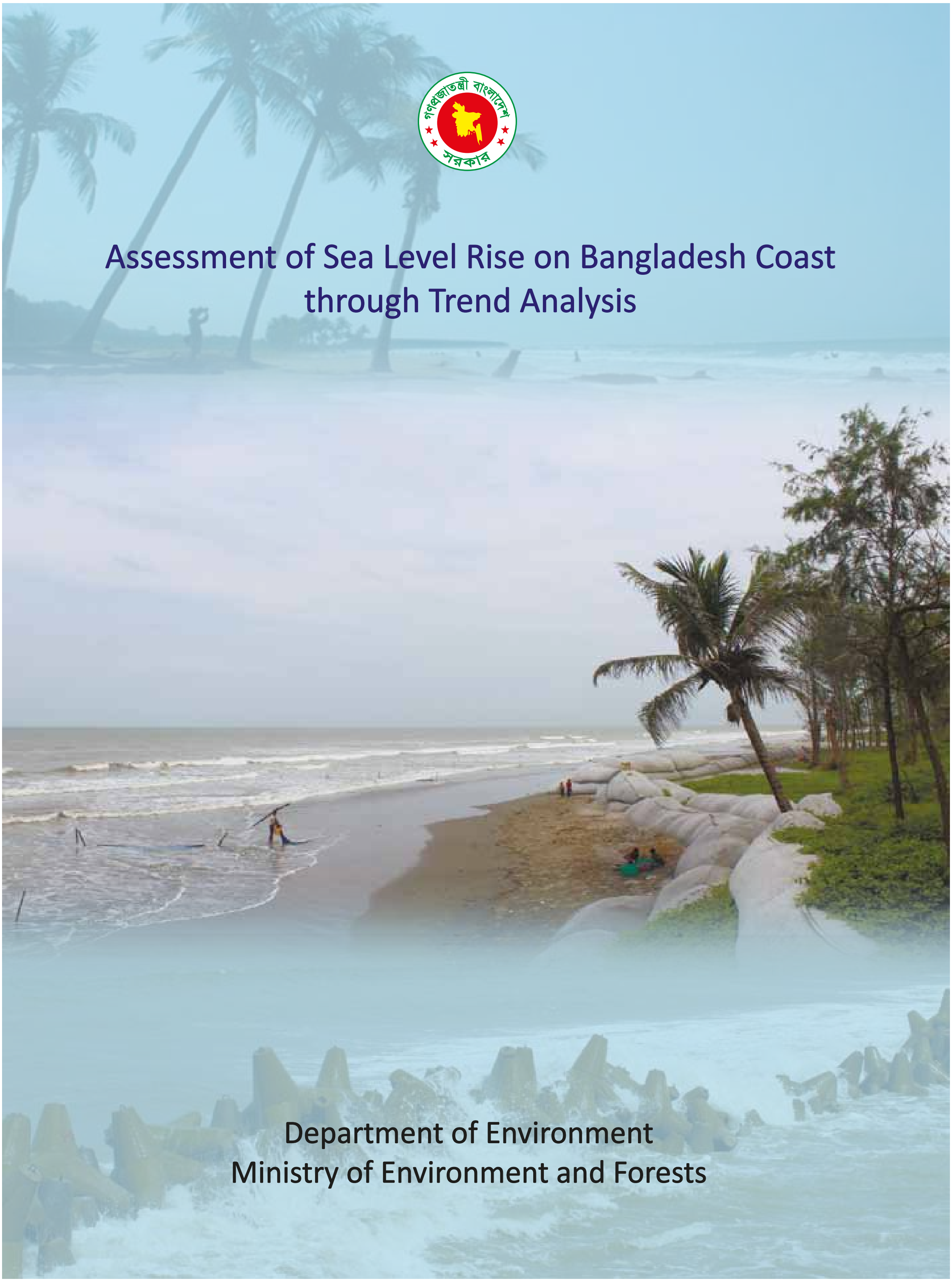

Assessment of Sea Level Rise on Bangladesh Coast through Trend Analysis

Department of Environment
Ministry of Environment and Forests

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July 2016

Climate Change Cell
Department of Environment
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CEGIS — Center for Environmental and Geographic Information Services

IWM — Institute of Water Modelling

Institute of Water and Flood Management, BUET

Minister
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Message

Sea level rise (SLR) has become an increasing global concern in recent decades. The issue is also very important for Bangladesh as the country is very vulnerable to the impacts of SLR because of its geo-physiographic settings. Given the scenario of projected climate change, sea level is assumed to continue rising at a very high rate and the country might face the multiple impacts of SLR with very high intensity in the days to come.

The extensive review of SLR literatures reveals that scientific research-based knowledge on SLR is mainly available on global scale mostly in IPCC Assessment Reports. In-depth national or local level SLR assessment information is still scanty and scattered.

I am pleased to know that, realising its national significance, the Climate Change Cell of the Department of Environment has carried out a scientific research entitled, "Assessment of Sea Level Rise on Bangladesh Coast through Trend Analysis" with the technical support of Centre for Environmental and Geographic Information Services (CEGIS), Institute of Water and Flood Management (IWFM), BUET and Institute of Water Modelling (IWM).

I hope the research findings will be of use to the scientific community, academics, professionals, practitioners, local government bodies and particularly to the policy-makers to formulate long-term policies and strategies in addressing SLR impacts in coastal Bangladesh.

My sincere thanks are due to those who have contributed to this study.

Anwar Hossain Manju, MP

Deputy Minister
Ministry of Environment and Forests
Government of the People's Republic of Bangladesh

Message

The recent scientific literatures indicate that the level of the seas is rising with the passage of time. Rise of sea level poses a potential threat to the coastal region of Bangladesh as it is sea-facing low elevated, poverty stricken and highly populated. At this backdrop, assessment of sea level rise trend on Bangladesh Coast is very important to determine the potential threats and to address these.

I am happy to know that the Climate Change Cell of the Department of Environment has carried out a study on Sea Level Rise Trend on Bangladesh Coast. And a few of the leading research organizations of the country, e. g., Centre for Environmental and Geographic Information Services (CEGIS), Institute of Water and Flood Management (IWFM), BUET and Institute of Water Modelling (IWM) have provided technical support to make this research initiative a success.

The findings of the study will be useful to know about the potential SLR threats in the coastal region of the country and to frame policy interventions to take in hand the menace.

I express my sincere gratitude to the Department of Environment for taking this great initiative. I extend my heartfelt thanks to the technical organizations and professionals for their praiseworthy contribution to this study.

Abdullah Al Islam Jakob, MP

Secretary
Ministry of Environment and Forests
Government of the People's Republic of Bangladesh

Message

Over the last few decades, the scientific communities of the world are raising their voice against SLR. It has also become one of the main talked about topics in international climate negotiations.

The coastal region of Bangladesh is very resourceful but geographically vulnerable to sea level rise. It has a vast natural resource base including the largest single tract mangrove forest, the Sundarbans. On the contrary, it is highly exposed to the Bay of Bengal. With reference to IPCC Fourth Assessment Report 2007, a sea level rise of just 45 cm in the Bay of Bengal will possibly put about 11 percent of the coastal area under water leaving 7-10 million people homeless among 39 million people living in 19 coastal districts.

International literatures indicate that sea level is rising over time on different scales in different parts of the oceanic world. But the scale of SLR in our coastal belt is remaining as a big question despite some research efforts based on IPCC data. This study shall try to answer some of the long-posed question.

I sincerely thank Department of Environment for this great effort. My gratitude is due to CEGIS, IWFM (BUET) and IWM for their technical support to conduct the study.

I believe the research findings will help make our voice stronger in international fora over our SLR vulnerability issue. It will also play a vital role in national policy implications to take care of potential SLR impacts in the coastal region of the country that might emerge as a national priority in future.

Dr. Kamal Uddin Ahmed

Director General
Department of Environment
Ministry of Environment and Forests

Forewords

Over the last few decades, SLR has become a growing concern in particular for the island and coastal countries of the world. As a coastal country, Bangladesh may face more loss, damage and even massive migration challenge because of country's a wide variety of geo-physiographic features including tropical geographic location, flat topography, sea-facing low elevation and funnel-shaped coastline. Again, quite a few socio-economic realities e. g., high density of population, high level of poverty and livelihood reliance on climate sensitive sectors (agriculture, fisheries, and water resources) might intensify SLR vulnerabilities of coastal Bangladesh.

Like other vulnerable nations, we also sincerely raise our voice against our SLR vulnerabilities. But we couldn't let the international community know research-based and evidence-led information about the scale on which the sea level on Bangladesh coast has been rising over time or is going to rise in future.

At this backdrop, Department of Environment (DoE) commissioned a research with a view to assessing SLR trend on Bangladesh coast with the technical support of CEGIS, IWFM (BUET) and IWM. The research used nationally generated tidal gauge data of about past 30 years. I believe the research findings will work as substantial evidence for us to talk about our SLR vulnerabilities in international fora. Again, the research will open new windows for undertaking further research initiatives on the issue in future.

I sincerely thank our honourable Minister, Deputy Minister and Secretary of MoEF for their continuous support and guidance. My gratitude is due to CEGIS, IWFM (BUET) and IWM for their technical support. Sincere acknowledgement goes to my colleagues at the Climate Change Section and erstwhile Climate Change Cell of DoE for this nationally important initiative. I am also thankful to the concerned experts who have helped review the research report to produce a quality knowledge document.

Md. Raisul Alam Mondal

Acknowledgement

The successful completion of the study, "Assessment of Sea Level Rise on Bangladesh Coast through Trend Analysis" is the ultimate result of concerted contributions made by a wide array of organizations and professionals.

A consortium of three renowned organizations of the country including Centre for Environmental and Geographic Information Services (CEGIS), Institute of Water and Flood Management (IWFM) of Bangladesh University of Engineering and Technology (BUET) and Institute of Water Modelling (IWM) has provided the technical support to the study. Our sincere thanks and profound gratitude go to these three organizations. Particularly, we appreciate the effort of Mr. Md. Motaleb Hossain Sarker, Mr. Malik Fida Abdullah Khan, and Ms. Farhana Ahmed from CEGIS, Mr. Zahirul Haque Khan from IWM and Professor Dr. Saiful Islam from IWFM (BUET) for taking the research to successful conclusion.

The study report has been finalized through a series of consultation workshops where the professionals of many technical organizations have participated and contributed a lot. We remember their valued contributions with due respect and gratitude.

We sincerely thank Professor Dr. Ainun Nishat under the very leadership of whom a panel of experts, namely Professor Dr. Shahidul Islam (Geography & Environment, DU) and Dr. Anwar Ali, reviewed the draft study report and provided their valuable feedback for its improvement.

Our sincere gratitude also extends to Mr. A. M. Monsurul Alam and Mr. AKM Mizanur Rahman for the contribution during their tenure as focal point of the Cell.

We highly evaluate the contribution of Mr. Md. Harun-Or-Rashid, Mr. Md. Mahmud Hossain and Ms. Dilruba Akter, Assistant Directors, DoE and also Mr. Gazi Sipar Hossain, Research Assistant, CCC, DoE towards successful Completion of the study. Sincere thanks also goes to Mr. Sordar Shariful Islam for his some sort of logistic support to this publication.

We appreciate Mr. Muhammad Selim Hossain, Research Assistant, CCC, DoE for his substantial editorial support in this publication.

The guidance from Mr. Md. Raisul Alam Mondal, Director General, Department of Environment and financial contribution from Comprehensive Disaster Management Programme (CDMP II) and other development partners are gratefully appreciated and acknowledged.

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List of Abbreviations

AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
BIDS	Bangladesh Institute of Development Studies
BIWTA	Bangladesh Inland Water Transport Authority
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
CEGIS	Center for Environmental and Geographic Information Services
COP	Conference of Parties
DoE	Department of Environment
ESLR	Effective Sea Level Rise
FAR	First Assessment Report
GCM	Global Climate Model
GMSL	Global Mean Sea Level
GSL	Geocentric Sea Level
IPCC	Intergovernmental Panel on Climate Change
IWFM	Institute of Water and Flood Management
IWM	Institute of Water Modelling
MoEF	Ministry of Environment and Forests
MSL	Mean Sea Level
NAPA	National Adaptation Programme of Action
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
RCP	Representative Concentration Pathways
SAR	Second Assessment Report
SDNP	Sustainable Development Networking Project
SLR	Sea Level Rise
SMRC	SAARC Meteorological Research Centre
TAR	Third Assessment Report
UNFCCC	United Nations Framework Convention on Climate Change
WARPO	Water Resources Planning Organization
WMO	World Meteorological Organization

Executive Summary

The coastal zone of Bangladesh is the most vulnerable to climate change because of its geographic location, flat topography, high population density, high levels of poverty, and reliance of many livelihoods on climate sensitive sectors particularly, agriculture, fisheries and water resources. The average elevation of the southwest coastal zone ranges from 1to 2 m and in the southeast coastal zone it is 4 to 5 m. The low elevation, active delta and dynamic morphology play a significant part in its vulnerability to sea level change. Sea level rise affects the coastal zone and its geometry in a number of ways including inundation, erosion and salt water intrusion into the water table. The risks from adverse climate change induced sea level rise will increase the risks of the already vulnerable population along the coast of Bangladesh.

The "Climate Change Cell" of the Department of Environment (DoE), initiated this study titled "Assessment of Sea Level Rise and Vulnerability in the Coastal Zone of Bangladesh through Trend Analysis". There are two major components under this study-sea level rise and vulnerability. According to the relevance of the study objectives, the report has been organized under two headings: a) Assessment of Sea Level Rise and b) Assessment of Vulnerability.

Sea level at a particular location changes regularly with the tides and irregularly due to conditions such as wind and currents. Other factors that contribute to such fluctuation include water temperature and salinity, air pressure, seasonal changes, the amount of stream runoff, and the amount of water that is stored as ice or snow. The components of sea level rise can be divided into global, regional and local sea level rise. Globally, the critical factors are: Thermal expansion; and Cryospheric contribution. The factors that have regional and local influence on SLR are Local atmospheric circulation; Tectonic movement; Land subsidence/soil compaction; Sediment contributions and Anthropogenic contributions.

Based on the understanding of the project objectives and activities a comprehensive methodology has been developed. The activities started with identification of knowledge gaps followed by literature review, evaluation of existing approaches on sea level change estimation and then assessment of observed trend. As part of the gap identification, existing literatures on sea level rise in both global and Bangladesh context have been extensively reviewed.

This study focused on the trend analysis of the tidal water level to visualize the historical change of sea level rise along the coast of Bangladesh. Based on the hydro-morphological characteristics, the coastal zone has been delineated into three regions: the Ganges Tidal Plain or the Western Coastal Region; the Meghna Deltaic Plain or the Central Coastal Region and the Chittagong Coastal Plain or the Eastern Coastal Region. Physiographic unit-wise the coastal region can be further subdivided into six sub-regions: the Ganges Tidal Floodplain (saline), the Ganges Tidal Floodplain (non-saline), Meghna River

Floodplain, Meghna Estuarine Floodplain (Charland), Chittagong Coastal Plains and St. Martin's Island. Water level stations for each of this sub-region have been selected and analyzed. 38 BIWTA stations, 127 tidal water level stations and 18 non-tidal water level stations of BWDB are located in the coastal zone. From these stations, 18 stations have been selected along the coasts to cover three major geo-morphological regions and six physiographic sub-regions.

A number of standard statistical analysis were conducted, which include the consistency checking of data, homogeneity test, serial auto-correlation testing etc. After consistency checking, 3 stations out of the initially selected 18 stations have been discarded for having inconsistent data. Observed trends are detected using both linear regression and Sen's slope methods and significance of the trends are tested using Mann Kendall test. The trends that are significant at 95% confidence level have been considered for SLR analysis. Finally, the results have been summarised for the three deltaic zones in the coastal area: the Ganges Tidal Plain or the Western Coastal Region; the Meghna Deltaic Plain or the Central Coastal Region; and the Chittagong Coastal Plain or the Eastern Coastal Region.

Analysis of tidal water of 30 years shows trends of water level in the Ganges tidal floodplain of 7-8 mm/year. On the other hand, the trend is 6-10 mm/year in the Meghna Estuarine flood plain and 11-21 mm/year in the Chittagong coastal plain areas. So, it has been found that the overall trend in the coastal zone in the last 30 years has been 6-21 mm/year. The trend obtained from this study corresponds to the trend cited by SMRC (2003), where the trend is lower in the Ganges followed by medium range values in the Meghna and highest values in the Chittagong coastal plain. In addition to similarities regarding rising trends, this study reveals that sea level has risen at a higher rate than in the past, thus consolidating the notion of rising sea level.

The trend derived from the global tide gauge data found that the long-term trend in GMSL is 1.7 [1.5 to 1.9] mm/year between 1901 and 2010 for a total sea level rise of 0.19 [0.17 to 0.21] m. Alternatively, the high-precision satellite altimetry record suggest that between 1993–2012, a GMSL rate of 3.2 [2.8 to 3.6] mm/year has been observed. Therefore, the MSL trend derived from the tidal gauge data along the coast of the Bay of Bengal is much higher than the GMSL trend derived from long-term global tide gauge data and short-term satellite data.

This study recommends installing at least 10 high precision automatic tidal gauge stations along the coastline of Bangladesh. The location of these stations along the coastal belt are near Hiron point, the Sundarbans, Khepupara, Char Changa, Sandwip, Moheshkhali, Noakhali, Chittagong Port, Cox's Bazar and Teknaf.

Introduction

1.1 Background

The IPCC fifth assessment report (IPCC, 2013) indicates that vast coastal communities living in the South Asian countries such as Bangladesh are becoming increasingly vulnerable to the imposing threat of sea level rise. Change in climate will result in an increased rate of rising sea levels with subsequent tidal flooding, accompanied by more intense tropical cyclones, storm surges and droughts that will have severe impacts upon life and economy of the country. These anomalies are already evident in recent time with the event of devastating cyclones such as SIDR in 2007 and AILA in 2009, exerting huge economic and social losses. In the coastal zone, more than half (56.37%) of the area is currently threatened with cyclonic storm surges with around 45% area under threat from surges of more than 1 metre (Sarker and Ahmed, 2015).

Physical risks associated with these extreme events in conjunction with the societal exposure risk levies immense pressure upon coastal habitat. Sea level rise comes as a direct result of the adverse influence of the changing climate upon global tidal patterns and is ultimately increasing the risks of the vulnerable population and their livelihood. Apart from being a catastrophe in itself, abrupt rise in sea level can cause a chain reaction of inimical natural calamities based on cause and effect. Salinity intrusion in the coastal regions is one of the major effects of sea level rise, which is currently evident in not only the various existent freshwater sources but also in the soil, thus threatening drinking water security and crop production. Intrusion of saline water will continue as the area under 1 ppt salinity line is expected to increase by 18.22% and area under 5 ppt salinity is expected to increase 24% by 2050 (CEGIS, 2011). Coastal flooding due to tidal surge along with the huge amount of sediment that is carried by the three major rivers through a steep flow gradient, coupled with the increase in sea level thus results in extensive flooding in coastal regions. The Bangladesh Climate Change Strategy and Action Plan (BCCSAP) stressed the need to understand, prepare and respond to these emerging challenges so that the wellbeing of the people is ensured (MoEF, 2009).

The Department of Environment (DOE) has, therefore, initiated this study for the "Assessment of Sea Level Rise and Vulnerability in the Coastal Zone of Bangladesh through Trend Analysis". There are two major components of the study; sea level rise and vulnerability. For ease of understanding and according to the relevance of the study objectives, the study report has been organized under two headings: a) Assessment of Sea Level Rise and b) Assessment of Vulnerability.

1.2 Rationale of the Study

The global climate change risk index indicated that high degrees of vulnerability of Bangladesh to climate change is mainly attributed to its geographic location, flat and low-lying topography, high population density, high levels of poverty, and reliance of many livelihoods on climate sensitive sectors, particularly agriculture, fisheries and water resources. For instance, people residing in coastal zones are directly dependent on the natural resource bases of coastal ecosystems. Climate change impacts including increasing temperatures, enhanced monsoon precipitation and run-off, potentially reduced dry season precipitation, and increase in cyclone intensity reinforce stress on many of these baseline resources. Rise in sea level will aggravate the risks to coastal zones. In particular, the poorest people living in the vulnerable regions are the most susceptible to climate-induced risks and will continue to suffer the most. It is therefore, important to know the trend of sea level rise in Bangladesh.

IPCC reports provide the trend of sea level rise and projections for the globe. Most importantly, the recently published Fifth Assessment Report (IPCC, 2013) has provided the trend of SLR based on gauge data and satellite altimetry data. This is the first time AR5 has provided the trend as well regional projections of SLR of Bay Bengal as a case study. These projections vary with time and changing scenarios and are based on model results. Studies done till now including the IPCC, have not provided sea level rise value for the Bangladesh coast taking into consideration the dynamic physical and morphological characteristics of the Bay of Bengal (Brammer, 2014a and Brammer, 2014b). For planning at local level, sea level needs to be assessed with local knowledge and information.

The study findings would support policy makers, planners and the government in climate change related policy and program development, as well as integration of climate change considerations into existing development interventions. It could also facilitate the Bangladesh Government in their negotiation efforts for climate change in the international platform.

1.3 Objectives

The overall objective of this study is to assess the potential sea level rise and vulnerability of the coastal zone of Bangladesh using trend analysis. The specific objectives are to:

- Identify the knowledge gaps on sea level rise due to climate change;
- Understand the existing approaches and models for estimation and assessment of sea level rise;
- Identify the trends in sea level rise based on stationary observed data;
- Obtain local knowledge and disseminate and share the study findings at national level.

1.4 Methodology

A comprehensive methodology has been developed for this study based on understanding the study objectives and activities. The activities started with identification of knowledge gaps followed by literature review, evaluation of existing models and approaches on sea level change estimation and then assessment of observed trend. As part of the gap identification, existing literatures on sea level rise in both global and Bangladesh context have been extensively reviewed. As per the ToR, this study focused on the trend analysis of the tidal water level to visualize the historical change of sea level rise in the coast of Bangladesh. The methodological steps in detail are as follows:

Review of literature on sea level rise

Existing literatures on sea level rise in both global and Bangladesh context have been extensively reviewed. In recent times, SLR related projects have been carried out by various national and international organizations. The national reports, articles and journals have been reviewed. Reports prepared such as the National Adaptation Programme of Action (NAPA), Final Report on Programmes Containing Measures to Facilitate Adaptation to Climate Change of the Second National Communication Project of Bangladesh, Impacts of Climate Change on the morphological processes of the main rivers and the Meghna Estuary of Bangladesh, Impact of Sea Level Rise on Suitability of Agriculture and Fisheries and similar other studies conducted by CEGIS, IWM and IWFM on climate modelling and SLR have been consulted. Research carried out by academicians worldwide in their own capacity and published in peer reviewed journals have been identified and conferred with. Authentic documents and information acquired from the websites of IPCC, WMO and UNFCCC provided the baseline information for the study.

