SALINITY HAZARD ASSESSMENT IN COASTAL AREA OF BANGLADESH

Thesis Submitted

By

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Dedicated to

All the kind hearts of this world

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ABSTRACT

Salinity hazard has become one of the major concerning problem in Bangladesh coast. It has several adverse impacts on ecosystem, agriculture and livelihood of people. Saline water intrusion is caused by a complex interaction between freshwater flow coming from upstream river systems and saltwater flow coming from tidal forcing of the ocean. Several parameters like upstream river discharge, sea water level, tidal storage, salinity magnitude, tidal excursion, residence time, etc. play the vital role in determining the intrusion process of salinity. Salinity hazard is generally assessed by salinity magnitude. In this research, a new indicator named as Non-Dimensional Index for Salinity (NDIS) is developed to assess salinity hazard that incorporates not only salinity magnitude, but also other governing parameters associated with saltwater intrusion process. Residence time of salinity, named as RT, is identified as one of the governing parameters in NDIS. RT represents residing time of saline water in an estuary. An equation is developed to compute the residence time for a specific salinity magnitude in an estuary. NDIS is developed through non-dimensional analysis. To calculate the spatial and temporal variability of the governing parameters of NDIS and RT, a 2-Dimensional salinity model, Delft3D is applied. Validated model simulations from Delft3D salinity model are used to compute NDI, RT and Tidal Excursion in base condition and in two future scenarios. Two future scenarios considered in this study are – sea level rise and cyclone superimposed on sea level rise condition. It is found that governing parameters of salinity intrusion are non-linearly interrelated. Residence time of salinity follows the general spatial variation trend of salinity magnitude along the coast but not maintaining exactly one to one relation. It is also found that in most of the estuaries, residence time and upstream discharge are the most dominant parameters of salinity hazard. In base condition, the south-central region has the lowest salinity hazard (NDIS<30) whereas southwest region has the highest salinity hazard (NDIS>700). It is also found that Residence Time is lowest (<15 hours) in the middle part of the south-central region and gradually increases toward the south west region to exceed 80 hours for a 12 hour tidal cycle. Hence, salinity of similar magnitude resides for a longer time in south-west region than in south-central region. Sea level rise mostly affects the mouth and upper part of south central coast. For a SIDR-like cyclone in sea level rise condition, salinity hazard is highest along the cyclone track and, also affects upper part of south central and southwestern coasts. It is found that assessment of salinity hazard with the new method realistically represent the salinity condition in the coast in a changing climate. This assessment method of salinity hazard can be used in Coastal Zone Management or in Delta Plan as it takes into account all the physical processes involve in salinity intrusion.

ABBREVIATIONS AND ACRONYMS

BUET - Bangladesh University of Engineering and Technology

BWDB - Bangladesh Water Development Board

CEGIS - Center for Environmental and Geographic Information Services

GBM - Ganges-Brahmaputra-Meghna

IMD - Indian Meteorological Department

IWM - Institute of Water Modeling

IWFM - Institute of Water and Flood Management

WARPO - Water Resources Planning Organization

RT - Residence Time

TE - Tidal Excursion

NDIS - Non-Dimensional Index for Salinity

SLR - Sea Level Rise

Cyc - Cyclone

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CHAPTER 1
INTRODUCTION

1.1 Background of the Study

The coastal area in Bangladesh is characterized by tides and salinity from the Bay of Bengal, known as GBM delta at the confluence of the Ganges, Brahmaputra, Meghna Rivers and their tributaries (Rahman et al., 2013). Salinity intrusion is one of the major concern in coastal area especially in low lying deltaic region around the world. Bangladesh being in low lying deltaic region, salinity intrusion is a serious problem and a serious threat to as much as one third of the country's land and millions of populations inhibiting in the coastal area (Mahmuduzzaman et al., 2014), (Gain et al., 2014), (Rahman, 2015). Salinity hazard is defined by the detrimental effects on agriculture, crop, drinking water and ecosystem by the salt magnitude (Abrol et al., 1988), (Burger and Celkova, 2003), (Shammi et al., 2016). In general, when surface water salinity hazard is refereed in scientific studies, it refers in terms of salinity magnitude that affects the irrigation, local ecosystem and human livelihood in general (Ayers, & Westcot, 1985), (Shammi et al., 2016), (Smedema & Shiati, 2002), (Nielsen, 2003). However, it has been observed that in case of many natural hazards like flood, draught, and river bank erosion, dominating factors were considered through a methodological structure for assessing these hazards (Tingsanchali and Karim, 2005), (Van Eps, 2004), (Thakur et al, 2012) and in many cases, there is an established index value to assess or evaluate the hazard for a local system (He et al, 2011), (Daneshvar, 2013), (Simpson et al., 2014). However, no such hazard index or hazard assessment method of salinity intrusion is developed yet. This research aims to establish a hazard assessment index for salinity hazard that is not based on salinity magnitude only rather incorporates other dominant parameters of salinity intrusion process i.e. sea water level, tidal prism, landward velocity, upstream river inflow and residence time of salinity.

Salinity intrusion becomes a grave concern in coastal areas of Bangladesh during dry season when upstream discharge is significantly low (Shamsuddoha & Chowdhury, 2007), (Dasgupta et al, 2014). In a normal dry condition (December to May), south central zone (Meghna to Baleshwar estuarine system) has low salinity (1-5 ppt) whereas southwest zone (Sundarban estuarine system) and eastern hill zone (Chittagong estuarine system) suffer from high salinity intrusion (Dasgupta et al., 2014). Previous studies on salinity intrusion in Bangladesh coast described present salinity condition, predicted future condition based on sea level rise and changing upstream discharge and effect of salinity magnitude on ecosystem as well as livelihood of people (Hussain et al., 2013), (Dasgupta et al., 2014), (Hussain et al., 2013), (Bashar & Hossain, 2006), (Bricheno et al., 2016), (Bhuiyan & Dutta, 2012) (Mirza & Sarker, 2005), (Akter et al., 2016), (Akhter et al., 2012). As none of these studies considered salinity hazard in terms of dominant parameters of salinity intrusion or developed an index to assess the hazard, this research targets to address this gap.

In addition to, study predicted that the rate of salinity intrusion has become faster than it was predicted in decade ago (Agrawala, 2003). IPCC AR5 (2014) predicted that the sea level rise is likely to continue for centuries. Any increase in sea level may intrude salinity much longer distance in inland as the topography of the coastal zone in Bangladesh is relatively low lying (Karim and Maimura, 2008). Moreover, cyclone induced storm surges will be further elevated by a rising sea level (Nicholls et al., 2007), Dasgupta et al., 2011) that is capable of exacerbating the salinity intrusion situation as storm surge carries large amount of salt water from ocean and propagates toward inland with a high velocity (Bhuiyan and Dutta, 2012). From this point of view, this research is also going to examine the future condition of salinity hazard due to sea level rise (SLR) and storm surge in SLR condition. Examination of SLR and cyclonic condition are shown as the application of the developed salinity hazard index for future scenarios in changing climatic conditions.

Considering all these, this study has developed a salinity hazard index incorporating all dominant parameters that can represent the relative condition of an estuary for salinity hazard. The selection and formulation of dominant parameters related to salinity hazard is based on detail investigation of the process. Formulated hazard index is applied to examine future condition of salinity hazard in the coastal zone of Bangladesh.

1.2 Rationale of the Study

To date, works on salinity hazard in Bangladesh coast use model based salinity predictions focusing on changes of salinity magnitude only for predicted climatic scenarios or impact of sea level rise or river discharge. There is no single index that can represent salinity hazard considering all dominating parameters in a rationale way. In Bangladesh, only flood hazard was studied to develop hazard index (Tingsanchali and

Karim, 2005), (Gaňova et al, 2014), (Kazakis et al, 2015). This research addresses these gaps by developing a non-dimensional index to assess salinity hazard. The index is applied to assess salinity hazard in three events that cause salinity intrusion - normal dry condition, SLR and cyclonic conditions. Salinity hazard map based on this index represent a generic scenario considering all the dominant salinity intrusion parameters (compared to only salinity magnitudes which is the current practice) that result salinity intrusion in Bangladesh coast.

1.3 Objectives of the Study

The objectives of this research are:

1. Computation of dominant parameters driving the salinity inside the coastal area.
2. Development of a non-dimensional parameter to assess the salinity hazard.
3. Preparation of salinity hazard maps based on non-dimensional parameter.

This research is going to use a new method for salinity hazard assessment by developing a non-dimensional index and prepare hazard map based on the index value.

1.4 Outline of the thesis

The thesis has been organized into six chapters which have been outlined below.

The first chapter (i.e, introduction) describes the issue with which the research work has been preceded for salinity issue. The chapter also describes the rationale behind the research, objectives and scope of the present study.

The second chapter (i.e., literature review) describes the related studies. The chapter summarizes studies on salinity issue in Bangladesh coast, their focuses and methods.

The third chapter (i.e., study area) provides the location and characteristic of estuaries of Bangladesh Coast.

The fourth chapter (i.e., methodology) describes the materials and methods employed to carry out the research. This chapter has described the formulation of equations their inherent assumptions, how the calculations were carried out etc.

The fifth chapter is results and discussion, provides description of quantification of salinity intrusion. This chapter has explained how salinity hazard is assessed and how each parameter is contributing.

The sixth chapter (i.e., conclusions and recommendations) has made remarks on the research findings. The chapter has also incorporated the limitations of the research.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Before going to assess the salinity hazard, a detail literature study is conducted on the concerned topic. It is found that large number of works have been carried out on salinity intrusion which help to get a detail picture of the scenario and in likely scenarios. It is also found that no study was conducted on surface water salinity hazard that incorporates governing parameters of salinity intrusion process other than salinity magnitude. This chapter is going to bring forth these works, based on which the methodological approach is formulated.

2.2. Surface Water Salinity Hazard

Salinity hazard is a natural hazard. The term natural hazard implies the occurrence of a natural event, which threatens or acts hazardously in a defined space and time (Alcantara-Ayala, 2002). Natural hazard has been expressed as the elements in the physical environment harmful to man (Burton and Kates, 1964); an interaction of people and nature (White, 1973); the probability of occurrence of a potentially damaging phenomenon (UNDRO, 1982); and as a physical event which makes an impact on human beings and their environment, (Alexander, 1993), (Alcantara-Ayala, 2002). Salinity hazard focuses on biophysical assessment (Csaky and Please, 2003). Salinity hazard assessment is a process to identify the threats, nature and behavior of salinity intrusion which helps the decision makers for hazard preparedness, mitigation and adaptation. Surface water salinity hazard is generally assessed by salinity magnitude which mainly affects the irrigation, crop, livelihood, and ecosystem (Ayers and Westcot, 1985), (Shammi et al., 2016), (Smedema and Shiati, 2002), (Nielsen, 2003), (Metternicht and Zinck, 2003). Numerous studies described soil salinity and dry-land salinity hazard, risk prediction through remote sensing data, considering various hazard factors, including soil texture, vadose zone salinity, deep drainage and groundwater table height (Huang et al., 2016), (McFarlane et al., 2004), (Douaoui et al., 2006). However, within the available literatures, no such studies on surface water salinity is found that considered driving parameters of surface water salinity intrusion process.

