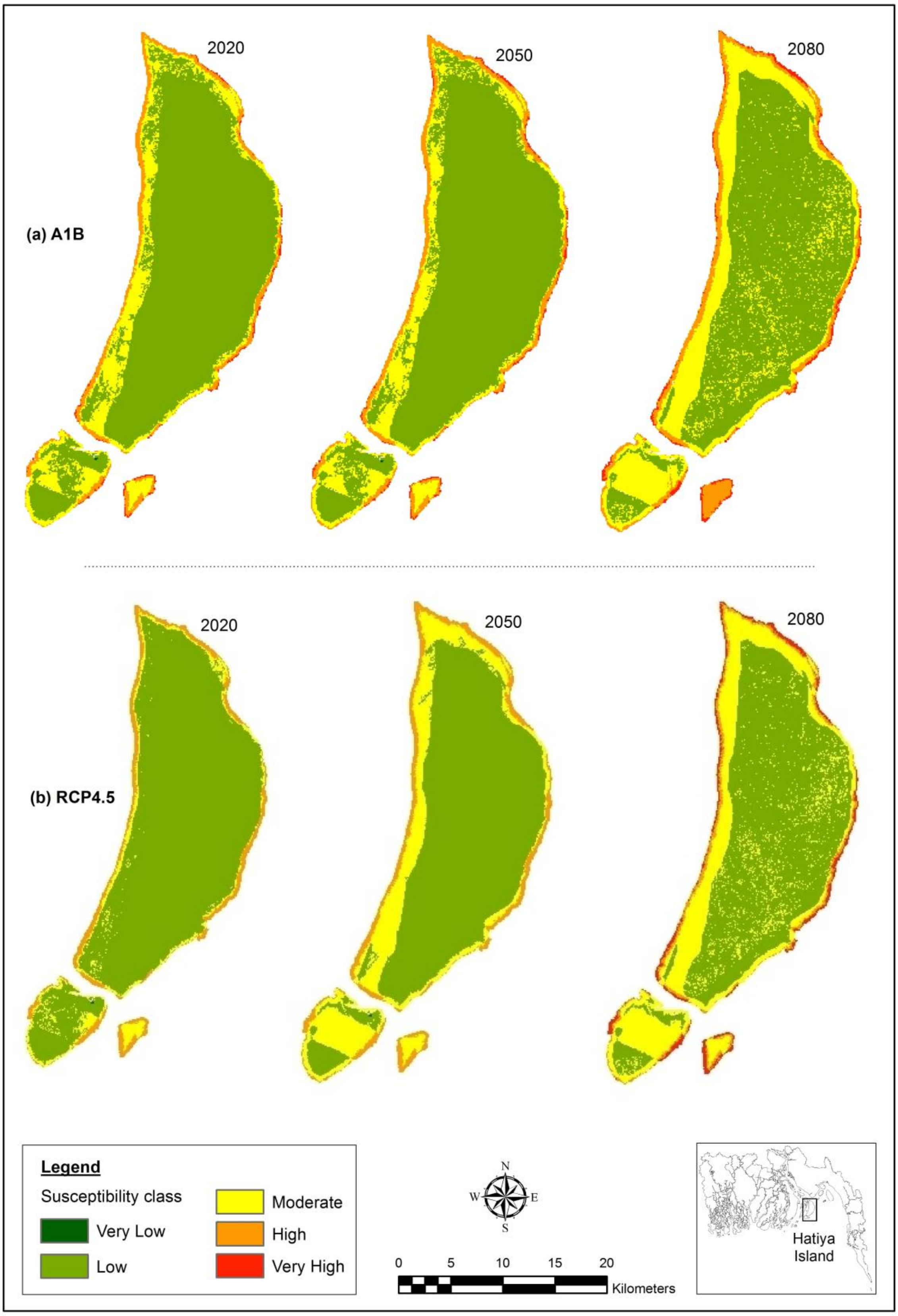

Figure 4.4.1f – An example of likely changes in the levels of erosion susceptibility of an offshore island (i.e. Hatiya) located in the central coastal zone under the (a) A1B and (b) RCP4.5 scenarios. The current amount of 0.87 km$^2$ very high susceptible lands of the island would be increased to 1.53 km$^2$, 5.32 km$^2$ and 8.42 km$^2$ under A1B scenario

for 2020, 2050 and 2080 time-slices respectively. The RCP4.5 scenario shows the likely increases of 1.04 km$^2$, 4.67 km$^2$ and 7.23 km$^2$ lands for the same time-slices respectively. The similar amounts of changes under the scenarios indicate the strong possibility of such changes in future land susceptibility to erosion of the island.

### 4.4.2 Seasonal variation

The A1B model scenario for different seasons indicates substantial amounts of spatial and temporal variations of land susceptibility to erosion in the area (Figure 4.4.2a). The results infer that winter would be the least susceptible and monsoon would be the highest susceptible season to erosion for all the time-slices (Appendix D). For instance, a total 14.39 km$^2$ of lands would be very highly susceptible to erosion by 2080 during winter whereas, this amount would be as high as 501.72 km$^2$ during monsoon by the same times (Figure 4.4.2a). The post-monsoon would be more susceptible to erosion than winter and pre-monsoon would be less susceptible to erosion than monsoon season. The increases of high and very high susceptible lands during future time-slices for all the seasons would consequently reduce the amounts of very low susceptible lands from baseline conditions. Moreover, these changes would make a 3.36% increase of moderate susceptible lands by far-future (2080).

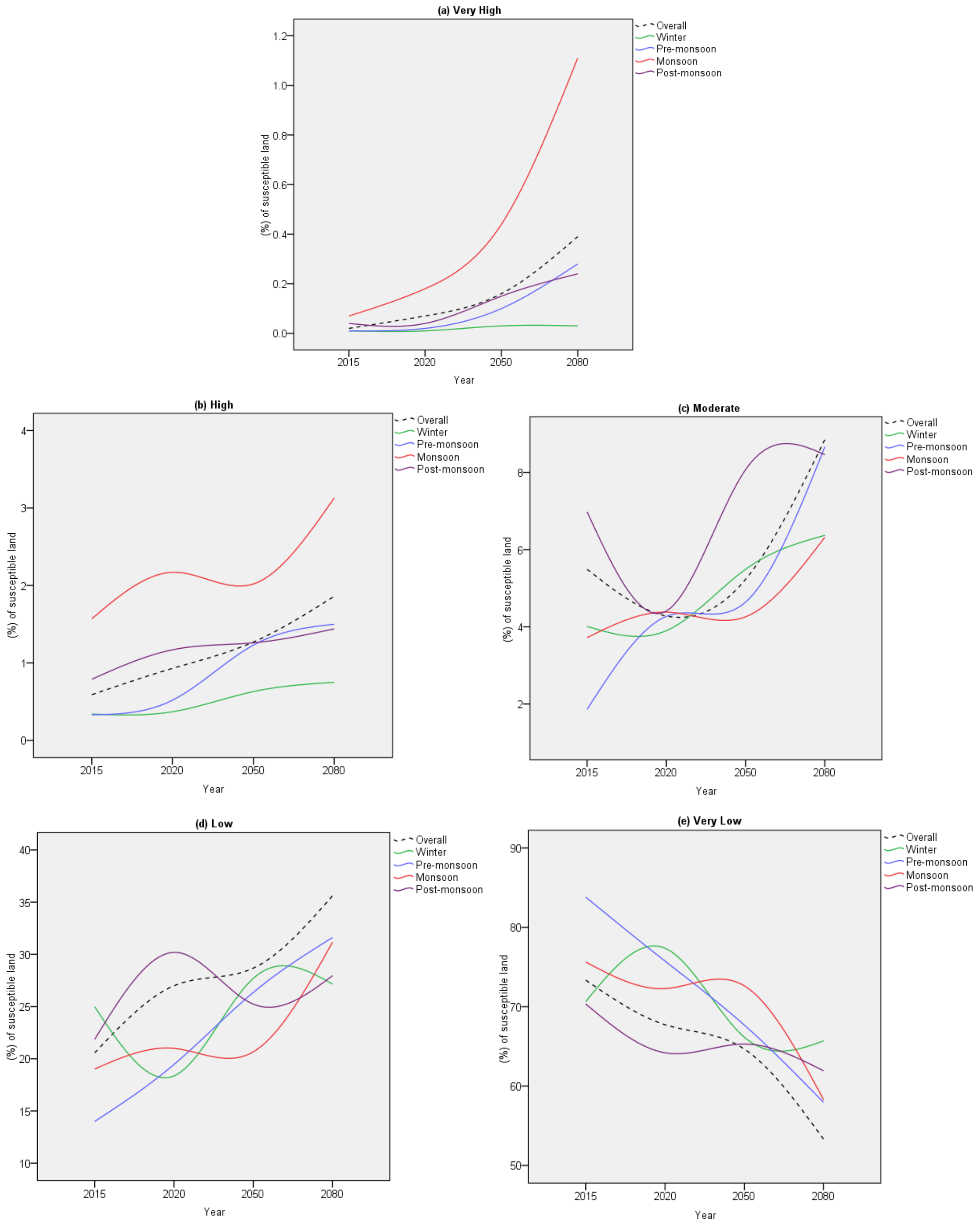

Figure 4.4.2a – The seasonal variation of the percentages of susceptible land changes for (a) very high; (b) high; (c) moderate; (d) low and (e) very low susceptibility categories under the A1B scenario in comparison with the overall baseline conditions for the three time-slices. The figure shows that the percentages of susceptible lands for very high and high susceptibility classes are varied from the baseline for monsoon season compared to pre-monsoon, post-monsoon and winter seasons.

The season-based model scenario designates spatial variation of erosion susceptibility in the three coastal zones. The very low and low erosion susceptible interior areas (i.e. 98.41%) in the western coastal zone would also be quite similar for future time-slices. However, there are exceptions for Kuakata and southern Barguna areas (Figure 4.3.1a). By 2020, these areas would be altered into moderate to high susceptibility during pre-monsoon and monsoon seasons (Figure 4.4.2c and Figure 4.4.2d). Moreover, the low susceptible areas of the Sundarbans would be moderately susceptible during pre-monsoon but, the area would be turned into highly susceptible during monsoon season by 2050. By 2080, the scenario of these areas would be as very high susceptibility to erosion during pre-monsoon and monsoon seasons. About 96.32% of the entire eastern coastal zone during winter and pre-monsoon seasons currently belong to very low and low erosion susceptibility (Figure 4.4.2b and Figure 4.4.2c). However, areas of Moheshkhali and Kutubdia islands (Figure 4.3.1a) were mostly identified as moderate and high susceptibility to erosion for all of the seasons under baseline conditions. Additionally, areas such as Bhatiari and Kumira (Figure 4.3.1a) were also identified as highly susceptible to erosion. By 2080, the scenario of these areas would be turned into high and very high susceptibility during pre-monsoon and monsoon seasons. Similarly, the areal extent of moderate susceptible lands would be increased in this coastal zone during pre-monsoon seasons by the same times. Moreover, the exposed part of this zone having very low susceptibility would turn into low to moderate susceptibility during post-monsoon seasons by 2080 (Figure 4.4.2e).

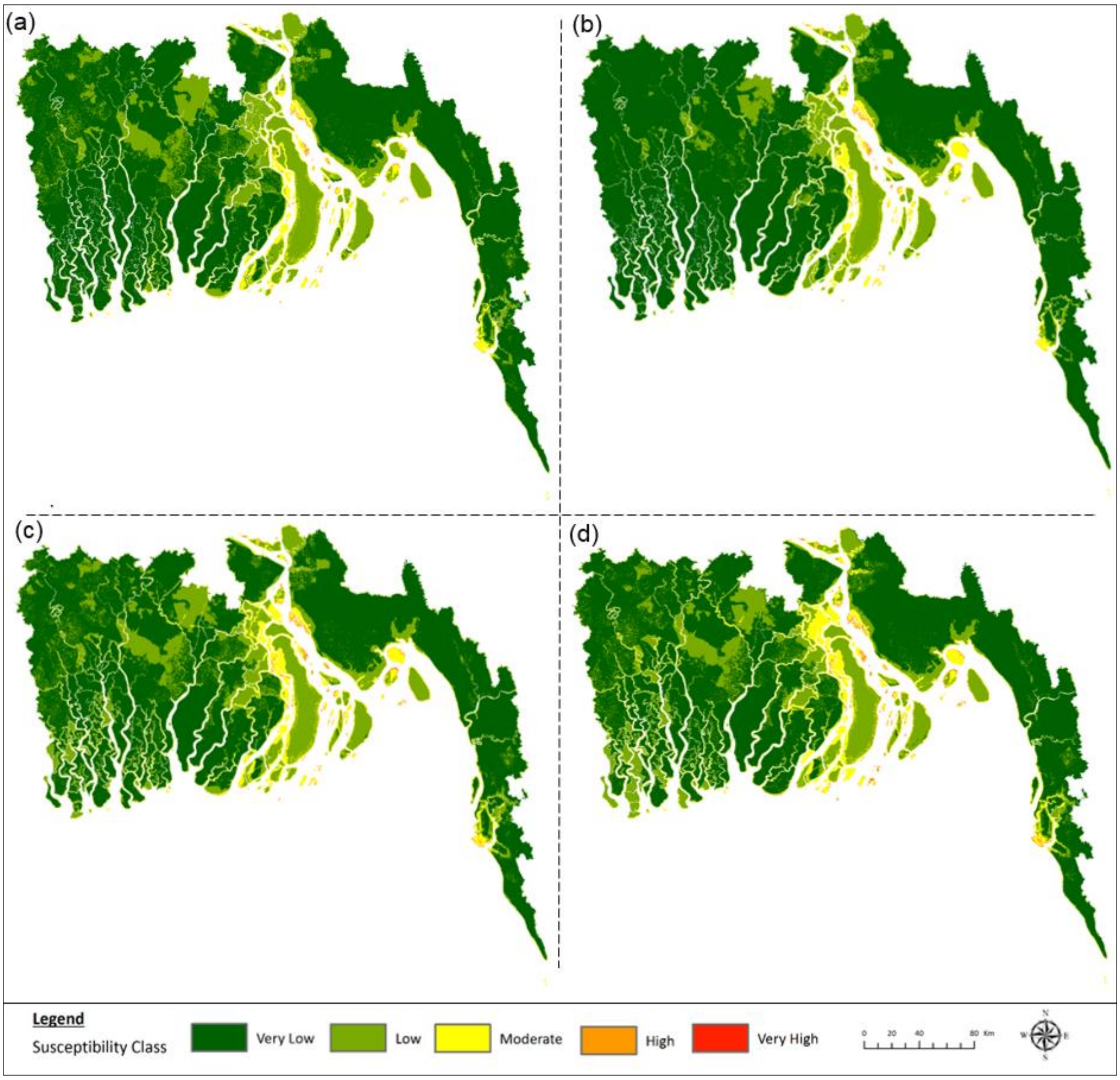

Figure 4.4.2b - The A1B scenario of land susceptibility to erosion during winter season for (a) baseline condition-2015, (b) near future-2020, (c) future-2050 and (d) far future-2080 time-slices. The changes in hydro-climatic conditions during winter seasons are less likely in future that might be the probable reason for less substantive variations in the levels of land susceptibility during the same season.

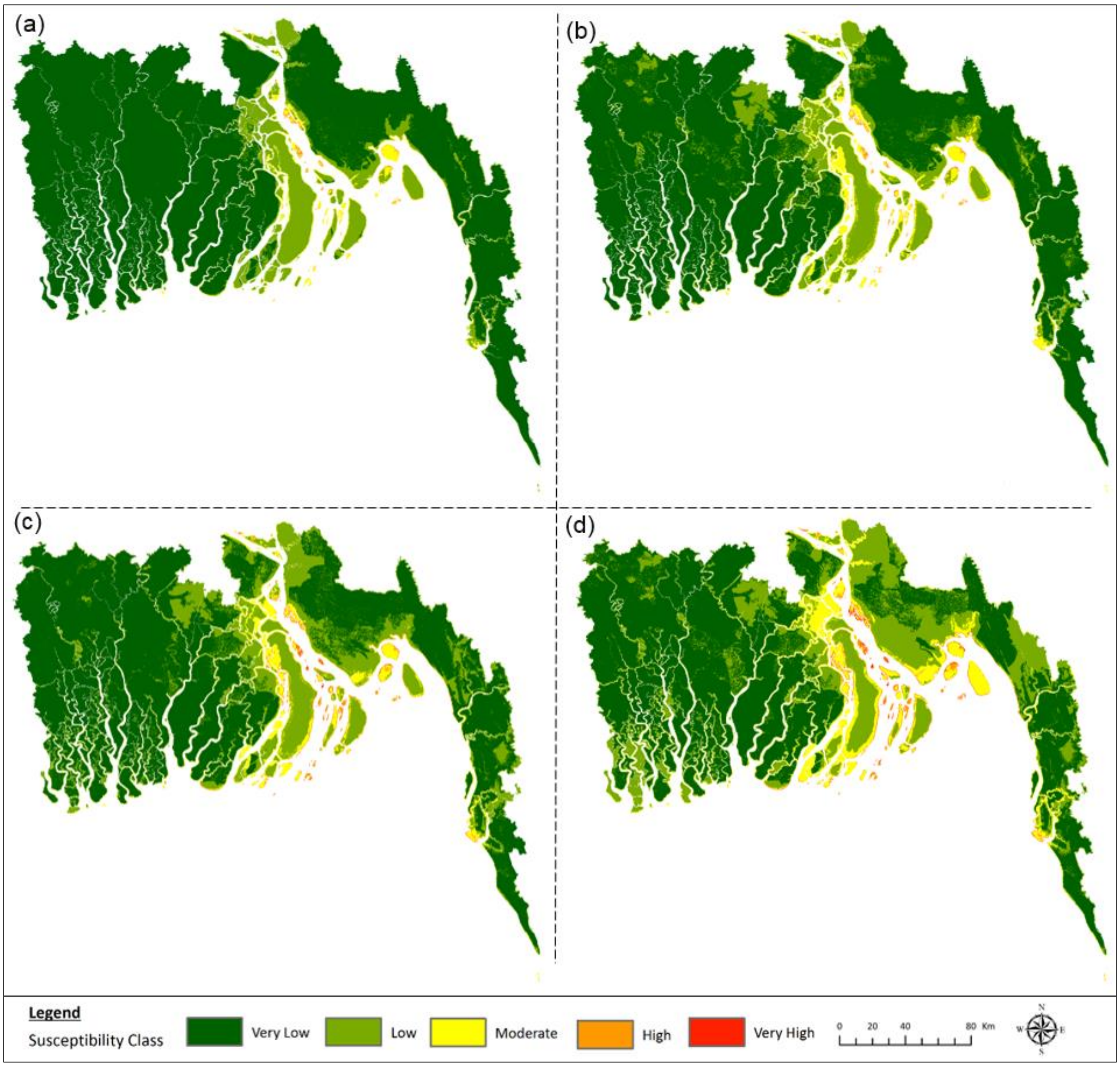

Figure 4.4.2c - The A1B scenario of land susceptibility to erosion during pre-monsoon season for (a) baseline condition-2015, (b) near future-2020, (c) future-2050 and (d) far future-2080 time-slices. The maps show a likely considerable change in the level of land susceptibility to erosion by 2080.

The central coastal zone, however, currently resembles sizeable amounts of moderate, high and very high erosion susceptible lands for all the seasons (vary from 2.2% during pre-monsoon to 7.81% during post-monsoon in total). The amounts of high and very high susceptible lands were 138.59 $km^2$ and 624.27 $km^2$ during pre-monsoon and monsoon seasons in this zone compared to 83.53 $km^2$ and 246.22 $km^2$ during winter and post-monsoon seasons respectively. By 2080, the areal extent of these lands would be comparatively higher than the baseline for all of the seasons. For instance, the shoreline and associated inland areas at Haiderganj, Rahamat Khali of Laksmipur district, Nazirpur and some islands such as Char Lakkhi, Char Kashem, Andher Char of Patuakhali district, Dhal Char, Char Nizam, Char Kukri-mukri, Sona

Char and Monpura of Bhola district (Figure 4.3.1a) would be high and very high susceptibility to erosion during monsoon season by that time (Figure 4.4.2d). However, some islands such as Urir Char, Char Pial, Char Hasan in this zone (Figure 4.3.1a) would be turned from low to moderate susceptibility during winter seasons by 2080 (Figure 4.4.2b). Some islands namely, Sandwip, Monpura and Jahajir Char (Figure 4.3.1a) currently belong to moderate to high and very high erosion susceptibility during post-monsoon seasons but, the situations of these areas would be severe during monsoon and post-monsoon seasons by 2080 (Figure 4.4.2e). On the other hand, the interior areas of this zone would be varied spatially for all the seasons by 2050 but, would be turned into moderate and high erosion susceptibility during pre-monsoon and monsoon seasons by 2080.

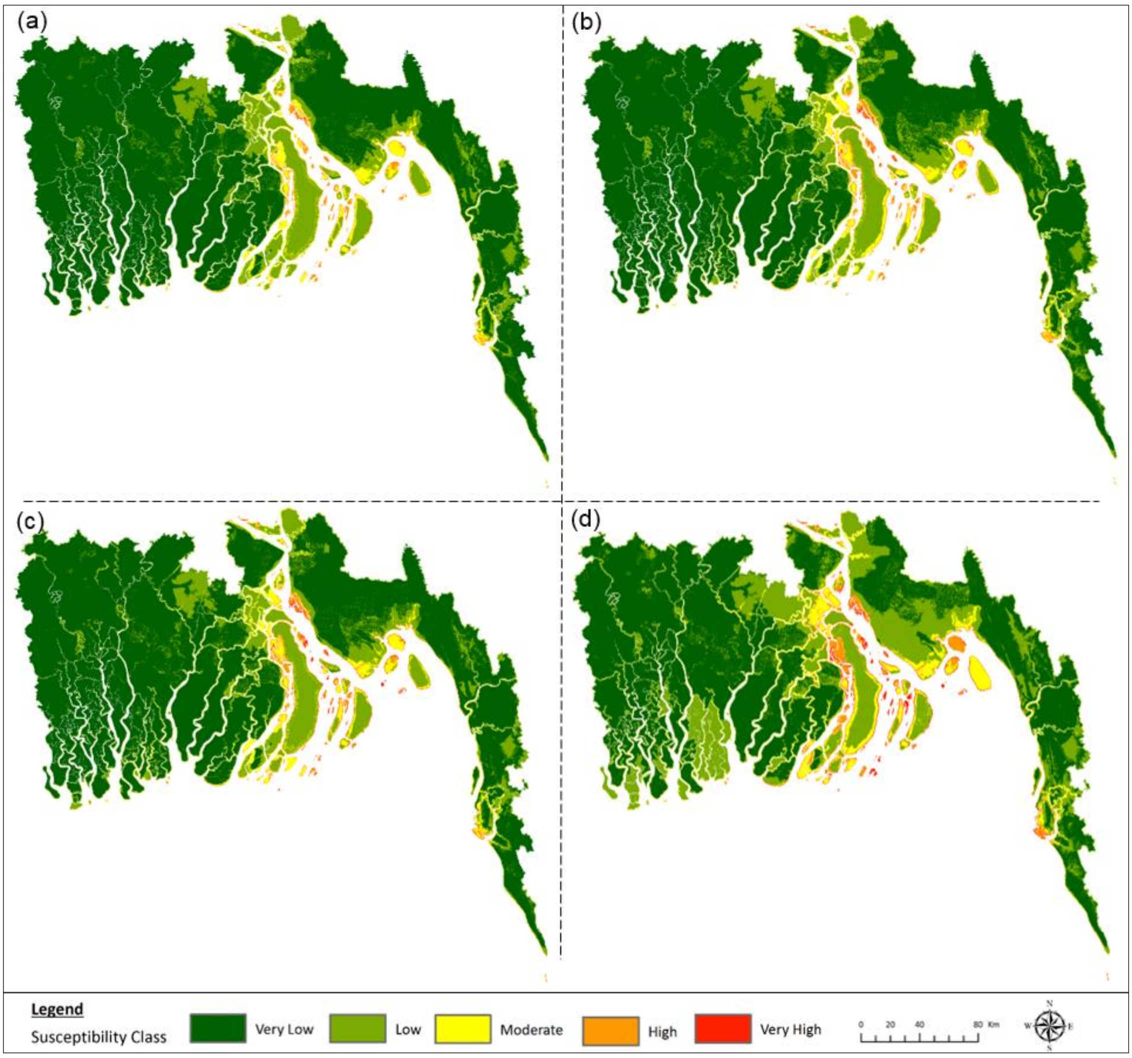

Figure 4.4.2d - The A1B scenario of land susceptibility to erosion during monsoon season for (a) baseline condition-2015, (b) near future-2020, (c) future-2050 and (d) far future-2080 time-slices. By 2080, future impacts of hydro-climatic factors on

erosion susceptibility would be considerable for monsoon season. Substantive changes in the levels of susceptibility are visible in the projected maps for the offshore islands in the central coastal zone of the country.

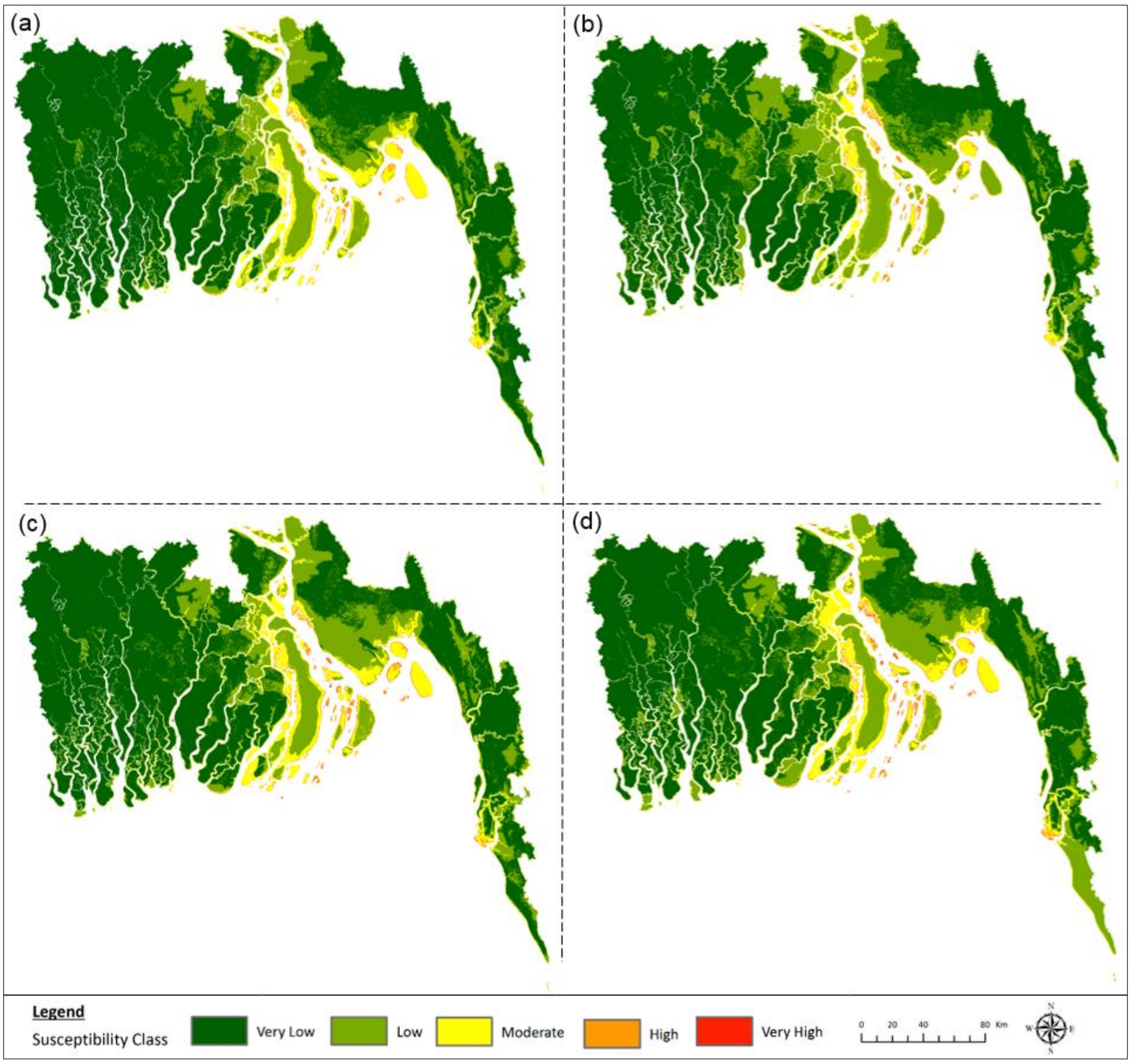

Figure 4.4.2e - The A1B scenario of land susceptibility to erosion during post-monsoon season for (a) baseline condition-2015, (b) near future-2020, (c) future-2050 and (d) far future-2080 time-slices. The susceptibility maps show that the variations in land susceptibility are less likely for 2020 and 2050 time-slices. However, the level of erosion susceptibility would be increased in the coastal area by 2080.

## 4.5 Discussion

### 4.5.1 Justification of the results

The panel of experts in the workshops identified, ranked and mapped 33 relevant components for baseline conditions and for near future (2020), 36 components for future (2050) and 42 components for far future (2080) that include both physical and human aspects of land susceptibility to erosion in the coastal area (Figure 5.4.2a, Figure 5.4.2b and Figure 5.4.2c in chapter 5) (Ahmed et al., 2018c). This study recognised the nine drivers used in the LSCE model that were identified as having higher centrality scores than other components in the FCMs by the panel of experts under three time-slices (Table 4.5.1a). The model outputs were also evaluated in the discussion segments of the workshops. Furthermore, the confidence ratings obtained from the workshops postulate that the ratings for sea level rise, water discharge, soil permeability and defence structures were assigned by the experts with high to very high confidence. The workshops rated the issues of accretion (sedimentation) with moderately high confidence whereas, the issue of wave actions was rated with moderately low confidence. The FCM-based high-scored components and their confidence ratings correspond with the model parameters and their given weights (Table 4.5.1a), that fairly justify the inclusion of the model parameters and their influences on future scenarios of erosion susceptibility in the area.