Assessment of sea level rise

SLR has the potential to interact with the coastal zone in a number of ways including inundation, erosion and salt water intrusion. Inundation and intrusion will clearly be affected by the relatively slow increases in mean sea level over the next century and beyond. The characteristics of extreme sea level rise events are dependent on the atmospheric storm intensity and movement of coastal geometry. A substantial number of studies have been carried out on potential sea level rise at national and international levels during the last two decades. Studies relevant to SLR and vulnerability assessment have served as the basis for the conceptualization of sea level rise and its effects. Different organizations and scientists have developed different approaches, models and methods to estimate the potential sea level rise.

Trend analysis has been carried out on the available water level data to identify the observed trend. A stepwise approach was followed mainly consisting of data consistency checking, homogeneity testing, trend identification, and testing of significance. Due to missing value and inconsistency of the tidal gauge data, these tests play a significant role to select tidal gauge stations to assess unbiased sea level rise along the coast. A criterion was set out for selecting stations that represents trends of sea level rise based on the available stations and statistical analysis of tidal water level. Finally, due to spatial variability of the sea level rise along the coast of Bangladesh, results are presented for the three zones of coastal area, namely, Ganges Tidal zone, Meghna Deltaic zone and Chittagong coastal zone.

Dissemination of research findings

A workshop has been organized to disseminate the study findings at the end of the research work. At the very onset of the study, initial results were shared with the stakeholders through an inception workshop. Publications in the form of journal papers have been targeted for the global audience doing research around the globe on SLR to inform them and give them an idea about the behaviour of sea level in the local context of Bangladesh.

Setting of the Area

2.1 Coastal Zone of Bangladesh

Bangladesh consists of 19 coastal districts along a coastline of 710 km. The coastal zone (Figure 2.1) extends over 47,150 sq km area and has a population of 38.52 million (BBS 2011). The coastal zone is quite distinct from the rest of the country and has been delineated based on three characteristics namely level of tidal fluctuations; salinity condition (both surface and ground water); and risks of cyclone, storm surge and tidal influence. The 19 coastal districts have been further divided into interior (7 districts, 48 upazilas) and exposed (12 districts, 99 upazilas) zones, with regards to distance from the coast or the estuaries, under the Integrated Coastal Zone Management Project (ICZMP) of Water Resources Planning Organization (WARPO).

The zone is characterised by a vast network of rivers and channels, enormous discharge of water with huge amount of sediments, many islands, the Swatch of No Ground (underwater canyon located 45 km south of the Sundarbans in Bangladesh), shallow northern Bay of Bengal, strong tidal influence and wind actions, tropical cyclones and storm surges.

2.2 Topography of the Coastal Zone

The country is located in the Bengal Basin, a low-lying very flat delta. About 80% of it is floodplains, which have very low mean elevation above the sea level. The average elevation of the southwest coastal zone ranges from 1-2 m and in the southeast coastal zone 4-5 m (Figure 2.2). The flat topography, active delta and dynamic morphology play a significant part in its vulnerability to sea level change.

Table 2.1: Land surface area under different elevation of the coastal area (sq km)

Elevation (m)	Area* (sq-km)	Area* (% of country)	Area* (% of coastal)
0-1	8,459	6	21
1-2	11,158	8	27
2-3	7,019	5	7
3-4	9,411	7	13
4-5	8,789	7	8
Total	44,836	33	76

**The estimation considers only land surface and excludes water area*

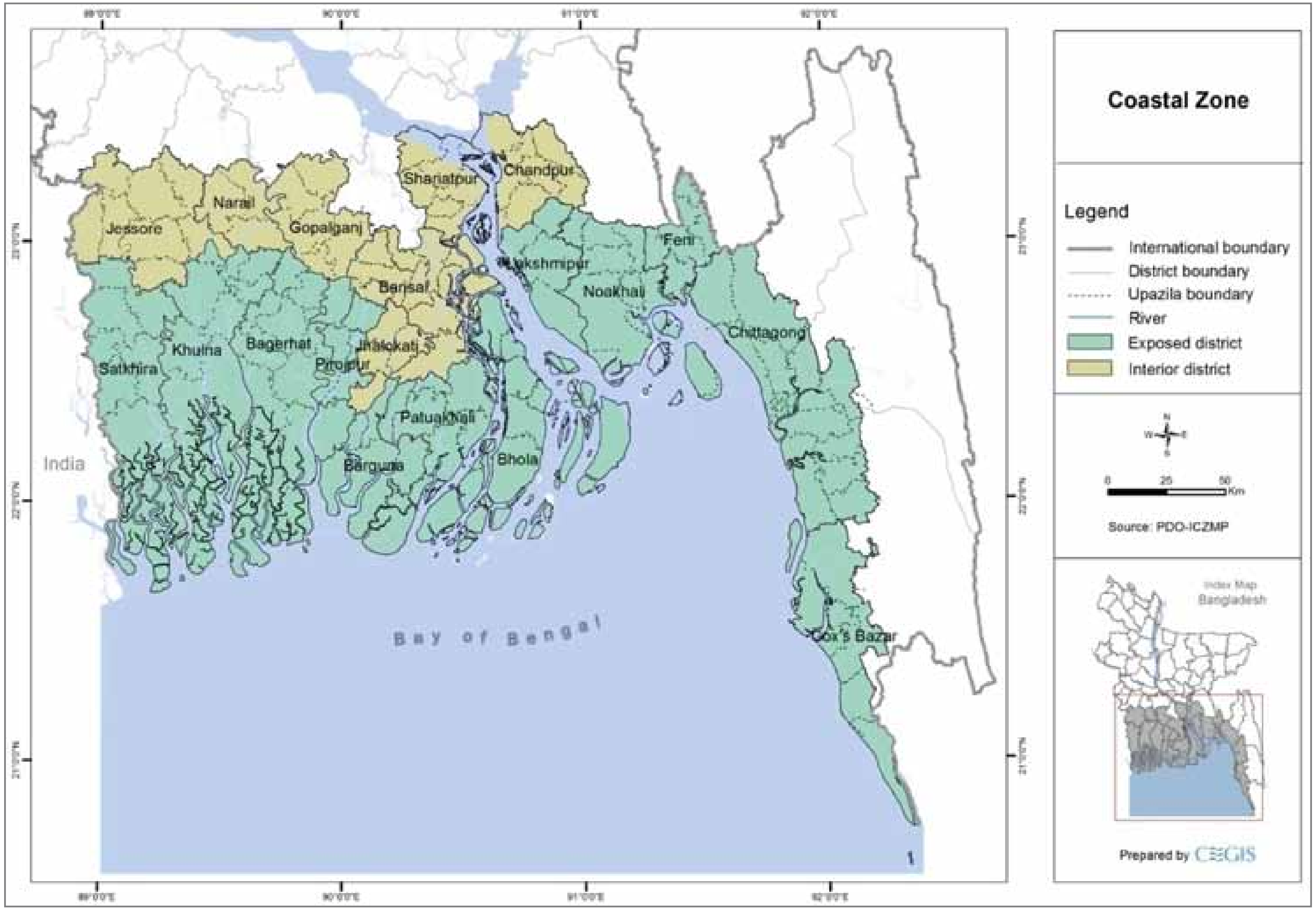

Figure 2.1: Delineated coastal zone based on distance from sea

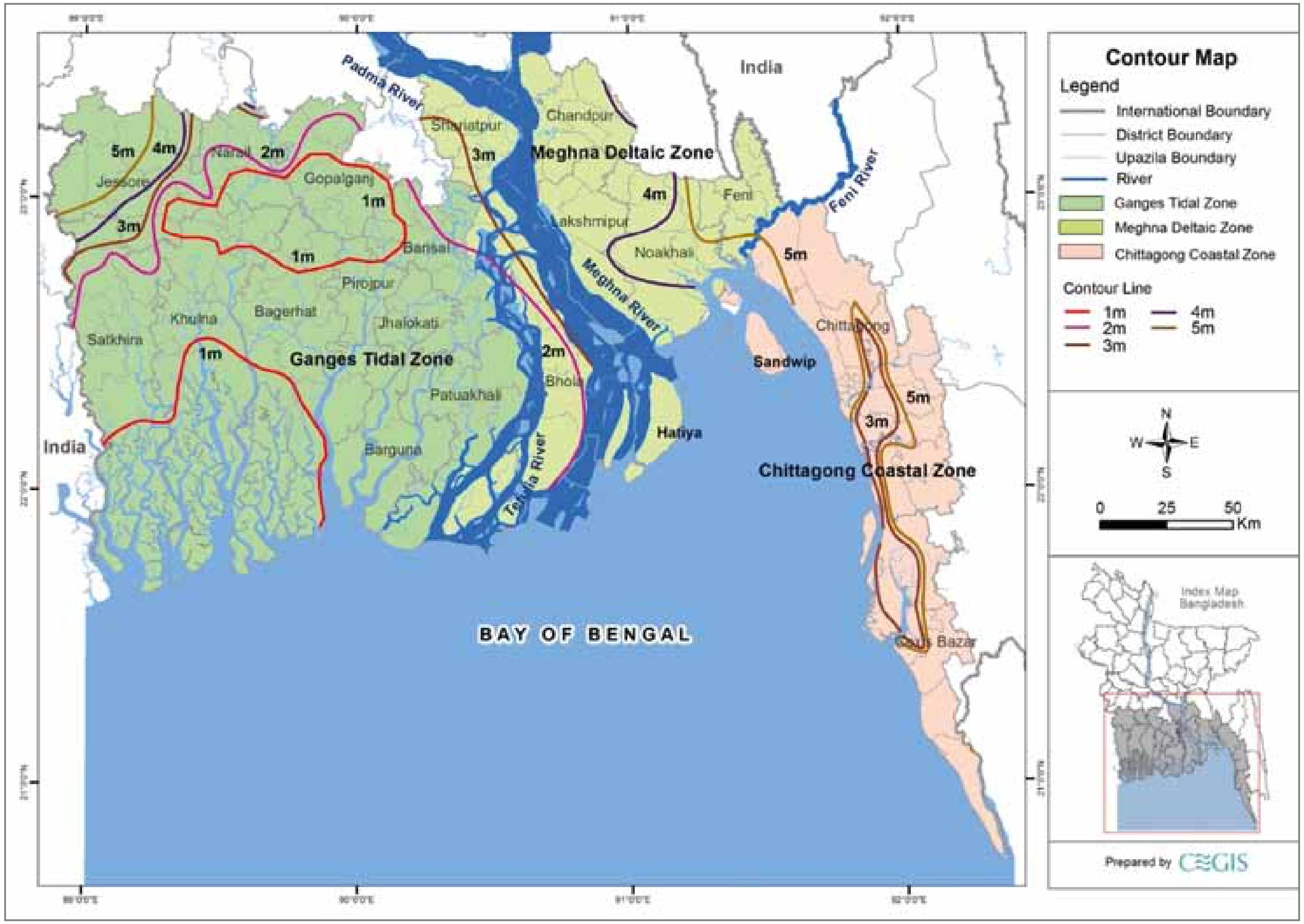

Figure 2.2: Contour map of the coastal zone

2.3 Geomorphology of the Coastal Zone

Throughout the centuries, the coast of Bangladesh has undergone massive changes due to the dynamic processes of erosion and accretion along the coastline and river estuaries. Based on the hydro-morphological characteristics, the coastal zone has been delineated into three regions: (i) the Ganges Tidal Plain or the Western Coastal Region, (ii) the Meghna Deltaic Plain or the Central Coastal Region and (iii) the Chittagong Coastal Plain or the Eastern Coastal Region (Pramanik, 1983 cited in Islam, 2001; BUET and BIDS, 1993). The coastal districts covered by these three regions are shown in Figure 2.3.

The Western Coastal Zone or Ganges Tidal Plain

The Western Coastal Zone or the Ganges Tidal Plain extends from the Bangladesh-India border in the west to the Tetulia River in the east. It is mainly covered by the Sundarbans mangrove forest, greater Khulna and part of Patuakhali district. The Sundarbans is the feeding and breeding ground for fish, shrimps and other aquatic species. The zone is relatively stable because of the mangrove forest which acts as a natural barrier against cyclones, storm surges and soil erosion. Swamps, tidal flood plain and natural levees are found with numerous tidal creeks. The topography is low with an elevation between 0.9 to 2.1 m above mean sea level (Iftekhar and Islam, 2004). This zone is a semi active delta mostly composed of silty loams or alluvium washed down from the Himalayas (Islam, 2001).

The Central Coastal Zone or Meghna Deltaic Plain

The Central Coastal Zone or Meghna Deltaic Plain starts from the Feni river estuary to the eastern corner of the Sundarbans, covering Noakhali, Barisal, Bhola and Patuakhali (part) districts. High amount of silt is deposited through huge volume of discharge from the Ganges-Brahmaputra-Meghna river system. This is why the sediment load is mainly composed of silt (70%) and 10% sand (Coleman, 1969; cited in Allison et al., 2003).

This zone is a very active delta with high rates of both erosion and accretion. Many islands including the country's only island district Bhola are located here. Islands have formed as well as have disappeared through the processes of accretion and erosion (Rahman et al. 1993; Pramanik, 1988 as cited in SDNP, 2004).

The Eastern Coastal Zone or Chittagong Coastal Plain

The Eastern Coastal Zone or Chittagong Coastal Plain extends from Teknaf upazila (the southern tip of mainland) to Mirsarai upazila along the estuary of the Feni River (Pramanik, 1983 as cited in Islam, 2001; BUET and BIDS, 1993). It is the most stable part of the Bangladesh coast and storm surge is less effective here (BUET and BIDS, 1993). The Naf River separates Bangladesh from Myanmar. The soil is mostly composed of submerged sands and mudflats (Islam, 2001). This submerged sand forms the 145 km long sandy beach from Cox's Bazar towards Teknaf. The beaches of Patenga and Cox's Bazar are situated in this zone.

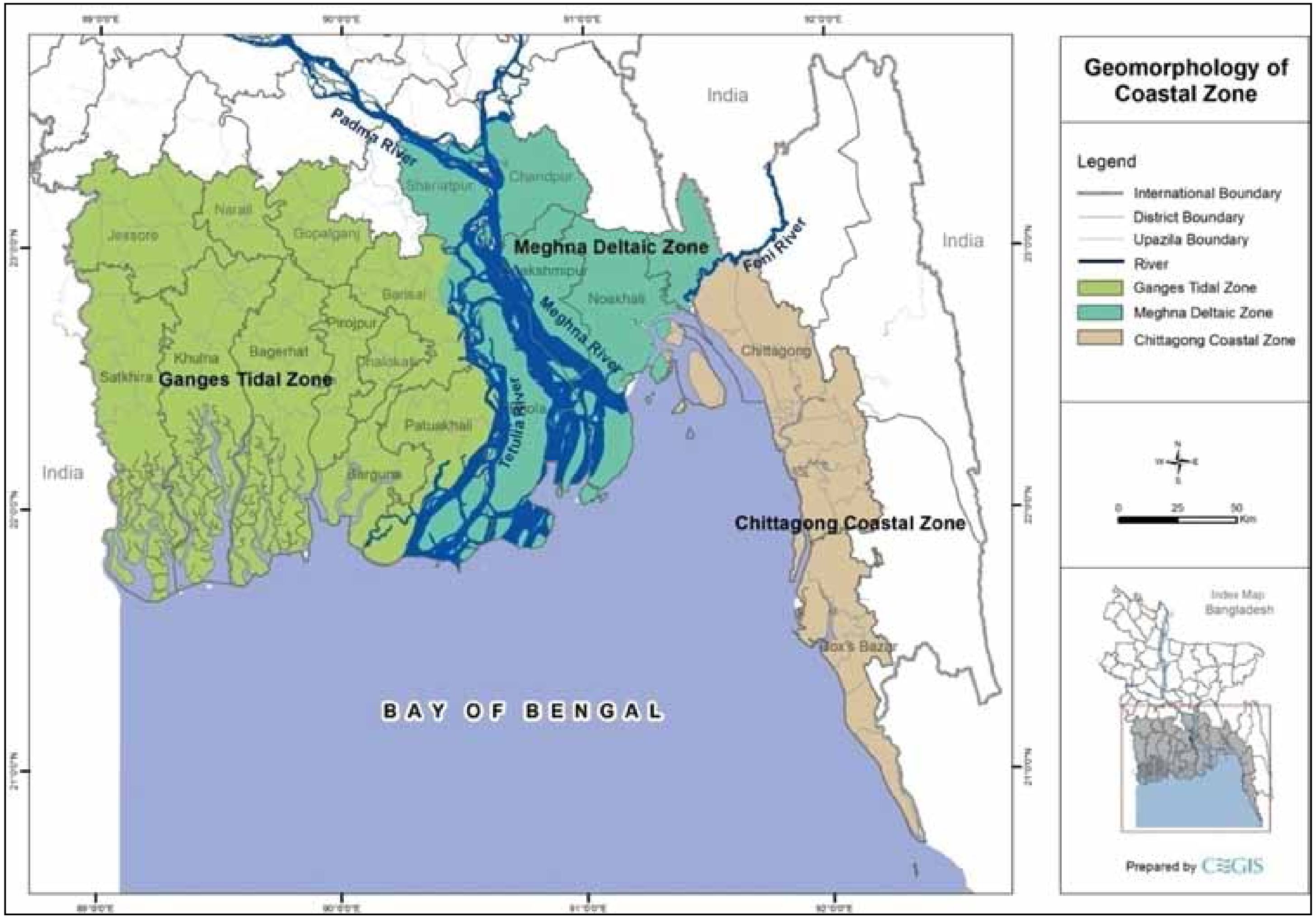

Figure 2.3: Delineated Coastal Zone based on Geo-morphological Characteristics

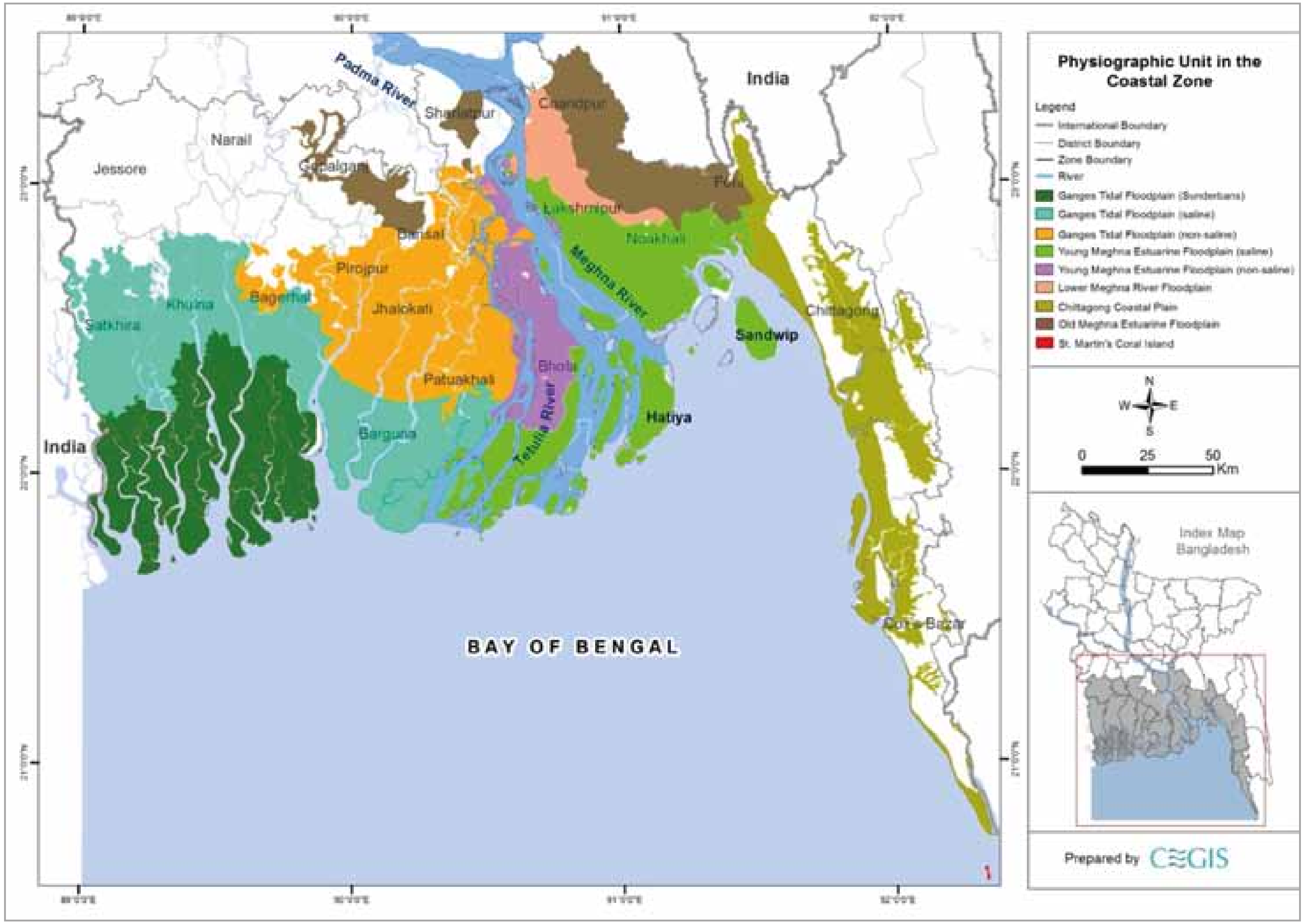

Figure 2.4: Delineated Coastal Zone based on Physiographic Characteristics

2.4 Physiography of the Coastal Zone

Bangladesh is covered by 20 physiographic units based on the pattern of agro ecology, soil physiographic and climatic factors. Floodplains, terraces and hills are the major physiographic units of Bangladesh. Physiographic unit wise the coastal region can be further subdivided into six sub-regions (Figure 2.4): the Ganges Tidal Floodplain (saline), the Ganges Tidal Floodplain (non-saline), Meghna River Floodplain, Meghna Estuarine Floodplain (Charland), Chittagong Coastal Plains and St. Martin's Island. The sub-regions can be described as follows (Adopted from Brammer, 2014b):

Ganges Tidal Floodplain

The Ganges Tidal Floodplain mainly consists of extensive area of tidal floodplain zone in south-west of country. This tidal river zone has narrow levees adjoining the numerous tidal rivers and creeks which are criss-crossed along the region. Except that, maximum area of this zone has a smooth relief with almost flat sloping. The rivers and soils remain non-saline all year round in the north-east and most of the south and the west regions experience slight saline condition in dry season. Saline river water accumulates more than 150 km inland in the west during dry season but only 50 km in east. Salinity tends to be washed out in monsoon because of high rainfall.