Studies on surface water salinity intrusion were carried out in all over the world. Liu et al., (2004) used a vertical (laterally integrated) two-dimensional numerical model to study the salt water intrusion in the Tanshui River estuarine system, focusing on quantitative estimation of the salinity changes due to human interference (Liu et al, 2004). Breeman (2008) simulated the hydrodynamic behavior of the Selangor Estuary at the Malaysian west coast by utilizing Delft3D numerical model and to assess the impact of water extraction for the salinity levels in the estuary. Xue et al., (2009) investigated physical mechanism causing saltwater intrusion using the high-resolution unstructured-grid Finite-Volume Coastal Ocean Model (FVCOM). The results suggest that the intrusion is caused by a complex nonlinear interaction process in relation to the freshwater flux upstream, tidal currents, mixing, wind, and the salt distribution in the inner shelf of the East China Sea (Xue et al., 2009). Heuvel (2010) studied salinity equilibrium and the impacts on the salinity (gradients) in the Pontchartrain Basin using Delft3D modeling suite. El-Adawy et al., (2013) also used Delft3D hydrodynamic modelling to efficiently simulate the hydrodynamic situation in El-Burullus Lake which can help to asses any proposed engineering solution for preserving the aquatic system of the Lake and stop the continuous deteriorating of the water quality (El-Adawy et al., 2013).

In several past studies, present salinity condition along the Bangladesh coast were explained. Most of the related study on salinity hazard are based on mathematical modeling of present salinity condition and prediction of future condition in terms of salinity magnitude. There are some proposed and recommended management strategies to reduce the effect of salinity hazard. These studies are summarized below:

One study used Delft3D model to assess salinity extremes in three flooding scenarios namely the wet, dry and normal flooding conditions (Sumaiya et al., 2015). Model results show a wide variation of temporal and spatial variability (as low as 0 ppt in the east to as high as 34 ppt in the west) of the salinity fields in the estuarine systems due to different seasonal and flooding conditions.

Another study depicted present day dry season salinity condition (for the year of 2011) as well (Dasgupta et al., 2014). This study used MIKE 11 Advection Dispersion Module to predict future location-specific river salinity by constructing 27 alternative scenarios of climate change from December 2049 to May 2050; the focus of which was changes in river salinity and probable impacts (Dasgupta et al., 2014).

A study applied salinity suite of Delft3D hydrodynamic model (Delft 3D) to predict maximum increase of salinity along the Sundarban coast of Bangladesh for the years 2020, 2050 & 2080 (Hussain et al., 2013). Numerical investigations showed the changes in salinity distributions due to the combined effect of sea level rise, altered discharge and also meteorology in future during the four different seasons. Maximum increase of salinity has been found during the monsoon season (average 4 psu), followed by the winter (average 2.4 psu), the post-monsoon (average 1.8 psu) and the pre-monsoon (average 1.7 psu) for 2080s time slice compared to base condition along the Sundarbans coast of Bangladesh (Hussain et al., 2013).

Another similar study (Bashar and Hossain, 2006) focused on the impact of Sea Level Rise (SLR) on the salinity of the south west (SW) region of Bangladesh and possible options to minimize adverse impacts using mathematical modeling. The study used MIKE 11 to simulate salinity which was coupled with Geographic Information System (GIS) for the estimation of extent of salinity intrusion considering Sea Level Rise (SLR) at one case and SLR with varied flow of Gorai River at another case of the present-day condition. From model simulation they found that for a SLR of 25cm, 50cm and 100cm, the 0.3ppt saline front in the Gorai River moved further inland 5, 17 and 28 km, respectively from base condition. The 1ppt salinity moved further inland 3, 10 and 23 km and the 3ppt salinity moved 1, 5 and 11 km from the base condition for the same extent of SLR (Bashar and Hossain, 2006).

Another study (Mohal et al., 2006) considered MIKE 21 and MIKE 11 for assessing the expected impacts on inundation, salinity intrusion, and cyclone induced storm surge inundation due to14 cm, 32 cm and 88 cm sea level rises. The study revealed that 5 ppt saline front will penetrate about 40 km inland for SLR of 88 cm in the Meghna Estuary. Sea level rise of 32 cm will intrude 10 to 20 ppt salinity level more in the Sundrabans (Mohal et al., 2006).

In one study (Akhter et al., 2012), mathematical modeling system MIKE 11 and MIKE21FM were used to assess the potential impacts of salinity intrusion due to climate change. This study used hydrological year of 2009 as base year and 0.6 to 1.2 m SLRs were selected for the analysis for the year 2050. The result indicated that the South West region is more vulnerable to salinity intrusion due to gradual decrease of upstream flow. Sea level rise (SLR) changed the low salinity zone to medium salinity zone and medium salinity zone to high salinity zone of Sundarban. The 5ppt isohaline intruded 55 km and 95 km towards land for 60cm SLR and 120 cm SLR respectively. The study showed that 0 to 2 ppt salinity zone became 7 to 11 ppt due to 120 cm SLR in the Passur, Baleswar and Tentulia estuaries. Results also indicated that the only freshwater pocket used for agriculture in the Tentulia estuary, will be lost with SLR of 120cm. There was no salinity intrusion takes place in the Halda estuary at 2009 but if SLR occurred by 120 cm, salinity level is predicted to be increased by 1 ppt in the Halda estuary and in the worst scenario when there is no Kaptai release salinity become 5 to 6ppt (Akhter et al., 2012).

A study developed a salinity flux model and integrate this with an existing hydrodynamic model to assess the impact of 0.59 m SLR on salinity in the coastal zone estuaries (Bhuiyan and Dutta, 2012). The simulation showed that salinity intrusion length of 10 ppt salinity line was 21 km upstream in the Passur estuary for the SLR. The model predicted salinity increment at Mongla to be 0.9 ppt due to 0.59 m SLR corresponding to a climatic effect of 1.5 ppt per meter sea level rise (Bhuiyan and Dutta, 2012).

Using hydrodynamic and transport models a study (Bhuiyan and Dutta, 2011) carried out focusing on the salinity impact due to sea level rise on rivers of Ganges River basin of Southwest region. Results showed that sea level rise of 59 cm will increase salinity at Mongla and Nalianala station by 1.4 and 0.8 ppt. But, if minimum flow of 100 m^3/s and 10 m^3/s could be maintained at the Gorai Railway Bridge and Garaganj station, it would restrict the salinity at Mongla up to a maximum of 14.8 ppt. Similarly, maintaining minimum flow of 5 m^3/s at Jhikargacha would restrict the salinity at Nalianala up to 20.6 ppt.

Another study (Mirza and Sarker, 2005) investigated the empirical relationship between the flow of the Ganges and the Gorai Rivers and salinity of southwestern part. The study focuses on the Ganges river flow that affects southwestern part, giving emphasize to the Gorai river flow and its changes during pre and post of Farakka Barrage. The discharge requirements resulting from the analysis indicated that in order to keep salinity below either of the threshold limits at Khulna, it is required that April has the highest discharge of 240 m3/sec and 158 m^3/s as opposed to the current 52 m^3/s. The analysis demonstrates the requirement of increased flow for the Ganges River at the Hardinge Bridge by as much as 1,844 m^3/s over the 1,044 m^3/s (Mirza and Sarker, 2005).

Khan and Kamal, (2014) assessed the current condition, future projections on Water Availability in the Ganges coastal zone. The present condition of salinity intrusions and availability of water are analyzed based historical data and field measurements on salinity, water flow, water level and applying numerical modelling technique (MIKE 11). In case of 22cm sea level rise, salinity remains within 2ppt in the low saline zone in Lower Meghna River (Khan and Kamal, 2014).

There are few studies that have brought the surface water salinity issue although the main focus of these studies is different (Nobi and Gupta, 1997); (Mirza, 1998); (Wahid et al, 2006).

It has been observed that all these studies address salinity issue from the perspective of either reduced discharge or sea level rise or both. These studies described present conditions of salinity and then presented predicted scenarios of the concerned situation (discharge and SLR). Some of them proposed some measures and recommendations to control salinity intrusion based on the results.

2.3. Storm Surge Induced Salinity

The coastal zone of Bangladesh is exposed to the risk of tropical cyclones in the pre-monsoon and post-monsoon seasons, with the associated risk of storm surges in areas close to the coast (Brammer, 2014). Storm surge induced salinity is a vital factor to assess salinity hazard as impacts of surge in Bangladesh accounted 40% of damage among the globe (Murty and El-Sabh, 1992). On average, more than 14 severe cyclones are generated in the Bay of Bengal in every ten years (IWM, 2002) and a severe cyclone strikes the country in every three years (GoB, 2009); (Rezaie, 2015). “In 2004, the United Nations Development Programme (UNDP) ranked Bangladesh the number one nation at risk for tropical cyclones and number six for floods” (Luxbacher and Uddin, 2011).

The coastal areas and off-shore islands of Bangladesh are low lying and very flat (Khan, 2013). The country’s topography is extremely low and flat with two-thirds of its land area less than 5 m above sea level (Dasgupta, 2011). A funnelling coast line reduces the width of storm induced waves and increases the height (Khan, 2013). Also, the fact that the coasts are situated at right angles in the northern corner of the Bay of Bengal causes higher storm induced waves compared to a straight coast line (Flierl and Robinson, 1972). Cyclone SIDR (November 2007) and Cyclone AILA (May 2009) provide recent examples of devastating storm-surge in Bangladesh that greatly affected the life, livelihood and ecosystem of affected area due to prolong exposure of salt water. In 2007, Cyclone SIDR, a 10-year return period cyclone (Dasgupta et al., 2010), (Dastagir, 2015), (Hossain, et al., 2008) with an average wind speed of 223 km per hour resulted in 4,234 casualties and 55,282 injuries (EMDAT –CRED, 2012) and livelihoods of 8.9 million people were affected and damages and losses from Cyclone SIDR totaled to US$1.67 billion (GoB, 2008).

Numerical models were developed for simulating storm surges in the Bay of Bengal especially along the Bangladesh coast by many scientists. Several notable numerical modeling works have developed to model the cyclone and predict the accurate information on the height and location of peak surge along the coastline (Das, 1972); (Dube et al., 1985); (Ali, 1996); (Dasgupta et al, 2010) (Sakib et al, 2015). Similarly, Das et al., (1974), (Qayyum, 1983), Johns and Ali (1980), Ghosh et al., (1983), Dube et al., (1985), Murty et al., (1986), Flather and Khandaker (1987), Abrol (1987), and Katsura et al., (1992), Ali, (1996), Ali (1999), (Unnikrishnan et al. 2011), Dasgupta et al., (2011), Ali et al., (2007) etc. are also notable works on cyclone surge in Bangladesh coast.

However, none of these studies focused on salinity intrusion caused by storm surge rather focus was on flooding and damage caused by surge water. Only Akter et al., (2016) approached on the idea of modelling salinity intrusion caused by storm surge.