Table 4.5.1a - Top 10 FCM components based on centrality scores (in bracket). The corresponding parameters of the LSCE model are marked as italic. The ranking of the FCM components is based on the four time-slices separately in which the centrality scores vary for different components.

| Baseline (2015) | Near future (2020) | Future (2050) | Far future (2080) |
|---|---|---|---|
| Rate of sedimentation (8.9)<br>*(Accretion moderator)* | Wave actions (9.82)<br>*(Proxy: Wind speed and direction)* | Rate of sedimentation (15.59)<br>*(Accretion moderator)* | Rate of sedimentation (20.28)<br>*(Accretion moderator)* |
| Wave actions (8.81)<br>*(Proxy: Wind speed and direction)* | Rate of sedimentation (9.76)<br>*(Accretion moderator)* | Wave actions (11.59)<br>*(Proxy: Wind speed and direction)* | Wave actions (16.83)<br>*(Proxy: Wind speed and direction)* |
| Variation of tidal range (7.79)<br>(Partially-Mean sea level) | Variation of tidal range (8.3)<br>(Partially-Mean sea level) | Upstream sediment input (10.75)<br>*(Accretion moderator)* | Variation of tidal range (13.86)<br>(Partially-Mean sea level) |

| | | | |
|---|---|---|---|
| Cyclone and storm surges (7.4)<br>*(Proxy: Wind speed)* | Cyclone and storm surges (7.93)<br>*(Proxy: Wind speed)* | Embankment (10.64)<br>*(Defence moderator)* | Embankment (10.71)<br>*(Defence moderator)* |
| Soft and unconsolidated soil (5.89)<br>*(Surface geology)* | Soft and unconsolidated soil (6.53)<br>*(Surface Geology)* | Variation of tidal range (10.53)<br>(Partially-Mean sea level) | Sea Level Rise (10.35)<br>*(Mean Sea Level)* |
| River water discharge (5.48)<br>*(River water discharge)* | River water discharge (5.81)<br>*(River water discharge)* | Cyclone and storm surges (9.49)<br>*(Proxy: Wind speed)* | River water discharge (10.33)<br>*(River water discharge)* |
| Embankment (5.01)<br>*(Defence moderator)* | Embankment (5.42)<br>*(Defence moderator)* | Soft and unconsolidated soil (8.59)<br>*(Surface Geology)* | Rainfall (7.71)<br>*(Rainfall)* |
| Rainfall (3.15)<br>*(Rainfall)* | Rainfall (3.47)<br>*(Rainfall)* | River water discharge (7.36)<br>*(River water discharge)* | Bathymetry (7.06)<br>*(Bathymetry)* |
| Bathymetry (2.73)<br>*(Bathymetry)* | Bathymetry (2.93)<br>*(Bathymetry)* | Sea Level Rise (7.12)<br>*(Mean Sea Level)* | Monsoon wind (4.74)<br>*(Proxy: Wind speed and direction)* |
| Sea Level Rise (2.59)<br>*(Mean Sea Level)* | Sea Level Rise (2.77)<br>*(Mean Sea Level)* | Rainfall (6.33)<br>*(Rainfall)* | Compaction of sediment (4.06)<br>*(Soil permeability)* |

### 4.5.2 Influence of hydro-climatic drivers

The impacts of the predicted changes in hydro-climatic triggering factors (Figure 4.3.3a) would be substantial for future land susceptibility to erosion (Figure 4.4.1a) in the coastal area. This study suggests water discharge and rainfall as key drivers of future susceptibility to erosion in the area. Except for RCP2.6, all other scenarios show a considerable increase of future water discharge of the coastal rivers in the area. For instance, the A1B and RCP4.5 climate scenarios show similar increases of future coastal river water discharges that would be increased as 30.7% and 27.4% respectively by 2080. This increase would be as high as 39.1% by 2080 under the RCP8.5 scenario. Along with discharge, the likely increases of future rainfall under A1B, RCP4.5 and RCP8.5 are noteworthy. Although the amount of rainfall under RCP8.5 is projected to decrease by 2050, it would be increased to 13.76% by 2080 from the baseline. These increases in future water discharge and rainfall seem to have extensive impacts on future land susceptibility generated by the model scenarios.

The future level of high erosion susceptibility might be accelerated by the likely increases of mean sea level. Model data for A1B scenario shows that there will be 0.08%, 0.24% and 0.42% increases in MSL from baseline by 2020, 2050 and 2080 respectively. In contrast, the RCP2.6 scenario shows an increasing scenario of MSL but, the increase would be comparatively lower than other scenarios. More importantly, the RCP8.5 scenario shows the highest increases of 0.31% and 0.48% MSL from baseline by 2050 and 2080 respectively. These increases of future mean sea level could inundate more coastal lands and hence, the lands would be highly affected by wave actions. Since all the climate scenarios show the likely increases in wind speeds, the probable impacts of the directions of prevailing southern and south-western winds (IWFM, 2012) would be higher in future than present times. Notably, the RCP8.5 scenario shows an increase of 5.31% wind speed by 2080 than baseline. The increasing scenarios of future wind speeds and consequent wave actions, together with the high volume of water discharge, heavy rainfall and high mean sea level would have probable impacts on erosion susceptibility in the coastal area that would turn more lands into high erosion susceptibility in future.

### 4.5.3 Response from physical elements

Although the impacts of the four hydro-climatic triggering factors are found to be increased in future for most of the scenarios, the underlying physical elements of the three coastal zones could react to the changes differently. For instance, the impacts of hydro-climatic triggering factors seem to be minimal in the western coastal zone compare to other zones for future time-slices and hence, the results of the LSCE model showed considerably lower erosion susceptibility in the western zone than the central and eastern zones. This result suggests probable responses from favourable surface geology and geomorphic features (i.e. Valley alluvium and Marsh clay and peat, Mangrove swamp) and moderate soli permeability of the zone on its low erosion susceptibility. Additionally, the interior western coastal zone is not very close to the exposed coast that would make the areas free from potential impacts of wave actions and longshore currents in future. However, shallow bathymetric depths (i.e. -5 to -15 metre) would have probable impacts on wave-induced erosions at Barguna and Patuakhali areas. Likewise, the reason behind the moderate susceptibility in the eastern coastal zone is closely associated with the underlying physical elements. It is important to note that the values of the three hydro-climatic drivers were found to be comparatively higher in this zone than other zones for current and future time-slices. However, the effects of the drivers would be less due to higher surface elevations, favourable geomorphic features and very slow permeability of soils in the zone. For instance, the probable occurrences of heavy rainfall might be increased to 403.74 millimetre by 2080 in the eastern coastal zone but, the potential impacts on erosion susceptibility would be minimal due to its hard and unconsolidated surface geology. The likely impacts of heavy rainfall would be highly visible only in the islands such as Kutubdia, Moheshkhali and St. Martin of the zone where the silt and clay-dominated soils are highly responsive to erosion. In contrast, the geomorphic features (e.g. newly formed ocean and riverine deposits, tidal sand, deltaic sand, beach and sand dune, estuarine deposits, tidal deltaic deposits etc.), together with mixed and rapid soil permeability in the central coastal area would be highly favourable for the hydro-climatic drivers to increase erosion susceptibility in future.

### 4.5.4 Seasonal influences

The seasonal fluctuations of the hydro-climatic drivers under the A1B scenario suggest considerable influences on land susceptibility to erosion in the coastal area. The likely impacts of the drivers would be highest during monsoon and lowest during winter compared to pre-monsoon and post-monsoon season. For instance, a comparatively less amount of total water discharge (i.e. 15,160.91 $m^3$/s) would be experienced by the coastal area during winter seasons but the volume of discharge would be as high as 96,459 $m^3$/s during monsoon seasons by 2080. These variations in water discharge would have probable impacts on future levels of erosion susceptibility in the Meghna estuary area where the bathymetric depths are high. Similar to water discharge, the future scenario for MSL would be least (i.e. 2.35 metre) during winter and highest (i.e. 4.51 metre) during monsoon season by 2080 that might inundate considerable amount of lands in the central coastal zone during monsoon season. Mean sea levels in areas attached to Sandwip channel, Urir Char and Jahajir Char in the central coastal zone (Figure 4.3.1a and Appendix C) would be increased between 4.18 and 4.51 meter during monsoon season from the baseline1.61 and 3.44 metres by 2080. Similarly, the current highest range of 777-896 mm rainfall in the coastal area would be increased to 1040-1199 mm by 2080. This amount of rainfall would have substantial influences to increase the level of erosion susceptibility at Patuakhali and Barguna (Figure 4.3.1a) in the exposed western coastal zone. Moreover, the projected scenario of wind speeds indicates frequent occurrences of tropical cyclone and associated storm surges during pre-monsoon and post-monsoon season in the area that would trigger wave actions in areas attached to shallow water depths in future.

## 4.6 Conclusion

This study assessed the impacts of likely changes in hydro-climate drivers on future coastal susceptibility to erosion along with the underlying physical settings by applying the LSCE model in the coastal area of Bangladesh. The scenarios show that with times, a substantial amount of land in the coastal area would be inclined to high and very high susceptibility to erosion. This amount would vary with the changing impacts of hydro-climatic triggering factors in future. Additionally, considerable seasonal variations in erosion susceptibility were predicted by the model scenarios. Spatially, the western and eastern coastal zones were modelled as low to moderately susceptible whereas, the central coastal zone was identified as moderate to high and very high susceptible to erosion in future. The islands and newly accreted lands in the central coastal zone were modelled as highly susceptible to erosion for all of the three future time-slices. The outputs of the model justified the assumed influences of likely changes in hydro-climatic drivers on future erosion susceptibility made in this study.

The model scenarios of increasing amounts of susceptible lands in future might be a matter of great concern for the densely populated coastal area of the country. However, the generated future scenarios could offer coastal managers and policymakers insights into the nature of future physical susceptibility to erosion for the entire coastal area. The outputs of this study might be helpful for future development projects and resettlement plans of the government. Future land-zoning projects of the government would also be benefited since the identification of the nature of future erosion susceptibility of the coastal area has now been accomplished by this study. More importantly, the century-long ‘Delta Plan 2100’ of the government might be advanced by the inclusion of the modelled results in the plan. This study recommends to include more scenario data to allow further analysis of seasonal variability of physical susceptibility to erosion. The application of the LSCE model would be of great importance in assessing the likely impacts of hydro-climatic drivers for similar dynamic coastal areas around the world.

## 4.7 Acknowledgement

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# Chapter 5: Beyond the tradition: Using Fuzzy Cognitive Maps to elicit expert views on coastal susceptibility to erosion in Bangladesh

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Key words: accretion; coast; erosion; FCM; susceptibility

## 5.1 Abstract

This paper interprets the application of Fuzzy Cognitive Maps (FCMs) to elicit expert views on current condition and future scenario of coastal susceptibility to erosion in Bangladesh. The geomorphological characteristic of the coastal area is highly dynamic where the land erosion and accretion with different rates are constant phenomena. This research focuses on three coastal zones: western, central and eastern that comprise the entire coastal area of the country. Using 'Mental Modeler' software this study quantified experts' judgements on the issue and developed FCMs by way of arranging workshops. At the basis, this study identified 33 factors of susceptibility to erosion for current baseline condition. Considering future projections of hydro-climatic phenomena, this study identified potential factors of susceptibility to erosion for the future scenario under three time-slices: near-future (2020), future (2050) and far-future (2080). The results generated from FCMs show that some factors such as sedimentation, soft and unconsolidated soils, shelf bathymetry, funnel shape of the Bay of Bengal, wave action, river discharge, monsoon wind, cyclone and storm surges, excessive monsoon rain, high tidal energy, variations of tidal range and sea level rise are highly influential that yielded higher centrality scores for both current and future susceptibility of the area to erosion. The experts' interpretations demonstrate that the future susceptibility to erosion might be higher in the central zone compared to the western and eastern zones of the coastal area. This is the first time that FCM based approach was applied to evaluate expert views on coastal susceptibility to erosion for the country. The methodological approach used in this study is useful to study coastal erosion susceptibility in a situation where the availability of data is limited. This study suggests coastal managers, planners and policymakers to consider the current and future factors of erosion susceptibility of coastal lands for taking specific measures options. The results found in this study is also important from socio-economic and demographic contexts of any densely populated coastal area like Bangladesh.

## 5.2 Introduction

Coastal areas of the world are identified as important zones for human settlement (Brooks et al., 2006; Barragán and Andrés, 2015). These areas are marked as buffer zones between land and sea that are physically dynamic in nature (Hanson and Lindh, 1993). Coastal erosion is taking place in about 70% of the world's beaches in different forms (Ghosh et al., 2015). It is reported that the magnitude and frequency of climate-induced coastal disasters are increasing as a result of global warming and consequent sea level rise (Choi et al., 2016). This situation might increase the future rate of erosion in coastal areas around the world. The coastal area of Bangladesh comprises about 32% of the total land area (Parvin et al., 2017) and 30.5% of the total population (Bangladesh Bureau of Statistics [BBS], 2015). However, continuous processes of erosion and accretion in the coastal area of Bangladesh (Ahmed et al., 2018a) indicate that the coastal land area of the country is highly dynamic. In this context, the interpretation of erosion susceptibility in the coastal area is an important task for Bangladesh.

The susceptibility of the coastal area of Bangladesh to erosion depends on several factors (often termed as forces) (Ahmed et al., 2018b). Some are endogenic forces (from the interior of the earth) such as the shifting of river channels by an earthquake and some are exogenic forces (on the earth surface) such as the changes in geomorphology (Sarker et al., 2011). The driving forces can also be categorised as physical factors and human-induced factors. The physical factors vary from earthquake, sedimentation and sea level rise to wave action, rainfall, prevailing south-western wind, soil compaction, vegetation cover, and storm surges etc. whereas, human-induced factors vary from construction of embankments, polders and dykes to deforestation, cross dam and modification of river flow etc. (Goodbred et al., 2003; Brammer, 2014). The variation of susceptibility to erosion in different parts of the coastal area relies on the combined strength of these physical and human-induced factors and hence, the factors do not act in a simple static way. Very often, one of the factors might be a dominating driving force for a region, which might not be common for other areas of the coast (Stephenson, 2013).

The effects of hydro-climatic factors such as water discharge, rainfall, wind speed, tidal variation and mean sea level were found as varied in the coastal area of the country for the last few decades (Minar et al., 2013). The continued changes in hydro-climatic drivers could lead to the changes in morphological pattern as well as the current susceptibility of the coastal area to erosion in future. For instance, rapid geomorphological changes are taking place in the Meghan estuary of the central coastal zone (Ahmed et al., 2018a) that are thought of as the probable results of such changes. The rate of changes in coastal lands could further be increased by future changes in climate and associated sea level rise. The future sea level rise could accelerate erosion in relatively older lands of major islands in the Meghna estuary (Brammer, 2014). However, there is still a great uncertainty in research as to how exactly the drivers of land dynamics (erosion and accretion) are influenced by the rising sea level (Brammer, 2016). It is also uncertain how the coastal areas of Bangladesh will respond to the likely changes of future climate.

Coastal erosion has been studied by applying different methods (discussed in chapter 3) (Ramieri et al., 2011). Since several physical and human-induced parameters are associated with coastal susceptibility to erosion, it is uncertain how precisely the aforementioned methods address the factors of coastal susceptibility to erosion. Furthermore, the evaluation of individual contributions of parameters in computer-based models requires sensitivity tests that would necessitate more time and manpower for computation. However, generation of knowledge on the issue of coastal erosion susceptibility by using methods beyond the traditional approach (i.e. generating computer-assisted models) bears importance. In reality, scientific knowledge essentially generated from humans which can largely be influenced by social, cultural and political values (Edge, 1995). The scientific ‘truth’ generally falsifies the previous truth (Popper, 1963) and hence, exist more than one truth in the scientific community on any concerned issue (Kuhn, 1962). Expert views are important to expand knowledge on a dynamic system (Morgan et al., 2001). Expert judgements are more diverse in nature (Hansson and Bryngelsson, 2009) that are suitable for a comprehensive representation of a system. Moreover, individuals at local levels have their ‘hazard perception threshold’ (Kates, 1971) that depends on their knowledge, perceptions and experiences on any hazards. Furthermore, scientists and experts are considered as most highly trusted sources of information (Hargreaves et al., 2003; CLAMER, 2011) since, their knowledge is based on shared understanding of established facts and theories (Breakwell, 2007).

There are two types of ‘temporal repertoire’ in the scientific community regarding how the experts think about the future (van-Asselt et al., 2010). The first group follows historic determinism in which, the future can be determined by considering the past and present whereas, the second group follow futuristic difference in which the future is disconnected from past. Most of the reports that addressed climate uncertainties are inclined to the central tendency of model values (Kunreuther et al., 2013) and hence are not as critical for the governments as a full exploration of uncertainty (Oppenheimer et al., 2007). In contrast, the process of presenting expert views by subjective probability elicitation is an established approach (Spetzler and Stael, 1975) in which individuals’ probabilistic idea can be converted into numbers (Jenkinson, 2005) as well as allow individuals to rate the levels of uncertainty on the given idea (Zickfeld et al., 2007). However, addressing the future by way of generating cognitive maps is more participatory in nature that represents an individual’s unique knowledge structure (Kearney and Kaplan, 1997). Cognitive maps facilitate to address multiple viewpoints of different experts since, the ideas and viewpoints on an issue are reasonably different among experts (Zickfeld et al., 2010). Additionally, changes in knowledge are intrinsic human nature where, existing mental construct can be replaced by the assimilation of new knowledge (Boyle, 1969). Mental models carry essence in which, the decisions people take, can largely be determined by the cognitions and perceptions they have in their mind (Breakwell, 2007). Mental models are good representations of datasets that derive from reasoning (Oberauer, 2006) and hence, able to provide a reliable ground for evaluating perceptions. Moreover, the cognitive approach has been used for previous research to evaluate the perceptions and understanding of individuals on climate change and hazards (Bostrom et al., 1994; Lowe and Lorenzoni, 2007). However, the nexus between future climate scenarios and coastal susceptibility to erosion has yet to be evaluated by applying a cognitive approach at local, regional as well as global levels (discussed in chapter 1).

In recent years, Fuzzy Cognitive Mapping (FCM) has become a popular participatory method. It has been used in fields ranging from fisheries management to agricultural development, climate vulnerabilities, environmental problems and policy design (Gray et al., 2014a). The benefits of using the approach are attached to the popularity of using ‘bottom-up’ approach and their ability to incorporate a range of individuals, community and expert into an accessible and standardized format (Table 1.1.4a) (Gray et al., 2014b). Although a Fuzzy Cognitive Map (FCM) based modelling approach is highly suitable for future studies (Jetter and Kok, 2014), only a few studies (Biloslavo and Dolinsek, 2010; Amer et al., 2011; Jetter and Schweinfort, 2011; van-Vliet, 2011 Salmeron et al., 2012; Soler et al., 2012) are identified in the field of climate change and natural disasters. Most of the studies mainly focused on future states of wind and solar energy and land cover changes. There is, however, still a great scope for using FCM based mental modelling approach for future climate change, hazard and disaster related issues (Gray et al., 2014b). The adoption of experts' judgements by FCMs insights into not only the details of the problem but also the causal relations among physical and human-induced driving forces (Jetter and Kok, 2014; Moschoyiannis et al., 2016).

This study applied an FCM based approach to evaluate experts' judgements on the current components associated with the coastal susceptibility to erosion in Bangladesh. This study then identified potential factors of future susceptibility of the coastal area to erosion with an aim to address the impacts of future changes in hydro-climatic drivers on erosion susceptibility in the area for the three time-slices such as 2020, 2050 and 2080. This research addressed the implicit assumptions of experts' opinions into explicit causal-relations among and between several physical and human-induced components of current and future susceptibility of the coastal area to erosion. The study supports discussion on the interrelationships between different components of coastal susceptibility to erosion that would be useful for coastal managers and policymakers in managing coastal lands.

## 5.3 Data and methodology

### 5.3.1 Study area

The coastal area of Bangladesh holds dynamic coastal lands along with diverse coastal characteristics identified by IPCC (2007 a, b). The total coastal area covered is 47,200 km$^2$ (Ministry of Environment and Forests [MoEF], 2016) which encompasses the land area (including islands), internal rivers, the Meghna estuary and nearshore water bodies (Figure 5.3.1a). The coastal area possesses diverse characteristics in terms of underlying physical elements such as surface elevations, bathymetry, soil permeability, surface geology and geomorphic features and hydro-climatic conditions such as discharge of water from coastal rivers, rainfall, mean sea level and wind speed and directions. For instance, surface elevations of the coastal land ranging from 0 metre to 327 metres but, most of the exposed coastal areas fall between 0 to 6 metres from mean sea level (Appendix C) (USGS, 2017). The surface elevations of the islands and areas attached to coastline ranging from 0 to 3 metres whereas, the exposed eastern coastal zone belongs to 3-6 metres. The elevations of some interior parts of the coastal area are more than 6 meters and the highest elevation of Chittagong hilly areas reaches to 327 metres. However, the offshore bathymetry represents a depth ranging from 0 to -1096 metres whereas, the near-shore bathymetry represents a depth ranging from 0 to -44 metres (MGDS, 2017). Both the interior and exposed parts of the central coastal zone characterize with varying depths. The Sandwip channel shows the depth ranging from -32 to -44 metres whereas, the depths of the Meghna river channels vary from -20 to -32 metres. The depths near the exposed eastern coast vary from -6 to -20 metres. However, the surface geology and associated geomorphic features of the coastal area represent 21 types of areas (USGS, 2001). In addition to surface geology and geomorphic features, about 63% of the coastal soils are inclined to moderate and rapid permeability classes. Moreover, about 94% lands of the newly accreted lands and small islands in the Meghna estuary area fall under moderate to rapid permeability classes. The high permeability indicates that the soils in the central coastal zone are highly responsive to erosion.

The hydro-climatic characteristics of the coastal area vary between the seasons and zones. For instance, the discharges from existing major rivers in the area show the lowest values 13.76, 4.30, 4.69, 29.07 and 16.06 $m^3/s$ and highest values 30626, 8816, 14013, 65396 and 34280 $m^3/s$ of water discharge for yearly average, winter, pre-monsoon, monsoon and post-monsoon seasons respectively (BWDB, 2016). The mean sea levels for the years from 1985 to 2015 of six stations set by Bangladesh Inland Water Transport Authority (BIWTA) demonstrate the mean value as 1.58 metre whereas, the histogram of the data reveals that most of the values fall between the range of 1.61 and 2.76 metres (BIWTA, 2017; PSMSL, 2017; UHSLC, 2017). Moreover, the lowest values 1.84, 1.61, 1.72, 2.12 and 1.95 metre and the highest values 3.50, 3.20, 3.41, 3.78 and 3.53 metre of mean sea levels were found for the yearly average, winter, pre-monsoon, monsoon and post-monsoon respectively. However, the average rainfall in the coastal area ranges from a low of 123 mm to a high of 301 mm whereas, the minimum and maximum rainfalls vary for different seasons (BMD, 2016). The minimum rainfalls of 10.22, 90, 303 and 86 mm and the maximum rainfalls of 16.79, 186, 896 and 176 mm were found for winter, pre-monsoon, monsoon and post-monsoon seasons respectively. Most part of the eastern coast exhibits heavy rainfall whereas, the estuarine and central parts of the exposed coast show moderate to high amounts of rainfall. The wind speeds in the coastal area vary from a low of 0.76, 0.52, 1.15, 0.96 and 0.36 m/s to a high of 2.79, 1.99, 3.49, 3.84 and 1.86 m/s for average, winter, pre-monsoon, monsoon and post-monsoon respectively (BMD, 2016). The southern and south-western winds blow over the eastern and the central zones of the coastal area.

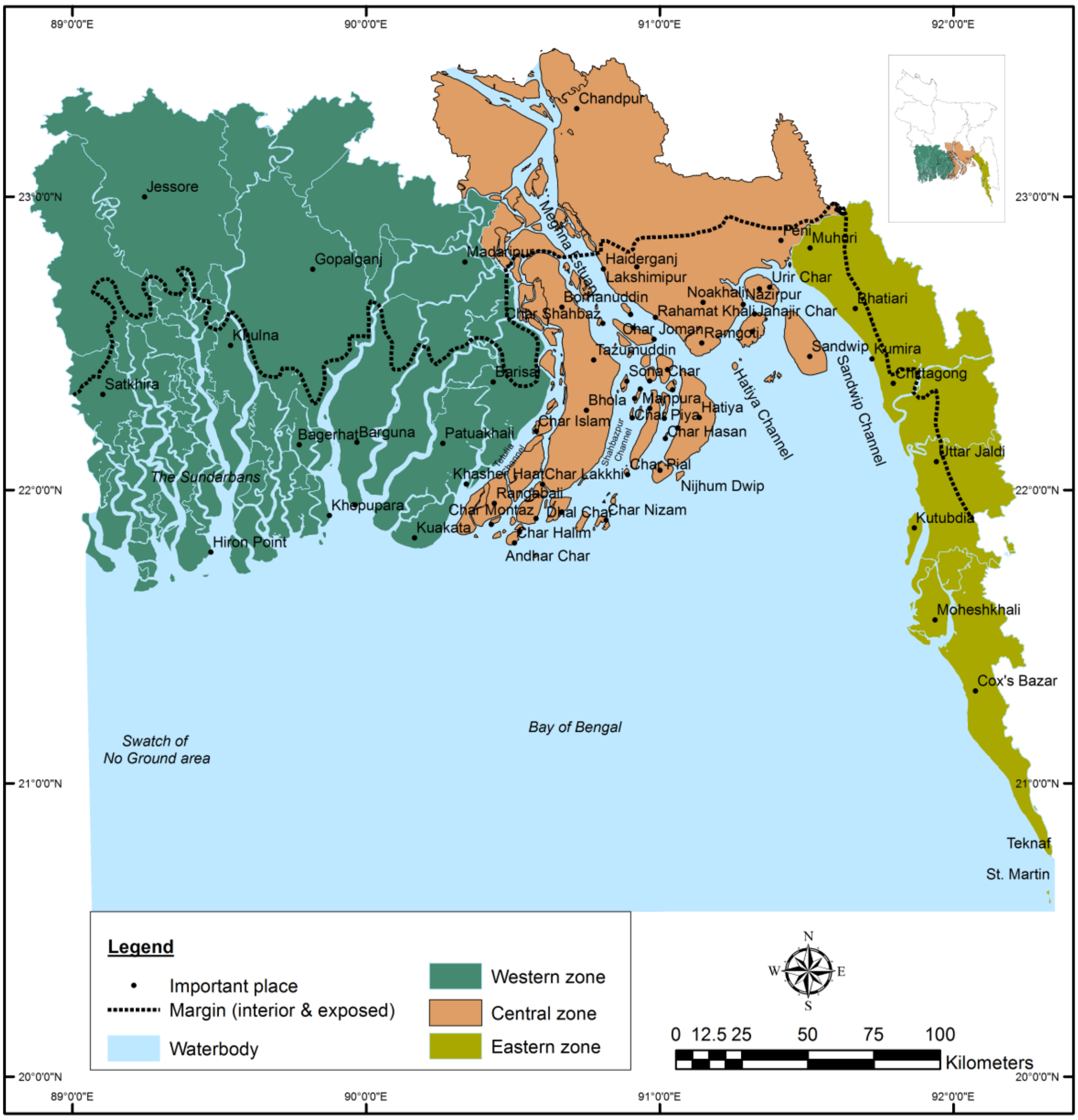

Figure 5.3.1a – The selected area of study (coastal area of Bangladesh) (Ahmed et al., 2018a). Several newly accreted lands and major offshore islands are located in the exposed central coastal zone of the country. Moreover, some islands such as Kutubdia, Moheshkhali and St. Martin are located in the exposed eastern coastal zone.

### 5.3.2 Concept of FCMs

Fuzzy Cognitive Mapping (FCM), originally developed by Kosko (1986), is a semi-quantitative method to structure qualitative knowledge and perceptions of an individual (Gray et al., 2015). The outputs are cognitive maps that represent structured associations of a person's internal knowledge on a specific subject (Novak and Caňas, 2008). Fuzzy Cognitive Maps (FCMs) comprise variables and map the causal relationships between those variables identified by individuals (i.e. experts) (Özesmi and Özesmi, 2004). Fundamentally, FCMs represent a system graphically that depict the nature and degree of relationships between concepts and their individual weights (Figure 5.3.2a) (Gray et al., 2015). The directed logical connections between concepts build the structures of FCMs (Novak and Caňas, 2008) that derive from constructivist psychology (Gray et al., 2014a). Individuals construct knowledge by way of using their internal associative representations (Raskin, 2002) in which FCMs are external illustrations of that knowledge (Jones et al., 2011). FCMs provide the base of participatory outputs that formulate the foundations of quantification which eventually bridge the gap between storylines and models (van-Vliet, 2011).

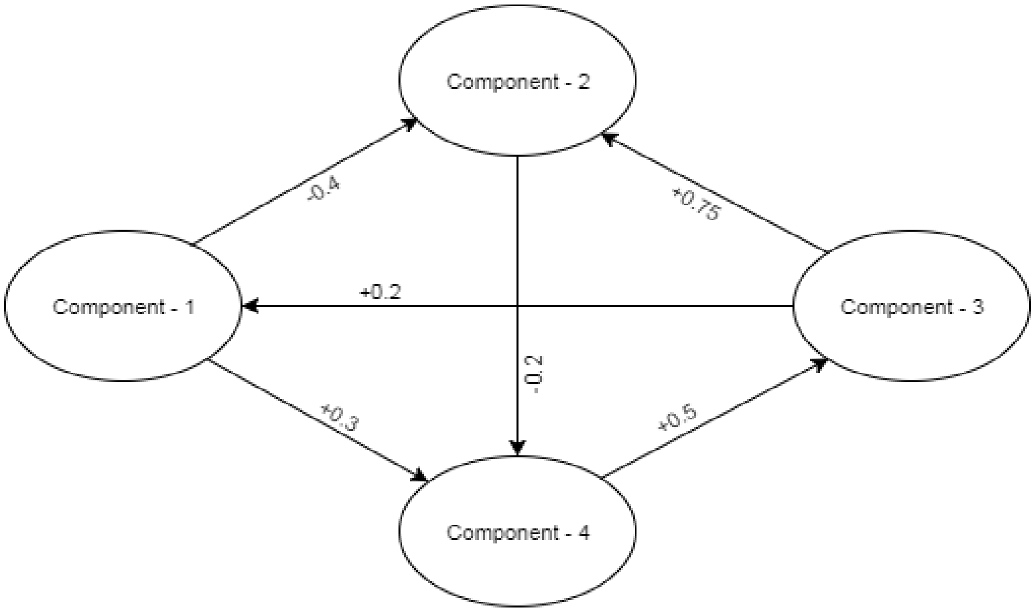

Figure 5.3.2a - Example of a generalised Fuzzy Cognitive Map (FCM) in which, the possible connections between the components are established based on their nature of relationships (i.e. either positive or negative). [Adapted from: Özesmi and Özesmi, 2004]

Table 5.3.2a - Adjacency matrix recorded from the example in the figure (Figure 5.3.2a). The matrix values indicate the strength of relationships between the components.

| | Component 1 | Component 2 | Component 3 | Component 4 |
|---|---|---|---|---|
| Component 1 | 0 | -0.4 | 0 | +0.3 |
| Component 2 | 0 | 0 | 0 | -0.2 |
| Component 3 | +0.2 | +0.75 | 0 | 0 |
| Component 4 | 0 | 0 | +0.5 | 0 |

Using basic principles of fuzzy logic, FCMs construct highly structured and parameterised cognitive maps (Glykas, 2010) in influential diagrams (Gray et al., 2015). Since FCMs use the notions of cognitive mapping and are semi-quantitative, they can be represented by mathematically pairwise associations either qualitatively such as low, medium and high or quantitatively by assigning negative (-1) to positive (1) weights of connections between concepts (or nodes) (Wei et al., 2008). The strength of relationships can be measured by calculating the simple mathematical average of these pairwise weights of the connections in an adjacency matrix (Table 5.3.2a).

