UNIVERSITY OF NEW ENGLAND

Mapping Long Term Changes in Mangrove Cover and Predictions of Future Change under Different Climate Change Scenarios in the Sundarbans, Bangladesh

Submitted by

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Abstract

The Sundarbans mangrove forest is an important resource for the people of the Ganges Delta. It plays an important role in the local as well as global ecosystem by providing ecological services and economic goods. However, this mangrove ecosystem is under threat, mainly due to climate change and anthropogenic factors. The aims of this Thesis are: (1) to apply remote sensing techniques and open source mid-resolution data, as cheap and reliable data, to identify and map mangrove composition at species level, (2) to monitor the impact of climate variability in this ecosystem , (3) assess spatial and temporal dynamics of tidal channels in the Bangladesh Sundarbans and finally (4) to predict the magnitude of mangrove area loss and future impacts on mangrove species composition and distribution due to a rise in Mean Sea Level (MSL

Chapter one evaluates the efficacy of mid-resolution Landsat satellite image combined with traditional classification algorithms to produce an acceptable accuracy at species level mapping of mangroves. A maximum likelihood algorithm was employed to identify and map mangrove species composition using open-source mid-resolution Landsat data, taking Bangladesh Sundarbans as a case study. The classified image achieved an overall accuracy of 89.10% and kappa coefficient of 0.87 for the five-identified species, viz. *Heritiera fomes*, *Ceriops decandra*, *Excoecaria agallocha*, *Sonneratia apelatala*, and *Xylocarpus mekongensis*, which is higher than the required minimum overall accuracy of 85% deemed suitable to use in most of the natural resource mapping applications. Based on our result, it can be concluded that mid-resolution images, such as Landsat, and the traditional classification algorithm can be applied with confidence for the identification and classification of mangrove forest resources at species level as an alternative to the high resolution satellite images.

The second research chapter is about mapping the long term changes in mangrove species composition in the Sundarbans. Maximum likelihood classifier technique was employed to classify images recorded by the Landsat satellite series and used post classification comparison techniques to detect changes at the species level. The image classification resulted in overall accuracies of 72%, 83%, 79% and 89% for the images of 1977, 1989, 2000 and 2015, respectively. We identified five major mangrove species and detected changes over the 38-year (1977–2015) study period. During this period, both *Heritiera fomes* and *Excoecaria agallocha* decreased by 9.9%, while *Ceriops decandra*, *Sonneratia apelatala*, and *Xylocarpus mekongensis* increased by 12.9%, 380.4% and 57.3%, respectively.

The third research chapter presents the relationship between temperature, rainfall pattern and dynamics of mangrove species in the Sundarbans, Bangladesh, assessed over a 38 year time period from 1977–2015. A three stage analytical process was employed to monitor the impact of climate variability in this ecosystem. Primarily, the trend of temperature and rainfall over the study period were identified using a linear trend model; then, the supervised maximum likelihood classifier technique was employed to classify images recorded by Landsat series and post-classification comparison techniques were used to detect changes at species level. The rate of change of different mangrove species was also estimated in the second stage. Finally, the relationship between temperature, rainfall and the dynamics of mangroves at species level was determined using a simple linear regression model. A significant statistical relationship between temperature, rainfall and the dynamics of mangrove species was obtained. The trends of change for *Heritiera fomes* and *Sonneratia apelatala* show a strong relationship with temperature and rainfall, while *Ceriops decandra* shows a weak relationship. In contrast, *Excoecaria agallocha* and *Xylocarpus mekongensis* do not show any significant relationship with temperature and rainfall. This chapter concluded that temperature and rainfall are important climatic factors influencing the dynamics of three major mangrove species viz. *Heritiera fomes*, *Sonneratia apelatala* and *Ceriops decandra* in the Sundarbans.

The fourth research chapter focuses on the spatial and temporal dynamics of tidal channels in the Bangladesh Sundarbans. Parts of the Passur River system were considered for this investigation. Tidal channel bank layers were extracted from aerial photographs from 1974 and 2011, and a Sentinel-2 image from 2017. Remote Sensing and Geographic Information System (GIS) platforms were used to analyse, interpret, and visualize data on accretion and erosion, as well as the locations of the tidal channel bank over different years. The results revealed that erosion was severe in the larger channels, whereas accretion was dominant in the smaller channels. Displacement of the tidal channel bank has had a profound impact on the Sundarbans mangrove ecosystem, and continued erosion and accretion processes are of concern for the future sustainability of biodiversity in the Sundarbans. While in the short term these changes may not have much impact, over decades the dynamics of tidal channels may significantly contribute to the imbalance of fauna and flora in the Sundarbans.

A synthesis of the forcing mechanisms of tidal channel dynamics in the context of natural and anthropogenic forces and their implications on the Sundarbans delta floodplain mangrove forest comes in the fifth research chapter. Natural tidal channel dynamics driving forces viz: tectonic and subsidence, sea level rise, tides, storms, cyclones and other climatic factors are discussed in this synthesis. Human induced morphodynamic factors that affect erosion and accretion processes in the Sundarbans tidal channel system are also discussed. Based on our discussion it can be concluded that natural and anthropogenic forces such as tides, storms and cyclones, fluctuations in seasonal rainfall, tectonic and subsidence forces, sea level rise, infrastructure development and changing pattern of land use plays a vital role in the erosion accretion processes in tidal channel dynamics in the study area, and subsequently have important implications on the sustainability of the Sundarbans mangrove ecosystem. Precise effects of these natural and anthropogenic forces are recommended for future research.

The sixth research chapter predicts the magnitude of mangrove area loss and future impacts on mangrove species composition and distribution due to a rise in Mean Sea Level (MSL). In this study, a geospatial model of potentially inundated areas was developed using Digital Elevation Model (DEM) data to assess the potential impacts of sea level rise (SLR) on the future spatial distribution of mangrove species and estimates the potential inundation and subsequent mangrove area loss. The mangrove areas of 2646 ha, 9599 ha and 74720 ha are projected to be inundated and subsequently lost by the end of the 21st century for the low, medium and high SLR scenarios respectively under the net subsidence rate -2.4 mm/year relative to the baseline year 2000. All the major five mangrove species of the Bangladesh Sundarbans will be affected and that can potentially contribute to a change in the present species composition and biodiversity of the forest. Results suggest that, under the extreme scenario, inundation and subsequent loss of different mangrove species will be substantial and this can bring a massive change in the species composition and their spatial distribution in the Bangladesh Sundarbans.

In conclusion, long term changes in mangrove cover at species level, and prediction of future spatial distributions under different climate change scenarios in the Bangladesh Sundarbans are mapped and analysed in this thesis. In addition, a newly developed geospatial model shows the future impact of sea level rise on species composition and their spatial distribution. This model can be used in future for the impact assessment of sea level rise on mangrove species in the Sundarbans and other parts of the world. Thus, this research provides some invaluable insights and techniques for the development of a proper monitoring strategies in the future for sustainable management of the forest in response to climate variability and change. Different relevant agencies of Bangladesh government, such as Bangladesh Forest Department and Ministry of Environment, can follow the approach and incorporate the outcomes of this research to develop a continuous and proper monitoring system in a time saving, efficient and cost effective way. Hope outcome of this study will be a stepping stone in the studies of the Sundarbans mangroves and its sustainable management using remote sensing techniques.

Declaration

I certify that the substance of this thesis has not been submitted for any degree and is not currently being submitted for any other degree or qualification. I certify that, to the best of my knowledge, any assistance received in preparing this thesis, and all sources used, have been acknowledged.

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Manoj Kumer Ghosh

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Dad you are certainly happy to see from the sky that your boy has done this ……………

Note to Examiners

This thesis has been written in journal-article format. I have attempted to minimise the duplication of material between chapters. However, some repetition remains, particularly in the methodology sections of certain articles. Although effort has been made to ensure consistency in the format for the purposes of this thesis, I acknowledge that some inconsistencies remain because of the requirements of each of the journals to which the separate papers were submitted.

Publications from this Thesis during Candidature

Ghosh, M. K., Kumar, L., & Roy, C. (2016). Mapping Long-Term Changes in Mangrove Species Composition and Distribution in the Sundarbans. *Forests*, 7(12), 305. Doi: 10.3390/f120305. **Chapter 3**

Ghosh, M. K., Kumar, L., & Roy, C. (2017). Climate Variability and Mangrove Cover Dynamics at Species Level in the Sundarbans, Bangladesh. *Sustainability*, 9(5), 805. doi: 10.3390/su9050805. **Chapter 4**

In addition, the following papers have been submitted to the journal for review and publication.

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Chapter 3

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Chapter 4

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Chapter 5

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Chapter 7

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Chapter 6

Tidal Channel Dynamics in the Sundarbans Mangrove Ecosystem: Responsible Forces and their implications

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Chapter 1.

General Introduction

1.1. Introduction

Mangroves are small evergreen trees that flourish in the intertidal zones of river deltas, lagoons, estuaries and coastal systems in the tropics, subtropics, and some temperate coastal regions (Liu et al. 2008; Sheridan and Hays 2003; Twilley et al. 1996). The term “mangroves” is used to characterize either a single plant or forest community which are salt tolerant woody halophytes. This forest community first appeared along the coasts of the Tethys Sea and then deviated from their terrestrial communities during the Late Cretaceous to Early Tertiary (Ricklefs et al. 2006). Though mangroves live in saline environment and are adapted to the high salinity (Mitra 2016), the optimal salinity for survival of healthy mangroves (some particular species) is 28 ppt to 34 ppt (Aksornkoae 1993; Duke et al. 1998) while most riverine mangroves need comparatively lower salinity for their survival. They have adaptation mechanisms mainly of three forms: morphological, physiological and anatomical (Naskar and Palit 2015) which ensure the long-term persistence and propagation success under extreme environments (Duke et al. 1998).

The appraised global coverage of mangrove forest is 137,760 km^2 (Giri et al. 2011) which equates to 0.1% of the earth’s surface (Cornforth et al. 2013) and is spread in 124 tropical and sub-tropical countries. Approximately three-fourths of the total mangroves are located along the coastline of 15 countries, of which most are in Southeast Asian region. Maximum presence of mangroves lies between 5^{o}N and 5^{o}S latitudes. This geographical distribution of mangroves can be categorized into two major regions: Indo-West Pacific (IWP) region and the Atlantic Caribbean Eastern Pacific (ACEP) region (Spalding 2010). Other important bio-geographical regions where the distribution of mangrove species is clearly evident includes Australia, Southcentral America, Brazil and Nigeria (Alongi 2002). The term “species zonation” is generally expressed by the abundance and occurrence of the mangrove species over space and is observed across environmental gradients in many types of ecosystems. In general, for each ecosystem, gradual pattern of species distribution is seen from the saline water setting through intertidal flats to the terrestrial setting. Lugo and Snedaker (1974) and Woodroffe (1992) broadly classified mangroves based on the location, into six functional types as follows: (1) overwash mangroves that formed in small islands by tidal washing, (2) fringing mangroves that formed along the borders of protected shorelines and are more exposed to turbulent waves and tides, (3) riverine mangroves that can be found along the creeks and rivers, and those rivers that are often inundated by tides, (4) basin mangroves that are located along the interior side of the swamps and drainage depressions, (5) hammock mangroves which are similar to basin but the only difference is that they are evolved in more elevated sites, and (6) scrub mangroves that are dwarf mangroves and located along flat coastal fringes.

Ecologically and economically, mangrove ecosystems are important to the human society. Mangroves are one of the most productive plants on earth with a mean production of 8.8 t C/ha/yr and also dominant along many tropical and subtropical coastlines (Jennerjahn and Ittekkot 2002; Kirui et al. 2013). They provide a wide range of ecosystem goods and ecological services to humans, such as wood and timber for fuel and furniture, medicine, food, construction materials, nursery grounds for fisheries, sediment trapping, sewage phytoremediation, protection of coasts from typhoon damage, pollutant absorption, and water purification, and these types of goods and services have immense value to local, national and global communities (Barbier et al. 2008; Kirui et al. 2013; Liu et al. 2008). For diverse flora and fauna, including many rare species, mangroves are considered as an important habitat (Blasco et al. 1996; Liu et al. 2008; Murray et al. 2003; Sheridan and Hays 2003). The estimated total economic value of mangroves ranges between USD 200,000 and 900,000 per ha/year (Wells and Ravilious 2006) . The cost of the products and services provided by the mangroves were considered for this estimation.

Mangroves are considered as an important candidate for conservation efforts, under schemes such as Reduced Emissions from Deforestation and Degradation (REDD+), for their ability to sequester and store carbon (Donato et al. 2011; Kirui et al. 2013). Despite its ecological and economic importance, mangrove forests are one of the most threatened habitats in the world (Kirui et al. 2013). These forests are declining at an alarming rate (Giri and Muhlhausen 2008; Valiela et al. 2001; Vo et al. 2013). Within the past 50 years, about one-third of mangrove forests have been lost worldwide (Alongi 2002; Liu et al. 2008). The decline in the rate of mangroves is even more rapid than inland tropical forests (Giri et al. 2007). Much of what remains is in a degraded condition (Giri et al. 2007; Wilkie and Fortune 2003), and under immense pressure from illegal tree felling, encroachment, hydrological alterations, chemical spills, coastal development, over- harvesting, aquaculture expansion and climate change (Blasco et al. 2001; Ghosh et al. 2017b; Giri et al. 2007; McKee 2004). The loss of this important ecosystem may be further accelerated by climate change induced rise in sea level, changes in precipitation patterns and increasing temperature and storminess (Ward et al. 2016).

The capacity of mangroves to deliver ecosystem services that are important for current and future human society can be affected by the loss and degradation of this important ecosystem.

1.2. The Sundarbans

The Sundarbans occupies parts of Bangladesh and India (21°32′ - 22°40′N, 88° 05′ - 89°51′E), and has an area of nearly one million hectares and is the largest contiguous mangrove forest in the world (Ghosh et al. 2015a; Rahman and Asaduzzaman 2013; Spalding 2010). This forest is part of the Ganges-Brahmaputra delta which lies in a zone of cyclonic storms and tidal bores that originate in the Bay of Bengal. The Bangladesh part of the Sundarbans is located approximately between 21°32′ to 22°30′ N latitude and 89° 00′ to 89°51′ E longitude and covers three-fifths of the entire forest. The hydrology of the Sundarbans depends on the fresh water discharge mainly from the Ganges and the saltwater influx from the Bay of Bengal. The Sundarbans is recognized as a site of national and international importance for conservation of biodiversity (Biswas et al. 2007; Hussain and Acharya 1994), and also plays a crucial role in the local coastal ecosystem as well as in the global environmental balance (Biswas et al. 2007) by providing a range of renewable resources. This forest is home to a diverse range of plants and animals (Giri et al. 2007) and is the largest source of forestry and non-forestry forest products for more than 2.5 million people of surrounding regions (Giri et al. 2007; Rahman 2000). The Sundarbans is also the last stronghold of the endangered Royal Bengal Tiger (*Panthera tigris*) along with others which are protected by legislation: notably by both the India and Bangladesh Governments (Rahman 2000; Rahman and Asaduzzaman 2013).

The Sundarbans has lost 50% of its original areal extent within the last 200 years due to different natural and anthropogenic forces (Siddiqi 2001). Over-exploitation of forests, reduction in freshwater flows, increasing salinity, extreme weather events, and water and soil pollution are the forces that have played an important role in the historical and ongoing degradation of the Sundarbans mangrove forest, and as a result of the degradation the populations of many threatened mangroves, including the globally endangered *Heritiera fomes*, gets affected (Ellison et al. 2000). Changing climate, particularly, rise in sea level and changes in rainfall patterns and temperature are likely to have a substantial influence on the Sundarbans (Karim and Mimura 2008). However, explicit baseline information on the mangrove species composition, spatial distributions and dynamics are still not well documented. To undertake effective conservation efforts for ensuring the sustainability of the Sundarbans mangrove forest, this inadequacy of baseline information can be considered as a major impediment (Aziz and Paul 2015; Islam et al. 2014).

1.3. Remote sensing of Mangroves

Traditional field surveys for mapping mangrove forest resources is very strenuous, time consuming and expensive. In addition, hostile environments of mangrove forest makes field survey difficult, time consuming and costly. In such situations, application of remote sensing techniques can play an important and effective role in mangrove forest resources mapping and monitoring with an acceptable level of accuracy and also it has advantages over traditional methods (Ghosh et al. 2016; Giri et al. 2007; Hirano et al. 2003; Kovacs et al. 2005). This technique provides supplementary information quickly and efficiently in addition to field inventory (Giri et al. 2007). Remote sensing data has proved to be of immense value in monitoring of coastal vegetation because of its repetitive, synoptic and multi-spectral nature (Nayak and Bahuguna 2001). For the past few decades, remote sensing techniques has been widely used in mapping and monitoring of such hostile mangrove environments in an effective way in terms of time, cost and accuracy. However, there are many mangrove management activities, such as species composition mapping and species composition dynamics, which are still highly dependent on traditional field surveys in countries with low institutional capacity such as Bangladesh. To reduce strenuous and costly activities, advanced techniques such as remote sensing can be explored.

Multispectral surface information at regional scales, provided by mid-resolution imagery, can serve a multitude of applications. This kind of imagery has played a significant role in mangrove mapping in last few decades. This imagery is suitable for regional scale mapping of mangroves. The major advantage of this imagery is that it provides proper coverage and information depth in a cost-effective manner. Its spatial and spectral resolution are good enough for many purposes, such as identification of mangrove and non-mangrove classes, regional level mapping and in rarely species composition mapping. In addition, mid-resolution data is expedient for long term monitoring of the ecosystem due to the free or low-cost availability of historical data. Free or low-cost availability of data supports the assessment of delicate changes over a long period of time (trends) as well as the identification of abrupt changes due to natural or dramatic human induced impacts. In many developing countries, the high cost of high resolution satellite imagery limits its routine use (Kirui et al. 2013). The free or low-cost availability of archived images enables the development of capacity and techniques in its use and also encourages researchers to develop a proper and continuous monitoring system to provide an information base and predictive route for sustainable management planning in a simple, time saving, efficient and cost effective way. Although the mid-resolution data has provided the opportunity to the researchers for ecosystem mapping and long-term monitoring with free or low-cost available data, its analysis has some difficulties in deriving useful information for in-depth studies such as species-oriented studies.

Some of the common issues in handling mid-resolution data includes requirement of skilled and trained personnel to best exploit the information content of the multiple bands, resolution is too coarse for local observations where in-depth species differentiation and parameterization is required, imagery is very much weather dependent especially in tropics and subtropics (cloud cover), temporal resolution is too low to record extreme weather events such as cyclone and floods, software required for image processing needs high license fees, spatial resolution is too coarse for some species oriented studies , and identification of species is rarely possible.

The above-mentioned limitations make the analysis of mid-resolution imagery more complex than the high-resolution image analysis. Even though this imagery has limitations, a number of researchers have successfully used mid-resolution imagery in mangrove mapping at species level (Ghosh et al. 2016; Giri et al. 2014; Myint et al. 2008).

1.4. Mapping and monitoring the changes in mangrove species composition and prediction of future distribution

Regular monitoring of mangroves has become an urgent need for its conservation and restoration measures. Mapping and change detection analysis are the two approaches that are extremely important for any kind of monitoring of the resources. Accurate change detection information helps to understand the interactions and relationships between natural phenomena and human activity. However, high quality and accurate change detection and identification of different mangrove species using public domain mid-resolution image data is a challenging task. At present, there is a lack of studies on whether the use of open source mid-resolution image and traditional classification techniques can produce high-quality outputs with sufficient levels of accuracy required to map mangrove forest trees at species level. Accuracy in feature identification and subsequent thematic mapping in remote sensing is a major concern and use of freely available open source satellite images, such as Landsat, is limited despite being an option for those who don’t have financial access to fine resolution image data.

The Sundarbans mangrove forest is an important resource for the people of the Ganges Delta and its significance extends from local to global scale. However, this resource is under threat from climate change and anthropogenic activities, therefore regular monitoring to ascertain mangrove species composition, their spatial distribution and the changes taking place over time is crucial for mangrove biodiversity understanding and adoption of management strategies in order to achieve maximum sustainable yield. Periodic monitoring and forest inventories have taken place in the Sundarbans approximately in every two decades. Based on the last inventory that was undertaken 30 years back, a mangrove cover map at a species level was produced. The preparation of this map was very strenuous and time consuming. Modern techniques such as remote sensing can be effective in terms of cost, time and accuracy for regular monitoring of the mangrove ecosystem (Myint et al. 2008; Wang et al. 2004a) such as the Sundarbans. For mapping and monitoring purposes, a number of researches conducted in the Sundarbans have applied remote sensing techniques (for example Blasco et al. 2001; Emch and Peterson 2006; Giri et al. 2007; Iftekhar and Islam 2004; Islam et al. 2014); but, most of the investigations have kept their focus only on determining spatial change. Giri et al. (2014) used remote sensing techniques to identify mangrove species composition and their changes in the Sundarbans, but this was only for the Indian Territory. Therefore, plant species and their distribution and dynamics remain unrecorded for the entire Sundarbans mangrove forest comprising both countries. This information on the composition, distribution and the dynamics of the mangrove species is an essential requisite (Giri et al. 2007) for regional management of mangroves.

Climatic variability and change have profound impacts on species composition, phenological pattern, salinity stress and productivity of mangroves (Agrawala et al. 2003; Gilman et al. 2008). Sea level rise (SLR) affects the distribution of mangroves in the long run (Eslami-Andargoli et al. 2009; Field 1995) and changes in regional temperature, rainfall and catchment runoff have more significant effects in the short term (Gilman 2004; Gilman et al. 2008). However, knowledge on climatic variables association with mangrove dynamics is limited given that research in this subject has been carried out in only a few areas over short time periods around the world (Gilman et al. 2008) but not in the Sundarbans.

The Sundarbans is a silt dominated mangrove habitat which has the funnel-shaped dense network of tidal channels. This mangrove habitat is maintained by the redistribution of onshore fluvial sediment advection by the tides (Wilson and Goodbred Jr 2015). For the survival and regeneration of some mangrove species, a continued supply of fresh water and the maintenance of the elevation of the tidal platform above the mean high water is necessary (Winterwerp and Giardino 2012). The elevation of the intertidal landscape of the Sundarbans mangrove forest has remained in tandem with relative sea level rise for decades (Auerbach et al. 2015) due to natural forces reworking the sediments. However, this status quo is not guaranteed to continue in future. The dynamic evolutions of the tidal channel in ecologically sensitive areas such as the Sundarbans can translate to the extreme fragility of biodiversity and may negatively impact on their sustainability. The dynamic tidal channels erosion and accretion processes may induce rapid changes in planform, and channel shifting and widening (CEGIS 2003) and thus render negative impacts socially and economically as well as constraint land development and more importantly threaten the Sundarbans ecosystem composition and its services provision. There is virtually no information on how tidal channels in the Bangladesh Sundarbans region have been altered through erosion/accretion processes. This information is crucial for planning of environmental management strategies.

The Bangladesh Sundarbans lies at the mean elevation of approximately two meters above mean sea level (Payo et al. 2016) making it most vulnerable to potential effects of SLR. The global SLR is projected to be approximately 1 m higher or above by the year 2100 (Church et al. 2013; Payo et al. 2016), and how this will impact on composition and distribution of mangrove species remains largely unknown. Given the low-lying elevation of the Sundarbans ecosystem and its vulnerability to any significant change in sea level, it is extremely important to understand the future effects on the mangroves.

1.5. Research Problem Statement

The Sundarbans is considered as a safe habitat for a wide range of plants and animals, including 27 mangrove species, 40 mammal species, 35 reptile species, and 260 species of birds. As mentioned in Section 1.4, there are many unexplored research areas in the context of conservation and management of mangroves, particularly in the Bangladesh Sundarbans that can, effectively, be supported through remote sensing and Geographic Information System techniques.

a. There is a lack of studies on whether the use of open source mid-resolution image and traditional classification techniques can produce a high-quality output with a sufficient level of accuracy required to map mangrove forest trees at species level. It is anticipated that successful mangrove cover mapping at species level with acceptable accuracy using mid-resolution satellite data such as Landsat will motivate other researchers and relevant stakeholders to develop a reliable time series database in a cost effective way that can be used in the continuous forest monitoring activities and also open up the avenue of such applicability for those who don't have financial access to fine resolution image data. Hence, there is a need to check the efficacy of such images to identify the mangrove species composition.

b. Mangroves face threats, such as reduction in areal extent and loss in species diversity, due to climate change and anthropogenic degradation. Considering the importance of the Sundarbans, accurate and up-to-date information on the composition, distribution and the dynamics of the mangrove species is an essential requisite. Hence, there is a need to map and monitor the changes in species composition and their spatial distribution regularly.

c. Research regarding climatic variables associated with mangrove dynamics is largely limited around the world, and no investigation has been conducted in the Sundarbans on the relationship between climate variability and mangrove dynamics at species level so far.

d. There are virtually no studies on the dynamic evolutions of the tidal channels in the Sundarbans. Tidal channel dynamics can translate to extreme fragility of biodiversity and may negatively impact on their sustainability in ecologically sensitive areas such as the Sundarbans. Hence, an understanding of the tidal channel dynamics and responsible forces for these dynamics is crucial for planning of environmental management strategies.

e. Low elevation areas of the Sundarbans floodplains are expected to be affected by climate change driven rise in the sea level, but the magnitude of the effects on future mangrove species composition and their spatial distribution remains largely unknown. Therefore, prediction of the SLR and its impacts on the Sundarbans mangrove forest composition and species distribution, given the low-lying elevation of the ecosystem and its vulnerability to any significant change in sea level, is extremely important.

To address the above-mentioned requirements of mangrove management practices, research initiatives are often triggered by the different national and international organizations and individuals' researchers. For monitoring purpose, 15 to 20 years periodic forest inventories have taken place in the Sundarbans. However, mapping of mangroves at species level are limited. To map the mangroves at species level and monitoring the ecosystem we need to think beyond traditional, time consuming and costly methods. This can be possible by utilizing modern techniques such as remote sensing.

1.6. Aims and Objectives of the Study

The main aim of this study was to map the long-term changes in mangrove cover at species level and prediction of future spatial distribution under different climate change scenarios in the Bangladesh Sundarbans to provide information base and predictive route, especially under climate change scenarios and different anthropogenic influences, for sustainable management planning and maintaining the sustainability of the Sundarbans mangrove forest. With the research gaps identified in Section 1.5, the present study aims at achieving the following objectives which can be a stepping stone in the context of effective and efficient management and prediction of future spatial distribution of the mangrove species of the Bangladesh Sundarbans. Our research objectives in this thesis are as follows:

1) To evaluate the efficacy of mid-resolution Landsat satellite image combined with traditional classification algorithms to produce an acceptable accuracy at species level mapping of mangroves.

2) To map the long-term changes in mangrove species composition and distribution in the Sundarbans.

3) To investigate the relationship between climatic variables and mangrove dynamics at species level in the Sundarbans, Bangladesh, over a 38-year period from 1977 to 2015.

4) To map and assess the tidal channel dynamics of the Bangladesh Sundarbans mangrove forest and suggest the factors behind the observed changes in the tidal channel morphology, and implications for the sustainability of the Sundarbans mangrove forest.

5) To model the impact of sea level rise on the future spatial distribution of mangrove species in the Sundarbans, Bangladesh.

1.7. Organization of the thesis

The thesis is structured in a manuscript style (as a series of journal papers) in which each chapter is treated individually. It is divided into eight chapters including this one. The remaining chapters of the thesis are organized as follows:

Chapter Two presents the evaluation of the of mid-resolution Landsat satellite image combined with traditional classification algorithms to produce an acceptable accuracy at species level mapping of mangroves. The high cost of fine resolution satellite data limits its widespread use, particularly, in developing countries. This chapter seeks to demonstrate that mid-resolution Landsat data can be of greater use in identification and mapping of mangrove species and provides a basis of such satellite data for regular monitoring purposes. This is of huge significance for the relevant stakeholders in developing countries in making better informed policy decisions, especially for the management of resources such as the Sundarbans mangrove forests in Bangladesh in a cost effective way.

Chapter Three investigates the dynamic nature of mangrove species and their spatial distribution in the Sundarbans, Bangladesh. Long-term changes in mangrove species composition and distribution in the Sundarbans are shown in this chapter. In addition, this chapter describes some of the driving forces that influence the mangrove cover dynamics at the species level. It investigates the dynamics of mangrove species of the Sundarbans at four time intervals (1977-1989, 1989-2000, 2000-2015 and 1977-2015) between 1977 and 2015. The main goal is to successfully map mangrove cover at species level and detect the species level dynamics in order to provide an information base and predictive route, especially under climate change scenarios and different anthropogenic influences, for sustainable management planning and maintaining the sustainability of the Sundarbans mangrove forest. The outcomes of this chapter are relevant for forest management planners, stakeholders and policy makers.

Chapter Four investigates the relationship between climatic variables and mangrove dynamics at species level in the Sundarbans, Bangladesh. The results of mangrove species composition change obtained from chapter three are used to investigate the relationship between climatic variables and mangrove dynamics at species level in the Sundarbans in this chapter. The aim is to identify the importance of temperature and rainfall and provide one dimension for assessing the impacts of climatic variables on mangrove species in the context of the vulnerability as a result of climate change. The results of this chapter can provide a better understanding of mangroves' response to climate variability in the Sundarbans and some invaluable insights for the development of proper adaptation strategies in the future.

Chapter Five maps the tidal channel dynamics of the Bangladesh Sundarbans mangrove forest, between 1974 and 2017, and discusses the implications for the sustainability of the Sundarbans mangrove forest. This investigation is about mapping and assessing tidal channel erosion and accretion in the hinterland areas of the Bangladesh Sundarbans mangrove forest. Also, factors associated with changes in the tidal channel morphology of the Sundarbans forest system are discussed. The information in this chapter not only provides scientific understanding of mangrove physical geomorphology environment but also adds to a limited tidal channel erosion and accretion process knowledge base with respect to mangrove forest ecosystems. This information can be integrated with other datasets such as those on mangrove species composition, sea level rise, and snow melt in the Himalayas, sedimentation rate, rainfall data, hydrological data, and anthropogenic activities for forest management planning in a sustainable manner.

Chapter Six addresses the responsible forces for tidal channel dynamics and their implications for the sustainability of the Sundarbans mangrove forest. This chapter synthesises the forcing mechanisms of river and tidal river dynamics in the context of natural and anthropogenic forces and their implications on the Sundarbans delta floodplain mangrove forest. This information is crucial for scientific understanding of the tidal channels geo-morphodynamic driving forces and their impacts from the point of climate change.

Chapter Seven predicts the future spatial distribution of mangrove species in the Sundarbans, Bangladesh in response to SLR. This chapter identifies vulnerable mangrove species as well as examines the severity of future risk of sink caused by SLR in order to develop the database for relevant stakeholders to develop a plan for the sustainable management of the forest. This chapter provides a glimpse of the SLR impacts on the future composition and spatial distribution of mangrove species as well as generates a geospatial model for research on potential SLR impacts on coastal communities. The outcome of this chapter is new knowledge and a crucial perspective on the impact of SLR on the future mangrove species composition and their spatial distribution in the largest contiguous mangrove forest of the world and in particular the Bangladesh Sundarbans.

Chapter Eight is a synthesis of the work undertaken as part of this thesis and it also lists the limitations of the work. This chapter also discusses how the results of this research can help planners and developers to develop a sustainable plan for the sustainability of the forest.

Chapter 2.

Does mid-resolution Landsat data provide sufficient accuracy for image classification and mapping at species level? A case of the Bangladesh Sundarbans, Bay of Bengal

This chapter is under review with the journal *Remote Sensing Applications: Society and Environment*:

Ghosh, M. K., Kumar, L. Does mid-resolution Landsat data provide sufficient accuracy for image classification and mapping at species level? A case of the Bangladesh Sundarbans, Bay of Bengal.

2.1. Introduction

Mangrove forests are one of the most dominant and productive ecosystems of the coastal environment (Kirui et al. 2013) and considered as an important resource for their ability to store and sequester carbon (Donato et al. 2011; Kirui et al. 2013; Suratman 2008). The Sundarbans mangrove forests occupies the landscape of both Bangladesh and India, occupying an area of almost one million hectares, and is the largest contiguous mangrove forest in the world (Ghosh et al. 2015a; Rahman and Asaduzzaman 2013; Spalding 2010). In 1992, the Sundarbans was designated as a Ramsar site under the Ramsar Convention while UNESCO declared it as a World Heritage Site in 1997 (Siddiqi 2001), citing its rich biological diversities and conservation values.

Mangrove forests play a crucial role in the maintenance of local coastal ecosystem and balancing the global environment (Biswas et al. 2007) by providing a range of renewable resources such as sources of food and medicine. The landscape is home to a diverse range of biota (Giri et al. 2007) and is a reliable source of forest and non-wood forest products (NWFPs) for the local people in the vicinity (Rahman 2000). For instance, the endangered Royal Bengal Tiger (*Panthera tigris*) along with other fauna such as *Batagur baska*, *Pelochelys bibroni*, *Chelonia mydas* are found in the Sundarbans. The landscape is ecologically endangered, highly populated, fragile but economically valuable (Danda 2007). Approximately 3 million people living in the villages surrounding the Sundarbans depend on mangrove forest resources for sustaining their livelihood and economic activities (Giri et al. 2007). Increasing use of such forest resources in the Sundarbans, however, could have detrimental effects on mangrove biodiversity where climate change is further exacerbating the extent of such impacts (Danda 2007). Cost and time effective mapping with acceptable accuracy levels is vital to monitor the state of such valuable resources in the Sundarbans.

Remote sensing techniques have the potential for identifying and mapping mangrove species composition effectively and at low cost. The data from different satellite sensors that have been used in the identification of mangrove forests include imagery from Landsat Thematic Mapper (TM) / Enhanced Thematic Mapper (ETM) (Giri et al. 2014; Long and Skewes 1996), SPOT (Franklin 1993; Pasqualini et al. 1999), China Brazil Earth Resource Satellite (CBERS) (Li et al. 2003), Spaceborne Imaging Radar (SIR) (Pasqualini et al. 1999), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Vaiphasa et al. 2006), IKONOS and Quick Bird (Wang et al. 2004b), and Compact Airborne Spectrographic Imager (CASI) (Green et al. 1998).

Among them, IKONOS, Quick Bird, and CASI are the high resolution sensors while Landsat, SPOT, ASTER, CBERS are the mid and low resolution sensors. According to Wang et al. (2004a) the application of Landsat and SPOT data in mapping mangrove species have produced mixed results. They also argued that spectral resolution is less effective in discriminating different mangrove species than spatial resolution. It has also been reported that airborne sensors like CASI are more successful in accurate discrimination among mangrove species than conventional satellite data (Green et al. 1998). However, acquiring most of the mid and high resolution satellite image apart from Landsat data, will results in substantial costs and is difficult for researchers and managers in developing countries, especially where large areas need to be mapped.

From the assessed literature, it appears that using public domain medium-resolution image data, such as Landsat TM, ASTER, SPOT etc., the identification of different mangrove species still remains a challenging task. In many less developed countries, the high cost of purchasing fine resolution satellite imagery prohibits its extensive use (Kirui et al. 2013). Use of freely available open source satellite image such as Landsat is the option for those who don't have financial access to fine resolution image data. However, the accuracy is always a concern in feature identification and subsequent thematic mapping in remote sensing. Therefore, taking Sundarbans as a case study, this work aims to (i) evaluate if mid-resolution Landsat satellite image combined with traditional classification algorithms produce an acceptable accuracy at species level, and (ii) identify and map major mangrove cover at species level. We anticipate that demonstration of the use of Landsat satellite data to successfully map mangrove cover at species level with an acceptable accuracy will motivate other researchers and relevant stakeholders to develop a reliable time series database that can be used in the continuous forest monitoring activities.

2.2. Method

2.2.1. Study area

The present work was conducted in the Bangladesh territory Sundarbans mangrove forest. This mangrove forest is located on the Ganges Delta that is created by the three mighty rivers Ganges, Brahmaputra and Meghna in the Bay of Bengal (Ghosh et al. 2017b; Giri et al. 2007). It extends approximately between 21°32′ to 22°30′N latitude and 89°00′ to 89°51′E longitude (Figure 2.1) and covers an area of around 6017 km^2 (Sarker et al. 2016) which is approximately three-fifths of the entire Sundarbans that is located in the Bay of Bengal. This forest comprises a number of mudflats and islands created as a result of the sedimentation process from the Ganges and its tributaries. This study site is characterized by a tropical climate with a dry season (November to April) and monsoonal period (May to October) (Ghosh et al. 2015a). The annual average precipitation is 192 cm, of which 75% occurs between June and September; the annual maximum temperature is 35 °C and average humidity is 82% (Islam et al. 2014). The elevation within the Sundarbans varies from 0.9 m to 2.11m above mean sea level (Rahman 2000). The amplitude of the tide within the estuaries is between 3.5 m and 4 m, but varies seasonally between 1m and 6 m (Ghosh et al. 2015a).

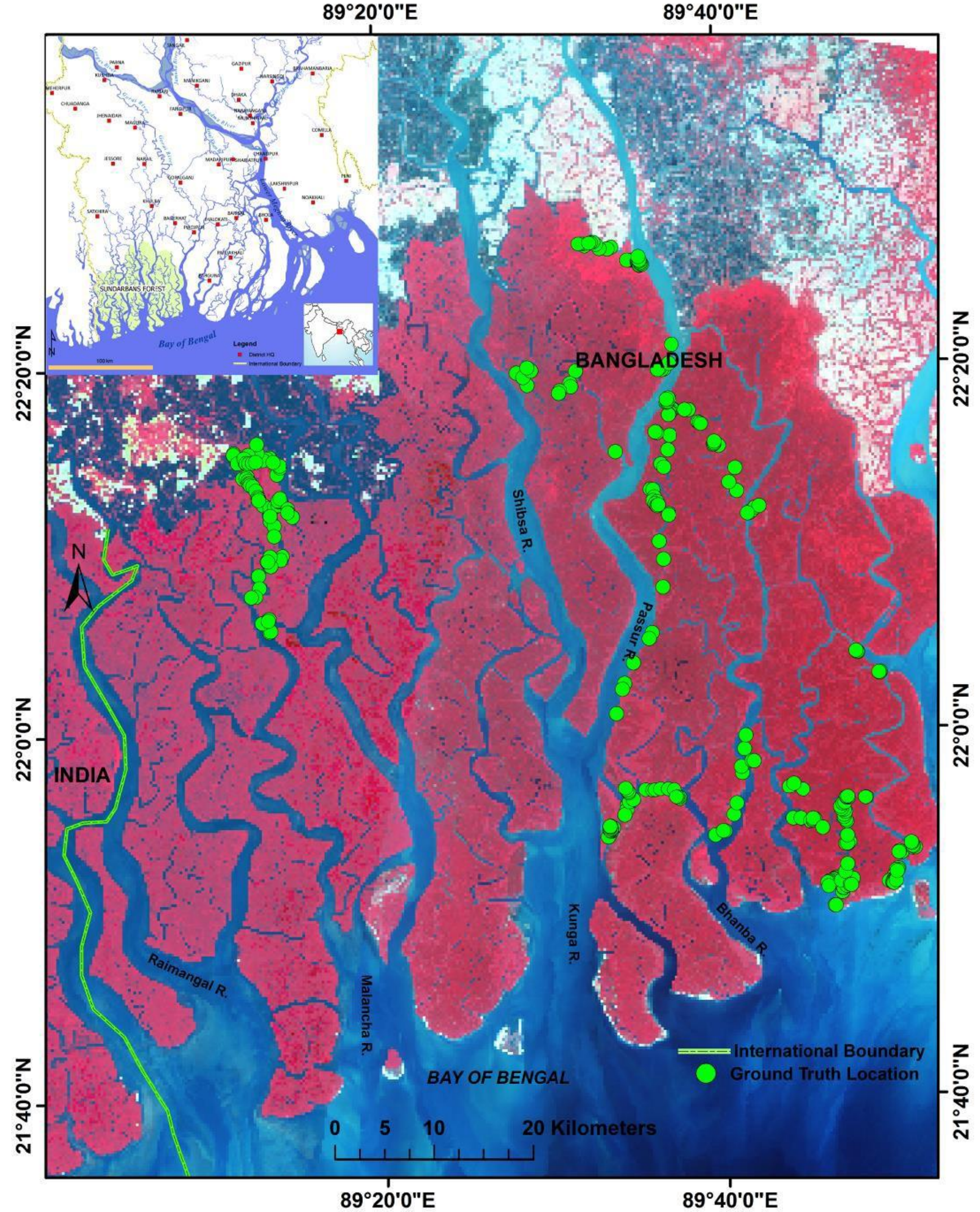

Figure 2.1 Study area in false color composite image showing ground truth points in different localities of the Sundarbans

2.2.2. Image used

Landsat image of the entire Sundarbans was acquired from the US Geological Survey, Center for Earth Resources Observation and Science (EROS) website (www.glovis. usgs.gov). In this study, Landsat Operational Land Imager (OLI) was applied to map mangrove cover at species level in the Sundarbans. The OLI image has eleven spectral bands that cover the visible, near infrared, short-wave infrared and thermal infrared regions of the electromagnetic spectrum (Table 2.1).