2.4. Parameters Governing Salinity Distribution in Estuaries

Salinity hazard is generally assessed by using the magnitude of salinity. The rate of water exchange between an estuary and the open sea plays a critical role in controlling the chemical (salinity) process of an estuary (Yuan et al., 2007). Warner et al., (2005) stated that estuarine salinity structure is a result of the interplay between the buoyancy flux from riverine inflow, advection by tides and the estuarine circulation, and mixing. Several studies on salinity intrusion remarked that salinity intrusion mainly expressed as the function of intrusion length and the longitudinal distribution of salinity that depends on estuary geometry, tidal characteristics and fresh water flow (Savenije, 1993); (Lerczak et al., 2006).

River discharges determine the volume of freshwater in an estuary and the distribution of the salinity (density) field. They will therefore determine the magnitude of the salinity gradients along the axis of the estuary. The influence of freshwater discharge on estuarine circulation is quite important (Kuijper and Van Rijn, 2011); (Dasgupta et al., 2014). It will produce seasonal variability in flow and salinity fields throughout the estuary. Different study on salinity intrusion in estuaries came along with intrusion length as it is important parameter without which salt intrusion extent cannot be measured (Kuijper and Van Rijn, 2011); (Bashar and Hossain, 2006); (Savenije, 1993). Residence time, on the other hand, is an important parameter, representing the time scale of the physical transport processes of saline water in estuaries (Bolin and Rodhe, 1973; Zimmerman, 1976; Takeoka, 1984; Duarte and Vieira, 2009; Li, 2010). Because it predicts the time taken to rid a salt mass from a specific location, it can be used as an indicator of ecosystem health too (Yuan et al, 2007; Miller and McPherson, 1991). The definition of residence time and its use varies widely (Yuan et al, 2007). This research uses the definition which states that the residing time taken by salt mass of particular concentration within the estuary that exposes estuaries to that particular salt concentration (adapted from Luketina, 1998).

Residence time is a new concept in Bangladesh coast and no study has addressed it yet. Braunschweig et al (2003) discussed different method of estimating residence time and importance of it by being an indicator both for pollution assessment and for ecological processes. The study developed a hydrodynamic model coupling transport model which quantified residence time by dividing estuary in boxes (Braunschweig et al, 2003). In a somewhat similar study Luketina (1998) showed different methods to calculate residence time though the focus of the study was into the modification of traditional tidal prism model. Rynne (2016) developed a transport model to quantify residence time based on tidal cycles for a pollutant. Yuan et al., (2007) used an integrated hydrodynamic dispersion model to predict the average residence time for salinity value in the Mersey Estuary, UK for various tidal level and freshwater discharge conditions. They have concluded that when the tidal range and freshwater discharge are both small, then the local tracer residence time in the upper part of the estuary can be significantly longer than the values predicted for the middle and lower reaches of the estuary. Another study on Westerschelde estuary (Netherland) calculated residence time of salinity using a simple compartment model focusing on dispersion coefficient and its relation with freshwater flow (Soetaert and Herman, 1995). In another study, water exchange and residence time are calculated for 31 small Danish estuaries to assess the spatial variability of estuarine processes and biogeochemical properties (Rasmussen and Josefson, 2002). The study identified the uncertainty of the residence time estimates by using three different model types and remarked that models may thus supplement one another for making quantitative variability between the estuaries (Rasmussen and Josefson, 2002). Warner et al. (2010) investigated the processes that influence residence time in a partially mixed estuary using a three-dimensional circulation model. They found that the residence time is a strong function of the time of release (spring vs. neap tide) and the along-channel location.

From these studies it can be summarized that salinity intrusion depends on availability of upstream discharge, tidal forcing, amount of salt water in flood tide, salinity magnitude, intrusion length and residence time. This research incorporates these governing parameters to develop a salinity hazard assessment index.

2.5. Hazard Assessment Index

Tingsanchali and Karim (2005) had assessed flood hazard and risk in the southwest region of Bangladesh. The maximum flooding depths at different locations in the rivers and floodplains were determined. Flood durations were determined by using satellite images of the observed flood in 1988, which has a return period close to 100 years. Flood hazard assessment was done considering flooding depth and duration. By dividing the study area into smaller land units for hazard assessment, the hazard index (examined four sets of indices value for depth and duration) and the hazard factor for each land unit for depth and duration of flooding were determined that is represented by a weight of value 1.0 (assigned the weight of 0.5 for depth and 0.5 for duration). From the hazard factors of the land units, a flood hazard map, which indicates the locations of different categories of hazard zones, was developed.

Gaňova et al., (2014) had studied on flood hazard assessment in Eastern Slovakia using Multi-Criteria Analysis (MCA) specifically Ranking Method (RM), Analytical Hierarchy Process (AHP) and Geographical Information System (GIS). The authors have selected soil type, rainfall, land use, size of watershed and slope as factors affecting flood hazard. Then ranking method was applied to find the most and least important factors and rank sum method to give them weightage. Hazard index was calculated by multiplying their corresponding weight and criteria value. Using AHP, 15 river stations were assigned weightage considering the hazard affecting factors.

Another similar flood hazard study was conducted by Kazakis et al (2015) at Rhodope–Evros region, Greece using an index-based approach and AHP. To identify the Flood Hazard Index (FHI), seven parameters were selected namely flow accumulation (F), rainfall intensity (I), geology (G), land use (U), slope (S), elevation (E) and distance from the drainage network (D) or in short, the initials of these criteria gave the name to the developed method as “FIGUSED”. AHP was used to find their relative weightage.

Hossain (2013) had approached to formulate a dimensionless flood hazard index through developing an equation, incorporating parameters associated with flood hazard. Based on the hazard index, hazard map was presented for the Haor basin of Sylhet region of Bangladesh.

Among the hydrological natural hazards, draught has predefined index value to assess the draught condition. One of the most widely used drought indices is the Standardized Precipitation Index (SPI) that was designed by McKee et al. (1993), (Tsakiris et al., 2007). SPI is based on the consideration that each component of a water resources system reacts to a deficit in precipitation over different time scales. Tsakiris et al., (2007) proposed another index to assess draught hazard named as Reconnaissance Drought Index (RDI) which is based both on precipitation and on potential evapotranspiration. Based on the SPI, He et al., (2011) investigated draught hazard by the Drought Hazard Index (DHI) that integrates the character of drought intensity and drought occurrence at 3-month time scale in China at a 10 km×10 km grid-cell scale using a GIS-based drought hazard assessment model, which was constructed by using 3-month Standard Precipitation Index (SPI). As the study focuses on draught impact on agriculture, hence 3-month time scale was considered for calculation. Standard Precipitation Index (SPI) was used to define draught condition and to calculate DHI.

There is also an index for river bank erosion hazard assessment that is called Bank Erosion Hazard Index (BEHI) (Rosgen, 2001). BEHI is a semi-quantitative multi-metric index for estimating bank erosion potential in streams and is a cumulative score of five discrete variables that is comprised of estimates and/or direct measurements of the bank height/bankfull discharge height (i.e., maximum height of water at bankfull discharge), the ratio of rooting depth/bank height, root density, bank angle, and the percent of surface protected by vegetation (Rosgen, 2001), (Simpson et al., 2014). Thakur et al., (2012) studied river bank erosion hazard focusing on finding major river morphological parameters and using cross-sections approach in GIS to map spatio-temporal changes in Ganga river. Based on morphometric parameters, such as, sinuosity, braided index, and percentage of the island area to the total river reach (for the year of 1955, 1977, 1990, 2001, 2003, and 2005) from LANDSAT and IRS satellite images, erosion hazard condition was assessed.

Till now, as per the available research sources, nowhere in the world has developed salinity hazard index to assess surface water salinity hazard.

CHAPTER 3

STUDY AREA

3.1. Introduction

As surface water salinity concerns all the coastal areas along the Bangladesh coast, the coastal areas are selected as study area in this study. The coastal zone of Bangladesh is marked by morphologically dynamic river network, sandy beaches and estuarine systems. All the rivers and estuaries in the coastal zone receive freshwater from the Ganges-Brahmaputra-Meghna river systems (Rezaie, 2015). Coastal zone of Bangladesh is known as the Ganges-Brahmaputra-Meghna delta (GBM delta) which is the largest tide dominated delta of the world (Goodbred and Saito, 2012) and acts as the combined outfall of GBM basins through which all the rivers/ estuaries of the basins discharge into the Bay of Bengal.

3.2. Location and Administrative Settings

Coastal zone of Bangladesh is in the southern part of the country facing the Bay of Bengal. The coastal zone comprises 19 administrative districts out of 64 districts encompassing a land area of 47,201 km^2 (32% of total area of the country) constituting 28 percent of the population of Bangladesh (Islam, 2004); (Islam *et al*., 2006). Coastline is 710 km long, which lies along the Bay of Bengal (Karim & Mimura, 2008).

3.3. Geomorphology and Estuary Classification

Based on geomorphologic and estuarine characteristics, the estuarine system of coastal zone is divided into three distinct systems, namely the Western Estuarine System (WES), Central Estuarine System (CES) and Eastern Estuarine System (EES) as shown in Figure 3.1 (Karim & Mimura, 2008); (Rahman *et al*, 2013); (Haque *et al*, 2016).

Eastern Estuarine System (EES)

Eastern Estuarine System (EES) is consisted of Lower Meghna, Tentulia and Lohalia in one hand and estuaries of Chittagong region namely Feni, Little Feni, Karnafuli, Halda, Sangu, Matamuhuri estuaries in other hand. EES is separated by Buriswar estuary in the central border and situated along the Chittagong coastline. The very active Meghna estuary lies in the region. The combined flow of 3 mighty rivers-the Ganges, the Brahmaputra, and the Meghna (commonly known as the GBM river systems and ranked as one of the largest river systems in the world)—discharges through the Lower Meghna into the northeastern corner of the Bay of Bengal (Ali, 1999). Meghna-Tentulia estuaries are the most active one, and continuous processes of accretion and erosion are going on here. These estuaries change courses due to various morphological reasons. The coastal line of this region is thus highly broken and consists of a series of islands (formed by sediment deposits). However, in Chittagong region, a continuous strip of sand runs from Cox’s Bazar to form a long beach (Sarker, 2012). The region is regular and unbroken. It is protected with sea coast by mud flats and submerged sands (Sarker, 2012). The region has a regular shape that submerged during flood tide and reappear during ebb time. This coastal region is known as Pacific type coast.

Central Estuarine System (CES)

Central Estuarine System (CES) is consisted by Buriswar, Bishkhali and Baleswar estuaries. CES is bounded by Tentulia estuary in the east and Sundarban in the west. The flow from Lower Meghna enters into the CES through 3 spill channels of Upper Meghna. CES also receives flow from Padma river through the Arial Khan river. The funnel shaped apex of the Bay of Bengal is relatively shallow near outfall of CES and the channels flowing into the Bay change their course rapidly (Sarker, 2012). This estuarine system experiences the most disastrous effects of tropical cyclones and storm surges in the world and is very vulnerable to such calamities (Ali, 1999).

Western Estuarine System (WES)

Western Estuarine System (WES) includes the Rupsha, Passur, Shibsha, Arpanghashia, Malancha and Sundar-Jamuna estuaries. WES is separated from CES by the Baleswar estuary in the east. The Gorai-Noboganga River is the only source of freshwater flow in the WES region. The western part, also known as the Ganges tidal plain, comprises the semi active delta and is crisscrossed by numerous channels and creeks of the estuaries of WES. The topography is very low and flat. The region of WES is covered by the largest mangrove forest of the world, the Sundarban. Tidal range is high in this region and due to low upstream river discharge in dry season, WES faces relatively high salinity intrusion compared to other regions of Bangladesh coast.