### 5.3.3 FCMs structure

The generation of FCMs can be accomplished by using several available software such as FCMapper, FCM Modeler, FCM Designer, Mental Modeler, Java FCM, Intelligent Expert System based on Cognitive Maps (ISEMK) and FCM Tool (later on FCM Expert) (Felix et al., 2017). This research used 'Mental Modeler' software to visualize expert views on coastal susceptibility to erosion by generating FCMs. The benefit of using this software predisposed to its web-based modelling implementation (Felix et al., 2017) that is freely available to use. This software is highly suitable for generating FCMs in a workshop involving experts and stakeholders where relevant experts are asked to quantify themselves their storylines, depending on their knowledge and experience.

The structural design of FCMs in 'Mental Modeler' software is segmented into three interfaces: concept, matrix and scenario. In concept mapping interface, the identified concepts by the experts can be shown. Concepts are the variables (components) in FCMs in which, a higher number of variables represents higher concepts in the model

(Özesmi and Özesmi, 2004). The matrix interface includes concepts and connections (i.e. positive and negative) between the concepts. Concepts can be of three types: transmitter, receiver or ordinary depending on the nature of relationships. Transmitter concepts are those that have forcing functions and affect other components but are not be affected by others. Receiver components are those that have only receiving functions and are affected by other components in the system but have no effect on others (Eden et al., 1992). On the other hand, the components that have both transmitting and receiving functions in the system are marked as ordinary components. Connections indicate the interactions between variables; a higher number of connections symbolises a higher degree of interactions and vice versa (Özesmi and Özesmi, 2004). A positive connection (e.g. blue tint used in this study) resembles the increase of influence of a transmitter component over a targeted receiver component whereas, a negative connection (e.g. grey tint) indicates an inverse condition. For instance, if experts are of the opinion that 'monsoon wind' could increase the 'wave action' then there will be a positive relationship between the transmitter (monsoon wind) and the receiver (wave action) in the FCM model and the matrix of this relationship will show a positive value (e.g. 0.45) of the degree of influence on a scale of -1 to 1. An inverse relationship can be established where the influence between a transmitter and a receiver is potentially negative. It is important to note that the FCMs are efficient to address the types of influences or relationships (i.e. positive, negative) but, lacks in mapping the kinds of relationships (e.g. linear, non-linear, exponential etc.). However, the word 'fuzzy' itself necessarily means no strict patterns of relationships between components in the FCMs.

Each FCM provides in-degree, out-degree, centrality, complexity and density scores for the model. In-degree (id) is the sum of column of absolute values of a variable in the matrix that indicates the inward cumulative strength of relationships (Equation 1) where $N$ is the total number of variables and $a_{ki}$ is the cumulative strength of relationships entering into that variable (Nyaki et al., 2014). On the other hand, out-degree (od) is the sum of row of absolute values of a variable in the matrix that indicates the outward cumulative strength of relationships (Equation 2) where $N$ is the total number of variables and $a_{ik}$ is the cumulative strength of relationships exiting from that variable (Nyaki et al., 2014). Whereas, centrality ($C_D(V)$) is the sum of both in-degree and out-degree (Equation 3) that measures the relative importance of a component within the FCMs (Gray et al., 2014b). In connection with centrality, a complexity score of an FCM indicates a ratio of receiver variables to transmitter variables that is a measure to which outcomes of driving forces in the system are considered. The density score indicates the number of connections compared to the number of all possible connections in the system (Özesmi and Özesmi, 2004).

$$\mathrm{id}(v_i) = \sum_{k=1}^{N} \overline{a}_{ki} \qquad (1)$$

$$\mathrm{od}(v_i) = \sum_{k=1}^{N} \overline{a}_{ik} \qquad (2)$$

$$c_D(V) = \sum \big(id(v) + od(v)\big) \qquad (3)$$

### 5.3.4 Selection of experts

There is always being a predisposition to amalgamate the margin between experts and the public (Collins and Evans, 2002). However, it bears importance to distinguish between these two groups of people in order to develop cognitive models based on expert judgements. Fundamentally, there is no universally accepted definition based on what experts can be separated from public (Lowe and Lorenzoni, 2007). Experts can be defined based on their approach to explaining a problem (O'Hagan et al., 2006). They can also be defined based on their acquired experiences on the concerned topic (Collins and Evans, 2002). However, they can simply be defined as the individuals whose knowledge we think to elicit (Garthwaite et al., 2005). The most important factors of selecting appropriate experts depend on their expertise, experiences, perspectives and publications (Lowe and Lorenzoni, 2007). Some other factors might include their balance of view and availability (Arnell et al., 2005). However, there are two approaches in terms of whose knowledge is being modelled: traditional expertise and non-traditional expertise (Gray et al., 2014a). Traditional experts are those who have an in-depth understanding of the concerned problem. In contrary, non-traditional experts include stakeholders where participatory planning and management need to be given priority. In relation to the selection of experts, there are two separate methods as to how knowledge can be collected: individual and group modelling. However, the group facilitation in the process of FCMs strengthens the free association of concepts (Gray et al., 2014a).

This study identified 15 relevant experts considering that they have threshold experience and expertise on the issues concerned (Table 5.3.4a). This number of selected experts followed no sampling procedure since it is recommended to select a favourable number of experts (Morgan and Keith, 1995) with a view to obtaining diversified opinions from the experts. Instead, an in-depth review of available literature was carried out prior to the workshops with a view to understand that what sorts of knowledge gaps can be covered by integrating expert views in FCMs. Furthermore, coastal susceptibility to erosion largely influenced by a number of local and regional forces and hence, the selected experts were local having international exposure on their field of expertise.

Table 5.3.4a - List of experts participated in the study. To make the study anonymous, the names and institutions of the experts are not provided herewith (alphabets are used instead). The experts were chosen that includes a number of physical and human fields of study relevant to the present study. All the selected experts ensured a minimum five year of experience in their relevant fields.

| Expert | Expertise | Affiliation | Year of experience |
|---|---|---|---|
| A | Coastal geomorphology | Academic | 14 |
| B | Coastal sedimentation | Academic | 8 |
| C | Meteorology | Government | 10-11 |
| D | Climate change | Academic | 8-10 |
| E | Soil science | Government | 14-15 |
| F | Water management | Government | 16 |
| G | Modelling coastal dynamics | Consultant | >5 |
| H | Marine science | Academic | 5-6 |
| I | Geology | Academic | 13-14 |
| J | Hydrology | Academic | >8 |
| K | Coastal zone management | Government | 11 |
| L | Land dynamics | Academic | 9 |
| M | Land policy | Government | 15-16 |
| N | Land management | Government | 8-10 |
| O | Forestry | NGO | 5 |

This study invited the selected experts in workshops where face-to-face interactions among the experts were possible. This method of interactions carries importance in that it expedites a continuous re-moulding of individual's viewpoints by interacting with others through visual cues (Stephens, 2007). Furthermore, the development of FCMs is quite difficult if the experts are not present in a participatory workshop. Considering the nature of the problem, this study involved traditional experts in the study that disentangled their knowledge in which, a group-wise participatory modelling of FCMs were accomplished.

### 5.3.5 Design of workshops and input data

Before started the workshops, a detailed description on the pattern of land dynamics in each zone from 1985 to 2015 was presented to the experts. This information has previously been gathered by assessing Landsat satellite images compiled over the past 30 years ranging from 1985 to 2015 with 30×30 m pixel resolution (Ahmed et al., 2018a). Furthermore, raster GIS-based Land Susceptibility to Coastal Erosion (LSCE) model has been derived as a part of the current study to generate the current levels (Ahmed et al., 2018b) and A1B (AR4 business-as-usual), RCP2.6 (low), RCP4.5 (moderate) and RCP8.5 (high) climate trajectory-based future physical susceptibility of the coastal area to erosion for three time-slices such as 2020, 2050 and 2080 (Ahmed et al., submitted). The data sets on the trends of hydro-climatic parameters were collected from BMD, 2016; BWDB, 2016 and BIWTA, 2017 whereas, the data sets on future hydro-climatic scenarios were collected from IWFM, 2012; Kamal et al., 2013; IPCC, 2014c; Kay et al., 2015; World Bank [WB], 2016 and CCCR, 2016. These data along with the outputs of the model were presented to the experts to facilitate the workshops with observed and scenarios of climate-driven factors in the study area. The scenarios of future hydro-climatic drivers that were used for the LSCE model and presented in the workshops are given in the table (Table 4.3.3b in chapter 4 and Table 5.3.5a).

Table 5.3.5a - Changes in hydro-climate drivers from base data (past average of stations) under different climate scenarios. The base corresponds to 2015 whereas, the values in brackets for future times indicate positive (+) and negative (-) changes of percentages for the associated drivers. [Data source: IWFM, 2012; Kamal et al., 2013; IPCC, 2014c; Kay et al., 2015; World Bank [WB], 2016; CCCR, 2016]

| Driver | Time-slice | Climate trajectory | | | |
|---|---|---|---|---|---|
| | | A1B | RCP2.6 | RCP4.5 | RCP8.5 |
| Water discharge ($m^3/s$) (Base: 5790.71) | 2020 | 6008.24<br>(+ 6.1) | 5414.32<br>(- 6.5) | 6149.74<br>(+ 6.2) | 6051.30<br>(+ 4.5) |
| | 2050 | 6333.28<br>(+ 16) | 5993.39<br>(+ 3.5) | 6618.79<br>(+ 14.3) | 6508.76<br>(+ 12.4) |
| | 2080 | 6809.16<br>(+ 30.7) | 6584.04<br>(+ 13.7) | 7377.37<br>(+ 27.4) | 8054.88<br>(+ 39.1) |
| MSL (mm) (Base: 2499.11) | 2020 | 2779.11<br>(+ 0.08) | 2539.11<br>(+ 0.04) | 2549.11<br>(+ 0.05) | 2559.11<br>(+ 0.06) |
| | 2050 | 2989.11<br>(+ 0.24) | 2679.11<br>(+ 0.18) | 2739.11<br>(+ 0.24) | 2809.11<br>(+ 0.31) |
| | 2080 | 3239.11<br>(+ 0.42) | 2799.11<br>(+ 0.30) | 2859.11<br>(+ 0.36) | 2979.11<br>(+ 0.48) |
| Rainfall (mm) (Base: 196.86) | 2020 | 217.16<br>(+ 2.85) | 189.77<br>(- 3.60) | 198.99<br>(+ 1.08) | 201.50<br>(+ 2.36) |
| | 2050 | 223.09<br>(+ 13.19) | 191.37<br>(- 2.79) | 192.27<br>(- 2.33) | 192.15<br>(- 2.39) |
| | 2080 | 260.81<br>(+ 27.46) | 192.86<br>(- 2.03) | 205.76<br>(+ 4.52) | 223.95<br>(+ 13.76) |
| Wind speed (m/s) (Base: 1.58) | 2020 | 1.57<br>(- 0.90) | 1.57<br>(- 0.92) | 1.57<br>(- 0.84) | 1.57<br>(- 0.51) |
| | 2050 | 1.62<br>(+ 3.45) | 1.61<br>(+ 1.64) | 1.64<br>(+ 3.62) | 1.64<br>(+ 3.84) |
| | 2080 | 1.63<br>(+ 2.63) | 1.61<br>(+ 2.12) | 1.64<br>(+ 3.73) | 1.66<br>(+ 5.31) |

Similarly, data, maps and information relating to the locations of potential human-induced drivers of susceptibility such as embankments, polders, dykes and mangrove afforestation were synoptically presented to the experts. Furthermore, future policy options of the government such as 'Delta Plan 2100', future 25 years plan by Bangladesh Water Development Board, Coastal Land Zoning Project and Land Reclamation Plan were discussed in the workshop. The presented data and information could be helpful for the experts to identify the current and potential future drivers of coastal susceptibility to erosion in the area and to assign weights of the connections (relationships) between the identified drivers.

The first workshop was segmented into three interfaces: concept mapping, matrix and scenario involving eleven experts, among which some experts having expertise on physical aspects and some experts having expertise on human aspects of erosion susceptibility (Table 5.3.4a). Prior to concept mapping, the experts were given a research question: what factors do you think contribute to the existing susceptibility of the coastal area to erosion? To secure answers, the experts were asked in concept mapping interface to identify current baseline components of susceptibility to erosion for the area studied. The identified components were presented on-screen and a discussion held on the components with an aim to facilitate any changes if required. In the matrix interface, the experts were asked to rate the relationships between the identified drivers in a rating scale from -1 to 1. The quantitative values on the rate of relationships then inserted in rows and columns in an adjacency matrix to find out the in-degree, out-degree and centrality scores of the components. The arrangements of relationships between the components were shown on screen during the session for further modifications. The complexity and density scores of the FCMs were also shown in the workshop by using the software.

In the scenario interface, this research identified the factors that are important for future susceptibility of the coastal area to erosion. To address potential factors of future susceptibility, this study engaged the experts in three subjective probability elicitations for three time-slices such as near-future (2020), future (2050) and far-future (2080). However, the common problem relating to scenario generation in 'scenario' interface of the software by changing baseline values of relevant components is that the results yield some changes in the relationships of FCM steady state condition but, lack to integrate additional future components in the model. Hence, this study initiated experts' oriented generation of future FCMs where it is possible to capture new components and their degree of relationships. In the scenario interface, the experts were given a different research question to respond: how do you evaluate the future susceptibility of the coastal area to erosion? Additionally, the experts were asked to consider the future scenarios of climate drivers provided for different time-slices while identifying new future drivers and rating the relationships between the drivers. To do this, several 'what if' situations were presented in the workshop based on the mentioned climate scenarios for future time-slices and the experts were asked to rate the changes of the relationships between the identified components of future susceptibility to erosion.

However, to facilitate discussions on the identified and rated factors of current and future susceptibility of the coastal area to erosion, this study provided a further research question to the experts: what implications do the current conditions and future changes of hydro-climatic drivers have on future susceptibility of the coastal area to erosion? Finally, to address future uncertainties, this study coded the 'confidence rating' for the established connections (relationships) in the FCMs models. The experts were also asked to rate their level of confidence on the assigned values of individual relationships between the components in seven points scale where, 1= very low; 2=low; 3=moderate low; 4= neutral; 5= moderate high; 6= high and 7= very high confidence.

### 5.3.6 Validation of FCMs

Since FCMs are based on diverse understandings of a system and hence, formal validation of the FCMs are not possible (Özesmi and Özesmi, 2004). These qualitative models (FCMs) produce outputs that are not possible to measure directly in the field. Rather, how well the outputs of individual experts matched with the reality can be measured qualitatively by performing reality checks (Özesmi and Özesmi, 2004). Validation might occur even if the results are qualitatively consistent with the empirically established relationships (Hobbs et al., 2002; Özesmi and Özesmi, 2004). It is important to note that the FCMs do not come up with estimates of real values or inferential statistical tests for the parameters (Craiger et al., 1996; Gray et al., 2014a). In parallel, the FCMs are capable of illustrating 'what-if' but, do not model 'why' of a system (Kim and Lee, 1998). The number of variables and their relationships might be independent in nature (Klein and Cooper, 1982). To qualitatively validate the FCM-based results of the present study, remaining four experts were involved in a second workshop. After having several iterations performed by the software, the final outputs of the first workshop went through reality checks by the second group of experts in the second workshop. The validated final outputs were then presented on-screen to check the consistency of the results.

## 5.4 Results

### 5.4.1 FCMs on current susceptibility to erosion

The outputs of combined FCMs on current susceptibility (2015) for the entire coastal area show a total number of 33 components that were identified by the experts in the workshops. Among the identified components, most of them (21 components) broadly represent physical drivers of susceptibility whereas, the remaining (12 components) are human-induced drivers (Table 5.4.2a). The figure (Figure 5.4.1a) shows the Fuzzy Cognitive Map in which, the nature of the relationships between the components are outlined. Out of the components, 26 are ordinary drivers that have both transmitting and receiving flows of relationships with other components. Among the remaining 7 components, 6 are identified as transmitter and 1 as receiver. Highest centrality score found for 'rate of sedimentation' (8.9) followed by 'wave action' (8.81) whereas, the lowest centrality score occurred for 'decomposition of undecomposed materials' (0.2). A total number of 149 connections established in the map that yielded 4.51 connections per components on average. This baseline FCM shows a 0.14 density score and 0.16 complexity score obtained from the matrix.

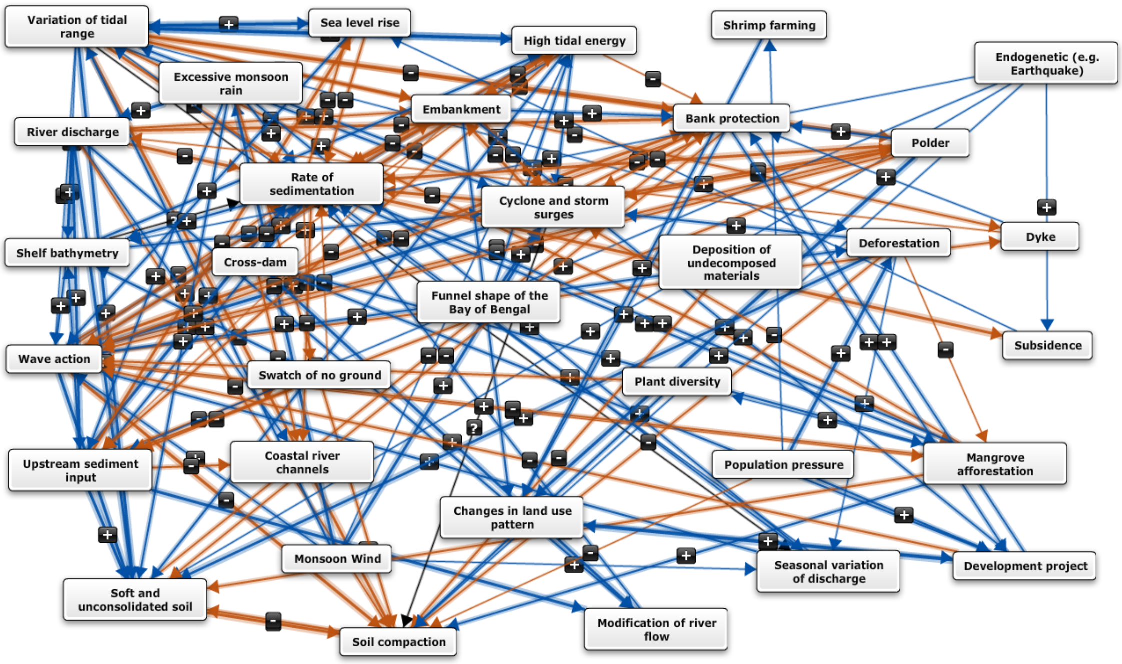

Figure 5.4.1a - FCM components and their relationships for baseline conditions of susceptibility. The blue tint represents positive (+) and the grey tint represents negative (-) relationships between the components.

#### 5.4.1.1 Zonal variation

The workshops investigated the zonal variation of current baseline susceptibility of the coastal area to erosion in which, substantially varied factors were identified for the three coastal zones. A total number of 10 components were identified for both western and eastern zones whereas, 19 components were recognised for the central coastal zone which indicates a diverse nature of factors that exists in the central coastal zone compared to the other zones (Table 5.4.1a). However, a total number of 29, 79 and 18 connections among the components were identified for the western, central and eastern coastal zones respectively (Figure 5.4.1b). Hence, the connections per components were also found as higher for the central zone (4.15) compared to the western (2.9) and eastern (1.8) zones. The complexity score was also higher for the central zone (0.5) in comparison with the western (0.0) and the eastern (0.0) zone. The highest number of 03 transmitter components (rock type, development projects and population pressure) were identified for the eastern coastal zone whereas, no receiver component was found for the western and eastern coastal zones, except one (afforestation) for the central zone.

Table 5.4.1a - Components of FCMs identified by the experts on current susceptibility to erosion for the three coastal zones of the country. The experts identified several components for the central coastal zone compared to the western and eastern coastal zones. Most of the components are ordinary in type that indicate both in-degree and out-degree of relationships with other components.

| Zone | Component | In-degree | Out-degree | Centrality | Type |
|---|---|---|---|---|---|
| Western Coastal Zone | Mangrove forest (Sundarbans) | 2.09 | 1.68 | 3.77 | ordinary |
| | Tidal variation | 0 | 0.68 | 0.68 | transmitter |
| | Wave action | 2.73 | 1.95 | 4.68 | ordinary |
| | Land slope | 1.56 | 0.98 | 2.54 | ordinary |
| | Cyclone and storm surges | 1.89 | 2.54 | 4.43 | ordinary |
| | Sediment input | 2.13 | 0.46 | 2.59 | ordinary |
| | Modification of river channel | 0.46 | 0.55 | 1.01 | ordinary |
| | Polder | 0.85 | 1.43 | 2.28 | ordinary |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  | Destruction of mangrove forest | 2 | 2.13 | 4.13 | ordinary |
|  | Population pressure | 0 | 1.31 | 1.31 | transmitter |
| Central Coastal Zone | Supply of sediment | 4.86 | 2.79 | 7.65 | ordinary |
|  | Ebb-tide current | 1.85 | 2.49 | 4.34 | ordinary |
|  | Bathymetry | 3.8 | 1.5 | 5.3 | ordinary |
|  | Cyclone and storm surges | 2 | 3.15 | 5.15 | ordinary |
|  | Wave action | 4.46 | 1.88 | 6.34 | ordinary |
|  | Variation in tidal range | 1.77 | 1.05 | 2.82 | ordinary |
|  | Anti-clock circulation of tide | 1.59 | 2.58 | 4.17 | ordinary |
|  | Funnelling effect | 1.4 | 3.57 | 4.97 | ordinary |
|  | River discharge | 0.82 | 3.84 | 4.66 | ordinary |
|  | Vegetation cover | 1.32 | 2.12 | 3.44 | ordinary |
|  | Soft and unconsolidated soil | 3.51 | 1.5 | 5.01 | ordinary |
|  | Land reclamation projects | 0.58 | 2.91 | 3.49 | ordinary |
|  | Deforestation | 0.75 | 1.21 | 1.96 | ordinary |
|  | River training | 0 | 0.90 | 0.90 | transmitter |
|  | Afforestation | 1.76 | 0 | 1.76 | receiver |
|  | Sand mining | 0.3 | 0.07 | 0.37 | ordinary |
|  | Development projects | 0.55 | 0.4 | 0.95 | ordinary |
|  | Polder and embankment | 0 | 1.63 | 1.63 | transmitter |
|  | Bank protection | 2.52 | 0.25 | 2.77 | ordinary |
| Eastern Coastal Zone | Counter clock-wise tidal circulation | 0.4 | 0.65 | 1.05 | ordinary |
|  | Cyclone and storm surges | 1.11 | 1.15 | 2.26 | ordinary |
|  | Wave action | 2.92 | 0.24 | 3.16 | ordinary |
|  | Rock type | 0 | 2.19 | 2.19 | transmitter |
|  | Sandy beach | 0.5 | 0.72 | 1.22 | ordinary |
|  | Bank protection | 2.13 | 0.98 | 3.11 | ordinary |
|  | Development projects | 0 | 1.15 | 1.15 | transmitter |
|  | Afforestation | 0.85 | 0.42 | 1.27 | ordinary |
|  | Population pressure | 0 | 0.4 | 0.4 | transmitter |
|  | Supply of sediment | 0.89 | 0.9 | 1.79 | ordinary |

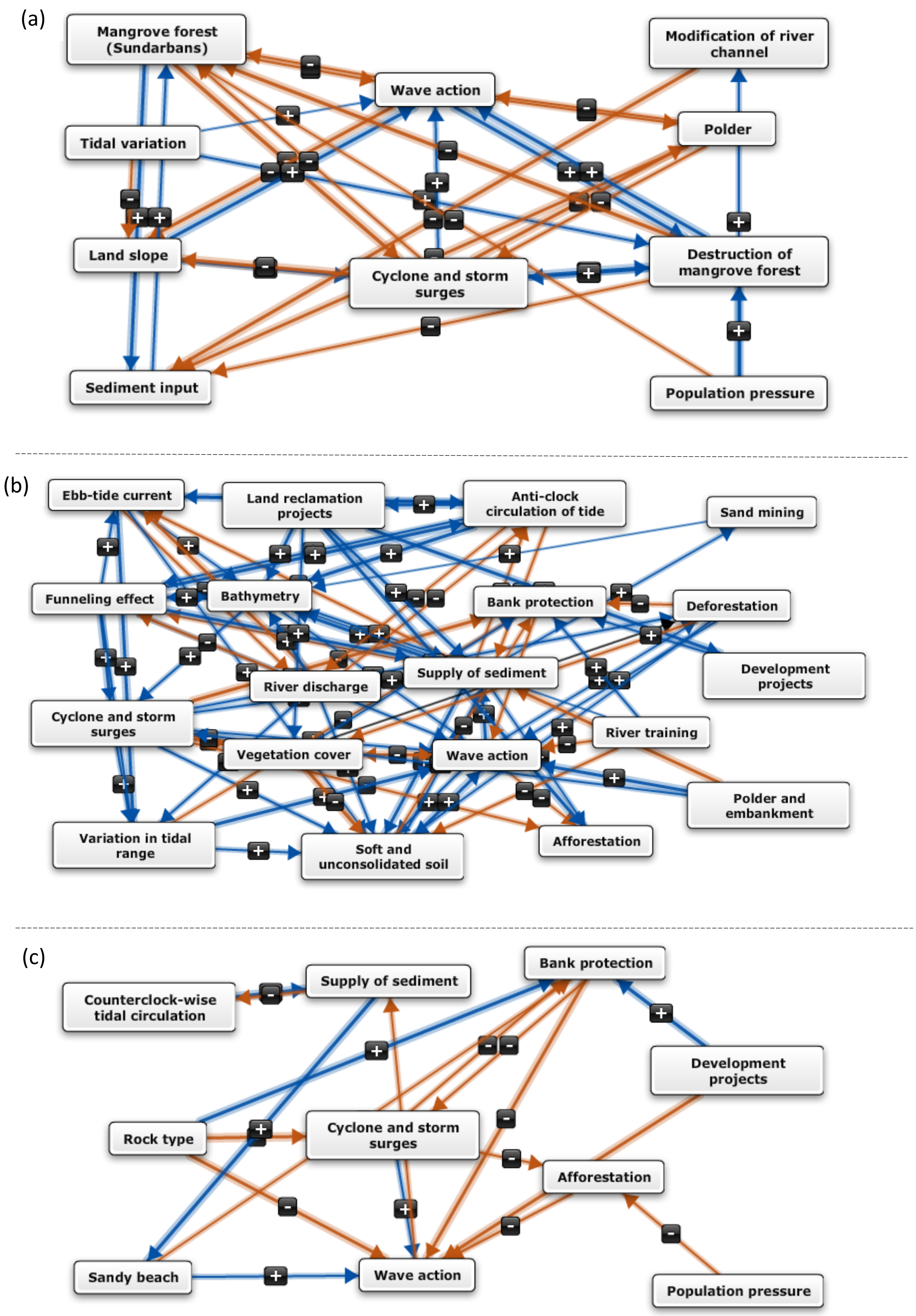

Figure 5.4.1b - Zone-wise FCMs for current susceptibility to erosion. The figure represents (a) western; (b) central and (c) eastern coastal zones of the area studied. The nature of relationships between the components in the western and eastern zones

resembles mostly negative relationships whereas, both the positive and negative relationships persist in the central coastal zone.

## 5.4.2 FCMs on future susceptibility to erosion

### 5.4.2.1 Near-future (2020)

The FCM for near-future (2020) did not vary considerably from the baseline conditions in respect of the total number and nature (transmitter, receiver and ordinary) of components, complexity and density scores (Figure 5.4.2a). However, the total number of connections increased to 153 and hence, on average connections per components was increased to 4.60 from the baseline value of 4.51. This scenario of increased connections indicates higher interactions between the components in near-future than the existing conditions. The confidence ratings for each near-future component are shown in the table (Table 5.4.2a).