Table 2.1 Information of Landsat data used in this study

Sensor	Path/Row	Resolution	Acquisition Date	Band	Wavelength (in μm)
OLI	137-138/45	30 M	4th February 2015	Coastal/Aerosol	0.435-0.451
				Blue	0.452-0.512
				Green	0.533-0.590
				Red	0.636-0.673
				Near infrared (NIR)	0.851-0.879
				Short-wave infrared-1(SWIR-1)	1.566-1.651
				Thermal infrared-1, (TIR-1)	10.60-11.19
				Thermal infrared-2, (TIR-2)	11.50-12.51
				Short-wave infrared- 2, (SWIR-2)	2.107-2.294
				Cirrus	1.363-1.384

2.2.3. Image pre-processing

First, radiometric corrections were carried out using sun azimuth and sun elevation data extracted from the image's header file to remove the influence of the atmosphere, and then image registration was carried out using 51 ground control points (GCPs) with a root mean square error (RMSE) of 0.004 pixels. GCPs used for the registration were collected from prominent geographic features and river channel junctions. The image frames were then mosaicked to get the study site as it is covered by two image frames. Afterwards, the mangrove areas were extracted from the images using on-screen digitization process as they had a clear boundary created by river channels. Thereafter water areas were masked from the images so the results would not be affected by water turbidity in the classified image.

2.2.4. Image Analysis

In the field of remote sensing, the maximum likelihood classification (MLC) algorithm is one of the most well-known parametric classifiers used for supervised classification (Bischof et al. 1992; Gao 1999; Green et al. 1998). The algorithm is used for computing the weighted distance or likelihood of unknown measurement vectors belonging to one of the known classes which is based on the Bayesian equation (Giri et al. 2014). The unknown measurement vector is assigned to the class based on the highest probability of fit. In MLC algorithm, spectral information in each class meets the normal distribution criteria (Bischof et al. 1992) and also is a very effective method in classifying mangroves with traditional remote sensing data. Although, MLC has some limitations in vegetation mapping, more specifically where in-depth species differentiation and parameterization is required (the limitations such as the spectral distributions of the categories if are very far from normal can provide inaccurate results), in this study MLC was used to classify and extract the mangrove species composition of the Sundarbans due to its well-developed theoretical base, simplicity and ease of use (Chen et al. 2013).

One of the authors (M.K Ghosh) has made several visits in the Sundarbans in last several years and mapped different mangrove species with GPS. Based on this extensive field experience and the information obtained from previously published literature (Chaffey et al. 1985; Emch and Peterson 2006; Giri et al. 2007; Treygo and Dean 1989) and species level map of the Sundarbans, five major mangrove species out of 19 known species (Sarker et al. 2016) were chosen for the classification viz. *Heritiera fomes*, *Excoecaria agallocha*, *Ceriops decandra*, *Sonneratia apelatala*, and *Xylocarpus mekongensis.* The majority of the remaining species are distributed in lower density, spreading over wide areas in small patches, and do not form large enough mono-specific patches for training site selection and therefore cannot be detected through medium-resolution satellite data. Hence, we purposively mapped five major mangrove species of the Sundarbans that constitute higher density cover and other remaining species were classified under the major five mangrove species on the basis of dominance. Training sites were selected for those five species visually on the satellite image prior to the field work. Afterwards, a detailed fieldwork for training and validation sampling of each representative mangrove species was completed during February and March 2016. Based on representation and distribution, training samples of between 53 and 144 for each mangrove species were selected randomly and stratified by land cover class. Care was taken to ensure the inclusion of all the targeted species in sample selection, with samples well distributed and fulfilling the minimum number required to validate the accuracy evaluation process (Congalton and Green 2008; Sinha et al. 2014). The training and validation sample sets for different mangrove species were collected from the field using handheld GPS. Therefore, collected GPS locations of various mangrove species were overlaid on the 2015 satellite image to extract the spectral signatures for each of the species. The absorption and peak point of reflectance characteristics were identified from the spectral profile which defined the identification characteristics of the species. Finally, those characteristics were applied for image classification. Spectral profiles of those identified mangrove species are shown in Figure 2.2. The spectral reflectance of all mangrove species showed very similar reflectance patterns in the lower wavelengths of the spectrum. In contrast, in the higher wavelengths, reflectance patterns were different from each other. Figure 2.3 shows the workflow of different stages for image processing and classification. The whole image processing was carried out using ENVI 5.1 software (Exelis Visual Information Solutions, Inc., Boulder, UT, USA).

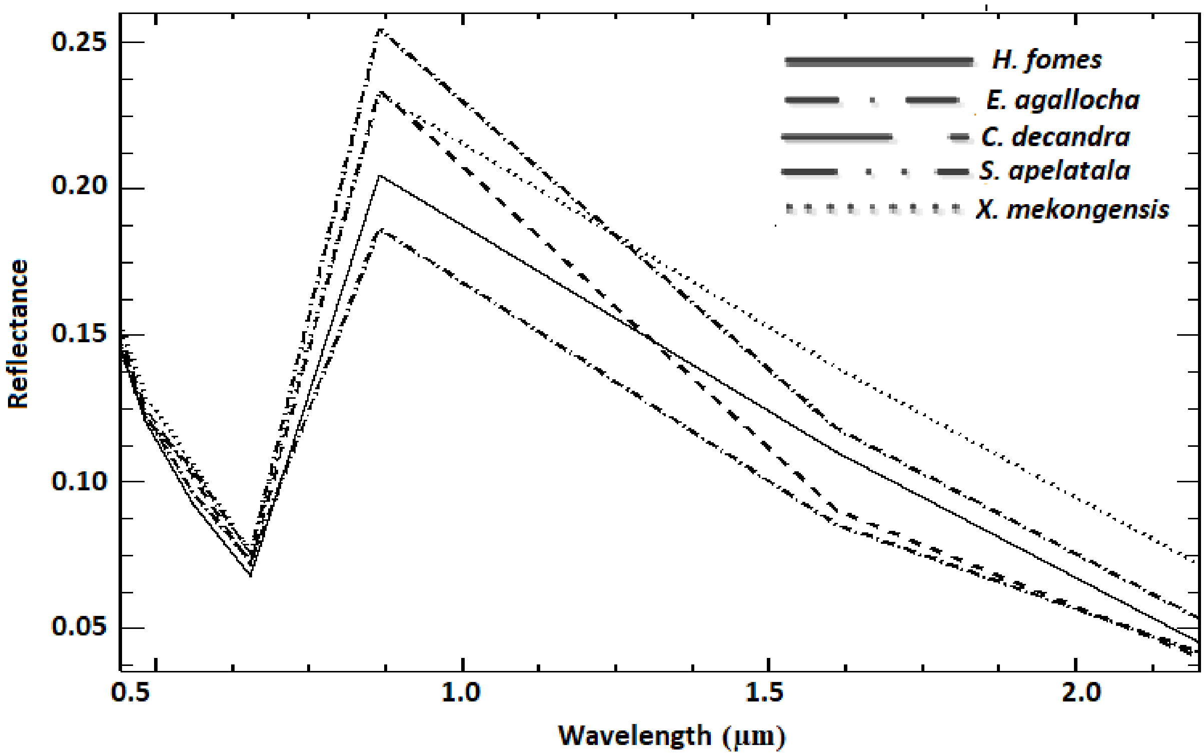

Figure 2.2 Spectral profiles of the five mangrove species

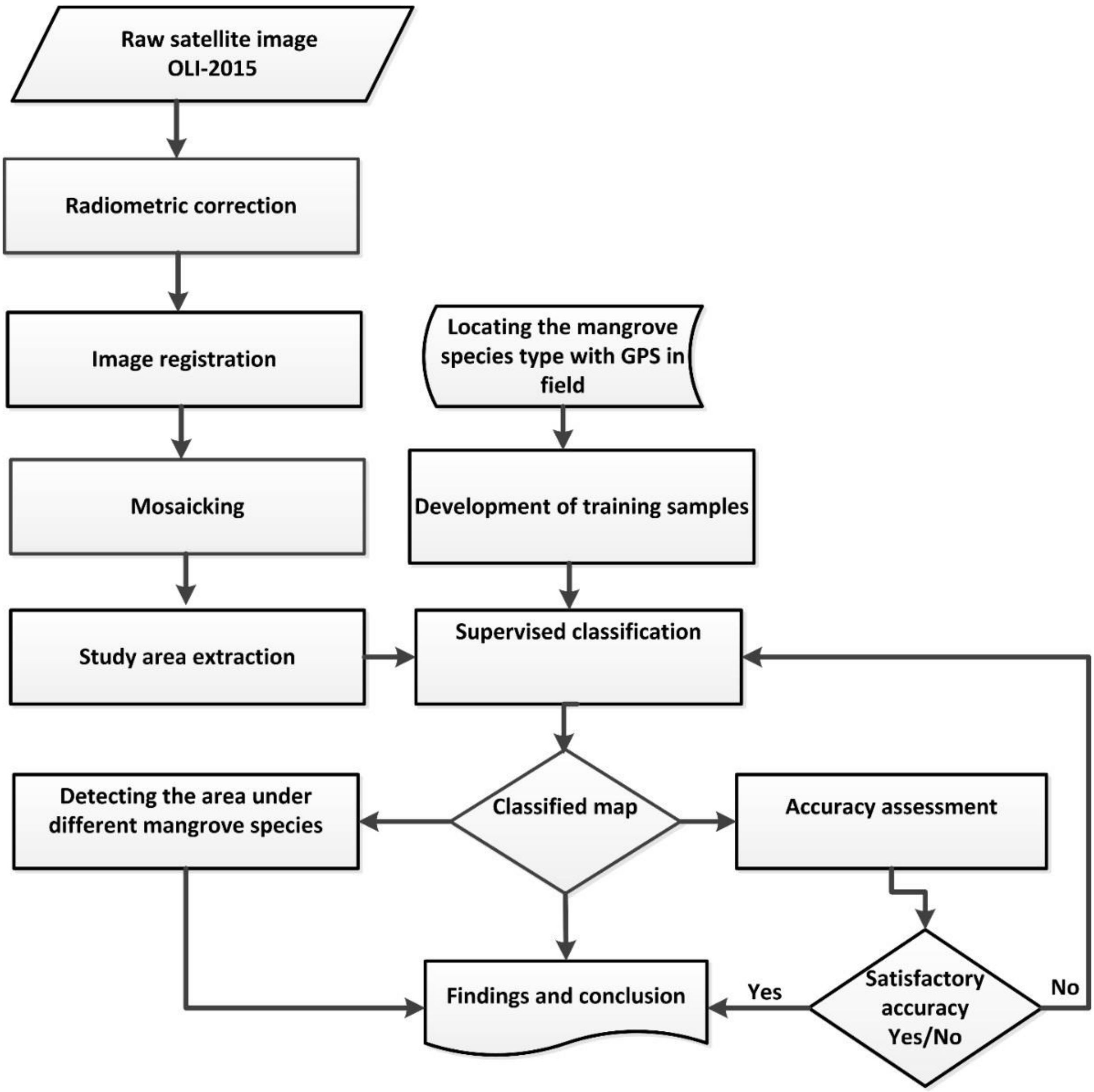

Figure 2.3 Work flowchart showing the methodology of the overall research.

2.2.5. Accuracy assessment

Validation or accuracy assessment of the classification is an important step in any image classification process (Sinha et al. 2014). To evaluate the efficacy of the classification, confusion matrix was developed through available ground truth data. Confusion matrix provides information on the number of pixels that are classified according to the reference dataset and the number of pixels that are classified otherwise (Bhowmik and Cabral 2013). Three different primary accuracies i.e. overall accuracy, producer's accuracy, and user's accuracy, and the kappa coefficient were calculated to quantify the assessment of satellite image analysis.

2.3. Results

This study has identified and mapped five mangrove species composition viz. *H. fomes, E. agallocha*, *C. decandra*, *S. apelatala*, and *X. mekongensis* and their distribution at species level in the Sundarbans based on Landsat satellite image classification (Figure 2.4). Error matrix of the image classification is shown in Table 2.2. The results indicate that the Landsat classification for mangrove species composition for the year 2015 had an overall accuracy of 89.10% and a kappa coefficient of 0.87. The results also revealed that the lowest producer's and user's accuracy were obtained for *X. mekongensis* (73%) and *E. agallocha* (84%) respectively. In contrast, *H. fomes* and *C. decandra* produced very high producer's accuracy whereas *X. mekongensis* produced the highest user accuracy. The producer's accuracy for *H. fomes* and *C. decandra* were 94% and 95% respectively while user's accuracy was 94% for *X. mekongensis* (Table 2.2).

Table 2.2 Confusion matrix for 2015 Landsat OLI image, Sundarbans

Class	H. fomes	E. agallocha	C. decandra	S. apelatala	X. mekongensis	Total	User's accuracy (%)
H. fomes	359	18	2	8	13	400	90
E. agallocha	21	546	17	7	59	650	84
C. decandra	0	12	476	5	39	532	89
S. apelatala	0	4	2	220	12	238	92
X. mekongensis	0	16	2	0	336	354	94
Total	380	596	499	240	459	2174	
Producer's accuracy (%)	94	92	95	92	73		

Overall accuracy: 89.10% and kappa coefficient: 0.87

Supply of freshwater, salinity level in water, erosion and sedimentation process and variation in drainage are the forces that substantially influence spatial distribution of mangrove species in the Sundarbans (Rahman 2000). Spatial composition and distribution of the five studied mangrove species are presented in Figure 2.4. *H. fomes* is distributed mostly in the central and eastern region of the Sundarbans, especially in the areas which are frequently flooded and less affected by water salinity. *E. agallocha* is the dominant woody species and is sparsely distributed all over the Sundarbans with dense patches in the north west and south central and east regions, where there are highest seasonal variation of salinity levels with relatively longer duration of moderate salinity. They are often mixed with *H. fomes* in the eastern and *C. decandra* in the western parts of the Sundarbans. Dense stands of *C. decandra* are located in the western region of the Sundarbans that is characterized by higher salinity and shares its habitat with *E. agallocha* and *H. fomes*. *S. apelatala* is an indicator species for newly accreted mud banks and is an important species for wildlife (Ghosh et al. 2016). Our analysis showed that *S. apelatala* is scantily distributed, mainly in the south eastern part of the eastern region, northern and southern parts of the central region and north-western parts of the western region of the forest. Similarly, *X. mekongensis* is distributed mostly in the western region of the study area and some parts of the central region. Overall, *H. fomes*, *E. agallocha*, *C. decandra*, *S. apelatala* and *X. mekongensis* occupy 196,090 ha (49.5%), 119,304 ha (30.1%), 70,610 ha (17.8%), 8,621 ha (2.2%) and 1,438 ha (0.4%) of the Sundarbans respectively. Our results demonstrate that among the five species, *H. fomes* is the most dominant species followed by *E. agallocha, C. decandra*, *S. apelatala,* and *X. mekongensis* respectively.

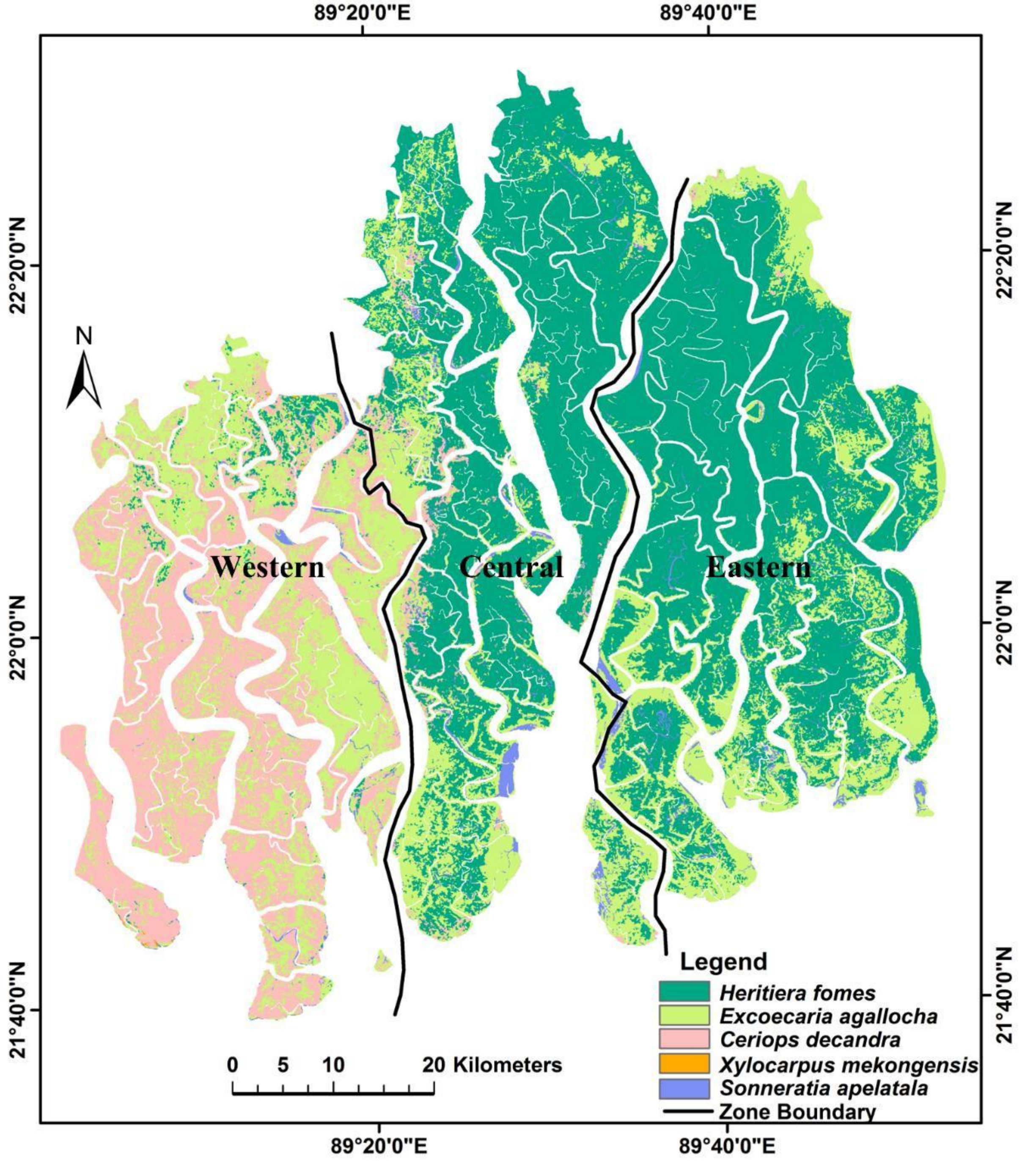

Figure 2.4 Classified image showing major mangrove species composition in the Bangladesh Sundarbans for the year 2015

2.4. Discussion and conclusion

Wetlands, including mangrove forest ecosystems, are some of the most important as well as vulnerable ecosystems in the world (Guo et al. 2017). Mangrove species are also projected to shift its niche. For instance, Record et al. (2013) modelled some major mangrove species at the global scale and found that mangrove species will shift their range by at least two degrees of latitude, with Central America and the Caribbean regions to be the highest sufferers. Mukhopadhyay et al. (2015) projected a loss of 17% mangrove cover of Bangladesh by 2105 that could result significant decline in freshwater loving species and ecosystem services they provide. This necessitates the protection and conservation of this precious ecosystem but with judicial management without hampering the livelihood rights of the low income communities that specifically depend on this mangrove forest ecosystem services. For instance, Abdullah et al. (2016) observed a heavy dependence of local people on the forest resources of the Sundarbans in Bangladesh, where forest income represent almost 74%, 48% and 23% of the household income for lower, middle and higher income households.

The quality of thematic maps produced from image classification techniques is evaluated mostly based on the criteria called accuracy assessment, which is historically set at ≥85% (Foody 2008). Liu et al. (2007) found user's accuracy, producer's accuracy and overall accuracy as consistent among fourteen different measures commonly used and suggested them to be used in accuracy assessment of classified imagery in remote sensing work. Many studies are available that achieved satisfactory accuracy level in the mangrove forest discrimination using fine resolution satellite images. Heenkenda et al. (2014) reported an accuracy level of 89% in discriminating five mangrove species at species level using high resolution (0.5m) World View 2 image in Northern Australia while Heumann (2011) obtained 94% of accuracy using the same sensor with the application of object based image analysis (OBIA) and support vector machine (SVM) in discriminating mangrove species at Isabela Island in the Galapagos Archipelago, Ecuador. Roslani et al. (2014) found an overall accuracy of 87.5% and kappa statistic of 0.85 for delineating mangrove species in Matang Mangrove forest, Malaysia using RapidEye image of 5m resolution integrated with NDVI. Koedsin and Vaiphasa (2013) found an overall accuracy of 86% (all spectral band combination), 87% (SFS feature selector), and 92% (genetic search algorithm) for five mangrove species at species level in Thailand using EO-1 Hyperion image having 220 spectral bands and 30m spatial resolution. Gao (1999) reported an overall accuracy of 81.4% for mapping mangrove species using SPOT multispectral data with three bands in Waitemata Harbor of New Zealand. Vo et al. (2013) obtained an overall accuracy of 75% for mapping mangrove stands using SPOT satellite image with object based approach at the Mekong Delta in Vietnam. Wang et al. (2004b) found an accuracy of 73% and 74% for IKONOS and QuickBird images respectively, both are very high resolution images, for mapping the mangroves of the Caribbean Coast of Panama using object based classification. Neukermans et al. (2008) used high resolution QuickBird imagery employing fuzzy per pixel classification technique to map and recognize mangrove stands at Gazi Bay of Sothern Kenya and obtained an overall accuracy of only 72%.

Our analysis with 30m resolution Landsat OLI data produced an overall accuracy of 89.10% with Kappa coefficient of 0.87 (Table 2.2), where the accuracy was well over the recommended value >85% as suggested by Foody (2008), and also highly comparable with the recent work of Giri et al. (2014) who obtained overall accuracy and Kappa value for the year 1999 and 2010 at 80% and 0.77 and 85.71% and 0.81 respectively for discriminating mangrove species at Indian Sundarbans using Landsat with Hyperion technique. Our analysis with mid-resolution Landsat data also produced very high user and producer accuracy for all the five identified mangrove species, this indicates the efficacy and reliability of the classification. The user's accuracy is a measure of the reliability of the map. It informs how well the map represents the real picture on the ground. On the other hand, producer's accuracy measures how well a certain areas has been classified (Banko 1998). This present analysis yielded the user's accuracy well over 80% for all the five species and producer's accuracy of more than 90% for all the identified mangrove species except *X. mekongensis* which yielded 73% producer's accuracy. It therefore, indicates high confidence level in this mapping.

The resultant thematic map (Figure 2.4) prepared with this accuracy level clearly discriminates all the five mangrove species of the Bangladesh Sundarbans with enough accuracy to be used as a baseline data for the future resource planning. The analysis further depicts that almost half of the Sundarbans is currently occupied by *H. fomes*, especially in the central and eastern parts and is in line with the finding of Sarker et al. (2016). Similarly, *E. agallocha* and *C. decandra* occupies 30% and 18% of the total area. *E. agallocha* is sparsely distributed all over the Sundarbans while *C. decandra* are found densely in the western part and in a mixed stand with other species, aligning with the results of Sarker et al. (2016). *S. apelatala* and *X. mekongensis* constitute the least coverage in the Bangladesh Sundarbans and is supported by the findings of Sarker et al. (2016). In spite of using Landsat image data with conventional image processing techniques, we found overall acceptable level of accuracy that signifies the applicability of conventional techniques and mid-resolution image for the classification and identification of mangrove forest at species level. Thus, our work clearly shows that even with the mid-resolution image and traditional classification algorithm of conventional Landsat sensor, high accuracy output with finer details at species level can be achieved. Valderrama-Landeros et al. (2018) obtained an overall accuracy of 64 % using the same coarse spatial resolution sensor in the arid regions. Our findings compared to the findings of Valderrama-Landeros et al. (2018) suggest that mangroves in tropical regions are more capable of being discriminated at species level with mid-resolution spaceborne data, compared to arid regions where pore-water hyper-salinity causes an increase of stress conditions, and consequently mangrove stands form dense clusters which are not feasible to discriminate. The availability of images such as Landsat at low or even no direct cost to the end user could enable greater use of such satellite imagery for making better informed policy decisions (Hansen et al. 2013), especially for the management of resources such as the mangrove forests in Bangladesh and other developing countries. The high accuracy obtained here gives confidence in the use of such images in regions where high spatial resolution imagery is not available or cannot be afforded.

Mapping current mangrove species composition using Landsat data is not enough to understand the dynamic and temporal change over time in the Bangladesh Sundarbans. Therefore, detailed investigations are recommended to understand the temporal change of the mangrove species composition.

Journal-Article Format for PhD Theses at the University of New England

STATEMENT OF ORIGINALITY

We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

Type of work	Page number/s
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Figure 2.3	21
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Name/title of Principal Supervisor: Professor Lalit Kumar

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23-05-2018

Candidate Date

[redacted]

23-05-2018

Principal Supervisor Date

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

	Author's Name (please print clearly)	% of contribution
Candidate	Manoj Kumer Ghosh	80
Other Authors	Lalit Kumar	20

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[redacted] 23-05-2018

Candidate Date

[redacted] 23-05-2018

Principal Supervisor Date

Chapter 3.

Mapping Long-Term Changes in Mangrove Species Composition and Distribution in the Sundarbans

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Ghosh, M. K., Kumar, L., & Roy, C. (2016). Mapping Long-Term Changes in Mangrove Species Composition and Distribution in the Sundarbans. *Forests*, 7(12), 305. Doi: 10.3390/f120305.

3.1. Introduction

The appraised global coverage of mangrove forest is 137,760 km^2 (Giri et al. 2011; Marchio et al. 2016); this equates to 0.1% of the earth's surface (Cornforth et al. 2013). These mangroves are declining worldwide at an alarming rate (Alongi 2002; Giri and Muhlhausen 2008; Myint et al. 2008; Valiela et al. 2001). Globally, 36,000 km^2 of mangroves have been lost since 1980, primarily due to conversion to agriculture and aquaculture, urbanization, and timber extraction (Asbridge et al. 2016). The Sundarbans, the largest contiguous mangrove forest in the world (Ghosh et al. 2015a; Spalding 2010), is considered as a site of national and international importance for the conservation of biodiversity (Biswas et al. 2007; Hussain and Acharya 1994). The Sundarbans covers an area of approximately 10,000 km^2 and lies in the territory of Bangladesh and India (Ghosh et al. 2015a; Rahman and Asaduzzaman 2013). This forest has enormous ecological and economic importance at local, national and global scales (Biswas et al. 2007). The Sundarbans plays an important role in the local as well as global ecosystem by absorbing carbon dioxide and other pollutants from air and water (Bose 2009), offering protection to millions of people in the Ganges Delta against cyclone and water surges (Giri et al. 2007), stabilizing the shore line, trapping sediment and nutrients, purifying water, etc. (Rahman 2000). According to Donato et al. (2011) and Rodda et al. (2016), mangroves are the most carbon-rich forests in the tropics. Despite their small spatial extent, mangroves are considered as an important resource around the world due to their ability to store and sequester carbon, compared to many freshwater wetlands (Marchio et al. 2016). The Sundarbans absorbs 469.2 to 569.2 Mega grams of carbon per hectare (Donato et al. 2011; Islam 2016). The total economic value of mangroves has been estimated between USD 200,000 and 900,000 per ha/year (Wells and Ravilious 2006), which is estimated through the cost of the products and services they provide. The total economic value of mangroves in Malaysia, Mexico and Sri Lanka were USD 61,357, USD 2,772 and USD 12,229 per hectare per year, respectively (Cabrera et al. 1998; Iftekhar 2008; Leong 1999). In 1997, the mangroves of Sundarbans, Bangladesh, were valued at USD 631 per hectare per year considering only the ecological services (Costanza et al. 1997). A complex and varied vegetation structure enhances the growth of a diverse range of plants and animals in the complex ecosystem of the Sundarbans, and it makes this ecosystem a unique one in the world (Rahman 2000; Syed et al. 2001). This forest is an example of an endangered ecological system that is highly populated and both fragile and economically valuable (Danda 2007). More than 2.5 million people live in the villages surrounding the Sundarbans, and this biodiversity hotspot has great socioeconomic value for the livelihood of the local people (Giri et al. 2007). The forest provides livelihood for over 300,000 people working within a range of seasonal areas such as wood cutters, fishermen, honey collectors, etc. (Cornforth et al. 2013; Giri et al. 2007). Apparently, like other mangrove forests of the world, this forest is under pressure due to a number of factors; historical and current, natural and anthropogenic, including global climate change (Danda 2007; Iftekhar 2006), and these factors could have a severe impact on the biodiversity of the forest in terms of sustainability in the long run. This mangrove ecosystem is under threat mainly due to climate change and anthropogenic degradation (Iftekhar 2006). Anthropogenic and climate change-induced degradation, such as over-exploitation of timber and pollution, coastal erosion, increasing salinity, effects of increasing number of cyclones and higher levels of storm surges, remains a recurrent problem in the Sundarbans (Cornforth et al. 2013), and recent changes in the intensity and location of these degradations have not been regularly assessed due to a lack of a proper and effective monitoring system.

Mapping and monitoring of the Sundarbans mangrove forest has become an urgent need due to its enormous ecological and economic importance. In the Sundarbans, periodic forest inventories have taken place approximately every 15 to 20 years (Giri et al. 2007) for collecting detailed information on the forest resources, but the focus has remained on timber yield (Chaudhuri and Choudhury 1994). The last detailed inventory was undertaken 30 years ago by the Department for International Development of the United Kingdom (formerly, Overseas Development Administration) in Bangladesh (Chaffey et al. 1985; Giri et al. 2007) and, based on this inventory, a mangrove cover map at a species level was produced. The preparation of this map was very strenuous and time consuming as it took around 5 years (1981–1985) using aerial photographs and ground surveys (Iftekhar and Saenger 2008). Remote sensing, on the other hand, is comparatively very effective in terms of cost, time and accuracy (Myint et al. 2008; Wang et al. 2004b) and therefore is efficient in monitoring mangrove species dynamics because of its synoptic and repeated coverage and historical data (Giri et al. 2008). For mapping and change detection purposes, a number of studies conducted in the Sundarbans have applied remote sensing tools (for example Blasco et al. 2001; Dwivedi et al. 1999; Emch and Peterson 2006; Giri et al. 2007; Iftekhar and Islam 2004; Islam et al. 1997; Islam et al. 2014); however, most of the studies have kept their focus only on determining spatial change. Giri et al. (2014) identified mangrove composition and their changes at the species level in the Sundarbans, but this was only for the Indian Territory. Also, Spalding et al. (2010) prepared two consecutive atlases of world mangrove forest.

Therefore, plant species and their distribution and dynamics remain unrecorded for the entire Sundarbans mangrove forest comprising both countries. Moreover, due to the unavailability of a detailed species level map and a continuous monitoring system, sustainable management planners, other relevant stakeholders and researchers are not well informed about the changes that are taking place as a result of changing climate and anthropogenic degradation. Considering the importance of the Sundarbans, accurate and up-to-date information on the composition, distribution and the dynamics of the mangrove species is an essential requisite (Giri et al. 2007) to avoid over- exploitation of resources and to ensure their sustainable management. Therefore, detailed species- level mapping and regular monitoring of their dynamics in the Sundarbans mangrove forest is urgently needed for ensuring sustainability. Detailed information on the mangrove species and their composition and dynamics can lead to adoption of management practices designed for maximum sustainable yield. This could be a crucial factor in preserving what remains of the Sundarbans. Emphasis on preparing a database related to mangrove species composition and dynamics of the Sundarbans mangrove forest for managing the entire ecosystem may help to sustain this valuable resource well into the future.

In this paper, we examine the mangrove species composition in the Sundarbans for four different periods to understand the species composition dynamics of this forest over the last 38 years using freely available multi-temporal Landsat imagery and conventional classification (maximum likelihood classifier) and change detection techniques. More importantly, we investigate the dynamic nature of mangrove species in the Sundarbans. Moreover, this study describes some of the driving forces (e.g., coastal dynamics, anthropogenic, natural forces) that influence the mangrove cover dynamics at a species level in the Sundarbans. We measure the mangrove species dynamics of the Sundarbans at four intervals between 1977 and 2015 (1977–1989, 1989–2000, 2000–2015 and 1977–2015). It is anticipated that successful mangrove cover mapping at the species level with acceptable accuracy and detection of species level dynamics using Landsat satellite data will provide an information base and predictive route, especially under climate change scenarios and different anthropogenic influences, for sustainable management planning and maintaining the sustainability of the Sundarbans mangrove forest. This will also encourage other researchers and relevant stakeholders to develop a proper and continuous monitoring system for the entire Sundarbans mangrove forest in a simple, time saving, efficient and cost-effective way.

This will also open up the avenue of such applicability for other developing countries having similar issues.

3.2. Materials and Methods

3.2.1. Study Area

The present study was conducted in the Sundarbans mangrove forest, the largest single tract of mangrove ecosystem in the world (Choudhury et al. 2001; Iftekhar and Islam 2004; Siddiqi 2001). This forest is located on the Ganges Delta created by the confluence of three mighty river systems, Ganges, Brahmaputra and Meghna, at the northern limit of the Bay of Bengal (Bhowmik and Cabral 2013; Iftekhar 2006) and it extends between approximately 21°32′ to 22°40′ N latitude and 88°05′ to 89°51′ E longitude (Figure 3.1). The Sundarbans is crisscrossed by a complex network of river channels and comprises a number of mudflats and small islands. These small islands and mudflats are created as a result of the sedimentation process that is influenced by the river system intersecting this forest (Bhowmik and Cabral 2013; Ghosh et al. 2015a). This forest region is characterized by a tropical climate with four main seasons that include pre-monsoon (March to May), monsoon (June to September), post-monsoon (October–November) and dry winter (December to February). Rainfall and temperature fluctuates between 1600 mm and 2000 mm and 11 °C and 37 °C, respectively in this region, while elevation varies between 0.9 and 2.11 m above sea level (Ghosh et al. 2015a; Iftekhar and Islam 2004). The Sundarbans is considered as a safe habitat for a wide range of plants and animals, including 27 mangrove species, 40 mammal species, 35 reptile species, and 260 species of birds (Giri et al. 2007). Floristically, mangrove species of the Sundarbans belong to the Indo-Andaman mangrove province within the species-rich Indo-West Pacific group (Duke 1993; Ghosh et al. 2015a).

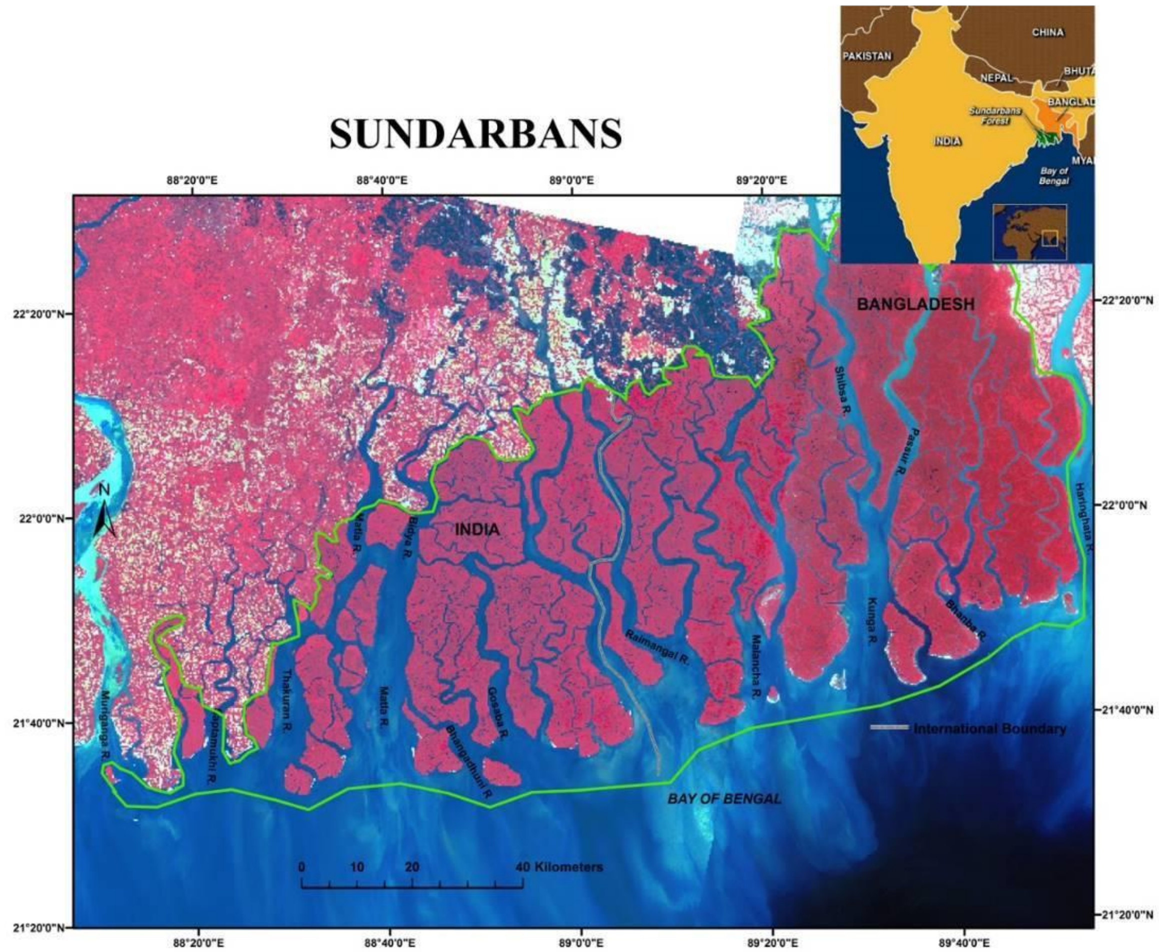

Figure 3.1 Location of the study area (False color composite image).

3.2.2. Images Used

In this study, satellite images of four time periods were used to quantify the dynamics of mangrove species composition of the Sundarbans: (a) the Landsat Multispectral Scanner (MSS) (57 m spatial resolution) acquired in February 1977; (b) the Landsat Thematic Mapper (TM) (28.5 spatial resolution) acquired in February 1989; (c) the Landsat Enhanced Thematic Mapper Plus (ETM+) (28.5 m spatial resolution) acquired in February 2000; and (d) the Landsat Operational Land Imager (OLI) (30 m spatial resolution) acquired in February 2015 (Table 3.1). The Landsat MSS has four spectral bands while TM and ETM+ have seven and OLI has eleven spectral bands. All the Landsat images covering the entire Sundarbans were acquired from the US Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) website (www.glovis.usgs.gov).

Table 3.1 Information of Landsat data used to map mangrove cover at the species level in the Sundarbans.

Sensor	Resolution (in Meter)	Path/Row	Date
MSS	57	147-148/45	1 February 1977
TM	28.5	137-138/45	5 February 1989
ETM+	28.5	137-138/45	28 February 2000
OLI	30	137-138/45	4 February 2015

3.2.3. Image Pre-processing

For all images (MSS, TM, ETM+ and OLI), radiometric correction was carried out to remove the influence of the atmosphere. Atmospheric interference caused by haze, dust, smoke, etc. was corrected using the dark-object subtraction method (Chavez 1996). Radiometric correction was performed using sun elevation and sun azimuth data extracted from the images' header file (Rahdary et al. 2008). To make the images comparable, all were converted from digital number values to top-of-atmosphere reflectance as per the suggestion of Chander and Markham (2003), and a relative radiometric normalization was performed by normalizing the variation in solar illumination and atmospheric conditions (Coppin et al. 2004; Ghosh et al. 2015b; Mas 1999). Registration of all the images was done using 51 ground control points (GCPs) with a root mean square error (RMSE) of 0.003957 pixels, and then the images were resampled to a 30 m pixel size using the nearest neighbor resampling method. The Sundarbans is covered by two frames (Path 137 Row 45 and Path 138 Row 45 for TM, ETM+ and OLI, and Path 147 Row 45 and Path 148 Row 45 for MSS) of Landsat satellite images. To consider the entire Sundarbans as a study site, all of the individual images were mosaicked. Using an on-screen digitization process, only the mangrove areas were extracted for further study and afterwards, waterbodies were masked out from the images so that the result would not be impacted by the effect of tide and different turbidity water that formed multiple classes in the classified image. The entire image-processing task was carried out using ENVI 5.1 software (Exelis Visual Information Solutions, Inc. , Boulder, United States of America).