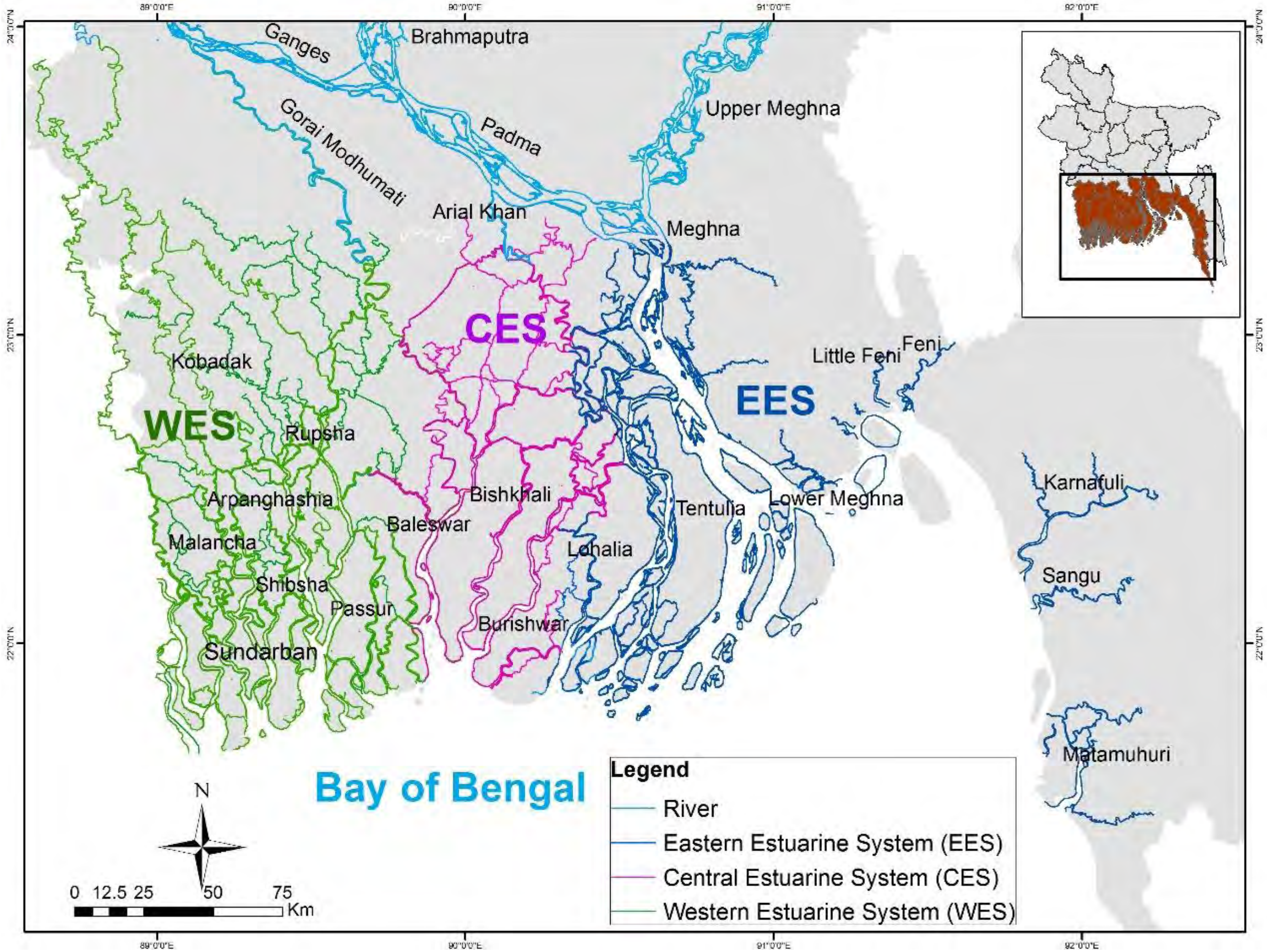


Figure 3.1: Estuarine systems of Bangladesh coastal zone

For analysis purpose in this study, EES is further sub-divided into EES and CtgES (Chittagong Estuarine System) (Figure 3.2) as estuaries of Chittagong region represents separate hydrologic characteristics than other estuaries of EES. In this study, EES consisted of Meghna, Tentulia and Lohalia estuaries whereas, CtgES consisted of estuaries of Chittagong region that are Little Feni, Feni, Karnafuli-Halda and Sangu estuaries (Figure 3.2). Estuaries of Chittagong region are flashy in nature and flash flood is a common phenomenon in these estuaries due to heavy rainfall upstream. Tidal characteristics of estuaries of CtgES is also different than other estuaries of EES (Akter and Ali, 2012), (Sumaiya, 2017).

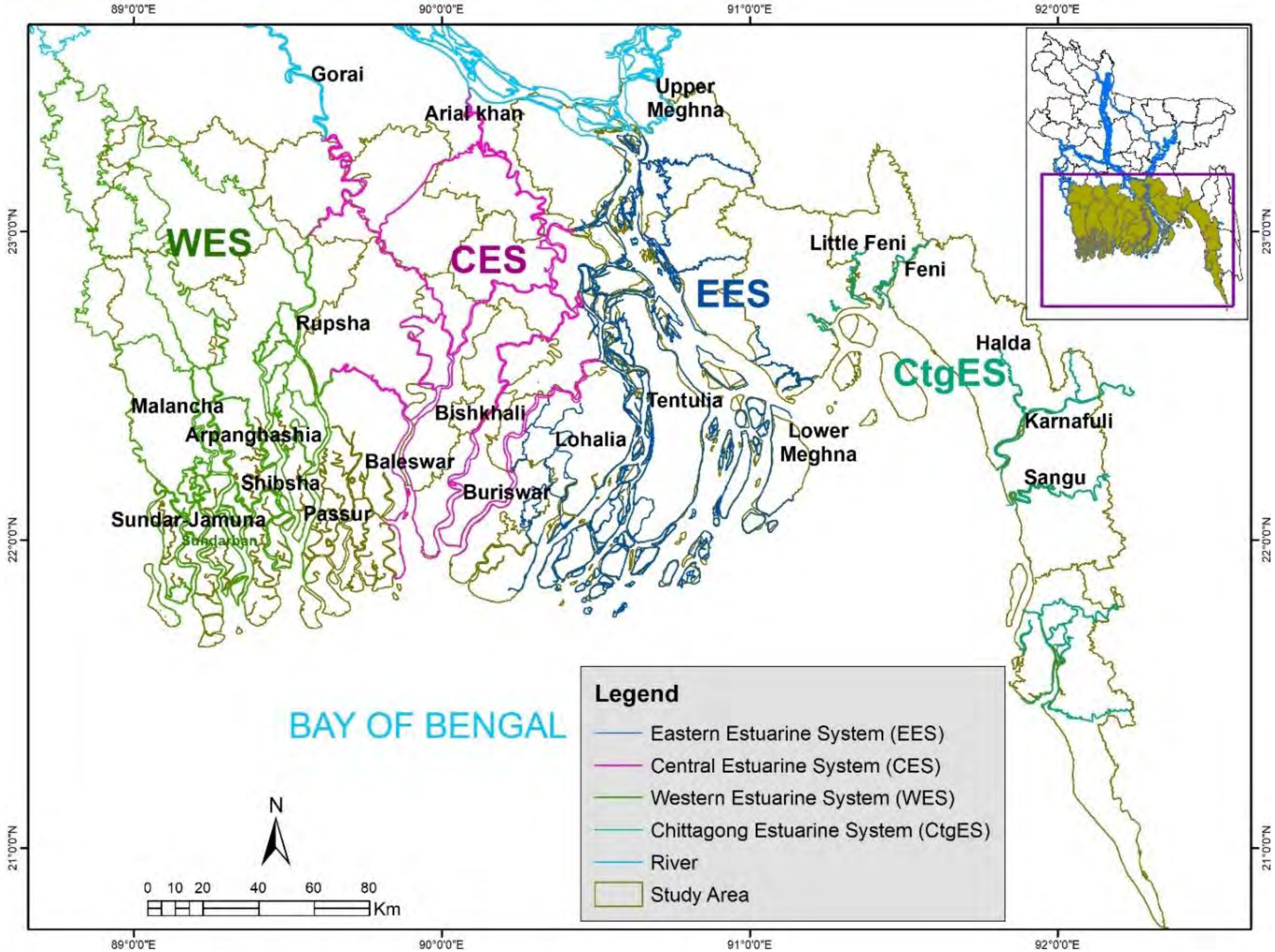


Figure 3.2: Study Area

3.4. Tidal Flow Dynamics in the Study Area

The effect of tides is manifested in a regular alternation of rise and fall of the water level of the sea and the estuarine/tidal channels and creeks. The flow distribution in the study area is determined by the combined action of tides and fresh water flow. Tides in the coastal and estuarine areas of Bangladesh are semi-diurnal in nature with two successive tidal cycles per lunar day of 24 hours and 48 minutes duration and each cycle having a period of 12 hours 24 minutes (Komol, 2011). The tides originate in the Indian Ocean and propagates faster along the western side of the Bay of Bengal. In general, the tidal range decreases gradually growing from the east to west in the Meghna estuary

(MES, 2001). The amplitudes of the two cycles differ slightly. Over a longer term, a fortnightly variation in amplitude between spring and neap tides is also evident, with spring tide amplitudes approximately 2.5 to 3 times higher than the neap tide (BIWTA, 2016). The high tide during summer rises up to 1.3 meter above the general ground level (Haque, 2006).

Annual maximum tidal range for the year 2000 showed that tidal ranges vary significantly along the coast (Sumaiya, 2017). It has been found that tidal range follows an increasing trend from the south central to the south eastern part of Bangladesh coast and the highest range is found at the mouth of the Meghna estuary in Sandwip Channel (Sumaiya, 2017). The Lower Meghna is meso-tidal, with tidal range of 2 to 4 m (Hussain *et al*, 2012). It was also observed that throughout the year a counterclockwise circulation (residual circulation) exists in the Meghna Estuary (Hussain *et al*., (2012, 2009a and 2009b)). In the western part of the coastal area of Bangladesh, the average tidal range is approximately 1.5 m (BIWTA, 2016). On the east coast of the Sundarbans, the highest tide could inundate lands up to a depth of 2.0 meter (Haque, 2006).

3.5. Surface water Salinity condition in the Study Area

Surface water salinity condition along the Bangladesh coast varies spatially and seasonally depending on availability of freshwater from upstream rivers and downstream tidal forcing (Dasgupta et al, 2014). Salinity is the minimum in monsoon season (July-September) when river discharge is at its peak. Salinity starts to increase from post monsoon (November-December) to reach at the maximum in dry season (January-May) (Dasgupta et al., 2014), (Clarke et al., 2015). Salinity is comparatively low in EES and highest in WES as well as in CtgES (Dasgupta et al., 2014). In dry season tidal effect is very strong and due to flat topography in the south central and the western region, salinity intrudes through the main estuaries of the Tentulia, the Lower Meghna, the Baleswar, the Bishkhali, the Buriswar and the Rupsha-Passur-Shibsha systems (Dasgupta et al., 2014). Studies suggest that salinity intrusion is accelerating in recent years through these estuaries and becoming one of the major concern for the people living in coastal region (Dasgupta et al., 2014).