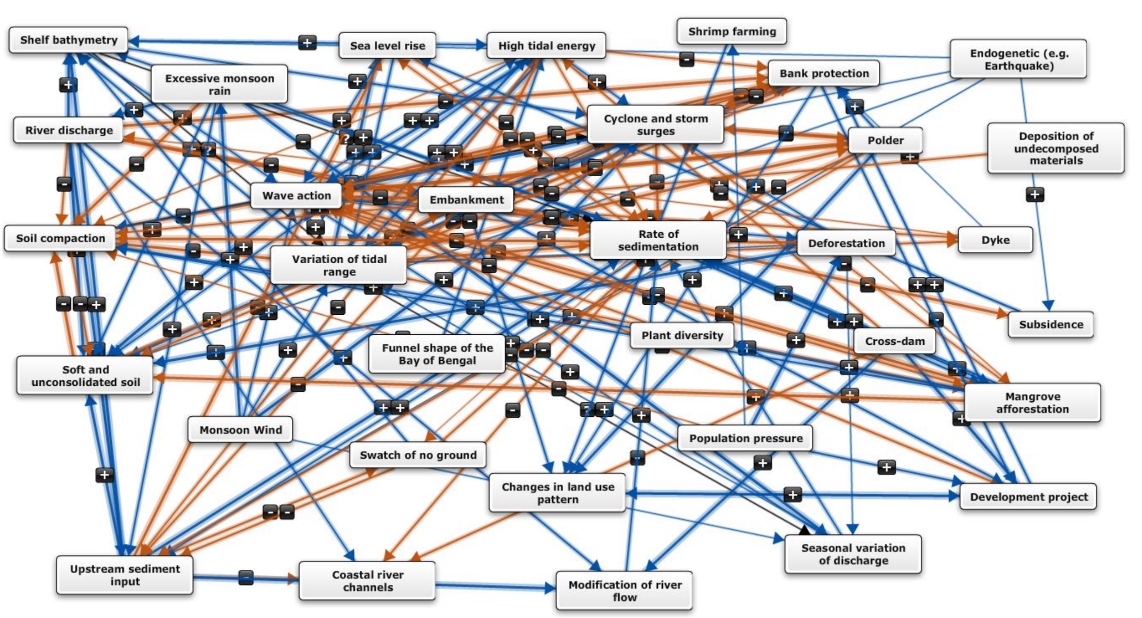

Figure 5.4.2a - FCM components and their relationships for near-future (2020) susceptibility to erosion. Although the number of components is similar to the baseline conditions, some components such as rate of sedimentation, wave actions, variation of tidal range and cyclone and storm surges show higher interactions during this time-slice than the baseline.

### 5.4.2.2 Future (2050)

The FCM-based scenario for future (2050) time-slice indicates a diverse nature of relationships between the components. Although only three components were added to the total, this FCM included 13 new components and excluded 10 components from the previous conditions that make 36 components in total (Table 5.5a). Total number of connections for this time-slice increased substantially (i.e. 293 in total) and hence, number of connections per components (8.13) also increased consequently on average from the previous states (Figure 5.4.2b). Most of the components (33) in this FCM are ordinary in nature in which, only 2 and 1 components were identified as transmitter and receiver respectively. The density (0.23) and complexity (0.5) scores of this FCM also show higher values than the previous times.

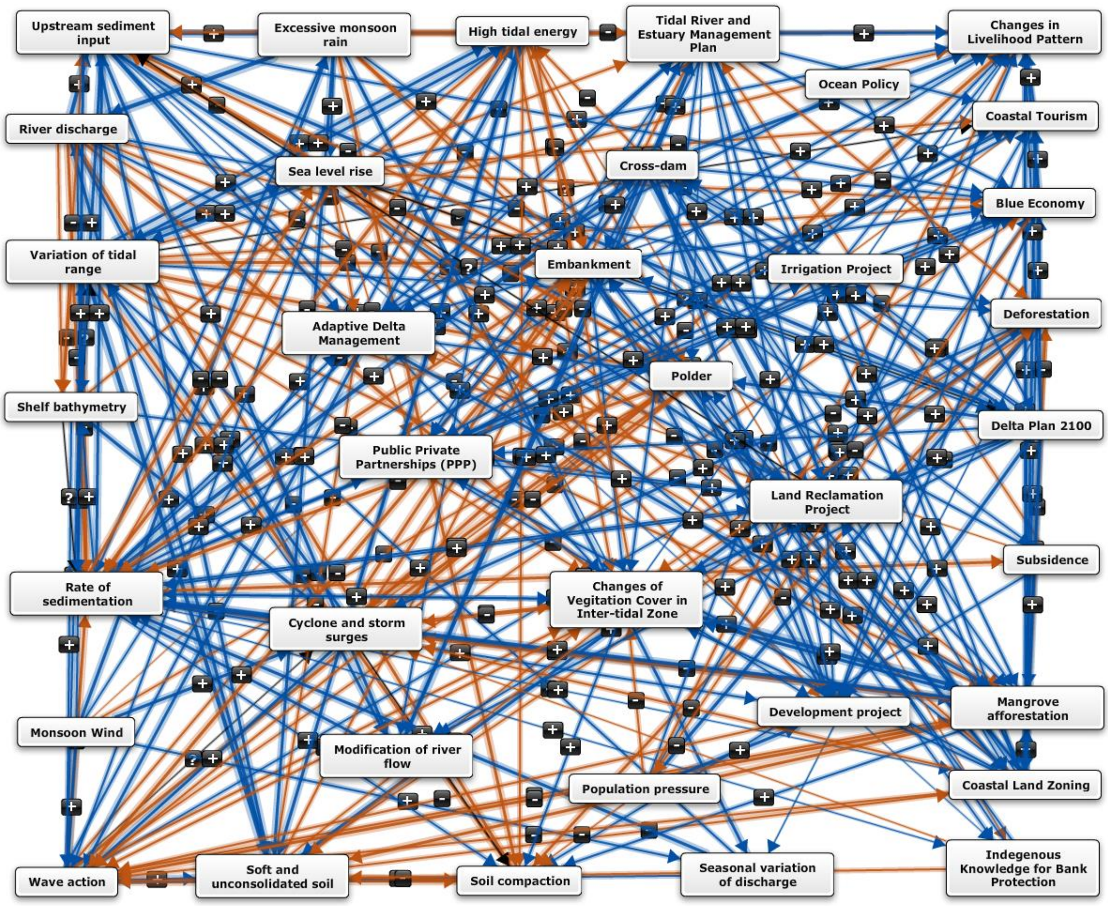

Figure 5.4.2b - FCM components and their relationships for future (2050) susceptibility to erosion. An increased interaction between the components is visible for most of the physical and human-induced factors of susceptibility to erosion in the coastal area.

Table 5.4.2a - Common components and associated confidence ratings for the three time-slices in relation to baseline condition identified and quantified by the experts. The very high and high confidence ratings in the table indicate the high probability of influence of the associated components on erosion susceptibility in the coastal area for current and future time-slices.

| Component | Level of Confidence | Centrality (In-degree + Out-degree) | | | |
|---|---|---|---|---|---|
| | | Baseline (2015) | Near future (2020) | Future (2050) | Far future (2080) |
| Rate of sedimentation | Very High | 8.9 (6.8+2.1) | 9.76 (7.47+2.29) | 15.59 (9.4+6.19) | 20.28 (12.21+8.1) |
| Wave action | Low | 8.81 (4.78+4.03) | 9.82 (5.22+4.6) | 11.59 (6.58+5.02) | 16.83 (10.16+6.7) |
| Variation of tidal range | High | 7.79 (1.65+6.14) | 8.3 (1.78+6.53) | 10.53 (2.41+8.12) | 13.86 (3.45+10.4) |
| Cyclone and storm surges | Moderately Low | 7.4 (4.2+3.2) | 7.93 (4.59+3.34) | 9.49 (5.1+4.39) | 10.07 (5.63+4.44) |
| Soft and unconsolidated soil | Very High | 5.89 (4.84+1.05) | 6.53 (5.38+1.15) | 8.59 (6.3+2.29) | 11.53 (9.28+2.25) |
| Upstream sediment input | Moderately High | 5.55 (2.5+3.05) | 6.04 (2.79+3.25) | 10.75 (3.65+7.1) | 11.39 (3.08+8.32) |
| River discharge | High | 5.48 (0.9+4.58) | 5.81 (0.93+4.88) | 7.36 (1.22+6.14) | 10.33 (1.61+8.72) |
| Embankment | High | 5.01 (2.21+2.8) | 5.42 (2.45+2.97) | 10.64 (5.28+5.36) | 10.71 (6.54+4.17) |
| High tidal energy | Moderately High | 4.73 (1.63+3.1) | 5.39 (1.79+3.59) | 8.45 (2.95+5.49) | 11.08 (4.21+6.87) |
| Soil compaction | Very High | 4.43 (4.25+0.18) | 5 (4.78+0.22) | 5.99 (5.74+0.25) | 8.42 (7.68+0.74) |
| Polder | High | 4.16 (1.66+2.5) | 4.41 (1.75+2.66) | 8.44 (5.37+3.07) | 9.77 (6.08+3.69) |
| Excessive monsoon rain | High | 3.15 (0.7+2.45) | 3.47 (0.75+2.72) | 6.33 (0.83+5.49) | 7.71 (0.89+6.82 |
| Mangrove afforestation | High | 3.05 (1.09+1.95) | 3.66 (1.29+2.37) | 8.92 (5.27+3.65) | 10.17 (5.91+4.26) |
| Cross-dam | High | 2.75 (0+2.75) | 2.99 (0+2.99) | 9.56 (1.81+7.75) | 7.42 (1.39+6.030 |
| Shelf bathymetry | Very Low | 2.73 (1.73+1) | 2.93 (1.93+1) | 4.51 (2.05+2.46) | 7.06 (4.02+3.04) |
| Development project | Moderately High | 2.7 (1.55+1.15) | 2.84 (1.67+1.17) | 5.15 (4.73+0.42) | 7.75 (5.89+1.86) |
| Deforestation | Low | 2.67 (1+1.67) | 2.89 (1.05+1.84) | 5.35 (2.8+2.55) | 7.08 (4.22+2.86) |

| | | | | | |
|---|---|---|---|---|---|
| Sea level rise | High | 2.59 (1.64+0.95) | 2.77 (1.71+1.06) | 7.12 (2.38+4.74) | 10.35 (3.19+7.15) |
| Modification of river flow | Neutral | 2.15 (1.7+0.45) | 2.31 (1.83+0.48) | 3.94 (3.42+0.52) | 4.16 (2.47+1.69) |
| Monsoon Wind | Low | 2.12 (0+2.12) | 2.32 (0+2.32) | 3.4 (0+3.4) | 4.74 (0+4.74) |
| Population pressure | High | 1.3 (0+1.3) | 1.3 (0+1.3) | 2.95 (0.32+2.63) | 3.51 (0.45+3.06) |
| Seasonal variation of discharge | Moderately High | 1.19 (0.64+0.55) | 1.49 (0.74+0.75) | 2.21 (0.94+1.27) | 3.27 (0.95+2.32) |
| Subsidence | Neutral | 0.70 (0.55+0.15) | 0.74 (0.57+0.17) | 1.89 (0.95+0.94) | 2.32 (1.46+0.86) |

#### 5.4.2.3 Far-future (2080)

Although the FCM-based scenario for far-future (2080) identified a total number of 42 components that were identified as potential for future susceptibility of the coastal area to erosion, this scenario included 09 new components and excluded 03 components from the previous scenario (2050) (Figure 5.4.2c). Along with the number of components, total connections (377) and consequently, connections per component (8.97) also increased on average from the previous state. Among the total number of 39 ordinary components identified, only 3 components were found as transmitter.

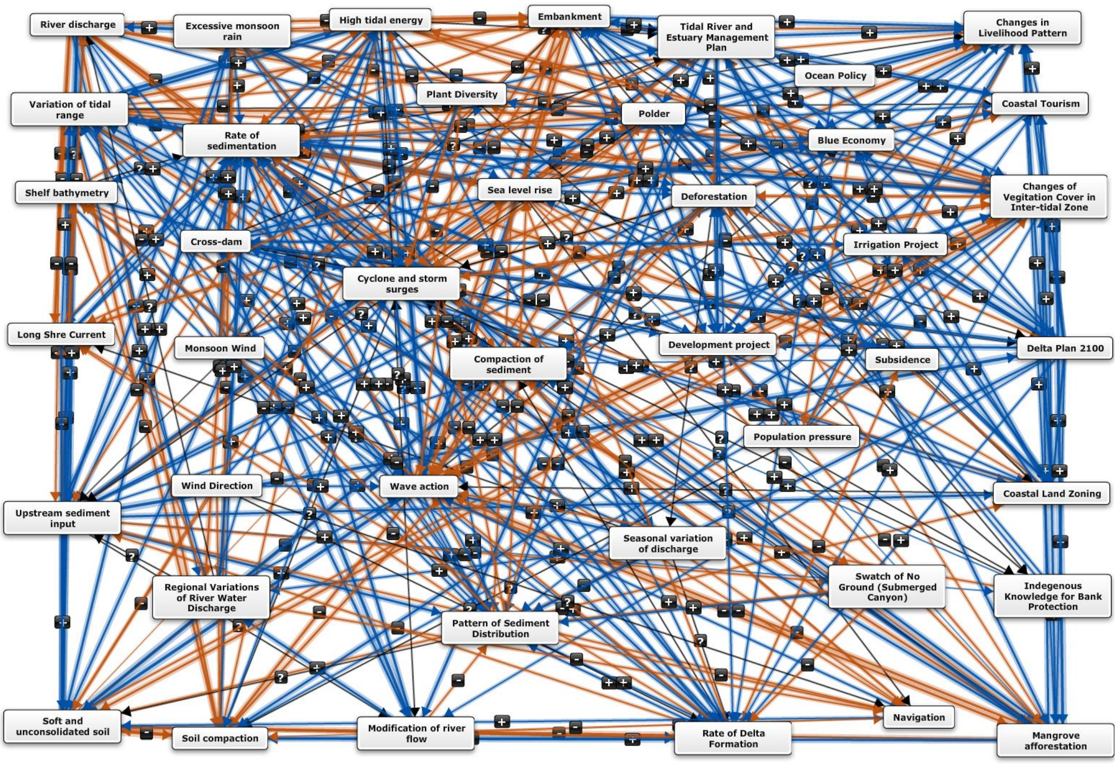

Figure 5.4.2c - FCM components and their relationships for far-future (2080) of susceptibility to erosion. This FCM for far future (2080) indicates that with times, the

interrelationships between the components would be more complex than the baseline conditions.

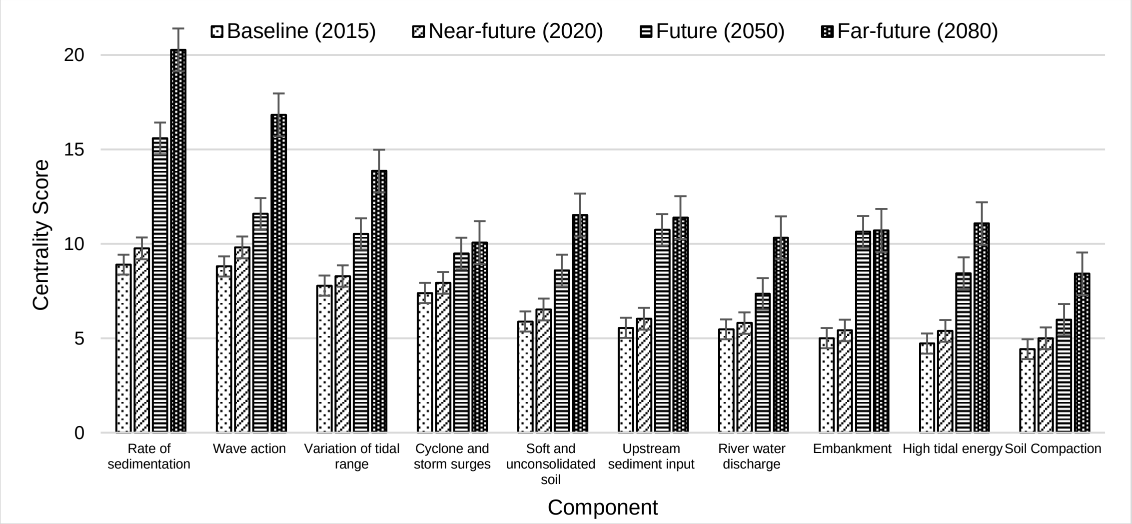

Figure 5.4.2d - Top 10 FCM components (based on centrality score) common for current (baseline) and future scenario of susceptibility to erosion for three time-slices. The centrality scores of the top-ten components represent the sum of scores calculated for the three time-slices.

## 5.5 Discussion

The workshops attempted to synthesize the nature and causes of relationships between the identified drivers of susceptibility to erosion in the coastal area. The discussions were the basis of final values in the matrices and the layouts of the developed FCMs. Among the identified factors for current susceptibility, most of the physical components were identified as having higher centrality scores (Table 5.4.2a and Figure 5.4.2d) that indicate the higher interactions and influences of the factors of susceptibility to erosion. The experts were agreed that the rate of sedimentation, soft and unconsolidated soils, shelf bathymetry, funnel shape of the Bay of Bengal, Swatch of No Ground (deep sea trench), and coastal river channels (Figure 5.3.1a) are the most influential geological and geomorphological factors of susceptibility to erosion in the area. They identified wave action, river discharge, monsoon wind, cyclone and storm surges, excessive monsoon rain, high tidal energy, variation of tidal range and sea level rise as dominating hydro-climatological factors of current susceptibility to erosion in the area.

Further discussions on the developed FCMs noticed that the bathymetric depths have a considerable influence on the susceptibility to erosion in the coastal area. The higher depths in the coastal river channels (due to erosion) and comparatively lower depths in and around the shoreline (due to sedimentation), make the discharge of the rivers to act predominantly at the interior coast. However, tidal energy and wave action play substantial roles for erosion at the exposed coast. Currently, most of the newly accreted small islands and major parts of the comparatively large islands located in the central coastal area (Figure 5.3.1a) are highly susceptible to erosion. The experts put emphasis on the linkages of continuous wave actions, high permeability of water into soils and variations in tidal ranges with the high susceptibility of the islands to erosion. For instance, major land areas of Sandwip Island located in the exposed central coastal zone (Figure 5.3.1a), has been eroded from the 1980s until recently. Erosion has also taken place at the north of Hatiya, north-east of Bhola and the south-west of the former Ramgati Island (Figure 5.3.1a). Additionally, the occurrences of excessive rainfall accentuate the volume of water discharge in the coastal area that contributes to the high level of susceptibility to erosion. Continuous wave actions initiating by south and south-western monsoon wind accelerate the process of erosion in most parts of the coastal area; especially in the exposed part of the central coastal zone. However, the soft and unconsolidated soils are highly sensitive to the waves that result in a high rate of erosion in the Meghna estuary, Kuakata, Moheshkhali, Kumira and Kutubdia coastal areas (Figure 5.3.1a). Frequent occurrences of tropical cyclones and consequent storm surges from April to June and September to November make the coastal area highly susceptible to erosion, they added. The identified factors from the discussions were also found as higher centrality scores in the FCMs (Table 5.4.2a).

The FCMs especially developed for the three coastal zones indicate that some physical factors such as wave action, variations of tidal range, cyclone and storm surges, supply of sediments and bank protection works act similarly for susceptibility to erosion in all the three coastal areas (Table 5.4.1a). However, the FCMs identified some spatial variations of the factors for the zones. For example, in the western coastal area, the manifest role of mangrove forest to lessen the erosion susceptibility was reported in the FCMs. Like mangrove, polders also showed a positive relationship in the FCM matrix for erosion susceptibility. The synthesis of their opinion postulates that the Meghna estuary in the central zone of the coast is currently a very active part of Bengal basin and highly susceptible to erosion. Rapid geomorphological changes are taking place in the area where a combined flow of water of the Ganges (the Padma in Bangladesh), Brahmaputra and Meghna Rivers initiates the process of erosion in one hand and supplies of a substantial amount of sediments in another hand. Furthermore, the wave actions, cyclone and storm surges, soft and unconsolidated soils, tidal circulations, funnelling effects and bathymetric depths were identified in the FCM as high influential factors of susceptibility of the zone to erosion. On the other hand, positive relationships for bank protection works such as embankments, polders, development projects, river training as well as afforestation programme were noticed in the FCM for this coastal area. The experts were opined that rock types, flat and long sandy beach and bank protection and development works (e.g. marine drive from Cox's Bazar to Teknaf) substantially reduced the level of susceptibility in the eastern coastal area. In contrast, counter-clockwise circulation of tidal water, wave action in shallow bathymetric depths as well as human interventions in the coast contribute to the erosion susceptibility in the area.

The experts identified, however, a diversified nature of human-induced factors influential for current susceptibility to erosion that included the issues of bank protection and development activities. Some factors such as embankment, mangrove afforestation, modifications of river flow etc. scored higher centrality values in the FCMs than other factors (Table 5.4.2a). For instance, the experts were opined that bank protection works of the Government such as embankment, dykes and polders lessen the susceptibility to erosion in Kuakata, Bhola, Sandwip, Chittagong and Cox's Bazar coastal areas but, the completed tasks seem currently not sufficient to protect the entire coast from erosion. Additionally, Government has taken major land reclamation projects in the coastal area, the ultimate results of which have already been observed in Noakhali coastal district. However, these reclamations of lands by diverting river water and tidal circulations created erosion in other parts of the coast those were highly visible in the eastern coastal area of Sandwip Island. On the other hand, mangrove afforestation projects are undertaken by the Government in newly accreted islands and mud flats indicate noticeable contributions to minimising the susceptibility of those lands from erosion.

The workshops considered the changing nature of presented scenarios (e.g. business-as-usual, low, moderate and high) on future climate-driven forces and their overall impacts, with a view to identifying the potential factors of future susceptibility of the coastal area to erosion for different time-slices. The developed FCM for near-future time-slice (2020) identified more complex relationships between the identified parameters. The experts were opined that the areas under Moheshkhali, Kutubdia and St. Martine islands of the eastern coastal zone (Figure 5.3.1a) might be moderate to high and very high susceptible to erosion by 2020. Most of the small islands and newly developed lands such as north of Monpura, Char Jonak, Bodnar Char and Dhal Char in the central zone (Figure 5.3.1a) might also experience high and very high susceptibility to erosion. Along with the increase of water discharge and rainfall, the probable increase of mean sea level and wave actions might affect the lands of the comparatively bigger islands in the central zone such as Bhola, Hatiya, Sandwip, Char Zahiruddin and Char Gazaria attached to the coast (Figure 5.3.1a). The level of susceptibility to erosion might be increased for Urir Char, Jahajir Char and Char Piya during that time. Due to the increased wind speeds, the wave actions might be negatively effective for erosion susceptibility of the lands attached to shallow depths. Under changing scenarios of future climate, the funnelling effects of the Bay of Bengal might increase the effects of tidal energy that could change the offshore and near-shore bathymetry of the coast, they opined. The supply of sediments from upstream might have substantial influences on the net balance of erosion and accretion especially, in the estuarine part of the coastal area. However, the role of bank protection works and mangrove afforestation in the inter-tidal mud flats of the central coastal zone might be crucial for limiting land susceptibility to erosion in that areas. Along with these, positive changes in land use pattern, plant diversity in coastal lands and reduction of deposition of undecomposed materials might be effective for low susceptibility of the coastal area to erosion.

The relationships between the parameters of the developed FCM indicate that projected changes in climate-induced drivers might have substantial roles on the higher susceptibility of the coastal area to erosion for future (2050) time-slice than previous times. The experts were agreed on a common consensus that an increase in water discharge, mean sea level, rainfall and wind speed by 2050 might also increase erosion susceptibility of the newly accreted small islands in the Meghna estuary of the central coastal zone. Some areas along Chittagong coast, Cox's Bazar and Noakhali (Figure 5.3.1a) might also be highly susceptible to erosion during that period. Besides addressing the potential physical factors of erosion susceptibility in the FCM for 2050, the workshops identified some human-driven measures such as delta plan 2100, land reclamation projects, ocean policy (yet to be formulated), indigenous knowledge for bank protection, changes in livelihood pattern, coastal land zoning, coastal tourism, blue economy (ocean-based economic development), changes in vegetation cover in inter-tidal zone, adaptive delta management plan, tidal river and estuary management plan and Public-Private Partnerships (PPP) that might have probable effects to limit the susceptibility of the coastal lands to erosion (Table 5.4.2a). The experts have agreed that bank protection works, and coastal river channels would be satisfactorily under control and hence were not included in the FCM developed for 2050 time-slice.

Table 5.5a - Changes in the components of FCMs developed for 2050 and 2080 time-slices. With times, several new components would be added to the future (2050) and far-future (2080) time-slices. Moreover, the impacts of some components would be less effective for land susceptibility to erosion in the coastal area.

| Time-slice | Component included (with previous time-slice) | Centrality (In-deg. +Out-deg.) | Component excluded (from previous time-slice) | Centrality (In-deg. +Out-deg.) |
|---|---|---|---|---|
| Changes in the FCM for future (2050) | Coastal land zoning | 8.24 (3.37+4.87) | Bank protection | 5.25 (3.59+1.65) |
| | Delta plan 2100 | 7.98 (1.84+6.14) | | |
| | Land reclamation project | 6.9 (4.54+2.36) | Changes in land use pattern | 2.19 (2.05+0.15) |
| | Irrigation project | 2.51 (1.52+0.99) | Deposition of undecomposed materials | 0.2 (0+0.2) |
| | Changes of vegetation cover in inter-tidal zone | 9.51 (5.81+3.7) | Funnel shape of the Bay | 0.9 (0+0.9) |
| | Blue economy | 6.19 (4.57+1.62) | Endogenic | 0.48 (0+0.48) |
| | Coastal tourism | 3.63 2.76+0.87) | | |
| | Ocean policy | 0.56 (0+0.56) | Swatch of no ground | 1.1 (0.30+0.8) |
| | Indigenous knowledge for bank protection | 1.47 (0.65+0.82) | | |
| | Changes in livelihood pattern | 6.89 (6.89+0) | Shrimp farming | 0.4 (0.15+0.25) |
| | Tidal river and estuary management | 7.14 (2.42+4.72) | Dykes | 1 (0.8+0.2) |

| | | | | |
|---|---|---|---|---|
| | plan | | | |
| | Adaptive delta management plan | 4.19 (2.69+1.5) | Coastal river channels | 1.2 (1.2+0) |
| | Public Private Partnerships (PPP) | 3.92 (2.38+1.54) | Plant diversity | 0.58 (0.15+0.43) |
| Changes in the FCM for far future (2080) | Rate of delta formation | 8.72 (5.58+3.14) | Land reclamation project | 6.9 (4.54+2.36) |
| | Pattern of sediment distribution | 10.54 (7.98+2.56) | | |
| | Wind direction | 1.02 (0+1.02) | | |
| | Regional variations of river water discharge | 4.07 (2.05+2.02) | Adaptive delta management plan | 4.19 (2.69+1.5) |
| | Longshore current | 7.13 (3.74+3.39) | | |
| | Navigation | 2.97 (2.02+0.95) | | |
| | Compaction of sediment | 4.06 (3.30+0.76) | Public Private Partnerships (PPP) | 3.92 (2.38+1.54) |
| | Plant diversity | 2.78 (0.88+1.9) | | |
| | Swatch-of-no-Ground (submerged canyon) | 2.24 (1.11+1.13) | | |

The interaction between the factors for far-future (2080) susceptibility of the coastal area to erosion might be highly complex and highly uncertain by 2080 under continued increases of influences of hydro-climatic forces (Table 5.4.2a). The increases of river water discharge, mean sea level, rainfall and wind speed in the coastal zone might alter the current susceptibility in most of the islands and newly developed lands in the central estuarine areas by that time. Most of these areas might be attached to high and very high susceptibility categories along with some moderate susceptible areas. Kuakata coastal area and some small islands in the exposed western coast might be highly susceptible to erosion by 2080 time-period. The situation might also be worsening at Moheshkahli, Kutubdia and St. Martine islands located in the exposed eastern coastal zone (Figure 5.3.1a). The impacts of natural forces such as wave actions, variation in tidal range, sea level rise, pattern and rate of sedimentation, longshore current and plant diversity might be highly visible during that time (Table

5.4.2a). The shape of the offshore islands in the Meghna estuary and the location of Swatch-of-no-ground (Figure 5.3.1a) motivated the experts to opine that the submerged canyon might have influences on erosion by pulling sediments from that areas through anti-clockwise circulations of currents. Along with other human-driven factors, coastal navigation might be an important reason identified by the experts for erosion susceptibility along the numerous river channels existing in the western coastal area.

## 5.6 Conclusion

This study applied an FCM based approach to assess the susceptibility to erosion for the entire coastal area of Bangladesh. The benefit of using this cognitive approach in this study over traditional models to address the factors of current and future coastal susceptibility to erosion is noteworthy. However, the cognitive maps derived in the present study strongly depend on the group of experts. The outcomes of the FCM approach addressed how the experts interpret the current as well as the future scenario of coastal erosion susceptibility. The FCMs identified 33 factors that are relevant to land susceptibility to erosion for current baseline conditions. The experts' interpretations suggest that the future rates of both erosion and accretion might be higher than the current in the central zone compared to the western and eastern zones of the coastal area. For future scenario, this study identified 33, 36 and 42 relevant factors of susceptibility to erosion for near future (2020), future (2050) and far future (2080) time-slices respectively. The identified factors include both physical (i.e. natural) and human-induced factors and their degree of relationships between them. The FCMs modelled higher centrality scores for rate of sedimentation, soft and unconsolidated soils, shelf bathymetry, funnel shape of the Bay of Bengal, wave actions, river discharge, monsoon wind, cyclone and storm surges, excessive monsoon rain, high tidal energy, variations of tidal range and sea level rise for both current baseline conditions and future scenario. This study identified some processes and inter-relationships of both physical and human-induced factors of coastal susceptibility to erosion, particularly for the three coastal zones, that might be helpful for policymakers to propose future interventions for the three coastal zones.

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## Chapter 6: Discussion

This chapter of the thesis synthesizes the outputs of the present study and then discusses the cross-cutting issues of land dynamics and land susceptibility to erosion. The novelty and impacts section identifies how the current research contributes new knowledge. The limitations of the present study are also discussed in this chapter.

### 6.1 Synthesis of the results

This section discusses the empirical findings of the present study and identifies the added value of each chapter. Moreover, how the research findings strengthen the key messages of the study are also deliberated in this section.