3.2.4. Image Classification

In this study, the supervised maximum likelihood classification algorithm (MLC) was used to classify and extract the mangrove species composition of the Sundarbans due to its well-developed theoretical base, simplicity and ease of use (Chen et al. 2013). The MLC algorithm is one of the most well-known parametric classifiers used for supervised classification. This MLC algorithm computes the weighted distance or likelihood of an unknown measurement vector that belongs to one of the known classes, based on the Bayesian equation. The unknown measurement vector is assigned to the class based on the highest probability of fit. Consideration of a variance-covariance matrix within the class distributions is considered one of the advantages of this algorithm. This technique is extensively used in remote sensing where a pixel with the maximum likelihood is classified in the corresponding class (Giri et al. 2014). For training and validation sampling, fieldwork and published maps were used. Fieldwork for training and validation sampling for the 2015 imagery was completed in February–March 2016, and Landsat image data, a printed image of Google Earth and a reference map of the Sundarbans (published by Bangladesh Forest Department) were used as guides. Fieldwork was conducted only in the Bangladesh territory of the Sundarbans mangrove forest. A species-level map of the Sundarbans mangrove forest that was mapped only for the Bangladesh territory by the Bangladesh Forest Department in 1985 was used as reference data for training and validation sampling for the 1989 image. Due to the unavailability of corresponding reference data for the 1977 and 2000 images, training and validation samples that were developed for the 1989 image classification and accuracy evaluation were also used for the classification and accuracy evaluation for the 1977 and 2000 images. To use these samples, a process called signature extension as suggested by Foody (2004) and Foody (2008) was undertaken as this allows us to use samples for unchanged areas for such purposes. In several studies in the recent past, this method has been used successfully (Alqurashi et al. 2016; Sinha and Kumar 2013; Sinha et al. 2016). To do this, additional processing was undertaken to include sample points that had not changed during the periods 1989–1977 and 1989–2000. An image differencing technique was used to generate difference images for the above images with respect to the 1989 image (e.g., 1989–2000 and 1989–1977). At first, the NDVI of each study year was computed, and by subtracting each year's NDVI from the 1989 NDVI, a difference image was generated. Due to the capabilities of reflecting both vegetation and non-vegetation areas, an NDVI image was used for this purpose. Afterwards, to separate the change/no-change areas, thresholds of ±1 standard deviation (SD) (Mas 1999; Sinha and Kumar 2013) were used. Pixels that were not changed during the above-mentioned periods usually clustered about the mean of the difference histogram distribution, whereas changed pixels were found within the tails. In comparison to the change images, all the training and validation samples developed for the 1989 image were assessed, and samples that fell in areas greater than ±1 SD from the mean were discarded. The remaining samples were assumed to have not changed over the years and were used as validation data for classification and accuracy evaluation, as supported by Sinha et al. (2014). All of the images were limited to only mangrove areas, thus training and validation samples were only developed for different mangrove species. Considering the true representation of class, accessibility and size of class, training samples between 51 and 141 for each species were randomly selected, stratified by land cover class. The numbers of training samples varied for different mangrove species based on class abundance and distribution in the study area. In addition, care was taken so that the samples were well distributed in the study area and also fulfilled the minimum number required for valid accuracy evaluation process (Congalton and Green 2008). Altogether 414, 429, 549 and 471 training samples were assessed throughout the study area to represent identified mangrove species and their natural variance for the 2015, 2000, 1989 and 1977 images, respectively.

On the basis of spectral signature-based satellite image classification, identification and distribution of mangrove species were analyzed in this study. A handheld GPS was used to collect the training sets for different mangrove species from the field, and collected GPS locations of various mangrove species were overlaid on satellite images from 2015 to extract the spectral signature. To classify the imagery of 1977, 1989 and 2000, training sites were developed from the reference map, and spectral signatures were generated for different mangrove species. Afterwards, extracted spectral signatures were used for image classification and identification of mangrove species. In addition to supplementary information obtained from various sources, the author's prior knowledge was also used to document characteristics of different mangrove species, as supported by Kumar and Ghosh (2012). There are 27 mangrove species in the Sundarbans (Giri et al. 2007), but many of these are present in small quantities, spread over wide areas in small patches and thus unable to be detected using medium-resolution satellite data. Hence, we mapped the five major mangrove species of the Sundarbans in this study, named *Heritiera fomes*, *Excoecaria agallocha*, *Ceriops decandra*, *Sonneratia apelatala* and *Xylocarpus mekongensis*. The remaining species were classified under the major five mangrove species on the basis of dominance. The spectral profiles of five species, *H. fomes*, *E. agallocha*, *C. decandra*, *S. apelatala* and *X. mekongensis*, are shown in Figure 3.2. The five major species were selected based on the information obtained from previously published literature (Chaffey et al. 1985; Emch and Peterson 2006; Giri et al. 2007; Treygo and Dean 1989) and species-level maps of the Sundarbans. Figure 3.3 shows the workflow for image processing and change detection.

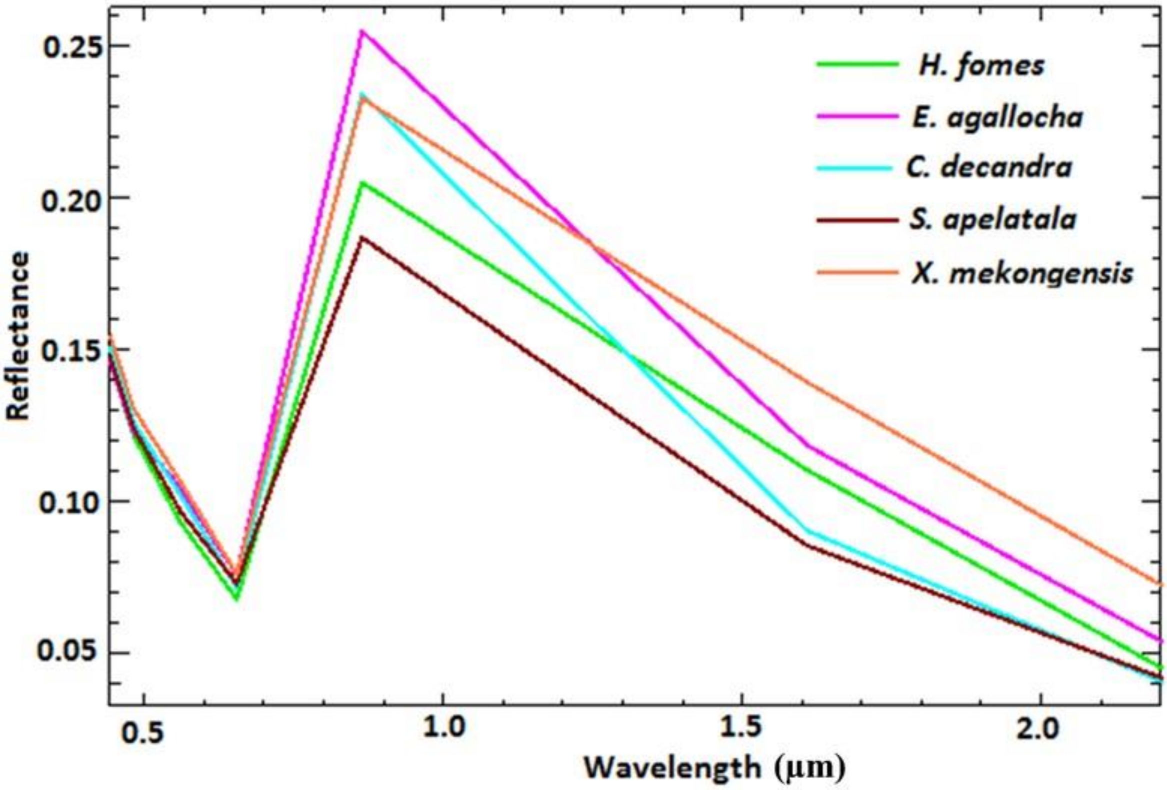

Figure 3.2 Spectral profile of various mangrove species. All five mangrove species show similar reflectance patterns in the lower wavelengths of the spectrum. In contrast, reflectance patterns are different in the higher wavelengths of the spectrum. To be more specific the spectral profiles of the five mangrove species follow each other between the wavelengths of 0.5 and 0.7 µm. The reflectance patterns become different after 0.7 µm, and this difference is maintained for the remaining portion of the spectrum.

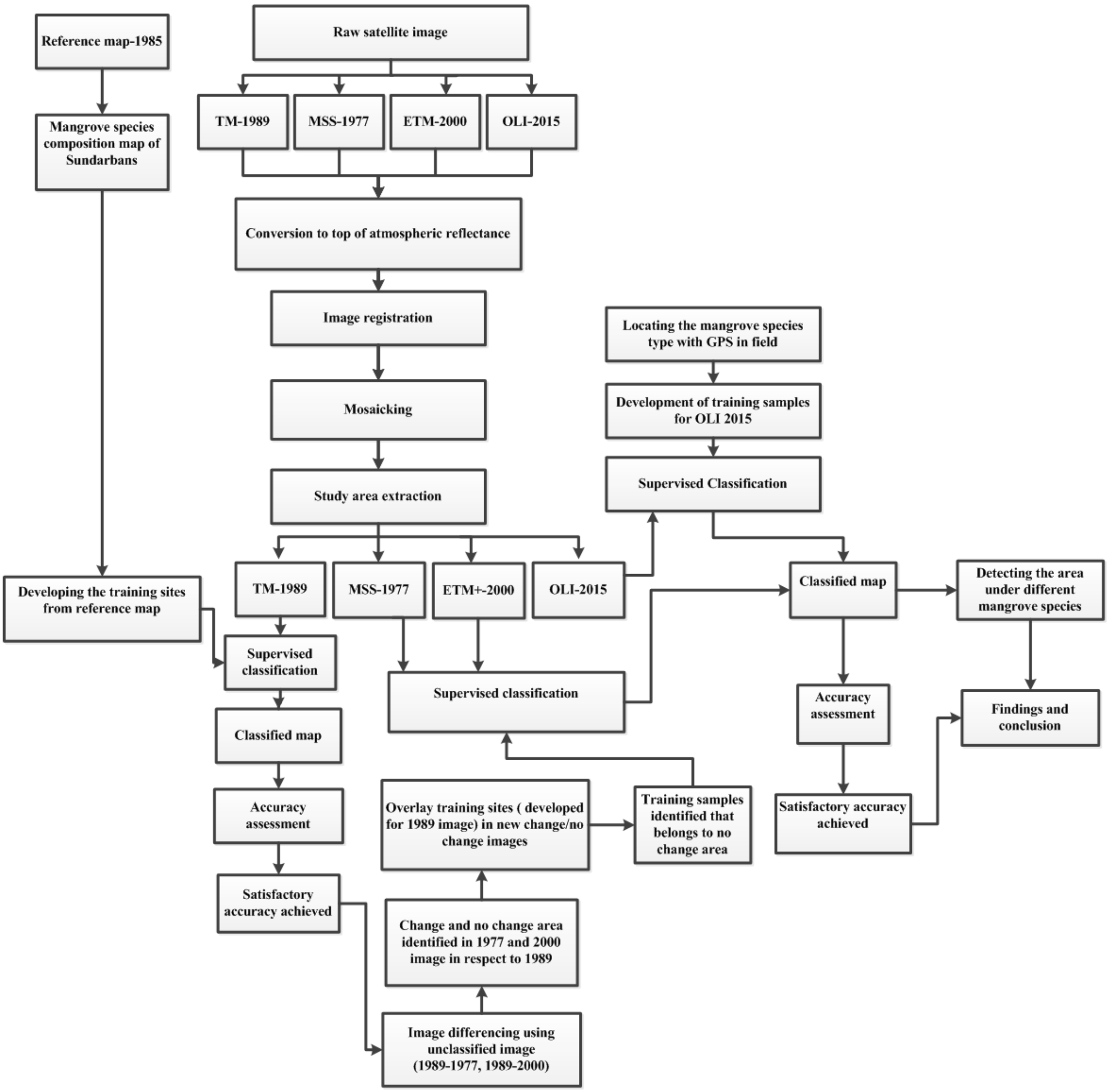

Figure 3.3 Work flowchart of research.

3.2.5. Change Detection Analysis

Post classification comparison techniques were used to detect changes in species composition from the four imagery dates. This approach provides "from–to" change information and is considered the most common change detection method. Changes in mangrove species composition were mapped by subtracting the classified maps between four periods: 1977–1989, 1989–2000, 2000– 2015 and 1977–2015. A change matrix was also developed to understand the dimension of the change. To identify the driving forces responsible for the change, change areas were visually interpreted. For better understanding of driving forces and their impacts on species dynamics, published documents were also used.

3.2.6. Classification Accuracy

Validation of classification is an integral part of any image classification process (Sinha et al. 2014). In this research, an accuracy assessment method described by Congalton and co-authors (Congalton 1991; Congalton and Green 2008; Congalton et al. 1983) was used to estimate the accuracy of the image classification.

3.3. Results

Spatiotemporal distributions of different mangrove species of the Sundarbans are shown for the years 1977, 1989, 2000 and 2015 in Figure 3.4, and statistics regarding species composition are shown in Table 3.2. Details of the detected change in the mangrove species composition in the study area are summarized in Table 3.3, and the change matrix is shown in Table 3.4.

The results indicate that during the study period, both *H. fomes* and *E. agallocha* decreased by 9.9%, while *C. decandra*, *X. mekongensis* and *S. apelatala* increased by 12.9%, 57.3% and 380.4%, respectively. However, the rate of change was not uniform during the study period between 1977 and 1989, 1989 and 2000 and 2000 and 2015. From 1977 to 1989, *H. fomes*, *E. agallocha* and *X. mekongensis* decreased by 1.7%, 2.5% and 36%, respectively, while *C. decandra* and *S. apelatala* increased by 4.3% and 159.4%, respectively, and from 1989 to 2000, *H. fomes* and *E. agallocha* decreased by 1.5% and 8.8%, respectively, whereas *C. decandra*, *X. mekongensis* and *S. apelatala* increased by 1.3%, 126.1% and 47.2%, respectively. Between 2000 and 2015, only the area under *H. fomes* decreased by 6.9%. In contrast, *E. agallocha*, *C. decandra*, *X. mekongensis* and *S. apelatala* increased by 1.3%, 6.9%, 8.7% and 25.8%, respectively. The spatiotemporal dynamics of the mangrove species are shown in Figure 3.5.

Four confusion matrices were created to compute overall accuracy, users' accuracy, producers' accuracy and the kappa coefficient. The image classification resulted in overall accuracies of 72%, 83%, 79% and 89% and a kappa index of 0.64, 0.74, 0.73 and 0.87 for the images of 1977, 1989, 2000 and 2015, respectively.

Table 3.2 Mangrove species composition pattern analysis of the Sundarbans (1977–2015).

Mangrove Species	Area in Hectares	Area in Percentage (%)						
	1977	1989	2000	2015	1977	1989	2000	2015
H. fomes	221,886	218,051	214,679	199,857	36.8	36.1	36.1	33.4
E. agallocha	200,662	195,692	178,425	180,742	33.3	32.4	30.0	30.2
C. decandra	171,590	178,972	181,238	193,698	28.5	29.6	30.5	32.4
X. mekongensis	5,383	3,444	7,788	8,466	0.9	0.6	1.3	1.4
S. apelatala	3,126	8,109	11,934	15,016	0.5	1.3	2.0	2.5
Total	602,646	604,267	594,062	597,779	100	100	100	100

Table 3.3 Analysis of mangrove species composition dynamics of the Sundarbans (1977–2015).

Mangrove Species	Change in Area (in Hectares)	Percentage Change	Annual Rate of Change (in Hectares)						
	1977 to 1989	1989 to 2000	2000 to 2015	1977 to 2015	1977 to 1989	1989 to 2000	2000 to 2015	1977 to 2015	1977 to 2015
H. fomes	**−3835**	**−3372**	**−14,822**	**−22,029**	**−1.7**	**−1.5**	**−6.9**	**−9.9**	**−580**
E. agallocha	**−4970**	**−17,267**	**+2317**	**−19,920**	**−2.5**	**−8.8**	**+1.3**	**−9.9**	**−524**
C. decandra	**+7381**	**+2266**	**+12,461**	**+22,108**	**+4.3**	**+1.3**	**+6.9**	**+12.9**	**+582**
X. mekongensis	**−1939**	**+4344**	**+678**	**+3083**	**−36.0**	**+126.1**	**+8.7**	**+57.3**	**+81**
S. apelatala	**+4984**	**+3825**	**+3082**	**+11,890**	**+159.4**	**+47.2**	**+25.8**	**+380.4**	**+313**

Note: (−) sign represents decreasing rate and (+) sign represents increasing rate.

Table 3.4 Mangrove cover change matrix of the Sundarbans between 1977 and 2015 (percentage).

	Class	1977				
		H. fomes	E. agallocha	C. decandra	S. apelatala	X. mekongensis
2015	H. fomes	81.1	7.4	2.3	10.0	0.2
	E. agallocha	16.2	48.7	26.1	20.1	16.3
	C. decandra	1.6	41.2	66.4	7.0	13.6
	S. apelatala	1.0	1.9	3.8	60.9	0.9
	X. mekongensis	0.01	0.9	1.4	2.0	69.1

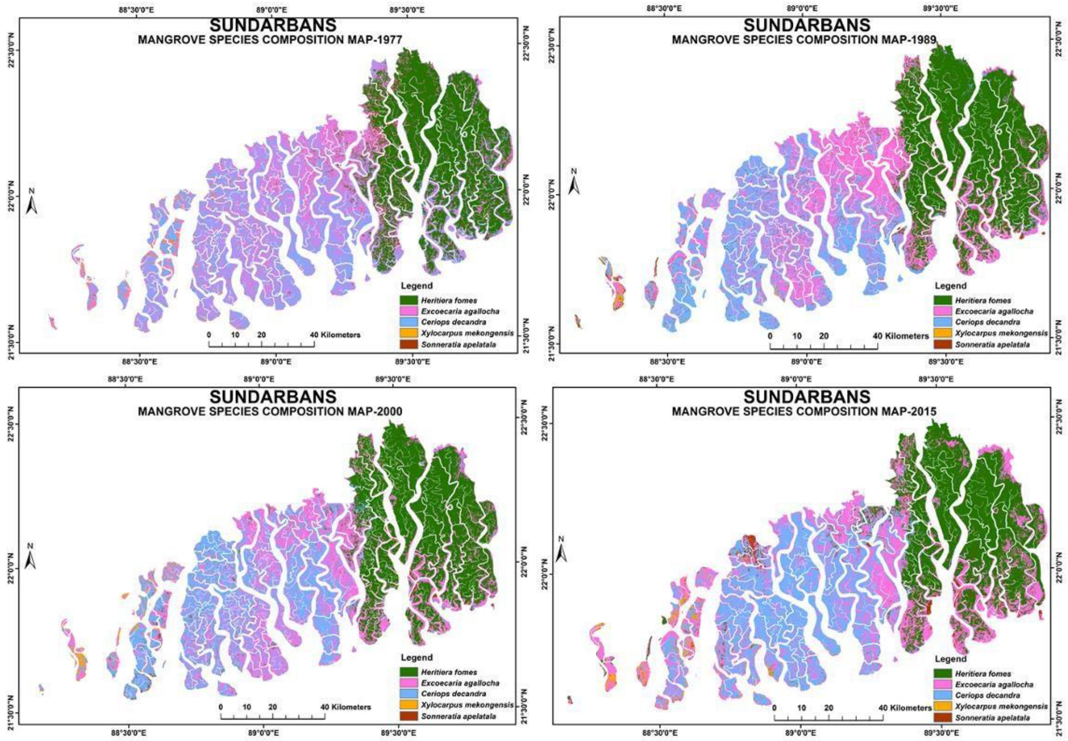

Figure 3.4 Mangrove species composition map of the Sundarbans mangrove forest.

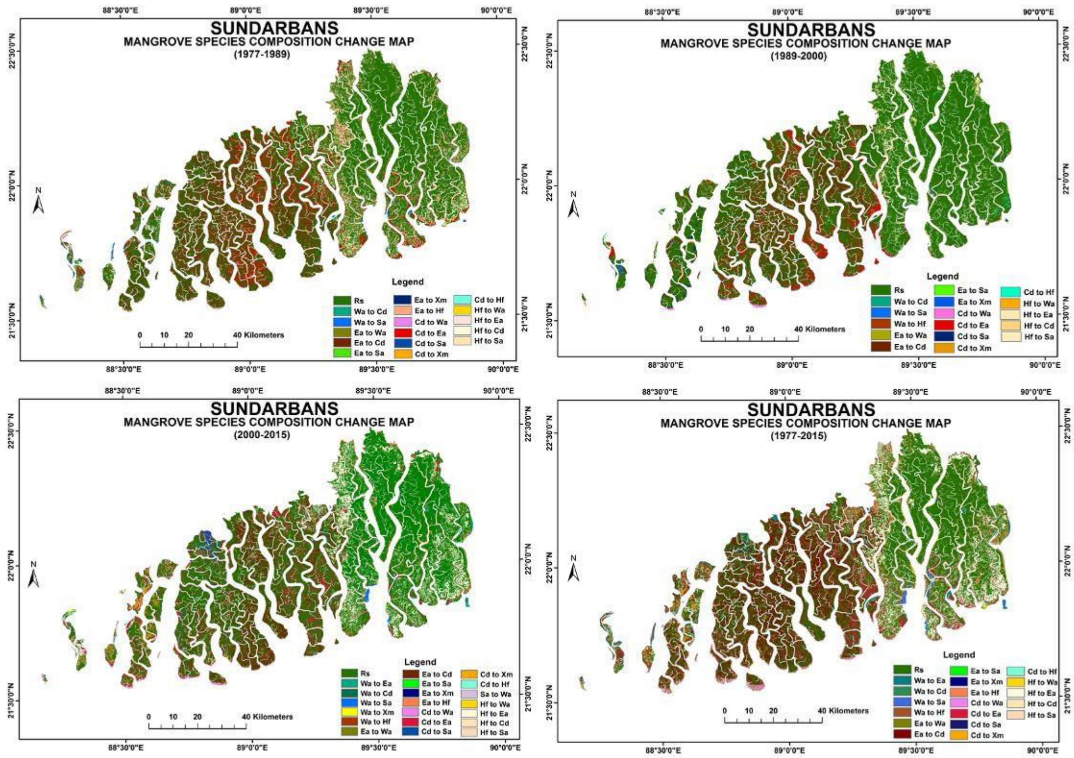

Figure 3.5 Mangrove species composition change map of the Sundarbans mangrove forest (Rs = Remained the same, Wa = Water, Ea = *Excoecaria agallocha*, Cd = *Ceriops decandra*, Sa = *Sonneratia apelatala*, Xm = Xylocarpus *mekongensis*, Hf = *Heritiera fomes*).

3.4. Discussion

The results reveal that the extent of the Sundarbans mangrove forest has changed little in net area (approximately 0.81%) despite having one of the highest population densities in the world in its immediate vicinity, but the forest health, structure and species composition have changed substantially in the last 38 years (1977–2015). This finding is consistent with other recent studies at the local level (Blasco et al. 2001; Dwivedi et al. 1999; Islam et al. 1997; Nayak and Bahuguna 2001).

The Sundarbans mangrove ecosystem is constantly changing across both temporal and spatial scales due to different natural and anthropogenic forces. Mangroves in other parts of the world are also experiencing similar changes due to similar types of forces. Global mangrove losses because of anthropogenic factors have increased substantially during the last three decades. Clear-cutting, land-use change, hydrological alterations, chemical spills and climate change are creating immense pressure on the existing mangrove forests worldwide. In the future, sea-level rise could be the greatest threat to mangrove ecosystems. According to the predictions suggested by the IPCC (Parry 2007), 30%–40% of coastal wetlands as well as 100% of the global mangroves (Duke et al. 2007) could be lost in the next 100 years if the present rate of loss continues. As a result, important ecosystem services and goods provided by mangroves could be diminished or lost forever (Parry 2007). The findings of this study are expected to serve as a baseline to develop adaptive management strategies in anticipation of sea-level rise, set conservation priorities, monitor deforestation and forest degradation, improve terrestrial carbon accounting and quantify the role of mangrove forests in saving lives and property from natural disasters such as cyclones and tsunamis.

Describing the reasons for changes in species composition of the Sundarbans mangrove ecosystem over time is an extremely complex task because of its multidimensional nature in terms of ecology and economy. The Total Economic Value (TEV) highlights the multidimensional nature of the economic value of this ecosystem, which includes direct-use values such as food, medicines, and forest products, and indirect-use values such as habitat provision, nutrient recycling, water purification, carbon absorption, flood control and protection against cyclones and water surges. This importance of ecology and economy has already been reported (Bose 2009; Costanza et al. 1997; Donato et al. 2011; Giri et al. 2007; Islam 2016; Rahman 2000). Due to this ecological and economic importance, the Sundarbans is faced with increased pressure from local demand, but the nature of pressure is not uniform, either spatially or temporally. As a consequence, it is difficult to specify the driving forces of change and their proportion of influence over time; therefore, such forces were only qualitatively identified.

Analysis of mangrove species composition change in the Sundarbans mangrove forest shows that the areas under *H. fomes* and *E. agallocha* decreased during the study period. In contrast, the area under *C. decandra*, *X. mekongensis* and *S. apelatala* increased during the last 38 years. Different natural forces, such as cyclones, coastal erosion and accretion, naturally shifting hydrology, changing climate and sea level rise, have adverse effects on the Sundarbans mangrove forest (see Table 3.5 for the underlying mechanism of the impact of these natural forces). Increasing water salinity and immersed areas in coastal regions as a result of changing climate are set to affect the ecosystem of the Sundarbans mangrove forest. As a result, a wide range of impacts is anticipated in the Sundarbans. The availability of freshwater, water salinity, variation in drainage and the siltation process have a substantial influence on the spatial distribution of mangrove species in the Sundarbans (Rahman 2000). Chaffey et al. (1985) divided the Sundarbans mangrove forest into three ecological zones: (a) freshwater or oligohaline (north-eastern part, the dominant species is H. fomes); (b) moderately saline or mesohaline (middle southern part, the dominant species is E. agallocha) and (c) saline or polyhaline (southern part, the dominant species is C. decandra). During the last four decades, salinity has increased in the Sundarbans region. For instance, Islam and Gnauck (2009b) analysed the time series salinity data of the Passur River-Mongla point and reported that the salinity rate was <10 ds/m in 1968 during the dry season, while in the same season in 2003, the highest salinity rate was 25 ds/m (see Figure 3.6 for details). Therefore, a large variation has been observed in salinity levels during the time period of 35 years. As a consequence of increasing salinity in the Sundarbans, mesohaline areas are transforming into polyhaline areas, especially in the western and south-western parts of the forest. On the other hand, oligohaline areas are transforming into mesohaline areas. Karim (1994) found approximately 60% of the western part was polyhaline, about 35% was mesohaline and less than 5% was oligohaline. Following the transformation of the ecological zones, new tree species that are more adapted to habitats with more salinity have encroached the areas that were previously occupied by other species.

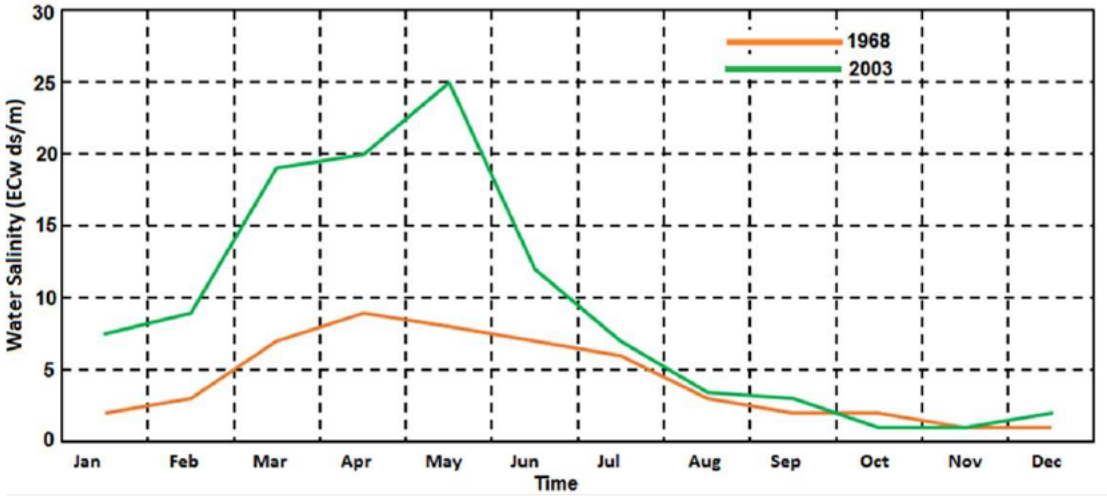

Figure 3.6 Water salinity density at the Passur-Mongla River site (1968–2003). (Based on data from Islam and Gnauck (2009b)).

H. fomes is distributed mainly in the Sundarbans eastern region, which is subject to more frequent flooding and less water salinity influence. *H. fomes* is the most commercially valuable species in the Sundarbans, contributing 60% of the forest's merchantable timber (Giri et al. 2007; Rahman 1990); however, it decreased by 9.9% in 2015 relative to 1977. A substantial change (6.9% decrease) was observed between the time period 2000 and 2015. A phenomenon commonly called die-back disease that is highly related to the level of salinity affects the *H. fomes* trees, and this is one of the major causes of deteriorating forest cover of *H. fomes* species.

Table 3.5 Mechanism underlying the impact of different natural forces on mangrove forests.

Natural Force	How It Works	Impact
Cyclone	High speed wind Flooding	Tree falling Salinity increase Soil erosion
Climate change	Global warming Sea level rise Changes in rainfall pattern in the catchment	Coastal inundation for longer periods Salinity increase Changes in germination rates Changes in flowering time
Coastal accretion	Fine sediment particles are carried in as suspension from upstream and by coastal waters. Sediments from coastal water settle in the forest during slack high tide as the friction caused by the high mangrove vegetation density slows tidal currents, whereas upstream sediments get trapped by the plant litter on the soil surface (Cahoon et al. 2006)	Settlement of new mudflat Germination of mangrove species in newly created mudflats Area under mangrove increases
Coastal erosion	Storms and other high water events washout the sediments	Loss of land Tree falling

Die-back disease started to spread over a large scale since 1980 (Rahman et al. 2010), bringing about the observed changes in *H. fomes*, which has also been confirmed by our study. *E. agallocha* is the dominant woody species in the Sundarbans southern region, where there is evidently the greatest seasonal variation in salinity levels and possibly represents an area of relatively longer duration of moderate salinity. It is often mixed with *H. fomes*, which it is able to displace under circumstances such as artificially opened canopies where *H. fomes* does not regenerate as effectively. It is also frequently associated with a dense understory of *C. decandra* (Rahman 2000). It is also interspersed with *H. fomes* and *C. decandra* in Sundarbans eastern and western regions, respectively. *E. agallocha* decreased by 9.9% in 2015 with respect to 1977 in the Sundarbans. In the first two intervals, the area under *E. agallocha* decreased, but the results suggest the situation was different for the 2000 to 2015 time period, where the area under *E. agallocha* actually increased, and this finding is also consistent with the reported result of Giri et al. (2014) for the Indian Sundarbans. Following the declaration of the Sundarbans as a world heritage site, the Forest Department imposed a ban on the felling of *E. agallocha* trees in 1999, which was the main raw material for the Khulna newsprint paper mill that was established in 1959, and this can be considered as one of the crucial factors for the observed changes in *E. agallocha* coverage, which increased during the study period. *C. decandra*, a species that is more adapted to habitats with more salinity and which is located in the Sundarbans western region and in more saline places in the Sundarbans eastern and southern regions, increased by 12.9% during the study period. Increasing salinity has played an important role in bringing the observed changes in *C. decandra* coverage and in species composition in the Sundarbans, especially in the western and southern part of the forest where *C. decandra* encroached the areas previously occupied by other species. *S. apelatala*, an indicator species for newly accreted mud banks and an important species for wildlife, increased by 380.4% in 2015 with respect to 1977. Coastal dynamics, land reclamation polices and afforestation programs of the Forest Department have played an influential role in the increment of *S. apelatala* trees in the Sundarbans. *S. apelatala* is distributed mainly in the south-eastern part (Sarankhola and Chandpai range) of the forest, the northern part of the Khulna range and the north- western part of the forest; *X. mekongensis* is distributed mainly in the western part of the forest (Indian portion) and some parts of the Khulna range. From 1977 to 2015, the area under *X. mekongensis* species increased by 57.3% in the Sundarbans.

Coastal dynamics (erosion and accretion) are one of the crucial factors that have played an important role in bringing about the changes in the Sundarbans mangrove forest. Geomorphology of the Sundarbans area is extremely dynamic due to the apparent acceleration of erosion and accretion (Ghosh et al. 2015b). Our results, based on the changes in species composition and habitats, suggest that erosion is more active than accretion in the study area.

Along the Sundarbans coastline, retreat is evident everywhere, but large areas of erosion have been observed in the south and south-western parts (sites A, B and C in Figure 3.7) during the study period. In contrast, small islands are currently forming at the mouth of Baleshwar, Bhanba and Haringhata Rivers (sites D, E and F in Figure 3.7). The highest coastal retreat was observed around the Bhangadhuni Island (site B) with an average annual rate of 66 m/year between 1977 and 2015, and this finding is consistent with the reported result of Rahman et al. (2011). Different anthropogenic and natural forces play a detrimental role in increasing the coastal retreat of the Sundarbans coast, which increases the vulnerability of mangroves (Cornforth et al. 2013). On the other hand, accretion of the Sundarbans coast plays an active role in the increment of the areal extent of mangrove forests and also in mangrove species composition dynamics. Most of the newly accreted islands are afforested by salt-tolerant *S. apelatala* trees in the preliminary stage, and this helps advance the sedimentation process. This is one of the major influential factors behind the observed changes in the area under *S. apelatala* trees in the Sundarbans mangrove forests during the study period.

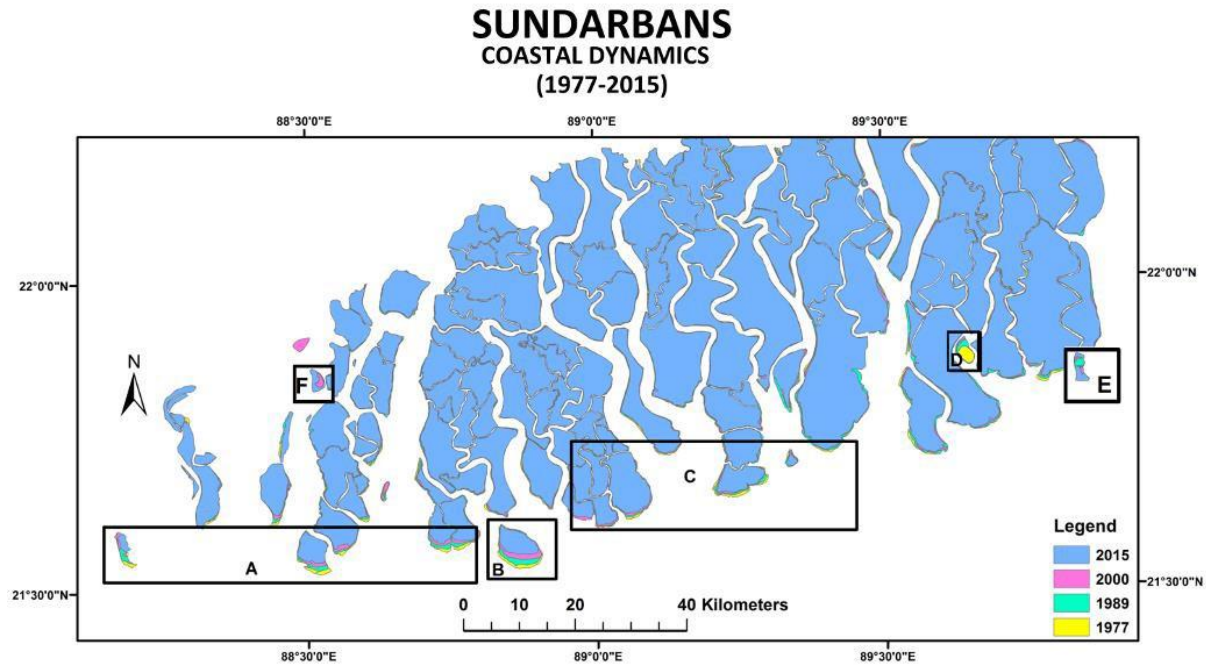

Figure 3.7 Effects of coastal dynamics (coastal erosion and accretion) showing the change between 1977 and 2015 in the Sundarbans coast.

Increasing population in the immediate vicinity of the Sundarbans has greatly increased the rate of exploitation of this forest, leading to serious degradation of the forest. As a result of the wide gap between the demand and supply of wood and almost permanent unemployment in the neighboring areas, there is an increasing dependence on the collection of wood from the forests for subsistence (Cahoon et al. 2006). Due to over-exploitation of timber, both legally and illegally, large woody trees like *E. agallocha* and *H. fomes* are disappearing at an alarming rate, and this affects the biodiversity of the forest. In addition, other anthropogenic activities, such as oil spills and fire for clearing forest for cultivation, put this mangrove forest under tremendous pressure in terms of sustainability.

To evaluate the accuracy of image classification, an overall classification accuracy and kappa index were calculated for each image. The classified image of 2015 resulted in the highest overall accuracy and kappa coefficient (89% and 0.87) followed by the classified images of 1989 (84% and 0.75), 2000 (79% and 0.73) and 1977 (72% and 0.63). It is notable that the MSS 1977 and ETM+ 2000 images resulted in relatively lower overall accuracies and kappa coefficient. This could be due to the fact that we developed training samples for them using the reference data that were not closely matched with the image dates, although we undertook additional processing to develop training samples for them due to the unavailability of reference data for these periods. Despite obtaining relatively low overall accuracies and kappa coefficient, the result is still acceptable considering the unavailability of reference data for older datasets and the coarse resolution of the MSS 1977 imagery.

3.5. Conclusions

The importance of the Sundarbans mangrove forest extends from the local to global scale, where different stakeholders' objectives attempt to decide its future. Due to unplanned and illegal anthropogenic activities, climate change and extreme weather events, this important mangrove ecosystem has been adversely affected during the last 250 years. In this situation, regular information on mangrove species composition, their spatial distribution and the changes that are taking place over time is very important for a thorough understanding of mangrove biodiversity and mangrove management in a sustainable manner. Emphasis on preparing databases related to mangrove species composition and the species-level dynamics of the Sundarbans mangrove forest for managing the entire ecosystem may help to sustain this valuable resource well into the future.

To do this, simple, time saving, efficient and low cost methods are required. In this study, we used conventional medium-resolution Landsat data and conventional classification and change detection methods to identify mangrove species composition and detect species level changes over time. Our results show the potential of producing relatively accurate mangrove species composition and change detection databases using Landsat images.

Over the study period, *H. fomes* and *E. agallocha* both decreased by 9.9% in the Sundarbans. In contrast, *C. decandra*, *S. apelatala* and *X. mekongensis* increased by 12.9%, 380.4% and 57.3%, respectively. Different natural and anthropogenic influences, such as over-exploitation of timber and pollution, coastal erosion and accretion, increasing salinity, die-back disease and changing climate, have played an important role in bringing about the observed changes in the mangrove species composition in the Sundarbans.

Describing the reasons for changes in species composition of the Sundarbans mangrove ecosystem over time is an extremely complex task because of its multidimensional nature in terms of ecology and economy. Due to this ecological and economic importance, the Sundarbans is faced with increased pressure from local demand, but the nature of pressure is not uniform, either spatially or temporally. As a consequence, it is difficult to specify the driving forces of change and their proportion of influence over time. Moreover, detailed studies are recommended to understand the role of responsible forces such as climatic variables, riverine erosion and accretion for the dynamics of mangrove species and their implications for the sustainability of the Sundarbans mangrove forest.

Continuous monitoring is important for developing a better management plan for the Sundarbans. In future, the results obtained in this study could provide invaluable quantitative information for better and sustainable management of the Sundarbans mangrove ecosystem. This result can also be shared with forest management planners, relevant stakeholders and policy makers for use in decision-making on such issues as forest management planning and identification of low cost methods, which could be used in the context of integrated forest management.

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Other Authors	**Lalit Kumar**	**15**
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Chapter 4.

Climate Variability and Mangrove Cover Dynamics at Species Level in the Sundarbans, Bangladesh

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4.1. Introduction

The impacts and vulnerabilities due to climate variability are becoming a growing global concern. Changes in temperature and rainfall are already evident around the world, as well as in Bangladesh (Ahmed and Alam 1999). Bangladesh is experiencing frequent natural hazards such as cyclones, high water events, floods and others, which have been intensified by climate change and its variability in recent years. Climate variability has profound impacts (such as change in species composition, change in phenological pattern, salinity stress, change in productivity) on mangroves, and the Sundarbans is an innocent victim of accelerated global warming and climate variability, and thereby faces a direct threat to its very existence (Mahadevia and Vikas n.d). Climate change and its variability is expected to have a substantial effect on the flow regimes of the major rivers in Bangladesh, including the Ganges. The Sundarbans could be severely affected by this change since the sustainability of the Sundarbans depends on the hydrology of the Ganges and its tributaries which supply fresh water to this ecosystem. In addition to the altered hydrology, sea level rise may also have adverse impacts on the forest (Agrawala et al. 2003). Therefore, it is important to investigate the trend of climate variability and its probable impact on mangroves. Detailed information about trends in climate variability and their probable impact on mangrove species composition can be used as a supporting database to help sustainable management planners and other relevant stakeholders to develop a proper adaptation strategy for this forest for maximum sustainable yield.

Components associated with climate change that are likely to affect mangrove forests include changes in temperature, rainfall, sea-level, frequency of storms and cyclones, concentration of atmospheric CO_2, high water events, and ocean circulation patterns (Eslami-Andargoli et al. 2009; Gilman et al. 2008). Although sea level rise is considered one of the most important factors that affect the distribution of mangroves in the long run (Field 1995; Gilman 2004), changes in regional temperature, rainfall and catchment runoff may be more significant in the short term (Eslami-Andargoli et al. 2009; Snedaker 1995). Rainfall over land has increased by about 2% in the twentieth century worldwide (Eslami-Andargoli et al. 2009), but this increase has not been uniform either spatially or temporally. Rainfall is predicted to increase by about 25% by 2050 as a result of climate change (Gilman et al. 2008), however, the distribution of rainfall will be uneven at a regional scale (Houghton et al. 2001). Growth and spatial distribution of mangroves are likely to be affected by any changes in rainfall patterns (Duke et al. 1998; Field 1995). In coastal regions, higher rainfall helps to increase the supply of sediments and nutrients, reduces water and soil salinity and decreases exposure to sulphates; and these factors can play a vital role in increasing diversity, growth and productivity of mangrove forests. It can also play a crucial role by increasing peat production to maintain the sediment elevation (Ellison 2000; Gilman et al. 2007; Snedaker 1995). On the contrary, lesser rainfall plays a vital role in increasing salinity, which is responsible for decreasing the growth, productivity and survival of seedlings, thus increasing competition for survival between mangrove species. This process can lead to reductions in mangrove area with possible increases in the extent of salt flats (Gilman et al. 2008; Lovelock and Ellison 2007) and can also change the species composition and their spatial distribution in the forest (Ellison 2000; Field 1995).