Lower Meghna River Floodplain

This transitional area between Middle Meghna River Floodplain and the Young Meghna Estuarine Floodplain is exposed to river flooding, tropical cyclones and storm-surges due to its topographical and geographical features. This zone has slightly irregular relief with little difference in elevation between the ridges and depressions. Relatively higher areas consist of silt loams and the lower regions area occupied by silty clay. Topsoil is moderately acidic and subsoil neutral in reaction.

Young Meghna Estuarine Floodplain

This region occupies young alluvial land in and adjoining the Meghna estuary. It is almost level with very low ridges and broad depressions. The major soils are grey to olive, deep, calcareous silt loam and silty clay loams and are stratified either throughout or at shallow depth. Calcareous Alluvium and Non-calcareous Grey Floodplain soils are the dominant general type. The soils in the south become saline in dry season. Top soils and sub-soils of the area are mildly alkaline. General fertility is medium but low in organic matter.

Old Meghna Estuarine Floodplain

This zone mainly formed through sedimentation, is a low-lying between south of the Surma-Kushiyara Floodplain and northern edge of the Young Meghna Estuarine Floodplain. The land formation is smooth, almost level, floodplain ridges and shallow basins. On highlands, silt loam soils predominate and silty clay to clay in lowlands. Non-calcareous dark grey floodplain soils are the only general type of the area. Moisture holding capacity is medium. Therefore, most of the area is flooded up to 180cm deep by ponding of rainwater in the monsoon season. The large areas in the south stay wet during the dry season.

Chittagong Coastal Plain

This zone is the plain land in greater Chittagong district and the eastern part of Feni district. This includes a compound unit of piedmont, river, tidal and estuarine floodplain landscapes. Seasonal flooding occurs here which is mainly shallow and by rainwater, but saline on young tidal floodplains. The whole region is exposed to tropical cyclones and coastal areas are subject to storm surges. Salinizations of soils occur due to these hazards for a time until rainfall leaching takes place.

St. Martin's Coral Island

This small but distinctive region occupies the whole of St. Martin's Island in the extreme south of the country. The area has very gently undulating old beach ridges and inter-ridge depressions surrounded by sandy beaches. The soils are developed entirely on old and young coral beach sands.

Chapter 3

A Comprehensive Review of Sea Level Rise

3.1 Concept of Sea Level Rise

Sea level is the level of the ocean's surface. Sea level at a particular location changes regularly with the tides and irregularly due to conditions such as wind and currents. Other factors that contribute to such fluctuation include water temperature and salinity, air pressure, seasonal changes, the amount of stream runoff, and the amount of water that is stored as ice or snow. The reference point used as a standard for determining terrestrial and atmospheric elevation or ocean depths is called the mean sea level and is calculated as the average of hourly tide levels measured by mechanical tide gauges over extended periods of time.

In addition, there is a subtle, but significant distinction to make when discussing sea level change and the context for which estimation of the change is required. This distinction is one between global sea level change and relative sea level change (Williams et al., 2009). Relative Sea Level (RSL) is measured with respect to the surface of the solid earth, whereas Geocentric Sea Level (GSL) is measured with respect to a geocentric reference such as the reference ellipsoid (IPCC, 2013). Mean Sea Level (MSL) is defined as the temporal average for a given location and Global Mean Sea Level (GMSL) is the spatial average of all the MSL (IPCC, 2013).

The level of the sea observed along the coast changes in response to a wide variety of geological, astronomical, meteorological, climatological, geophysical, and oceanographic forcing mechanisms. From the highest frequency wind waves and sea swell to tsunamis and local seiches, to the daily tides, to monthly, seasonal, and annual variations, to decadal and multi-decadal variations, and finally, to changes over hundreds of millions of years, sea level is constantly changing at any given location (NOAA, 2010).

3.2 Causes of Sea Level Rise

The notion that sea level is changing was recognized in the IPCC's First Assessment Report (FAR), where the changes from the year 1880 to 1982 were addressed (Warrick and Oerlemans, 1990). Two major causes of sea level rise were identified. First one is the expansion of ocean water due to global warming induced thermal expansion and the second is the addition of ice water on the ocean from the land through the melting of glacier ice sheets (Church et al., 2011). The report also expressed that SLR rate will be higher in the 21st century than the 20thand will continue to rise even if reduction in the GHG emissions is achieved. SLR projections in the Second Assessment Report (SAR) drew findings similar to the FAR.

In the IPCC Third Assessment report (TAR), the energy balance climate models based projection were replaced by Ocean General Circulation Models (AOGCMs) and ice-sheet models. This introduced the idea of regional variation along with the global average mean sea level change.

The Fourth Assessment report revealed that the temporal variation of sea level observed from historical data analysis is significant and additionally, the spatial variation evident through the analysis of satellite altimeter data is also very important.

Processes that contribute to global and regional sea level changes encompass the ocean, atmosphere, land ice, and hydrological cycle. So, the two main factors that are critical to sea level rise are: Thermal expansion and Cryospheric contribution. However, a local perturbation in sea level is influenced by local atmospheric circulation; local tectonic movement; local subsidence/soil compaction; sediment contributions; and anthropogenic contributions.

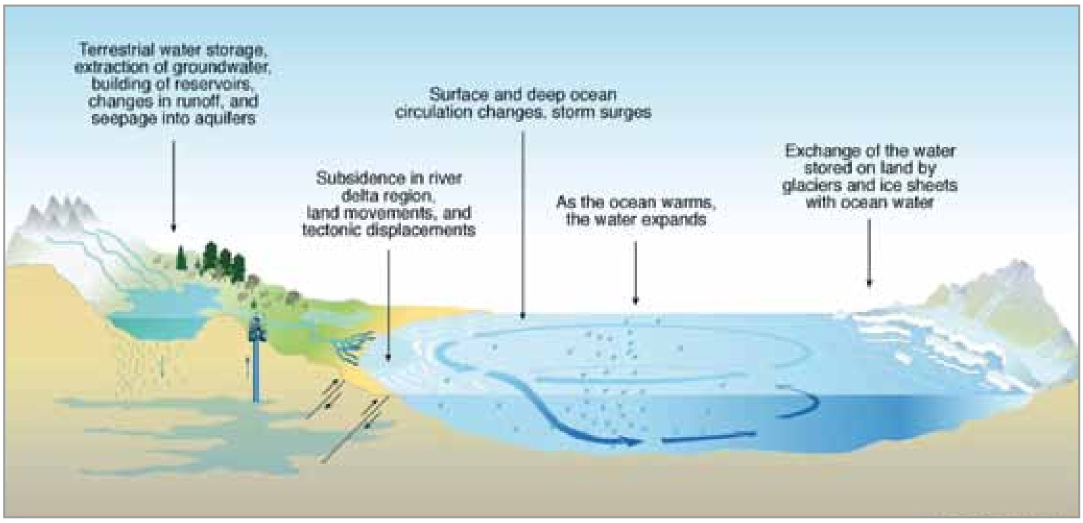

Figure 3.1: Components of sea level rise

(Source: Griggs, 2001)

So, the components of sea level rise can be addressed in two ways:

a. Global Sea Level Rise

b. Regional and Local Sea Level Rise

3.2.1 Global Sea Level Rise

Thermal expansion

Sea level is affected by changes in the density of sea water, induced by temperature changes (thermosteric) or by salinity changes (halosteric). Freshening of the water column (halosteric expansion) has been estimated to account for about 10 % of the global average steric sea-level rise during recent decades (e.g., Munk, 2003; Antonov, Levitus and Boyer, 2005; Ishii et al., 2006). However, only about 1 % of the halosteric expansion contributes to the global sea-level-rise budget as ocean mixing increases the salinity and thus decreases the volume of the added freshwater (Bindoff et al., 2007).

Water vapor increases the greenhouse effect and a warmer atmosphere will hold more water. The earth's atmosphere continues to warm with a 2-10°F (1.1-6.4°C) increase in average global temperature predicted by the end of the century (IPCC, 2007a). For each degree centigrade of global warming, the atmosphere can hold an additional 7.5% of water vapor (Horváth and Soden, 2008). Growing concentrations of water vapor will result in a 2% increase in global precipitation (Held and Soden, 2006). The current warmer atmosphere has nearly 5% more water vapor compared to pre-industrial levels. Pinatubo in 1991 produced the last transient global cooling (-0.5°C) and drying event. The water vapor reduction was responsible for a significant portion of the global cooling observed, which validated the water vapor feedback mechanism as a contributor to climate impacts in Global Climate Models.

The ocean has absorbed roughly 80% of the heating of the climate system associated with rising greenhouse gases during the past 50 years (IPCC, 2007b), leading to substantial amount of ocean warming. Because seawater expands slightly when warmed, the volume of the ocean has increased and the ocean is expected to continue expanding as a result of projected increases in 21st century global temperature.

Cryospheric contribution

Rising temperature expands the ocean volume in two ways-firstly, it melts mass volume of ice of the polar region and secondly, it causes thermal expansion of water of the ocean. Wigley and Raper (1987) mentioned that the relative contributions of thermal expansion and ice melting to this sea level rise are uncertain and estimates vary widely, from a small expansion effect through roughly equal roles for expansion and ice melting to a dominant expansion effect. These two factors increase the volume of ocean water of the earth and raise the sea level.

Melting of glaciers and ice caps is presently, and is projected to remain, the largest cryospheric contribution to SLR. However, several independent measurements of Greenland and Antarctic mass balance using lasers and gravity measurements indicate that both Greenland and Antarctica have recently (2002-2006) been substantial contributors to global SLR (IPCC, 2013; Zwally et al., 2005; Thomas et al., 2006; Velicogna and Wahr, 2005).

3.2.2 Regional/Local Sea Level Rise

Atmospheric circulation

Globally, monsoon influences large climatic regions. Tropical monsoon climates are most commonly found, in addition to South Asia, in South and Central America, Southeast Asia, Africa (particularly West and Central Africa), the Caribbean and North America. Here, we shall confine our focus to South Asian monsoon. Monsoon is a complex tropical weather phenomenon. It is traditionally defined as a seasonal reversing wind accompanied by corresponding changes in precipitation. The term is said to have been derived from the Arabic word 'mawsim', meaning 'season' or 'season of the wind'. Monsoon wind may therefore be called a seasonal wind. It reverses its direction with seasons. The term was first used in English in British India.

As per the IPCC "A monsoon is a tropical and subtropical seasonal reversal in both the surface winds and associated precipitation, caused by differential heating between a continental-scale land mass and the adjacent ocean. Monsoon rains occur mainly over land in summer" (IPCC, 2013).

In the subcontinent, monsoon is one of oldest weather observations, an economically important weather pattern and the most anticipated weather event and unique weather phenomenon.

Since the general direction of wind blowing over the South Asia region changes with seasons, the wind has been given directional names: South West monsoon wind blowing from the south-west direction during summer and North East (NE) monsoon wind blowing from the north-east direction during winter. SW monsoon wind that blows over the region from the Northern Indian Ocean brings in a lot of moisture to produce heavy rains. On the other hand, NE monsoon wind, blowing from the Himalayan region towards the Northern Indian Ocean, gives rise to cold weather. The monsoon wind, as is always understood, is a lower atmospheric or near surface phenomenon.

The South West (SW) monsoon wind, a large scale air flow system, blows over this region during summer and raises the level of water along the northern coast of the Bay of Bengal, particularly along the coastal belt of Bangladesh.

Monsoon in South Asia is categorized into two branches based on their spatial spreading:

- The Bay of Bengal Branch
- The Arabian Sea Branch

SW monsoon wind pushes ocean water towards the northern coast of the Bay of Bengal, particularly along the coastal belt of Bangladesh and raises the sea level there. Climate change through strengthening the monsoon wind is likely to raise the sea level further.

Climate change will alter the conditions of the sea more slowly than that over land because of their difference in the rate of response to heating (land responding more quickly than water). We would, then, expect SW monsoon wind to get stronger and push more water towards our coast and hence raise the sea level.

Alternatively, it can be categorized into two segments based on the direction of rain bearing winds:

- South-West Monsoon (SW Monsoon)
- North-East Monsoon (NE Monsoon)

Based on the time of the year that these winds bring rain to South Asia, they can also be categorized in two rain periods called:

- The Summer Monsoon and
- The Winter Monsoon

Weather pattern involves winds blowing from the south-west direction (known as South-West Monsoon) from the Indian Ocean onto the South Asian landmass during the months of June through September. These are generally rain-bearing winds, blowing from sea to land, and bring rains to most parts of the subcontinent. They split into two branches, the Arabian Sea Branch and the Bay of Bengal Branch near the southernmost end of the subcontinent. The SW monsoons are eagerly awaited in most parts of the sub continent for their agricultural and economic importance.

Subsequently later in the year, around October, these winds reverse direction and start blowing from a north-easterly direction. Without it, the SW Monsoon winds would blow right over the Indian subcontinent into China, Afghanistan and Russia without causing any rain. In some years, it rains too much causing floods in several parts of the sub continent, in others it rains too little or not at all causing droughts. In some years when the rain quantity is sufficient, its timing may be arbitrary. In some years, in spite of average annual rainfall, its daily distribution or the areal distribution might be substantially skewed. Such is the variability in the nature of monsoon rains and weather.

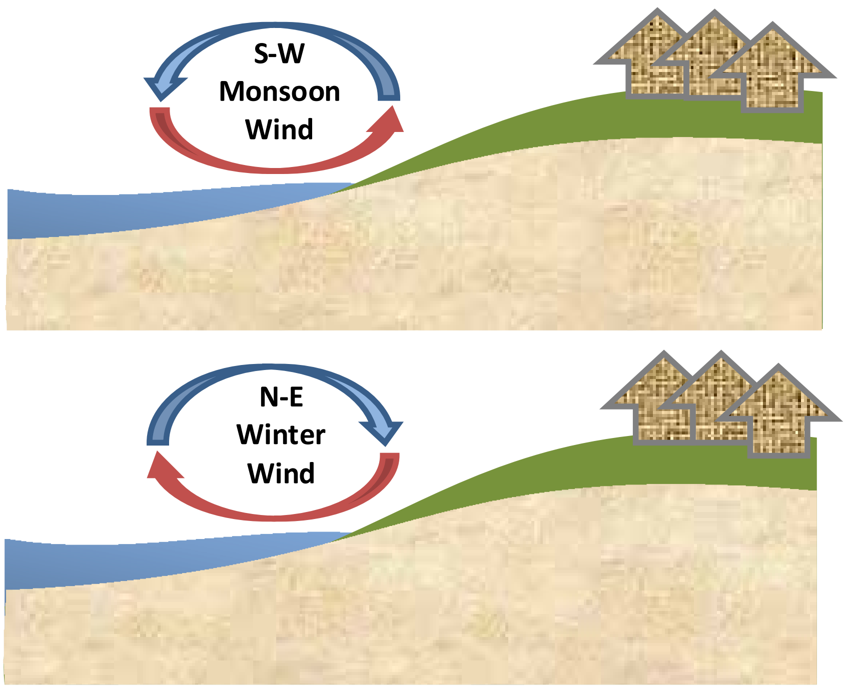

Figure 3.2: Schematic diagram of south-west and north-east monsoon wind

The pattern of monsoon wind flow is schematically shown in Figure 3.2. However, the geophysical factors like revolution of earth, its rotation and its axial tilt result in gradual shifting of these belts northwards and southwards following the Sun's seasonal shifts.

Climate Change Impacts on Monsoon

Mean sea level pressure is projected to decrease in high latitudes and increase in the mid-latitudes as global temperatures rise. In the tropics, the Hadley and Walker circulations are likely to slow down. Pole ward shifts in the mid-latitude jets of about 1-2 degrees latitude are likely at the end of the 21st century under Representative Concentration Pathways RCP8.5 in both hemispheres (medium confidence), with weaker shifts in the Northern Hemisphere. In austral summer, the additional influence of stratospheric ozone recovery in the Southern Hemisphere opposes changes due to greenhouse gases there, though the net response varies strongly across models and scenarios. Substantial uncertainty and thus low confidence remains in projecting changes in Northern Hemisphere storm tracks, especially for the North Atlantic basin. The Hadley cell is likely to widen, which translates to broader tropical regions and a pole ward encroachment of subtropical dry zones. In the stratosphere, the Brewer-Dobson circulation is likely to strengthen.

The IPCC found evidence of increased precipitation in the equatorial Pacific and decreased precipitation to the north in the last few decades, and predicts that El Nino conditions will become more persistent over coming decades, resulting in a general increase in precipitation in the tropical Pacific (IPCC, 2001). It is uncertain how precipitation patterns will change in for individual Pacific island countries over the coming decades. Some mangroves may experience increases in salinity from sea-level rise, increased evaporation, and groundwater depletion from human extraction (Ellison, 2000). Also, areas with decreased precipitation will have a smaller water input to groundwater and less freshwater surface water input to mangroves, increasing salinity. Increased salinity decreases mangrove net primary productivity, growth, and seedling survival, and may possibly change the competition between mangrove species (Ellison, 2000; Ellison and Fiu, 2010). Areas with higher rainfall have higher mangrove diversity and productivity due to higher supply of fluvial sediment and nutrients, as well as reduced exposure to sulphate and reduced salinity (Ellison, 2000; Ellison and Fiu, 2010).

Future increase in precipitation extremes related to monsoon is very likely in South America, Africa, East Asia, South Asia, Southeast Asia and Australia. Global measures of monsoon by the area and summer precipitation are likely to increase in the 21st century, while the monsoon circulation weakens. Monsoon onset dates are likely to become earlier or not to change much while monsoon withdrawal dates are very likely to delay, resulting in a lengthening of the monsoon season. The increase in seasonal-mean precipitation is pronounced in the East and South Asian summer monsoons while the change in other monsoon regions is subject to larger uncertainties. There is medium confidence that overall precipitation associated with the Asian-Australian monsoon will increase. Indian monsoon rainfall is projected to increase. There is medium confidence in that the Indian summer monsoon circulation weakens, but this is compensated by increased atmospheric moisture content (IPCC, 2013).

Land subsidence and soil compaction

Besides, thermal expansion, melting of glaciers and polar ice caps and ice loss from Greenland and West Antarctica, there are also some local factors like land subsidence and siltation which play a role in the sea level rise process. Because of subsidence from groundwater and hydrocarbon withdrawal and active thrust faulting, vertical land motions vary on small spatial scales (Bawden et al., 2001; Lanari et. al, 2004; Argus et al., 2005). Brooks et al. (2007) used land motion rates to adjust local tide gauge records to produce a profile of relative sea-level change along the coast of the Los Angeles basin. They used Synthetic-aperture radar (SAR) to create a vertical land motion map of the basin. Vertical land motion differs on the west and east side of the Palos Verdes Peninsula. Brooks et al. (2007) results show the danger of assuming that a tide gauge is representative of relative sea level for a region undergoing uplift or subsidence. For example, interpretation of the Los Angeles Harbour tide gauge alone would miss the spatial variability in sea level to the east and assume the wrong sign of relative sea-level change to the west.

Nicholls et al., (2011), have argued that the uncertainty associated with the melting of ice-sheets has led several authors to predict that sea level rise by 2100 may be as much as 2.0m and conclude that the increase in sea level by 2100 may range between 0.5m and 2.0m. However, they go on to point out that such global predictions must be rescaled using estimates of local adjustments that include natural subsidence in deltas, which they assume will be 2mm/year, but which will vary and will be most 'sensitive around south, southeast and east Asia'.

Sedimentation

One of the critical factors for sea level rise is the contributions of river sedimentation. It has been found that in the right conditions a sufficiently high sediment supply can prevent river mouths from drowning due to sea level rise (Parker et al., 2004). According to Syvitski et.al (2009) land dynamics of any delta coastline is mainly controlled by three major factors, namely 1) compaction and tectonic subsidence, 2) relative sea level rise (SLR) and wave action, and 3) sediment supply from the rivers. Muto and Steel (1992, 1997) described the process of "auto-retreat" due to sea level rise. The process auto-retreat begins as soon as the shoreline starts to move landward. As long as sediment is being delivered to the delta face, no embayment is created. However, if sea level rise continues for a sufficiently long duration, the amount of sediment delivered to the delta face eventually drops to zero, and rapid sediment auto-retreat occurs with the creation of a deep embayment.

For any delta, Effective Sea Level Rise (ESLR) is a net rate, defined by the combination of eustatic sea level rise, the natural gross rate of fluvial sediment deposition and subsidence, and accelerated subsidence due to groundwater and hydrocarbon extraction

(Ericson et al., 2006). An assessment was conducted by Ericson et al. (2006) on the sample of 40 deltas distributed worldwide to find out the contemporary ESLR. The deltas in this study represented all major climate zones, levels of population density, and degrees of economic development and ESLR was estimated under present condition using a digital data set of delta boundaries and a simple model of delta dynamics. Collectively, the sampled deltas serve as the endpoint for river basins draining 30% of the Earth's landmass, and 42% of global terrestrial runoff. For the contemporary baseline, ESLR estimates ranged from 0.5 to 12.5 mm/year. Decreased accretion of fluvial sediment resulting from upstream siltation of artificial impoundments and consumptive losses of runoff from irrigation were the primary determinants of ESLR in nearly 70% of the deltas. Approximately 20% of the deltas showed accelerated subsidence, while only 12% show eustatic sea-level rise as the predominant effect.

Tectonic movement

Direct measurements of sea level at tide gauges are difficult to interpret because tide gauges record the difference between local sea level and local land level, with inter annual variability and measurement uncertainty clouding the picture. Without additional evidence it is difficult to separate sea level rise from local land level change, which itself could be caused by a variety of factors including tectonic movement or soil compaction.

Marine seismic profiling (Eittreim and Ewing, 1972; Weissel et al., 1980; Geller et al., 1983) reveals widespread deformation of originally flat lying sediments. The deformation includes reverse faults and unusual undulations of acoustic basement with wave lengths of approximately 200 km and relief of up to 3 km. The undulations and reverse faults both strike roughly east-west, suggesting they may result from north-south shortening. Deep-sea drilling and piston coring results indicate a Late Miocene Age for a prominent unconformity separating deformed sediments from overlying deposits (Moore et al., 1974). The absence of sedimentary deformation below the unconformity suggests that this age provides an approximate date for the onset of deformation (Weissel et al., 1980) Substantial heat flow anomalies are also found, suggesting heat generation at shallow depths by some process possibly related to the deformation (Geller et al., 1983).