#### 6.1.1 Land dynamics and land susceptibility

To support the assessment of land susceptibility of the coastal area to erosion, the study first analysed the pattern of land dynamics for the past 30 years (the detailed reasons are discussed in chapter 1) in which, variations were observed for the three coastal zones due to several natural and human-induced forces (discussed in chapter 2). One of the major observations from the pattern of land dynamics is that there was a net gain of 237 km$^2$ of land for the entire period, but constant changes in the eroded and accreted land areas were identified for the three coastal zones. Moreover, the LSCE model provides a comprehensive analysis of the existing conditions of land susceptibility to erosion in the coastal area. However, the results of land dynamics correspond with the results of existing land susceptibility to erosion in which, about 95.7% highly susceptible lands were identified as highly dynamic in the inventory map (Figure 3.5.1a). The existing highly erosion susceptible coastal lands (i.e. 276.33 km$^2$) indicate the probable impacts and interactions of underlying physical elements, hydro-climatic conditions and preparatory factors in the area (Figure 6.1a). This is because the LSCE model evaluated the weighted influences of each parameter for each cell of the raster layers under five susceptibility classes that represents the potential influences of the selected parameters on erosion susceptibility in the coastal area. These influences were further interpreted by segmenting the hydro-climatic factors into four prevailing seasons for the baseline year. The daily and monthly hydro-climatic data showed substantial variations in the data ranges (Table 3.3.2a) and hence, it was necessary to identify if these variations had any influence on erosion susceptibility in the coastal area. However, the results indicate that a substantial impact of seasonality exists in the hydro-climatic factors which exert influences on erosion susceptibility of the coastal lands. For instance, a total amount of 462.94 km$^2$ highly erosion susceptible coastal land was identified for monsoon season compared to 276.33 km$^2$ highly erosion susceptible coastal land identified for overall land susceptibility to erosion in the area. On the other extreme, the highly susceptible coastal land during winter season was found as low as 158.18 km$^2$, which is 118.15 km$^2$ lower than the overall condition of the highly susceptible land.

The use of a geospatial approach (i.e. raster GIS-based LSCE model) made an important contribution to studying land susceptibility to erosion in the coastal area. The sensitivity analysis (SA) of the LSCE model identified the impacts of selected parameters on the model results. Moreover, the application of the model for each zone under SA addressed the impacts of zonal factors on land susceptibility to erosion. Hence, it is now clear that the LSCE model identified the erosion susceptibility of the coastal area in a more robust way. The validated model results and SA of the model together strengthen the recommendations made to policymakers in managing erosion susceptibility in the coastal area. Moreover, the approach of using raster GIS-based LSCE model provides added value when assessing land susceptibility to coastal erosion since the model is capable of addressing both the impacts of underlying physical elements and hydro-climatic factors on land susceptibility to erosion for dynamic coastal areas around the world.

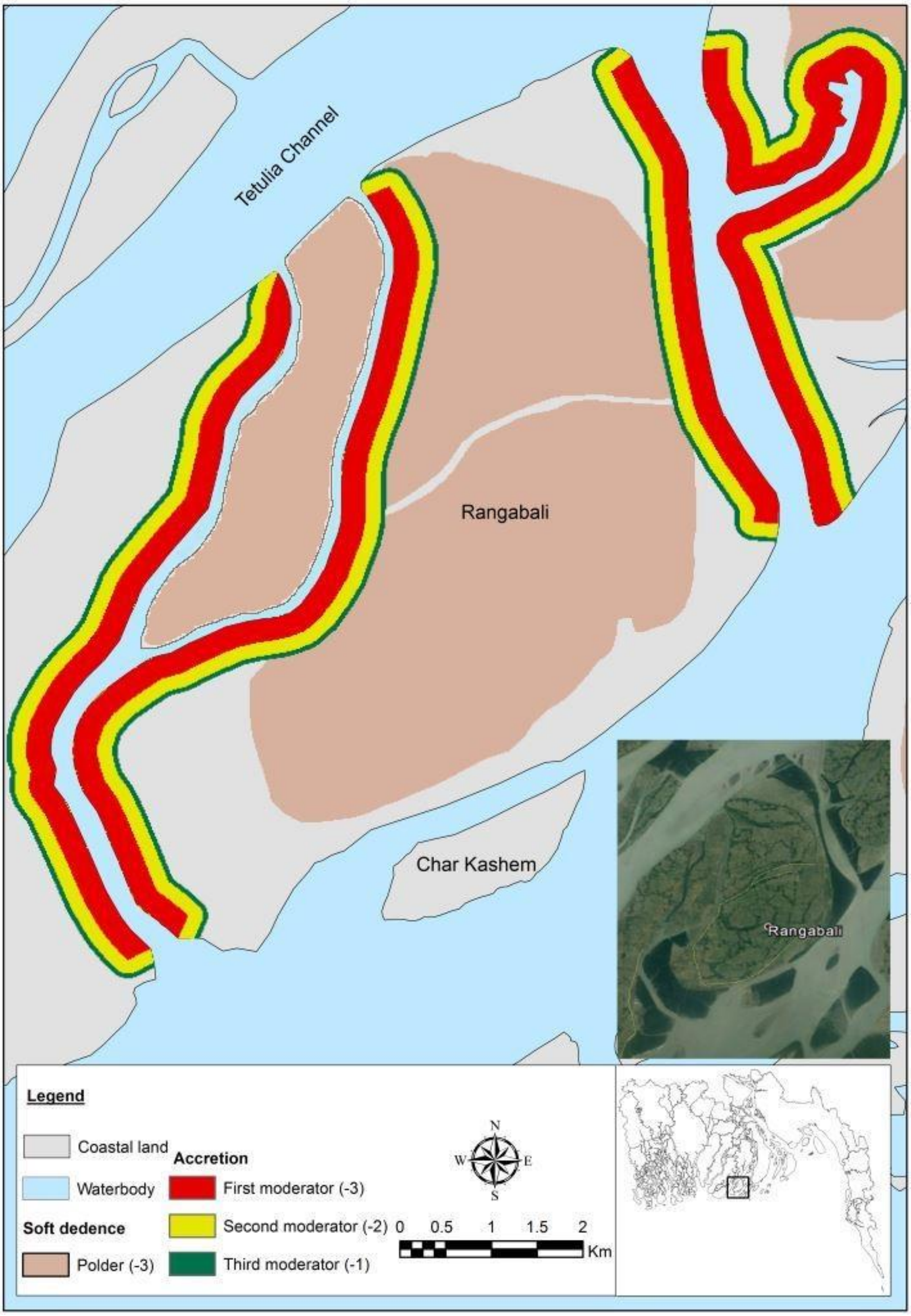

Figure 6.1a – An example of the uses of moderators in the LSCE model domain. The three sets of accretion moderators (discussed in chapter 3) were used to address the impacts of accretion whereas, the moderators for defence structures were used to discourse the human interventions in the process of erosion. The map shows the use

of such moderators for Rangabali area in the central coastal zone where a substantial amount of land was accreted for the years from 1985 to 2015 (Figure 2.5.4a).

### 6.1.2 Changing scenarios of erosion susceptibility

The assessment of existing land susceptibility to erosion by using the LSCE model provided the basis of generating possible future scenarios of land susceptibility under future hydro-climatic changes in the study area (Figure 6.1b). Having comprehensive results on the existing land susceptibility to erosion, this study aimed to identify the probable impacts of hydro-climatic factors on future erosion susceptibility in the coastal area. Hence, the likely impacts of future hydro-climatic forces were modelled in which, an increasing rate of future land susceptibility to erosion was identified under the four scenarios for three time-slices. This increasing scenario of erosion susceptibility clearly informs the baseline conditions that the existing land susceptibility will undergo changes due to the changing hydro-climatic factors in the area in future. The generated scenarios indicate that there would be a substantial influence of hydro-climatic drivers on future erosion susceptibility of the coastal lands. This influence of hydro-climatic changes could alter more coastal lands to high and very high susceptibility to erosion. It is notable that the identified 10.01 km$^2$ existing coastal lands as very high susceptibility to erosion would be increased to 176.43 km$^2$ and 218.74 km$^2$ by 2080 under the A1B and RCP4.5 scenarios respectively. However, the model outputs of high scenario (i.e. RCP8.5) differ markedly from the A1B and RCP4.5 scenarios. The results under the RCP8.5 suggest 1006.41 km$^2$ of coastal lands that would be turned into very high susceptibility by 2080. The generated future land susceptibility to erosion under the present study contributes important knowledge in studying the interactions of hydro-climatic factors with the physical conditions of the study area in future.

### 6.1.3 Addressing broad aspects of erosion susceptibility

In addition to the model results, the present study elicited experts' opinions on the wide aspects of land susceptibility to erosion in the area. This elicitation provides notable contribution to study land susceptibility to erosion in the coastal area in several ways (Figure 6.1b). Due to data limitations (discussed in chapter 1), the LSCE model included nine factors of erosion susceptibility as model parameters. The selected parameters fairly addressed the impacts of each parameter in the model.

However, it was difficult to address the impacts of mangrove vegetation cover, longshore currents and indirect influences of human-induced factors of erosion susceptibility by the LSCE model. Considering the identified limitations (discussed in section 6.6), the present study adopted human-value judgement on erosion susceptibility in the study area. The experts' interpretations of current and future erosion susceptibility in the area were semi-quantified by identifying the factors responsible for erosion susceptibility and evaluating the nature of interrelationships among the identified factors in adjacency matrixes. The relationship matrixes (both positive and negative) were visualised by generating Fuzzy Cognitive Maps (FCMs). The FCMs provided explanations on how the physical and human-induced factors are interacting with each other and exert their influences on erosion susceptibility in the coastal area. For instance, the FCM on existing land susceptibility to erosion in the three coastal areas (Figure 5.4.1b) visualised the interactions of the regional (zonal) factors on erosion susceptibility in the area.

The generated FCMs in the present study enhanced the LSCE model results by addressing the relevant factors and associated uncertainties that were not possible to include as model parameters. Moreover, the FCMs were acted as an effective way of explaining the causes of spatial and temporal variations of the identified levels of land susceptibility to erosion by the LSCE model. The cognitive map on overall existing land susceptibility to erosion (Figure 5.4.1a) indicates that most of the parameters used for the LSCE model were also identified by the experts. This correspondence would seem to justify the inclusion of appropriate parameters in the model. The experts also identified several factors that would be vital for future land susceptibility to erosion in the area. The experts expressed their common consensus on the likely increase of land susceptibility to erosion in the coastal area in the future that was reflected in the FCMs (Figures 5.4.2a, b and c). This elicitation on future land susceptibility to erosion in the coastal area was similar to the model results. However, the experts were also concerned with how the physical settings of the area will adjust to future changes in hydro-climatic scenarios. With regards to this, the experts emphasized that government interventions would be highly important for managing future erosion susceptibility under changing scenarios of hydro-climatic factors in the area. These elicitations of experts' views support the LSCE model-based results and hence, strengthen the key messages and recommendations of the present study (Figure 7.1b).

The experts emphasized the potential impacts of mean sea level rise on erosion susceptibility in the coastal area in future. The increasing influences of sea level rise on future land susceptibility to erosion in the coastal area were evaluated by the experts. In the workshops, although the impacts of sea level rise were not highly emphasized for the current and near future erosion susceptibility, the impacts were highly prioritised for future (2050) and far-future (2080) time-slices. The centrality score of sea level rise was increased to 10.35 in the FCM developed for 2080 time-slice which was higher than the scores of some top-listed factors such as soil compaction and cyclone and storm surges. Moreover, the out-degree score of FCM for mean sea level appeared from baseline 0.95 to 7.15 for 2080 time-slice.

From a wider perspective of land dynamics in the coastal area of the country, the experts discussed the probable impacts on the Swatch of no Ground in the Bay of Bengal. The Swatch of no Ground is a trough-shaped marine canyon which is 5-7 km wide and walls with 12 inches inclination (Figure 1.2.4a) (Banglapedia, 2018). The shape of the major offshore islands pointing towards the Swatch of no Ground in the central coastal zone indicates the possible tunnelling of upstream sediments from GBM river basin through this canyon to the deep-sea Bengal fan (largest submarine fan on earth) (Covault, 2011; Shanmugam, 2016). Major erosion events occurred at the eastern coast of Sandwip, south-eastern coast of Hatiya and eastern coast of Bhola islands evident in the current study might strengthen the proposition of such tunnelling effect in the area.

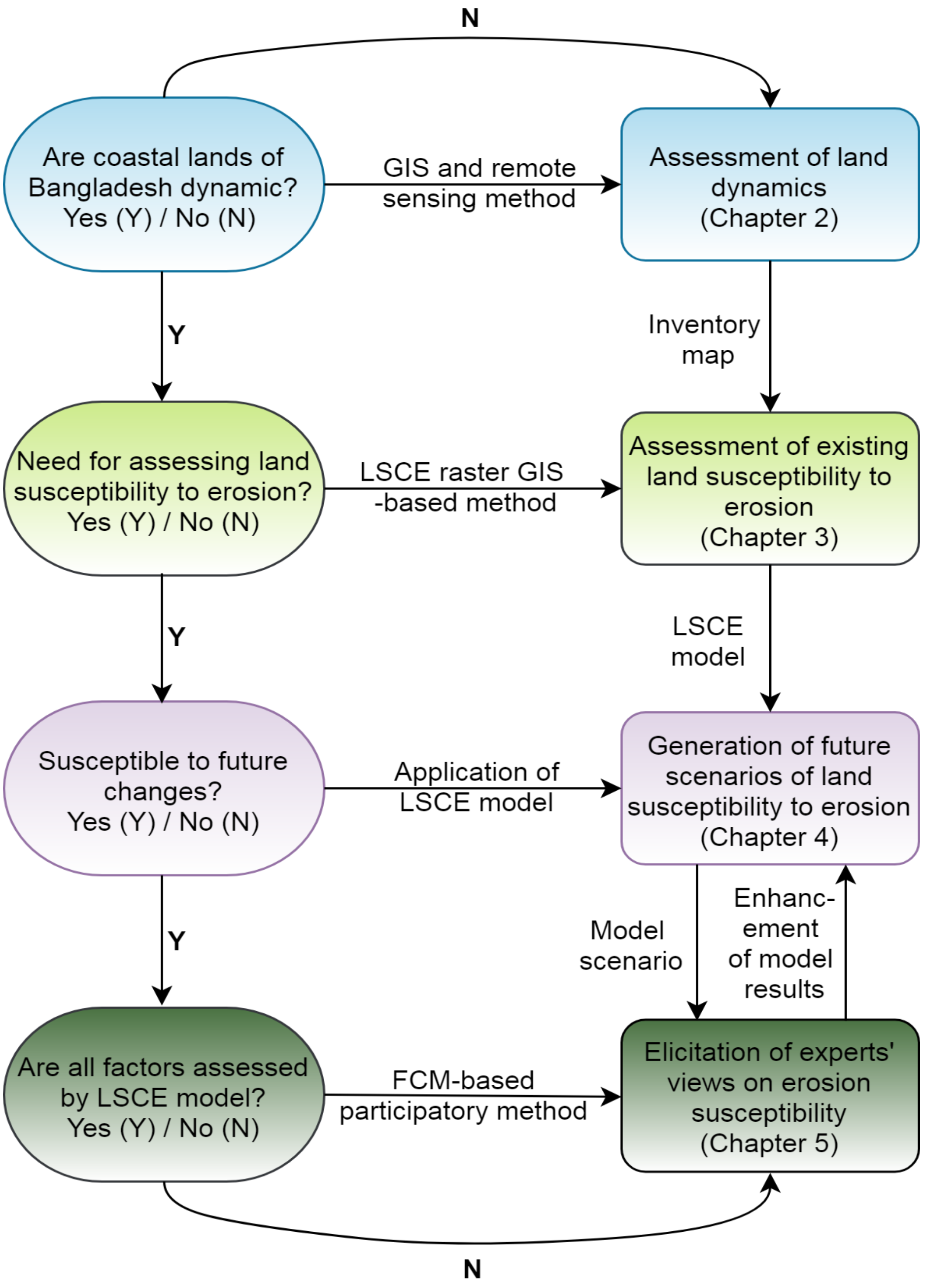

Figure 6.1b – The logical sequence of the study. The figure indicates the justification of each part of the study and the connections of the results of each chapter to the results of the next chapter. Each part was motivated by a rational question, the answer of which initiated the next part of the study. The assessment of land dynamics is required for both types of situation (i.e. Yes [Y] and No [N]). The present study initiated the assessment of land susceptibility to erosion based on the results that the coastal lands of the area are highly dynamic. However, the elicitation of experts' views was required in a situation when it was difficult to address the diverse factors of land susceptibility to erosion by the LSCE model.

## 6.2 Dichotomy of land dynamics

The assessment of land dynamics in the present study brings a new dialogue to the table. Nowadays, it is frequently discussed in the media that the negative impacts of hydro-climatic changes have led to the net loss of coastal lands around the world. Moreover, the scientific community predicts that the future rate of coastal erosion might be increased due to the increasing rate of sea level rise together with the propagation of waves. The ultimate result of which might be a substantial amount of net loss of coastal lands in future. However, analysing the past trends of land dynamics, this study came to a different conclusion. The study reveals a net gain of land (i.e. 1812 km$^2$) which is slightly higher than the net loss of land (i.e. 1576 km$^2$) for the past 30 years but, the results demonstrate that the overall rates of both erosion and accretion were high in the coastal area (Figure 6.2a). The study envisages that the likely changes in hydro-climatic scenarios would make the coastal lands more dynamic. The net balance of land would possibly be highly influenced by site-specific factors such as geomorphic features, sediment supply, tidal currents, discharge of coastal river water and the extent of human interventions. For instance, the present study identified the dual controls of underlying physical elements and hydro-climatic drivers on the pattern of erosion and accretion in the three coastal zones of the country (discussed in chapter 3 and chapter 4). The effects were highly visible in the exposed central coastal zone (Figure 3.4.1a and Figure 4.4.1b). The constant supply of sediments by the river channels is playing an active role for the accretion of land in the area. As a result, the bathymetric depths close to the shoreline are gradually reducing. The comparatively lower depth is creating a barrier for the upstream sediment loads to dispose into the Bay of Bengal. This gives rise to several newly accreted small islands in the mentioned area (Figure 2.5.4a) but, the wave actions are prominent in those areas due to shallow water depth. However, the site-specific factors such as low discharges of river water, less rainfall and the existence of mangrove vegetation have made the western zone less dynamic than the central coastal zone (Figure 6.2a). On the other hand, the eastern coastal zone is visited by heavy rainfall and high mean sea level but, is less dynamic due to its consolidated surface geology, less river water discharge and comparatively effective coastal protection measures than the other zones.

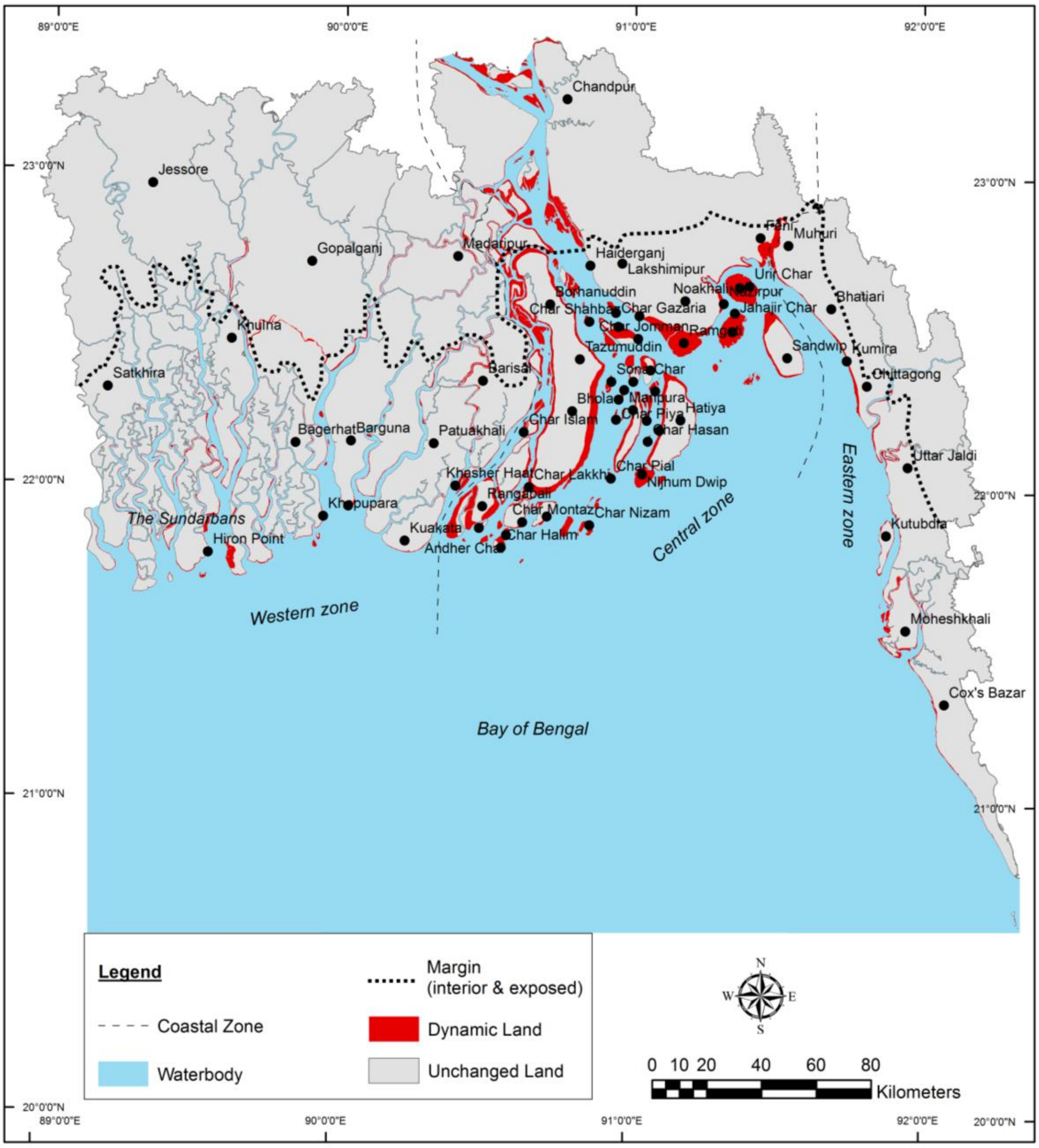

Figure 6.2a - Inventory map prepared for identifying currently existing dynamic lands characterised as having erosion and/or accretion for the past thirty years. The map shows that the exposed area of the central coastal zone was highly dynamic compared to the interior area. Substantial changes in lands were identified for the offshore islands and Ramgoti area in the central coastal zone.

### 6.3 Mediations in the coastal system

The potential human interventions (i.e. building of polder, land zoning, mangrove afforestation and land reclamation project) mentioned in the previous chapters might create an enabling condition for the government to manage highly erosion susceptible coastal lands in the area. As a reflection of fragmented coastal land management policies (discussed in chapter 2), a number of incoherent projects have already been completed by the government. Moreover, the government is currently planning to execute some short-and long-term projects relevant to coastal land management. This section articulates the nature of interventions that are vital for an effective science-policy-practice interface (United Nations Environment Programme [UNEP], 2012; Luc Hoffmann Institute [LHI], 2017) in managing highly erosion susceptible coastal lands in the area.

Government intervention in managing coastal erosion has long been in place. From the 1960s until recently 139 polders were constructed to serve as the first defence against wave actions in the coastal area (Figure 6.3a). However, instead of having a few positive socio-economic impacts, the polders have been creating negative impacts on the natural sedimentation process in the coastal area. The deposition of sediments in the peripheral areas surrounding the polders have already initiated water-logging problem within the polder areas. Moreover, following national land use policy, the government is planning to execute a land zoning project in the area. The planned land zones are the geographic areas that will demarcate the lands based on some specific environmental (i.e. physiography, flood level, soil texture, pH and salinity) and socio-demographic (i.e. population, land use, land governance) criteria (Ministry of Land [MoL], 2018). A total number of 301 land zones are initially identified among which 99 zones are recognised in the coastal area of the country. In parallel, a Land Zoning Law has already been enacted to include the zones under a regulatory framework. It would be fascinating to observe the impacts of the land-zoning project on the management of high erosion susceptible and newly accreted coastal lands in future. However, it is a matter of concern that the project is not considering erosion susceptibility while preparing land zones for the area. This study infers that the project needs to incorporate the likely impacts of potential drivers of land susceptibility to erosion in the coastal area. Moreover, the levels of erosion susceptibility of the entire coastal lands need to be included as an essential criterion for preparing land suitability maps under the project. Along with the land zoning project, the impacts of the century-long

‘Delta Plan 2100’ by the government will be important for the country and could change prolonged institutional inertia in managing coastal erosion.

Current plantation program of the government is thought to be a positive initiative to protect the coastal lands from erosion in future. The existence of 6,017 km$^2$ Sundarbans mangrove forest (Aziz and Paul, 2015) and 2,164.15 km$^2$ mixed plantation areas (i.e. mangrove and non-mangrove) (Ahmed et al., 2018) would have substantial influences on erosion susceptibility of the coastal lands. The Sundarbans mangrove forest occupies 4.2% lands which is about 44% of the total forest cover of the country (Figure 6.3a) (MoEF, 2010). The area is a flat deltaic swamp with alluvium soils (Iftekhar and Islam, 2004). Mangrove and other coastal plantation could protect the coast against wave actions in areas attached to shallow water depths (Fritz and Blount, 2007). Mangrove plantations stabilize sediments (Prasetya, 2007) and trap soil particles by their long roots and thus help in accreting new lands (Islam et al., 2015). The current study identified the lands under mangrove forest and plantation areas as very low to low and moderate susceptibility to erosion. However, large-scale plantation program in the newly accreted lands is vital for the coastal area. Vegetation provides a new window of opportunity to build sustainable ‘bioprotection’ (Naylor, 2005), that would be helpful to protect the lands from erosion in the rapidly changing central coastal zone of the country (Figure 6.3b). Additionally, the forest department of the government needs to control the increasing rate of deforestation that would exert positive influences on land susceptibility to erosion in the area in future.

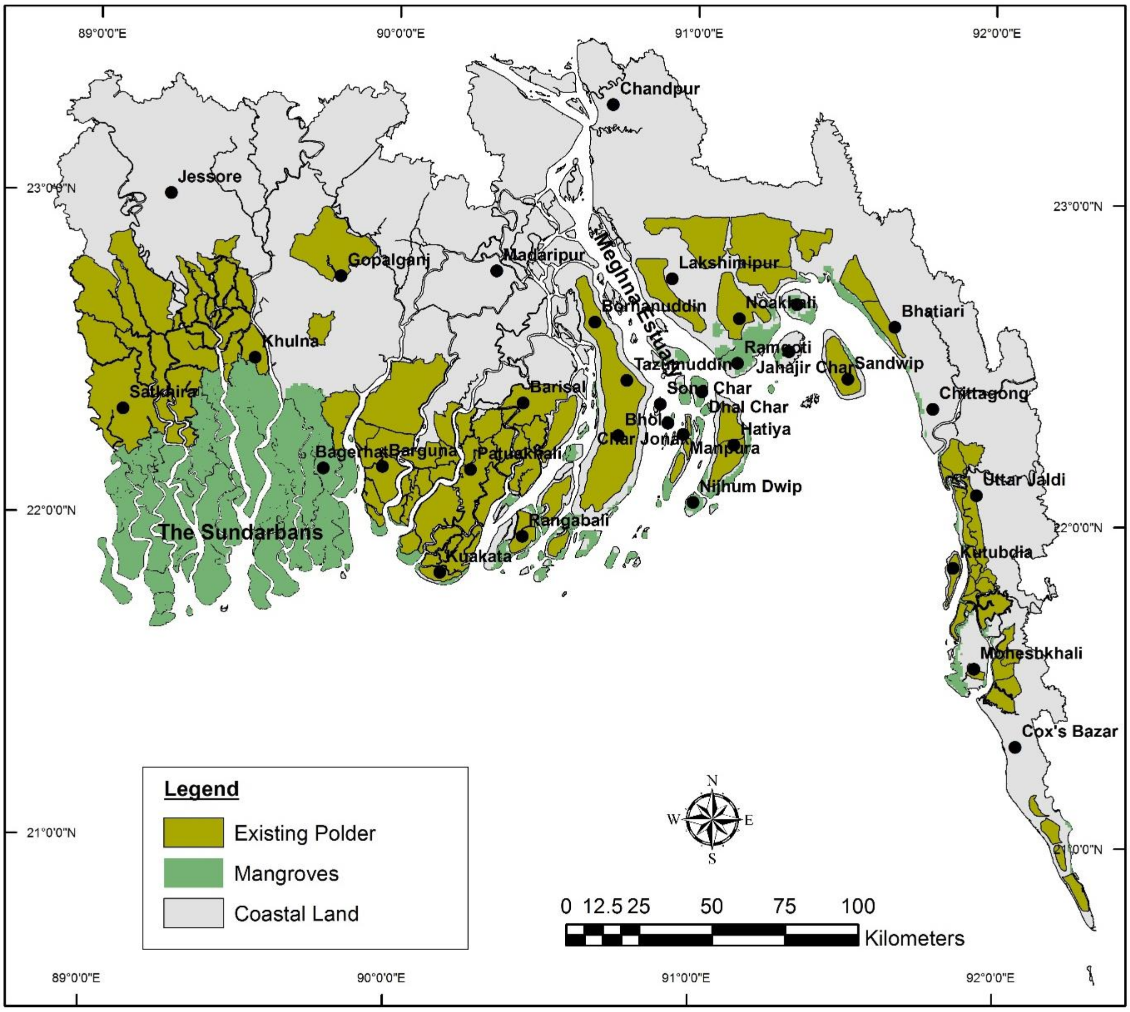

Figure 6.3a – Construction of major polders and existence of mangrove vegetation cover (i.e. forest and plantation) in the study area. However, providing ecological enhancement (Naylor et al., 2012) by planting mangroves surrounding the polders could reduce erosion susceptibility of the lands included into the polders. [Data source: UNEP-WCMC, 2011; BWDB, 2016]

*The existence of newly accreted land is highly evident in the central coastal zone.*

*Mangrove afforestation could be a first defence line to settle newly accreted lands in the coastal area.*

Figure 6.3b – Accretion of new land and the role of bioprotection in the coastal area of the country. The images show the newly accreted Later Char (left) and mangrove afforestation at Sona Char (right) in the highly dynamic central coastal zone. To protect such type of newly accreted lands, the government needs to initiate large-scale mangrove afforestation plan in the central zone (more photographs are provided in Appendix G). [Source: The candidate, for all the photographs used in this thesis]

Land Reclamation Project (LRP) of the government would be a crucial issue to follow-up its effects on land dynamics and erosion susceptibility in the coastal area. The prevalence of mudflats in the central coastal zone (Figure 6.3c) has the potential to reclaim lands in the area. The task force of Bangladesh Water Development Board (BWDB) recommends reclaiming lands in the Meghna estuary area by trapping naturally available suspended sediments that come through upstream rivers. The task force identified a total number of 19 sites (Figure 6.3c) for building closure dams in the central coastal zone (BWDB, 2007). Followed by the positive feedbacks of Meghna-1 (1957) and Meghna-2 (1964) cross dam projects (discussed in chapter 2), the government is currently planning to build closures under 'Sandwip-Urir Char-Noakhali' project (BWDB, 2016). It is expected by the government that the project might reclaim approximately 360 km$^2$ land area within a period of 30 years (Figure 6.3c). The bathymetric survey under Meghna Estuary Study (BWDB, 2001) suggests that there would be less impacts of planned closures on tidal circulations in the area. However, this study infers that the project would be a problem due to the dynamic nature of lands in the area. Recent bathymetric surveys and charts (Bangladesh Navy [BN], 2010; Global Multi-Resolution Topography [GMRT], 2015) conducted thereafter signpost substantial bathymetric changes have occurred in the area. While completing the two proposed closures (i.e. Sandwip-Urir Char and Urir Char-Noakhali) (Figure 6.3c), Hatiya and Sandwip offshore islands would be directly affected by the likely changes in tidal circulation. The likely return-flow could hit the south-eastern coastal area of Sandwip Island which would cause erosion in that area. The probable accreted lands in the project area would divert the tidal circulation and flow of Hatiya channel to north-eastern Hatiya Island that could accelerate the ongoing erosion at north-eastern Hatiya in future. However, the effects of tidal flow would be less in Chittagong coastal area due to the low level of land susceptibility in the area.