Mangrove species also show considerable variation in their sensitivity to temperature (Field 1995). Globally the average temperature has increased by 0.74 °C between 1906 and 2005 (Solomon 2007) and the linear warming trend of the last five decades is nearly twice that of the last ten decades (Gilman et al. 2008). The projections for global average temperature rise to the end of the twenty-first century is 1.1 to 6.4 °C (Solomon 2007). The impact of this increasing temperature on the generative capacity of mangroves is difficult to predict. Increased temperature is expected to affect mangroves by changing phenological patterns (timing of flowering and fruiting), changing species composition, increasing mangrove productivity where temperature does not exceed an upper threshold and expanding mangroves ranges to higher latitudes where temperature only limits the range among other factors (Ellison 2000; Field 1995; Gilman et al. 2008).

The pattern of change of the Sundarbans mangrove forest in Bangladesh is commonly associated with the change in species level composition of mangroves and seaward expansion in some parts of the forest (Ghosh et al. 2016). Due to high population densities in its immediate vicinity, landward expansion of the Sundarbans are limited. Researchers have identified rainfall as a mechanism for mangroves encroachment into salt marsh (see, for example McKee 2004; McTainsh et al. 1986; Saintilan and Williams 1999; Saintilan and Wilton 2001) around the world. According to them it can also affect the spatial distribution of mangrove species. In addition, Jagtap and Nagle (2007), Field (1995), Ellison (2000) and Gilman et al. (2008) found rising temperature to be one of the important factors responsible for changes in mangrove species composition.

Research regarding climatic variables' association with mangrove dynamics have only been conducted in a few areas over short time periods around the world (Gilman et al. 2008). However, in the Sundarbans, no investigation has been conducted on the relationship between climate variability and mangrove dynamics at species level so far.

The aim of this research was to investigate the relationship between climatic variables and mangrove dynamics at species level in the Sundarbans, Bangladesh, over a 38-year period from 1977 to 2015. Our specific research questions included (1) what changes in local climate (e.g., annual average maximum and minimum temperature and annual total rainfall) over the period 1977–2015, have occurred in the study area? (2) How and at what rate has the mangrove composition in the Sundarbans changed during the study period? And finally, (3) is there any relationship between change in climatic variables and change in mangrove species composition? The results of the study is expected to provide a better understanding of mangroves' response to climate variability in the Sundarbans.

4.2. Method

4.2.1. Study Area

The Sundarbans is at the Ganges delta where the three mighty river systems: Ganges, Brahmaputra and Meghna converge (Bhowmik and Cabral 2013; Ghosh et al. 2016; Iftekhar 2006) and is characterized by a complex pattern of tributaries (Chowdhury et al. 2016). The Sundarbans extends between 21°32′ to 22°40′ N latitude and 88°05′ to 89°51′ E longitude (Figure 4.1) and covers an area of around 10,000 km^2. Approximately 62% of the Sundarbans is located in Bangladesh and the rest is in India (Spalding 2010). Four main seasons, including pre-monsoon, monsoon, post-monsoon and dry winter, form the tropical climate of the area. The hot and humid pre-monsoon season with irregular rainfall ranges from March to May and is followed by a monsoon (June to September), a post-monsoon (October to November) and dry winter (December to February) (Ghosh et al. 2015a; Iftekhar and Islam 2004). In this study only the Bangladeshi part of the Sundarbans was considered as the study site due to the difficulties in fieldwork on the Indian side.

Climate data is available since 1948 for each of the three weather stations (Khulna, Satkhira and Bagherhat) that covers the Sundarbans mangrove forest region of the Bangladesh part. Climatic conditions of all the three stations are similar due to the close association between rainfall and temperature (Bhowmik and Cabral 2013). In this region, temperature varies between 11 °C and 37

°C, while rainfall fluctuates between 1600 mm and 2000 mm. The elevation varies between 0.9 and 2.11 m above sea level (Ghosh et al. 2015a; Spalding 2010).

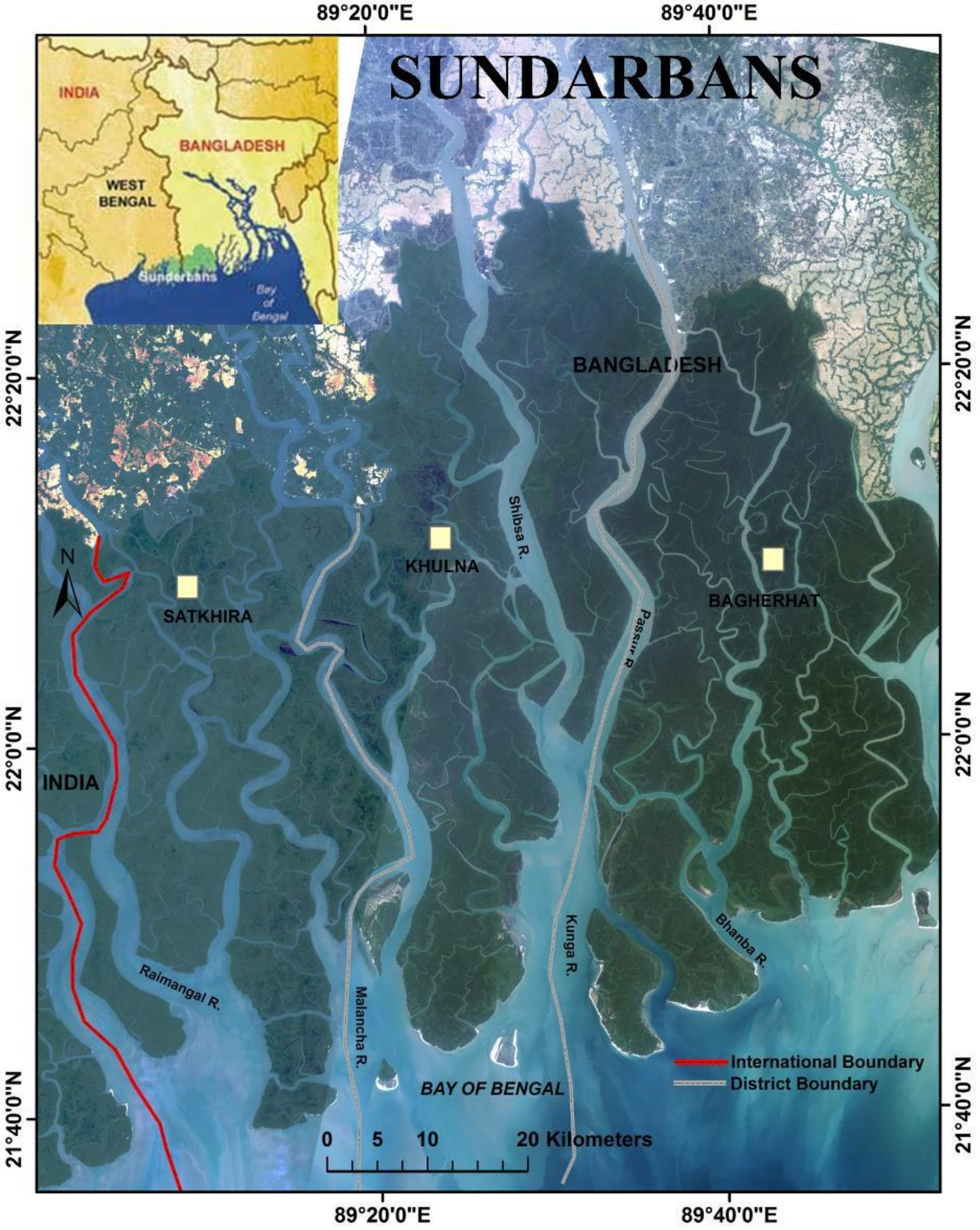

Figure 4.1 Location of the study area (True color composite image).

4.2.2. Data Used in This Research

Ground-based readings of temperature and rainfall, as well as satellite imagery, were used in this study. Ground-based meteorological information was obtained from Bangladesh Meteorological Department (BMD) for the period 1977 to 2015 to determine the trends of rainfall and temperature.

Satellite images obtained from the US Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) website (www.glovis.usgs.gov) in four time periods were analysed to assess the dynamics of mangrove population. Due to a lack of spatial data at a relevant scale and difficulty in accessing the mangroves for field survey, monitoring of the changes in mangrove species composition has been limited (Eslami-Andargoli et al. 2009). In this regard, remote sensing techniques could play an important and effective role in identifying and mapping mangrove species composition changes with an acceptable accuracy and it also has advantages over traditional methods (Ghosh et al. 2016; Giri et al. 2007; Green et al. 1998; Hirano et al. 2003; Kovacs 1999; Kovacs et al. 2005; Sader et al. 1995). To identify mangrove forests, a number of satellite sensors have been used, including Landsat TM/ETM/OLI (Ghosh et al. 2016; Giri et al. 2014; Long and Skewes 1996), SPOT (Franklin 1993; Pasqualini et al. 1999), CBERS (Li et al. 2003), SIR (Pasqualini et al. 1999), ASTER (Vaiphasa et al. 2006), and IKONOS and Quick Bird (Wang et al. 2004b). According to Wang et al. (2004a), conventional satellite imagery such as Landsat and SPOT have been used for mapping mangrove species with mixed results. They also pointed out that spatial resolution is more effective than spectral resolution in discriminating different mangrove species. Green et al. (1998) reported that airborne sensors, such as CASI, were more successful in accurate discrimination among mangrove species than conventional satellite data. From the above discussion, it is apparent that using conventional medium-resolution remote sensor data (e.g., Landsat TM, ASTER, SPOT), the identification of different mangrove species remains a challenging task. In many developing countries, the high cost of acquiring high-resolution satellite imagery excludes its routine use (Kirui et al. 2013). The free availability of archived images enables the development of useful techniques in its use, with this in mind; Landsat imagery were used in this study for mangrove species classification. Even though it has limitations, such as coarse resolution, many researchers have used this imagery successfully in mangrove mapping at species level (for example Ghosh et al. 2016; Giri et al. 2014; Myint et al. 2008). Satellite imagery used in this study includes: Landsat Multispectral Scanner (MSS) of 57 m resolution acquired on 1st February 1977, Landsat Thematic Mapper (TM) of 28.5 m resolution acquired on 5th February 1989, Landsat Enhanced Thematic Mapper (ETM+) of 28.5 m resolution acquired on 28th February 2000 and Landsat Operational Land Imager (OLI) of 30 m resolution acquired on 4th February 2015.

4.2.3. Trend Analysis of Climatic Variables

This analysis was carried out to verify the variation of average maximum temperature, average minimum temperature and annual total rainfall to understand the climate variability throughout the period 1977–2015. To understand the trend of annual average maximum and minimum temperature and annual total rainfall, climatic conditions of three time periods extending from 1977 to 1989, 1989 to 2000, 2000t o2 015 and the overall period of 1977 to 2015 were analyzed. Initially, the representation of time series (time series plot) was examined to select the appropriate trend model for the datasets. As the representation of time series exhibited a linear form, linear trend model was used for this analysis since it provides the best fit for the dataset and also provides linear unbiased estimation. Mangrove species change per district (Satkhira, Khulna and Bagherhat) was trended with climate data for that district. The entire statistical analysis was carried out using Minitab software (Version 17, Minitab Inc., State College, PA, USA).

4.2.4. Analysis of Satellite Images to Identify the Changes in Mangrove Cover

The supervised maximum likelihood classification algorithm (MLC) was used to classify and extract the mangrove population by species of the Sundarbans. Fieldwork and published maps were used to develop training and validation samples. Field data was used for training and validation sampling for 2015 imagery while reference map of the Sundarbans that was mapped at species level by Bangladesh Forest Department in 1985, was used for the 1989 image. Fieldwork was carried out between February–March 2016. A reference map of the Sundarbans (published by Bangladesh Forest Department), printed image of Google Earth and Landsat image data were used in this fieldwork as guides. Training and validation samples that were developed for the 1989 image were also used for the 1977 and 2000 images for training and validation sampling because reference data were not available for the corresponding years. A process called signature extension, suggested by (Foody (2004); Foody 2008), was undertaken to use these samples, and this allowed us to use samples for unchanged areas for such purposes. The detailed methodology for this is given in Ghosh et al. (2016). Training samples of between 51 and 141 for each species were randomly and carefully selected, stratified by land cover class based on true representation and distribution. These sample points were used to create sample polygons of 3 ×

3 or 5 × 5 pixels depending on the class homogeneity. To include all defined mangrove species in the Sundarbans altogether 414, 429, 549 and 471 sample polygons were assessed for the images of 2015, 2000, 1989 and 1977 respectively.

The composition and distribution of the mangrove species were identified on the basis of signature-based satellite image classification. For 2015 imagery, training sets for different mangrove species were obtained using GPS during the fieldwork and, for rest of the imagery (1977, 1989 and 2000), training sets were developed from the reference map. Using these training sets, spectral signatures for different mangrove species were generated. Afterwards, extracted spectral signatures were used for the classification and identification of mangrove species. Five major mangrove species namely *Heritiera fomes*, *Excoecaria agallocha*, *Ceriops decandra*, *Sonneratia apelatala* and *Xylocarpus mekongensis* were mapped in this study out of 27 species present in the Sundarbans (Giri et al. 2007). On the basis of dominance, the remaining species were classified under the five major mangrove species as those are difficult to detect using medium-resolution satellite data due to their small quantities and presence in small patches over the wide areas, as reported by Ghosh et al. (2016). To detect changes in mangrove species composition, post classification comparison techniques were used. Afterwards, the rate of change of different mangrove species were estimated. Overall accuracy and kappa index were calculated to estimate the accuracy of the image classification with respect to reference points. Image classification accuracy from the 1977 MSS image was lower (overall accuracy 72%, Kappa index 0.73) than that of the other TM, ETM+ and OLI images from other years. The highest overall accuracy (89%) and kappa index (0.87) were achieved from the 2015 OLI image.

4.2.5. Impacts of Climate Variability on Mangrove Cover Change

To investigate the relationship between the climate variability and the change in species composition in the Sundarbans, an effort was made to explore the impact of climate variability on mangrove species composition change. For this analysis, the data revealing mangrove species composition change were used to understand the trend of those changes in response to the average maximum and minimum temperature and the amount of annual total rainfall, for the period of 1977–2015. Then an attempt was made to identify any possible relationship between the trends of local climate variability and trend of change in mangrove species composition. Simple linear regression method was used to determine the relationship between climate variability and change in mangrove species composition.

4.3. Results

4.3.1. Trend of Climatic Variables

The results show that over the period 1977–2015 average maximum and minimum temperature have been increasing in the Sundarbans, while annual total rainfall has been decreasing. However, the trend of change was not similar for all the three sites. The historical trend of climatic variables, viz. average maximum and minimum temperature as well as the annual total rainfall pattern of all the three weather stations (Satkhira, Khulna and Bagherhat) that cover the Sundarbans, are shown in Figures 4.2–4.4. During the study period, average maximum temperature shows an increasing trend in Khulna and Bagherhat, and a decreasing trend in Satkhira, while average minimum temperature shows an increasing trend for all the three stations. Annual total rainfall shows a decreasing trend in Satkhira and Khulna but an increasing trend in Bagherhat.

During the study period, the average maximum temperature at Satkhira has been decreasing at a rate of 0.0078 °C per year (Figure 4.2a), while the average minimum temperature has been increasing at a rate of 0.0102 °C per year (Figure 4.2b). The average maximum and minimum temperature at Khulna has been increasing at a rate of 0.0226 °C (Figure 4.3a) and 0.0220 °C (Figure 4.3b) per year, respectively. The average maximum and minimum temperature at Bagherhat has also been increasing at a rate of 0.0325 °C (Figure 4.4a) and 0.0043 °C (Figure 4.4b) per year, respectively. The total annual rainfall in Satkhira and Khulna has been decreasing at a rate of 0.1716 (Figure 4.2c) and 0.0204 mm (Figure 4.3c) per year, respectively. In contrast, the total annual rainfall in Bagherhat has been increasing at rate of 0.1200 mm per year (Figure 4.4c). However, the changing trend and the rate of change was not uniform during the study period between 1977 and 1989, 1989 and 2000 and 2000 and 2015. Rate of change for average maximum and minimum temperature and annual total rainfall for the different study periods and meteorological stations are shown in Table 4.1.

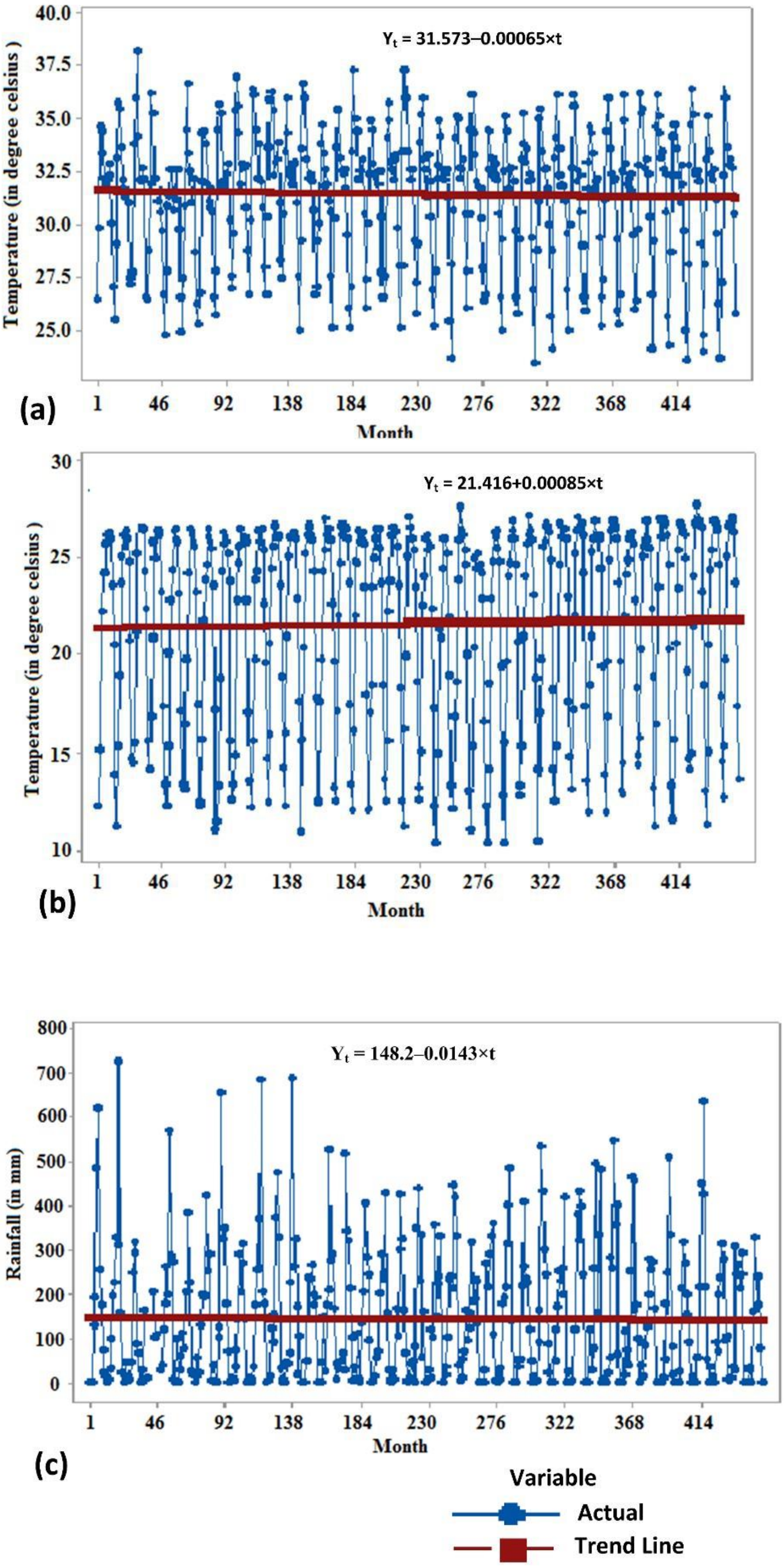

Figure 4.2 Trend analysis for climatic variables over Satkhira during the period 1977–2015, (a) maximum temperature; (b) minimum temperature and (c) rainfall.

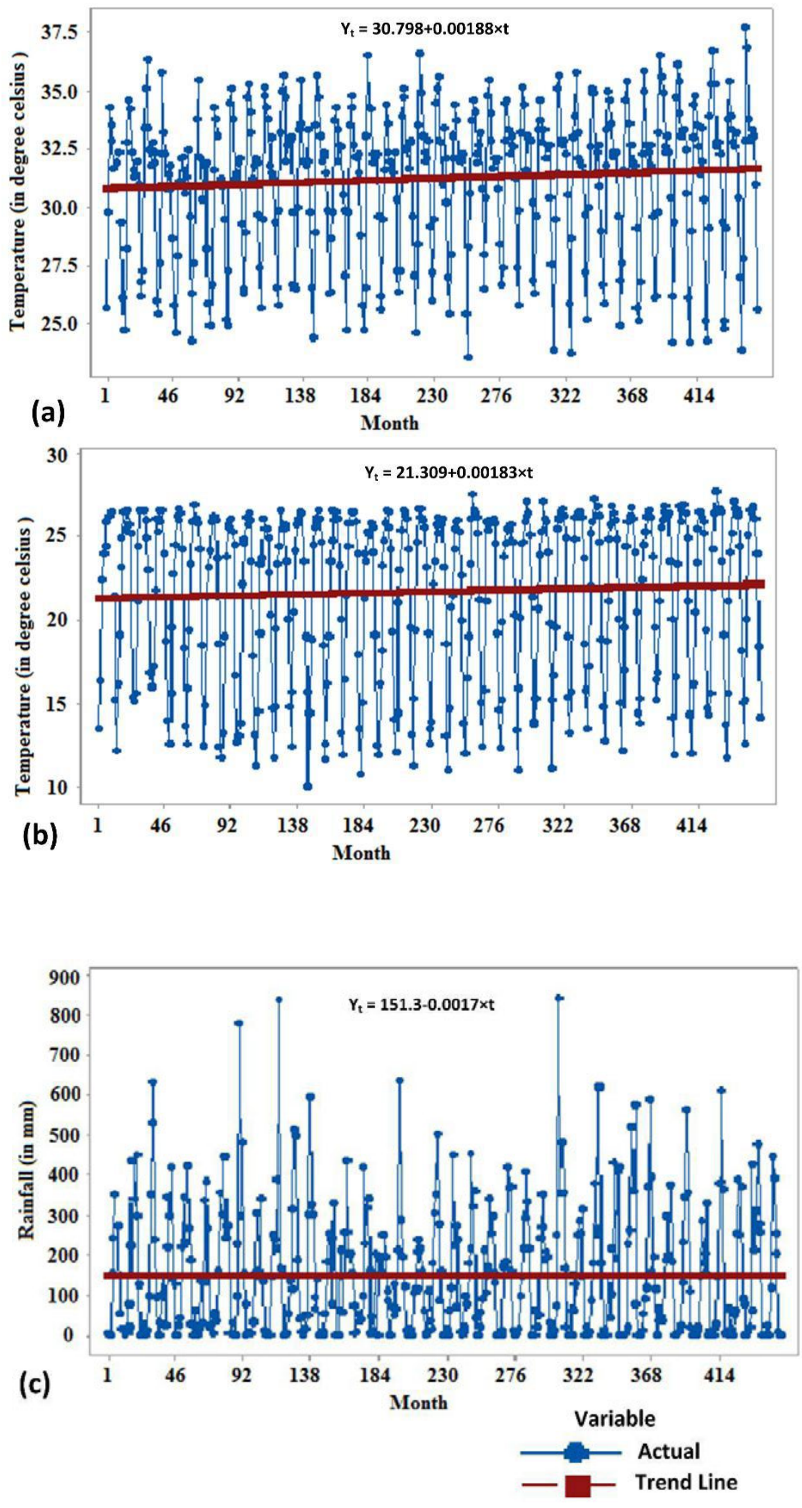

Figure 4.3 Trend analysis for climatic variables over Khulna during the period 1977–2015, (a) maximum temperature; (b) minimum temperature and (c) rainfall.

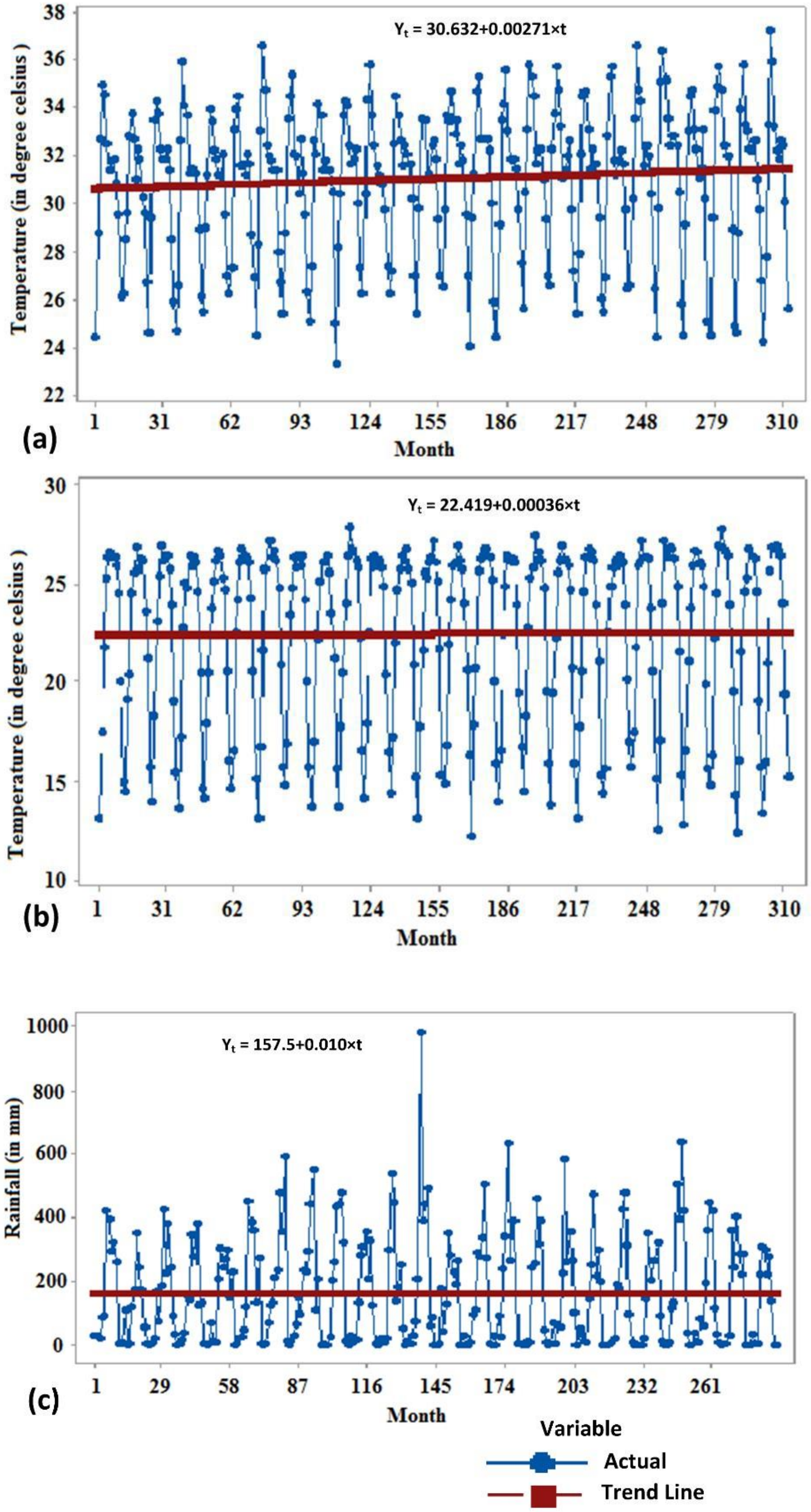

Figure 4.4 Trend analysis for climatic variables over Bagherhat during the period 1989–2015, (a) maximum temperature, (b) minimum temperature and (c) rainfall.

Table 4.1 Changing rate of climatic variables in the three meteorological stations in the Sundarbans during study period.

Study Site	Time Period	Change Rate of Climatic Variables		
		Maximum Temperature (°C Per Year)	Minimum Temperature (°C Per Year)	Rainfall (mm Per Year)
Satkhira	1977–1989	+0.0763	−0.0094	−0.444
	1990–2000	−0.009	−0.066	+1.392
	2001–2015	+0.0048	+0.0247	−2.184
Khulna	1977–1989	+0.0616	−0.0502	+0.588
	1990–2000	+0.0594	+0.0552	+1.308
	2001–2015	+0.0226	+0.0194	-1.632
Bagherhat	1990–2000	+0.0302	+0.0402	+5.928
	2001–2015	+0.0132	−0.0020	−2.436

Note: (−) sign represents decreasing rate and (+) sign represents increasing rate.

4.3.2. Satellite Image Analysis

Spatiotemporal changing pattern of mangrove species of the Sundarbans are shown for the years 1977, 1989, 2000 and 2015 in Figures 4.5–4.6. According to our results, *H. fomes* and *E. agallocha* decreased by 10.7% and 4.8%, respectively, during the study period; whereas *C. decandra*, *X. mekongensis* and *S. apelatala* increased by 35.7%, 76.3% and 212.1%, respectively. However, the rate of change was not uniform either spatially or temporally (for instance see Table 4.2). For example *H. fomes* decreased by 1.9%, 0.4% and 0.08% per year in three different study sites Satkhira, Khulna and Bagherhat respectively during the period 1977–2015. *E. agallocha* showed a decreasing trend in Satkhira (0.8% per year) and an increasing trend in Khulna (0.6% per year) and Bagherhat (0.4% per year). *C. decandra* and *X. mekongensis* showed an increasing trend in Satkhira and Khulna and decreasing trend in Bagherhat. *S. apelatala* showed an increasing trend in all three study sites. It increased by 22.1%, 1.7% and 23.5% per year in Satkhira, Khulna and Bagherhat, respectively.

Table 4.2 Area and rate of change of mangrove species composition in different parts of the Sundarbans.

Study Site	Mangrove Species	Area in Hectares				Change in Area				Rate of Change % Per Year			
		1977	1989	2000	2015	1977–1989	1989–2000	2000–2015	1977–2015	1977–1989	1989–2000	2000–2015	1977–2015
Satkhira	H. fomes	4118	2940	1853	1114	−1178	−1087	−739	−3004	−2.38	−3.36	−2.66	−1.92
	E. agallocha	58,611	54,956	45,002	40,270	−3655	−9954	−4732	−18,341	−0.52	−1.65	−17.02	−0.82
	C. decandra	41,760	45,484	53,343	59,346	+3724	+7859	+6003	+17586	+0.74	+1.57	+21.60	+1.11
	X. mekongensis	503	798	1125	1134	+295	+327	+9	+631	+4.89	+3.73	+0.03	+3.30
	S. apelatala	93	765	718	875	+672	−47	+157	+782	+60.22	−0.56	+0.56	+22.13
Khulna	H. fomes	106,498	104,366	98,769	89,486	−2132	−5597	−9283	−17,012	−0.17	−0.49	−0.63	−0.42
	E. agallocha	30,086	28313	28,590	36,331	−1773	+277	+7741	+6245	−0.49	+0.09	+1.81	+0.55
	C. decandra	3186	6017	6869	8956	+2831	+852	+2087	+5770	+7.40	+1.29	+2.03	+4.77
	X. mekongensis	206	250	355	280	+44	+105	−75	+74	+1.78	+3.82	−1.41	+0.95
	S. apelatala	2268	2385	2521	3760	+117	+136	+1239	+1492	+0.43	+0.52	+3.28	+1.73
Bagherhat	H. fomes	109,002	110,143	112,762	105,490	+1141	+2619	−7272	−3512	+0.09	+0.22	−0.43	−0.08
	E. agallocha	36,658	33,407	31,610	42,703	−3251	−1797	+11,093	+6045	−0.74	−0.49	+2.34	+0.43
	C. decandra	7103	7775	4195	2308	+672	−3580	−1887	−4795	+0.79	−4.19	−3.00	−1.78
	X. mekongensis	107	50	118	100	−57	+68	−18	−7	−4.44	+12.36	−1.02	−0.17
	S. apelatala	401	409	724	3986	+8	+315	+3262	+3585	+0.17	+7.00	+30.04	+23.53

Note: (−) sign represents decreasing rate and (+) sign represents increasing rate.

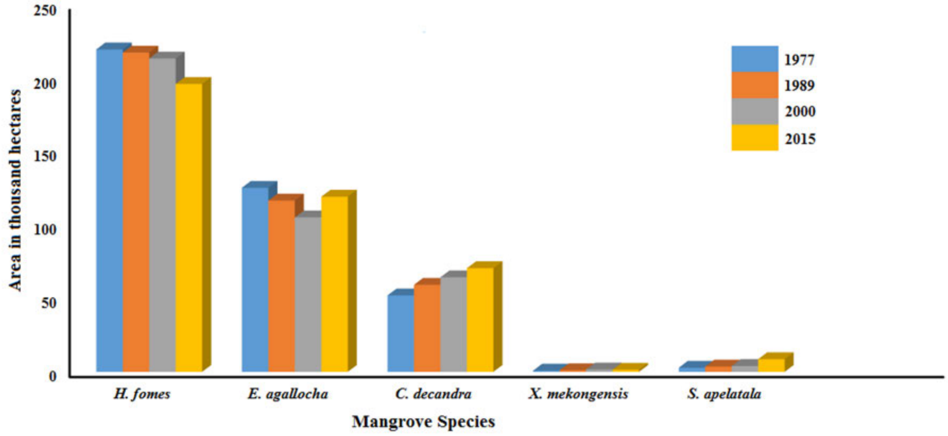

Figure 4.5 Changing pattern of mangrove species composition in the Sundarbans mangrove forest, Bangladesh between 1977 and 2015.

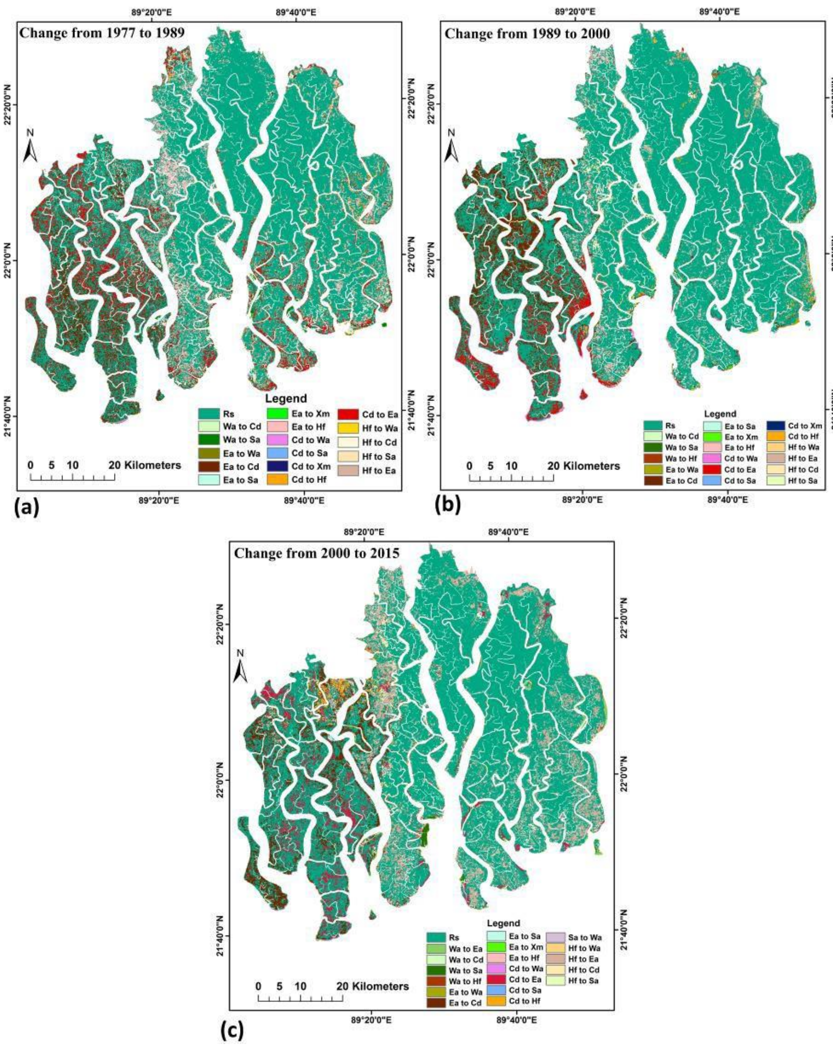

Figure 4.6 Mangrove species composition change map of the Sundarbans mangrove forest, Bangladesh. Prepared on the basis of image analysis from (a) 1977 to 1989, (b) 1989 to 2000 and (c) 2000 to 2015 (Rs = Remain same, Wa = Water, Ea = *Excoecaria agallocha*, Cd = *Ceriops decandra*, Sa = *Sonneratia apelatala*, Xm = *Xylocarpus mekongensis*, Hf = *Heritiera fomes*).

4.3.3. Relationship between Climate Variability and Mangrove Cover Change

The results of linear regression show climatic variables have a considerable impact on the coverage of *H. fomes*, *S. apelatala* and *C. decandra*; while coverage of the other two species (*E. agallocha* and *X. mekongensis*) are not much influenced by climatic variables (see Table 4.3 for details). The dynamics of *H. fomes* and *S. apelatala* with response to average maximum temperature during 1977–2015 exhibited a strong relationship. The dynamics of *H. fomes* and *S. apelatala* were also strongly related to the rainfall pattern. In contrast, the dynamics of *E. agallocha* and *X. mekongensis* did not have a significant relationship with average maximum temperature or the rainfall pattern. *C. decandra* showed a weak relationship with average maximum temperature and rainfall pattern. The dynamics of all five mangrove species with response to average minimum temperature during 1977–2015 did not exhibit any significant relationship.

Table 4.3 Relationship between mangrove species dynamics and climatic variables (average maximum and minimum temperature and annual total rainfall) in the study area over the period (1977–2015).

Mangrove Species	Maximum Temperature	Minimum Temperature	Rainfall			
	p Value	R-Square	p Value	R-Square	p Value	R-Square
H. fomes	0.006	98.81%	0.401	35.87%	0.0001	99.90%
E. agallocha	0.936	0.42%	0.352	42.02%	0.993	0.01%
C. decandra	0.147	72.75%	0.128	76.09%	0.116	78.12%
X. mekongensis	0.489	26.12%	0.169	69.09%	0.427	32.86%
S. apelatala	0.001	99.84%	0.406	35.33%	0.002	99.59%

4.4. Discussion

An analysis of 38 years' worth of climatological data (average maximum and minimum temperature and annual total rainfall considered for this study) shows variable trends of average maximum and minimum temperature and annual total rainfall in the Sundarbans mangrove forest in Bangladesh. Over the period 1977–2015, average maximum and minimum temperature have been increasing in the Sundarbans, while annual total rainfall has been decreasing. This local climate variability is likely to be highly important to understanding the future spatial distribution of mangrove ecosystems. Changes in regional temperature and rainfall are the two important factors, along with runoff, that affects the spatial distributions and mangrove species composition in the short term (Eslami-Andargoli et al. 2009; Snedaker 1995).

Noticeable relationships have been found between average maximum temperature and mangrove species dynamics in the Sundarbans during the study period. The changes in area under *H. fomes* has shown a negative relationship with response to average maximum temperature, while *S. apelatala* has shown a strong positive relationship. It has been observed that the area under *H. fomes* has decreased considerably with the increase of average maximum temperature. On the other hand, the area under *S. apelatala* has been increasing considerably in response to a rise in average maximum temperature. In the case of *E. agallocha* and *X. mekongensis* there is no significant relation between the dynamics of these mangrove species and the rise of average maximum temperature. Although the area under *C. decandra* has been increasing in response to the rise in average maximum temperature, only a weak relationship has been found between them. The relationship between the average maximum temperature and the dynamics of *H. fomes*, *S. apelatala* and *C. decandra* support Field (1995) and Ellison (2000), who argued that a rise in temperature can change mangrove species composition. No significant statistical relationship has been found between the average minimum temperature and dynamics of mangrove species in the study area.