CHAPTER 4

METHODOLOGY

4.1. Introduction

Salinity hazard is a serious concern for coastal area of Bangladesh. To assess the hazard, this chapter presented a theoretical approach incorporating the driving parameters of salinity intrusion and formulation of required equations. This chapter also describes model development, scenarios and calibration of model.

4.2. Driving Parameters

Salinity intrusion is associated with tidal motion in the estuary as tides are the primary source of energy for turbulent mixing of fresh water coming from upstream and salt water entering from ocean within estuaries (Ippen and Harleman, 1961). Saline water intrusion through the estuaries and its longitudinal distribution are governed by several parameters (Melo et al, 2014); (Bashar and Hossain, 2006). Salt water intrusion decreases with increasing freshwater discharge (Bashar and Hossain, 2006). Velocity is related with salinity intrusion as higher the flood tide velocity, the more salt water will be intruded inland (Bashar and Hossain, 2006); (Savenijie, 1993). Tidal excursion is important because larger the tidal excursion path, the larger the salt intrusion length at high water slack (Bashar and Hossain, 2006). To add to, residence time of salinity depicts the residing time taken by salt mass of concentration within the estuary that exposes estuaries to particular salt concentration (Sheldon and Alber, 2002); (Wang and Kuo, 2004); (Takeoka, 1984).

For this research, dominant parameters for salinity intrusion are selected as: salinity magnitude, upstream river discharges (Q), sea water level (WL), velocity (ν), tidal prism (P), tidal excursion (TE), and residence time (RT). Tidal prism (P) and sea water level (WL) are expressed through RT as the equation of RT incorporates them.

Given the dominant parameters, would not represent the salinity hazard as each one of them affects the salt transport mechanism differently and differs by dimension as well as unit wise. Hence, there should be an equation that would represent these different dominant parameters together in a way so that the equation does not violate the physical process of the salt transport mechanism and at the same time, mathematically correct. To do so, an equation was developed combining all the dominant parameters in a non-dimensional way. This equation which is named as 'Non Dimensional Index for Salinity (NDIS)' will quantify salinity hazard by combining all the driving parameters of salinity intrusion in an estuary. Formulation of NDIS will be described in this chapter too.

4.2.1. Tidal Excursion (TE)

Tidal excursion is the distance travelled by a water parcel within a tidal cycle (Savenijie, 1993); (Savenijie, 2012). It moves inland during flood tide and moves out during ebb tide. Tidal excursion is a form of horizontal tidal range, which is the integral over time of the tidal velocity between the two moments of slack: low water slack (LWS) and high water slack (HWS) (Savenijie, 1993); (Savenijie, 2012). By denoting velocity as v and time as t, we can define Tidal Excursion by Equations (4.1) and (4.2):

$$Tidal\ Excursion\ during\ Flood\ Tide, TE_{flood} = \int_{LWS}^{HWS} vdt \ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

$$Tidal\ Excursion\ during\ Ebb\ Tide\ TE_{ebb} = \int_{HWS}^{LWS} vdt \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

To calculate the maximum distance travelled by salt water within a tidal cycle, only flood tide was considered. For salinity intrusion process, ebb tide is not important rather the highest intrusion distance during flood tide is needed to assess the hazard condition. In this study, the maximum intrusion length during flood tide is named as TE. The basic equation to calculate TE is:

$TE = \int vdt \ldots\ldots\ldots\ldots\ldots$ (4.3); where maximum intrusion length (TE_{max}) corresponds to maximum velocity magnitude (v_{max}) during flood tide.

4.2.2. Development of an analytical model to compute Residence Time (RT)

Simple tidal prism models to transport pollutants in well-mixed estuaries were used and discussed in most text books on estuaries because of its appeal of being a model with simplicity (Luketina, 1998). Simple tidal model is defined in Cameron and Pritchard (1963) as that 'An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage'. However, there are several flaws in the logic behind the models developed using simple tidal prism theory which was pointed out by Luketina (1998) and a more theoretically correct simple tidal prism model is derived (Luketina, 1998). This research adapted the method of Luketina (1998) to develop the analytical model of residence time of salinity.

The derivation of equation by Luketina (1998) started by assuming a steady river inflow (Q) where,

V = Low tide volume

Q = River inflow

Q_i = Instantaneous flow between estuary and ocean

T= Tidal period

t = Instantaneous time

The continuity equation for an estuary is given by:

$\frac{dP_i}{dt} = Q - Q_i$ ……….. (4.4);

Here, P_i depicts instantaneous tidal prism. The tidal prism is stated as the volume of water contained in an estuary between the low and high tide levels (Luketina, 1998).

Tidal prism & tidal amplitude is varying sinusoidally with period T and can be expressed by Equation (4.5).

$P_i = \frac{P}{2}\left\{\sin\left(\frac{2\pi t}{T}\right) + 1\right\}$------------(4.5)

Where, P is the tidal prism (which is assumed to be tidal storage for this particular research) & the tidal amplitude is assumed to vary sinusoidally with period T.

[Note: the form of equation is such that high tides occur at t= (n+0.25)T & low tides at, t= (n+0.75)T ; n is an integer (Luketina, 1998)]

Substituing Equation (4.5) into Equation (4.4),

$$\frac{d[\frac{P}{2}[\{\sin\left(\frac{2\pi t}{T}\right) + 1\}]}{dt} = Q - Q_i$$

$$\Rightarrow \frac{P}{2}\cos\left(\frac{2\pi t}{T}\right) \times \frac{d}{dt}\left(\frac{2\pi t}{T}\right) = Q - Q_i$$

$$\Rightarrow \frac{P}{2} \times \frac{2\pi}{T}\cos\left(\frac{2\pi t}{T}\right) = Q - Q_i$$

$$\Rightarrow \frac{\pi P}{T}\cos\left(\frac{2\pi t}{T}\right) = Q - Q_i$$

$$\Rightarrow Q_i = Q - \frac{\pi P}{T}\cos\left(\frac{2\pi t}{T}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.6)$$

The change from ebb to flood flow and flood to ebb flow occur when Q_i is equal to zero. Equation (4.6) becomes,

$$\Rightarrow 0 \ = Q - \frac{\pi P}{T} \cos\left(\frac{2\pi t_0}{T}\right)$$

$$\Rightarrow \frac{QT}{\pi P} = \cos\left(\frac{2\pi t_0}{T}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4.7)$$

Where, t_0 specifies the time at which Q is zero. It can be expressed as:

$$t_0 \ = t_e + \ \tau_e$$

$$t_0 \ = t_f + \ \tau_f$$

Where t_e and t_f are the times at which the ebb and flood flows start in the absence of any river flow (freshwater flow) and τ_e and τ_f are the time lags introduced by the presence of river flow (freshwater flow).

For ebb tide,

starting time: $t_e + \ \tau_e$ and finish time: $t_f + \ \tau_f$

$$\text{Duration: } t_f + \ \tau_f - t_e - \ \tau_e$$

$$= \tau_f - \tau_e + (t_f - t_e)$$

$$= \frac{T}{2} + \tau_f - \tau_e \ \ ; here \ [t_f - t_e = \frac{T}{2}]$$

For flood tide,

starting time: $t_f + \ \tau_f$ and finish time: $T + t_e + \ \tau_e$

$$\text{Duration: } T + t_e + \ \tau_e - t_f - \ \tau_f$$

$$= T - (t_f - t_e) - \tau_f + \tau_e$$

$$= T - \frac{T}{2} - \tau_f + \tau_e$$

$$= \frac{T}{2} - \tau_f + \tau_e \ \ \ ; here \ [t_f - t_e = \frac{T}{2}]$$

Now, substituting $t_0 \ = t_e + \ \tau_e$ and $t_0 \ = t_f + \ \tau_f$ into Equation (4.7)

Putting $t_0 = t_e + \tau_e$ into Equation (4.7),

$$\Rightarrow \frac{QT}{\pi P} = \cos\left(\frac{2\pi\,(t_e + \tau_e)}{T}\right)$$

$$\Rightarrow \frac{\cos^{-1}\left(\frac{QT}{\pi P}\right)}{2\pi} = \frac{t_e}{\mathrm{T}} + \frac{\tau_e}{\mathrm{T}}$$

$$\Rightarrow \frac{\tau_e}{\mathrm{T}} = \frac{\theta}{2\pi} - \frac{t_e}{\mathrm{T}} \ldots\ldots\ldots\ldots (4.8)$$

Considering, $\theta = \cos^{-1}\left(\frac{QT}{\pi P}\right)$

Same way, putting $t_0 = t_f + \tau_f$, we get from Equation (4.7),

$$\frac{\tau_f}{\mathrm{T}} = 1 - \frac{\theta}{2\pi} - \frac{t_f}{\mathrm{T}} \ldots\ldots\ldots\ldots (4.9)$$

If river flow rate increases, flood flow is delayed and vice-versa. Also, when there is no river flow, the ebb and flood flow occur for equal period of time (Luketina, 1998). Conservation of mass was applied to get the high tide salinity within the estuary. Luketina assumed that salinity in the ocean adjacent to the estuary is the same as the normal oceanic salinity value S_0. This happens when all the water that exits from an estuary on an ebb tide is advected away before the flood tide starts. In reality, some fraction of the water that enters estuary during the flood tide is made up of water that left the estuary on the previous ebb tide. This fraction of water is known as return flow factor, b. A negligible return flow factor (close to zero) can only happen if the receiving water is well flushed (Luketina, 1998).