Similar to Sandwip-Urir Char-Noakhali, the government is planning to undertake another land reclamation project at the southern part of Bhola Island (Figure 6.3c). The MES II study suggested constructing two closures by connecting Char Montaz and Char Islam Islands with the Bhola Island. The first closure could be built in Montaz channel to connect Char Montaz with Char Islam whereas, the second closure could be constructed in Mainka channel to connect Char Islam with Bhola Island. The preparatory works for the first channel have already been started by the Bangladesh Water Development Board. The project might yield about 150 $km^2$ land area in between Tetulia and Shahabazpur channels. This study suggests that the likely impacts of the project on erosion susceptibility would be positive due to less considerable effects of upstream water discharge and tidal currents in the area. The project could alter the high and very high erosion susceptible lands into low and moderate susceptibility in the area.

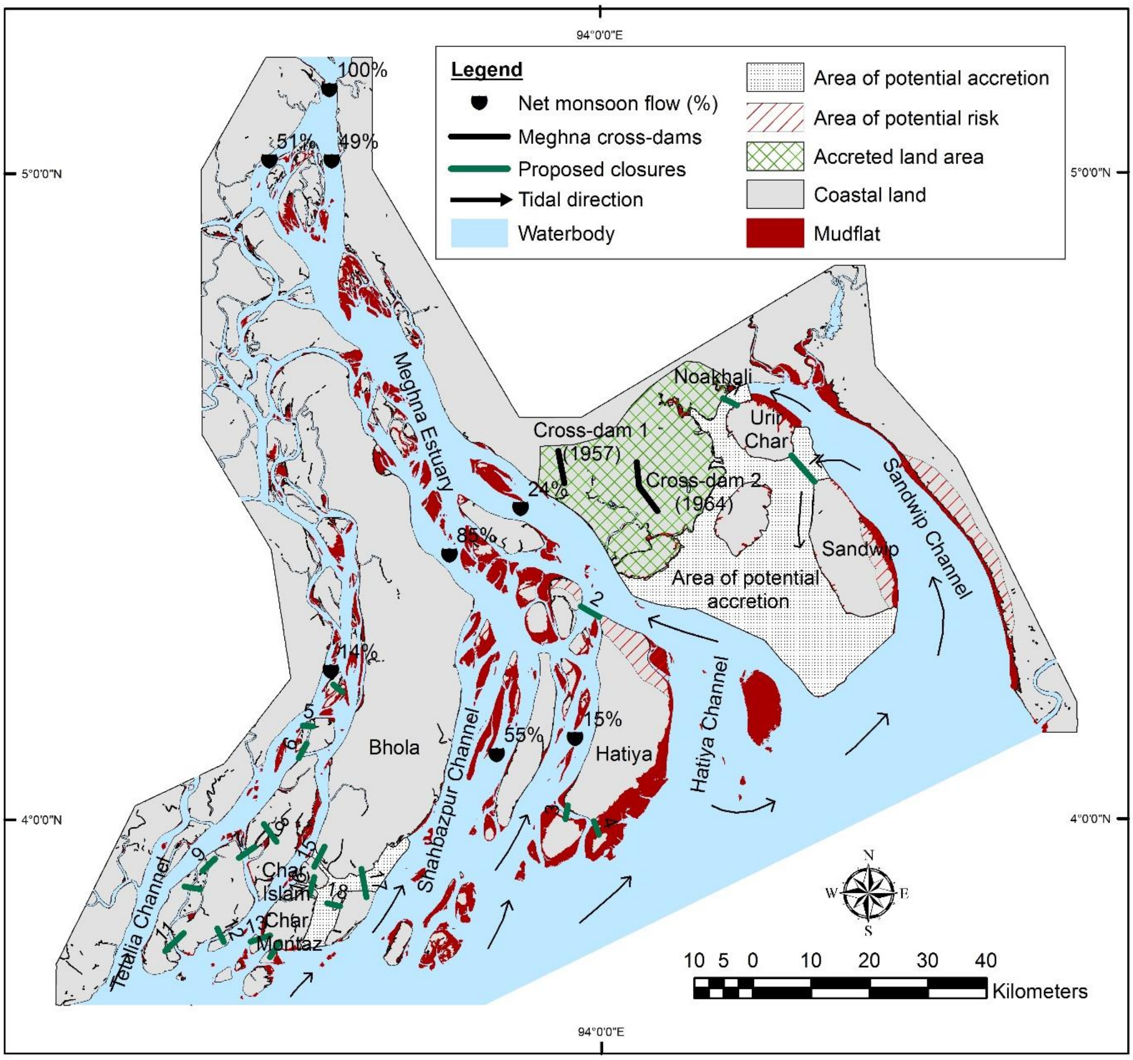

Figure 6.3c – Potential impacts of human intervention in the central coastal zone. The net monsoon flow in Tetulia and upper Hatiya channels are comparatively lower than the main Shahbazpur channel (Akhter and Mahmud, 2007). The net flow of southern Shahbazpur channel splits into different directions. The map shows the outcome of past land reclamation projects as well as future predictions. Among 19 proposed closures, Sandwip-Urir Char-Noakhali and Char Montaz-Char Islam-Bhola would be highly crucial for land reclamation in the area. [Data source: BWDB, 2016; WARPO, 2018]

### 6.4 Human-nature jeopardy

The elicitation of expert views brings a new outlook on the increasing human interventions in the coastal area of the country. The experts opined that the future intervention plans by the government in managing coastal lands might introduce a two-dimensional threat for human settlements as well as for the natural environment under changing scenarios of hydro-climatic forces in the area. Their discussion indicates that the likely impacts of Land Reclamation Project of the government could bring both positive and negative impacts on lands in the area. For instance, the proposed plan for Sandwip-Urir Char-Noakhali closures (Figure 6.3c) might increase prolonged waterlogging and drainage congestion problem in Noakhali coastal area. The likely reclamation of new lands would stop the south-ward natural drainage network in the area. Moreover, the impacts might aggravate the existing condition of ecology and biodiversity in the area. However, they recommended diverting the existing channels to the eastern and western perennial channels as a probable solution to the problem but, it would be economically less viable. On the other hand, the expert opined that the construction of closures connecting small islands in the area between Tetulia and Shahbazpur channels might bring positive impacts on the stabilization of lands and hence, could reduce erosion susceptibility of lands in the area. The experts recommended assessing the controls of physical settings over the existing hydro-climatic conditions before implementing any development projects in the area. Moreover, they argued that the assessment of likely changes in hydro-climatic conditions for each project site is crucial for the entire coastal area.

It is conventional for the government to protect coastal lands from wave actions by building embankments. Until recently, the local government and engineering department in collaboration with Bangladesh Water Development Board raised a total length of 5,017 km earth embankment in the three coastal zones (Rahman and Rahman, 2015). The sustainability of the embankments in the coastal area is very low due to continuous wave actions and increased amount of rainfall (Figure 6.4a). Hence, the earth embankments have been regarded as a less effective way of reducing erosion susceptibility and contribute far less to increase the resilience capacity of the coastal communities.

*Destruction of soft defence structure by wave actions at Hatiya in the western coastal zone of the country.*

*The wave actions at Kuakata coastal area affected the hard defence structure.*

Figure 6.4a – Mismanagement of defence structures in the coastal area of the country. The embankment as a soft defence structure (left) at Hatiya Island has been washed away during monsoon season by wave actions. The hard defence structure (right) at Kuakata coastal area needs to be repaired on an urgent basis.

### 6.5 Novelty and impacts

The present study contributes new knowledge to studies on coastal land dynamics in several ways. The in-depth analysis of land dynamics in the coastal area of Bangladesh is one of the few studies in the Bay of Bengal region that used multi-temporal satellite images and hence, provides insights into a comprehensive and efficient method of studying coastal land dynamics. Moreover, this is the first study that identified the dynamic nature of land for the entire coastal area of the country. More importantly, the identification of dynamic land areas that experienced erosion and/or accretion (or the both) for the past thirty years has now been accomplished. This identification of dynamic lands would be useful for coastal land management in the area.

This study accomplished important methodological improvements in studying coastal land susceptibility to erosion. Since erosion susceptibility plays major roles in the pattern and process of land dynamics in the coastal area, the LSCE model used in the present study could be useful for assessing land susceptibility to erosion in dynamic coastal areas around the world. The developed model is capable of addressing the impacts of hydro-climatic triggering factors on coastal erosion susceptibility along with the controls of underlying physical elements. Moreover, the model could be suitable for assessing seasonal variability of erosion susceptibility by integrating the roles of triggering factors in the model domain. To apply the model, this study used fine pixel resolution (30×30 metre) that is useful to address local situations of erosion susceptibility. Both offshore (i.e. offshore islands) and inland susceptibility of the coastal lands were considered in the current study. The inclusion of inland areas in the assessment is important for a highly dynamic coastal area like Bangladesh.

Unlike previous studies, the LSCE model is devised in such a way that it is possible to generate future scenarios of land susceptibility to coastal erosion. The generation of future erosion susceptibility for a hydro-dynamically active deltaic coastal area like Bangladesh offers pathways to identify the compelling interactions of the drivers of erosion susceptibility. Moreover, the impacts of future hydro-climatic changes are likely to be severe in the coastal area of the country. In this circumstance, the generation of future scenarios on erosion susceptibility helps in understanding a wide range of possible futures for the area. Furthermore, the hydro-climatic factors are greatly influenced by the seasonality of Asian monsoon climate. The present study addressed the influences of seasonal variability of the triggering factors on erosion susceptibility in the coastal area that would be helpful for advocating timely mitigation plans.

This study incorporated experts' opinion in advancing the model results and addressing future uncertainties relevant to erosion susceptibility. The use of FCM approach provided opportunities to identify the interactions and interrelationships between a wide range of physical elements, preparatory factors and driving forces of erosion susceptibility that could be difficult to address by computer-based models. Moreover, the generation of fuzzy cognitive maps helped in understanding the general consensus expressed by the experts on land susceptibility to coastal erosion. Additionally, the use of FCMs evaluated a vast number of human-induced factors responsible for accelerating and/or reducing erosion susceptibility in the area.

## 6.6 Limitations

The study confronted some limitations due to constraints of time, data, finance and manpower. The study excluded the impacts of mangrove forest cover from the LSCE model domain due to the exaggerated nature of data on their exact locations. Although some raster layers exist of world mangrove coverage, the resolution is very coarse. The figure (Figure 6.3a) represents the raster surface that was collected from the UN Environment Programme-World Conservation Monitoring Centre (UNEP-WCMC, 2011). This raster surface was generated by using data from the Global Land Survey (GLS) and archive of Landsat satellite images. One of the major problems of using the dataset for the LSCE model is that the scale of the spatial data varies for different coastal zones as well as for the same coastal zone of the country. The range of the scale varies from 1:1,128 (1 pixel = 0.29 m) to 1:591,657,528 (1 pixel = 156543.03 m). Further, the identification of the mangrove vegetation cover is derived by unsupervised digital image classification technique and hence, the surface lacks ground verification. There are some data available from the Ministry of Environment and Forest on the total area covered by mangrove vegetation but, the data lack the spatial extent of mangrove forest in the coastal area (Table 1.2.5a). However, the present study addressed the probable impacts of mangrove vegetation (natural and plantation) on land susceptibility to erosion by eliciting experts' views through FCMs.

The inclusion of the continuous process of coastal sedimentation in the LSCE model is limited. However, the use of moderators for the accreted lands areas identified by using satellite images provides the way to address the impacts sedimentation on erosion susceptibility by the model. As discussed (in chapter 1), the present study surveyed 5 hard defence and 10 soft defence structures from 26 and 60 selected structures respectively used for the LSCE model. The remaining structures were identified by reviewing documents from government sources, available topographical maps collected from Survey of Bangladesh (SoB), sub-district and union level maps from Local Government and Engineering Department (LGED) and recent Google Earth images. The major problem of dealing with the mentioned sources is that the maps and images are not up to date. Some topographical maps are old and do not fully represent the real ground situations. Further, the Google Earth images can provide information about the existence of the structures (provided that there is no artifact in the image such as tree cover, bridge) and very often do not exactly match with the real-world position.

The present study identified the seasonal variation of land susceptibility for current baseline conditions, however, the study lacks a way of generating future scenarios of land susceptibility for the Representative Concentration Pathways (RCPs) of four Greenhouse Gas (GHG) emission trajectories due to data unavailability (Table 1.2.5a). Hence, the future seasonal variability of land susceptibility to erosion under low scenario (i.e. RCP2.6) and high scenario (i.e. RCP8.5) were not evaluated in the study. However, the study generated future scenarios of land susceptibility to erosion for A1B trajectory-based secondary data on the seasonal variation of future hydro-climatic factors for the three time-slices. Moreover, the future changes in mean sea level rise may inundate a considerable part of the coastal land and future sedimentation may change the existing shoreline, for both the cases, the distance from shoreline might change in future. Under this situation, the capability of the LSCE model is limited in generating the future scenarios of land susceptibility by adjusting the future changes in underlying physical elements due to the potential changes in hydro-climatic factors. Further, due to the unavailability of future scenario data for the hydro-climatic factors used for the LSCE model, the present study generated the near-future scenario for 2020 time-slice while the baseline condition is 2015. Hence, the temporal gap between the baseline and the near-future scenario is only 5 years. However, it is realised that the generation of future land susceptibility for 2030 or 2035 time-slice could provide a better representation of the near-future scenario.

The study was limited up to the extent of identifying the current level of land susceptibility to erosion in the coastal area and evaluated the future impacts of triggering factors (i.e. hydro-climatic factors). However, the study was unable to identify the total number of properties at risk due to the limitation of having no spatial dataset on the exact locations of the properties in the study area. Regarding the number of populations, Bangladesh Bureau of Statistics (BBS) only provides population dataset based on administrative boundaries, which is problematic in calculating the total number of population at risk for each susceptibility class. Hence, this study identified the estimated number of populations at risk (in chapter 3) based on the average population density in the coastal area. Similar to population dataset, the spatial data on the settlement locations collected from LGED provide only areas of human settlement in the coastal area but, do not provide the exact location of each settlement. Further, the study did not find any dataset on postcode-based households in the area and hence, it was problematic to identify the total number of properties that are presently at risk of erosion susceptibility in the coastal area. However, to carry out future research on risks of erosion susceptibility in the area, it is vital to generate location-specific datasets for each settlement in the three coastal zones. The Survey of Bangladesh (SoB) (the responsible authority to conduct topographic surveys), in collaboration with Local Government Engineering Department (LGED) needs to generate such datasets for the coastal area of the country.

The weightings and classification methods of the LSCE model parameters might influence the model outputs (discussed in chapter 3: sensitivity analysis). Due to this limitation, the present study addressed other human-induced issues of land susceptibility to erosion such as population pressure, development activities and deforestation (the weightings and classifications of which are difficult to determine) by eliciting experts' views through FCMs. Consequently, the LSCE model aimed at finding out the physical susceptibility of the coastal lands to erosion and addressed the roles of coastal defence structures and sedimentation on physical susceptibility by using several moderators in the model domain. Further, the study used wind speed and directions as a proxy to wave actions due to the unavailability of data on the propagation of waves in the area. Due to the lack of data, the impacts of longshore currents on coastal erosion susceptibility were substituted by bathymetric depths in the LSCE model assuming that the higher depths resemble higher impacts of longshore currents and vice versa.

Along with the limitations, the study faced some challenges regarding model data and FCM-based workshops. Further, due to the existence of artifacts in the raw DEM, the study had to remove the elevation values of the artificial structures and then to check the consistency with real-world values. The identification of shoreline and demarcation of land-water boundary under the situation of varied tidal range in the area were very difficult tasks. Gathering historical records of hydro-climatic data from different sources was time-consuming. Moreover, organizing two workshops with prominent experts from different fields was another challenge for the current study. Depending on their limited time, it was very difficult to gather the FCM components, fulfilling matrix tables and presenting the causal relations between the components of the fuzzy cognitive maps.

## Chapter 7: Conclusion and further recommendations

### 7.1 Major outcomes of the study

The outputs of the present study provide vital information on spatial and temporal aspects of land dynamics and land susceptibility to erosion for the entire coastal area of the country. More specifically, this study contributes new knowledge to the trends of morphological changes and the zonal and seasonal variations of existing and future scenarios of land susceptibility to erosion in the coastal area. The conclusive results of the study are as follows:

- Constant changes in lands are identified in the coastal area of the country.
- A considerable amount of existing lands (i.e. 276.33 km$^2$) is highly susceptible to erosion.
- The erosion susceptibility of existing coastal lands of the country would be substantially increased in future.
- Seasonal impacts of the hydro-climatic factors are noticed in the coastal area

The following sections discuss how the study results can contribute to particular actions that the implementing bodies (i.e. government and non-government organizations) could follow in formulating policies and managing lands (in-situ) in the coastal area of the country.

#### 7.1.1 An effective management of dynamic coastal lands

Constant changes in the coastal lands (discussed in chapter 2) clearly indicate that the morpho-dynamic processes are active in the entire coastal area. The changes are predominantly visible in the central coastal zone of the country. The present study suggests taking the following options to manage such changes:

1. <u>Understanding long-term coastal behaviour</u>:

The present study identified major erosion events in Bhola, Manpura, Hatiya, and Sandwip islands. Moreover, accretion events are identified in Noakhali, Urir Char, Jahajir Char and numerous small islands in the exposed central coastal zone. To identify these changes, the present study used Landsat satellite images for the past 30 years from 1985 to 2015. This long-term assessment of land dynamics provides reliable outputs on understanding the morphological behaviour of the coastal area.

However, monitoring future changes is vital for the coastal area where a substantial amount of land would be highly susceptible to erosion due to probable changes in hydro-climatic conditions (discussed in chapter 4). Coastal plans and projects need to use technological advancements in different phases of planning, implementation, monitoring and evaluation. In this regard, the use of GIS and remote sensing techniques would be highly useful for the government to monitor future changes in lands in the coastal area.

2. Updating existing policies relevant to coastal lands:

The present study prepared an inventory map based on the dynamic nature of lands in the coastal area for the past 30 years (Figure 6.2a). The inventory map provides the specific areas of dynamic lands in the three coastal zones of the country. The map could provide inputs for the policymakers to update existing Coastal Zone Policy (CZP) and Coastal Development Strategies (CDS) with the specific interventions that need to be taken for the particular coastal lands identified in the map. The ongoing land zoning project of the government (discussed in chapter 6, section: 6.3) would benefit from the updated CZP to address the dynamic lands of the coastal area. Moreover, the national Land Use Policy (LUP) of the government relevant to the coastal area would benefit by incorporating specific policy provision for the identified dynamic lands. This amendment in the coastal land use policy would be useful to regulate the proper use of lands and to protect uncontrolled extraction of natural resources (i.e. sand mining, vegetation cover) in the area. Moreover, the results of the present study are useful in identifying the *Khash* lands (government owned lands) in the coastal area and to redistribute those lands to the erosion victims under existing land use policy. Additionally, proper implementation of the resettlement plan of the government demands accurate information on the areal extent and changing pattern of lands in the coastal area. This study represents decadal changes in land dynamics in the coastal area that would provide additional support for the local land authority to pinpoint the most suitable lands in implementing the resettlement plan.

### 7.1.2 Managing existing lands with high erosion susceptibility

The highly erosion susceptible lands identified in the present study need special attention from the authority. This section discusses the possible areas where the results can add in-situ and policy contributions to minimize potential erosion-induced risk in the area.

1. <u>Transformative management approach</u>:

The formation of newly accreted lands in the exposed central coastal zone (i.e. Sona Char, Char Gazaria, Char Shahbaz, Bodnar Char, Char Jonak, Latar Char, Char Tazul and Char Piya) were the results of natural sedimentation and land reclamation projects. The present study identified the existing level of erosion susceptibility of the newly accreted lands as high and very high susceptible to erosion. To settle newly accreted lands, the current approach of the government is to plant mangrove vegetation and to remain the lands as unused for the next 20-years period (Sarwar and Islam, 2013). This approach brings no success due to weak administrative control and the increasing scarcity of lands in the coastal area as a result of high population growth. Local people illegally settle their homes in the newly accreted lands and destroy the mangrove vegetation. Moreover, local land grabbers are getting privileges to take control of those lands. Previous coastal afforestation projects did not involve coastal communities in managing mangrove vegetation cover (Islam and Rahman, 2015). Further, existing Social Forestry Rule-2011 of the government does not permit rightful shares of the communities (i.e. access to timber products from forests). The communities can access only the non-timber products such as honey, grasses etc. from the vegetative areas. However, to settle the newly accreted lands, the government needs to adopt a more cost-effective and sustainable approach. Therefore, the involvement of local communities in the management process is essential. An ecosystem-based soft adaptation approach (i.e. mangrove and non-mangrove afforestation) (Nandy and Ahamad, 2012), would be highly effective to involve coastal communities in managing newly accreted lands (Figure 7.1a). Hence, the afforestation program of the government needs to operate under the mechanism of social forestry in which the communities may involve themselves as beneficiaries. More specifically, the government needs to implement a plan for large-scale social forestry by legally allowing local communities to build settlements in the newly accreted lands. This would be particularly beneficial for three reasons: (a) to protect the newly accreted lands in a cost-effective manner (would cut the cost of building hard defence structures at initial stage of land formation); (b) to involve communities in managing vegetation cover and (c) to resolve the impending issue of re-settling the erosion victims. Additionally, promoting vegetation-based coastal defence strategy in the newly accreted lands would allow further sedimentation in the areas. Moreover, an ecosystem-based defence approach would settle the new lands by maintaining the biological diversity of the areas. However, considering the specific levels of erosion susceptibility identified in the present study, the government needs to operate a series of pilot projects at the newly accreted lands to justify the applicability of the proposed transformative approach.

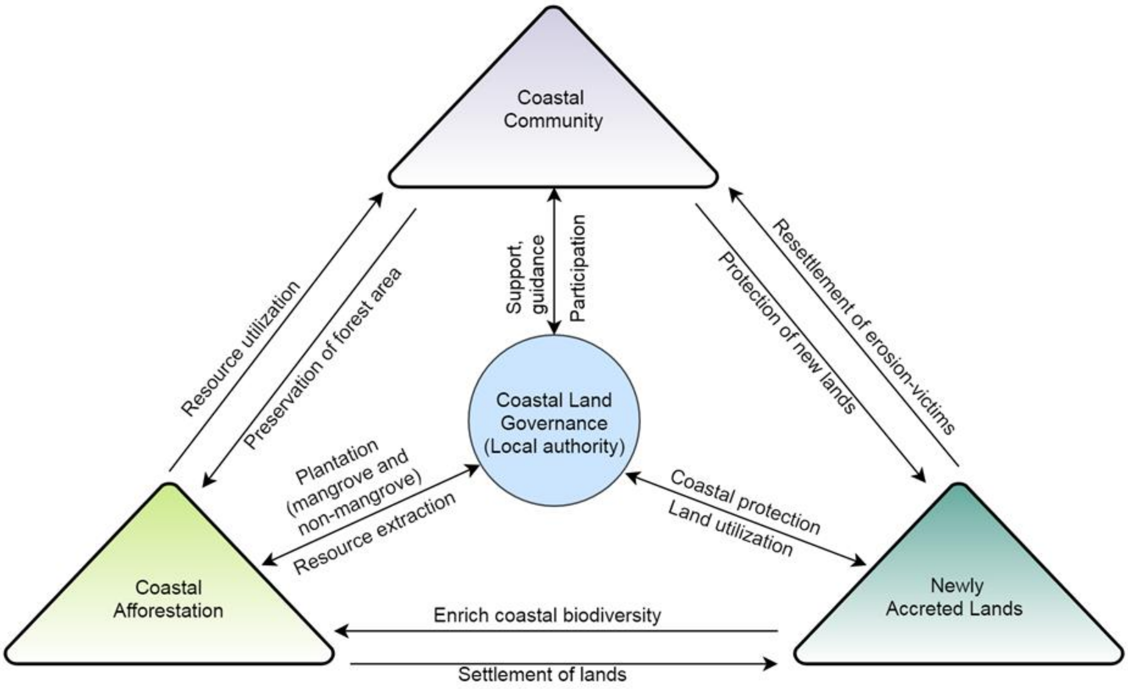

Figure 7.1a – Transformative management approach of newly accreted lands in the coastal area (especially in the central coastal zone) of the country. The local land authority, in collaboration with the forest department of the government, could protect the newly accreted lands from potential erosion by involving coastal communities in afforestation programs and providing support (e.g. financial support for plantation) and guidance. In reply, the communities would benefit from the newly accreted lands by building their houses and utilizing forest resources. However, at an initial stage of land formation, building hard defence structures to protect the newly accreted lands might not sustainable. Like other major offshore islands (discussed in the following section), hard defence structures would only be useful for the newly accreted lands immediately after settling the sediments.

2. Proper implementation of coastal projects:

Ongoing projects in protecting coastal erosion lack proper integration of information on erosion susceptibility of the coastal lands. One such project is the Coastal Embankment Improvement Project (CEIP) which started its first phase in 2013 in collaboration with the World Bank and will end in 2020. The initial aim of the project was to repair the existing polders and to build new polders in the major offshore islands (i.e. Bhola, Hatiya, Monpura, Sandwip, Kutubdia and Moheshkhali) where continuous wave actions are causing erosion events. The outcomes show that the project is not very effective so far for the long-term sustainability of the coastal embankments. This is because several earthen embankments were built in areas where the level of land susceptibility to erosion is very high. Another example is the Char (newly accreted land) Development and Settlement Project (CDSP), which has been ongoing by the government for more than two decades. The major goal of the project is to protect newly accreted lands from the consequent impacts of climate change and sea level rise such as tidal surges and erosion by building dyke, embankment and polder. The current CDSP is the fourth phase of the series that is now in operation at five newly accreted lands in the central coastal area of the country.

To minimize the risk of highly erosion susceptible coastal lands, it is important to make the projects effective for coastal protection. However, the results of the present study are useful in identifying the areas where immediate coastal protection measures are necessary. The government requires to consider the levels of land susceptibility identified by the present study in selecting the locations and types of defence structures. The results of the present study on land dynamics (discussed in chapter 2) suggest that soft defence structures (i.e. earthen embankment and dyke) are not effective whereas, the hard defence structures are not sustainable for a long time to protect the newly accreted lands and the offshore islands from erosion. The adoption of a more transformative approach to protecting the newly accreted lands is discussed in the preceding section. However, to protect major offshore islands from further erosion, it is also vital for the coastal defence projects to adopt the ecosystem-based soft adaptation approach (i.e. large-scale social forestry) along with long-term and evidence-based engineering approach (i.e. hard defence structure). The approach of large-scale plantation around hard defence structures would enhance the sustainability of the structures in the project areas.

3. Long-term funding and investment:

A total 243.54 $km^2$ of the existing highly erosion susceptible coastal lands are identified in the central coastal zone. This amount of land would be increased in future due to hydro-climatic changes in the area. However, the central coastal zone is highly dynamic in which, building soft defence structure is not a sustainable coastal defence approach. As discussed, along with large-scale plantation programme, building hard defence structures in highly erosion susceptible and historically morpho-dynamic areas (e.g. Haiderganj, Ramgoti, Bhola, Hatiya, Monpura and Sandwip) in the exposed central coastal zone is also necessary. Bangladesh Water Development Board (BWDB) is the responsible authority to construct defence structures in the coastal area. However, BWDB is facing funding shortages to build new defence structures and to maintain existing structures. For instance, the estimated budget of BWBD under Annual Development Program (ADP) for 2015-2016 fiscal year was 28.59 billion Bangladeshi currency to implement 28 projects relevant to coastal defence and coastal development (BWDB, 2017). Due to the shortage of funding, they started just 11 projects by the end of 2016. Under these circumstances, government needs to arrange long-term funding and future investment (i.e. Public Private Partnership [PPP], Foreign Direct Investment [FDI]) for implementing coastal defence and development projects.

4. Necessary changes in coastal policy:

Potential changes in CZP: The present study carries essential policy implications for land susceptibility to erosion in the coastal area. Elicitation of experts' views on existing land susceptibility of the coastal area to erosion suggests some specific policy changes in managing highly erosion susceptible coastal lands identified by the present study. The following recommendations would be vital to include in the existing CZP:

- Guidance to the increase vegetation cover in inter-tidal zone
- Provision to accelerate ocean-based economic growth
- Directions to promote coastal tourism (that would initiate coastal development projects)
- Initiatives for livelihood development projects
- Promotion of social forestry (might change the economic status of the coastal population that would reduce deforestation)
- Formulation of a tidal river and estuary management plan

Policy supports for development projects: The model outputs on current erosion susceptibility in the coastal area could be very useful for the current and future development projects in the area. For instance, the Delta Plan 2100 could incorporate a Tidal River Management (TRM) approach to resolve the prolonged waterlogging issue and to retain the upstream sediments in the polder areas of the western coastal zone. The idea of TRM permits free flows of tides that allow navigability of the rivers and sedimentation in the enclosed area (Paul et al., 2013). However, permitting free flows of tides may lead to initiate further erosion in the polder area. The outputs of the LSCE model would be vital to implement the TRM approach in the area. The TRM approach needs to consider the levels of existing erosion susceptibility of the lands along the river channels in selecting the channels to allow free flows of tides in the polder areas.