A noticeable relationship has been found between annual total rainfall and mangrove species dynamics over the period 1977–2015. Area under *H. fomes* has decreased considerably with the decreasing total rainfall. On the other hand, an inverse relation has been found between annual total rainfall and *S. apelatala*, where area under *S. apelatala* increased with decreasing annual total rainfall. This situation is also similar for *C. decandra*, where it increased with decreasing annual total rainfall. No significant relationship has been found between the annual total rainfall and the dynamics of *E. agallocha* and *X. mekongensis*. The relationship between the dynamics of *H. fomes*, *S. apelatala* and *C. decandra*, and change in rainfall pattern support Field (1995) and Ellison (2000) who argued that rainfall patterns affect spatial distribution of mangrove species. This may also be related to higher supply of sediment, lower exposure to sulphates, increased salinity (Ellison 2000; Eslami-Andargoli et al. 2009; Field 1995; Ghosh et al. 2016; McKee 1993) and reduced discharge of freshwater flows from the upper stream (Islam and Gnauck 2008). In the present study, the decreasing trend of *H. fomes* and increasing trend of *C. decandra* support the suggestion that decreased rainfall and resulting higher salinity may be a factor that contributes to the observed change. In the case of *E. agallocha* and *X. mekongensis*, it should be noted that other factors, such as a ban on tree felling for newsprint paper mills, strong monitoring to reduce illegal use of timber and anthropogenic activities, may have played an influential role rather than climatic variables.

The impacts of climate variability in the Sundarbans would be considerably more critical in the future. Climate models predict a decrease in rainfall (Agrawala et al. 2003), which might further reduce fresh water flows and promote more water withdrawals for agriculture upstream. This reduction in freshwater inflows into the Sundarbans could be exacerbated by increased evapo-transpiration losses and water use on account of global warming, and this reduced freshwater flows would consequently further enhance the salinity levels in the Sundarbans (Agrawala et al. 2003). In this situation, diseases such as die-back that is highly related to the level of salinity, will spread rapidly and affect the less salt tolerant species such as *H. fomes* in the Sundarbans. As a result of increasing salinity, less salt-tolerant mangrove species may be replaced by species that prefer habitats with high salinity (Ghosh et al. 2016). This could change the existing mangrove species composition and affect the biodiversity of the forest.

Although this research has found a decreasing trend of *H. fomes* and increasing trend of *S. apelatala* and *C. decandra* in response to increasing average maximum and minimum temperatures and decreasing total annual rainfall in the Sundarbans, the rates of change varied between sites, whereas rainfall and temperature did not vary that much. Thus, changes in species composition are likely to also be related to factors outside the scope of this research, such as sea-level rise, sediment composition, salinity stress, site-specific characteristics, anthropogenic influences and reduced freshwater flows from upper stream. For instance, the imposed ban on felling *E. agallocha* trees has facilitated the increasing trend of this species over the period 2000–2015, which is totally opposite to its previous two periods (Ghosh et al. 2016); similarly, coastal dynamics, more specifically accretion, also could have played an influential role in facilitating species composition change in the Sundarbans. Afforestation programs of salt tolerant *S. apelatala* trees in the newly accreted land could have played an important role in the increasing trend of this particular species, and overall species composition change during the study period; simultaneously, anthropogenic activities, such as over-exploitation of forest resources (specially the use of large woody trees like *H. fomes* and *E. agallocha*) for timber and other purposes, also could have played a vital role in the observed changes in the species composition (Ghosh et al. 2016), though these issues are not considered here. However, this paper finds interesting relationships between temperature, rainfall and mangrove species dynamics. A future study that incorporates these other factors could generate more realistic outcomes.

4.5. Conclusions

Mangrove ecosystems are complex in nature. For monitoring the impact of climate variability on this ecosystem, a multi-dimensional approach is a prerequisite. To understand the impact of climatic variables on mangroves, identification of relationships between climatic variables and the dynamics of mangrove species is essential. In this study, an effort was made to investigate the relationship between climatic variables and mangrove dynamics at species level in the Sundarbans of Bangladesh over a 38-year time period from 1977–2015. Some significant relationship have been found between temperature, rainfall and the dynamics of mangrove species.

The results reveal that over the study period, average maximum and minimum temperature have been increasing in the Sundarbans, while total annual rainfall has been decreasing. However, the trend of change was not similar for all three sites. During the study period, average maximum temperature has shown an increasing trend in Khulna and Bagherhat, and a decreasing trend in Satkhira. Similarly, average minimum temperature has shown an increasing trend for all three stations. Annual total rainfall has shown a decreasing trend in Satkhira and Khulna and an increasing trend in Bagherhat.

Five major mangrove species have been identified in the study area, which are *H. fomes*, *E. agallocha*, *C. decandra*, *X. mekongensis* and *S. apelatala*. According to our results, *H. fomes* and *E. agallocha* decreased by 10.7% and 4.8%, respectively, during the study period; whereas *C. decandra*, *X. mekongensis* and *S. apelatala* increased by 35.7%, 76.3% and 212.1%, respectively.

Linear regression results highlight a significant relationship between climate variables (maximum temperature and rainfall) and dynamics of mangrove species (especially *H. fomes*, *S. apelatala* and *C. decandra*) in the Sundarbans mangrove forest in Bangladesh. Over the study period, a strong relationship was found between the dynamics of *H. fomes* and *S. apelatala* with temperature and rainfall, while *C. decandra* showed a weak relationship. In contrast, no significant relationship has been found between the dynamics of *E. agallocha* and *X. mekongensis* and temperature or the rainfall pattern.

Identifying the importance of temperature and rainfall provides one dimension for assessing the impacts of climatic variables on mangrove species in the context of the vulnerability as a result of climate change. Continuous assessment is important to understand the impact of climatic variables on mangrove forests as well as for the development of adaptation strategies for the forest. The results obtained in this study could provide some invaluable insights for the development of proper adaptation strategies in the future.

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We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

Type of work	Page number/s
Figure 4.1	57
Figure 4.2	62
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Figure 4.6	67
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Name/title of Principal Supervisor: Professor Lalit Kumar

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We, the PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

	Author's Name (please print clearly)	% of contribution
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Other Authors	Lalit Kumar	15
	Chandan Roy	5

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23-05-2018

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23-05-2018

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Date

Chapter 5.

Mapping Tidal Channel Dynamics in the Sundarbans, Bangladesh, between 1974 and 2017, and Implications for the Sustainability of the Sundarbans Mangrove Forest

This chapter is under review with the journal *Environmental Monitoring and Assessment*:

Ghosh, M. K., Kumar, L., & Langat, P. K. (Under review). Mapping Tidal Channel Dynamics in the Sundarbans, Bangladesh, between 1974 and 2017, and Implications for the Sustainability of the Sundarbans Mangrove Forest.

5.1. Introduction

Mangrove forests occupy tropical low-energy depositional coastal and river deltaic regions worldwide (Kanniah et al. 2015; Kuenzer et al. 2011). Mangroves thrive in geomorphologically and hydrologically active areas of large sediment deposition with fresh water inputs and a rapid inflow of terrigenous sand, silt and clay, high salinity, high temperature, extreme tides and muddy anaerobic soils (Giri et al. 2011). However, mangrove communities are sensitive to the adverse effects of some natural and anthropogenic fluvial and oceanic changes (Ghosh et al. 2015a; Liu et al. 2008; Valiela et al. 2001), which usually occur in global, geologically unstable deltas and estuaries. Common phenomena include coastal and tidal channel erosion and accretion processes, salt water incursion, and rising sea levels, resulting in the loss of mangrove cover and a change in species composition (Danda 2010). Intertidal, sheltered, and low-energy muddy sediments provide the most optimal habitats for mangroves (Blasco et al. 1996). Condition changes caused by temperature, soil type, salinity, duration and frequency of inundation, accretion and erosion of soil, and tidal and wave energy may affect mangrove species development, composition, and distribution, and hence impact their sustainability (Islam et al. 2015).

The Sundarbans form one of the most vulnerable deltaic ecosystems worldwide with respect to fluvial and oceanic dynamics such as coastal erosion, sea level rise, and tropical cyclones (Roy 2010). Despite these threats, its mangrove flora form an ecologically important natural buffer and bulwark against coastal erosion and seawater ingress, and at the same time continue to represent an economic pillar of the most densely populated rich coastal regions in the world. Coastal diversity in the Sundarbans, for example in Sagar Island, has recently come under environmental threat from a variety of anthropogenic activities that cause multiple stressors, resulting in beach erosion, shoreline modifications, and the destruction of natural habitats (mud-flats, coastal dunes, mangrove vegetation, etc.) (Rakshit et al. 2015). Besides a human-induced impact on coastal biodiversity, natural forces such as rising sea levels and tidal currents also play key roles. Fluvial dynamics in the upper subaerial delta plain and marine processes in the active Bangladesh Sundarbans are a result of long-term tectonic processes and short-term tidal currents (Das 2004). River-borne sediment deposited annually by the Ganges and Brahmaputra rivers in the Bengal Basin during the monsoon flood pulse find their way to the vast mangrove ecosystem tidal delta through tidal inundation, the seasonal monsoonal rise in sea level, and storm surges (Rogers et al. 2013) .

A large part of the sediment is transported through tidal rivers and channels from the sea to delta flood plains of the Sundarbans by onshore propagation of the tidal currents and relative sea level rise. The western reach of the Sundarbans is no longer connected to significant upstream river sources of sediments (Allison and Kepple 2001; Rogers et al. 2013; Wilson and Goodbred Jr 2015) and greatly benefits from landward advection of sediments from the Ganges and Brahmaputra river mouths. The dense network of funnel-shaped tidal channels and the silt-dominated mangrove habitat of the Sundarbans is maintained by redistribution of onshore fluvial sediment advection by the tides (Wilson and Goodbred Jr 2015). Maintenance of the elevation of the tidal platform above the mean high water in the Sundarbans estuarine tidal platform, and a continued supply of fresh water from rivers are necessary for some of the mangrove vegetation survival and regeneration (Winterwerp and Giardino 2012). Although the elevation of the intertidal landscape of the Sundarbans mangrove forest has kept pace with relative sea level rise for decades (Auerbach et al. 2015) owing to natural forces reworking the sediments, it is not guaranteed that this status quo will continue. Like similar landscapes across the world, the Sundarbans face potential threats from changing climatic and anthropogenic forces (Chu et al. 2006; Day et al. 2007; Stanley and Warne 1998).

The River Ganges system, one of the major sources of fresh water for the Ganges–Brahmaputra tidal delta plains, has changed significantly, partly due to construction of a barrage in 1975 by the Indian government to divert large quantities of fresh water from the Ganges in order to flush the silt of the Hooghly River to save the Kolkata port (Mikhailov and Dotsenko 2007; Winterwerp and Giardino 2012), and partly as a result of a shift in the river bed channel (Wilson and Goodbred Jr 2015; Winterwerp and Giardino 2012). Effects of salinity ingress due to tidal amplification, sea level rise and tidal sediment advections, as well as climate change-induced altered river flows, may have implications for the aquatic mangrove ecosystem environment (Dasgupta et al. 2014; Pethick and Orford 2013).

Many studies (Alongi 2008; Gilman et al. 2007) have focused on geomorphic changes at the land– ocean interface in relation to mangrove stability, but relatively few studies have examined the land–river interface that comprises a large areal extent in deltaic systems. Few researchers have considered the changing tidal channel patterns of accretion and erosion in the deltaic plains around the world (Chu et al. 2006; Day et al. 2007). Dynamics of accretion and erosion are crucial to understanding coastal and mangrove forest environments, particularly in the highly sensitive Sundarbans coastal inlands. Some work on erosion–accretion processes of the channels and islands of the estuarine delta caused by tidal processes and regional subsidence patterns have been documented (Barua 1997; Brammer 2014; Hassan et al. 2017) but these studies did not cover active tidal floodplains channel dynamics. Allison et al. (2003) studied a sedimentary sequence resulting from lower delta plain progradation in the late Holocene, and concluded that the subsidence patterns in the tectonically active Bengal Basin controlled distributary channel avulsion and migration, and the creation of accommodation space. Chatterjee et al. (2015) applied Landsat satellite data and a GIS platform to study coastal shoreline accretion and erosion in the Indian Sundarbans. In the Bangladesh Sundarbans, Allison (1998) used geo-referenced and projection-corrected early and modern charts as well as Landsat imagery to document the morphology of shoal growth of the mouth of the Ganges over the late Holocene as a series of digitate shoal-channel complexes and reported an average accretion of approximately 7.0 km^2/year since 1792, with eastward evolution and westward retreat at a rate of 1.9 km^2/year. The author documented large tidal channel migration that extended inland but did not show evidence of net infilling or widening.

Many studies (Allison and Kepple 2001; Allison 1998; Wilson and Goodbred Jr 2015) have been performed on variations in delta and estuarine sediment deposition, topography, and hydrology, but the changing dynamics of the sediments advected from marine areas through the tidal inundation seasonal monsoon set-up of sea level and storm surges by erosion and accretion processes in the Sundarbans hinterland mangrove ecosystem are not yet fully understood. Climate and land use have the potential to vastly alter the sediment and hydrologic regime of rivers, with implications for their morpho-dynamic evolution. The dynamic evolutions of the tidal channel in ecologically sensitive areas such as the Sundarbans can translate to the extreme fragility of biodiversity, and may negatively impact on their sustainability. There are virtually no studies on how tidal channels in the Bangladesh Sundarbans region have seen their erosion/accretion rates altered as a result of these tidal disturbances. An understanding of the tidal channel dynamics that maintain the Sundarbans deltaic system elevation is crucial for planning of environmental management strategies.

This investigation is about mapping and assessing tidal channel erosion and accretion in the hinterland areas of the Bangladesh Sundarbans mangrove forest and suggests the factors behind the observed changes in the tidal channel morphology of the Sundarbans forest system. Aerial photographs and satellite imagery have been used in remote sensing and GIS platforms to analyse accretion and erosion and locations at three different time points over a period of 43 years. This study not only provides scientific understanding of mangrove physical geomorphology environment but also adds to a limited tidal channel erosion and accretion process knowledge base with respect to mangrove forest ecosystems.

5.2. Methods

5.2.1. Study area

The Sundarbans tidal delta plain, created by the confluence of three major river systems of the Ganges, Brahmaputra, and Mehgna in the Bay of Bengal, covers an area of approximately 10,000 km^2 (Chatterjee et al. 2015; Ghosh et al. 2016). The Sundarbans tidal delta plain can be divided into four specific zones: the inactive delta (once an active part of delta, but with currently reduced or no fluvial activity), mature delta (moribund deltas that have ceased), tidally active delta (a still active part with water channeling through it carrying sediment), and sub-aqueous delta (part of the delta that is below the low-tide mark) (Chatterjee et al. 2015). The Bangladesh part of the Sundarbans occupies the entire part of the active delta (Chatterjee et al. 2015) and is crisscrossed by a complex network of tidal channels which are more stable than the main stream of the Ganges, Brahmaputra, and Meghna (Ghosh et al. 2016; Islam and Gnauck 2011). Although there have been some micro topographical exceptions due to rivers, streams, and tidal flow (Begum 1987; Islam and Gnauck 2011), this deltaic wetland of the Sundarbans is almost flat. The land slope in this region is 0.03 m vertically per km of horizontal distance from north to south (Islam and Gnauck 2011). The elevation of the forest area varies between 0.9 and 2.1 m above mean sea level (Ghosh et al. 2015a; Ghosh et al. 2017b). The Bangladesh Sundarbans spreads over three administrative districts, namely Satkhira, Khulna, and Bagherhat, commanding an area of three- fifths of that of the entire Sundarbans (Ghosh et al. 2017b). Geographically, it spans the approximate latitudes of 21° 32' N to 22° 30' N, and longitudes 89° 00' E to 89° 51' E. However, for the present study, parts of the Passur tidal channel from the tidally active delta of the Bangladesh Sundarbans (latitudes 21° 52' N to 22° 06' N, and longitudes 89° 31' E to 89° 36' E) have been selected for the study of tidal channel dynamics (Figure 5.1). This study site has been selected as a representative of the active delta of the Sundarbans, partly because of the availability of good aerial photographs for this specific site for the year 1974. Secondly, the Passur River channel is strategically located between the eastern and western portion of the Bangladesh Sundarbans, offering a suitable area where anthropogenic and natural forces (tidal currents, sea level set-up and storm surges) of tidal channel dynamics may be at play. The Passur River system contains large intertidal areas affected by high floods during the monsoon season and receives fine sediments transported by tidal advection (Winterwerp and Giardino 2012). These changing patterns were observed by Aziz and Paul (2015) and were re-confirmed during our field visit in February–March 2016.

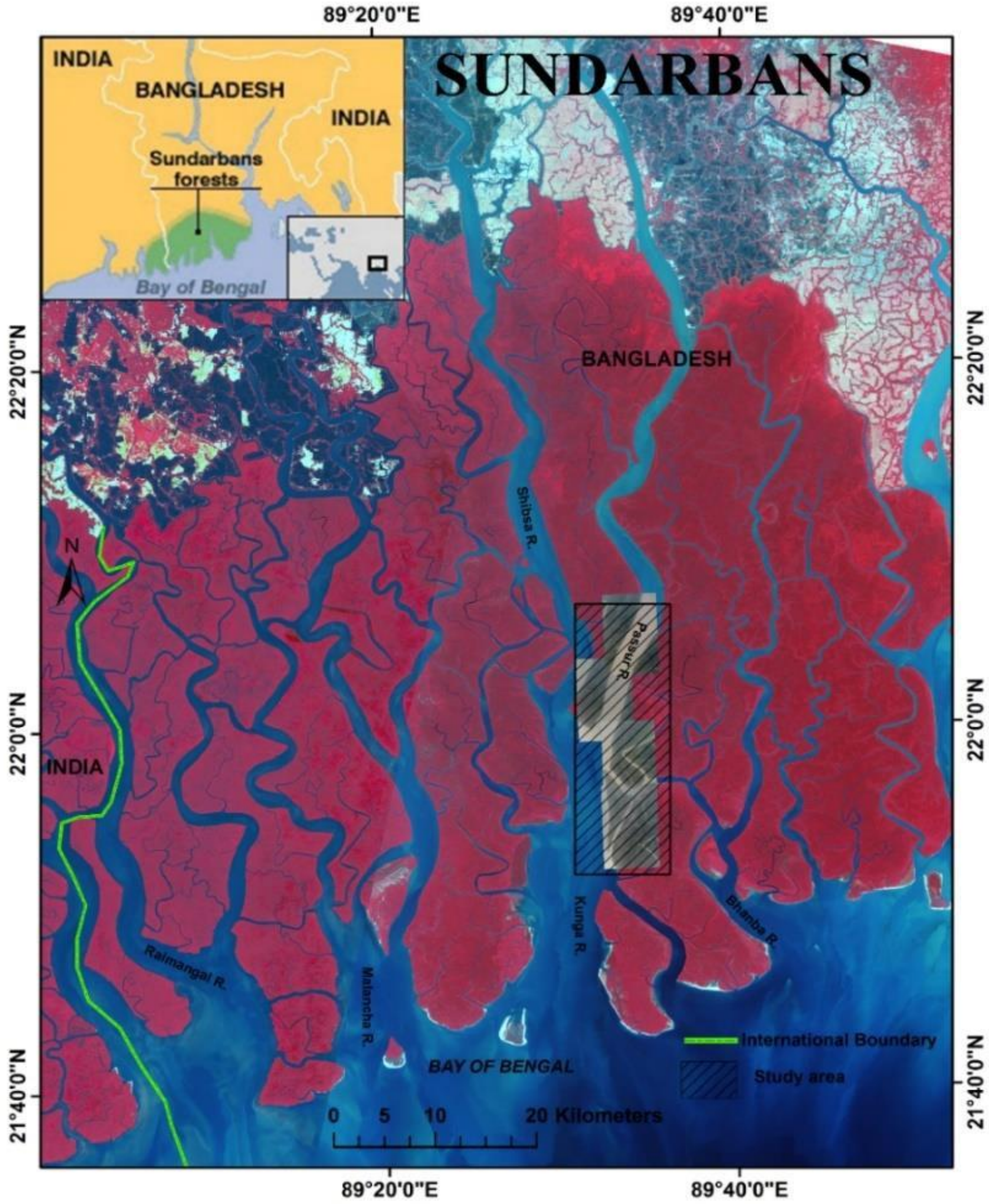

Figure 5.1 Location of the study area marked in the shaded box within the map (false colour composite) of the Bangladesh Sundarbans.

5.2.2. Data Used in This Research

To understand tidal channel dynamics of the study area, aerial photographs from 1974 and 2011, and a satellite image from 2017 were used. Satellite images from 1974 with good spatial resolution of the area were not available, and therefore aerial photographs of comparatively high and fine resolution were considered adequate to obtain information on tidal channel dynamics. Although high-resolution satellite imagery was available for 2011, aerial photographs were used for this study due to their effectiveness in terms of cost and also ease of comparison with the 1974 photographs. The aerial photographs were sourced from the Survey of Bangladesh (SOB). The Sentinel-2 satellite image from 2017 was downloaded from the European Space Agency (ESA) website (https://scihub.copernicus.eu/). The aerial photographs from 1974 and 2011 were taken with scales of 1:30000 and 1:20000, respectively. The satellite imagery of Sentinel-2 (10 m spatial resolution) acquired in April 2017 was used to identify the changes in tidal channels which occurred only at larger scales because the resolution of the image was not sufficiently high as compared to aerial photographs. Comparatively, larger changes in the tidal channel were considered for the period from 2011 to 2017, keeping in mind the possible error of identification of tidal channels due to spatial resolution of the image and with the assumption that the error was low compared to the scale of tidal channel shifts. A Sentinel-2 image was used in this study, as aerial photographs for this date were not available and the Sentinel-2 image provided the only high-resolution data among the freely downloadable datasets.

5.2.3. Identification of Tidal Channel Dynamics

The aerial photograph frames from 1974 were scanned from black and white (B/W) printed copies at a resolution of 600 dpi, whereas the photographs from the year 2011 were supplied in digital form by the SOB. All the images were imported into ArcGIS (ESRI Inc. version 10.1) as digital images and were georeferenced to the UTM 45° N, WGS 84 map system using at least 16 ground control points (GCPs) since none of the photographs were georeferenced. The image to image registration technique was used for the registration of the images. A satisfactory root-mean-square (RMS) error was achieved (less than 4 m) for the registered images. Visual inspection was also undertaken to confirm that the overlaid images matched each other well. Thereafter, aerial photographs were mosaicked for the whole study site. Registration of the Sentinel-2 image was undertaken using 47 GCPs with an RMS error of 0.002439 pixels. Tidal channels were then extracted from both of the mosaicked aerial photographs and Sentinel-2 image. On-screen digitization of the tidal channel was undertaken to create the tidal channel layers and special care was taken during digitization to obtain more accurate results. Layers were overlaid together so that the tidal channel position could be seen at each date. Tidal channel positions were highlighted to infer the erosion/accretion sectors along the channel and the tidal channel dynamics were calculated. Demarcation of tidal channel banks showed some uncertainties because of the existence of indistinct boundaries due to tidal effects. However, the uncertainty of demarcation of tidal channel banks was minimized by including the muddy areas with grasses (accretion) and by excluding the muddy areas with no grasses in the calculation, keeping in mind that muddy areas with grasses are already established and could be considered as an established tidal channel bank (see Figure 5.2(a)). In addition, tides would not make a difference in calculations as banks are vertical in most of the places, and for others with floodplains we have taken the vegetation edge as a tidal channel bank. Ideally, for the best accuracy, comparisons over long periods of time must be made at exactly the same tide level. However, the reality is that over such long periods of time (in this case 1974–2017) data management is limited by the data available. Satellite overpasses are also at a fixed time of the day and cannot be modified for each capture. These are sources of error in studies of this kind that use historical data. However, we travelled extensively through the Sundarbans study area over a three-week period and are certain that most of the channels, especially the wide channels, have vertical banks (for instance see Figure 5.2(b)). For the narrower channels, instead of the water line, the mud line was used for the channel widths. This improves the accuracy and is a standard technique in remote sensing work.

Figure 5.2 Photographs showing (a) tidal area with grasses; (b) evidence of tidal channel bank erosion; and (c) accretion and sediments deposits. These photographs were taken on 25 February 2016 in the Sundarbans.

5.3. Results

Mapping and assessing tidal channel erosion and accretion to obtain information on tidal channel dynamics indicated large displacement of tidal banks. The shift in the tidal channel bank between

1974 and 2011 is shown in Figure 5.3. The red line in the map represents the position of the tidal channel bank in 1974, whereas the green line shows the position of the tidal channel bank in 2011. The most remarkable result observed in this study is the large shift of the tidal channel bank. In this study, four channel locations (A, B, C, and D) were identified from aerial photographs where the shift of the tidal channel bank was prominent. Channel locations A and C were erosion-dominant, while channel locations B and D were dominated by accretion. There were also some unaffected channel locations in the study area between these erosion and accretion-prone segments. The changes in tidal channel bank positions for these four sites are shown in Figures 5.4(a)–(d) (the red line in the map represents the position of tidal channel bank in 1974 and the green line represents the position of the tidal channel bank in 2011) while the changing width of the channel and the extent of the shift are given in Tables 5.1 and 5.2, respectively.

Figure 5.5 further illustrates the images and changes in the selected sites in Figure 5.4 for the years 1974, 2011, and 2017. Channel location A, which extended for 12.18 km with a maximum channel width of 2.17 km and a minimum channel width of 1.66 km in 1974, experienced major erosion, with the tidal channel bank displacement ranging between 0.007 and 0.36 km in the right bank, and between 0.012 and 0.15 km in the left bank. The maximum and minimum widths of this channel location became 2.43 and 1.85 km, respectively, in 2011 due to the displacement of the tidal channel bank as a result of erosion. Channel locations B, C, and D, which extend for 4.15, 2.25, and 7.50 km respectively, had maximum channel widths of 1.33, 0.42, and 1.16 km, and minimum channel widths of 0.26, 0.29, and 0.67 km, respectively, in 1974. They had maximum channel widths of 0.71, 0.60, and 0.26 km, and minimum channel widths of 0.50, 0.46, and 0.11 km, respectively, in 2011. The displacement of the tidal channel bank for the channel locations B, C and D ranged between 0.063 and 0.82, 0.013 and 0.12, and 0.046 and 0.80 km in the right bank and 0.015 and 0.26, 0.014 and 0.20, and 0.014 and 0.34 km in the left bank, respectively. The total land area within the study landscape was 130.54 km^2 in 1974 and 130.75 km^2 in 2011, giving a net accretion of 0.21 km^2 and a yearly rate of accretion of 0.0057 km^2 within this period. Channel locations A and C, where the overall trend is towards erosion, witnessed a retreat of the tidal channel bank, and this played an influential role in the widening of the tidal channel, while channel locations B and D, where the overall trend was towards accretion, experienced an advancement of the tidal channel bank which played a vital role in raising the tidal channel bed and also making the channel narrower.

Figure 5.6 illustrates the changes of the tidal channel bank between 2011 and 2017. The positions of the tidal channel bank in 2011 and 2017 in the map are represented by red and black lines, respectively. Channel locations A1 and B1, which extend for 1.1 and 0.8 km, had maximum channel widths of 0.65 and 0.26 km, and minimum channel widths of 0.57 and 0.083 km, respectively, in 2011, but the maximum and minimum channel widths at location A1 were found to be 0.73 and 0.58 km, respectively, in 2017. For location B1 the maximum and minimum channel widths were 0.26 and 0.059 km, respectively. The displacement of the tidal channel bank for channel locations A1 and B1 was 0.016–0.041, and 0.011–0.048 km in the right bank and 0.030–0.063, and 0.012–0.030 km in the left bank, respectively. At channel location A1, the sedimentation process was dominant in the right bank, while the erosion process was dominant in the left bank. On the other hand, the sedimentation process was dominant in channel location B1 on both sides of the tidal channel.

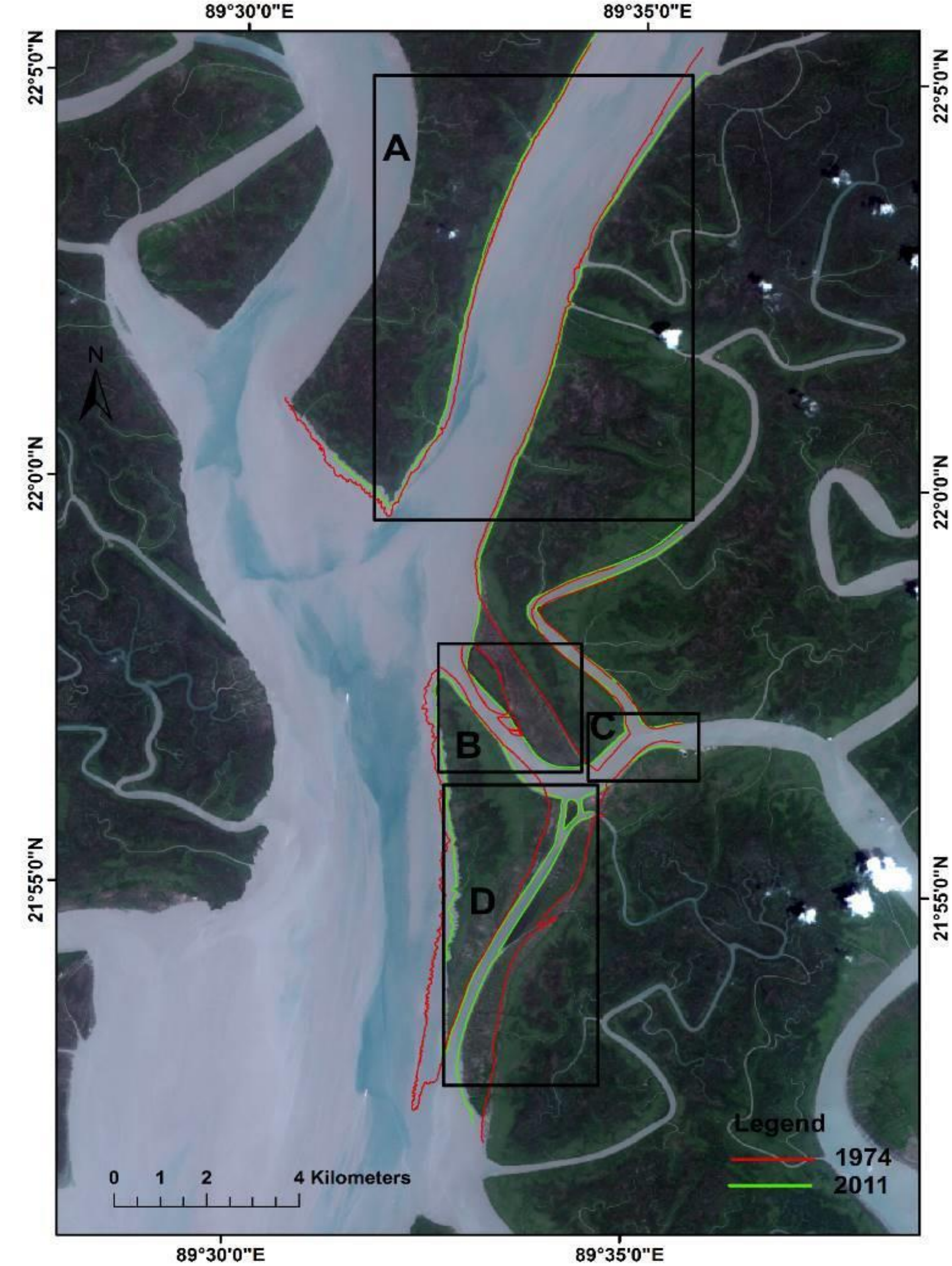

Figure 5.3 Tidal channel bank change map of selected channel locations in the Sundarbans, Bangladesh between 1974 and 2011.

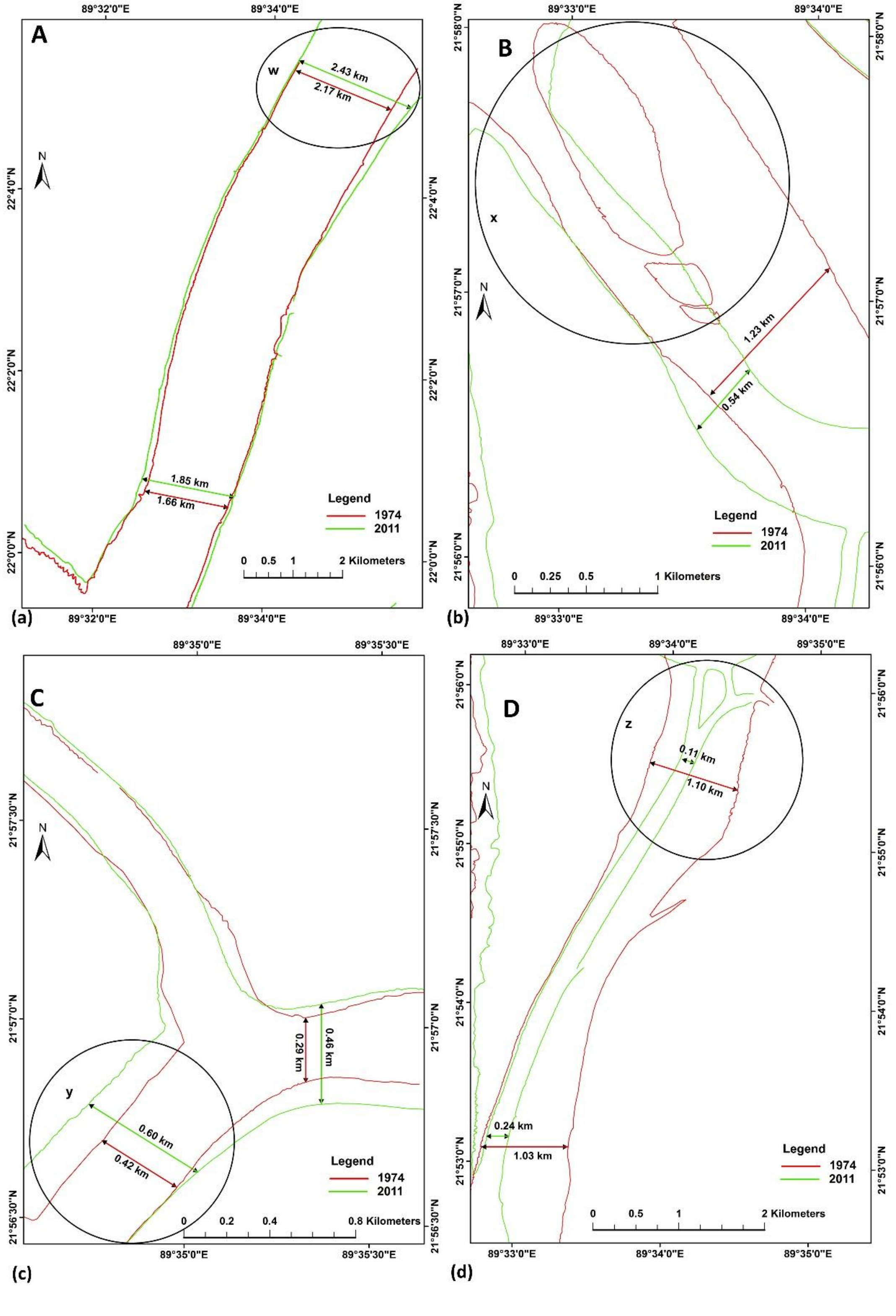

Figure 5.4 Tidal channel bank change map of selected channel locations in the Sundarbans, Bangladesh between 1974 and 2011. (a) Channel location A; (b) channel location B; (c) channel location C; and (d) channel location D. Aerial photographs and satellite images for circles marked with w, x, y and z are shown in Figure 5.5.

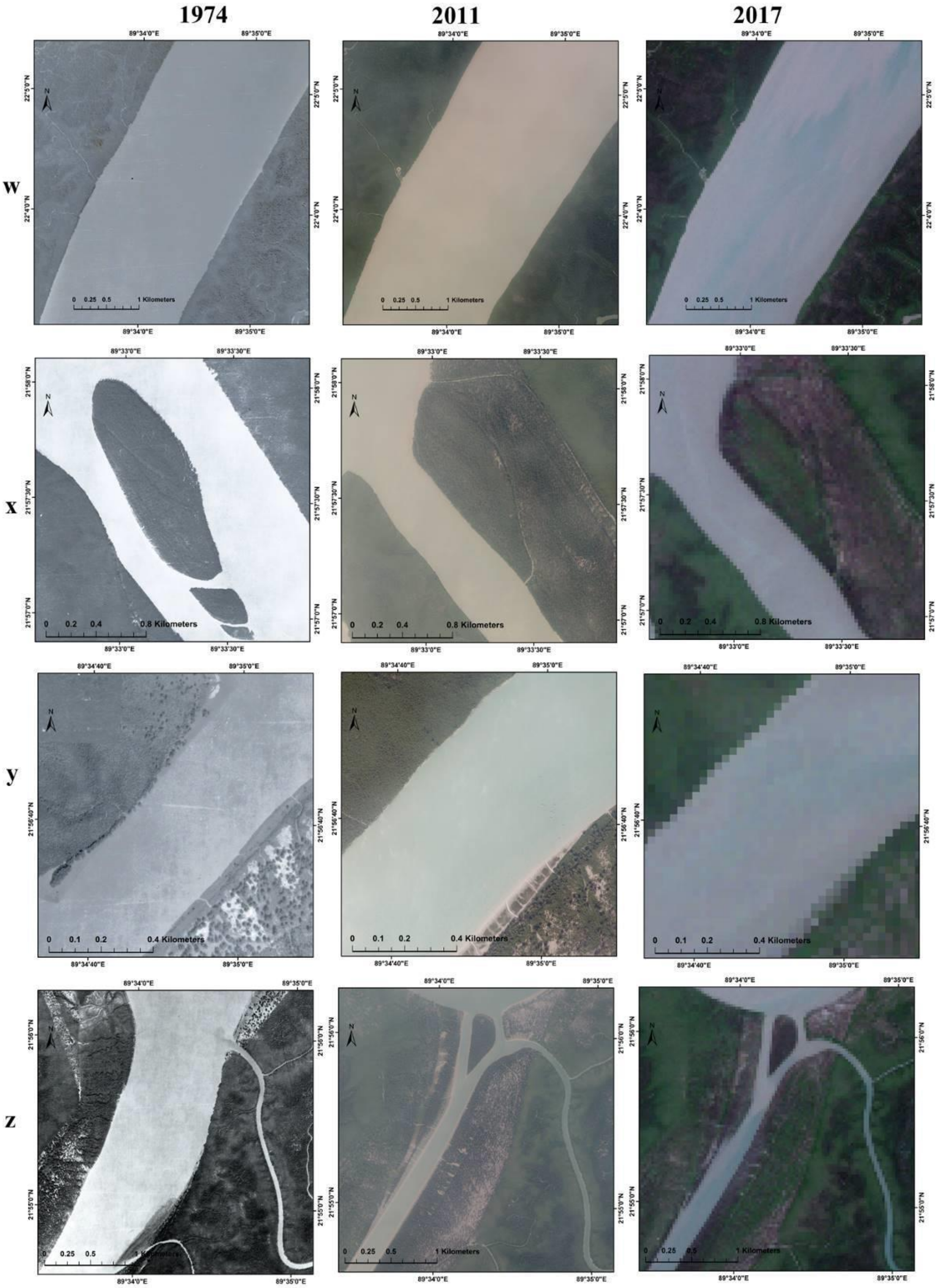

Figure 5.5 Tidal channel bank images showing changes of selected channel locations in the Sundarbans, Bangladesh between the time points in 1974, 2011, and 2017. w: taken from channel location A; x: taken from channel location B, y: taken from channel location C; and z: taken from channel location D. Each set of three images has the same scale, for ease of comparison.

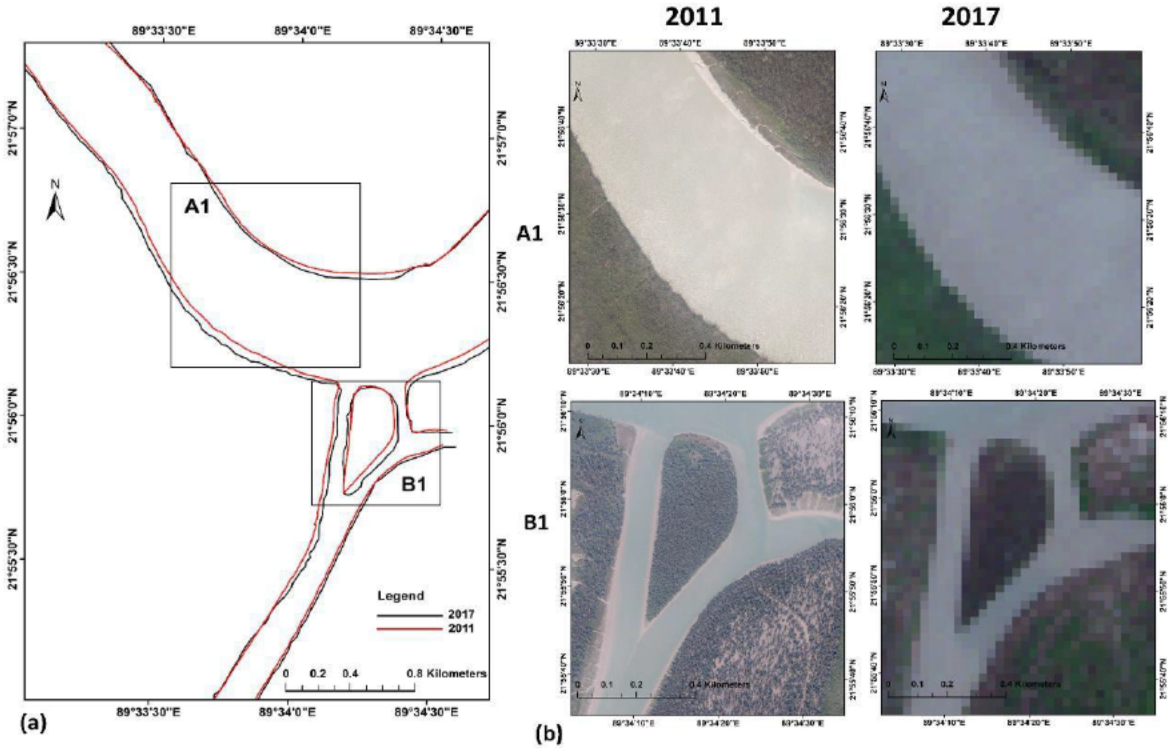

Figure 5.6 Tidal channel bank change map of selected channel locations in the Sundarbans, Bangladesh between 2011 and 2017. (a) Tidal channel bank layers; and (b) tidal channel bank images. A1 was taken from channel location A1, and B1 was taken from channel location B1. Each set of two images has the same scale for ease of comparison.