Based on earthquake focal mechanisms and locations, Stein and Okal (1978) suggested that much of the seismicity reflects left lateral strike slip motion along the northern Ninety east Ridge and estimated the slip rate along the Ninety east Ridge as 2 cm/ year based on the summed moments of earthquakes. They further suggested that this slope represents relative motion between the western half of the Indian Plate, which presumably encounters greater resistance along the Himalayan zone of continental collision, and the eastern half, which sub-ducts normally beneath the Indonesian Arc.

Anthropogenic contribution

Due to various human activities, carbon dioxide (CO2) and other greenhouse gases are accumulated in the earth's atmosphere, resulting in climate change. The human factor that is mainly responsible for global warming and sea level rise is the burning of fossil fuels. Deforestation is another human activity, responsible for decreasing the CO2 sink. Miller (2004) states that, 75% of the human caused emissions of CO2 since 1980 are due to fossil fuel burning and the remainder is the result of deforestation, agriculture, and other human changes in the land use. The two largest contributors to current CO2 emissions are the world's thousands of coal-burning power and industrial plants and more than 700 million gasoline-burning motor vehicles (555 million of which are cars). Emissions of CO2 from the U.S. coal burning power and industrial plants alone exceeded the combined CO2 emissions of 146 nations, which contain 75% of the world's people (Miller, 2004). As a small nation, Bangladesh plays an ignorable role in greenhouse gas emission.

It is evident from various studies that many anthropogenic processes over the last 100 years may have also influenced sea-level changes (Gornitz, 1994). For example, deforestation has accelerated runoff, soil erosion, flooding and downstream siltation in many parts of the world (Bird, 1985), leading to increased sediment loading along the shore. On the other hand, dams and reservoirs have reduced sediment supply to the oceans in many localities, such as the Mississippi (Meade et al., 1985) and the Nile (Stanley, 1990) deltas, thus exacerbating beach erosion (Bird, 1985). The volume of water held in dams and reservoirs, as well as that lost by infiltration into aquifers, between 1932 and 1982, is equivalent to a reduction in SLR of 0.75 mm/year (Newman and Fairbridge, 1986). However, this effect could be nearly offset by groundwater mining, irrigation, and conversion of deforested biomass into water. These processes combined could contribute 0.54mm/year to an increase in SLR (Sahagian et al., 1994).

3.3 Observed changes in Global Sea Level Rise

Warming of the climate system is unequivocal, as evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. An increasing trend in the global mean sea level has been observed under different climate change scenarios as seen from the IPCC reports (IPCC, 1990; IPCC 1996; IPCC, 2001; IPCC, 2007; IPCC, 2013). Figure 3.3 illustrates the observed trend in the GMSL values. IPCC derived the observed changes in sea level from geological records and instrumental data.

The FAR report summarised from several studies dated until 1990 that, one of the most extensive analyses by Gornitz and Lebedeff (Gornitz and Lebedell, 1987, Gornitz, 1990 as cited in IPCC, 1990) used tide-gauge data from 130 stations with minimum record length of 20 years to estimate the average sea level change over the period of 1880-1982. The study estimated an average global sea level rise of 1.2 ± 0.3 mm/year for the period of data.

The SAR report stated an observed SLR of about 10-25 cm (1.8 ± 0.8 mm/year) over the 20th century. This range is slightly higher than the FAR estimates.

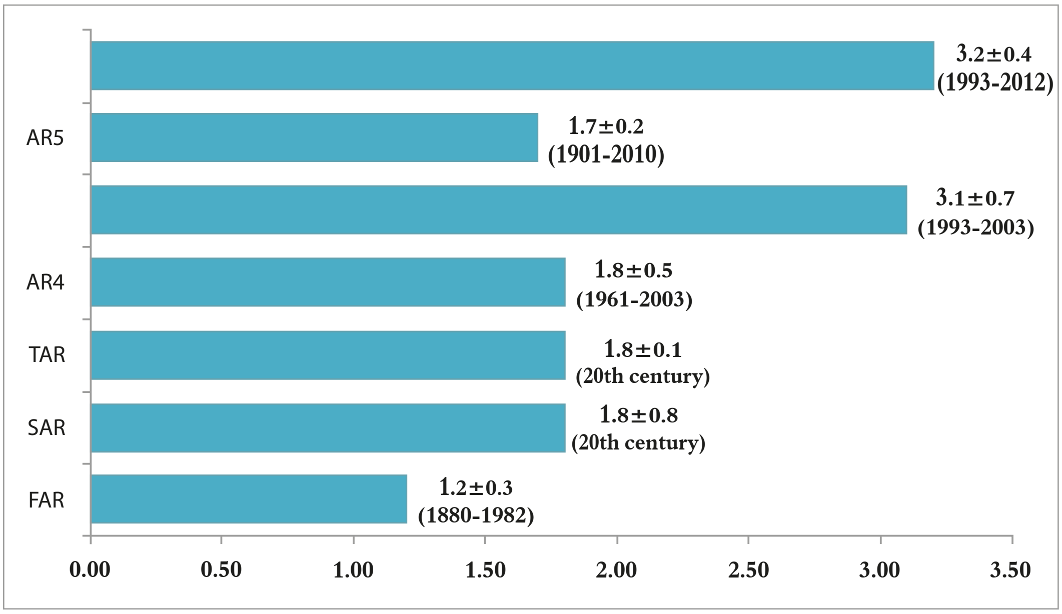

Figure 3.3: Comparative graph of observed GMSL values (mm/year)

(Source: compiled from all the IPCC reports)

In the TAR the observed SLR estimate was presented from Douglas, (1997). The study reported a rate of 1.8 ± 0.1 mm/year which is almost similar to SAR estimates but with reduced uncertainty.

The AR4 suggested two SLR rates based on time slices and ongoing studies. These rates are 1.8 ± 0.5 mm/year based on tide gauge data from 1961-2003 and 3.1 ± 0.7 mm/year based on satellite altimetry data from 1993-2003. So, it was seen that in recent times the SLR to be much higher.

The AR5 also followed similar approach as in AR4. AR5 estimated observed SLR rates based on geological data and instrumental record (tide gauge and satellite data).

Geological records in the AR5 are divided under four time periods: Middle Pliocene (3.3 to 3.0 Ma), Marine Isotope stage 11 (MIS 11; 401 to 411 ka), the Last Interglacial Period (LIG, ~129 to 116 ka), the Late Holocene (last 7000 years) Period. During the Holocene Period (~7to 3 ka), the GMSL rise was from 2 to 3 m to near present-day levels. At the later stage of the Holocene period (last two thousand years), variation did not exceed ~ ±0.25 m.

Instrumental data are collected from tide gauge station and from satellite altimetry. Records of tide gauge stations suggest that, the long-term trend in GMSL is 1.7 [1.5 to 1.9] mm/year between 1901 and 2010 for a total sea level rise of 0.19 [0.17 to 0.21] m. From the high-precision satellite altimetry record of 1993–2012, a GMSL rate of 3.2 [2.8 to 3.6] mm/year have been observed.

Observed Trends of Sea Level in Bangladesh

4.1 Reflection from previous studies

Bangladesh is vulnerable to current coastal hazards and anticipated SLR because of its low elevation. Drainage congestion and water logging are already an alarming problem in Bangladesh and likely to be exacerbated by SLR and increased river flooding. Large uncertainties are associated with regional to district level estimates of inundation which is due to the compounding effects of the variable rates of uplift and sedimentation, river flooding and erosion. Siltation is gradually increasing due to SLR. As a result of reduced upstream flow, the silt flocculate/deposit in the riverbed which restricts removal of excess water from the countryside and causes drainage congestion.

The Northern Indian Ocean, which includes the Bay of Bengal, has also been reported to experience a relatively high rate of SLR compared to other oceans globally (Han et al., 2010; Unnikrishnan and Shankar, 2007). Based on global sea level data and modelling, Ericson et al. (2006) have estimated that the SLR of the Bay of Bengal is the world's highest, at 10 mm/year.

The Ministry of Environment and Forests (MoEF) has prepared NAPA as a response to the decision of the Seventh Session of the Conference of the Parties (COP7) of the United Nations Framework Convention on Climate Change (UNFCCC). The observed trend in sea level rise used in that document was cited from the study conducted by the SAARC Meteorology Research Centre in 2003. The study (SMRC, 2003) found that the tidal level in Hiron Point, Char Changa and Cox's Bazar rose by 4.0 mm/year, 6.0 mm/year and 7.8 mm/year respectively, observing tidal gauge record of 22 years from 1977-1998 (Table 4.1). The rate of the tidal trend is almost double in the eastern coast than that of the western coast. This difference could be due to subsidence and uplifting of land.

Table 4.1: Increase of tidal level in three coastal stations of Bangladesh coast

Tidal Station	Region	Latitude (N) (degree)	Longitude (E) (degree)	Datum (m)	Trend (mm/year)
Hiron Point	Western	21.80	89.47	3.784	4.0
Char Changa	Central	22.13	91.10	4.996	6.0
Cox's Bazar	Eastern	21.43	91.98	4.836	7.8

(Source: SMRC, 2003)

Under the Second National Communication Project, according to the CEGIS estimates (Table 4.2) some variations have been found in the observed data of the above-mentioned stations. In the South West region at Hiron Point station the mean annual rise of water level has been found to be 5.5 mm/year. Maximum rise in the water level is observed in the South East region at the Moheshkhali station which is 7.5 mm/year followed by 7.04 mm/year in the Sandwip station and 5.05 mm/year in the Cox's Bazar station. However, in the Maheshkhali and Sandwip area, change in sea level is due to continuing morphological dynamism, tidal amplification or dampening caused by natural accretion and formation of new funnel shaped chars and islands and also due to several other human interventions like cross-dam implementation. In the south western (Sundarbans) and south eastern part (Cox's Bazar), the observed change in sea level is mostly free from any sort of artificial or man-made interventions and thus the most reliable estimate of mean sea level rise was taken from the remaining two stations. It should be noted that the mean sea level is rising and the observed range of sea level change was found to be 5.05 mm/year to 7.5 mm/year. (CEGIS and DOE, 2011)

Table 4.2: Analysis of observed sea level rise at different tidal water level stations

Period of analysis	Observed Water Level (m, PWD) per year			
	Hiron Point	Moheshkhali	Cox's Bazar	Sandwip
1968-1977		207.10		
1977-1986	177.35	214.35	199.87	279.31
1987-1996	182.76	214.97	213.68	337.75
1997-2002	186.20		206.54	291.29
Change in the mean sea level (from trend line) in mm/year	5.5	7.5	5.05	7.04

(Source: CEGIS and DOE, 2011)

4.2 Method for analysing observed sea level trend

Current rate of sea level rise is assessed using two techniques: tide gauges and satellite altimetry (Bindoff et al., 2007). Instrumental records of satellite altimetry are being used for assessment of sea level rise trends since 1993 (IPCC, 2007a; Stocker et al., 2013). For this research tidal gauge data has been used for trend analysis which compared to the satellite altimetry based data is easily available, more accurate and widely used (Unnikrishnan and Shankar, 2007; CEGIS and DoE, 2011; Church et al., 2013; Palanisamy et al., 2015).

4.3 Trend analysis of observed sea level

Trends in water level has been analysed to see the observed trend of changes in sea level. The most common instruments used to determine global sea level changes are tide gauges and satellite altimetry. Tide gauges, usually placed on piers, measure the sea level relative to a nearby geodetic benchmark. There are 47 stations of BIWTA and 188 tidal water level stations of BWDB in Bangladesh. Out of which 38 BIWTA stations, 127 tidal water level stations and 18 non tidal water level stations of BWDB are located in the coastal zone (Figure 4.1 and Figure 4.2). From these stations, 18 water level stations have been selected along the interior and exposed coasts covering three major geo-morphological regions and six physiographic sub-regions (Table 4.3). The reason for selecting these stations is based on the assumption that these stations represent the regional variations in water level.

Table 4.3: Selected water level stations according to geo-morphological and physiographic zones

Sl No.	Organization	Location	Geo-morphological Zone	Physiographic Subzone
1	BIWTA	Hiron Point	Ganges	Ganges tidal floodplain (saline)
2	BIWTA	Khepupara	Ganges	Ganges tidal floodplain (saline)
3	BWDB	Barguna	Ganges	Ganges tidal floodplain (saline)
4	BWDB	Patharghata	Ganges	Ganges tidal floodplain (saline)
5	BWDB	Khulna	Ganges	Ganges tidal floodplain (non-saline)
6	BIWTA	Mongla	Ganges	Ganges tidal floodplain (non-saline)
7	BIWTA	Chitalkhali	Meghna	Meghna estuarine floodplain (saline)
8	BIWTA	Char Chenga	Meghna	Meghna estuarine floodplain (charland)
9	BIWTA	Sandwip	Meghna	Meghna estuarine floodplain (charland)
10	BWDB	Hatiya	Meghna	Meghna estuarine floodplain (charland)
11	BIWTA	Dasmonia	Meghna	Meghna estuarine floodplain (non-saline)
12	BIWTA	Kaukhali	Meghna	Meghna estuarine floodplain (non-saline)
13	CPA	Khal No. 10	Chittagong	Chittagong coastal plain
14	BIWTA	Cox's Bazar	Chittagong	Chittagong coastal plain
15	BWDB	Saflapur	Chittagong	Chittagong coastal plain
16	BWDB	Banigram	Chittagong	Chittagong coastal plain
17	BWDB	Lemiskhali	Chittagong	Chittagong coastal plain
18	BIWTA	Rangadia	Chittagong	Chittagong coastal plain

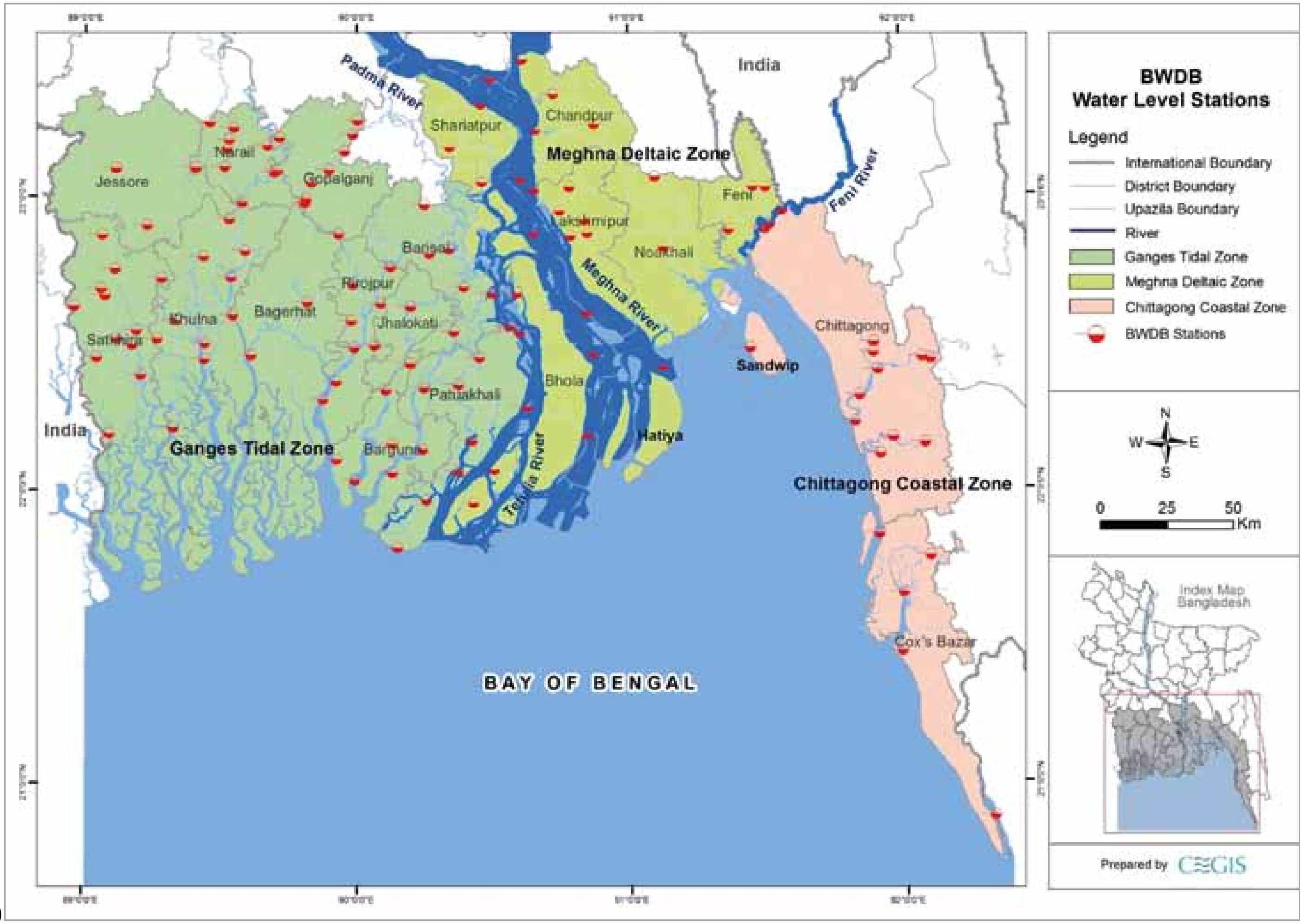

Figure 4.1a: Locations of all water level stations of BWDB

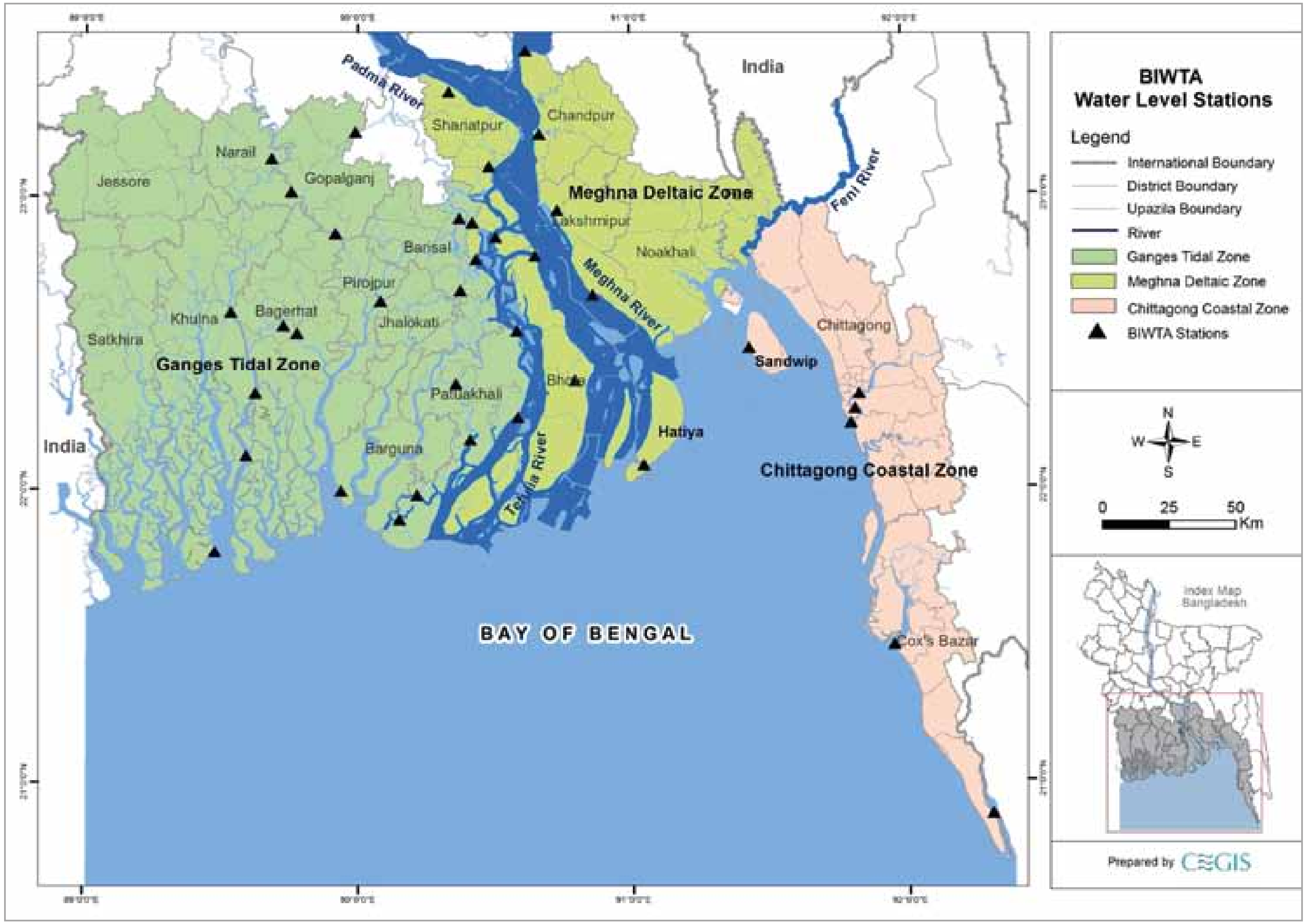

Figure 4.1b: Locations of all water level stations of BIWTA

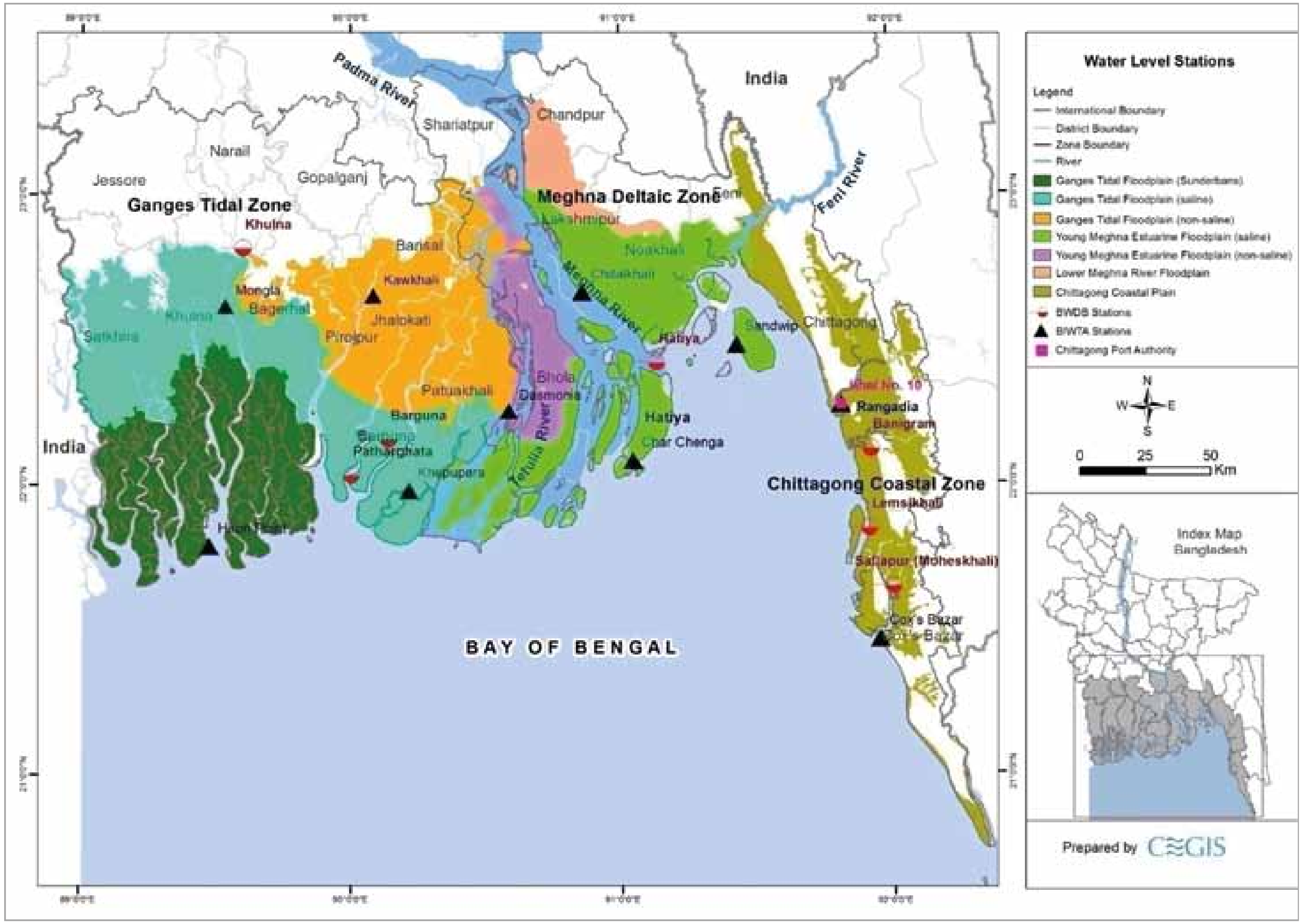

Figure 4.2: Locations of selected water level stations according to geo-morphological and physiographic zones