### 7.1.3 Preparation for future erosion susceptibility

Based on the model scenarios, the present study suggests the following measures options and policy interventions in managing highly erosion susceptible lands in the coastal area in future.

1. Effective land reclamation project:

This study assumes that the implementation of the planned Sandwip-Urir Char-Noakhali land reclamation project might bring considerable changes in bathymetry and hence, would have considerable impacts on tidal circulation and sediment movement in the area. These changes could lead to increase erosion susceptibility of the coastal lands surrounding the project area (Figure 6.3c). This study predicts direct impacts of the project in the south-eastern area of Sandwip and north-eastern area of Hatiya Island (Figure 1.2.4a) where, erosion susceptibility is predicted in the present study as high and very high for future scenarios (Figure 4.4.1c, d, e). Under this situation, the government needs to take proper interventions for the high and very high susceptible lands of the mentioned areas of Sandwip and Hatiya islands while implementing the project in the area.

Uncertainties pertaining to the changes in hydro-climatic triggering factors in the area might alter the predicted impacts of land reclamation projects on future erosion susceptibility in the area. Historical data and model projections found in the literature reveal an increasing trend of water discharge, mean sea level, rainfall and wind speed in the coastal area of the country. Hence, further land reclamation projects of the government need to consider the probable increase of the volume of water discharge in the Meghna estuary along with the likely increases of rainfall and mean sea level in the eastern coastal zone.

2. Proper management interventions:

The present study indicates that the interior central coastal zone would be highly affected by the probable increase of river water discharge in future. Moreover, the exposed central coastal zone would be highly affected by the probable wave actions in future due to the decreasing rate of bathymetric depths. However, large-scale river training project would be vital to minimise future erosion events for both situations. To manage the huge volume of water discharge of the Meghna river in the central coastal zone, it is vital to maintaining the channel depths in the area by implementing regular dredging. Additionally, sand mining accelerates the rate of coastal erosion (Gavriletea, 2017) and hence, it is necessary to prohibit the uncontrolled sand mining from the river beds in the area. Moreover, future engineering interventions for the highly susceptible coastal lands need to be strengthened by building climate resilient infrastructure in the area. The outputs of the present study on land susceptibility would provide vital information in this regard in which, the likely impacts of hydro-climatic forces are assessed for the three coastal zones.

3. Institutional capacity building:

Bangladesh Water Development Board (BWDB) conducted a bathymetric survey in the exposed central coastal zone (known as Meghna Estuary Study) as a feasibility study of Sandwip-Urir Char-Noakhali land reclamation project. However, the current study suggests conducting regular bathymetric surveys for the entire coastal area when implementing future land reclamation projects. Like Meghna Estuary Study (MES), BWDB needs to conduct further research and survey activities on hydrodynamics and sedimentation for the entire coastal area of the country. This is vital due to the fact that the present study identified a probable increase of erosion susceptibility in the newly accreted lands and major offshore islands in the exposed part of the three coastal zones. Hence, the government needs to strengthen the capacity of BWDB as well as other relevant institutions such as Bangladesh Inland Water Transport Authority (BIWTA) and Water Resources Planning Organization (WARPO). This would also be helpful for implementing continuous dredging in the central coastal zone.

4. Policy for future changes:

The Coastal Zone Policy (CZP) that was formulated in 2005 needs to be updated considering the results of the present study on future land susceptibility to erosion for each coastal zone (Figure 7.1b). The scenarios of erosion susceptibility for the newly accreted lands and offshore islands in the exposed central coastal zone, Kuakata area in the exposed western coastal zone and Kutubdia, Kumira, St. Martin and Moheshkhali areas in the exposed eastern coastal zone need to be prioritised by including specific management interventions (discussed in section: 7.1.2) in the existing CZP of the government. Moreover, the likely impacts of hydro-climatic changes in future scenarios of land susceptibility to erosion also need to be reflected in the CZP to manage future land dynamics in the coastal area. The ongoing land suitability mapping under the land zoning project would benefit from the outputs of the study by evaluating the future land susceptibility of each zone as one of the criteria of land suitability. Moreover, the project could be improved by considering the levels of future erosion susceptibility of each coastal zone. Along with physical interventions, the government needs to include specific measures options in the CZP to reduce human-induced pressures on coastal lands.

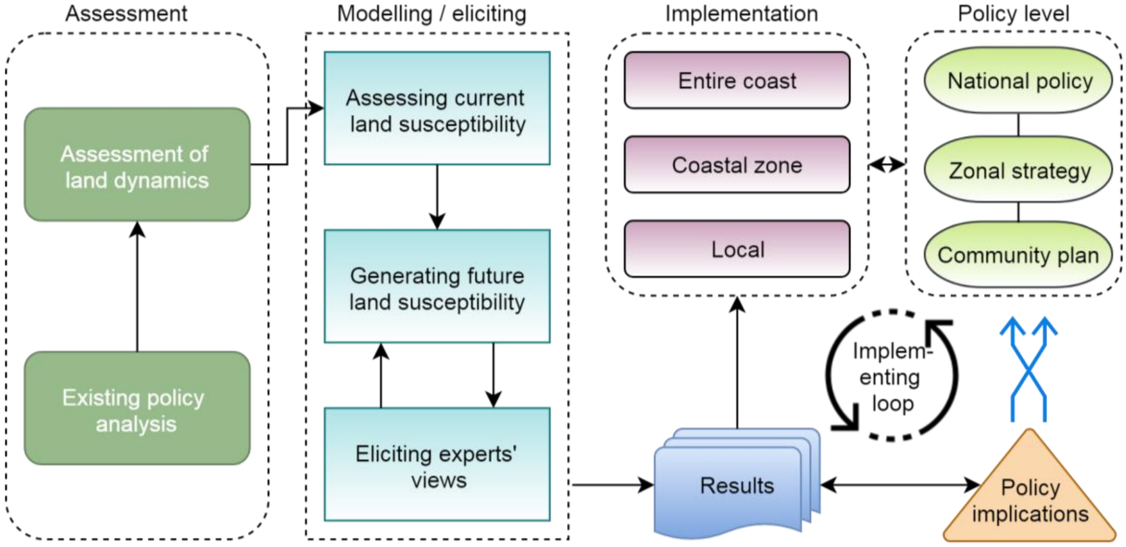

Figure 7.1b – Policy implications of the results obtained from the present study. The combined results on land dynamics and land susceptibility to erosion would be vital to implement for the three spatial levels (i.e. entire coast, zones and local area). The policy aspects of the results would be indispensable inputs for national policies, zonal strategies and community plans. The implications of the relevant policy aspects might

need to reorder in accordance with the institutional arrangements. However, an iterative implementing loop might create an enabling condition to change the prolonged institutional inertia and to permit re-implementation of the policy inputs in future.

### 7.1.4. Addressing seasonal variation of land susceptibility

The present study identified monsoon as the most erosion susceptible season of the year due to higher influences of hydro-climatic factors during this season than other seasons. The variation in tidal range is also higher during this season (i.e. 2.32 to 3.48 metre) than other seasons (BWDB, 2016). Currently, the coastal areas of Ramgoti, Jahajir Char, Hatiya, Haiderganj, Moheshkhali, St. Martin and most of the newly accreted lands in the exposed central coastal zone are high and very high susceptible to erosion during monsoon season. The existing defence structures in Hatiya (hard and soft defence), Haiderganj (soft defence), St. Martin (soft defence) and Moheshkhali (soft defence) are highly exposed to wave actions during this season. Moreover, Jahajir Char, Ramgoti and newly accreted lands are completely exposed to the Bay of Bengal in which, no hard or soft defence structures exist. To reduce the seasonal high erosion susceptibility, the government is advised to deposit concrete blocks at foreshore of the mentioned areas as an added measure in parallel with plantation and existing defence structures.

## 7.2 Key messages for local people

This study has important advice for local people of the coastal area. Consultations with local people in the present study suggest that a majority of people are unaware about the potential risk of erosion in the area and they are unable to identify the levels of erosion susceptibility of their residential land areas. As a consequence, many people had to shift the location of their houses five to ten times. The case is especially severe for the residents in the highly dynamic land areas such as Laxmipur, Noakhali, Hatiya, Sandwip and Bhola in the exposed central coastal zone. People who are residing in the highly dynamic coastal areas are unaware about the future risk of erosion in those areas. Hence, it is vital for the local people to be informed of the likely erosion in the area.

The outputs of the LSCE model would provide knowledge to the residents living in the highly erosion susceptible coastal lands. Moreover, future scenarios of land susceptibility would be helpful for taking initiatives to build coastal defence structures and to evacuate residents from highly erosion susceptible lands. These initiatives should be implemented by two local administrative bodies of the government:

1. <u>Local land management office</u>: The local land management office (i.e. union level land management office in which, a union consists of some villages) in collaboration with Local Government and Engineering Department (LGED) might play effective roles to identify such lands and to regulate settlements. Moreover, the local authority needs to stop the development of uncontrolled settlements in highly erosion susceptible coastal lands by guiding them about the levels of erosion susceptibility of those lands.
2. <u>Union Disaster Management Committee</u>: The Standing Orders on Disaster (SOD) of Bangladesh (Ministry of Food and Disaster Management [MFDM], 2010) outlines the role and responsibility of relevant authority and stakeholders before, during and after disaster events. The existing SOD includes the provision for Union Disaster Management Committee (UDMC). This is a grass-root level committee which consists of 35 members from local government, stakeholders and local Non-Governmental Organizations (NGOs). The UDMC should consider the results of the study on existing and potential erosion susceptible areas in managing the erosion-induced coastal disaster. Moreover, local people would benefit from their guidance on the levels of erosion susceptibility of the lands and they can build their residences in areas with low erosion susceptibility.

### 7.3 Future research needs

It is true that the shaping of foresight plan is a long game (Hines and Gold, 2015). The present study provides an indication of where further research on relevant aspects of land dynamics and land susceptibility to erosion in the coastal area of Bangladesh is required. Depending on the availability of data, the outcomes of the LSCE model on erosion susceptibility could provide a baseline for conducting further research on erosion risk for property and livelihood originating from erosion susceptibility. Moreover, it is predicted that the coastal area of the country is likely to be faced with frequent flooding events due to climate change and sea level rise which might flood an additional 14% of the country's coastal lands by 2050 (Dasgupta et al., 2010). The consequent effect may dislocate more than 35 million people in the coastal area. The current study indicates an increased rate of future erosion susceptibility in the area that would have probable influences on the rate of erosion. The effects of coastal flooding could be aggravated by the increasing rate of erosion in the area. However, future studies on coastal flooding might be conducted to explore the nexus between erosion susceptibility and flooding in the coastal area of the country. Further, follow-up study needs to be conducted on the impacts of future hydro-climatic changes on erosion susceptibility that was addressed in the current study. The present study opens scope for conducting future research on mangrove and plantation forest-based future study on coastal bioprotection. Further study could justify the potentiality of mangrove forest to reduce erosion susceptibility in the area. Future studies might be conducted on the pattern of future sediment flow and its likely impacts on erosion susceptibility in the area. Additionally, further research might explore how science-policy-practice interfaces should work in the area to reduce erosion susceptibility.

## 7.4 Concluding remarks

The present study contributes important knowledge in managing highly dynamic and highly erosion susceptible lands for the densely populated coastal area of the country. However, much remains to do from the government side in managing the full spectrum of risks originating from coastal erosion in the area. Moreover, further studies need more robust datasets on hydro-climatic as well as human-induced factors. Future data generation based on hydro-dynamic models might be important for conducting follow-up studies on erosion susceptibility in the area. Collection of long-term data on water discharge in major coastal rivers and the use of such data for further research would be important to conduct further research on the hydro-dynamically active coastal area. Generating datasets on wave heights and wave propagation in the Bay of Bengal region would be highly suitable for assessing the future impacts of wave actions on erosion susceptibility in the area. Additionally, regular collection of data on longshore currents in the coastal area is vital for assessing its impacts on the changes in bathymetry. Moreover, continuous monitoring of the pattern and rate of net sedimentation in the coastal area could provide a better understanding of the dynamic nature of lands in the coastal area.

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References in this section cover chapter 6 and 7 only. References for other chapters are given at the end of corresponding chapter and papers.

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**Appendix A:** Metadata on satellite images used for analysing land dynamics.

Year: 1985

Image: Landsat_4 (TM)

| Path | Row | Date Acquired | Scene Centre Time |
|---|---|---|---|
| 138 | 044 | 1985-01-24 | 03:59:41.0940750Z |
| 138 | 045 | 1985-01-24 | 04:02:00.7000250Z |
| 137 | 044 | 1985-01-19 | 03:54:29.4400250Z |
| 137 | 045 | 1985-01-19 | 03:54:53.3650560Z |
| 136 | 044 | 1985-01-13 | 03:48:47.8240130Z |
| 136 | 045 | 1985-01-28 | 03:49:21.3200690Z |
| 135 | 046 | 1985-01-21 | 03:42:57.0410500Z |

Year: 1995

Image: Landsat_5 (TM)

| Path | Row | Date Acquired | Scene Centre Time |
|---|---|---|---|
| 138 | 044 | 1995-01-28 | 03:43:05.3140060Z |
| 138 | 045 | 1995-01-28 | 03:43:29.3090880Z |
| 137 | 044 | 1995-01-05 | 03:37:45.7980440Z |
| 137 | 045 | 1995-01-05 | 03:38:09.7920500Z |
| 136 | 044 | 1994-01-13 | 03:32:21.3430060Z |
| 136 | 045 | 1995-01-14 | 03:31:39.5660630Z |
| 135 | 046 | 1995-01-23 | 03:25:32.3210630Z |

Year: 2005

Image: Landsat_7 (ETM+)

| Path | Row | Date Acquired | Scene Centre Time |
|---|---|---|---|
| 138 | 044 | 2005-12-07 | 04:17:00.3560810Z |
| 138 | 045 | 2005-12-07 | 04:17:24.3300000Z |
| 137 | 044 | 2005-12-16 | 04:10:56.3970690Z |
| 137 | 045 | 2005-12-16 | 04:11:20.3700940Z |
| 136 | 044 | 2005-12-10 | 04:05:05.9670130Z |
| 136 | 045 | 2005-12-10 | 04:05:30.0830060Z |
| 135 | 046 | 2005-12-02 | 03:59:12.5690060Z |

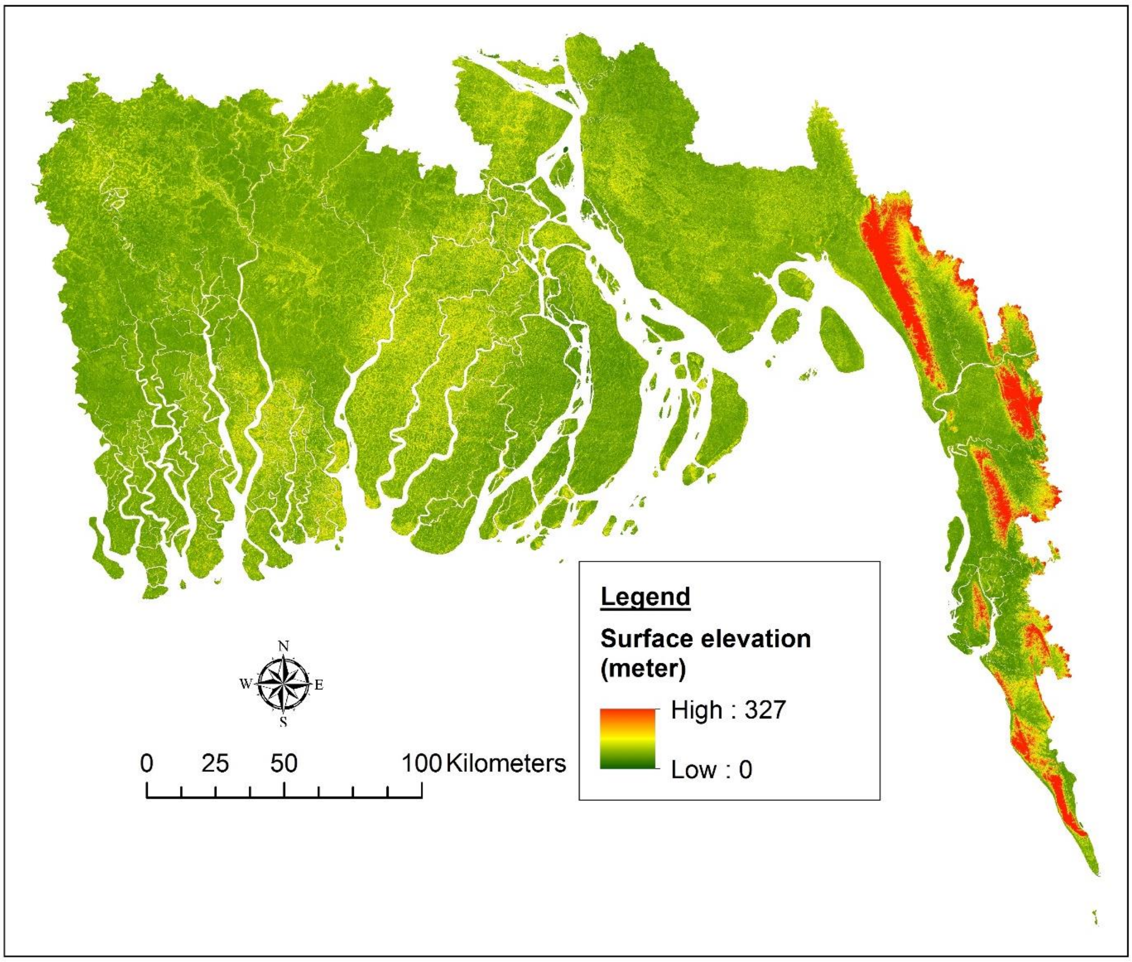
Year: 2015

Image: Landsat_7 (ETM+)

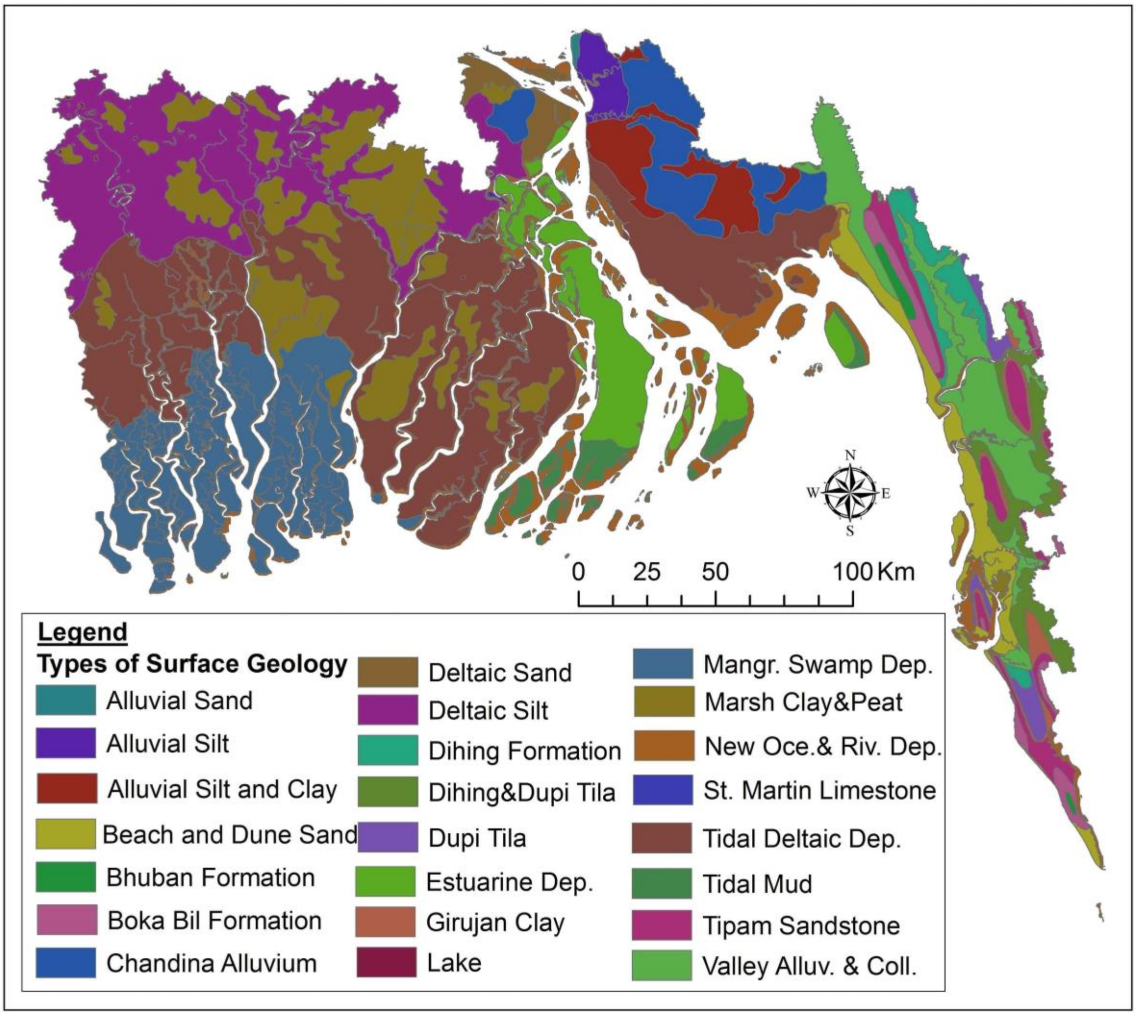
| Path | Row | Date Acquired | Scene Centre Time |
|---|---|---|---|
| 138 | 044 | 2015-01-08 | 04:30:41.1745791Z |
| 138 | 045 | 2015-01-08 | 04:31:05.0701191Z |
| 137 | 044 | 2015-01-17 | 04:24:24.7528712Z |
| 137 | 045 | 2015-01-17 | 04:24:48.6513670Z |
| 136 | 044 | 2015-01-26 | 04:18:09.1074221Z |
| 136 | 045 | 2015-01-10 | 04:18:41.4147228Z |
| 135 | 046 | 2015-01-15 | 04:13:03.7691414Z |

**Appendix B:** Processes involved in the LSCE model domain.

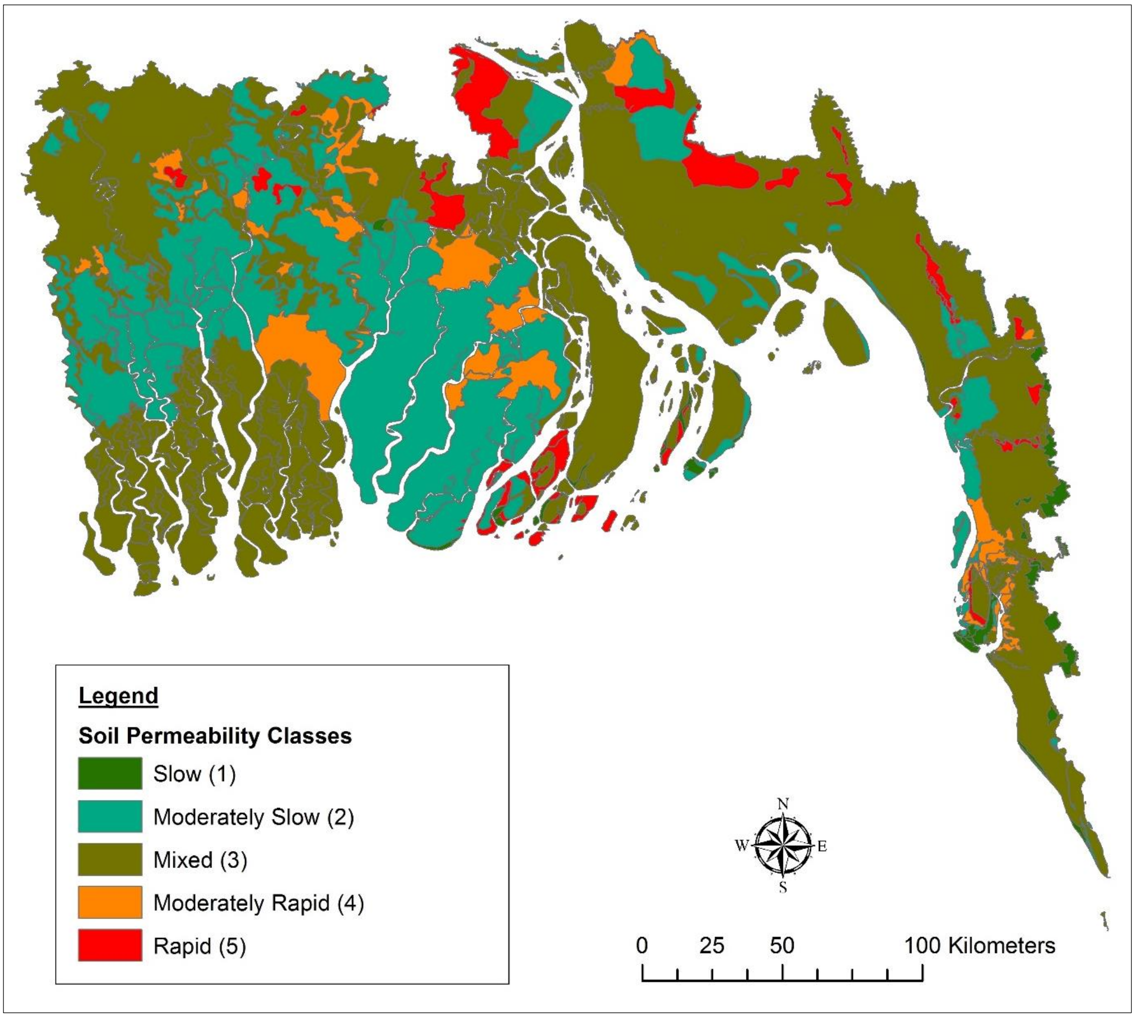
**Appendix C:** Parameter-wise raw raster surfaces used for further processing and applied for the LSCE model to assess overall baseline condition of land susceptibility to erosion.



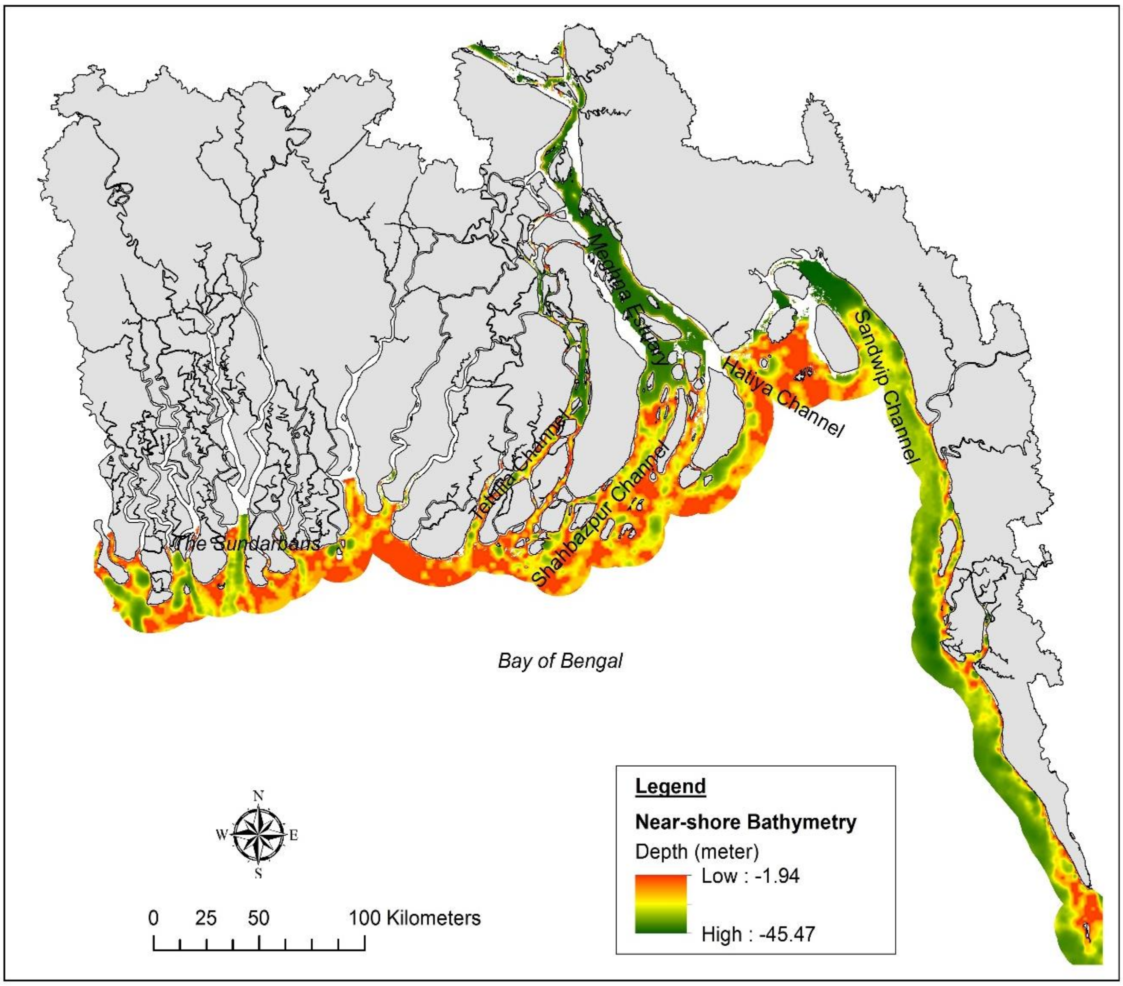
**Surface elevation:** The pixel values extracted from ASTER-DEM and then processed by 'majority filter' to remove artifacts from the surface. The surface then used for scaling and weighting in the model.