Table 5.1 Changing patterns of channel width at selected channel locations in the Sundarbans, Bangladesh (1974–2011).

Channel Location	1974 (width in km)		2011 (width in km)		Dominant Process
	Highest	Lowest	Highest	Lowest	
A	2.17	1.66	2.43	1.85	Erosion
B	1.33	0.26	0.71	0.50	Accretion
C	0.42	0.29	0.60	0.46	Erosion
D	1.16	0.67	0.26	0.11	Accretion

Table 5.2 Displacement of the tidal channel bank at selected channel locations in the Sundarbans, Bangladesh (1974–2011).

Channel Location	Displacement of the tidal channel bank between 1974 and 2011 (in km)			
	Right bank		Left bank	
	Highest	Lowest	Highest	Lowest
A	(–) 0.36	(–) 0.007	(–) 0.15	(–) 0.012
B	(+) 0.82	(–) 0.063	(–) 0.26	(–) 0.015
C	(–) 0.12	(–) 0.013	(–) 0.20	(–) 0.014
D	(+) 0.80	(+) 0.046	(+) 0.34	(+) 0.014

Note: The (–) sign represents retreat (erosion) and the (+) sign represents advancement (accretion) of the tidal channel bank.

5.4. Discussion

The Sundarbans mangrove forest ecosystem is a wetland of international importance. It was designated a Ramsar site in the year 1992 and a UNESCO World Heritage site for the conservation of unique plant and animal communities. Although, natural processes, such as cyclonic storms and tidal surges have always existed, recent years events have severely affect the biotic life of the deltaic system by uprooting plants, eroding tidal channels and coastal soils, breaking stems and branches, and threatening human livelihoods.

Within the period covered in this study, two main disastrous cyclonic/major flood hazards occurred. The first was a cyclone in April 1991 which affected the Sundarbans coastal region, and the second was the super cyclone SIDR of 2007, which had huge negative impacts on the Sundarbans ecosystem (Bhowmik and Cabral 2013). Other hazardous events include the devastating floods of 1998 which inundated one-third of the Sundarbans (Ali 1996; Kunii et al. 2002) and 14 other cyclones reported since 1990 (Siddiqui 2013). The tidal channel morphology dynamics observed in this investigation are partly attributed to the disturbance of these cyclones. It was found that large mangrove forests in the riparian areas at the study site were washed away in the period between 1974 and 2017. The erosion–accretion processes of the tidal channels between 1974 and 2011 are fundamentally the result of channel dynamics as observed in the study area. A similar observation has been reported by Ghosh et al. (2015b), and Kumar and Ghosh (2012) for the Meghna River estuary. Amalgamation of factors and processes offer an explanation of the patterns and dynamics of tidal and intertidal channels in the Sundarbans. The morphologic changes of the Passur tidal channels are attributable to oceanographic, terrestrial, and anthropogenic factors which commonly affect coastal regions.

The results observed in this study can be attributed to many factors driving the processes. As for oceanic factors, tidal currents have also been suggested to have a strong influence on coastal tidal channel erosion and accretion processes due to their modulation and their different response to dynamics of the natural propagations (Kumar et al. 2014). Erosion processes in some channels (channel location A in Figures 5.2 and 5.3 (a)) occur due to the strength of intertidal mud, level of compaction of the mud, and also the absence of salt marsh vegetation supported by the shape and size of the channels. Channel banks erode in very sharp bends where the flow separates from the inner-bend channel boundary and impinges directly on the bank on the opposite side of the channel (Kleinhans et al. 2009; Winterwerp and Giardino 2012) as canbe observed in channel location C of Figures 5.2 and 5.3(c). The eroded soils deposited when the channels banks overtop were dynamically rearranged in the deltaic floodplains. The river propagation of the sediment loads during monsoons and channel storm discharges, combined with sea level rise, earth subsidence, and floods, enhance the erosive capacity and widening of the tidal channels (Barua 1997; Brammer 2014; Hassan et al. 2017). On the other hand, the accretion of fine sediments (channel location D in Figures 5.2 and 5.3(d)) occurs as a result of overbank sedimentation enhanced by several factors including river slope, lateral channel movement at inner bends, base level, and the occurrence and increased magnitude of channel discharge (Zwoliński 1992). Accretion processes, due to overbank flooding, create a shallow stratigraphy of finer-grained soil deposits, with sand deposits restricted to the channel thalweg, proximal levees, and small crevasse splays along the stable, meandering channel floodplains. There is a later stabilization in aggradation which forms gained lands of shallow, intertidal flats colonized with mangrove vegetation (Wilson and Goodbred Jr 2015). The interaction between the flood plains, channels, and vegetation drives the tidal channels dynamics of the Sundarbans mangrove vegetated floodplains.

Terrestrial factors include river discharge, sediments, earthquakes, local neo-tectonics, and land slope, which strongly influence the dominant erosion–accretion processes in the tidal areas (Wadman 2008). Although the Ganges hydrological regime has generally reduced since the early 1970s in the Bangladesh part supplied by Gorai River, for instance from 3338 m^3/s in 1962 to 500 m^3/s in 2003 (Islam and Gnauck 2009a), the Ganges River system delivers a significant amount of sediment to the coastal delta (Winterwerp and Giardino 2012). This sediment is usually transported by tides to the Passur tidal channel system. The seasonal monsoon (July to September) causes a major increase in streamflow, which erodes and accretes the tops of predominantly fine sand bars created by dynamic processes of erosion and deposition, natural levees and crevasse splays formed along local distributaries and breaches, and proximal floodplains within the Ganges–Brahmaputra–Meghna delta (Wilson and Goodbred Jr 2015). The sediment supply is due to the advection of river sediment transport and the reworking of sediment deposited in the lower deltaic plains by tidal currents. Upstream human activities, viz. establishment of dams and barrages and water withdrawals for irrigation, can have profound impacts on the morphology of the tidal channels in the Sundarbans. For instance, low sediment deposition as a result of very low discharge (sometimes nil) in the dry period, and erosion of the tidal channel banks and marginal areas of the forestland due to high discharge (around 4000–8880 m^3/sec) in flood periods, could be considered an effect of the Farakka Barrage (Aziz and Paul 2015) during this time.

The net accretion in the study area within the study period was 0.21 km^2 (130.75 km^2 in 2011 compared to 130.54 km^2 in 1974). Although variability in the physical environment and differences in subsidence, compaction, and alterations of the tidal regime exist in the Sundarbans, the local tidal dynamics observed in the study area may be applicable to many parts of the Bangladesh Sundarbans, owing to similar floodplain areas, soil sediment types, and vegetation homogeneities. The sedimentation process in the mangrove vegetated floodplains plays an active role in the increment of the aerial extent of mangrove forests, in mangrove species composition dynamics, and also in maintaining forest elevation and stability in response to sea level rise. Rogers et al. (2013) observed that the Sundarbans is capable of mean annualized accretion rates of 1.1 cm/ yr^{-1} on the tidal delta plain, which is roughly equivalent to the mean regional rate of relative sea level rise (RSLR) of 1.0 cm/$year^{-1}$. This sedimentation process has helped the Sundarbans mangrove forest to remain relatively stable over the past several thousand years (Allison et al. 2003) with no major land loss like in other parts of the world (Auerbach et al. 2015). The long-term stability of the Sundarbans reflects the robust capacity for the Ganges–Brahmaputra delta to disperse and aggrade sediment in response to historical and recently increased rates of effective sea level rise (Auerbach et al. 2015). If these rates of sedimentation and subsidence persist over the next century, the Sundarbans may continue to maintain its elevation and stability.

The channel dynamics of the study area are may be the result of erosion (Figure 5.2 (b)) and accretion (Figure 5.2 (c)). Observed erosion dominance in the wider channels and accretion dominance in smaller channels (Figures 5.3 and 5.4) may be a function of channel discharge currents via waves and tides. Wider channels are principal tidal/river channels with strong tidal and wave-driven bed shear that prevent the deposition of fluvial sediments and encourage erosion. Smaller channels are basically intertidal channels, and these channels are sometimes starved by discharge, which encourages accretion. Loss of land due to erosion causes tree falling (see Figure 5.2(b)). On the other hand, new lands are gained through the accretion process, for example the island in the north- eastern part of channel location D in Figures 5.3, 5.4(d) and 5.5(z), which had developed by 2011. These lands are usually more saline due to frequent inundation, and are dominated by salt-tolerant mangrove species such as *Ceriops decandra* and *Sonneratia apelatala*. The salinity tolerance levels of various mangrove species found in the Sundarbans vary spatially (Ghosh et al. 2016).

The bank line of the channel location A that experienced the major erosion during the study period was occupied primarily by the salt-tolerant species *C. decandra*, followed by the less salt-tolerant species *Heritiera fomes* in the left bank, whereas the right bank was occupied by *H. fomes* entirely. As a result of erosion, both the banks lost their bank line tree species and exposed the freshwater-loving *H. fomes* to salinity and made them vulnerable. Details are documented in Ghosh et al. (2016). On the other hand, in channel location B and D, where the accretion was the dominant force, the newly accreted lands are colonized by the salt-tolerant *S. apelatala* trees. Most of the newly accreted lands are afforested by this particular tree species in the preliminary stage to help the sedimentation process, as a part of land reclamation polices and afforestation programs of the Forest Department (Ghosh et al. 2016). When newly accreted land is colonized by salt-tolerant trees, it is usually not replaced by other trees unless a deforestation process by artificial means or natural forces occurs. As a result, mangrove species that forests lose through land erosion, and new mangrove species that forests gain through accretion, are not always the same and this may have implications with respect to the composition and sustainability of some non-salt tolerant species, as documented by (Ghosh et al. 2016). In addition, sedimentation in the forest has a substantial impact on the existence and vigorous growth of some mangrove species, since it raises the forest floor and the flow of tidal water becomes irregular. As a result of the irregular flow, some mangrove species that require regular inundation for their regeneration are not properly regenerated. While in the short term these changes are minor, over decades the dynamics of tidal channel might have significant implications in mangrove species composition change in the Sundarbans, and these continued erosion and accretion processes raise concerns with respect to the future sustainability for some of the mangrove species and also the biodiversity of the Sundarbans.

The observations from this study and many others indicate that the delta coast as a whole can be considered relatively robust against environmental variability and perturbations, as reflected in the land gains which is largely consistent with rates over the last five decades. However, coastal areas of Bangladesh are potentially sensitive to changing sea levels, extreme weather events (viz. cyclones), increased levels of precipitation, and warmer sea temperatures. As a part of Bangladesh's coastal area, the Sundarbans mangrove forest is not an exception. The situation could become more serious due to the changing patterns of global climate. It is expected that changing climate will influence and exacerbate those issues that the coastal areas are sensitive to. Several factors, such as rapid glacier melt, enhanced monsoon precipitation, and sea level rise, are expected to contribute to increased flooding risk and higher levels of storm surges along the Bangladesh coast, and the Sundarbans will be the innocent victim of these events (Mahadevia and Vikas n.d). Although the sedimentation process helps the Sundarbans mangrove forest to remain relatively stable in response to rising sea levels, other afore-mentioned factors can affect the mangrove forest in the future. Continuous monitoring of tidal channel dynamics or tidal channel morphology is important for a thorough understanding and management of the forest ecosystem, as tidal channels act as a lifeline for the mangrove forest ecosystem.

5.5. Conclusions

Tidal channel dynamics have been mapped in parts of the Sundarbans in this study over a period spanning 43 years (1974-2017). Aerial photographs and satellite imagery were used in remote sensing and GIS platforms to analyse accretion and erosion and locations in different years. The results showed that substantial displacement of tidal channel banks took place over the period 1974–2017. Although the demarcation was difficult for the Sentinel-2 image due to its coarse resolution, the large changes in tidal channel widths observed would not have been greatly be affected by the less than 5-m error (the root-mean-square error was less than half a pixel during geo-registration) commonly associated with Sentinel-2 images. The channel changes were an order of magnitude higher than the errors associated with the images. Our analysis shows that the change in tidal channel bank location in some places was over a kilometer, and if this rate of change continues then there could be major changes in the forest ecosystem. This could also affect the sustainability of the forest ecosystem and the biodiversity therein.

Moreover, studies are recommended to link data on rising sea levels, snow melt in the Himalayas, sedimentation rate, rainfall in the overall catchment, hydrological data, anthropogenic activities, and other processes taking place in the Ganges delta and Sundarbans mangrove ecosystem. Furthermore, studies are also recommended to synthesize the forcing mechanisms of river and tidal river dynamics in the context of natural and anthropogenic forces and their implications on the Sundarbans delta floodplain mangrove forest. This would be useful for scientific understanding of the tidal channels geo-morphodynamic driving forces and their impacts from the point of climate change, which could have severe consequences on these low-lying forest ecosystems, such as the Sundarbans mangrove forest. To predict the future of this important mangrove ecosystem in terms of mangrove community and their habitat, the results of this study could be integrated with other datasets such as those on mangrove species composition, sea level rise, snow melt in the Himalayas, sedimentation rate, rainfall data, hydrological data, and anthropogenic activities. These findings can also be shared with sustainable management planners, other relevant stakeholders, and policy-makers for use in decision-making with respect to forest management planning in a sustainable manner.

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Type of work	Page number/s
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Chapter 6.

Tidal Channel Dynamics in the Sundarbans Mangrove Ecosystem: Responsible Forces and their implications.

This chapter is under review with the *Journal of Coastal Research*:

Ghosh, M. K., Kumar, L., & Langat, P. K. (Under review). Tidal Channel Dynamics in the Sundarbans Mangrove Ecosystem: Responsible Forces and their implications.

6.1. Introduction

Coastal floods associated with natural and anthropogenic forces constitute the world's foremost natural hazard to flood plain deltaic life, ecosystem and ecosystem services. The coastal delta systems face a number of key challenges, and its vulnerability require precise understanding if disastrous coastal erosion, submergence and flooding consequences for the environment and delta residents are to be addressed. Erosion and accretion processes are one of the fundamental challenges as they play an active role in the displacement of tidal river banks which subsequently have profound impact on ecosystem functioning and provisioning (Kaliraj et al. 2015).

The tidal channel patterns of distinct planforms and braids evolution, as a result of spatial arrangements of sediment fluxes, has been understood to be an interaction between bar channels, floodplains and vegetation. Floodplain determines the style and rate of channel avulsion after an aggradation process while sediments provide boundary conditions for formation of distinct bar patterns which create conditions for erosion and accretion dynamics of tidal river networks through bifurcation destabilization (Kleinhans 2010). Meandering is a result of alternate bars formed in a straight channel with static perturbation upstream (for instance by vegetation resistance) which grow to maximum amplitude before cut-offs (Dijk et al. 2013). Studies have shown that tidal river dynamics can assume simple (symmetrical in shape) to complex asymmetrical with steep bank on one side and shallow bar on the opposite (typical cut bank/ point bar morphology) or even more complicated with flood and ebb tidal channels hugging shorelines and shoal in between (Auerbach et al. 2015). While river channel dynamic processes at coastlines and delta mouths are fairly well understood, knowledge on erosion and accretion processes and their impacts in active deltaic floodplains, particularly in vegetated wetland flood plains such as Bangladesh Sundarbans, remains scanty.

Allison (1998) found annual land accretion of 7 km^2/ year in the river-mouth region of the Ganges-Brahmaputra while Allison and Kepple (2001) using ^{137}Cs and radiocarbon, indicated sediment accretion on decadal and millennial time scales at the rates reaching 1.1 cm/year at the deltaic floodplain of the Sundarbans. Wu (2007) attributed hurricanes, sea level change, variations in coastal circulation, riverine discharge patterns and beach nourishment to the shoreline erosion and accretion processes in the region of Nouakchott, Mauritania. Yu et al. (2011) assessed shoreline changes at the west-central Florida and reported similar influences of natural and artificial forces.

The Sundarbans coastline of the Bengal delta in Bangladesh and India, like many world deltas, is affected by sea level rise and variation of tidal level actions, natural subsidence and river sediments supply (Raha 2014; Syvitski and Saito 2007). The dynamics of erosion and accretion of the Sundarbans coastlines have been reported to show varied direction and extent of erosion and accretion rates throughout different periods with high erosion rates and declining accretion rates in the recent past (Rahman et al. 2011). These tidal river dynamics create large-scale net annual land gains and losses leading to the formation of a subaerial landscape which are commonly capped by silty mud (Brammer 2014) as the landscape moves from subtidal to intertidal conditions (Goodbred Jr and Saito 2012). Erosion and accretion processes are not confined to tidal rivers but the processes are also happening in tidal channel systems in vegetated marshlands. However, driving forces of these dynamics still require more work to be understood.

A network of rivers and creeks criss-cross the Sundarbans dense evergreen rain mangrove forest at the delta plains and the tidal river dynamics can be impactful to the mangrove ecosystem. Erosion processes have been found to be dominant along the banks of major tidal channels and at the land−water interface at the Bay of Bengal (Giri et al. 2011). While coastal shoreline suffers only major erosion (Shearman et al. 2013), the hinterland deltaic tidal channels suffer a net onshore advection, redistribution and onshore transport processes of fluvial sediment causing the dynamics of the channel system of the delta (Allison and Kepple 2001; Rogers et al. 2013) and subsequently affecting the ecosystem biodiversity including mangrove composition (Ghosh et al. 2016). The dynamic tidal channels erosion and accretion processes are responsible for rapid changes in planform evolution and major channels lateral shifting and widening (CEGIS 2003). Such morphological dynamics not only render negative impacts socially and economically but also constraint land development and more importantly threaten the Sundarbans ecosystem composition and its services provision. Changes in size of the forestlands due to the tidal river dynamic nature of the Sundarbans may wash away forestland near the coast and hinterland of the active Sundarbans from time to time and may negatively impact on the mangrove species composition.

Although previous researchers have studied the coastal shoreline dynamics with a discourse on the possible driving forces (Allison 1998; Allison et al. 2003; Rahman et al. 2011; Rogers et al. 2013), little can be said of the tidal channel dynamics and their responsible forces in the landward mangrove forests. Ghosh et al. (2017a) assessed tidal river erosion and accretion in the hinterland areas of Bangladesh Sundarbans mangrove forest and observed changes in river/channel morphology of the Sundarbans forest system. Neogi et al. (2017) reviewed the major functional aspects and highlighted biodiversity and ecosystem dynamics services of the Sundarbans in relation to climatic factors variabilities. Chatterjee et al. (2015) identified 16 possible erosion and accretion forcing parameters at the shoreline of the Sundarbans, India but this review did not cover the hinterland coastal environment. In the Sundarbans ecosystem, erosion-accretion processes may have short or long-term implications with potential impacts on the environment and society. This paper aims to demystify further on the possible factors behind the tidal river mophodynamics in the Bangladesh Sundarbans whose forest, unlike the Indian part of the Sundarbans, has remained largely intact in size and areal extent in the last three decades (Dwivedi et al. 1999; Emch and Peterson 2006; Ghosh et al. 2016; Islam et al. 1997). This study synthesises the forcing mechanisms of river and tidal river dynamics in the context of natural and anthropogenic forces and their implications on the Sundarbans delta floodplain mangrove forest. Published data and information as well as observation data such as seasonal variation of rainfall and glacial retreat are used in this discourse to highlight the tidal river dynamics and their impacts in the Sundarbans. This information is crucial for scientific understanding of the tidal channels geo-morphodynamic driving forces and their impacts from the point of climate change, which could have severe consequences on these low-lying forest ecosystems, such as the Sundarbans mangrove forest.

6.2. Description of the Sundarbans

The Sundarbans wetland ecosystem is the world's single largest mangrove forest hosting about 4 percent of the world's mangroves population and covers an area of 10000 km^2 (Spalding 2010). It is located in the southwest of Bangladesh and south-eastern portion of the state of West Bengal in India (Figure 6.1). Approximately three-fifths of the Sundarbans is located in Bangladesh and the rest is in India (Spalding 2010). The Sundarbans landscape consists of many fluvial and tidal lands formed by sediments deposited by the gigantic and complex Asian river system of the Ganges, the Brahmaputra and the Meghna at the Bay of Bengal. The Ganges and Brahmaputra rivers emanate from the Himalaya plateau and discharge into the Bay of Bengal along a delta front of 380 km. The Ganges distributaries provide freshwater runoff to the Sundarbans. The world's only uninterrupted mangrove forest, the Sundarbans, lies on the lower delta plain and is characterized by a network of mudflats, tidal and tidal channels, and creeks of different sizes and lengths crisscrossing the dense mangrove forest. Most of these network of river distributaries and secondary tidal channels were formed in an earlier phase of Holocene period

(Allison 1998). This lowland area has a humid tropical monsoon climate and its temperature ranges from 11°C to 37°C (Ghosh et al. 2017b) with an annual mean range of about 8°C. The Sundarbans forms part of the Ganges-Brahmaputra river delta system which displays a dynamic geomorphic river and tidal channels form similar to other major delta systems of the world; the Mississippi and Mekong delta. Unlike the other coastal deltaic floodplains, tectonic and subsidence forces as well as structural changes, and coastal processes are unique to the Ganges-Brahmaputra active deltaic floodplains (Morgan 1970). The Sundarbans mangrove resources play a crucial role in the local regional economy and supports other ecosystem services such as stabilizing the coastline, enhancing landscape formation and enriching both soil and aquatic environments. The coastal mangrove wetlands are dynamic and the ecosystem sustainability faces potential threats of the present soil, water and environment driving forces.

The Bangladesh Sundarbans Mangrove forest, the main focus area of this article, was designated as a UNESCO World Heritage site in 1997 and was first declared a forest reserve in 1875 to provide habitat for Bengal Tiger (*Panthera Tigris*) and other endangered flora and fauna species. The Bangladesh Sundarbans is one of the three deltaic zones formed by the Ganges- Brahmaputra floodplains. The other two are the Meghna Estuary (Ganges-Brahmaputra riverine discharge area) and the central Peninsula (between the Meghna Estuary and Haringhata River) including the lower delta plain (Allison and Kepple 2001), in the west of the Ganges-Brahmaputra- river mouth. Out of the total forested area of approximately 6000 km^2 in the Bangladesh Sundarbans, 29% is covered by tidal channels (Allison 1998).

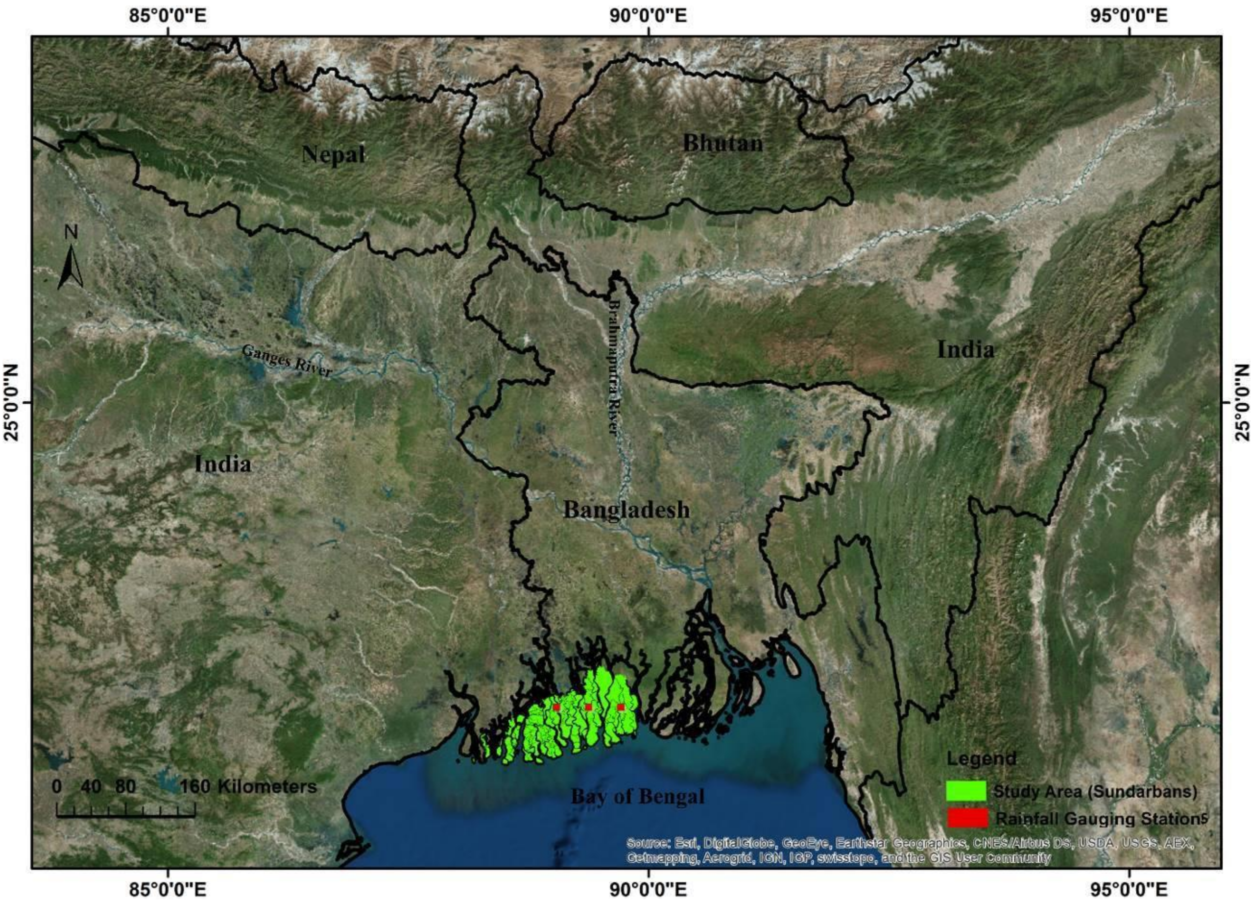

Figure 6.1 Location of the study area

6.3. Erosion and accretion dynamics in the Sundarbans

Ghosh et al. (2017a) assessed tidal channel erosion and accretion in the hinterland Passur Tidal channel system of Bangladesh Sundarbans mangrove forest using remote sensing and GIS platforms. The authors applied aerial photographs and satellite imagery to analyze accretion and erosion at three different periods over a period of 43 years (1974 - 2017). This investigation found severe erosion in bigger channels with large tidal channel bank widening whereas accretion was dominant in the smaller channels. The authors observed a net accretion of 0.21 km^2 and yearly rate of accretion of 0.0057 km^2 within this period. Rogers et al. (2013) observed that the Sundarbans is capable of mean annualized accretion rates of 1.1 cm/ yr^{-1} on the tidal delta plain. Other investigations using Landsat satellite have shown that over 40 years (1970s to 2000s) a net forestland equivalent to 1.1 % (110 km^2) of the total Sundarbans was lost (Giri et al. 2015). This loss compared to world's estimated mangrove forest loss rate of 12.3% (between the years 1980 and 2000) (Duke et al. 2007) is may not be significant but there is a concern on the sustainability of some of the Sundarbans mangrove species. It is therefore of vital importance to better understand the driving forces of the morphological changes of alluvial and floodplain tidal environments and landforms through erosion and accretion processes and their implications in this world heritage site for formulation of possible adaptation and mitigation plans and management strategies by all stakeholders. Current knowledge indicates that sea level rise, due to both eustatic rise and subsidence, is causing wetland loss, coastal erosion, and saltwater intrusion in a number of coastal areas in the globe (Day Jr and Templet 1989; Ericson et al. 2006). Also, if deltas and estuaries floodplains do not accrete vertically at a rate equal to the rate of relative sea level rise (RSLR), they will become stressed due to waterlogging and salt built-up.

The Sundarbans has platforms and channel networks cutting through it with an interplay between hydrodynamics, morphological and ecological dynamics that require an in-depth understanding if sound and robust conservation measures are to be instituted. Accretion of mud flats and the wetland vegetation naturally provide response mechanism to the coastal tidal systems of the Sundarbans in a regime of natural forcing factors such as rising sea level, tides, tectonic and subsidence, and cyclonic waves and it would be of crucial importance to understand these forcing factors.

6.4. Driving forces

The tidal river dynamics of the coastal deltaic landscape system of the Sundarbans are driven by natural forces and human activities that require clear understanding for sustainability of the ecosystem. Climatic forces include rainfall variabilities which influences river sediments and discharge and global warming which manifests in rising temperatures and sea level, and melting of snow and glacier. Human activities that have been identified to be responsible for environmental deterioration of the world’s deltaic mangrove wetlands like Mississippi include distributary network alterations for transportation, levees for flood control, dams in the catchments and water withdrawal for irrigation (Stanley and Warne 1998). This section strives to unravel tidal river dynamic natural and anthropogenic driving forces unique to the Sundarbans and their impacts on mangrove sustainability.

6.4.1. Natural Forces

Natural factors driving tidal channel erosion and accretion processes include coastal waves (tides, storm surges and cyclones), seasonal rainfall fluctuations, sea-level rise (thermal expansion of ocean water), tectonic and subsidence, and melting of mountain glaciers. These are tidal channel dynamics' external and internal inputs of energy and materials responsible forces which dynamically occur as pulses as they produce benefits and deleterious effects over different spatial and temporal scales (Day Jr et al. 1997). Infrequency of some of these events (cyclones, heavy seasonal rainfall and strong storm surges) are important in sediment delivery to the delta and major spatial changes in geomorphology whereas frequent ones such as annual river floods, seasonal storms, and tidal exchange are beneficial in accretion processes for maintaining salinity gradients, delivering nutrients, and regulating biological processes (Day Jr et al. 1997). These forcing factors are discussed in this section.

6.4.1.1. Tides, Storms and Cyclones, and Rainfall

Tides, usually amplified by the nonlinear shallow-water effect, in the Bay of Bengal originate in the Indian Ocean and the amplitude of tide within the estuaries is between 3.5 m and 4 m (Ghosh et al. 2015a). In the Sundarbans, the seasonal tidal fluctuations range approximately between 1 m and 6 m (Ghosh et al. 2015a; Islam et al. 2014) with respect to known elevation of the Bangladesh Sundarbans that varies between 0.9 and 2.11 m (Ghosh et al. 2016; Islam and Gnauck 2011) above the Mean Sea Level (MSL).

The semi-diurnal tidal fluctuations in the Sundarbans mangrove may be responsible for alternating wetting and drying processes that causes significant subaerial loosening of material. According to Winterwerp and Giardino (2012), the tides amplification increases moving towards the landward boundary through the forest and tends to decrease seaward. Tidal range changes and tidal wave action augment coastal erosion and the coastal morphodynamics. Water sediments transported through the tidal channels towards the complex network of tidal channels and creeks and, during high tide, towards the higher part of the Sundarbans mangrove forest are possibly trapped by the highly efficient vegetated systems. However, precise effects of tides on the erosion and accretion processes and the morphodynamics in the Bangladesh Sundarbans is yet to be fully understood and there is virtually no long–term tide gauge data available to show any trend of changes in sea level and its effect on erosion-accretion processes (Begum and Fleming 1997). Moreover, it is difficult to compare data from different tide gauges along the Bangladesh coast since the gauges are not linked to a common datum (Begum and Fleming 1997). Tide gauges provide useful in-situ data for studying tidal channel erosion and accretion in coastal locations and are more beneficial if they are geologically linked to a common datum.

The Sundarbans is in a tropical region and is usually affected by tropical cyclones. A tropical cyclone, described as a low-pressure system which develops in the tropics, can produce sustained hurricane force winds greater than 221km/h in which case it is categorized as a super tropical cyclone as per the classification of Indian Meteorological Department (IMD) (Mitra et al. 2011). Cyclones with very high speeds can cause substantial impact on the coastal communities and the environment (Mitra et al. 2011).

These cyclones come in the form of destructive winds and heavy rainfall that can lead to flooding and erosion. Tropical cyclones generally hold enormous amounts of moisture because they are formed over warm tropical oceans and can produce heavy rainfall over extensive areas which may cause severe impacts in the form of floods and landslides. Bangladesh Sundarbans river system benefits from tropical cyclone rainfall through sediment supply and salinity control. At the coastal Sundarbans, storm surge caused by a combination of strong winds driving water onshore and the lower atmospheric pressure in a tropical cyclone, can potentially make landfall and commonly occur approximately every three years (Murty et al. 1986).

Tidal channels in the Sundarbans deltaic floodplains may be as a result of tropical cyclonic primary mechanisms of wind destructive forces, storm surge and sedimentation. Storms, cyclones and tidal surges are common occurrences throughout the Sundarbans. In the last decade, four major disastrous cyclones; Aila, Bijli, Nargis and Sidr have affected the Sundarbans (Roy 2010). Sediments carried by storm surges are deposited on the floodplains when the surges recede. Unlike normal rainfall periods associated with moderate overbank deposition, major floods cause rapid accretion that can result in splay formation or bar creation. Goodbred and Kuehl (1998) used ^{137}Cs and ^{210}Pb radioisotope geochronology at 60 sites located in three regions of the Bengal Basin differing in age, physiography, and river influence and observed that accretion is most rapid in the river braid belt and adjacent floodplain, decreasing rapidly with distance from the main channel and accumulation rates increase again in low-lying distal basins.

The sediments are usually carried westwards by prevailing currents, and finally advected to the inland low-lying saline Sundarbans delta floodplain by monsoonal coastal tides and cyclonic events (Allison and Kepple 2001). Also during high storms, the Ganges distributaries deliver unknown amounts of sediments to the Sundarbans from the inland. Allison and Kepple (2001), argues that the river sediments reaching the Sundarbans is important for maintaining the coastal land elevation in response to the rising sea level. Reed (1989) observed that where sediment supply from offshore during tidal and storm high water events is small, such as in the Mississippi, significant loss of lower delta floodplain wetlands through subsidence occur. Continued stability of the Sundarbans depends on the continued supply of sediments to the Bay of Bengal.

Rainfall plays a key role in offshore sediment supply to lower delta plains during tidal and storm high-water events. Sediments are primarily derived from offshore sources and can ameliorate wetland loss through subsidence in areas where there is limited tidal range (further inland). Also the net effect between rainfall and evapotranspiration in association with variabilities of cyclonic currents and tide surges influence the vegetation and productivity (Oliver 1982) in the mangrove wetland due to water salinity and tidal phases in the form of ebbs and flood tides (Lara et al. 2011). Seasonal evolution of rainfall in the last four decades has shown high variability and dry winter season has seen a decrease in rainfall and an intensification of precipitation events between June and October (Figure 6.2) in the Bangladesh Sundarbans area. Such fluctuations have huge implications on the mangrove composition and distribution dynamic as well as erosion and accretion dynamics.

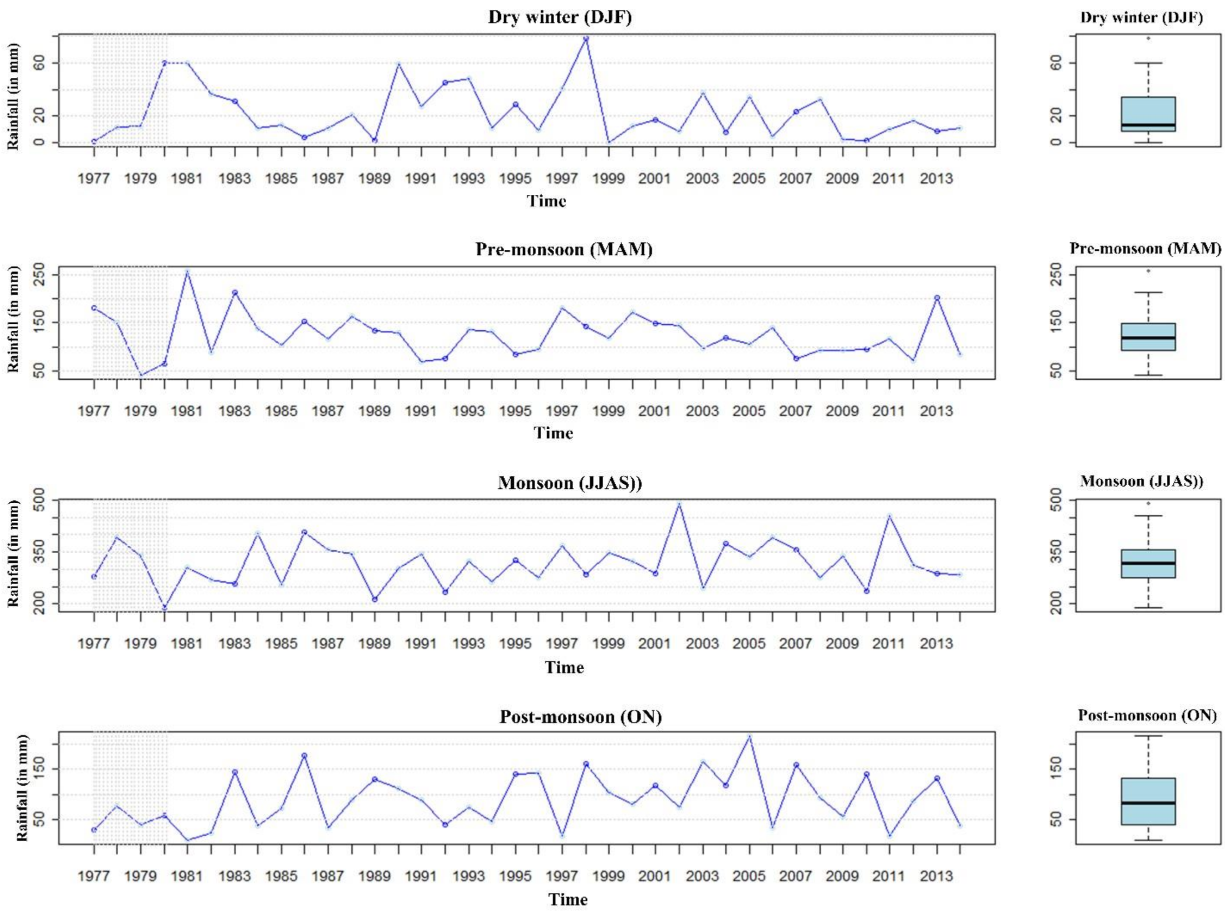

Figure 6.2 Seasonal variation of rainfall based on 36 years (1977-2013) rainfall data obtained from three meteorological station (Satkhira, Khulna and Bagherhat) located within the Bangladesh Sundarbans (Boxplots show the median value)

6.4.1.2. Temperature, Snow and Glacier Melt in the Himalaya

Snow and glacial melt in the Himalayas significantly contribute to the head waters of the Ganges outside the monsoon season (Moors and Stoffel 2013). The Himalayan range contains high altitude glaciers that supply water to many rivers in the Asia region (Savoskul and Smakhtin 2013) and some of these rivers are major sources of sediments to the Sundarbans (Wasson 2003). Temperature rise has led to increased glacial and snow-melt and this has enhanced increased summer flows in some river systems in the recent decades elsewhere in the globe. Future outlook is uncertain if the glaciers disappear and snowfall diminishes, and this can potentially lead to reduced rivers flows to the world's sensitive ecosystem. Bangladesh is one of the countries considered as vulnerable to glacier retreat and temperature increase (Vinodan 2010). Lutz et al. (2014) used cryosphere–hydrological model to quantify the upstream hydrological regimes of the Himalaya including Ganges and Brahmaputra rivers and observed that the monsoon precipitation dominates the hydrology regime of the Ganges and Brahmaputra. The Ganges gets only 11.5 % of its streamflow from glacier melt and snow melt despite its larger relative glaciered area as compared to the Brahmaputra whose benefits from glacier melt and snow melt is slightly higher. In the post-monsoon period when precipitation is low, the glacier melt and snowmelt contribution is important for sediment supply and salt washout in the tidal delta.

Scientific evidence indicates that glaciers are retreating at high rates in many parts of the world, including Himalaya region. In this region, glacial meltwater is an important supplement to naturally occurring run-off from precipitation and snowmelt to the Ganges- Brahmaputra river system. However, the accelerated rates of glacial retreat and the resulting increase in glacial water for downstream populations nor their implications have been precisely characterized. To understand the threats of global warming on the hydrological regimes contribution, glacier melt spatial data (of 1980 and 2010) for the Ganges and Brahmaputra catchment portion of the Himalaya were collected and analysed for glacier melt time series using remote sensing and GIS platform. The spatial data were obtained from International Centre for Integrated Mountain Development (ICIMOD). The Nepal part of the Himalaya is the Ganges catchment and the Brahmaputra catchment constitutes the Bhutan part of the Himalaya (Figure 6.3). The results of this analysis indicate a glacier retreat rate of 23.34 % (837.59 to 642.07 Km^2) and 24.50% (5168.58 to 3902.44 Km^2) for Bhutan and Nepal respectively over the period of study. In the three decades, overall retreat was 24.43 % (6006.16 to 4544.51 Km^2). Generally, retreating glaciers may not pose a significant threat to the hydrodynamics of the Sundarbans, which depend primarily on monsoon precipitation and snowmelt but if current rates of glacial retreat continue, it may be sufficient enough to alter the seasonal and temporal hydrodynamics (floods and sediment supply) and ecological dynamics (plant communities) of the flood plain and ultimately the tidal system dynamics.