Considering return flow factor (Luketina, 1998), the mass of salt leaving and entering the estuary on the ebb m_e and flood m_f flows are:

$$m_e = S \int_{t_e + \tau_e}^{t_f + \tau_f} Q_i dt \ldots\ldots\ldots\ldots (4.10)$$

$$m_f = bS \int_{t_f + \tau_f}^{T + t_e + \tau_e} Q_i dt + (1 - b) S_0 \int_{t_f + \tau_f}^{T + t_e + \tau_e} Q_i dt \ldots\ldots\ldots\ldots (4.11)$$

Putting Equation (4.6) into Equation (4.10),

$$m_e = S \int_{t_e + \tau_e}^{t_f + \tau_f} \left\{Q - \frac{\pi P}{T} \cos\left(\frac{2\pi t}{T}\right)\right\} dt$$

$$= S\left\{Q\,[t]_{t_e + \tau_e}^{t_f + \tau_f} - \frac{\pi P}{T}\left[\sin\frac{2\pi t}{T} \times \frac{T}{2\pi}\right]_{t_e + \tau_e}^{t_f + \tau_f}\right\}$$

$$= S\left\{Q\left[t_f + (\tau_f - t_e) - \tau_e\right] - \frac{\pi P}{T} \times \frac{T}{2\pi}\left[\sin\frac{2\pi}{T}\left(\tau_f + t_f\right) - \sin\frac{2\pi}{T}\left(t_e + \tau_e\right)\right]\right\}$$

$$= S\left\{Q\left[\frac{T}{2} + \left(T - \frac{T\theta}{2\pi} - t_f\right) - \frac{T\theta}{2\pi} + t_e\right] - \frac{P}{2}\left\{2\cos\frac{\left[\frac{2\pi}{T}(\tau_f + t_f) + \frac{2\pi}{T}(t_e + \tau_e)\right]}{2} \times \sin\frac{\left[\frac{2\pi}{T}(\tau_f + t_f) - \frac{2\pi}{T}(t_e + \tau_e)\right]}{2}\right\}\right\}$$

$$= S\left\{Q\left(\frac{T}{2} + T - \frac{T\theta}{\pi} - \frac{T}{2}\right) - \frac{P}{2} \times 2\left\{\cos\frac{\frac{2\pi}{T}(\tau_f + t_f + t_e + \tau_e)}{2} \times \sin\frac{\frac{2\pi}{T}(\tau_f + t_f - t_e - \tau_e)}{2}\right\}\right\}$$

$$= S\left\{QT\left(1 - \frac{\theta}{\pi}\right) - P\left\{\cos\frac{\pi}{T}\left(t_f + t_e + \frac{\theta T}{2\pi} - t_e + T - \frac{\theta T}{2\pi} - t_f\right) \times \sin\frac{\pi}{T}\left(\frac{T}{2} + \tau_f - \tau_e\right)\right\}\right\} \;;$$

(using the value of Equations (4.8) and (4.9)

$$= S\left\{QT\left(1 - \frac{\theta}{\pi}\right) - P\left\{\cos\pi \times \sin\frac{\pi}{T}\left(\frac{T}{2} + T - \frac{\theta T}{\pi} - \frac{T}{2}\right)\right\}\right\}$$

$$= S\left\{QT\left(1 - \frac{\theta}{\pi}\right) - P\left\{(-1) \times \sin\frac{\pi}{T} \times T\left(1 - \frac{\theta}{\pi}\right)\right\}\right\}$$

$$= S\left\{QT\left(1 - \frac{\theta}{\pi}\right) + P\sin\pi\left(1 - \frac{\theta}{\pi}\right)\right\}$$

$$= S\left\{QT\left(1 - \frac{\theta}{\pi}\right) + P\sin\theta\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (4.12)$$

Now from Equation (4.11),

$$m_f = bS\int_{t_f + \tau_f}^{T + t_e + \tau_e} Q_i\,dt + (1 - b)S_0\int_{t_f + \tau_f}^{T + t_e + \tau_e} Q_i\,dt$$

$$= bS\int_{t_f + \tau_f}^{T + t_e + \tau_e}\left\{Q - \frac{\pi P}{T}\cos\left(\frac{2\pi t}{T}\right)\right\}dt + (1 - b)S_0\int_{t_f + \tau_f}^{T + t_e + \tau_e}\left\{Q - \frac{\pi P}{T}\cos\left(\frac{2\pi t}{T}\right)\right\}dt$$

;[from Equation (4.6)]

$$= bS\left\{Q\,[t]_{t_f + \tau_f}^{T + t_e + \tau_e} - \frac{\pi P}{T}\left[\sin\frac{2\pi t}{T} \times \frac{T}{2\pi}\right]_{t_f + \tau_f}^{T + t_e + \tau_e}\right\} + (1 - b)S_0\left\{Q\,[t]_{t_f + \tau_f}^{T + t_e + \tau_e} - \frac{\pi P}{T}\left[\sin\frac{2\pi t}{T} \times \frac{T}{2\pi}\right]_{t_f + \tau_f}^{T + t_e + \tau_e}\right\}$$

$=bS\left\{Q\left[T+t_e+\tau_e-t_f-\tau_f\right]-\frac{\pi P}{T}\times\frac{T}{2\pi}\left[\sin\frac{2\pi}{T}(T+t_e+\tau_e)-\sin\frac{2\pi}{T}(t_f+\tau_f)\right]\right\}+(1-b)S_0\left\{Q\left[T+t_e+\tau_e-t_f-\tau_f\right]-\frac{\pi P}{T}\times\frac{T}{2\pi}\left[\sin\frac{2\pi}{T}(T+t_e+\tau_e)-\sin\frac{2\pi}{T}(t_f+\tau_f)\right]\right\}$

$=bS\left\{Q\left[\frac{T}{2}-\tau_f+\tau_e\right]-\frac{P}{2}\left\{2\cos\frac{\left[\frac{2\pi}{T}(T+t_e+\tau_e+t_f+\tau_f)\right]}{2}\times\sin\frac{\left[\frac{2\pi}{T}(T+t_e+\tau_e-t_f\pm)\right]}{2}\right\}\right\}+(1-b)S_0\left\{Q\left[\frac{T}{2}-\tau_f+\tau_e\right]-\frac{P}{2}\left\{2\cos\frac{\left[\frac{2\pi}{T}(T+t_e+\tau_e+t_f+\tau_f)\right]}{2}\times\sin\frac{\left[\frac{2\pi}{T}(T+t_e+\tau_e-t_f\pm)\right]}{2}\right\}\right\}$

$=bS\left\{Q\left[\frac{T}{2}-\tau_f+\tau_e\right]-P\left\{\cos\frac{\pi}{T}\left(T+t_f+t_e+\frac{\theta T}{2\pi}-t_e+T-\frac{\theta T}{2\pi}-t_f\right)\times\sin\frac{\pi}{T}\left(T-t_f+t_e+\frac{\theta T}{2\pi}-t_e-T+\frac{\theta T}{2\pi}+t_f\right)\right\}\right\}+(1-b)S_0\left\{Q\left[\frac{T}{2}-\tau_f+\tau_e\right]-P\left\{\cos\frac{\pi}{T}\left(T+t_f+t_e+\frac{\theta T}{2\pi}-t_e+T-\frac{\theta T}{2\pi}-t_f\right)\times\sin\frac{\pi}{T}\left(T-t_f+t_e+\frac{\theta T}{2\pi}-t_e-T+\frac{\theta T}{2\pi}+t_f\right)\right\}\right\}$;[from Equations (4.8) and (4.9)]

$=bS\left\{\left[\frac{T}{2}-T+\frac{\theta T}{2\pi}+t_f+\frac{\theta T}{2\pi}-t_e\right]-P\left\{\cos\frac{\pi}{T}(2T)\times\sin\frac{\pi}{T}\left(2\times\frac{\theta T}{2\pi}\right)\right\}\right\}+(1-b)S_0\left\{\left[\frac{T}{2}-T+\frac{\theta T}{2\pi}+t_f+\frac{\theta T}{2\pi}-t_e\right]-P\left\{\cos\frac{\pi}{T}(2T)\times\sin\frac{\pi}{T}\left(2\times\frac{\theta T}{2\pi}\right)\right\}\right\}$

$=bS\left\{\left[-\frac{T}{2}+\frac{\theta T}{\pi}+\frac{T}{2}\right]-P\left\{\cos 2\pi\times\sin\frac{\pi}{T}\left(\frac{\theta T}{\pi}\right)\right\}\right\}+(1-b)S_0\left\{\left[-\frac{T}{2}+\frac{\theta T}{\pi}+\frac{T}{2}\right]-P\left\{\cos 2\pi\times\sin\frac{\pi}{T}\left(\frac{\theta T}{\pi}\right)\right\}\right\}$

$=bS\left\{Q\left(\frac{\theta T}{\pi}\right)-P\sin\theta\right\}+(1-b)S_0\left\{Q\left(\frac{\theta T}{\pi}\right)-P\sin\theta\right\}$ …………………………….(4.13)

And,

The mass of salt leaves the estuary over a tidal cycle, $\Delta m=m_e+m_f$ where, m_f possesses negative sign when salt enter the estuary during flood tide (Luketina, 1998). Hence, difference of Equations (4.12) and (4.13) gives,

$$\Delta m=S\left\{QT\left(1-\frac{\theta}{\pi}\right)+P\sin\theta\right\}-\left\{bS\left\{Q\left(\frac{\theta T}{\pi}\right)-P\sin\theta\right\}+(1-b)S_0\left\{Q\left(\frac{\theta T}{\pi}\right)-P\sin\theta\right\}\right\}$$

= $$QT\left[S\left(\frac{\theta}{\pi}+b\left(1-\frac{\theta}{\pi}\right)\right)+(1-b)S_0\left(1-\frac{\theta}{\pi}\right)\right]+(S-S_0)(1-b)P\sin\theta$$
……………(4.14)

For an estuary in steady state, $\Delta m = 0$ and Equation (4.14) changes to,

$$S=\frac{P-\frac{QT}{2}}{P+\frac{QT}{2}\left(\frac{1+b}{1-b}\right)}S_0 \quad \ldots\ldots\ldots\ldots\ldots. (4.15)$$

According to Luketina (1998), till now assumptions were for tidally averaged sense, in a steady state or equilibrium state of estuaries. This is true for salinity but not for other substances, hence he modified the model to a continuous unsteady model which incorporates additional source or sink terms. With the continuation of Equations (4.14) and (4.15) Luketina modified Equation (4.14) as follows:

$$\Delta m=\left(P+\frac{QT}{2}\right)C-b\left(P-\frac{QT}{2}\right)C-(1-b)\left(P-\frac{QT}{2}\right)C_0-QTC_R-WT+KC(V+P)T \quad \ldots\ldots\ldots\ldots(4.16)$$

where C is the high tide concentration, C_0 is the background concentration in the ocean, C_R is the concentration in the river, W is a source term of negligible volume flux within the estuary and K (s^{-1}) is decay rate.