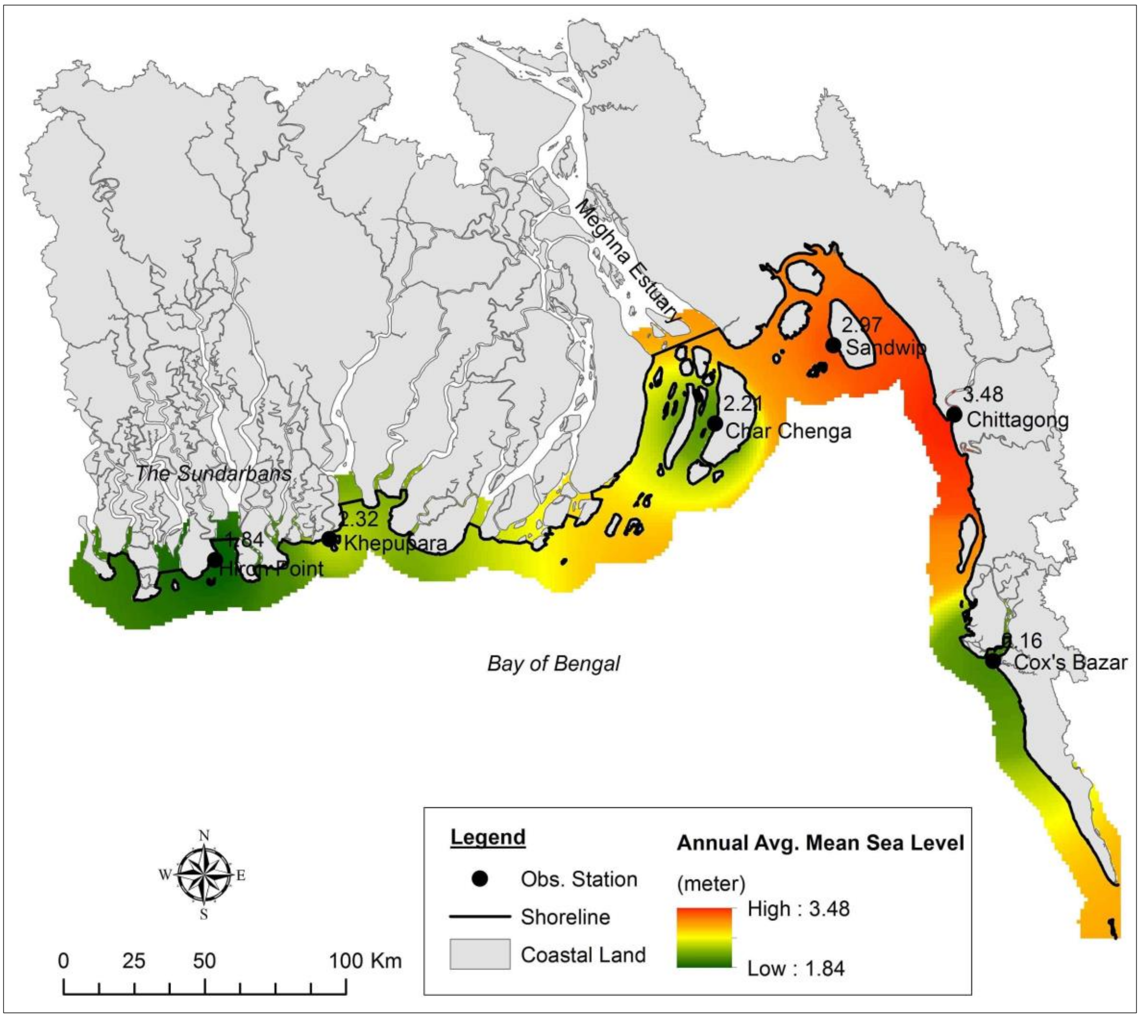
**Surface geology:** The types of surface geology that includes major types of geomorphic features in the study area. The types were arranged into five susceptibility classes based on their resistant capacity to erosion.



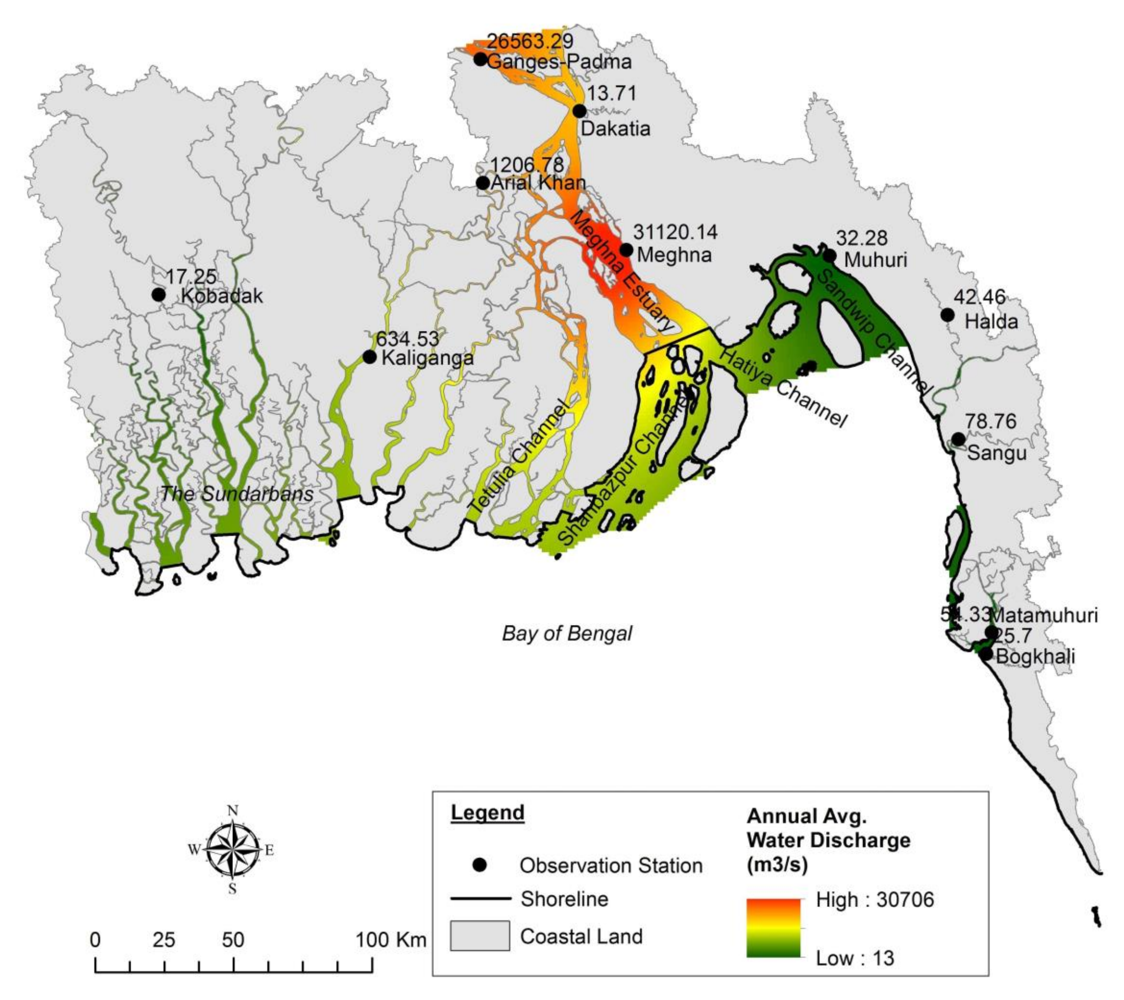
**Soil permeability:** The generalized soil permeability classes obtained from Bangladesh Agricultural Research Council (BARC).



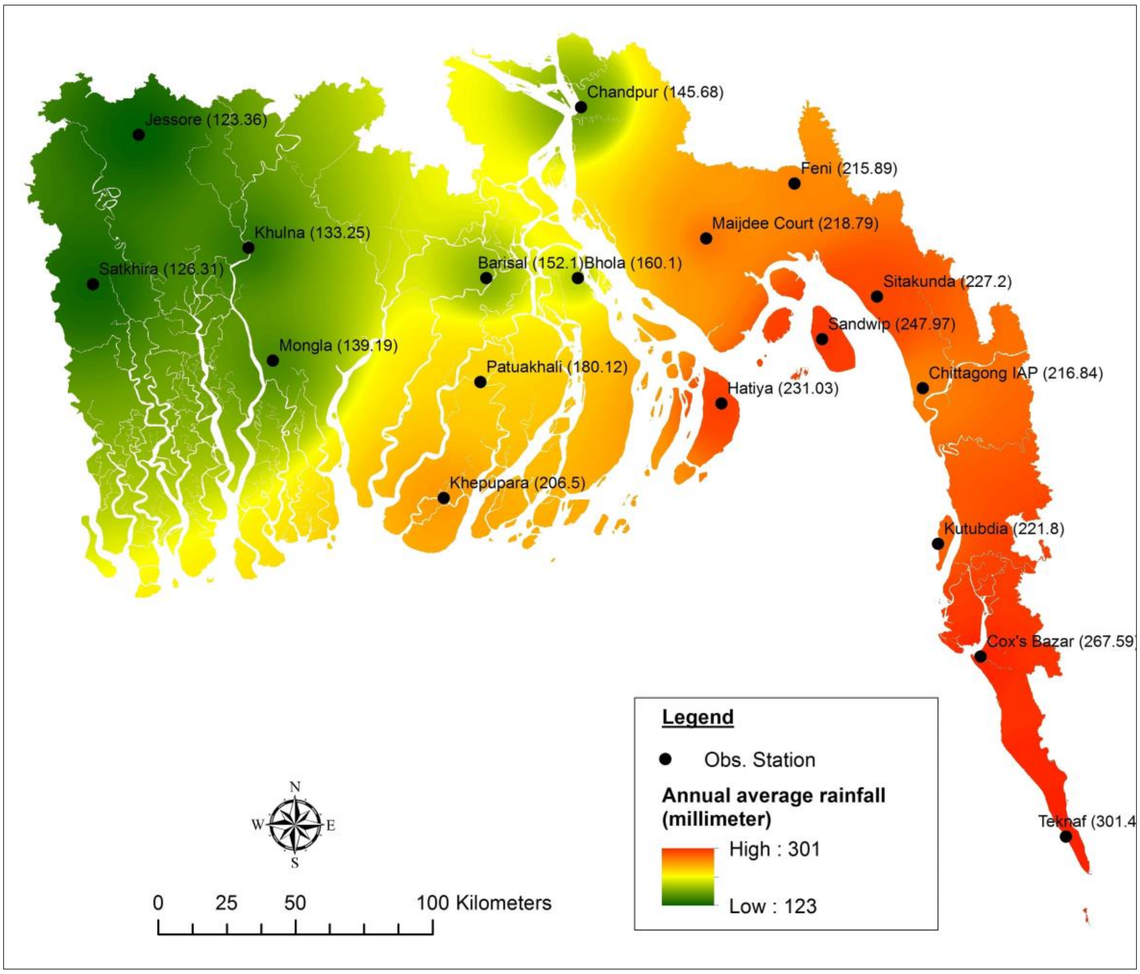
**Near-shore bathymetry:** The area includes near-shore, offshore islands, and Meghna estuary. As mentioned (in chapter 3), the surfaces went through 'rescale by function' and 'fill' operation in ArcMap to generalize the sinks and peaks.



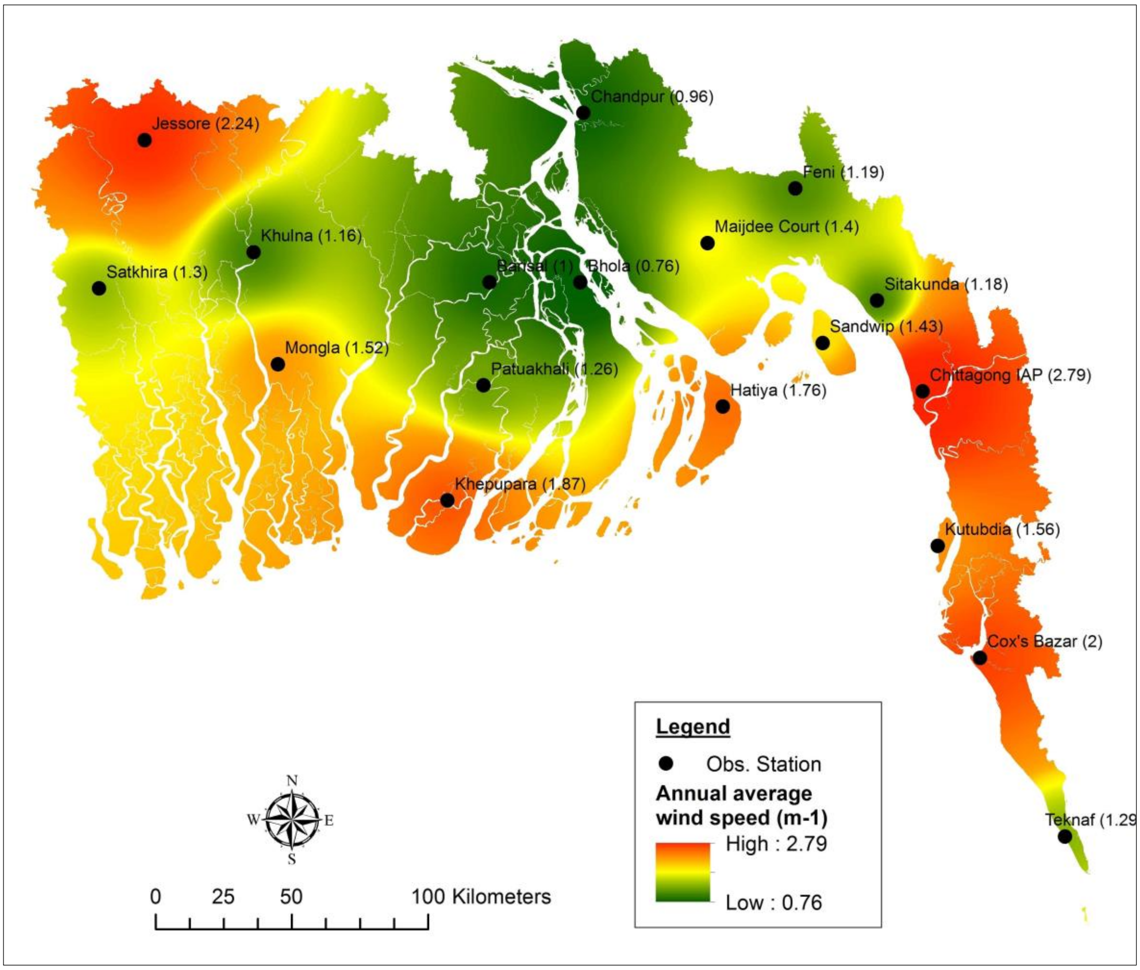
**Mean sea level:** The raster surface represents the spatial variations of mean sea level around the existing shoreline in the coastal area.



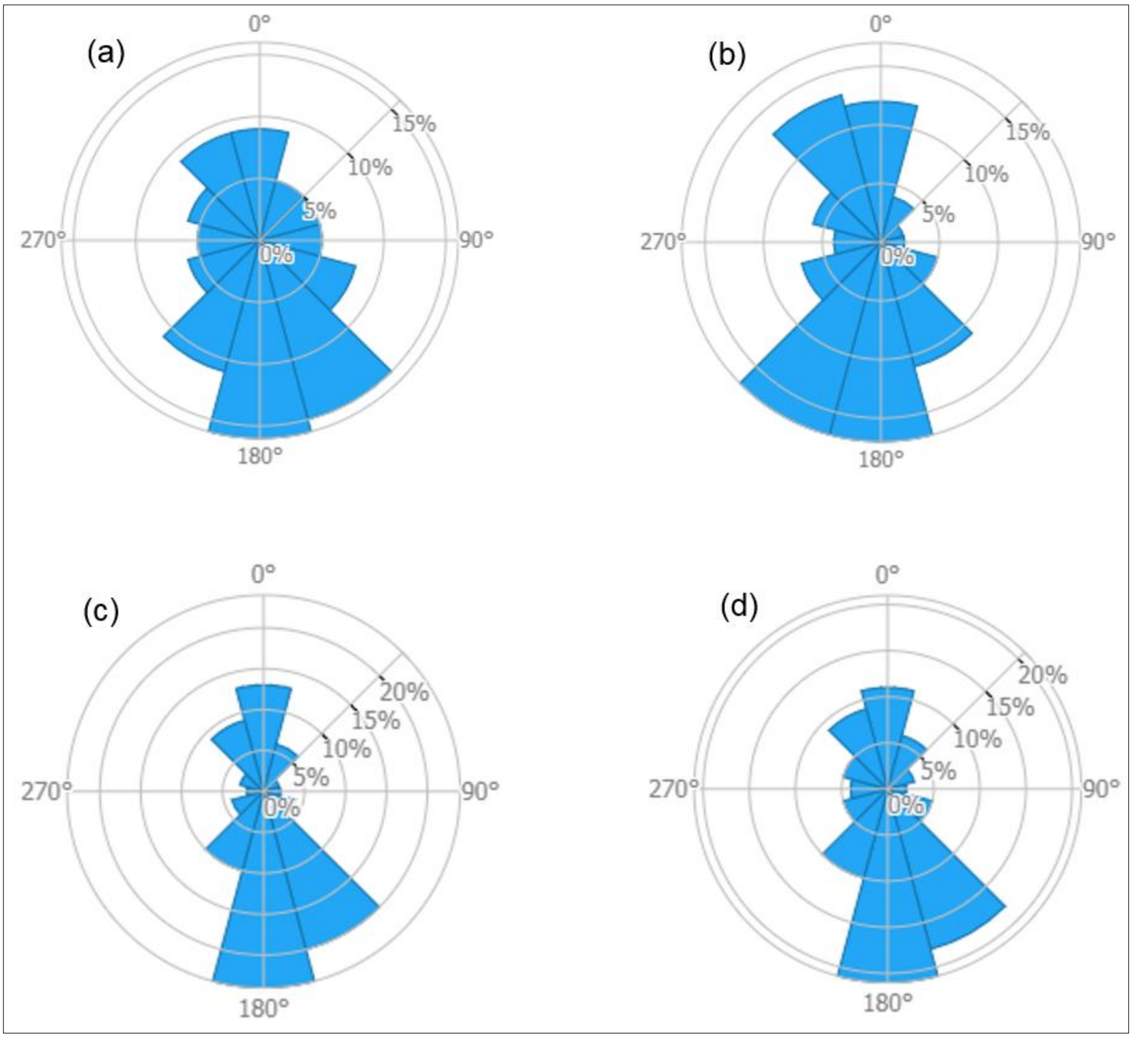
**Coastal river water discharge:** The discharge of water from major coastal rivers propagate throught the river channels and the estuary to the areas beyond the shoreline. Literature (Sarker et al. 2013 and 2015) suggests that the influence of river water discharge could be extended up to the end of Tetulia and Shahbazpur channels and south of Hatiya and Sandwip islands. However, the river water discharges are highly influenced by and mingled with tidal circulations and longshore currents beyond the shoreline.



**Rainfall:** The interpolated surface for average rainfall over the coastal lands. The surface was then scaled and weighted to be used for further processing in the LSCE model.



**Wind speed:** The interpolated raster surface used buffer land areas attached to waterbody. The areal extent of the buffer zones followed 500 m conventional set-back distance used for the coastal area and considered for potential impacts of wave actions.



**Wind roses:** The annual average wind directions (%) for (a) the entire area and the three coastal locations: (b) Khulna; (c) Barisal and (d) Chittagong.

**Appendix D:** Results obtained from LSCE model for overall baseline and seasonal variation under A1B future scenario.

**Overall susceptibility to erosion**

| Susceptibility Class | Total area of land (km$^2$) and percentage for different time-slices | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current (2015) | | Near future (2020) | | Future (2050) | | Far future (2080) | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 33163.79 | 73.34 | 30626.73 | 67.73 | 29236.95 | 64.65 | 24091.24 | 53.28 |
| 2 (low) | 9296.71 | 20.56 | 12205.06 | 26.99 | 12970.19 | 28.68 | 16106.77 | 35.62 |
| 3 (moderate) | 2483.70 | 5.49 | 1934.96 | 4.28 | 2364.77 | 5.23 | 4003.40 | 8.85 |
| 4 (high) | 266.32 | 0.59 | 421.71 | 0.93 | 576.13 | 1.27 | 842.70 | 1.86 |
| 5 (very high) | 10.01 | 0.02 | 32.10 | 0.07 | 72.50 | 0.16 | 176.43 | 0.39 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Winter (December – February)**

| Susceptibility Class | Total area of land (km$^2$) and percentage for different time-slices | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current (2015) | | Near future (2020) | | Future (2050) | | Far future (2080) | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 31947.47 | 70.65 | 34983.59 | 77.36 | 29912.79 | 66.15 | 29711.60 | 65.70 |
| 2 (low) | 11300.64 | 24.99 | 8302.51 | 18.36 | 12526.56 | 27.70 | 12275.59 | 27.15 |
| 3 (moderate) | 1814.24 | 4.01 | 1763.55 | 3.90 | 2484.31 | 5.49 | 2879.72 | 6.37 |
| 4 (high) | 155.16 | 0.34 | 167.72 | 0.37 | 285.08 | 0.63 | 339.24 | 0.75 |
| 5 (very high) | 3.02 | 0.01 | 3.17 | 0.01 | 11.80 | 0.03 | 14.39 | 0.03 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Pre-monsoon (March – May)**

| Susceptibility Class | Total area of land ($^2$km) and percentage for different time-slices | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current (2015) | | Near future (2020) | | Future (2050) | | Far future (2080) | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 37894.94 | 83.80 | 34249.46 | 75.74 | 30605.28 | 67.68 | 26196.68 | 57.93 |
| 2 (low) | 6328.46 | 13.99 | 8797.06 | 19.45 | 11917.63 | 26.35 | 14300.18 | 31.62 |
| 3 (moderate) | 842.54 | 1.86 | 1931.85 | 4.27 | 2096.81 | 4.64 | 3915.65 | 8.66 |
| 4 (high) | 150.71 | 0.33 | 234.68 | 0.52 | 556.90 | 1.23 | 679.15 | 1.50 |
| 5 (very high) | 3.88 | 0.01 | 7.48 | 0.02 | 43.91 | 0.10 | 128.87 | 0.28 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Monsoon (June – September)**

| Susceptibility Class | Total area of land (km$^2$) and percentage for different time-slices | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current (2015) | | Near future (2020) | | Future (2050) | | Far future (2080) | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 34199.54 | 75.63 | 32685.73 | 72.28 | 32840.09 | 72.62 | 26345.27 | 58.26 |
| 2 (low) | 8600.73 | 19.02 | 9492.05 | 20.99 | 9341.30 | 20.66 | 14101.57 | 31.18 |
| 3 (moderate) | 1680.98 | 3.72 | 1979.94 | 4.38 | 1928.46 | 4.26 | 2856.79 | 6.32 |
| 4 (high) | 708.12 | 1.57 | 979.81 | 2.17 | 911.53 | 2.02 | 1415.18 | 3.13 |
| 5 (very high) | 31.15 | 0.07 | 83.00 | 0.18 | 199.15 | 0.44 | 501.72 | 1.11 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Post-monsoon (October – November)**

| Susceptibility Class | Total area of land (km$^2$) and percentage for different time-slices | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current (2015) | | Near future (2020) | | Future (2050) | | Far future (2080) | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 31809.93 | 70.34 | 29025.38 | 64.19 | 29526.29 | 65.29 | 27994.19 | 61.91 |
| 2 (low) | 9879.51 | 21.85 | 13652.15 | 30.19 | 11407.92 | 25.23 | 12641.61 | 27.96 |
| 3 (moderate) | 3155.37 | 6.98 | 1995.65 | 4.41 | 3649.77 | 8.07 | 3825.25 | 8.46 |
| 4 (high) | 358.11 | 0.79 | 531.11 | 1.17 | 567.95 | 1.26 | 652.53 | 1.44 |
| 5 (very high) | 17.61 | 0.04 | 16.24 | 0.04 | 68.60 | 0.15 | 106.95 | 0.24 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Appendix E:** LSCE model scenarios for current and future time-slices.

**Scenario A1B**

| Susceptibility Class | Total area of land (km$^2$) and percentage for different time-slices | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current (2015) | | Near future (2020) | | Future (2050) | | Far future (2080) | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 33163.79 | 73.34 | 30626.73 | 67.73 | 29236.95 | 64.65 | 24091.24 | 53.28 |
| 2 (low) | 9296.71 | 20.56 | 12205.06 | 26.99 | 12970.19 | 28.68 | 16106.77 | 35.62 |
| 3 (moderate) | 2483.70 | 5.49 | 1934.96 | 4.28 | 2364.77 | 5.23 | 4003.40 | 8.85 |
| 4 (high) | 266.32 | 0.59 | 421.71 | 0.93 | 576.13 | 1.27 | 842.70 | 1.86 |
| 5 (very high) | 10.01 | 0.02 | 32.10 | 0.07 | 72.50 | 0.16 | 176.43 | 0.39 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Scenario RCP2.6**

| Susceptibility Class | Total area of land (km$^2$) and percentage for different time-slices | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current (2015) | | Near future (2020) | | Future (2050) | | Far future (2080) | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 33163.79 | 73.34 | 33245.41 | 73.52 | 29559.31 | 65.37 | 25460.63 | 56.30 |
| 2 (low) | 9296.71 | 20.56 | 9350.20 | 20.68 | 13680.26 | 30.25 | 16921.43 | 37.42 |
| 3 (moderate) | 2483.70 | 5.49 | 2331.12 | 5.15 | 1438.36 | 3.18 | 2039.31 | 4.51 |
| 4 (high) | 266.32 | 0.59 | 284.33 | 0.63 | 464.14 | 1.03 | 642.72 | 1.42 |
| 5 (very high) | 10.01 | 0.02 | 9.47 | 0.02 | 78.46 | 0.17 | 156.44 | 0.35 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Scenario RCP4.5**

| Susceptibility Class | Total area of land (km$^2$) and percentage for different time-slices | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current (2015) | | Near future (2020) | | Future (2050) | | Far future (2080) | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 33163.79 | 73.34 | 29525.58 | 65.29 | 28842.56 | 63.78 | 23576.71 | 52.15 |
| 2 (low) | 9296.71 | 20.56 | 13350.72 | 29.52 | 13241.36 | 29.28 | 16330.74 | 36.11 |
| 3 (moderate) | 2483.70 | 5.49 | 1822.51 | 4.03 | 2245.45 | 4.97 | 4131.71 | 9.13 |
| 4 (high) | 266.32 | 0.59 | 487.21 | 1.08 | 748.52 | 1.65 | 962.63 | 2.13 |
| 5 (very high) | 10.01 | 0.02 | 34.51 | 0.08 | 142.64 | 0.32 | 218.74 | 0.48 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Scenario RCP8.5**

| Susceptibility Class | Total area of land (km$^2$) and percentage for different time-slices | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current (2015) | | Near future (2020) | | Future (2050) | | Far future (2080) | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 33163.79 | 73.34 | 28455.31 | 62.92 | 24239.41 | 53.61 | 21444.16 | 47.51 |
| 2 (low) | 9296.71 | 20.56 | 12566.53 | 27.79 | 11782.32 | 26.06 | 10659.24 | 23.55 |
| 3 (moderate) | 2483.70 | 5.49 | 3264.92 | 7.22 | 6144.36 | 13.57 | 9076.42 | 20.07 |
| 4 (high) | 266.32 | 0.59 | 876.93 | 1.94 | 2488.60 | 5.51 | 3034.30 | 6.73 |
| 5 (very high) | 10.01 | 0.02 | 56.84 | 0.13 | 565.84 | 1.25 | 1006.41 | 2.23 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Appendix F:** Results of sensitivity analysis.

**Table 1:** Results of sensitivity analysis for four types of weighting tests.

| Susceptibility Class | Total area of land (km$^2$) and percentage for different conditions | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Test 1 | | Test 2 | | Test 3 | | Test 4 | |
| | Area | % | Area | % | Area | % | Area | % |
| 1 (very low) | 32848.19 | 72.64 | 32744.18 | 72.41 | 32522.61 | 71.92 | 33163.79 | 73.34 |
| 2 (low) | 9215.94 | 20.38 | 9270.21 | 20.50 | 9301.86 | 20.57 | 9296.71 | 20.56 |
| 3 (moderate) | 2808.19 | 6.21 | 2866.98 | 6.34 | 3002.64 | 6.64 | 2483.70 | 5.49 |
| 4 (high) | 334.64 | 0.74 | 325.59 | 0.72 | 375.34 | 0.83 | 266.32 | 0.59 |
| 5 (very high) | 13.57 | 0.03 | 13.57 | 0.03 | 18.08 | 0.04 | 10.01 | 0.02 |
| Total | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 | 45220.53 | 100 |

**Table 2:** Comparison of the results obtained for the three coastal zoned under general and regional LSCE model.

| Coastal zone (general assessment) | | | | | | |
|---|---|---|---|---|---|---|
| Susceptibility class | Western | | Central | | Eastern | |
| | Area | % | Area | % | Area | % |
| 1 (very low) | 25459.53 | 95.58 | 3011.05 | 26.96 | 4693.21 | 63.29 |
| 2 (low) | 1023.41 | 3.83 | 6227.9 | 55.77 | 2045.40 | 27.58 |
| 3 (moderate) | 141.36 | 0.53 | 1684.72 | 15.08 | 657.62 | 8.87 |
| 4 (high) | 12.43 | 0.05 | 237.36 | 2.13 | 16.53 | 0.22 |
| 5 (very high) | 1.51 | 0.006 | 6.18 | 0.06 | 2.32 | 0.04 |
| Total | 26,638.24 | 100 | 11,167.21 | 100 | 7,415.08 | 100 |
| Coastal zone (sensitivity analysis) | | | | | | |
| Susceptibility class | Western | | Central | | Eastern | |
| | Area | % | Area | % | Area | % |
| 1 (very low) | 23843.88 | 89.51 | 2852.11 | 25.54 | 4678.92 | 63.10 |
| 2 (low) | 1776.77 | 6.67 | 5841.57 | 52.31 | 2017.64 | 27.21 |
| 3 (moderate) | 996.27 | 3.74 | 2079.33 | 18.62 | 699.24 | 9.43 |
| 4 (high) | 18.66 | 0.07 | 381.92 | 3.42 | 15.57 | 0.21 |
| 5 (very high) | 2.66 | 0.01 | 12.28 | 0.11 | 3.71 | 0.05 |
| Total | 26,638.24 | 100 | 11,167.21 | 100 | 7,415.08 | 100 |

**Appendix G:** Photographs taken from the coastal area of Bangladesh.

*Erosion prone area at Kuakata in the western coastal zone of the country.*

*The soft and unconsolidated soils in Sandwip island are highly susceptible to erosion by wave actions during monsoon season.*

*Wave actions together with discharge of water are responsible for high erosion at Hatiya island in the central coastal zone.*

*The continuous process of erosion is active in the eastern part of Bhola island.*

*Newly accreted land (Sona Char) in the exposed central coastal zone is highly susceptible to erosion.*

*The hard defence structure at Kutubdia island in the eastern coastal zone substantially reduced erosion.*