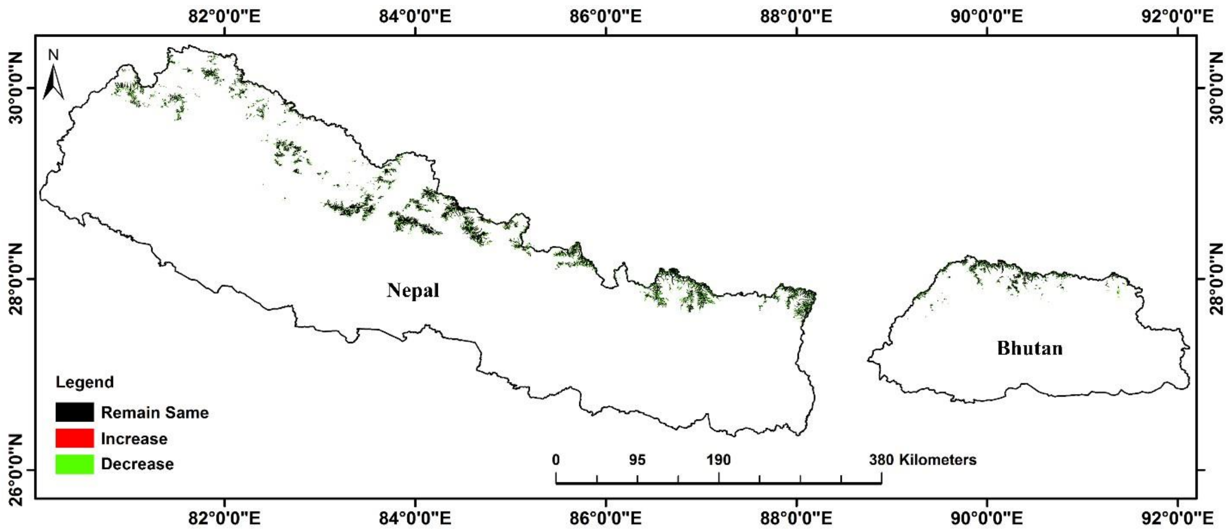

Figure 6.3 Himalayan glacier cover change map of Nepal and Bhutan (1980-2010). Black color represents no change area, red colour represents increasing area and green colour represents decreasing area of glacier cover during the study period. Overall the glacial increase part is very small while the glacial decrease is considerable. (Based on ICIMOD data (ICIMOD, 2014)).

6.4.1.3. Tectonic and Subsidence Forces

The Ganges-Brahmaputra river deltaic system is dominated by tectonic and subsidence forces (Morgan 1970) that influence the coastal sediments reworking processes through waves, tides, and currents on the seaward margins of the deltaic environment. At a local scale, lithological, topographic differences, and tectonic factors such as shear zones and faults may contribute to spatial variations in erosion processes giving credence to why some areas erode and others accrete. However, the Sundarbans flood plains are low-lying and therefore such factors may not be major influences at a larger scale. Nonetheless, gradual tectonics may be responsible for gradual and sometimes progressive tidal channels dynamics. It has been reported that the long-term patterns of the Brahmaputra and Ganges river systems migration have been changing with the Ganges migrating eastward and Brahmaputra westward due to major faults or fractures in the earth's crust (Coleman 1969). This indicates that influences of tectonic and subsidence forces may obviously be at play in the deltaic floodplain of the Sundarbans morphodynamics and subsequently affecting tidal river erosion and accretion processes. According to Allison and Kepple (2001) regional subsidence patterns control distributary channel avulsion and migration, and the creation of accommodation space in the Sundarbans floodplain. Syvitski et al. (2009) attributed accretion in the coastal deltaic floodplains to subsidence driven by delta aggradation rates which depend on sediment availability in the estuary, natural and anthropogenic compaction of sediments, and other vertical movements influenced by the redistribution of the Earth's masses.

Allison (1998) suggested that regional subsidence may have exacerbated the morphology of shoal growth that created a series of shoal-channel complexes at the eastward side of the Ganges-Brahmaputra delta front and may be fuelling shoreline and tidal river erosion by oceanographic processes. Chatterjee et al. (2015) reported land loss of 53.85 km^2 in the Sundarbans due to variable pattern of shoreline erosion attributable to sub-surface geomorphology (tilting towards east and localized subsidence). Wilson and Goodbred Jr (2015) identified some areas of the tidal delta plans of the Indian and Bangladesh Sundarbans that are at risk of natural driving forces due to insufficient sediment supply to offset the rate of geologic subsidence or rate of sinking of the delta. Due to reduced sediment input, and floodplain engineering tidal channels are expected to become deeper when deltas are sinking and this amplifies the tidal river dynamics and promotes salinity intrusion with possible shift of geographic location of the tidal freshwater zone to inland.

6.4.1.4. Sea Level Rise

The mean sea level rise at the Sundarbans has been estimated to be 3.14 mm yr^{-1} (Hazra et al. 2002) and is considered a major driving force for coastal erosion, coastal flooding, and an increase in the number of tidal creeks and channels. The Sundarbans landscape is naturally flooded by tidal influx of salty waters which support regular sediment deposits and maintenance of its elevation. The sea level rise has the potential to contribute to the phenomenon of losing land through erosion, including mangrove forests in the Sundarbans. The mudflats, which are exposed during low tide and submerged during high tide, develop within the low energy environment.

Subsidence in coastal deltas are naturally caused by compaction, consolidation, and dewatering of sediments while sinking of the land surface may be as a result of factors other than geological subsidence such as drainage of wetlands which can lead to subsidence due to oxidation of soil organic matter. The other sinking responsible factors such as groundwater and oil and gas withdrawals are not at present in the Sundarbans. The sea level rise can have greater impact when combined with other natural factors on the tidal river dynamics of the Sundarbans islands (Raha 2014). However, a study of nine southern-most islands of Indian Sundarbans estuary, facing the

Bay of Bengal, for the period 1999 till 2013 using time-series analysis of satellite imageries has shown that the islands are undergoing gradual erosion with emergence of new islands due to tidal and ocean currents and deposition of sediments in almost equal measure as combined contribution of sea level rise and gradual sinking of the Sundarbans delta (Raha 2014). A coastal deltaic landscape is considered stable if the rate of vertical accretion and surface elevation gain is greater than or equal to the rate of relative sea-level rise (RSLR) (Day Jr et al. 1997). The accretion rate depends on the rate of inputs of sediment materials from either sea or terrestrial (usually riverine) sources (inorganic) and organic material, usually from in situ vegetation production.

6.4.2. Anthropogenic Forces

Key anthropogenic forces associated with modification of natural geo-morphological dynamics of the river systems in the Sundarbans include land use patterns and infrastructure constructions. Human activities including construction of dams, impoundments, dikes and canals, water and mineral extraction, and habitat destruction have caused enhanced subsidence and reduced accretion, salinity intrusion, erosion, water quality deterioration, and decreased biological production in other world deltaic wetlands. Bangladesh Sundarbans is not affected much by water and mineral withdrawals and direct human habitat destruction and hence this section presents anthropogenic forces relevant to the Sundarbans.

6.4.2.1. Land Use Changes

In the Bangladesh tidal floodplain, hitherto agricultural area is rapidly being converted to shrimp farming, at of rate of 2·05% per annum, giving rise to growth of salt farms because of sea water used in shrimp farming (Islam et al. 2016). This in turn has increased soil salinity in the coastal tidal plains. Sodic soils decrease mean aggregate/particle size of the eroded sediment and contributes to the weakening of soil aggregates and their dispersion (Ghadiri et al. 2004) under the storm surges, cyclonic, and tidal forces including raindrop impacts. High sodium has deleterious effects on soil structure, dispersion and hydraulic properties and has commonly been associated with increased soil erosion and runoff. Within the active Ganges-Brahmaputra deltaic floodplain area, frequently re-worked sediments are loose and unconsolidated and so are highly susceptible to erosion and accretion processes (Hossain et al. 2013). Increased soil salinity would therefore accelerate the erosion and accretion processes.

6.4.2.2. Infrastructure Development

Upstream hydraulic regime changes of a river system through human induced activities can easily be felt downstream**.** The Ganges-Gorai system sediment-laden discharges have decreased since 1975 with the construction of the Farakka Barrage to divert water into tributaries in eastern India to augment low dry season flow (Allison 1998), flush the sediment load into the deeper part of estuary and resuscitate the navigational status of the Kolkata port (Rudra 2011). This hydraulic control through the barrage may have induced impacts on riverine sediment discharges, important for maintaining the coastal land elevations in response to relative sea level rise, to the deltaic plains of the Sundarbans. Riverbank erosion and channel oscillations in the Ganges-Gorai system, at least in the medium term, is partly contributed by Farakka Barrage which has affected sediment transport to the lower delta through tributaries (Sarker 2004). Aziz and Paul (2015) argues that the Ganges water carries 262 million tons of sediments/year and only 7% is diverted to southern distributaries (Sundarbans) and this low discharge retards sediment deposition in the Mangrove forestlands' base as well as the formation of forestlands.

The polders constructed at the lower delta plains of Bangladesh Sundarbans may have disastrous implications on land elevation due to decreased Ganges-Brahmaputra sediment influx during tidal and cyclonic floods and subsequently impact on the river/tidal river dynamics. Auerbach et al. (2015) observed that constructed polders are the most important agent of change in the western Ganges-Brahmaputra tidal delta plain as compared to global sea-level rise. The authors argued that the polders, combined with other forces, have contributed to a loss of 1.0 to 1.5 m of elevation over the last five decades due to landscape starving of sediments. This observation agrees with that of Allison and Kepple (2001), who asserted that the polders constructed along the lower delta plain shoreline of the Bangladesh Sundarbans might have detrimental effects of erosion and land elevation by reducing the Ganges-Brahmaputra sediments influx during tides and cyclonic floods. Allison and Kepple (2001) assertion was prompted by Allison (1998) study that compares historical and remote sensing evidence from 1770s-1990s indicating that, despite influx of large sediments, shoreline erosion continues on the western part of Bangladesh Sundarbans and its India neighbourhood. It is argued that the tidal volume entering into the estuary has been reduced by the polder construction, leading to lower flow velocities in the main channels, enhanced funneling shape of the estuary and, as a result of this, there has been tidal amplification and increased import of fine sediments from the sea, leading to increased accretion rates (Pethick and Orford 2013). The Sundarbans wetlands maintains its sea-level elevation by trapping sediments and forming organic- rich soil supported by expansive mangrove forests and thus the effects of infrastructure developments on the sediment supply needs to be scientifically verified.

Studies have shown that the Ganges streamflow reduced from 3700 m^3/s in 1962 to 364m^3/s in the year 2006 as a result of infrastructure development, leading to an increase of high saline sea water in the upstream areas (Islam and Gnauck 2011). Islam and Gnauck (2011) indicated a strong correlation between Ganges discharge reduction and salinity increase in the Passur-River, one of the key Sundarbans source of freshwater supply. The high salinity of river water augments salinity induced by onshore water tides and surges is a potential threat to the mangrove ecosystem composition. Although high salinity may be beneficial to many mangrove species, it can also be harmful to some mangrove families (Islam and Gnauck 2011). Ghosh et al. (2017b) studied long-term (over 38-year (1977–2015)) changes in mangrove species composition and distribution in the Bangladesh Sundarbans using maximum likelihood classifier technique to classify images recorded by the Landsat satellite series and post classification comparison techniques to detect changes at the species level. The authors observed that, over the period, *Heritiera fomes* and *Excoecaria agallocha* mangrove plants decreased by 10.7% and 4.8% respectively, while more saline tolerant *Ceriops decandra*, *Sonneratia apelatala*, and *Xylocarpus mekongensis* population increased by 35.7%, 76.3% and 212.1%, respectively in the Sundarbans. For details regarding species composition and cover dynamics of mangroves readers are referred to Ghosh et al. (2017b).

6.5. Conclusion

The Sundarbans delta plain is one of the world's important regions where the effects of global warming on sea level and freshwater discharge occur. In this study, a synthesis of the tidal river erosion and accretion driving forces in the context of natural and anthropogenic factors and their impacts on the Sundarbans delta floodplain mangrove forest has been presented. Through accretion, new lands are made afresh in the Sundarbans to offset a large part of the loss due to erosion by the tidal river dynamics. Once new land is created, it is typically colonized by a sequence of plant communities, culminating in the establishment of mangrove forest areas and grasslands. However, the newly created lands may be present only seasonally and thus such dynamic erosion and accretion processes affect physical and biological dynamics of the landscape if the net balance is skewed. Stable beneficial condition is attained once the point bar that has aggraded develops to tidal elevation. In this discussion, two key questions are put in context:

why is tidal river/ channel morphology dynamics occurring? and what are the implications of these geomorphologic changes on ecosystem to plant communities in the Sundarbans? Natural tidal channel dynamics driving forces viz: tectonic and subsidence, sea level rise, tides, storms, cyclones and other climatic factors are discussed. Human induced morphodynamics factors that affect erosion and accretion processes in the Sundarbans tidal channel system are also synthesized. Based on our discussion it can be concluded that natural and anthropogenic forces such as tides, storms and cyclones, fluctuations in seasonal rainfall, tectonic and subsidence forces, sea level rise, infrastructure development and changing pattern of land use plays a vital role in erosion accretion processes in tidal channel dynamics in the study area. Tides, storms and cyclones, fluctuations in seasonal rainfall, infrastructure development and changing pattern of land use are important factors in sediment supply and salinity influence on the Sundarbans ecosystem. Tectonic and subsidence forces control distributary channel avulsion and migration, and the creation of accommodation space in the Sundarbans floodplain. Both natural and human induced tidal system dynamics responsible forces require to be dealt with holistically and specifically in temporal and areal extent if tidal systems are to be sustained. However, precise conclusion on effects of infrastructure developments on the sediment supply needs more scientific verification and that for proper monitoring of sea level rise and its effect on erosion-accretion processes, more tide gauges need to be installed and more importantly they should be geologically linked to a common datum.

The Sundarbans mangrove wetlands management strategies, such as construction of salt marshes and tidal flats with dredge material, vegetative plantings, and re-introduction of river inflow to the delta for sediments and salinity management, and use of wetlands to reduce nutrient levels, require the understanding of tidal morphodynamic driving forces.

Moreover, it is important to understand the future mangrove species composition and their spatial distribution in response to the changing climate scenarios, especially Sea Level Rise (SLR), to help sustainable management planners and relevant stakeholders and policy makers for sustainable management of the Sundarbans mangrove forest ecosystem. Therefore, detailed investigations of the Bangladesh Sundarbans are recommended regarding the impact of SLR. This would be useful for the conservation management of the Sundarbans.

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Figure 6.1	101
Figure 6.2	105
Figure 6.3	107

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Chapter 7.

Geospatial modelling of the impact of sea level rise on the spatial distribution of different mangrove species in the Sundarbans, Bangladesh

This chapter is under review with the journal *Geomatics, Natural Hazards and Risk*:

Ghosh, M. K., Kumar, L., & Langat, P. K. (Under review). Geospatial Modelling of the impact of sea level rise on the spatial distribution of different mangrove species in the Sundarbans, Bangladesh.

7.1. Introduction

Mangrove forests thrive in tropical and subtropical coastal regions globally and provide support to coastal communities' livelihoods and contribute at least US $1.6 billion each year in ecosystem services (Costanza et al. 1997). The mangroves provide buffer from floods, erosion and natural threats to coastal populations (Chatenoux and Peduzzi 2007; Das and Vincent 2009; Ismail et al. 2012; Kathiresan 2012). However, declines for all the known 70 world mangrove species (Polidoro et al. 2010) are occurring in many regions due to climate change and anthropogenic threats (Economics 2007). Accelerated global warming and climate variabilities have been blamed for the decline in mangrove forests (Eslami-Andargoli et al. 2009; Gilman et al. 2008). Among the climate related factors, SLR affects coastal wetlands and mangroves in the long term (Field 1995; Gilman 2004; Kassakian et al. 2017; LaFever et al. 2007). Loss of fringe mangrove species, locally and regionally, exposes coastal areas to storms, erosion and flood hazards, and tidal waves and reduces habitat quality (Barbier et al. 2008; Ewel et al. 1998; Glaser 2003) and may lead to biodiversity loss and ecosystem services disruption that include impacting negatively on human livelihoods (Polidoro et al. 2010). Thus there is a need to have mitigation adaptation strategy plans for sustainable mangrove forest management based on sound and robust information.

The Bangladesh Sundarbans is a globally important mangrove ecosystem which lies at the mean elevation of approximately two meters above mean sea level (Payo et al. 2016), making it the most vulnerable to potential effects of the SLR due to climate change threats to the mangrove forest composition and distribution (Field 1995). Investigation has shown that climatic variables of temperature and rainfall influence the composition and distribution of major mangrove species viz. *Heritiera fomes, Sonneratia apelatala* and *Ceriops decandra* in the Sundarbans (Ghosh et al. 2017b). The global SLR is projected to be approximately 1 m higher or above by the year 2100 (Church et al. 2013; Payo et al. 2016), but future impacts on composition and distribution of mangrove species remains largely unknown. In the pristine Bangladesh Sundarbans Mangrove Forest, an analysis of tidal gauge records has indicated an increasing east–west trend of 4 mm–7.8 mm $year^{-1}$ rise in sea level from 1977 to 1998 (Alam 2003; SMRC 2003), which is well above the average global SLR estimate during the same period (Bindoff et al. 2007). Climate change driven rise in the sea level will affect floodplain low elevation areas of the Sundarbans. Research has also predicted that, with the increase in sea level due to global warming, more storm surges in the form of hurricanes and cyclones will be experienced in many coastal areas. Prediction of the SLR and its impacts on the Sundarbans mangrove forest composition and species distribution, given the low-lying elevation of the ecosystem and its vulnerability to any significant change in sea level, is extremely important.

Many prediction models have been developed for studying potential impacts of sea-level rise on coastal ecosystems and environmental changes. Among them are: Coast CLIM (Warrick and Cox 2007) which uses a database of regional grid cells and down-scaled Global Circulation Models (GCMs) to generate localized rates of sea-level and climate impacts and the Sea-Level Rise Rectification Program (SLRRP) (Keim et al. 2008). Also available are: Temperature-Based Sea- Level Rise Model (Rahmstorf 2007), University of Arizona Web Map Visualization Tool (Strauss et al. 2012), Sea Level Over Proportional Elevation (SLOPE) model (Doyle et al. 2010), Sea Level Affecting Marshes Model (SLAMM) (Geselbracht et al. 2011) and recently available Geographic Information System (GIS) sea-level rise mapping tools. None of these models is comprehensive enough to analyze and visualize the impacts of SLR on composition and spatial distribution of mangrove species and their hazard scenarios related to sea level.

A host of researchers have used GIS and geospatial analysis tools to investigate SLR impacts on the coastal ecosystems in pursuit of developing informed policy in many parts of the world (Gravelle and Mimura 2008; Li et al. 2009; Malik and Abdalla 2016; Natesan and Parthasarathy 2010). GIS and geospatial analysis techniques have proven useful for predicting the impact under various scenarios related to SLR. Malik and Abdalla (2016) created an ArcGIS model of potentially inundated areas, based on a DEM to analyze the local impact of SLR on Richmond, British Columbia, Canada. El-Nahry and Doluschitz (2010) used GIS and field based data in conjunction with Landsat and ASTER imagery to study SLR impacts on the Nile Delta. They created three SLR scenarios of 1.0 m rise, 1.5 m rise, and 2.0 m rise for their study. Li et al. (2009) applied GIS methods to develop a comprehensive universal model for assessing and visualizing the potential inundation based on a global SLR of 1–6 m.

In the Bangladesh Sundarbans, Lovelock et al. (2015) developed a model for predicting the time of submergence of a mangroves within a suitable inundation regime (between Highest Astronomical Tide and MSL). The authors' model assumes an estimation based on MSL rise and does not consider tides, coastal erosion and subsidence. Several modelling on the impacts of SLR on the Sundarbans coastal areas have used relatively coarse (>1 m vertical accuracy) elevation data (Chowdhury and Faruqee 2000; Sarwar 2005). Payo et al. (2016) applied the latest DEM data and the Sea Level Affecting Marshes Model (SLAMM) to investigate the response to various SLR scenarios on the Sundarbans mangrove ecosystem. The authors' used remote sensing and prediction modelling to study potential impacts of three SLR scenarios on the Bangladesh Sundarbans. Their work was about Sundarbans mangrove ecosystem inundation and area loss. Loucks et al. (2010) employed geospatial tools and scale-appropriate elevation data to assess the potential impact of SLR on Bangladesh's Sundarbans tiger population. None of the studies covers the mangrove composition and species distribution which is of immense importance since ecosystem services and functions provided by mangroves are also affected by the diversity and distribution of the mangroves and is therefore crucial to understand how future composition and patterns in their distributions would be affected by the SLR. Many mangrove types can tolerate inundation due to tides but when frequency and duration of inundation exceeds physiological thresholds for the specific species, the death of the trees occur and their occupancy can convert to open water or tidal mud flats (Payo et al. 2016).

This present study examines the impacts of SLR on mangrove species composition, individual species decline, or population distribution in the Sundarbans using remote sensing and Geographic Information System (GIS) techniques. The uniqueness of this investigation is that it recognizes the low elevation conditions and geomorphologic dynamics in the Sundarbans mangrove ecosystem and applies DEM data and geospatial techniques to develop a detail and robust model to analyze and illustrate the impacts of SLR on composition and spatial distribution of mangrove species and hazard scenarios while considering net subsidence rate uncertainties (sinking and no change). The present research identifies vulnerable mangrove species as well as investigates the severity of future risk of sink caused by SLR in order to develop the database for relevant stakeholders to develop a plan for a sustainable management of the forest. This work is of significant importance as it provides a glimpse of the SLR impacts on the future composition and spatial distribution of mangrove species and as well as generates a geospatial model for research on potential SLR impacts on coastal communities.

7.2. Materials and methods

Geospatial techniques have been used in this study to develop the SLR scenarios and to assess the future impact of SLR on the mangrove species composition and their future distribution. The methodological framework applied was divided into three sections; the first section describes the study site, data used and their relevancy in this work, while the second and third sections deal with geospatial analysis that includes DEM processing, SLR scenarios preparation, identification of mangrove species composition and spatial analysis of impacted areas. The entire spatial analysis was carried out using ArcGIS 10.4 and ENVI 5.1 software.

7.2.1. Study site and focus

The present study site is the Bangladesh Sundarbans located approximately between 21° 32' to 22° 30'N latitude and 89° 00' to 89° 51' E longitude (Figure 7.1). It covers an area of 6017 km^2 (Sarker et al. 2016) and is characterized by tropical climate with temperature ranging from 11°C and 37° C and four seasonal patterns. Hot and humid pre-monsoon season starts from March to May followed by monsoon period from June to September and then October and November post-monsoon months and finally December to February being dry winter period. The Sundarbans is a low-lying floodplain with elevation which varies from 0.9 to 2.11 m above sea level (Ghosh et al. 2015a; Spalding 2010) and land slope is 0.03 m vertically per km of horizontal distance moving from north to south (Islam and Gnauck 2011). An average relative sea-level rise (RSLR) of 1.07 mm/yr from early to mid-Holocene period has been estimated for this region (Islam and Tooley 1999). However, recent estimates indicate SLR of 3.14 mm per year, which is way beyond the global SLR estimate of 2.0 mm per year and, based on this rate, the compound sea level elevation is predicted to be close to the 1 m scenario by 2050 (Hazra et al. 2002). The Sundarbans mangrove ecosystem is likely to be seriously vulnerable to SLR effects, particularly during the pre- and post-monsoon phases when most of the cyclonic storms occur. The Bangladesh Sundarbans hosts 19 species of mangroves (Sarker et al. 2016) out of which five species are dominant (Ghosh et al. 2016). The focus of this work is the impact of SLR on those five major mangrove species in the Bangladesh Sundarbans.

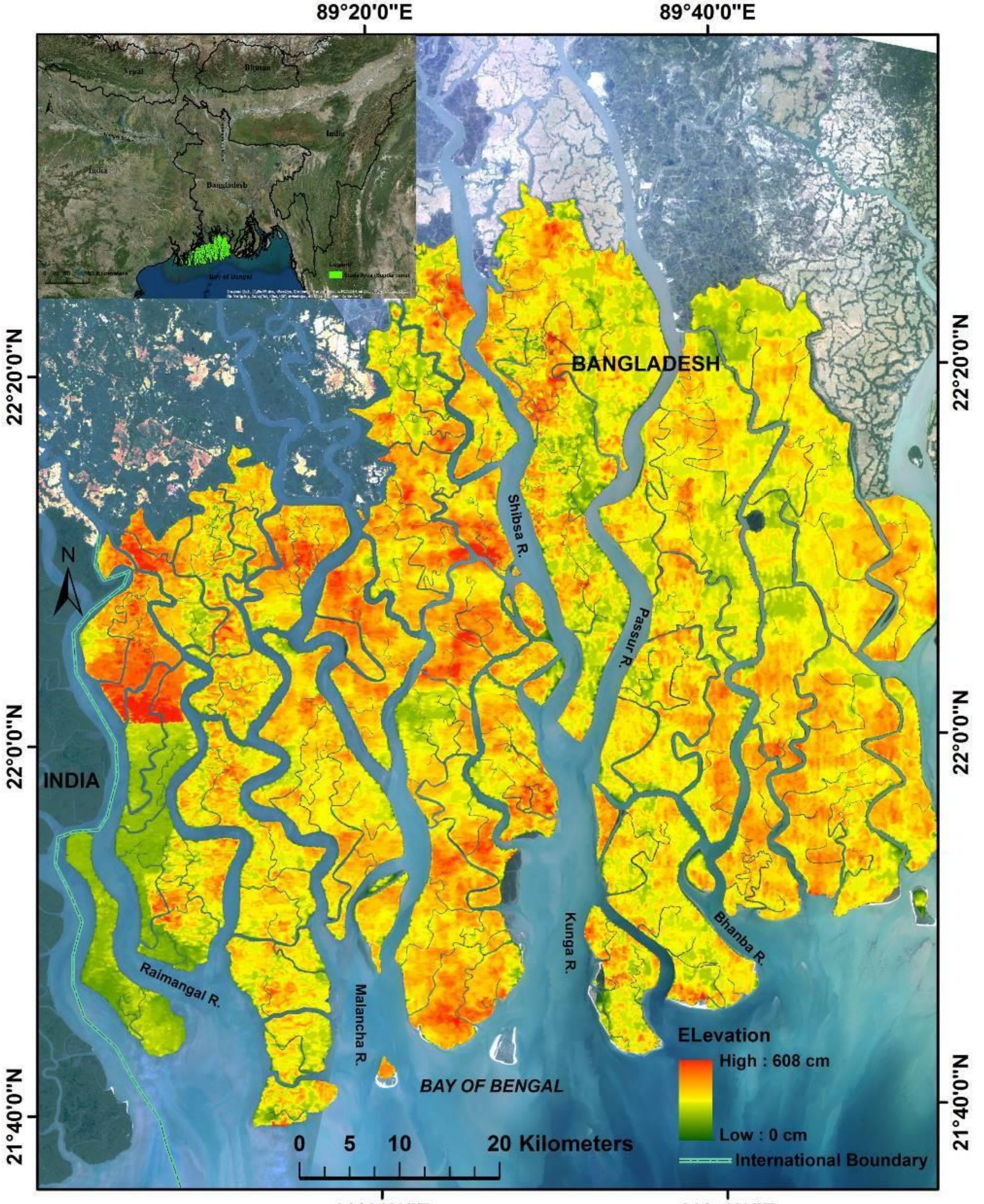

Figure 7.1 Study area map showing the elevation for the Bangladesh Sundarbans

7.2.2. Data

In this research, elevation data acts as the main parameter in the determination of the SLR impacts on the spatial distribution of the future mangrove species of the Bangladesh Sundarbans. High resolution elevation data is essential for this kind of research where every centimeter counts due to the low-lying characteristics of the study area. The high resolution (less than 1m vertical error) DEM data used in this study was obtained from Water Resources Planning Organization (WRPO), Bangladesh. The elevation information used to construct the DEM was originally collected by a Finnish consulting firm known as FINNMAP in 1991 for the Bangladesh government. FINNMAP measured 80584 GPS elevation points in mm above sea level. These points were used to create a continuous DEM of the Sundarbans. Initially, the data was georeferenced in accordance to the Survey of Bangladesh (SOB) datum. The SOB datum is a stable datum representing the present mean sea level. The DEM data was restructured using the Google images from 2006-2007 to correct obsolete FINNMAP data by the Institute of Water Modelling (IWM) Bangladesh. This updated data was resampled at 30 m resolution and transferred to the Public Works datum (PWD). The PWD datum has been recognized by the Bangladesh government at 0.459 m below mean sea level (MSL) (Payo et al. 2016). The vertical resolution of the DEM data is expressed in centimeters and varies from 0 to 608 cm.

In addition to the DEM data, Landsat Operational Land Imager (OLI) data, obtained from the Center for Earth Resources Observation and Science (EROS) website (www.glovis. usgs.gov), was also used in this study to map the mangrove species composition of the Bangladesh Sundarbans. This OLI image was acquired in February 2015. The OLI image information is as follows: 30 m resolution, 137-138/45 path/row and 11 Spectral band (covering visible, near infrared, short-wave infrared and thermal infrared regions of the electromagnetic spectrum).

7.2.3. Data processing, sea level rise scenarios selection and preparation

To analyse and understand the impact of SLR on the future distribution of mangrove species, it was crucial to create potentially inundated areas and the information of DEM was used to create this. However, DEM data provided by WRPO had several sinks which presented negative values for the corresponding cells and could be problematic for further analysis. To remove anomalies and to keep the reliability in the generated results, sinks were removed by altering the negative values into meaningful values using the 'fill' tool in ArcGIS software and a depression less DEM was created.

Three different SLR scenarios of 0.46 m (low), 0.75 m (medium) and 1.48 m (extreme) were selected for this study. The 0.46 m and 0.75 m SLR scenarios are based on the mean and peak projections under the RCP 4.5 scenario for West Bengal, India (Pachauri et al. 2014; Payo et al. 2016) and the extreme case scenario resembles to H++ scenario range which considers the 95 % value for RCP 8.5 (0.98 m) plus 0.5 m associated with Ice Sheet melting (Levermann et al. 2014; Lovelock et al. 2015). The extreme case scenario is considered plausible but unlikely (Jevrejeva et al. 2014).

Subsidence rate considered for this model was selected based on Brown and Nicholls (2015), who found the mean net subsidence rate of 2.8 mm/year and median net subsidence rate 2.0 mm/year for the Sundarbans. This mean subsidence rate of the Sundarbans was lowest compared to other land uses in the Ganges delta. The authors studied the difference between the sedimentation, isostatic rebound and subsidence rates in the Ganges–Brahmaputra–Meghna delta to come up with the net subsidence rates based on a range of approaches and temporal scales. They considered natural geological processes and compaction of soil, anthropogenic effects and sediment supply delivered by the river system. They preferred the median rate of subsidence to the mean because some large measurements of subsidence and anthropogenic effects skewed their mean results. In this study, therefore, a value of −2.4 mm/year of net subsidence in the Sundarbans was adopted as a representative value taking into account the shortcomings of Brown and Nicholls (2015) to investigate possible inundation in response to different SLR scenarios on the Sundarbans mangrove ecosystem. To assess the sensitivity of the results to the ambiguity on net subsidence rate in our model, net subsidence rate of 0.0 mm/year (in case of no subsidence) was also applied.

Raster Calculator in ArcGIS was used to generate new rasters from the desired cells. Using the elevation values of 46 cm, 75 cm and 148 cm under the net subsidence rate of -2.4 and 0.0mm/year, six raster files were generated for developing the SLR scenarios. The newly generated raster files contained the cells with two values 0 and 1, where 1 characterized the cells of interest while 0 characterized the remaining cells. Therefore, reclassification approach was used to reclassify those newly generated rasters to assign the 0 values to no data. Afterwards, reclassified rasters were converted to polygons for further analysis. The newly created shapefiles were used to prepare SLR scenarios for studying the impact of SLR on future spatial distribution of mangrove species. For 46 cm SLR under the two different subsidence rates (-2.4 mm/year and 0.0 mm/year) SLR scenarios were prepared for the year 2100 in respect to base year 2000. Following the same procedure SLR scenarios were also created for 75 cm and 148 cm SLR under the two different subsidence rates.

7.2.4. Analysis of satellite image to identify the mangrove species composition

Maximum likelihood classifier (MLC) algorithm that is widely used in remote sensing applications to classify traditional satellite remote sensing data (Gao 1999; Green et al. 1998) was adopted in this study to identify the mangrove population by species. Prior to fieldwork, the first author's extensive field experience, and information from published literature (Chaffey et al. 1985; Emch and Peterson 2006; Ghosh et al. 2016; Ghosh et al. 2017b; Giri et al. 2007; Treygo and Dean 1989) were used to select five major mangrove species out of 19 known species of Bangladesh Sundarbans (Sarker et al. 2016) for this classification. The major five species were *Heritiera fomes*, *Excoecaria agallocha*, *Ceriops decandra*, *Sonneratia apelatala* and *Xylocarpus mekongensis*. Due to the absence of large enough monospecific patches for the training site selection, the remaining 14 species were considered under the five major mangrove species on the basis of dominance. Training and validation sites for this study were created using field data collected in February- March 2016. Training and validation samples were selected randomly and stratified by land cover class and also care was taken to ensure well distribution of samples and the minimum requirements for validating the accuracy assessment process (Congalton and Green 2008; Sinha et al. 2014). Field data were collected using handheld GPS. The GPS locations of different mangrove species were overlaid on the 2015 OLI image to extract the spectral signatures for each of the species. Thereafter, spectral signatures were used to classify the image to identify the mangrove population by species. Validation of the image classification was also performed to evaluate the efficacy of the classification and overall accuracy of 89% and kappa coefficient of 0.87 were achieved.

7.2.5. Spatial analysis of impacted area

The impact of SLR on future mangrove species distribution were analyzed through spatial analysis using newly generated SLR scenarios. The SLR scenarios were overlaid on the species composition map and the impact on overall area and the future distribution of mangrove species were analyzed through SLR scenarios. The analysis included impacts on overall inundated mangrove area, inundated area of each species under different SLR scenarios and potential future species composition of the forest. Figure 7.2 shows the methodological structure used to generate the SLR scenarios and study the SRL impacts.

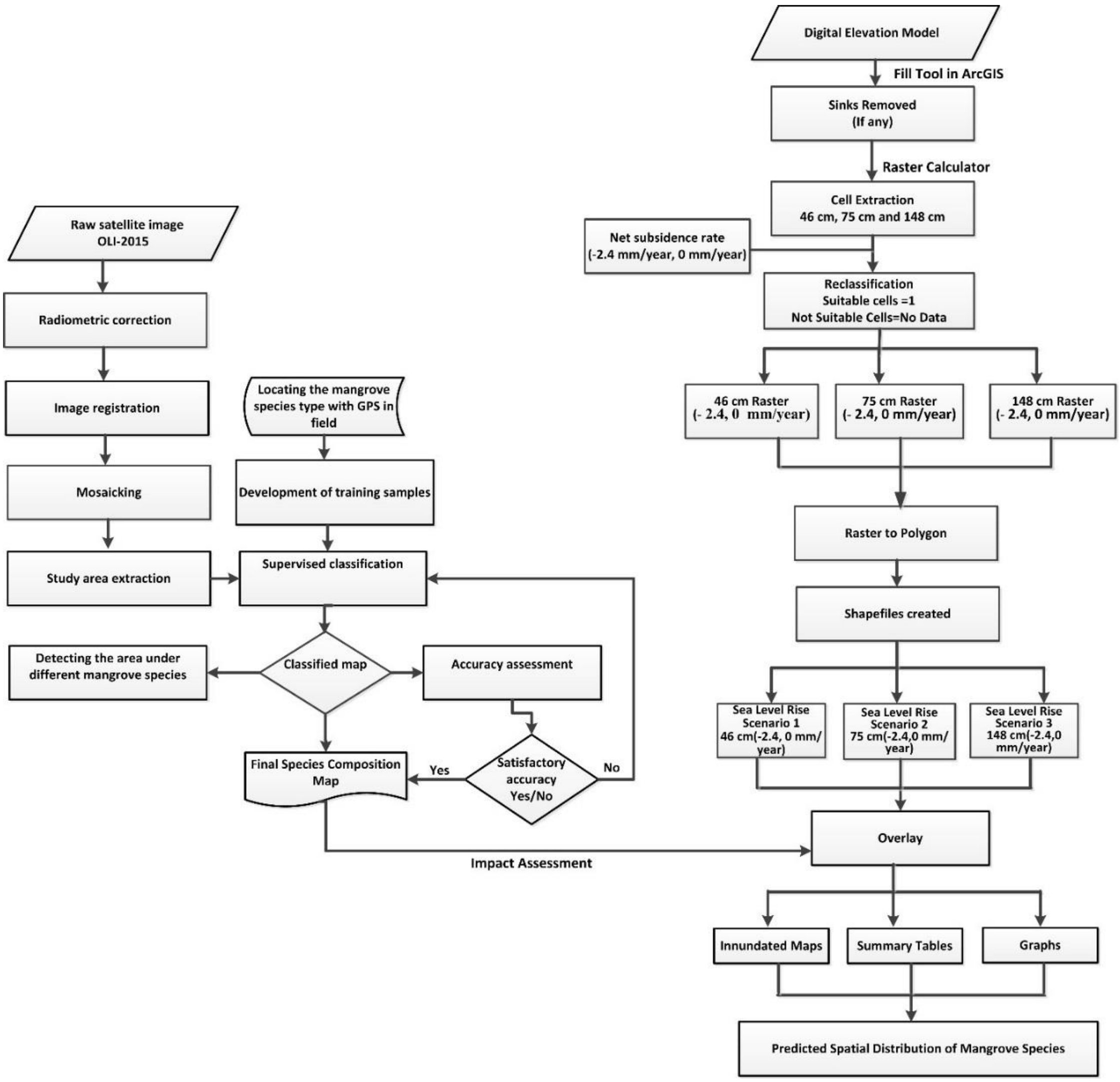

Figure 7.2 Methodology flowchart

7.3. Results

Five major mangrove species viz. *H. fomes, E. agallocha, C. decandra, S. apelatala* and *X. mekongensis* and their spatial distribution has been identified and mapped in this research (Figure 7.3). According to our findings *H. fomes* is the most dominant species in terms of occupancy in the Bangladesh Sundarbans. Nearly 50% of Bangladesh Sundarbans are occupied by the fresh water loving *H. fomes* species, followed by *E. agallocha* (30.1%), *C. decandra* (17.8%), *S. apelatala* (2.2%) and *X. mekongensis* (0.4%) respectively.

The results indicate that potential inundated mangrove area by the end of the 21^{st} century will be nominal for the low and medium SLR scenarios, but substantial for the extreme SLR scenario (Figures 7.4 and 7.5). The potential inundated mangrove area is predicted to increase for the scenarios under 0 mm/year (or absence of net subsidence) and -2.4 mm/year net subsidence. The mangrove area is projected to be inundated by 2646 ha, 9599 ha and 74720 ha by the end of the year 2100 for the low, medium and high SLR scenarios respectively under the net subsidence rate -2.4 mm/year relative to the baseline year 2000. On the other hand, the mangrove area is projected to be inundated by 1037 ha, 3231 ha and 44002 ha by the end of the 21^{st} century for the low, medium and high SLR scenarios respectively under the net subsidence 0 mm/year.