Those assumptions of Luketina are modified in this research because only salinity is concerned here, not other substances. For considering salinity in unsteady flow condition, Equation (4.16) is modified to omit additional source or sink terms (C_R,W) as follows:

$$\Delta m=\left(P+\frac{QT}{2}\right)S-b\left(P-\frac{QT}{2}\right)S-(1-b)\left(P-\frac{QT}{2}\right)S_0+KS(V+P)T$$

In the present study, the rate of change of concentration of salinity S in the estuary is also modified from Luketina as:

$$\frac{dS}{dt}\approx\frac{-\Delta m}{(V+P)T}=\frac{1}{(V+P)}\left[b\left(\frac{P}{T}-\frac{Q}{2}\right)S-\left(\frac{P}{T}+\frac{Q}{2}\right)S+(1-b)\left(\frac{P}{T}-\frac{Q}{2}\right)S_0\right]-KS \quad \ldots\ldots\ldots(4.17)$$

For salinity K=0 within the estuary, because decay process is absent when transported substance is salinity. Equation (4.17) becomes (Luketina, 1998):

$$\frac{dS}{dt} \approx -\left[\frac{(1-b)\frac{P}{T} + (1+b)\frac{Q}{2}}{V+P}\right] S$$

Solving this for initial condition (Luketina, 1998), where S=S_i at t=0,

$S \approx S_i exp\left[-\frac{t}{RT_p}\right]$where RT_p is the partial Residence Time (partial in the sense that instantaneous high salinity value is not represented in this equation yet)

Hence,

$RT_p = -\left[\frac{V+P}{(1-b)\frac{P}{T}+(1+b)\frac{Q}{2}}\right]$…………….. (4.18)

Luketina did not consider instantaneous salinity value and considered RT_p as final residence time. This research modified RT_p to attain instantaneous salinity value. Now, introducing salinity concentration in a particular section at a particular time, we get actual residence time as,

$RT = RT_p \times \frac{S}{S_0}$ …………………..(4.19)

From Equation (4.15) we know that,

$$S = \frac{P - \frac{QT}{2}}{P + \frac{QT}{2}\left(\frac{1+b}{1-b}\right)} S_0$$

$$S = \frac{(2P - QT)(1-b)}{2P(1-b) + QT(1+b)} S_0$$

$$\Rightarrow S(2P - 2Pb + QT + QTb) = S_0(2P - QT - 2Pb + QTb)$$

$$\Rightarrow 2P(1-b)(S - S_0) = -QT(S + S_0) - QTb(S - S_0)$$

$$\Rightarrow P = \frac{-QT\left(\frac{S+S_0}{S-S_0}\right) - QTb}{(1-b)}$$

again,

$$\frac{S}{S_0}=\frac{P-\dfrac{QT}{2}}{P+\dfrac{QT}{2}\left(\dfrac{1+b}{1-b}\right)}$$

$$=\frac{\left\{\dfrac{QT\left(\dfrac{S+S_0}{S-S}\right)-QTb}{1-b}\right\}-\dfrac{QT}{2}}{\left\{\dfrac{QT\left(\dfrac{S+S_0}{S-S}\right)-QTb}{1-b}\right\}+\dfrac{QT}{2}\left(\dfrac{1+b}{1-b}\right)}$$ (putting the value of P)

$$\frac{S}{S_0}=\frac{2\left\{-QT\left(\dfrac{S+S_0}{S-S}\right)-QTb\right\}-QT(1-b)}{2\left\{-QT\left(\dfrac{S+S_0}{S-S}\right)-QTb\right\}+QT(1+b)}$$

Now, putting Equation (4.18) and the value of $\frac{S}{S_0}$ into the Equation (4.19) we get Residence Time as,

$$RT=\frac{(V+P)T}{(1-b)P+(1+b)\dfrac{QT}{2}}\times\frac{S}{S_0}$$

$$RT=\frac{(V+P)T}{(1-b)P+(1+b)\dfrac{QT}{2}}\times\frac{2\left\{-QT\left(\dfrac{S+S_0}{S-S}\right)-QTb\right\}-QT(1-b)}{2\left\{-QT\left(\dfrac{S+S_0}{S-S}\right)-QTb\right\}+QT(1+b)}$$

……………….…………….. (4.20)

Equation (4.20) represents the analytical model which is developed in this research to compute residence time of salinity.

4.3. Development of Non-Dimensional Index for Salinity (NDIS) to Assess Salinity Hazard

To date, salinity hazard is represented by salinity magnitude only (Dasgupta *et al*., 2014), (Akter *et al*. 2016), (Bashar and Hossain, 2006), Akhter *et al*, (2012). Though several studies have developed single index incorporating dominant parameters to assess flood hazard (Kazakis et al 2015), (Hossain, 2013), for salinity hazard such type of index is not yet developed that can represent the salinity hazard as a whole by a single index value. In this research, such an index is developed that can be applied to assess the salinity hazard for any coastal setting. To incorporate all the necessary variables as described in Section 4.2 (Residence Time, Tidal Excursion, Discharge, Density and Viscosity) in a single dimensionless index, dimensional analysis is conducted. To do so, Buckingham π method (Douglas *et al.*, 1995) was applied as it is the most relevant method that considers dimensionless grouping. Through this dimensional analysis, a non-dimensional index is developed (NDIS) which represents the state of salinity hazard in any coastal setting.

The initial step of developing NDIS through Buckingham π method is to list the significant variables which are dominant parameters of salinity hazard in this case and form a matrix with the dimensions of these variables. Here, to follow the basic rules of dimensional balance in Buckingham π method, Velocity (ν) was used as a proxy of tidal excursion (TE) to ensure the balance in dimensional groupings (Douglas *et al.*, 1995).

In this method, if there are n concerning variables and these variables contain m primary dimensions (M, L, T), the equation relating all the variables will have (n-m) dimensionless groups. Buckingham referred to these groups as π groups. The final equation obtained is in the form of (Douglas *et al.*, 1995).

$$\pi_1 = f(\pi_2, \pi_3, \ldots\ldots \pi_{n-m})$$

Now m number of repeating variables are selected in such a way that combining them will include all the dimensions taken to describe the system (M, L, T). Repeating variables do not have to appear in all π groupings (Douglas *et al.*, 1995).

Here for calculating NDIS,

List of variables with dimensions are:

density, $\rho = ML^{-3}$

viscosity, $\mu = ML^{-1}T^{-1}$

discharge, $Q = L^3T^{-1}$

velocity, $\upsilon = LT^{-1}$

residence time, $RT = T$

Total number of variables n= 5, Dimensions m =3

Number of non- dimensional groupings = n-m = 5-3 = 2

Let, repeating variables = ρ, υ, RT

Solutions:

$\pi_1 = \varphi\pi_2$

$\pi_1 = \mu\upsilon^a RT^b \rho^c$ …………………………… (4.21)

$[M^0L^0T^0] = [ML^{-1}T^{-1}][LT^{-1}]^a[T]^b[ML^{-3}]^c$

considering the M dimension of Equation (4.21),

$0=1+c$

or, $c= -1$

considering the L dimension of Equation (4.21),

$0= -1+a-3c$

or, $a= -2$

and considering the T dimension of Equation (4.21),

$0= -1-a+b$

or, $b= -1$

Hence, Equation (4.21) becomes, $\pi_1 = \mu\upsilon^{-2}RT^{-1}\rho^{-1}$ …………………………… (4.22)

Again,

$\pi_2 = Q\nu^c RT^d$…………………………… (4.23)

$[L^0T^0]=[L^3T^{-1}][LT^{-1}]^c[T]^d$

considering the L dimension of Equation (4.23),

$0=3+c$

or, $c= -3$

considering the T dimension of Equation (4.23), 0= -1-c+d

or, d= -2

Hence, Equation (4.23) becomes, π_2= Qν^{-3}RT^{-2} ………………… (4.24)

From Equation (4.22) and Equation (4.24),

$$\frac{\pi_1}{\pi_2} = \frac{\mu v^{-2} RT^{-1} \rho^{-1}}{Q v^{-3} RT^{-2}}$$

$$\frac{\pi_1}{\pi_2} = \frac{\mu \times v \times RT}{\rho \times Q}$$

Or, $\frac{\pi_1}{\pi_2} = \frac{\mu}{\rho} \times \frac{v \times RT}{Q}$

Or, $\frac{\pi_1}{\pi_2} = \kappa \times \frac{v \times RT}{Q}$ where, ratio of viscosity (μ) and density (ρ) refers to kinematic viscosity (κ) which is a fluid property.

Or, $NDIS = \frac{\kappa \times v \times RT}{Q}$…………………..(4.25)

NDIS shows a direct relation with kinematic viscosity (κ), Velocity (υ), Residence Time (RT) and an inverse relation with discharge (Q). As the relation is non-linear hence the high value of kinematic viscosity (κ), Velocity (ν) and Residence Time (RT) and low value of discharge (Q) does not necessarily mean that the value of NDIS will always be high and vice-versa. NDIS represents a complex interaction among all the parameters.

4.4. Model Description

The focus of this study is to calculate salinity hazard index value NDIS. To calculate the value of NDIS (Equation (4.25)) together with the value of RT, and TE (Equation (4.25), (4.20) and (4.3)), it is necessary to calculate the value of their corresponding parameters as spatial and temporal variables within an estuary. To get the values of these parameters, model simulation was needed. In this research, Delft3D open-source hydrodynamic and salt-transport model was selected to simulate salinity, discharge, velocity, tidal range and tidal periods in estuaries. Delft3D is a widely used open source numerical model suite (Lesser *et al.*, 2004; Ranasinghe et al, 2011). Delft3D-FLOW solves the continuity (Equation (4.26)), momentum equations (Equation (4.27) and (4.28)) and transport equation (Equation (4.29)) for an incompressible fluid (Broomans and Vuik, 2003). Underlying assumptions of the Delft3D model is that equation developed for shallow water and variable density is taken account in pressure terms (Deltares, 2014). The Delft3D-FLOW module solves the unsteady shallow-water equations in two (depth-averaged) dimensions. Vertical accelerations are not considered as it is assumed to be small compared to gravitational acceleration. Hence, vertical momentum equation is reduced to the hydrostatic pressure relation (Lesser, 2009). For such assumption, Delft3D-FLOW model is considered acceptable to model hydrodynamics in shallow seas, coastal areas, estuaries, lagoons, rivers, and lakes (Lesser, 2009). It aims to model flow phenomena of which the horizontal length and time scales are significantly larger than the vertical scales (Lesser, 2009). Delft3D system considers the horizontal momentum equations, the continuity equation and the transport equation for modeling salinity intrusion.

Continuity equation:

$$\frac{\delta\zeta}{\delta t}+\frac{\delta[d+\zeta)u]}{\delta x}+\frac{\delta[d+\zeta)v]}{\delta y}=0 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.26)$$

Momentum equation:

$$\frac{\delta u}{\delta t}+u\frac{\delta u}{\delta x}+v\frac{\delta u}{\delta y}-fx=-\frac{1}{\rho 0}\frac{\delta p}{\delta x}+v_v\Delta u+F_x \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.27)$$

$$\frac{\delta v}{\delta t}+u\frac{\delta v}{\delta x}+v\frac{\delta v}{\delta y}-fy=-\frac{1}{\rho 0}\frac{\delta p}{\delta y}+v_v\Delta v+F_y \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.28)$$

Salinity equation: $\frac{\partial c}{\partial t}+\frac{\partial uc}{\partial x}+\frac{\partial vc}{\partial y}=\frac{\partial}{\partial x}\left(D_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial c}{\partial y}\right)$ …………………. (4.29)

where u, v denote the velocity components in the x, y direction respectively, d means water depth, ζ free surface elevation, ρ^0 the reference density, p the hydrostatic pressure gradient, v_v vertical eddy viscosity, fx, fy are x & y components of the Coriolis forces per unit mass, F_x, F_y are turbulent momentum fluxes (Reynold"s stresses), c is salinity concentration and D_x *and* D_y are eddy diffusivity coefficients. The model equations and parameters are described in detail elsewhere (Deltares, 2014). When modeling the flow in a saline environment, the salinity concentration is considered to affect the flow through the extra forcing terms induced by the density gradients caused by salinity (Deltares, 2014).

4.4.1. Model Domain and Grid Properties

Model domain covered the three major rivers that contributed to coastal system of GBM delta (Figure 4.1). The grid size varies over the domain being 100-1700 m in ocean and 186-243m in estuaries and land. Aspect ratio (ratio of length and width of each grid) and orthogonality (cell centered cosine value) were maintained in a range that match the requirement of Delft3D flow (Deltares, 2014).