The steps (Figure 4.4) followed for the trend analyses are:

a) Consistency checking of data: Consistency of the data has been checked using visual data exploration. The time series values of the maximum and minimum water levels have been plotted to detect outliers, and then these have been removed from the main data.

b) Homogeneity test: Homogeneity of the water level values has been checked to examine the variability of data values throughout a dataset. For homogeneity testing, methods such as Standard Normal Homogeneity Test (Alexandersson, 1986), Von Neumann (Von Neumann, 1941), Pettitt (Pettitt, 1979) and Buishand (Buishand, 1982) tests have been applied on some stations. Most of the data have been found non-homogenous. Globally, statistical analysis for homogeneity testing is mostly applied for meteorological and hydrological data and its performance for coastal data is mostly found weak (Van Gelder and Vrijling, 1998). Therefore, for this study homogeneity testing has not been considered for the assessment of sea level rise.

c) Serial auto-correlation testing: It has been assessed whether there is any serial auto-correlation within the dataset and removed if any.

d) Identification of observed trend: The linear regression and Sen's slope have been calculated to detect the trend in water level data. Then the Mann Kendall test has been applied to check whether there is any significant positive or negative trend.

e) Correlation test: The daily observational data of tidal water level has been analyzed annually, to find the correlation within the data set. The significance of the correlation of existing trend in water level has been assessed using the Kendall's tau test.

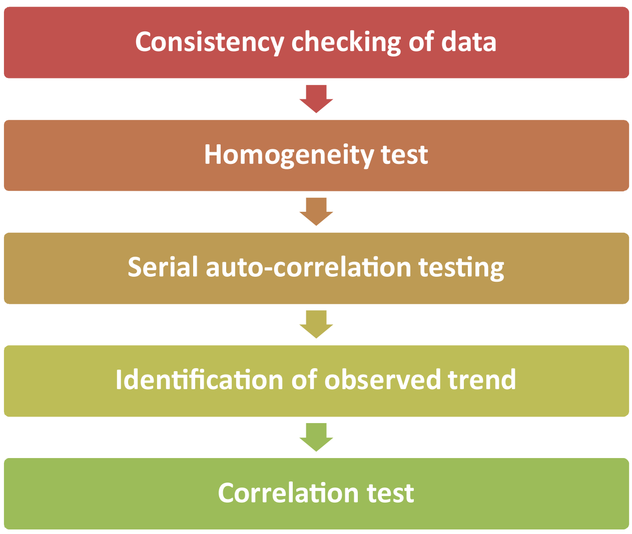

Figure 4.3: Steps for conducting trend analysis of tidal water level data

4.3.1 Consistency checking of tidal data

Historical time series data of water level has been collected from the stations of BWDB, BIWTA and the Chittagong Port Authority stations for the analysis. However, tide gauges may move vertically with the region as a result of post-glacial rebound, tectonic uplift or crustal subsidence. This greatly complicates the problem of determining global sea level change from tide gauge data. Differences in global sea level estimated from tide gauge data usually reflect the investigator's approach in considering these vertical crustal movements. Therefore, to remove the anomalies, the data has been checked for consistency.

Initially 18 coastal stations were selected. But after checking of consistency, three stations out of the selected 18 stations have been found to have inconsistent data (Table 4.4). So, finally 15 stations have been selected for trend analysis (Figure 4.3).

Table 4.4: Identification of inconsistent water level station

Station Name	Source	Reason of Inconsistency
Mongla	BIWTA	Close to ship jetty. Hence, susceptible to abrupt fluctuation of water level due to ship generated wave.
Dasmonia	BIWTA	Tidal station is affected by river bank erosion.
Kaukhali	BIWTA	Tidal station is far inside the coast.

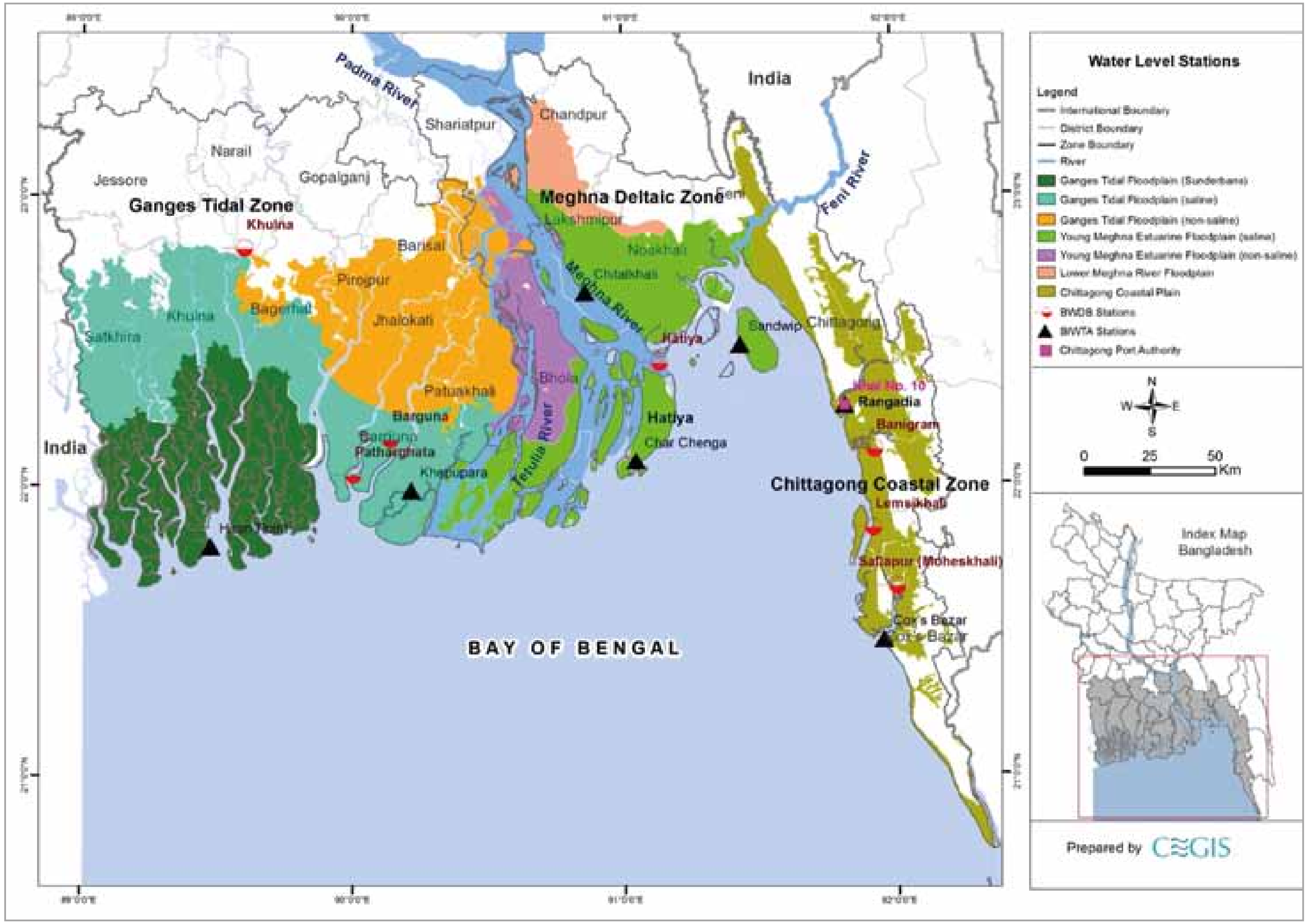

Figure 4.4: Locations of finally selected water level stations after consistency checking

Hourly historical tidal data are not free from errors. Before trend analysis annual maximum, average and minimum data have been calculated using expert judgment. Types of error that are most commonly found are: a) Data gaps, b) Spike in data during high tide and low tide, and c) Aberrant nature of hourly tidal data.

a) Data gaps

In some stations, gaps in the time series data have been found. Gaps in the data make it difficult to draw actual trend. Annual average water level trend will not be practical if there is too much data gap. Hence, the years with data gaps have been excluded from trend line analysis.

b) Spike in data of high and low tide

Abnormal water level data should be avoided for trend line analysis of annual maximum and annual minimum water level data. Spike data, which is generated during extreme condition or human induced error. It will give abnormal estimation of water level trend.

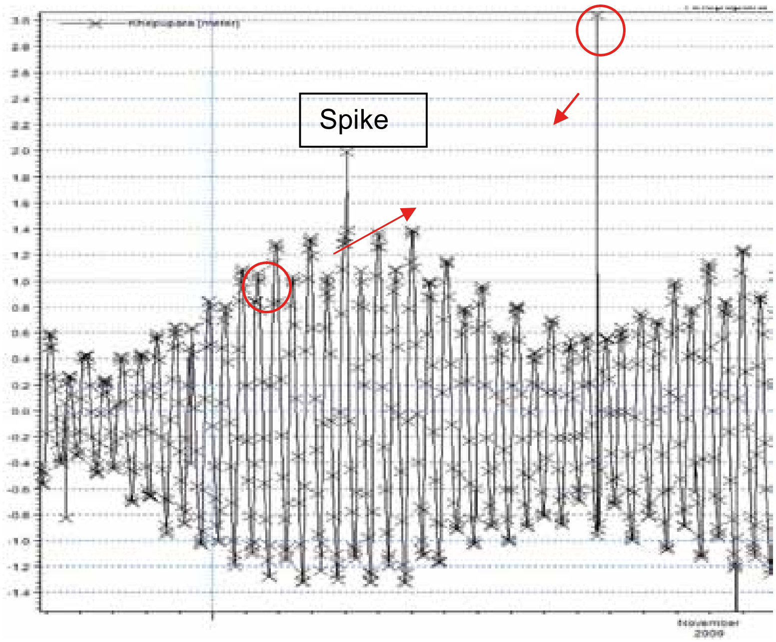

Figure 4.5: Example of spike water level existing in water data at Khepupara

c) Aberrant nature of hourly tidal data

Sometimes semidiurnal pattern is not observed in tidal water level data. In Bangladesh tidal data must be semi diurnal, if semi diurnal pattern of tide is not observed it should be excluded from analysis. For example, water level at Khepupara station in the year 2002 (Figure 4.6a), does not show semi diurnal pattern of tide. Actual pattern of semidiurnal tide is shown in Figure 4.6b.

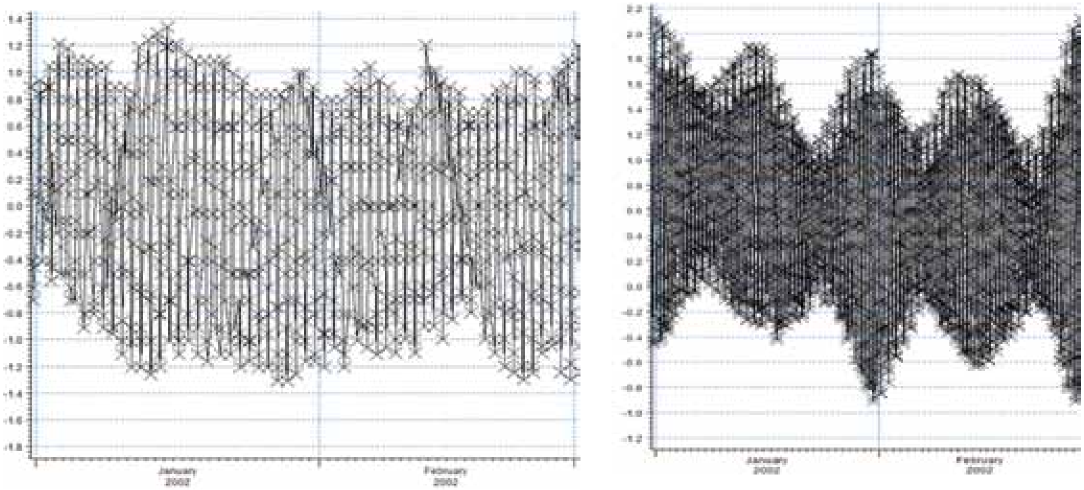

Figure 4.6: Aberrant nature of hourly tidal data

4.3.2 Trend Detection of Water Level Data

Trend analysis has been conducted using the linear regression method and Sen's slope. Then, Mann Kendall non-parametric test have been performed on annual maximum, annual minimum and annual average water level to determine whether the trend is positive or negative. Finally, significance of the trend has been checked by using the Kendall's tau test.

The results of trend analysis of tidal water level (one each from the three zones) for a period of 30 years and 20 years are given in the Table 4.5 and Table 4.6 respectively. The graphs (Figure 4.9 to Figure 4.35) show the observed trend of annual maximum, annual minimum and annual average tidal water level at different stations based on the linear regression and Sen's slope analysis over the last 30 and 20 years respectively.

Table 4.5: Trend of the selected water level stations for 30 years in the coastal region of Bangladesh

Location	Subzone	Analysis Period	Trend (avg)	Rise (mm/year)	Regression Slope	Sen's Slope	Mann-Kendall Trend	Correlation Co-efficient (Kendall's tau-b)	Significance level
Hiron Point	Ganges tidal floodplain (saline)	1981-2013	Increasing	8	0.008	0.0076	Positive trend	0.466	significant at 99%
Patharghata	Ganges tidal floodplain (saline)	1980-1999,2001-2012	Increasing	35	0.035	0.0381	Positive trend	0.810	significant at 99%
Khulna	Ganges tidal floodplain (non-saline)	1980-2009	Decreasing	-6	-0.006	-0.0077	Negative trend	-0.284	significant at 95%
Chitalkhali	Meghna estuarine floodplain (saline)	1980-1986,1990-2012	Increasing	43	0.043	0.035	Positive trend	0.541	significant at 99%
Char Chenga	Meghna estuarine floodplain (charland)	1980-2012	Increasing	6	0.006	0.0059	Positive trend	0.4310	significant at 99%
Sandwip	Meghna estuarine floodplain (charland)	1977-1990, 1996-2012	Increasing	10	0.01	0.0171	Positive trend	0.369	significant at 99%
Hatiya	Meghna estuarine floodplain (charland)	1980-1981, 1983-2012	Increasing	9	0.009	0.0081	No trend	0.071	not significant
Khal No. 10	Chittagong coastal plain	1983-2014	Increasing	15	0.015	0.0142	Positive trend	0.587	significant at 99%
Cox's_Bazar	Chittagong coastal plain	1980-2011	Increasing	14	0.014	0.0149	Positive trend	0.553	significant at 99%
Saflapur	Chittagong coastal plain	1983-1998,2004-2012	Increasing	28	0.028	0.0128	No trend	0.093	not significant
Banigram	Chittagong coastal plain	1981-2012	Decreasing	-26	-0.026	-0.0158	No trend	-0.228	not significant
Lemiskhali	Chittagong coastal plain	1981-88,1990-2012	Increasing	21	0.021	0.0181	Positive trend	0.601	significant at 99%

(Source: Estimate by CEGIS and IWM)

Table 4.6: Trend of the selected water level stations for 20 years in the coastal region of Bangladesh

Location	Subzone	Analysis Period	Trend (avg)	Rise (mm/year)	Regression Slope	Sen's Slope	Mann-Kendall Trend	Correlation Co-efficient (Kendall's tau-b)	Significance level
Hiron Point	Ganges tidal floodplain (saline)	1992-2012	Increasing	4	0.004	0.0043	No trend	0.297	not significant
Barguna	Ganges tidal floodplain (saline)	1992-2012	Increasing	6	0.006	0.007	Positive trend	0.343	significant at 95%
Patharghata	Ganges tidal floodplain (saline)	1992-2012	Increasing	37	0.037	0.0408	Positive trend	0.726	significant at 99%
Khepupara	Ganges tidal floodplain (saline)	1988-2005	Increasing	9	0.009	0.0113	Positive trend	0.459	significant at 95%
Khulna	Ganges tidal floodplain (non-saline)	1992-2012	Decreasing	-19	-0.019	-0.015	No trend	-0.328	not significant
Chitalkhali	Meghna estuarine floodplain (saline)	1992-2012	Increasing	59	0.059	0.0442	Positive trend	0.498	significant at 99%
Char Chenga	Meghna estuarine floodplain (charland)	1992-2012	Increasing	8	0.008	0.01	Positive trend	0.388	significant at 95%
Sandwip	Meghna estuarine floodplain (charland)	1996-2012	Increasing	11	0.011	0.0133	No trend	0.317	not significant
Hatiya	Meghna estuarine floodplain (charland)	1992-2012	Decreasing	-35	-0.035	-0.0539	Negative trend	-0.410	significant at 99%
Khal No. 10	Chittagong coastal plain	1992-2014	Increasing	18	0.018	0.012	Positive trend	0.619	significant at 99%
Rangadia	Chittagong coastal plain	1994-2011	Increasing	3	0.003	0.0033	No trend	-0.32	not significant
Cox's Bazar	Chittagong coastal plain	1992-2011	Increasing	23	0.023	0.0229	Positive trend	0.586	significant at 99%
Saflapur	Chittagong coastal plain	1992-1998,2004-2012	Increasing	59	0.059	0.113	No trend	0.367	significant at 95%
Banigram	Chittagong coastal plain	1992-2012	Decreasing	-58	-0.058	-0.0341	Negative trend	-0.473	significant at 99%
Lemiskhali	Chittagong coastal plain	1992-2012	Increasing	19	0.019	0.0188	Positive trend	0.549	significant at 99%

(Source: Estimate by CEGIS and IWM)

It has been found from Table 4.5 and Table 4.6 that trends of various stations is not significant. Also, trends of interior station is much higher or deviated from actual water level trends (which we assume to represent sea level rise) which might be due to the effect of other processes such sedimentation, subsidence, data error, changes of fresh water flows. It is essential to determine trends of all the stations for a homogenous time periods as the recent trends of water level is much higher comparing to the long time trends as shown in the Table 4.5 and Table 4.6. In this context, a summary of the trend analysis has been produced considering the following-

- Trend should be significant at least 95% level.
- Station should be located very close to the coastline to avoid influence of other land-sea interaction related processes such as sedimentation, subsidence or other anthropogenic process.
- Time frame of conducting trend analysis to determine trends should be same for all the stations in order to get a consistence results.

The summary of the trends of sea level rise in the coastal zone of Bangladesh has been presented in Table 4.7 and 4.8. Trends of water level for three coastal sub zones namely, Ganges, Meghna and Chittagong are shown in Figure 4.7 and 4.8.

Analysis of tidal water of 30 years show trends of water level in the Ganges tidal floodplain of 7-8 mm/year. On the other hand, the trend is 6-10 mm/year in the Meghna Estuarine flood plain and 11-21 mm/year in the Chittagong coastal plain areas (Figure 4.7). Considering tidal water level of 20 years, the rate for the Ganges flood plain varies from 6-11 mm/year, for the Meghna Estuarine flood plain it is from 8-10 mm/year and at the Chittagong coastal plain it varies from 12-23 mm/year (Figure 4.8).

The highest trend has been observed in the Chittagong and Cox's bazar region of Bangladesh compared to other two coastal sub-zone of the country. The primary reason of this variation is the exposure or proximity to the sea. Another reason could be the variation in the tidal fluctuations between the high and low water tide meaning that the high tide level is higher in the Chittagong coastal plain compared to the Ganges and Meghna subzones. Other processes could be the impact of local factors such as sedimentation and subsidence process. However, it is not possible to comment on the exact reason of this zone variation of the trend without conducting long term research on the changes of various contributing processes and also without having high precision accurate sea level time series data.

Interestingly, the trend obtained from this study corresponds with the trend cited by SMRC (2003), where the trend is lower in the Ganges followed by medium range values in the Meghna and highest values in the Chittagong coastal plain. Also, in addition to similarities, this study implies that sea level has risen at a higher rate in recent times, thus consolidating the notion of rising sea level.