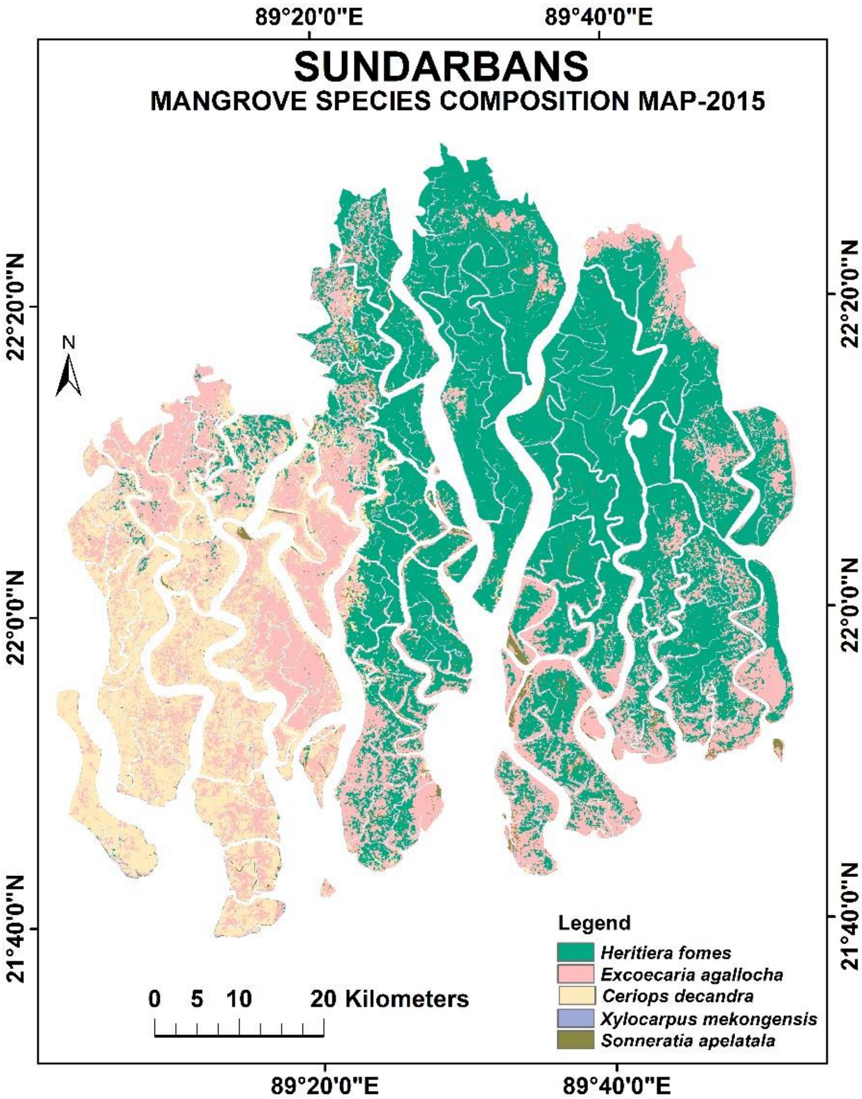

Figure 7.3 Mangrove species composition map of the Bangladesh Sundarbans for the year 2015

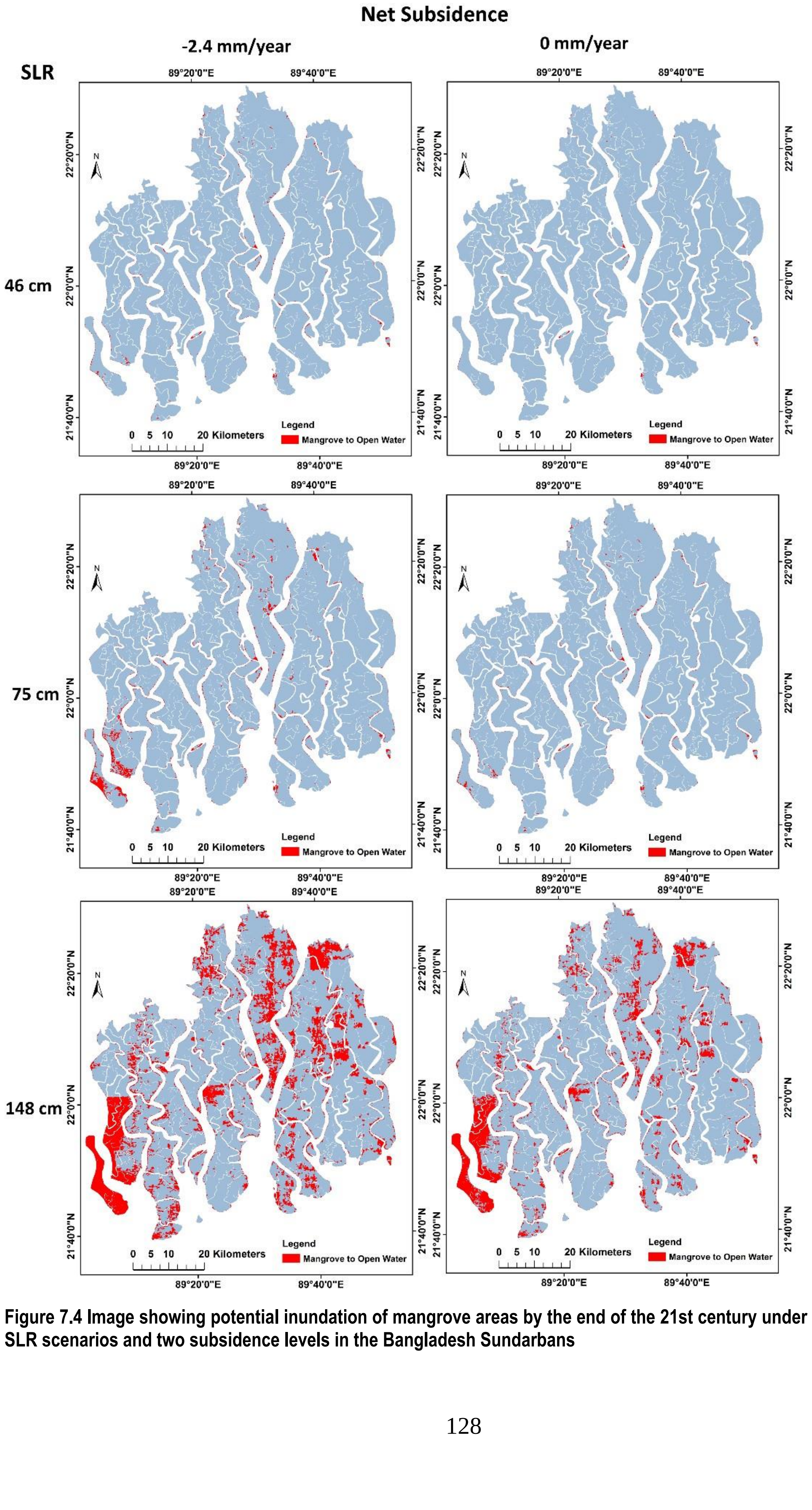

Figure 7.4 Image showing potential inundation of mangrove areas by the end of the 21st century under three different SLR scenarios and two subsidence levels in the Bangladesh Sundarbans

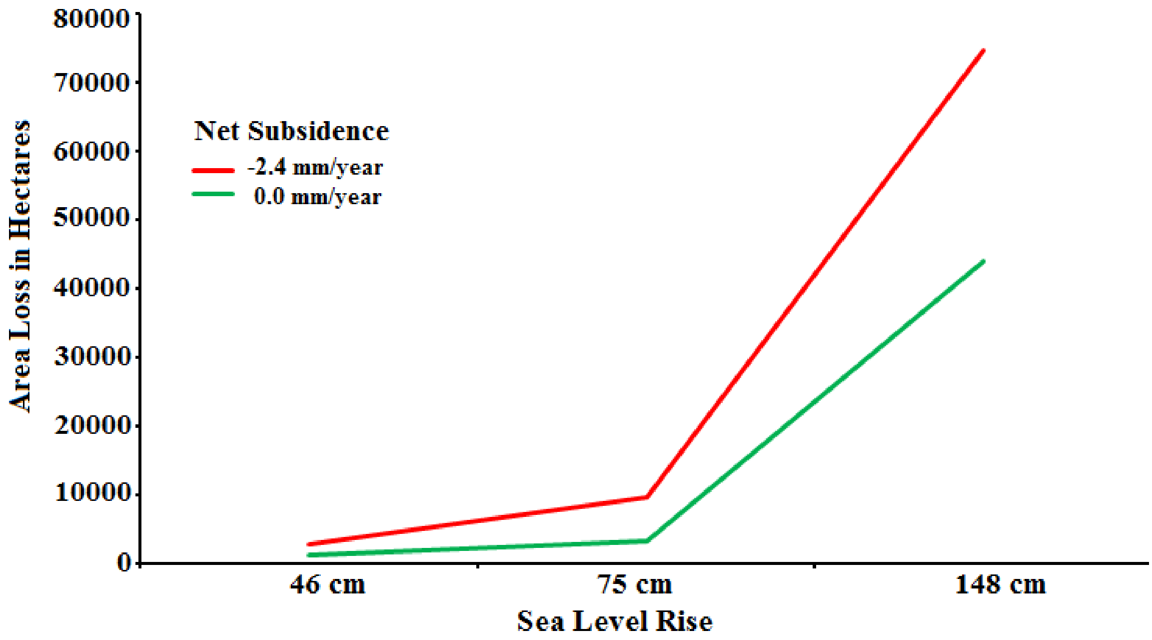

Figure 7.5 Total area under potential inundation by the end of the 21st century under the selected SLR scenarios and subsidence levels in the Bangladesh Sundarbans

The results also reveal that the impact on different mangrove species will be minimal for low (46 cm) and medium (75 cm) SLR scenarios while extensive for the extreme (148 cm) SLR scenario (Figures 7.6 and 7.7). *C. decandra, S. apelatala and X. mekongensis* will likely be the most affected species for all the SLR scenarios. 0.85%, 5.70% and 30.53% area of *C. decandra* will be inundated for low, medium and extreme SLR scenarios respectively under the net subsidence rate of -2.4 mm/year while 4.04%, 6.85% and 25.03% area of *S. apelatala* will be inundated for the same SLR scenarios and subsidence rate respectively. Although *X. mekongensis* does not make up a substantial share of the forest, it will be one of the most affected species of the Sundarbans. 2.69%, 9.65% and 31.50% area of *X. mekongensis* will be inundated for low, medium and extreme SLR scenarios respectively under -2.4 mm/year net subsidence rate. On the other hand, two major mangrove species of Bangladesh Sundarbans namely *H. fomes* and *E. agallocha* which form nearly 80% of the forest will be inundated by 0.41%, 1.29%, 16.73% and 0.72%,1.94%, 14.88% for low, medium and extreme SLR scenarios respectively under -2.4 mm/year net subsidence rate. More details regarding inundation under 0 mm/year net subsidence rate are provided in Table 7.1.

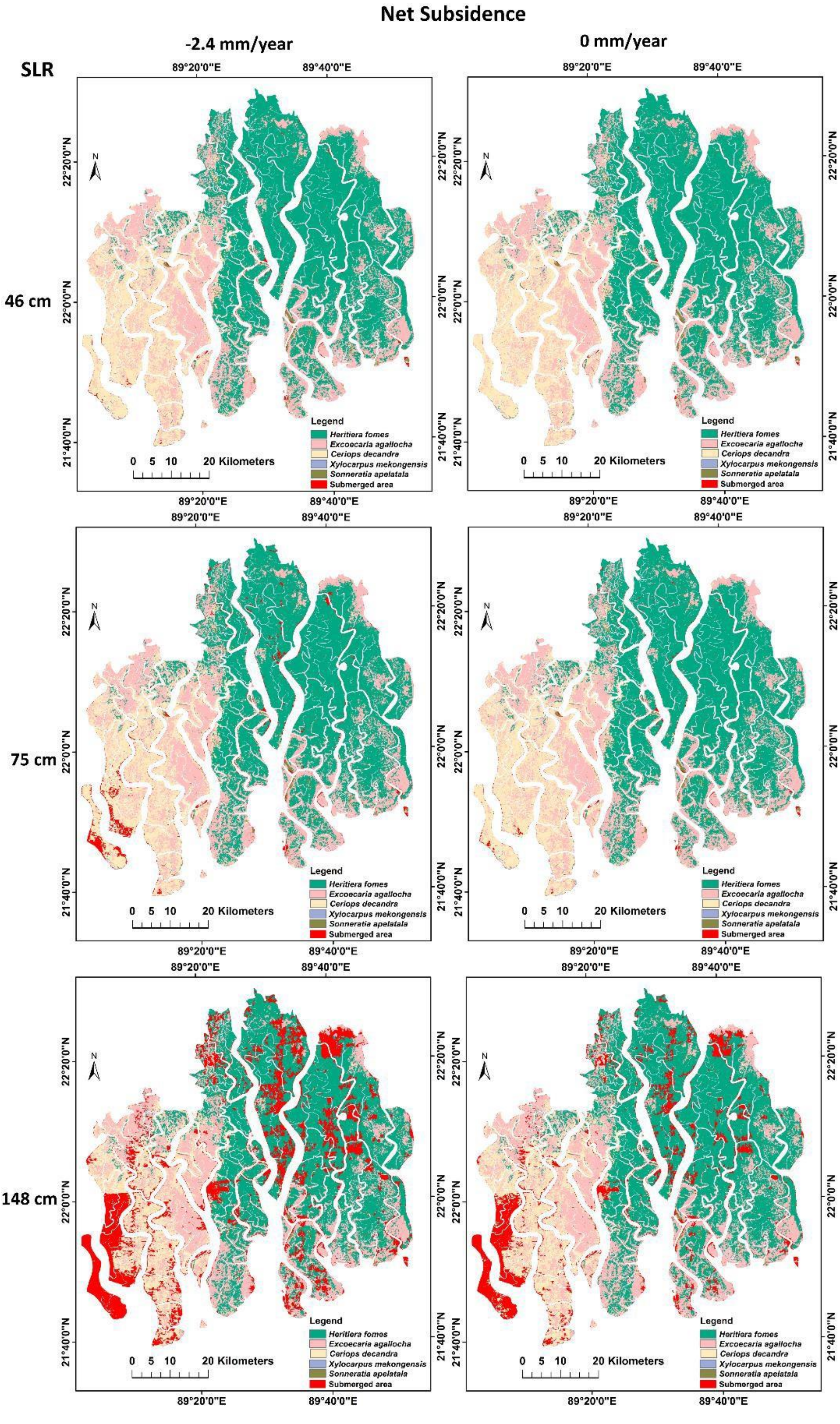

Figure 7.6 Image showing potential impact of SLR on future mangrove species composition by the end of the 21st century in the Bangladesh Sundarbans

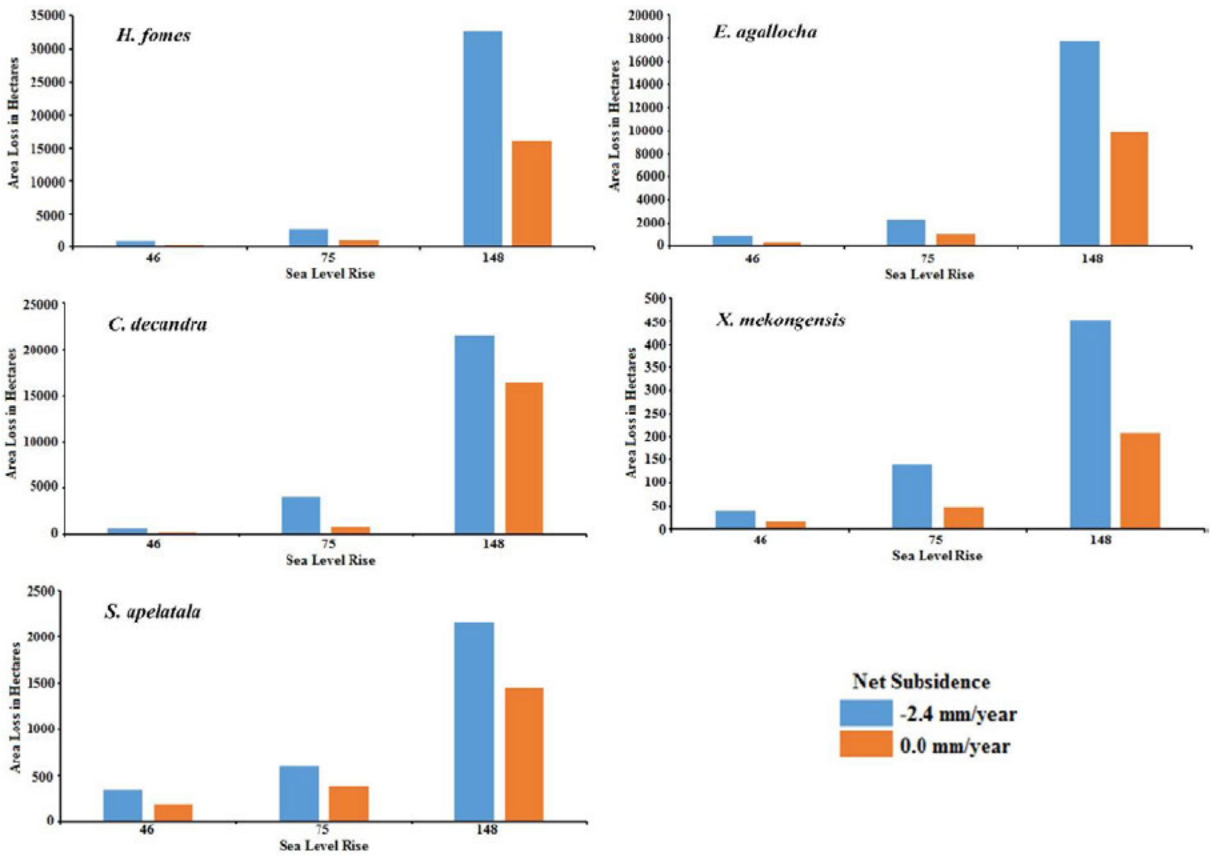

Figure 7.7 Area of different mangrove species under potential inundation by the end of the 21st century under selected SLR scenarios and subsidence levels in the Bangladesh Sundarbans

Table 7.1 Analysis of potential inundation area of different mangrove species under different SLR scenarios and subsidence levels by the end of the 21st century in the Bangladesh Sundarbans

Mangrove Species	Sea Level Rise					
	46 cm		75 cm		148 cm	
	Net Subsidence (mm/year)		Net Subsidence (mm/year)		Net Subsidence (mm/year)	
	-2.4	0	-2.4	0	-2.4	0
H. fomes	0.41%	0.15%	1.29%	0.49%	16.73%	8.15%
E. agallocha	0.72%	0.30%	1.94%	0.86%	14.88%	8.25%
C. decandra	0.85%	0.25%	5.70%	1.16%	30.53%	23.40%
X. mekongensis	2.69%	1.10%	9.65%	3.35%	31.50%	14.44%
S. apelatala	4.04%	2.14%	6.85%	4.43%	25.03%	16.80%

7.4. Discussion

Mangroves are considered one of the important constituents as well as the most vulnerable species in the tropical and subtropical inter-tidal ecosystems of the world (Eslami-Andargoli et al. 2009). Climate change components, such as changes in rainfall pattern, temperature, concentrations of atmospheric CO_2, sea-level, high water events, intensity of cyclones and storms, and patterns of ocean circulation are likely to affect mangrove forests (Ghosh et al. 2017b; Gilman et al. 2008). Among them, SLR is considered one of the most important factors affecting the mangroves in terms of their distribution in the long run (Eslami-Andargoli et al. 2009; Ghosh et al. 2017b). The results of this investigation are crucial for understanding the magnitude of the SLR in the Bangladesh coast as well as the Sundarbans mangrove forest. Payo et al. (2016) projected a total loss of nearly 10% mangrove area of Bangladesh Sundarbans by 2100 because of SLR. This loss definitely could affect the ecological balance of this ecosystem. The protection and conservation of this important ecosystem is necessary as indicated by the potential impact of future SLR on the Sundarbans mangrove forests in this study.

According to Colette (2013) a 45 cm global SLR by the year 2100 can potentially be a risk to 75 % of the Sundarbans mangroves. Loucks et al. (2010), using different DEMs predicted that most parts of the Sundarbans will be inundated for a SLR of +28 cm. Payo et al. (2016) work on the cumulative elevation frequency analysis indicated that even 2.19 m relative SLR would not completely inundate the Sundarbans but may potentially affect 50% of the area. Therefore, the accuracy of the DEM used plays a significant role in determining potential inundation levels in relatively flat plains such as the Sundarbans. The results of this study indicates a level of inundation which is contrary to the works of Loucks et al. (2010) and Colette (2013) but close to the condition of the extreme scenario and projections by Payo et al. (2016). The deviation of our results could be attributed to the fact that our study considered only the vegetated area while that of Payo et al. (2016), in addition, covered beach and mudflat areas. More plausible information on the fate of mangrove composition and distribution in the Sundarbans by the end of 21st century could be made clear with a more accurate and up-to-date DEM data, possibly LiDAR data.

In terms of mangrove species composition and their spatial distribution, potential impacts of low (46 cm) and medium (75 cm) SLR scenarios are expected to be minimal while extreme (148 cm) SLR scenario will have more detrimental effects as the area under inundation will increase. *C. decandra, X. mekongensis* and *S. apelatala* will be at high risk as they will lose more than 25%

of their habitat although the other two (*H. fomes* and *E. agallocha*) will also be at risk in the long term. *H. fomes* and *E. agallocha*, which make up four-fifths of the forest, will be the most affected species in terms of area loss. The south-western part of the Bangladesh Sundarbans, which is occupied mainly by the salt loving *C. decandra* and northeastern part of central area that is occupied mainly by *H. fomes*, will be the main victims due to the SLR. The worst scenario case is expected if Brown and Nicholls (2015) mean subsidence rate of -2.8 mm/year is anything to go by. More mangrove forest area would be inundated than the area inundated with our representative value of -2.4 mm/year.

Inundation, due to SLR, will increase water and soil salinity in the Sundarbans and is set to affect the mangrove ecosystem, especially the species composition. SLR will not only be responsible for area loss of different mangrove species through inundation for longer periods, but it will also expose the rest of the mangrove vegetated area to salinity. According to Ghosh et al. (2016), in the Sundarbans, salinity tolerance levels of different mangrove species are different and vary spatially. Increasing soil and water salinity will have a detrimental effect on species such as *H. fomes* which is less salt tolerant. *H. fomes* is the most dominant species in the Bangladesh Sundarbans and this species is thought to suffer from die-back disease that is highly related to the level of salinity. In response to the increasing salinity, there will be some possibilities of expansion of salt tolerant species such as *C. decandra* by encroaching the non-salt tolerant species areas such as *H. fomes*, which can play a vital role in changing the existing mangrove species composition and ecosystem of the forest. In the short period, these changes may not be that much significant but the continued process of such changes raises concerns with respect to the future sustainability for some of the mangrove species and the biodiversity of the Sundarbans. The Sundarbans mangrove species *H. fomes*, *E. agallocha*, X. *mekongensis* and *S. apelatala* are economically valuable timber species while *C. decandra* is a major non-timber forest product for the Sundarbans communities (Uddin et al. 2013). This implies that a change in the existing mangrove species composition and ecosystem of the forest due to climate change (SLR) would affect the economic and livelihood systems in this part of the world.

In this study, spatially variable impacts of isostatic rebound or land subsidence are considered in elevation computations taking account of the minimum elevation and slope of that cell. However, there are few limitations in this research that are important to emphasize. Different influential processes and interactions that might be effective for potential changes in the mangrove area are not considered in this research. For instance, the relation between sediment accretion and growth of mangroves, assumption of uniform net subsidence, sediment supply changes, or erosion rate caused by different natural forces such as cyclones and water surges are not considered. Responsible anthropogenic forces of current time which may induce future mangrove area loss are also not considered here. Despite these limitations, nevertheless, the results of this study can potentially be used in conservation management of the Sundarbans. The results can be shared with relevant stakeholders, policy makers and sustainable management planners to develop a coping strategy against the SLR impact on the mangrove forest and develop a sustainable plan.

7.5. Conclusion

Due to the low-lying physiographical setting, SLR above the MSL may potentially pose a threat to Bangladesh Sundarbans mangrove forest. This mangrove forest has rich biological diversity and conservation values. The key objective of this research was to generate potentially inundated floodplains due to SLR using DEM data for Bangladesh Sundarbans to understand the impact of SLR on future spatial distribution of mangrove species.

To understand the SLR impact on future species composition of the mangroves and their spatial distributions, a geospatial model of inundation was developed. Three SLR scenarios viz. low (46 cm), medium (75 cm) and extreme (148 cm) were prepared and these scenarios were overlaid on mangrove species composition map of the Sundarbans to visualize and quantify the impacted area.

According to our findings, potential impact of low (46 cm) and medium (75 cm) SLR scenarios will be minimal on mangrove species composition and their spatial distribution while the impact will be extensive under the extreme (148 cm) SLR scenario. All the five major mangrove species will be affected by the SLR and can potentially contribute to a change in the existing species composition and biodiversity of the forest. This present study provides a new knowledge and crucial perspective on the impact of SLR on the future mangrove species composition and their spatial distribution of the largest contiguous mangrove forest of the world and in particular the Bangladesh Sundarbans. It is apparent from the present research that Bangladesh Sundarbans is more resilient to SLR as opposed to predictions by some previous researchers. The main reason for this is that most of the previous researchers used lower accuracy DEMs for modelling. Although this mangrove forest shows resilience to SLR, the trend of resilience will be highly dependent on the subsidence rate which is uncertain. Furthermore, detailed investigations of the Bangladesh Sundarbans regarding the impact of SLR would be useful for the conservation management of the Sundarbans.

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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Chapter 8.

Summary and Conclusions

8.1. Introduction

The Sundarbans mangrove forest is an important resource for the people of the Ganges Delta. It plays an important role in the local as well as global ecosystem by absorbing carbon dioxide and other pollutants from air and water, offering protection to millions of people in the Ganges Delta against cyclone and water surges, stabilizing the shore line, trapping sediment and nutrients, purifying water, and provisioning services such as fuel wood, medicine, food, and construction materials. However, sustainability of these benefits of the mangrove ecosystem is under threat from climate change and anthropogenic related activities. Anthropogenic and climate change-induced degradation, such as over-exploitation of timber and pollution, changes in rainfall and temperature pattern, sea level rise (SLR), coastal erosion, increasing salinity, effects of increasing number of cyclones and higher levels of storm surges function as recurrent threats to mangroves in the Sundarbans. In addition, low-lying physiographical setting of the mangrove ecosystem makes it more vulnerable to changing climate scenarios, especially against SLR. To maintain the ecosystem services, regular and detailed information on mangrove species composition, their spatial distribution and the changes taking place over time is very important. This is significant for a thorough understanding of mangrove biodiversity and developing strategies and adoption of management practices for maximum sustainable yield. Emphasis on preparing databases related to mangrove species composition, species level dynamics and their responsible forces may help to sustain this valuable resource well into the future. Thus, the main aim of this study was to map the long-term changes in mangrove cover at species level and prediction of future spatial distribution under different climate change scenarios in the Bangladesh Sundarbans to provide the information base and predictive route, especially under climate change scenarios and different anthropogenic influences, for sustainable management planning and maintaining the sustainability of the Sundarbans mangrove forest.

Initial literature on mangrove forest settings, as part of this study, highlighted four major issues relating to long term change mapping of mangrove species and predictions of future spatial distribution studies. These issues included; (a) the selection of reliable data for identification of mangrove species and change-detection analysis, (b) the selection of suitable change-detection techniques, (c) the evaluation of the classification accuracy, and (d) the importance of prediction for understanding the future spatial distribution and composition of mangrove species. The data used for identification of mangrove species and change-detection analysis should be trustworthy and accurate enough for identification of mangrove species composition. Remote- sensing (RS) data can be effectively used to identify and monitor the changes and can provide the essential information for mangrove cover dynamics analysis at species level. Several reviewed articles on mangrove forest settings used high resolution data to identify and detect the changes of mangrove species composition. However, wide application of such data is limited in developing countries due to its high cost. Mid-resolution data such as Landsat can be a very effective source for identification and change detection of mangrove species due to their low or no cost availability and high temporal resolution as well as their reasonable spatial resolution. Thus, Landsat imageries have been used in this study for identification of mangrove species composition and change detection analysis.

The selection of an appropriate change-detection technique is also a key concern in any change analysis. To achieve comprehensive change-detection matrices, a method is needed that can provide meaningful change-detection evidence ('from–to' change trajectories). For change detection analysis different methods have been used by different researchers in the past. These methods included pre-classification and post-classification techniques using pixel-based image analysis (PBIA) or object-based image analysis (OBIA). In this present study image classification and post-classification comparison using PBIA were undertaken to ensure reliable and accurate identification and change detection of mangrove species composition at species level due to its well-developed theoretical base, simplicity and ease of use.

The evaluation of the classification accuracy is an important step in any image classification process, and error matrix is the most frequently used method for such evaluation. In change detection analysis, the assessment of the accuracy of the classified historical maps is essential to deliver reliable and trustworthy change-detection information. Accuracy of classified maps is usually conducted based on a single-date error matrix and the classification error matrix of the newest years is then adapted to a change-detection error matrix for the historical image classification but such methods cannot accurately provide an assessment of the classification accuracy of the previous years. To address this gap, an appropriate approach has been used in this study in which the classification accuracy of the previous years could be precisely evaluated.

The mangrove species composition dynamics in the Sundarbans is a result of vigorous and complex processes. The dynamics of mangrove species in this particular mangrove ecosystem are considerably influenced by some other factors such as climatic variability, river channel dynamics, rise in sea level and sedimentation and erosion, these factors can also affect the future spatial distribution of mangrove species. Thus, above-mentioned factors should be included to understand the current and future dynamism and status of this important ecosystem.

In this thesis all these issues were considered in the different research chapters. This chapter provides a summary of the main findings, study implications, scope for future research and recommendations.

8.2. Summary of the Key Findings

The efficacy of mid-resolution Landsat imagery combined with traditional classification algorithms to produce an acceptable accuracy at species level mapping of mangroves was evaluated in this research. Based on the extensive field experience and the information obtained from previously published literature and species level map, we purposively mapped five major mangrove species viz. *Heritiera fomes, Excoecaria agallocha*, *Ceriops decandra*, *Sonneratia apelatala*, and *Xylocarpus mekongensis* of the Sundarbans that constitute higher density cover. The other remaining species were classified under the major five mangrove species on the basis of dominance because the majority of the remaining species are distributed in lower density, spreading over wide areas in small patches, and do not form large enough mono-specific patches for training site selection and therefore cannot be detected through medium-resolution satellite data. The results indicate that the classification of Landsat imagery for mangrove species composition achieved an overall accuracy of 89.10% and a kappa coefficient of 0.87 which is above the minimum value required for most applications. The classified thematic map prepared with this accuracy level clearly discriminates all the five mangrove species of the Bangladesh Sundarbans with sufficient accuracy to be used as a baseline data for future resource planning. The investigation further illustrates that almost half of the Bangladesh Sundarbans is currently occupied by *H. fomes*, especially in the central and eastern parts, followed by *E. agallocha*, *C. decandra*, *S. apelatala* and *X. mekongensis*. *E. agallocha* are sparsely distributed all over the Sundarbans while *C. decandra* are found densely in the western part and in a mixed stand with other species. In spite of using Landsat image data with conventional image processing techniques, the achieved overall accuracy of this research signifies the applicability of conventional mid-resolution images for the classification and identification of mangrove forest at species level. Thus this work clearly shows the potential of Landsat image and traditional classification algorithm to produce high accuracy output with finer details at species level.

Following the successful use of Landsat imagery with traditional classification algorithms to identify and map mangrove composition at species level, this study mapped the long term changes in mangrove species composition in the Sundarbans. In particular, this study examined the mangrove species composition in the Sundarbans for four different periods to understand the species composition dynamics of this forest over the study period 1977-2015. Five major mangrove species viz; *H. fomes*, *E. agallocha*, *C. decandra*, *S. apelatala*, and *X. mekongensis* were identified for all the four study years (1977, 1989, 2000 and 2015), and afterwards post classification comparison techniques were used to detect the changes in mangrove species composition from the four imagery dates. Results indicate that, throughout this study period, *H. fomes* and *E. agallocha* decreased in terms of area while *C. decandra*, *S. apelatala*, and *X. mekongensis* increased. The responsible forces that have played an important role in bringing about the observed changes in the mangrove species composition in the Sundarbans includes over-exploitation of forestry and non-forestry resources, pollution, coastal erosion and sedimentation, increasing salinity, die-back disease and changing climate.

The identification of relationships between climatic variables and the dynamics of mangrove species is very important for understanding the impact of climatic variables on mangroves. In this thesis, an effort was made to examine the association between climatic variables and mangrove dynamics at species level in the Sundarbans of Bangladesh using linear regression model. Some significant associations have been observed between temperature, rainfall and the dynamics of some mangrove species. The outcome of this investigation indicates a significant association between climate variables, more specifically maximum temperature and rainfall, and the dynamics of mangrove species, particularly *H. fomes, S. apelatala* and *C. decandra,* in the Sundarbans mangrove forest in Bangladesh. Over the period 1977-2015, a strong association was observed between the dynamics of *H. fomes* and *S. apelatala* with temperature and rainfall, while *C. decandra* showed a weak relationship. With the increasing average maximum temperature and decreasing annual total rainfall, area under *H. fomes* decreased, while *S. apelatala* has increased in both the cases considerably. However, no significant association was observed between the dynamics of *E. agallocha* and *X. mekongensis* and temperature or the rainfall pattern.

Spatial and temporal dynamics of tidal channels were investigated and mapped in parts of the Bangladesh Sundarbans over a period covering 43 years (1974-2017). RS data were used to examine sedimentation and erosion as well as the locations in different years. The results indicate that considerable shift of tidal channel banks took place over the study period. This investigation also indicates that, in some locations, the bank of tidal channels shifted over a kilometer. The dynamics of the channel are the result of erosion and sedimentation. The resultant maps show that erosion process is dominant in the wider channels while sedimentation process is prominent in smaller channels. Erosion process is responsible for land loss leading to tree falling in the study area. On the other hand, through the sedimentation process, new lands are gained. These newly gained lands are usually more saline due to frequent inundation, and are dominated by salt-tolerant mangrove species such as *C. decandra* and *S. apelatala*. Mangrove species that forests lose through land erosion, and new mangrove species that forests gain through accretion, are not always the same and this may have implications with respect to the composition and sustainability of some species. While in the short term these changes are minor, over future decades, the dynamics of tidal channel might have significant implications in mangrove species composition change in the Sundarbans, and these continued erosion and sedimentation processes raise concerns with respect to the future sustainability for some of the mangrove species of the Sundarbans.

Responsible forces for tidal river erosion and sedimentation in the context of natural and human induced factors as well as their impacts on the Sundarbans mangrove forest have been synthesized in the sixth chapter of this thesis. Two key questions are put in context in this synthesis: why is tidal river/ channel morphology dynamics occurring? And what are the implications of these geomorphologic changes on ecosystem to plant communities in the Sundarbans? Based on our discussion it can be concluded that natural and anthropogenic forces such as tides, storms and cyclones, fluctuations in seasonal rainfall, tectonic and subsidence forces, SLR, infrastructure development and changing pattern of land use plays an important role in erosion and sedimentation processes in tidal channel dynamics and subsequently have important implications on the species composition of the Sundarbans mangrove ecosystem. This could also affect the sustainability of the ecosystem and biodiversity.

It is important to understand the future mangrove species composition and their spatial distribution in response to the changing climate scenarios, especially SLR, to help sustainable management planners and relevant stakeholders and policy makers for sustainable management of the Sundarbans mangrove forest ecosystem. A geospatial model of inundation was developed with three SLR scenarios (low, medium and extreme) to visualize and quantify the impact of SLR on future mangrove species composition and their spatial distribution. Results indicate that potential impact of low and medium SLR scenarios will be minimal on mangrove species composition and their spatial distribution while the impact will be extensive under the extreme SLR scenario. The model also shows that SLR will affect all the five major mangrove species in the Sundarbans and can potentially contribute to a change in the existing species composition and biodiversity of the forest.

8.3. Contribution to Science and Knowledge

This study exhibited how mid-resolution RS data and conventional classification techniques can be effectively used to identify and monitor the mangrove species composition dynamics as well as future distribution. The methodologies used in this research provide easy-to-use and step-wise approaches to extract, analyse and detect changes in mangrove cover using time-series Landsat images.

The method used in this research for image classification and accuracy assessment delivered a trustworthy approach. This approach allows to evaluate the classification accuracy of the previous years with the absence of reference data. This method was tested throughout this study and showed its effectiveness in terms of assessing the historical classifications. This research also introduced a geospatial model to quantify and visualize the impact of SLR on future mangrove species composition and their distribution. The step-wise processes of this model can be easily followed to quantify and predict the future impact of SLR on mangrove population.

In general, this study provides the essential knowledge to support the decision-making processes of forest management planning in a sustainable way in the Sundarbans mangrove forest. The successful application of mid-resolution Landsat data and conventional classification method to identify and map mangrove species composition with acceptable accuracy in chapter two gives confidence in the use of such images and methods in regions where high spatial resolution imagery is not available or cannot be afforded, and this will also motivate different government agencies, researchers and relevant stakeholders to develop a proper and continuous monitoring system in a simple, time saving, efficient and cost effective way. This will also open-up the avenue of such applicability for other developing countries having similar issues.

The analysis of mangrove species composition dynamics in the Sundarbans between 1977 and 2015 in chapter three helps to understand the past changes and to quantify the overall rate of change as well as to identify the vulnerable species. For example *H. fomes* and *E. agallocha*, two species which form a substantial part of the forest, are decreasing at an alarming rate. Therefore, future conservation and protection initiatives should focus on these two species to avoid their further degradation. The species composition maps, and the species composition change maps (chapter three) have shown the locations where the areal extent of the particular threatened species are reduced or encroached by the others. Therefore, we suggest to bring these species under protection to ensure their long-term conservation. Although illegal tree felling has been prohibited since 1989, opportunistic harvesting of valuable timber-yielding species, specifically *H. fomes* and *E. agallocha*, by poachers is a common phenomenon. The Bangladesh Forest Department (BFD) has ratified the 'Bangladesh Biodiversity Act 2017' to reduce biodiversity loss and also recently initiated the SMART patrol management system to stop such illegal practices in the Sundarbans. The species composition map, prepared using free source mid-resolution data in the RS and Geographic Information System (GIS) platform (chapter three and four), can be helpful in the protection and monitoring initiatives through tracking individual species populations and predicting changes that could be affected by anthropogenic activities. The information obtained from this study could provide an invaluable quantitative information to different agencies of Bangladesh government such as BFD, Ministry of Environment and non-government organizations and educational and research institutes for better and sustainable management of the Sundarbans mangrove ecosystem. This outcome, also, could be used in the context of integrated forest management. Also, the proposed approach (chapter three) for mapping the mangrove species composition dynamics is not restricted to mangroves. Therefore, other forest ecosystems such as boreal, temperate, and tropical forests could be benefitted from this approach to address various management and conservation issues therein.

Identifying the association between climatic variables with mangrove species composition dynamics provides a dimension for assessing the impacts of climatic variables on mangrove species in the context of the vulnerability as a result of climate change. However, inadequate understanding of climatic factors affected the regulating of mangroves abundances, composition and functions that results in unsuccessful mangrove enhancement and restoration projects in many countries including the Bangladesh Sundarbans. This fourth chapter of this thesis determined the influence of different climatic variables responsible for species composition dynamics in the Sundarbans. For example, rainfall and temperature predominantly influence the dynamics of *H. fomes, S. apelatala and C. decandra.* These invaluable insights and the species composition dynamics map can guide BFD and the other relevant stakeholders for the future mangrove enhancement and restoration initiatives in the Sundarbans. This study provides some invaluable insights to the BFD and other relevant stakeholders for the development of proper adaptation strategies in the future for sustainable management of the forest in response to climate variability and change. The Bangladesh government can take advantage of this research outcome to design site specific adaptation strategies in order to aim for the sustainable management of this valuable forests.

The investigation of tidal channel dynamics and responsible forces for this dynamics provides some scientific understanding of mangrove physical geomorphology and adds knowledge to limited tidal channel erosion and sedimentation processes with respect to mangrove forest ecosystem (chapters five and six). The outcome of these chapters helps to understand the dynamic nature of the tidal channels in the Sundarbans and the forces that are responsible for the dynamism. National authorities and organizations could consider the outcome of this research for the management strategies to ensure sustainability of the mangroves and also sets a basis for further work for researchers within this field.

Further, the geospatial modelling of the impact of SLR on the spatial distribution of different mangrove species (chapter seven) helps to understand and quantify the risk of the ecosystem in the future. The seventh chapter of this thesis quantified and visualized the future species composition and their spatial distribution in response to different SLR scenarios. According to the outcome of our research all the five major mangrove species of the Sundarbans will be affected by SLR in the future and that can potentially contribute to a change in the present species composition. For example *H. fomes* and *E. agallocha,* which make up four-fifths of the Bangladesh Sundarbans, will be the most affected species in terms of area loss. The south-western part of the Bangladesh Sundarbans, which is occupied mainly by the salt loving *C. decandra* and north-eastern part of central area that is occupied mainly by *H. fomes*, will be the main victims due to the SLR. This information can be used to ensure the sustainable management of the Sundarbans forest ecosystem. National authorities and organizations can use our results to implement policies and programs, ensuring the sustainability of the forest. In addition, with this information, individual researchers, policy makers and the government could implement adaptation measures, such as the use of new technology and management practices, to overcome the impact of SLR on this important ecosystem. Also, the proposed model is not restricted to only the Sundarbans mangrove ecosystem; it can also be readily applied to similar forest ecosystems of the world to address various management and conservation issues therein.

Overall, the outcomes of this research should provide an overview of the Sundarbans mangrove ecosystem to ensure better management of the forest and its resources.

8.4. Limitations and Future Directions

The classification methods used in this research were based on the spectral signature of the Landsat images employing the PBIA approach. A comparison between OBIA and PBIA approach could provide an opportunity to highlight the strengths and weaknesses of both approaches in terms of identifying mangrove species and their dynamics using Landsat images. Accuracy assessment is an integral part of the change detection analysis. Development of other method to assess the historical image classification is an important aspect for future research. Such methods can be inspected using other automatic improved techniques rather than using NDVI differencing.

In terms of SLR modelling, it would be more constructive if different influential processes and interactions such as the relation between sediment accretion and growth of mangroves, assumption of uniform net subsidence, sediment supply changes, or erosion rate caused by different natural forces such as cyclones and water surges are considered.

The Sundarbans is the largest contiguous mangrove forest of the world. This forest is recognized as a global priority for biodiversity conservation because of its rich biological diversities and conservation values. This important forest ecosystem needs effective conservation and management practices for sustainable development. The efficiency of such management practices can be significantly enhanced by adopting appropriate monitoring system using remote sensing based technologies and developing integrated geospatial tools. This present research sets a basis for future development of a proper and efficient monitoring system using geo-information technologies in a cost effective and time saving manner in the Bangladesh Sundarbans mangrove forest ecosystem as well as other part of the world.

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