Table 4.7: Significant trends derived of the selected water level stations (near the coastline) in the coastal region of Bangladesh based on the data of last 30 years

Source	Location	Subzone	Analysis Period	Trend based on Regression Slope (mm/year)	Trend based on Sen's Slope (mm/year)	Significance level
BIWTA	Hiron Point	Ganges tidal floodplain (saline)	1981-2013	8	7	significant at 99%
BIWTA	Char Chenga	Meghna estuarine floodplain (charland)	1980-2012	6	6	significant at 99%
BIWTA	Sandwip	Meghna estuarine floodplain (charland)	1977-2012	10	10	significant at 99%
BIWTA	Khal No. 10	Chittagong coastal plain	1983-2012	15	20	significant at 99%
BIWTA	Cox's Bazar	Chittagong coastal plain	1980-2012	11	13	significant at 99%
BWDB	Lemiskhali	Chittagong coastal plain	1981-88, 1990-2012	21	18	significant at 99%

Table 4.8: Significant trends derived of the selected water level stations (near the coastline) in the coastal region of Bangladesh based on the data of last 20 years

Source	Location	Subzone	Analysis Period	Trend based on Regression Slope (mm/year)	Trend based on Sen's Slope (mm/year)	Significance level
BWDB	Barguna	Ganges tidal floodplain (saline)	1992-2012	6	7	significant at 95%
BIWTA	Khepupara	Ganges tidal floodplain (saline)	1988-2005	9	11	significant at 95%
BIWTA	Char Chenga	Meghna estuarine floodplain (charland)	1992-2012	8	10	significant at 95%
BIWTA	Khal No. 10	Chittagong coastal plain	1992-2012	18	12	significant at 99%
BIWTA	Cox's Bazar	Chittagong coastal plain	1992-2012	23	23	significant at 99%
BWDB	Lemiskhali	Chittagong coastal plain	1992-2012	19	18	significant at 99%

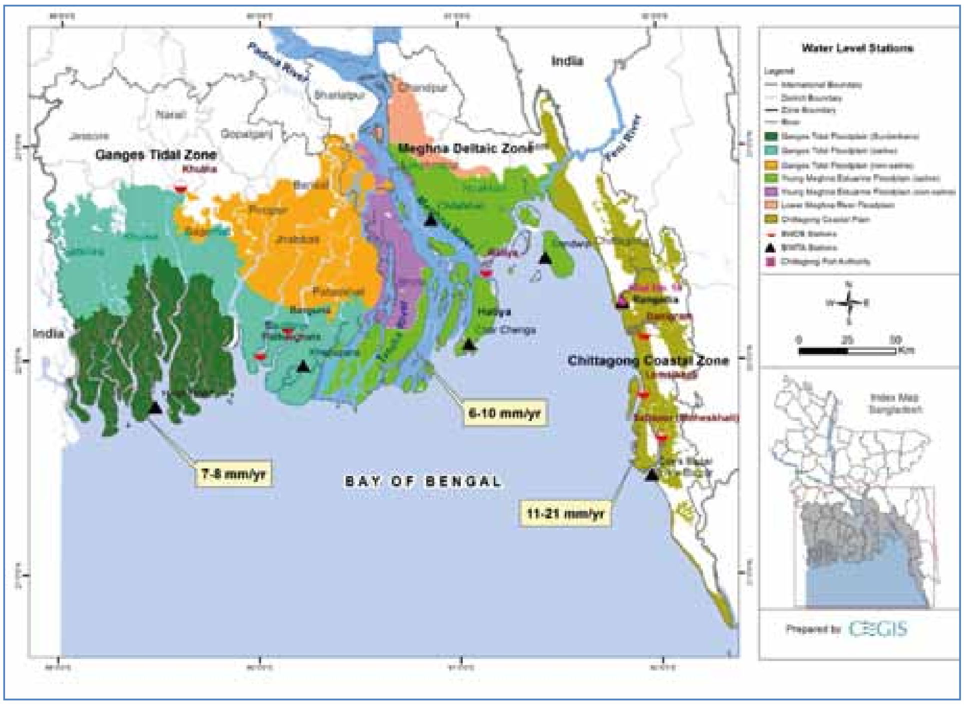

Figure 4.7: Water level trends for the Ganges, Meghna and Chittagong coastal sub zone of Bangladesh based on the data of last 30 years

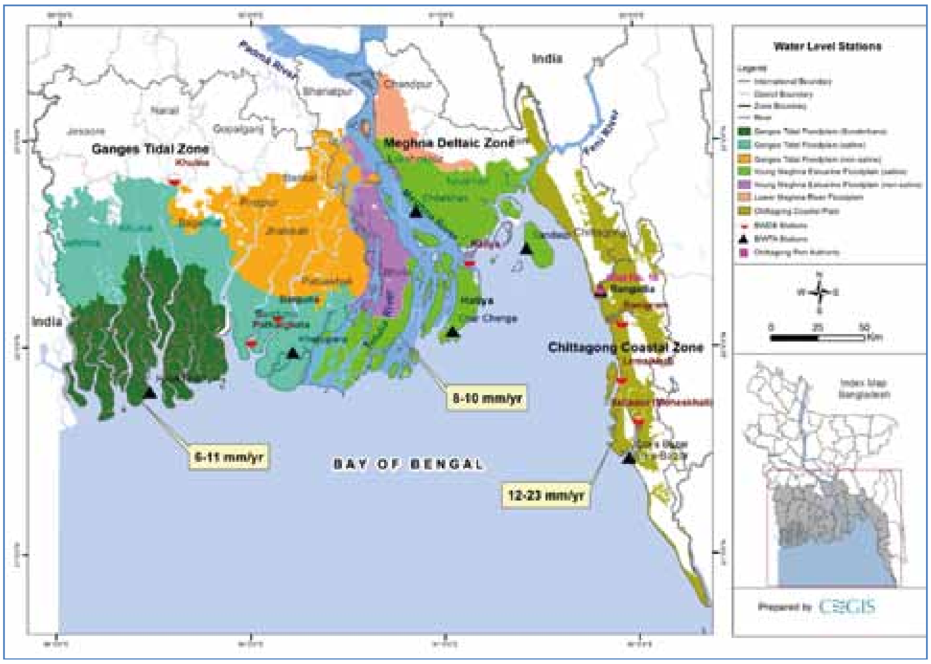

Figure 4.8: Water level trends for the Ganges, Meghna and Chittagong coastal sub zone of Bangladesh based on the data of last 20 years

Water Level Trends of last 30 years:

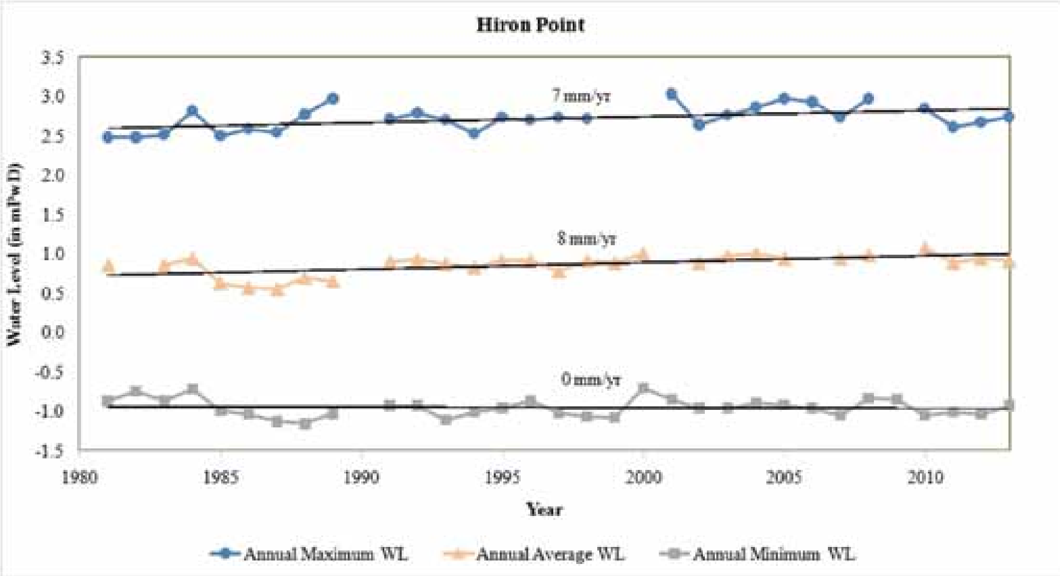

Figure 4.9: Observed trend of tidal water level at Hiron Point based on the linear regression analysis over the last 30 years

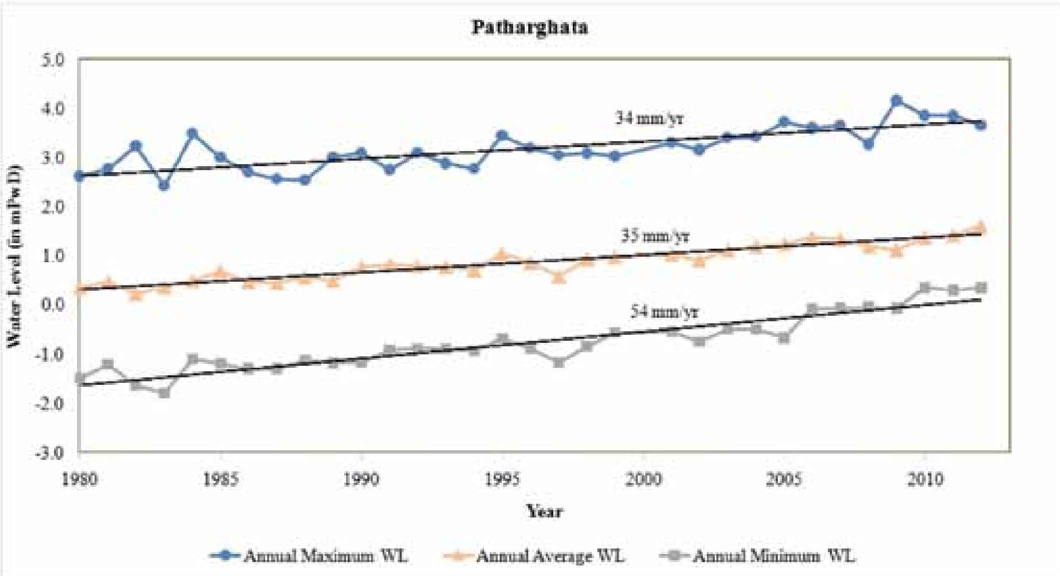

Figure 4.10: Observed trend of tidal water level at Patharghata based on the linear regression analysis over the last 30 years

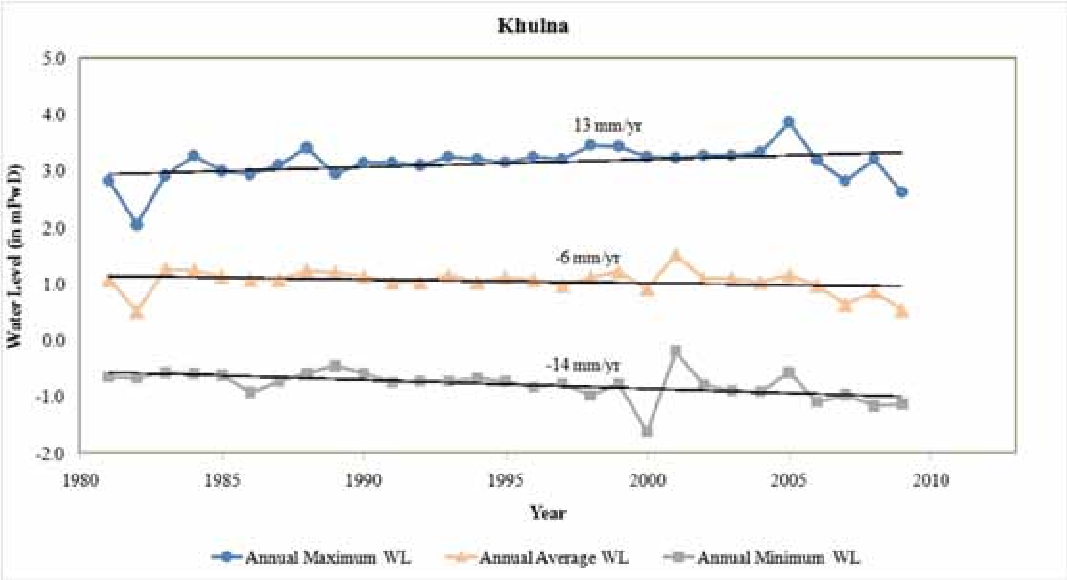

Figure 4.11: Observed trend of tidal water level at Khulna based on the linear regression analysis over the last 30 years

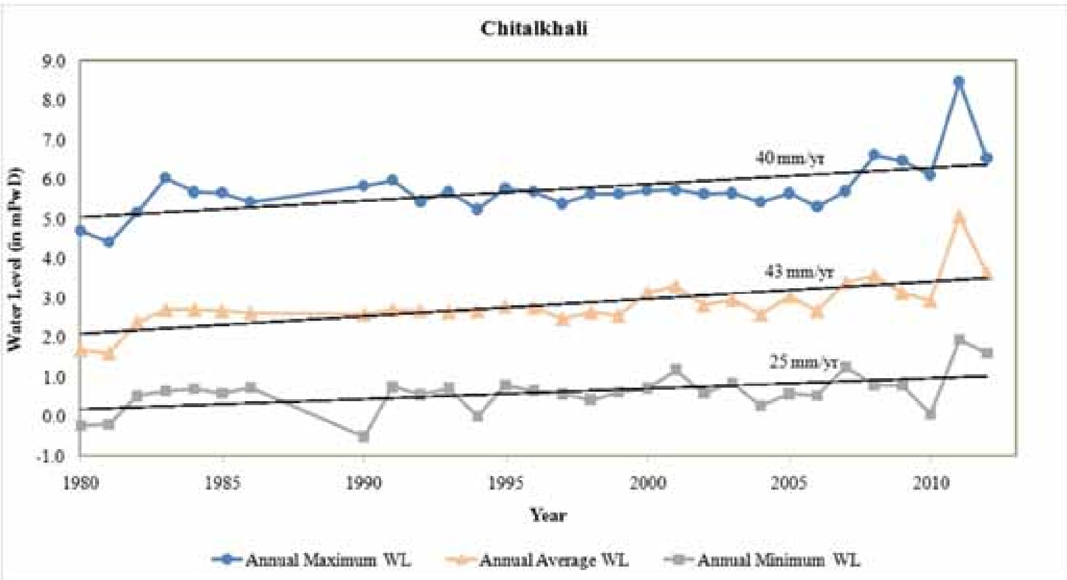

Figure 4.12: Observed trend of tidal water level at Chitalkhali based on the linear regression analysis over the last 30 years

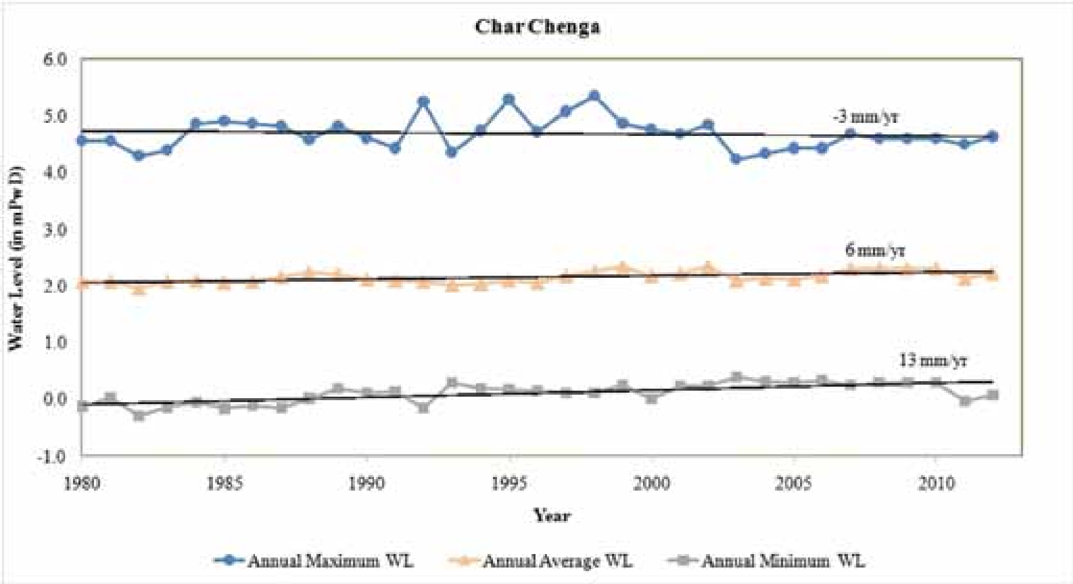

Figure 4.13: Observed trend of tidal water level at Char Chenga based on the linear regression analysis over the last 30 years

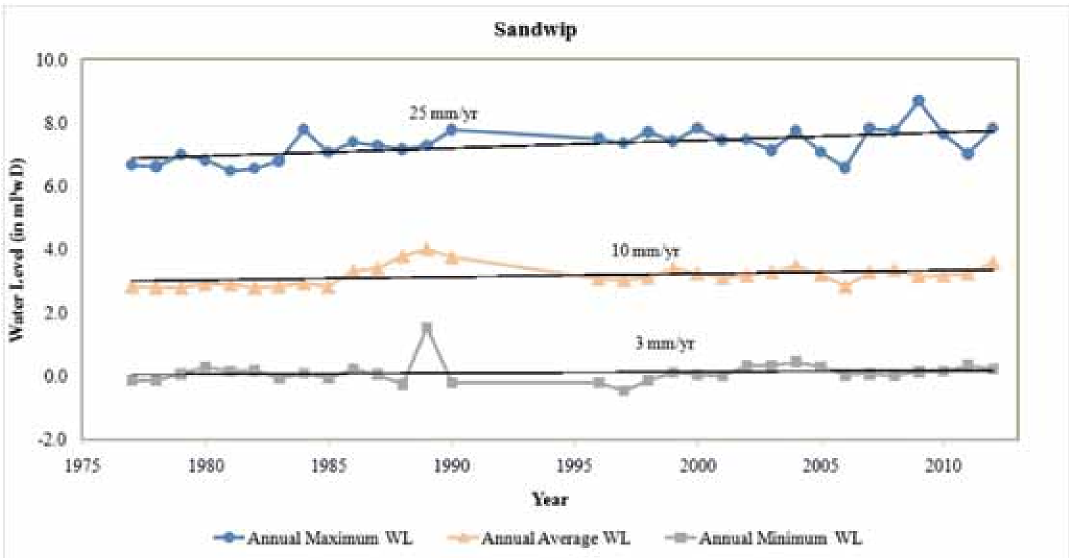

Figure 4.14: Observed trend of tidal water level at Sandwip based on the linear regression analysis over the last 30 years

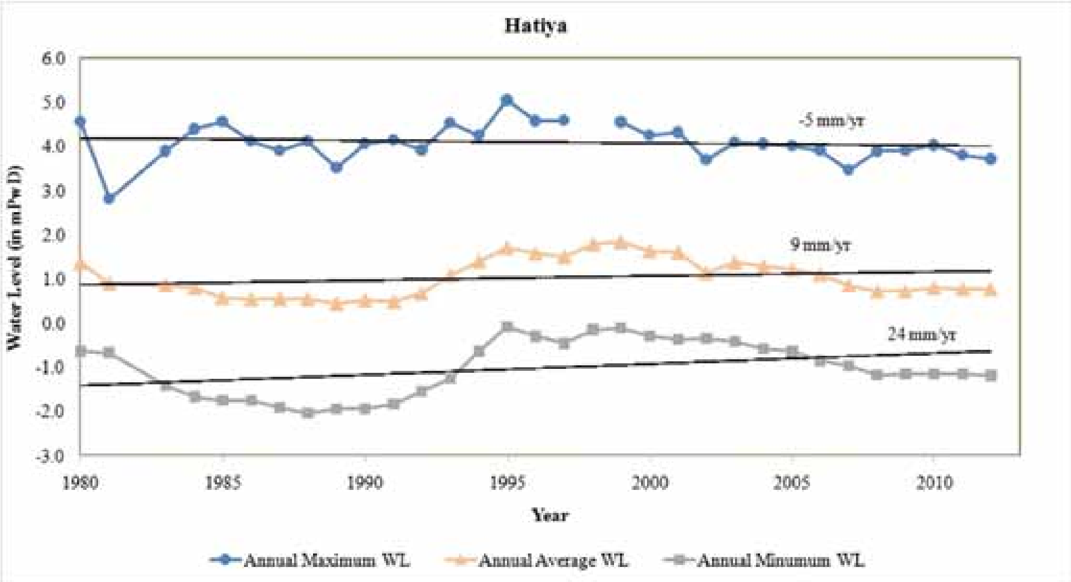

Figure 4.15: Observed trend of tidal water level at Hatiya based on the linear regression analysis over the last 30 years

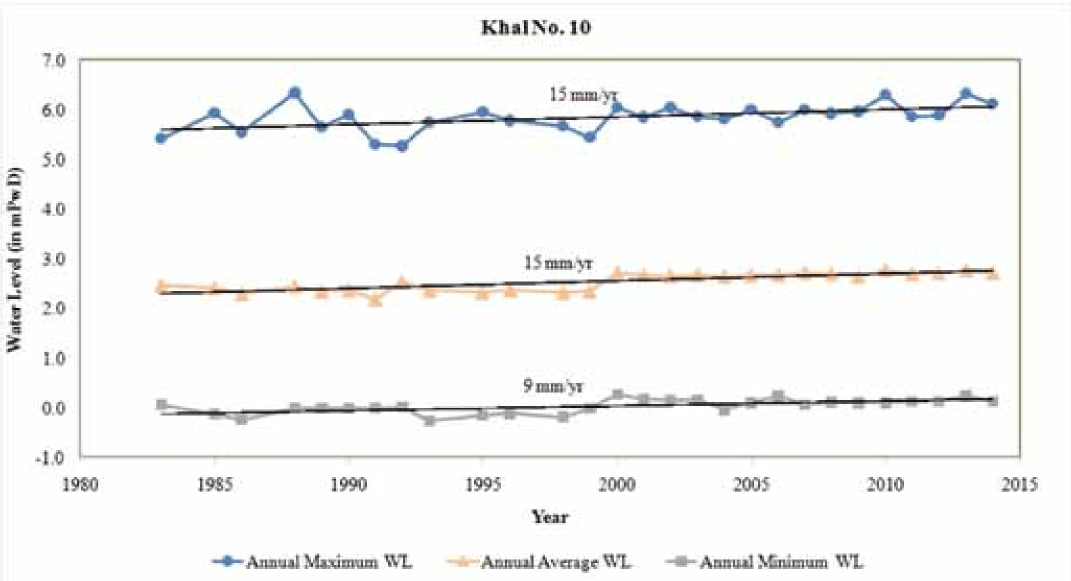

Figure 4.16: Observed trend of tidal water level at Khal No. 10 based on the linear regression analysis over the last 30 years

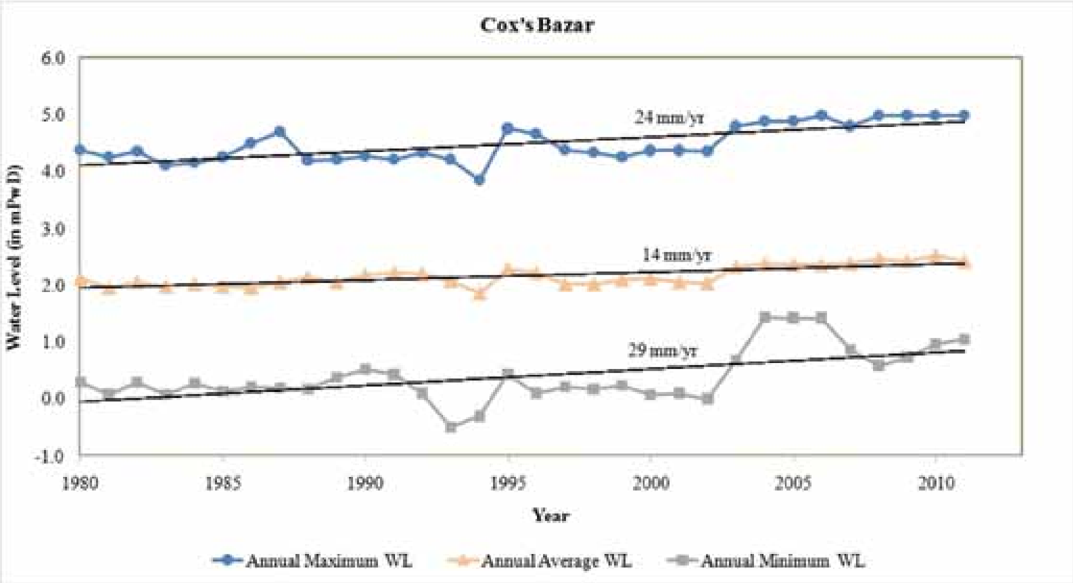

Figure 4.17: Observed trend of tidal water level at Cox's Bazar based on the linear regression analysis over the last 30 years

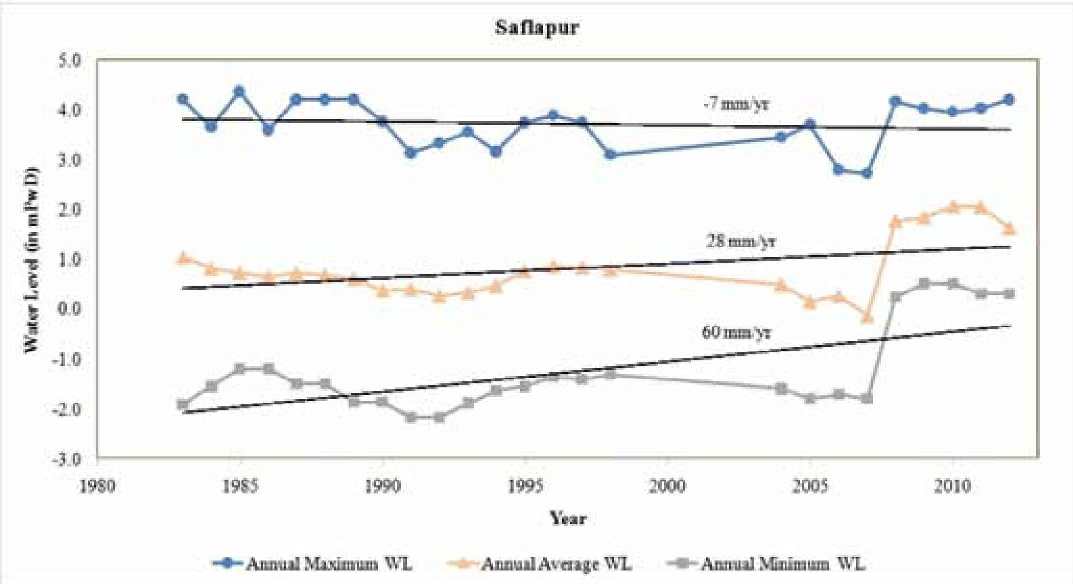

Figure 4.18: Observed trend of tidal water level at Saflapur/Moheshkhali based on the linear regression analysis over the last 30 years

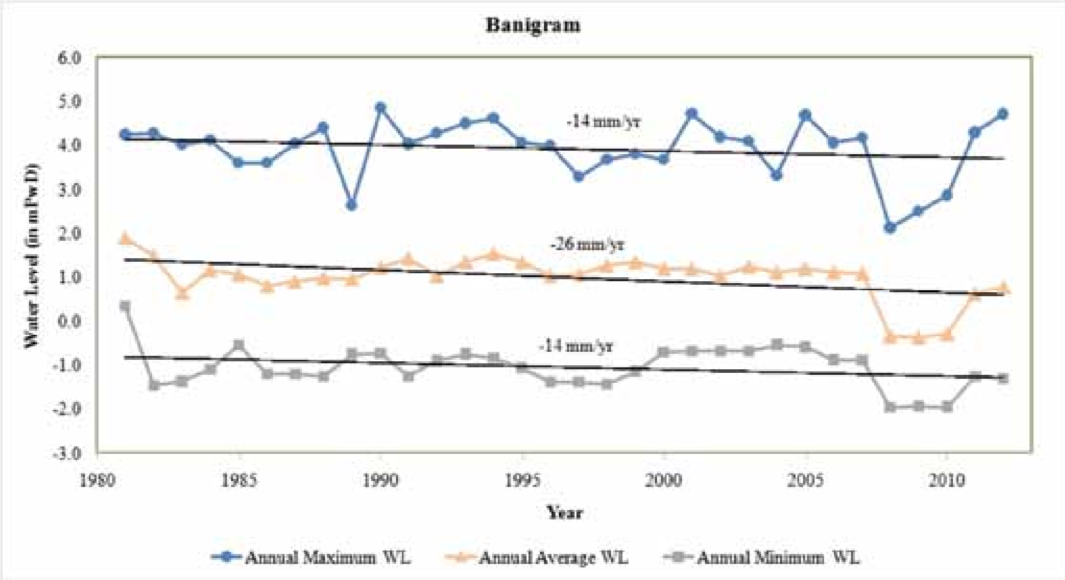

Figure 4.19: Observed trend of tidal water level at Banigram based on the linear regression analysis over the last 30 years

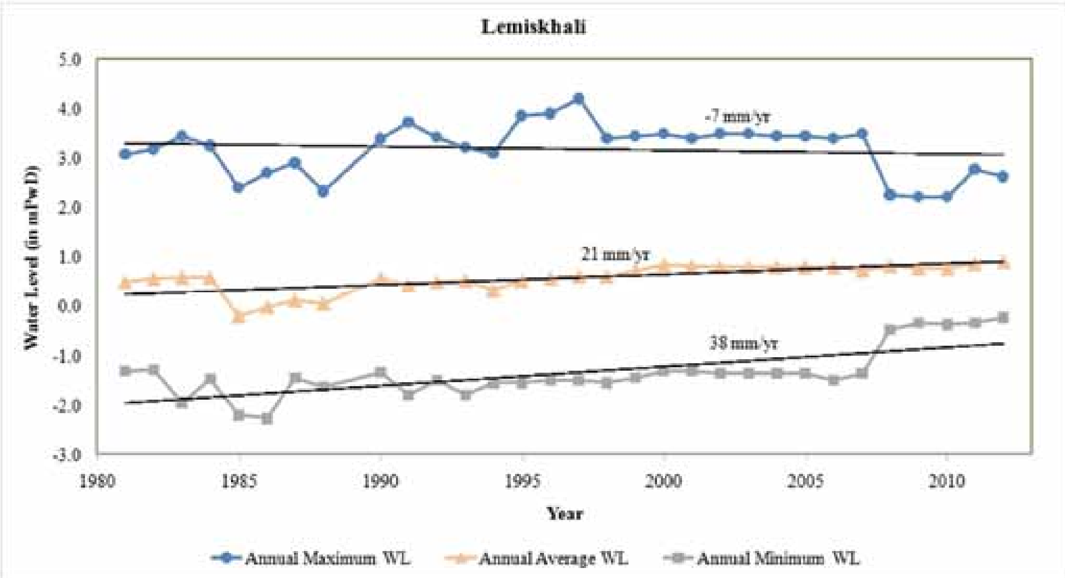

Figure 4.20: Observed trend of tidal water level at Lemiskhali based on the linear regression analysis over the last 30 years

Water Level Trends of last 20 years:

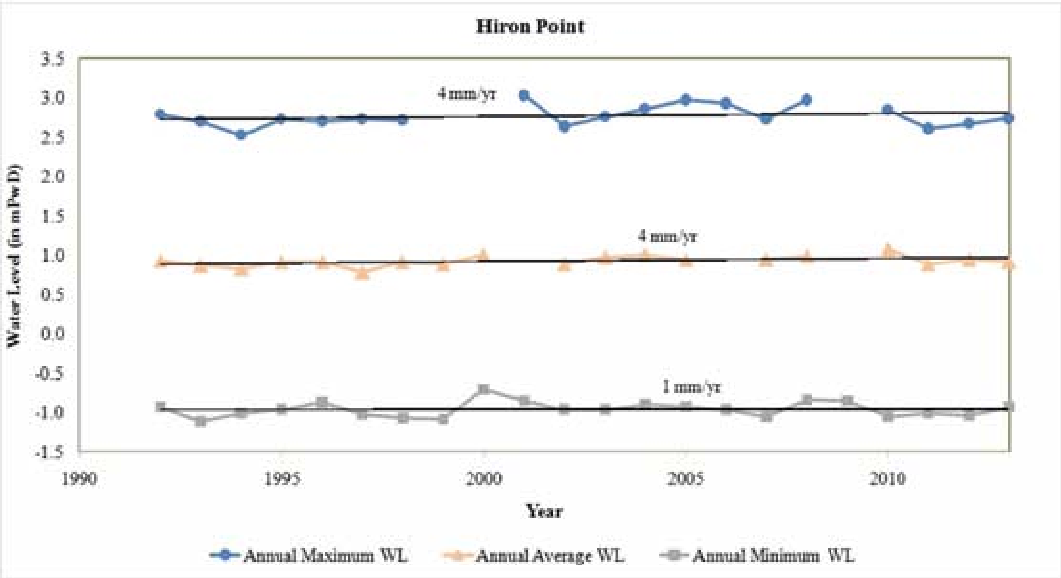

Figure 4.21: Observed trend of tidal water level at Hiron Point based on the linear regression analysis over the last 20 years

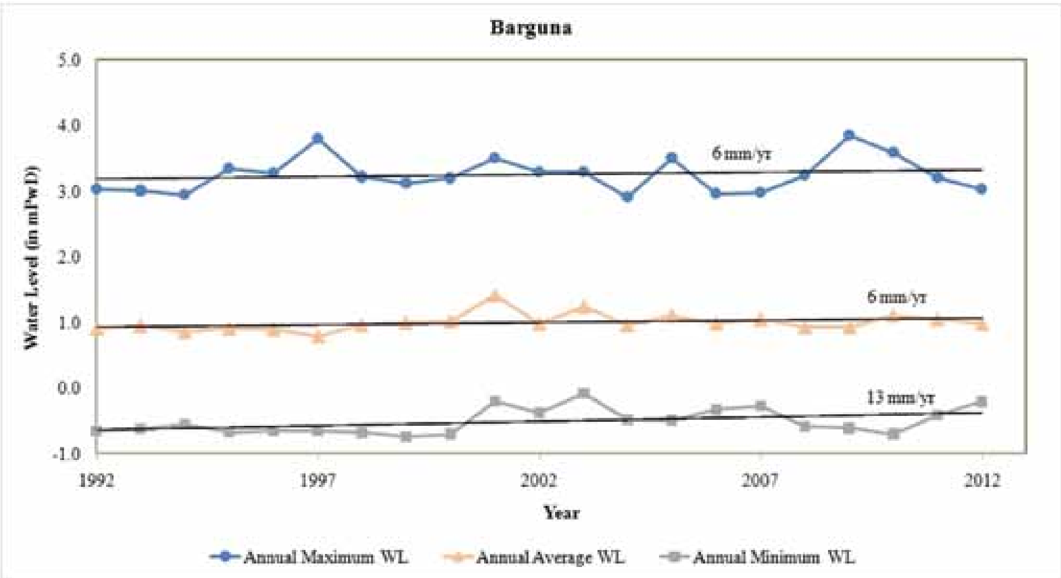

Figure 4.22: Observed trend of tidal water level at Barguna based on the linear regression analysis over the last 20 years

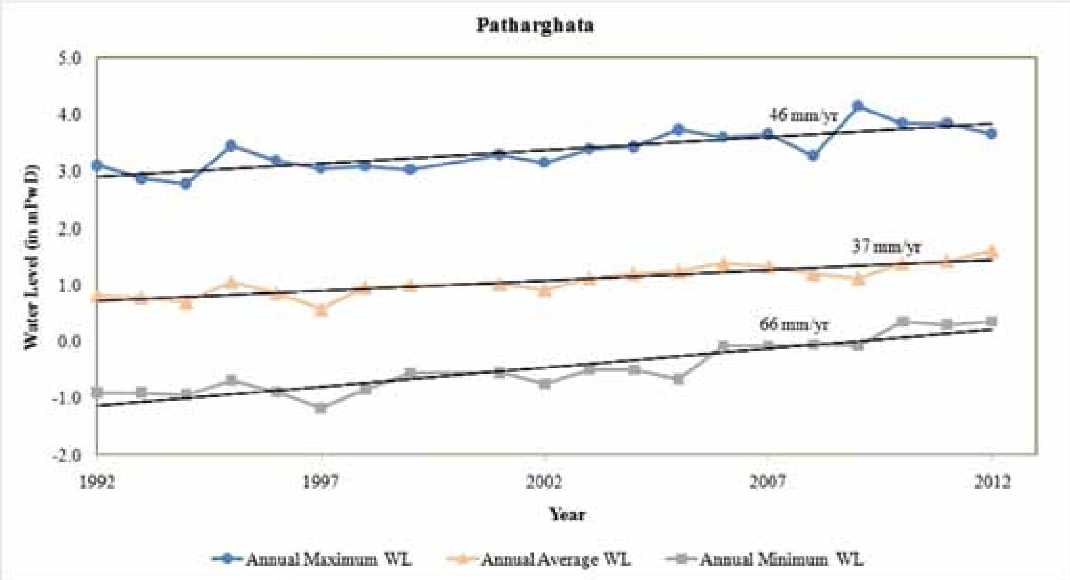

Figure 4.23: Observed trend of tidal water level at Patharghata based on the linear regression analysis over the last 20 years

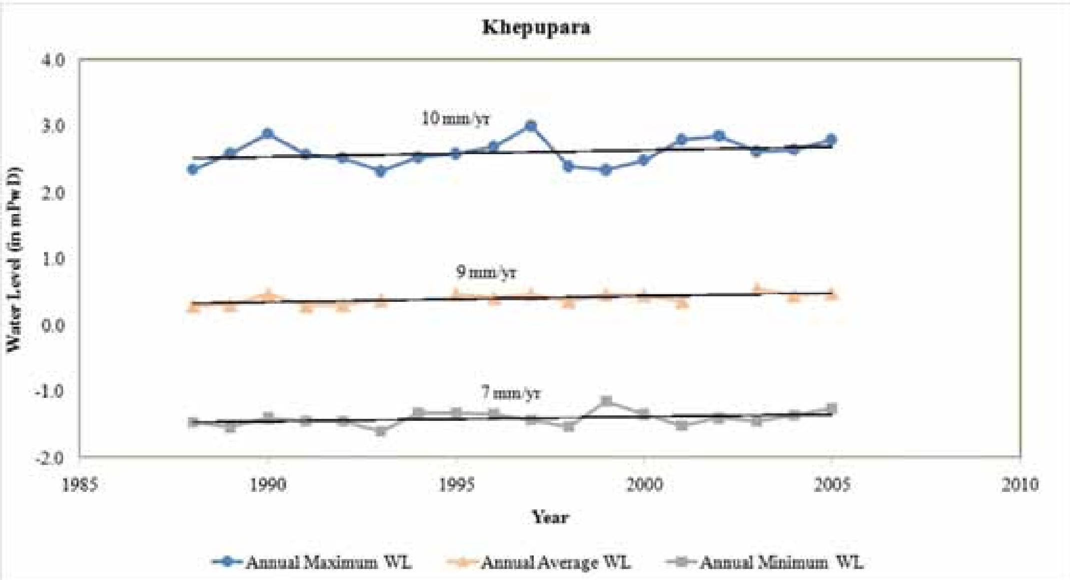

Figure 4.24: Observed trend of tidal water level at Khepupara based on the linear regression analysis over the last 20 years

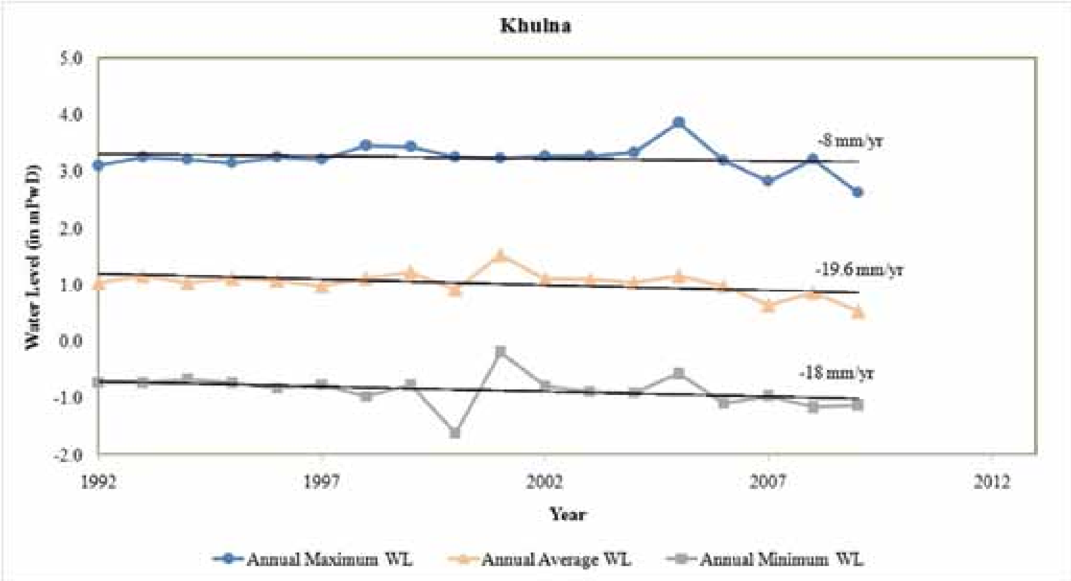

Figure 4.25: Observed trend of tidal water level at Khulna based on the linear regression analysis over the last 20 years

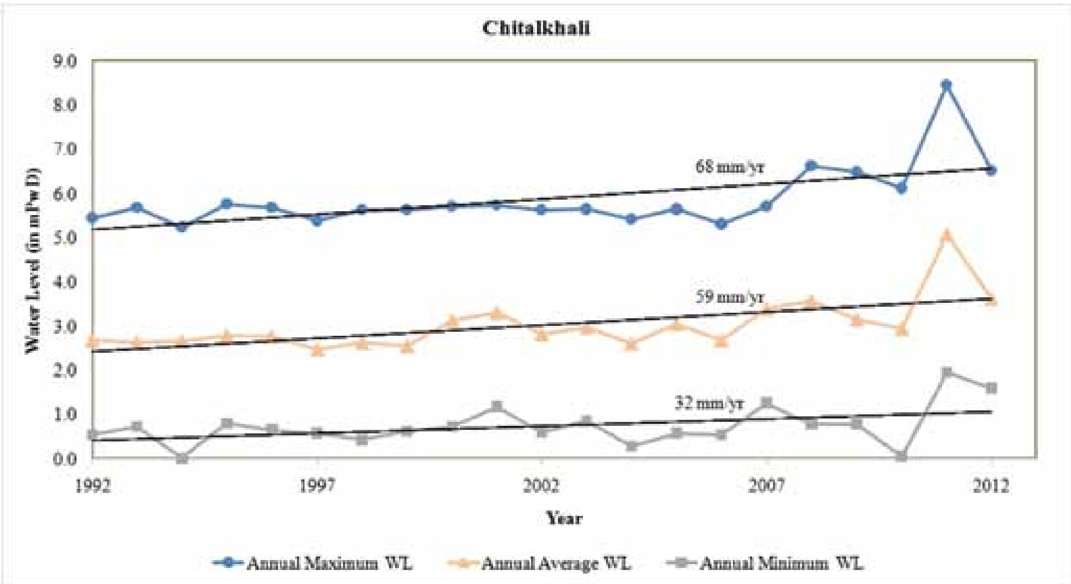

Figure 4.26: Observed trend of tidal water level at Chitalkhali based on the linear regression analysis over the last 20 years

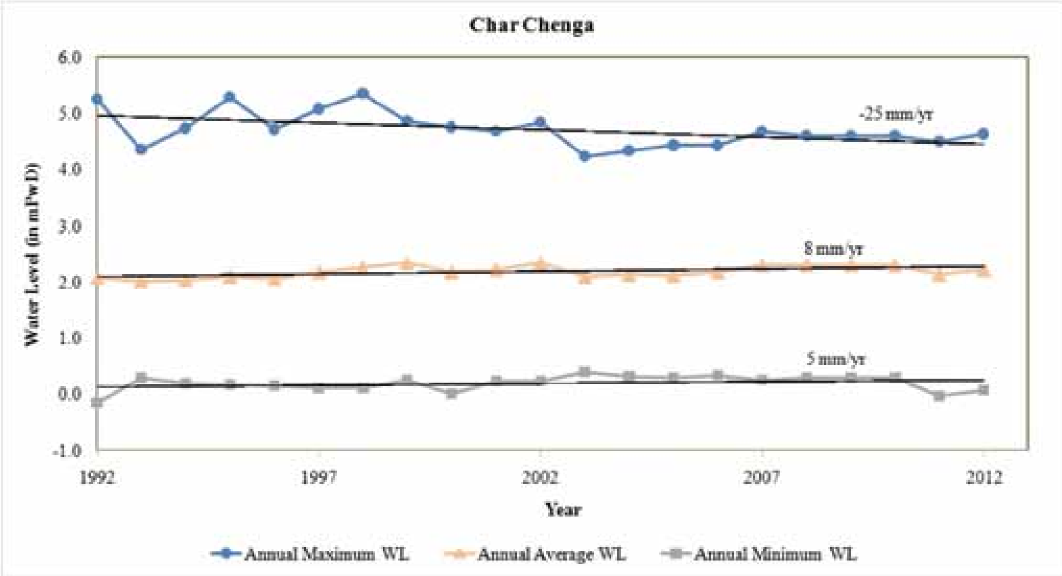

Figure 4.27: Observed trend of tidal water level at Char Chenga based on the linear regression analysis over the last 20 years

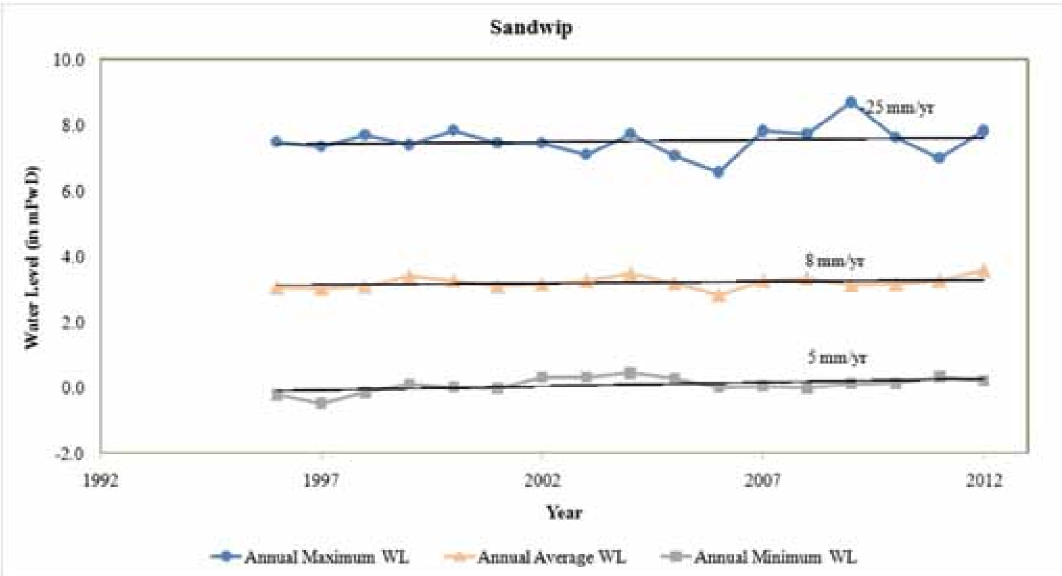

Figure 4.28: Observed trend of tidal water level at Sandwip based on the linear regression analysis over the last 20 years

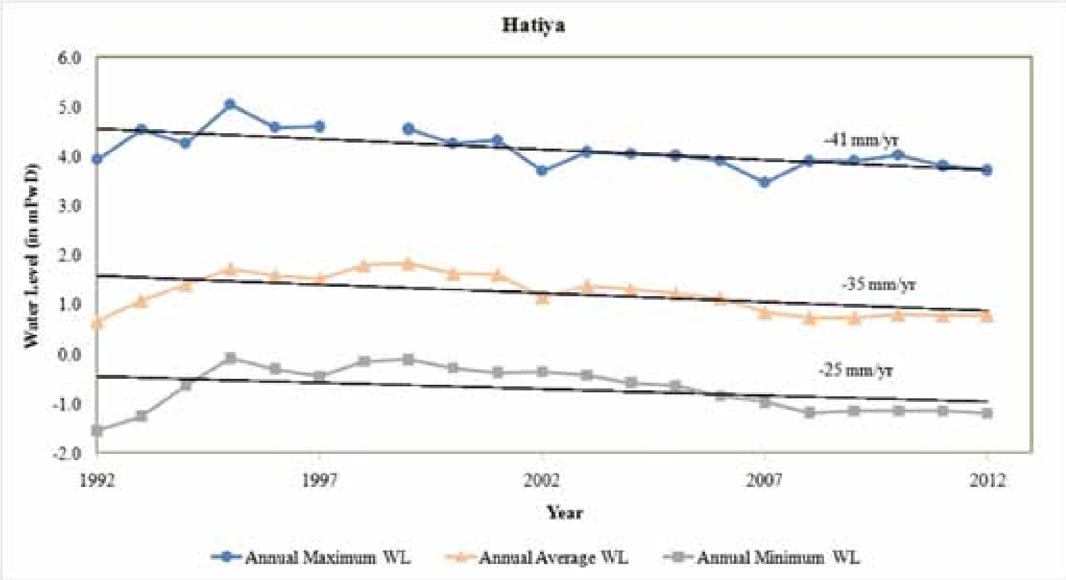

Figure 4.29: Observed trend of tidal water level at Hatiya based on the linear regression analysis over the last 20 years

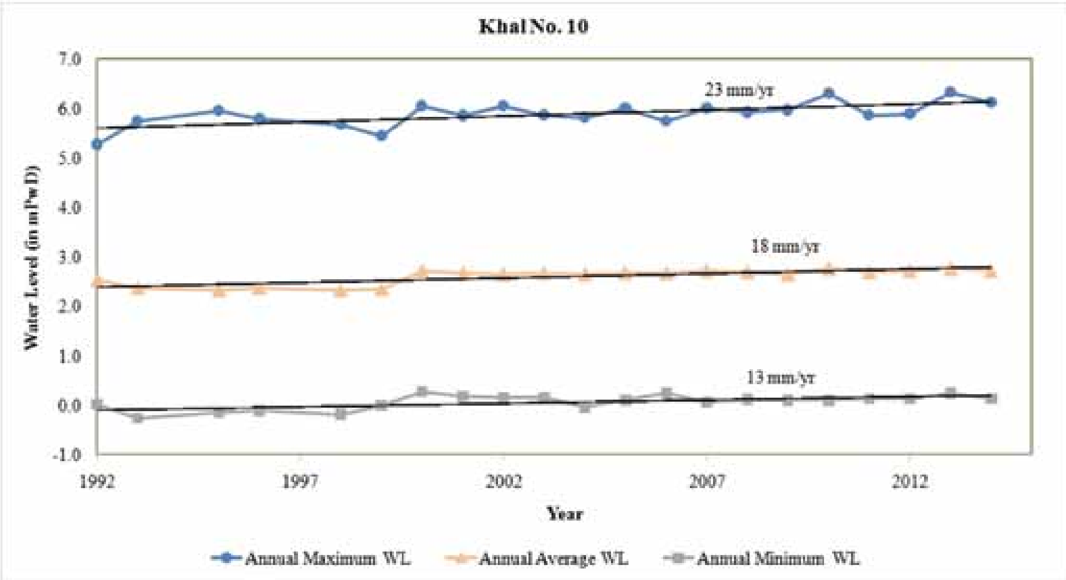

Figure 4.30: Observed trend of tidal water level at Khal No. 10 based on the linear regression analysis over the last 20 years

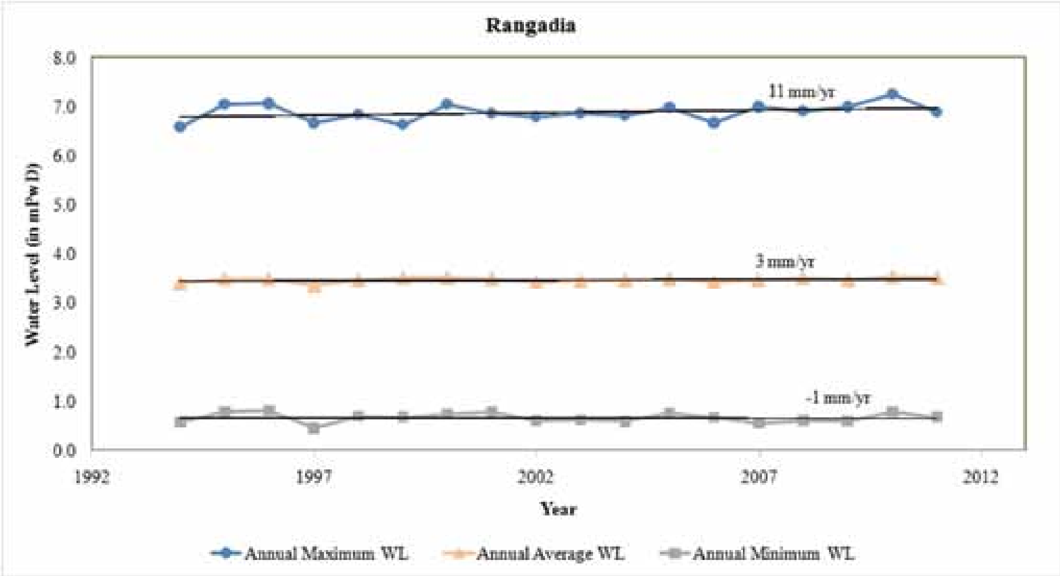

Figure 4.31: Observed trend of tidal water level at Rangadia based on the linear regression analysis over the last 20 years

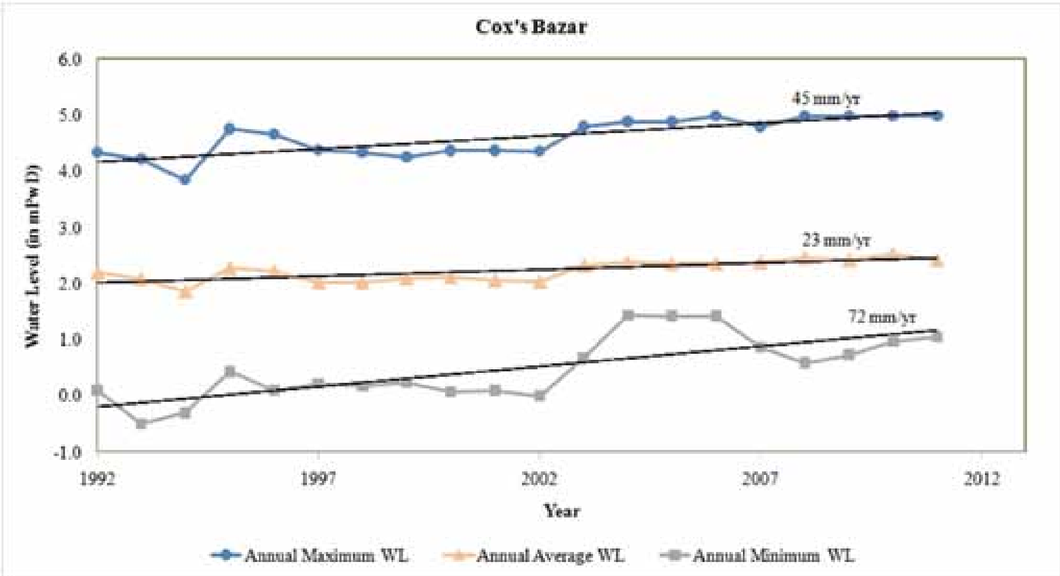

Figure 4.32: Observed trend of tidal water level at Cox's Bazar on the linear regression analysis over the last 20 years

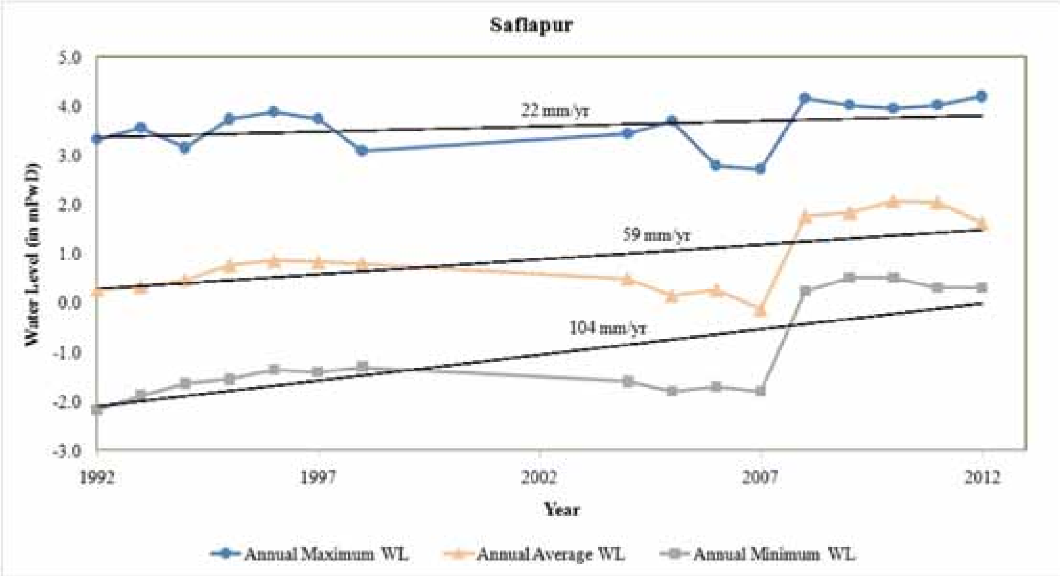

Figure 4.33: Observed trend of tidal water level at Saflapur based on the linear regression analysis over the last 20 years

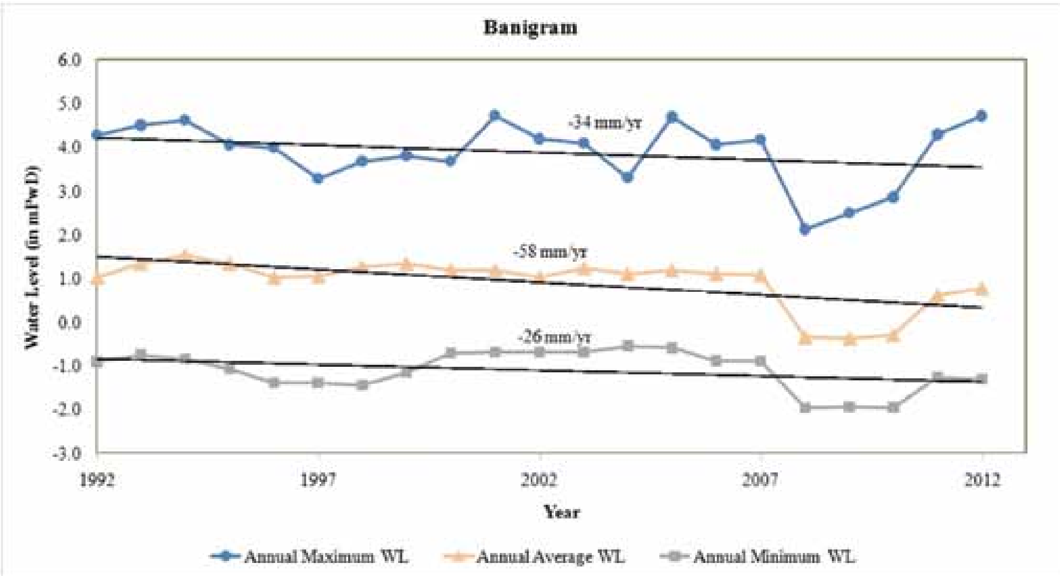

Figure 4.34: Observed trend of tidal water level at Banigram on the linear regression analysis over the last 20 years

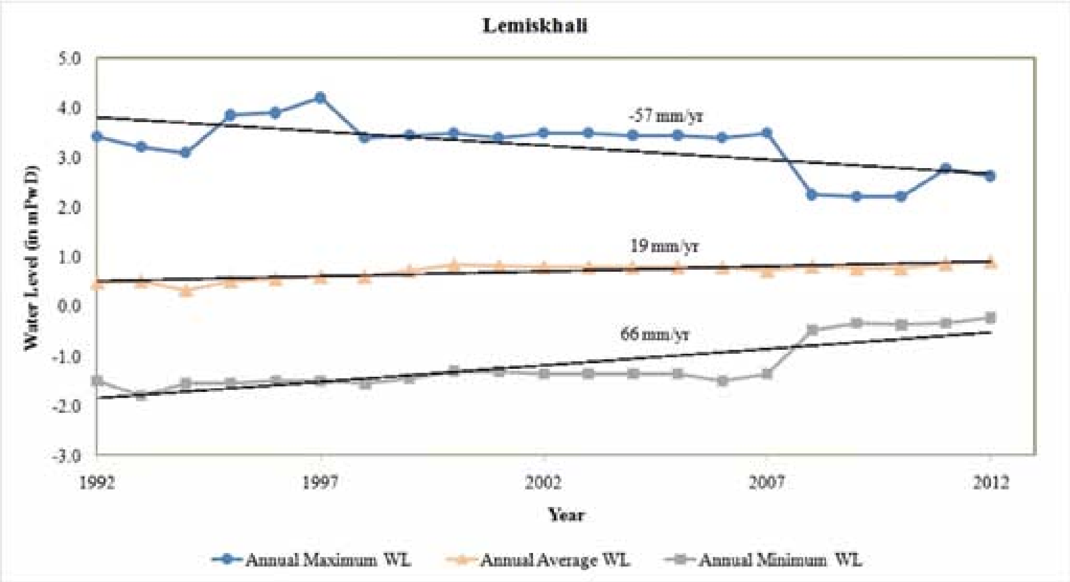

Figure 4.35: Observed trend of tidal water level at Lemiskhali based on the linear regression analysis over the last 20 years

Chapter 4

Findings and Recommendations

5.1 Findings

Bangladesh, located along the Bay of Bengal is highly vulnerable to sea level rise. There is no comprehensive and up to date study on Sea Level Rise based on trend analysis. The study focused to visualize the change of sea level in the coast of Bangladesh through analysis of the observed tidal water level. In this study, short term trend of tidal water level for a period of 30 years have been analysed to identify the change in sea level rise along the coast of Bangladesh. This comprehensive dataset of 30 years has been prepared from the available data, which were consistent and of good quality.

The trend analyses have been carried out using the water level data of BIWTA, BWDB and Chittagong Port Authority. Stations were selected close to the coastline. However, BIWTA and BWDB are maintaining 47 and 188 tidal water level stations throughout the country. Out of which 38 BIWTA stations, 127 tidal water level stations and 18 non tidal water level stations of BWDB are located in the coastal zone. From these stations, 18 stations have been selected along the coasts to cover three major geo-morphological regions and six physiographic sub-regions. The criterion for selecting these stations was that each of the station represents the regional variations in water level. However, after consistency checking, 3 stations out of the initially selected 18 stations have been discarded for having inconsistent data.

A number of standard statistical analysis were conducted which include the consistency checking of data, homogeneity test, serial auto-correlation testing etc. Observed trends are detected using both linear regression and Sen's slope methods and significance of the trends are tested using Mann Kendall test. The trends that are significant at 95% confidence level have been considered for SLR analysis.

Following are the major conclusions based on the study findings:

Analysis of tidal water of 30 years shows rising trends of water level in the Ganges tidal floodplain of 7-8 mm/year. On the other hand, the trend is 6-10 mm/year in the Meghna Estuarine flood plain and 11-21 mm/year in the Chittagong coastal plain areas. Considering tidal water level of 20 years, the rate for the Ganges flood plain varies from 6-11 mm/year, for the Meghna Estuarine flood plain it is from 8-10 mm/year and at the Chittagong coastal plain it varies from 12-23 mm/year. So, it has been found that the overall trend in the coastal zone in the last 30 years has been 6-21 mm/year. Overall, the study has considered the 30-year trends of SLR as more reliable long-term trends. According to the trends, the range of sea level rise on Bangladesh coast over the 30 years is 6-21mm/year.

The trend obtained from this study corresponds with the trend cited by SMRC (2003), where the trend is lower in the Ganges followed by medium range values in the Meghna and highest values in the Chittagong coastal plain. For example-upto 2003 the SLR trends were 4.0 mm/year, 6.0 mm/year and 7.8 mm/year in Hiron Point, Char Changa and Cox's Bazar respectively (SMRC, 2003). However, this recent study has found higher trends of SLR in the Chittagong coast.

In addition to similarities regarding rising trends between the two studies, it has been found that the trend of sea level rise is much higher in recent years. It implies that sea level has risen at a higher rate than in the past, thus consolidating the notion of rising sea level. One of reason of higher trend could be the exposure or proximity of the station to the sea. The variation in the tidal fluctuations between the high and low tide and the influence of tidal circulation process is much higher in the Chittagong Coastal plain and complex than the other two regions.

The trend derived from the global tide gauge data found that, the long-term trend in GMSL is 1.7 [1.5 to 1.9] mm/year between 1901 and 2010 for a total sea level rise of 0.19 [0.17 to 0.21] m. Alternatively, the high-precision satellite altimetry record suggest that between 1993–2012, a GMSL rate of 3.2 [2.8 to 3.6] mm/year have been observed. Therefore, the MSL trend derived from the tidal gauge data along the coast of the Bay of Bengal is much higher than the GMSL trend derived from long term global tide gauge data and short term satellite data.

5.2 Recommendations

A set of recommendations have been put forward based on the study findings including collecting and updating primary level data and conducting SLR oriented thematic studies. The specific recommendations of this study are:

The existing water level stations are not installed for the monitoring of sea level change and are operated in different ways for data collection. Therefore, the available stations are not sufficient for trend analysis. Many of these stations are not able to provide good quality of historic tide records. So some of the existing stations may be converted to automated gauge stations. There is also the need to immediately setup new 10 high precision automatic gauge stations along the coastal zone of Bangladesh. These stations could be at Hiron point, Sundarban, Khepupara, Char Chenga, Sandwip, Moheshkhali, Noakhali, Chittagong Port, Cox's Bazar and Teknaf. However, the location should be selected in consultation with the BWDB, BIWTA and the Chittagong Port Authority.

Regular monitoring of the tidal water level data is required to assess the sea level rise. Water level data should be collected in a similar technique.

Changes in the ocean bathymetry due to sedimentation should be regularly monitored and studied. Bathymetric survey along the coastal region could be one of the important approaches to monitor the changes of the bathymetry.

The local factors such as subsidence, sedimentation and tectonic movement etc on sea level rise should be investigated and monitored which has influence for estimation of relative sea level rise

Impact of wind circulation on the sea level rise should be investigated through existing coastal tidal models. The anthropogenic effect such as impact of fresh water flows or polderization in the coastal region on the relative sea level rise requires further investigation.

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The Climate Change Cell was established in the Department of Environment in 2004 under the Comprehensive Disaster Management Programme (CDMP) of the Government. On successful completion of its first phase, the second phase started in 2010 under CDMP II. It responds to the recognition that Bangladesh is particularly vulnerable to the effects of climate change, and that the number and scale of climate related disasters are likely to increase.

The objective of the Cell is to enhance the technical capacity of DoE in supporting the Government in climate change related policy and programme development, to integrate climate change considerations into existing development interventions and to support the Government in its role in coordination and negotiation efforts.

The second phase came to an end in 2015.

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