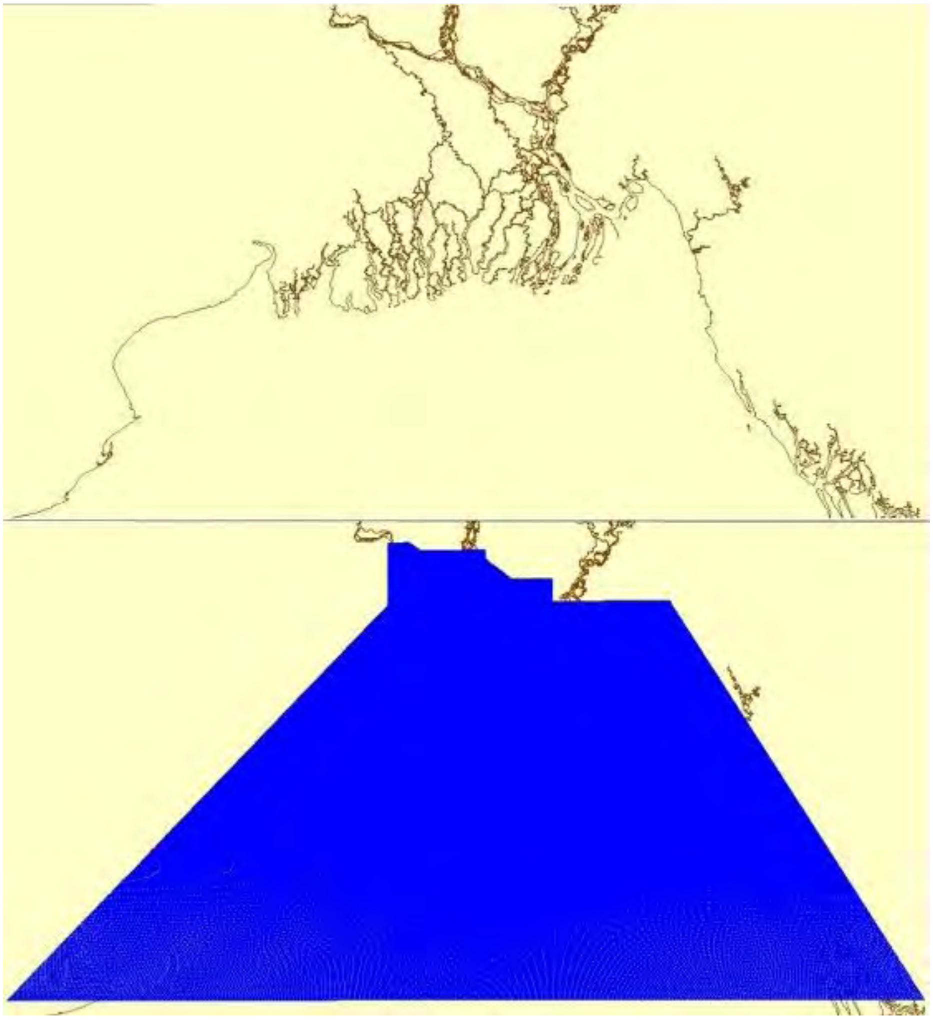


Figure 4.1: Model domain and Grid

4.4.2. Data Collection

Different kinds of data used to develop the model are collected and generated from various sources. Types of collected data, their source, temporal & spatial frequency and years of availability are described in Table 4.1.

Table 4.1 Overview of data sources of the study area

Data	Source	Unit	Temporal frequency	Spatial frequency	Yearly availability
Salinity	BWDB	Chloride concentration (salinity)	One time daily salinity value for 2/3 days in a month (Irregular: not covering all months of dry season)	Coastal rivers (varying availability)	1991- 2013
Discharge	BWDB	m^3/s	Weekly	Ganges, Bhrmaputra and Meghna rivers (station at Hardinge Bridge, Bahadurabad and Bhairab Bazar)	1972-2011
Digital Elevation Model (DEM)	WARPO	Meter, Grid size: 50 m	Not Available	Inland Topographic data	1991
Cross sections	(BWDB and ESPA)	Meter,	Not Available	Major estuaries of Bangladesh coast and estuaries of western region (ESPA)	(1995-2013) not continuous
Ocean Data	(GEBCO and NAO tide)	meter	Hourly for NAO tide	GEBCO for ocean bathymetry	NaoTide (year: 2011)

4.4.3. Boundary Conditions

The upstream boundaries were specified as measured discharges (Table 4.1) in three main rivers namely Ganges, Brahmaputra and Meghna (Figure 2). For the base condition (year of 2011), discharge data of the major rivers, i.e., at the Hardinge bridge station of Ganges, Bahadurabad station of Brahmaputra and Bhairab Bazar of Upper Meghna were used from the measurements provided by Bangladesh Water Development Board (BWDB) (Table 4.1) (Figure 4.3: yellow circles).

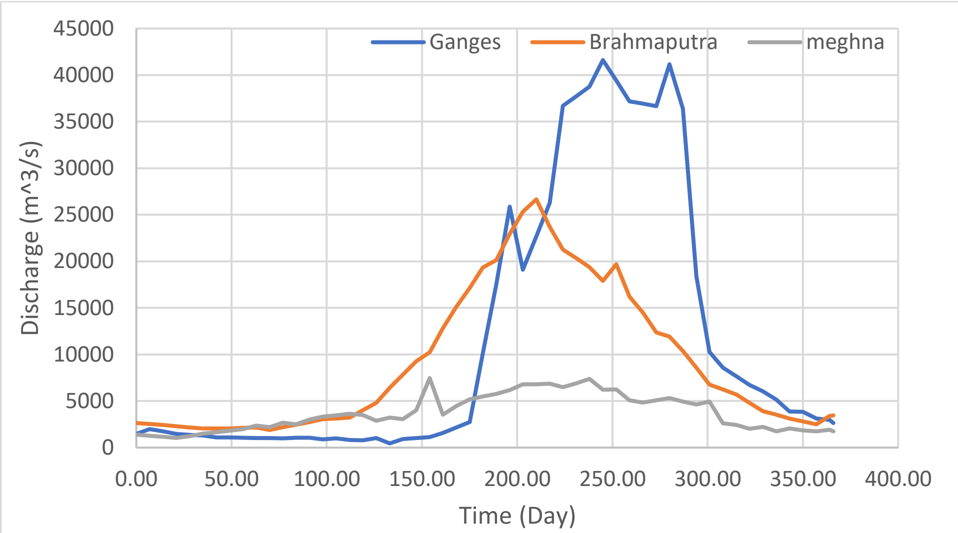


Figure 4.2: Upstream discharges at model boundaries for the year of 2011

For Karnafuli River, a model generated hydrograph following the linear interpolation method was produced based on the available secondary data (BWDB, 2006). In Chittagong region, discharge time series of eight rivers (collected from BWDB in 2016) were used for model simulation as internal discharge boundaries (Figure 4.3: red star marks). These rivers were used as internal discharge boundary. Downstream boundaries were specified as tidal water levels at the sea where tides were generated using a global ocean tide model called as ‘NAO tide’ that used Nao 99b tidal prediction system considering 16 major tidal constituents (Matsumoto et al., 2000) (Sumaiya *el al*, 2015). Figure 4.3 shows locations of upstream and downstream boundaries.

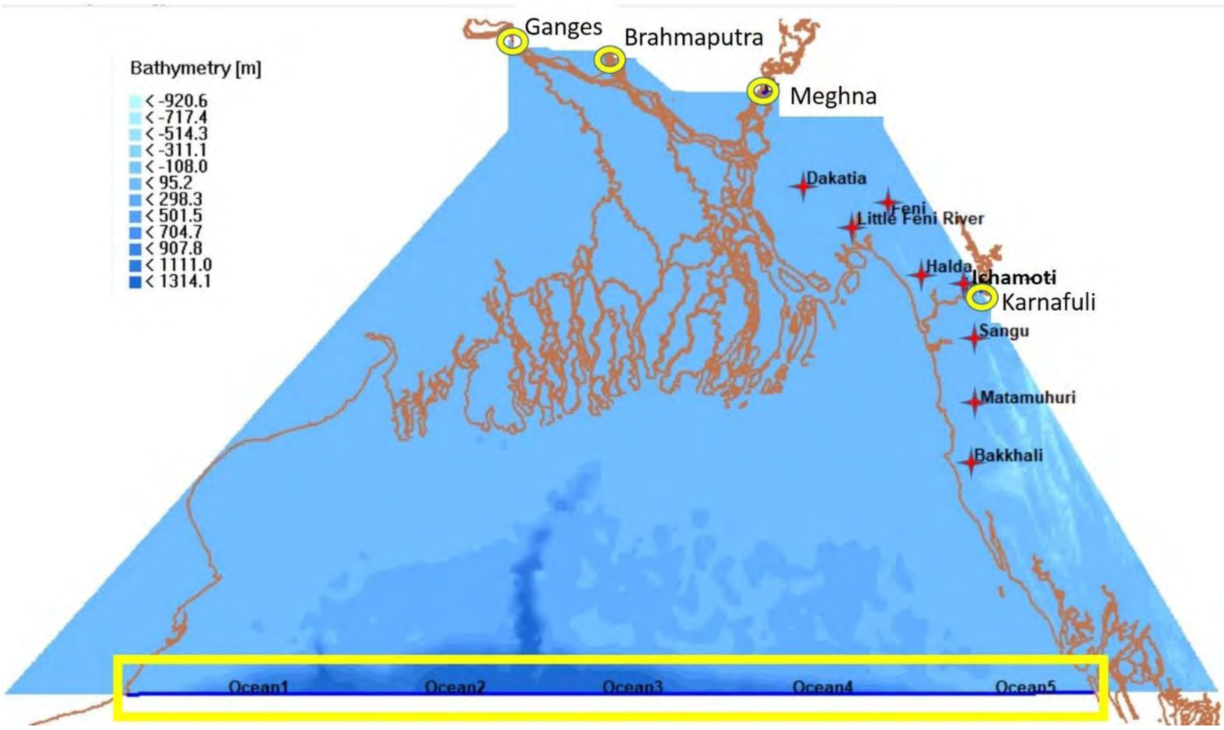


Figure 4.3: Upstream and downstream boundary locations marked in yellow color (circular shapes denotes upstream and rectangular shape denotes downstream boundary locations). The red star marks show the locations where boundaries are specified as internal boundary.

4.4.4. Bathymetry

As downstream water level boundaries in ocean, tides at the sea boundary are generated by using Nao 99b tidal prediction system for base condition (Matsumoto et al., 2000). For SLR scenario, ocean bathymetry (Bay of Bengal) was generated using the open-access bathymetry data produced by General Bathymetric Chart of the Oceans (GEBCO). The inland ground elevation of the model domain was generated by using Digital Elevation Model (DEM) collected from Water Resources Planning Organization (WARPO), Bangladesh. DEM is generated from FINNMAP Land Survey 1991 and National DEM from FAP19. Measured cross sectional data for each of the estuary at selected location, were surveyed by ESPA delta (http://www.espa.ac.uk) and DECCMA (http: //www.deccma.com) projects and used to generate bathymetry of the estuarine systems. In few locations particularly in major rivers, cross section data were provided from Bangladesh Water Development Board (BWDB). Design polder heights in the study area were collected from BWDB and were incorporated in the model (CEIP, 2013). All of these data were processed and synchronized to develop the model bathymetry (Figure 4.4).

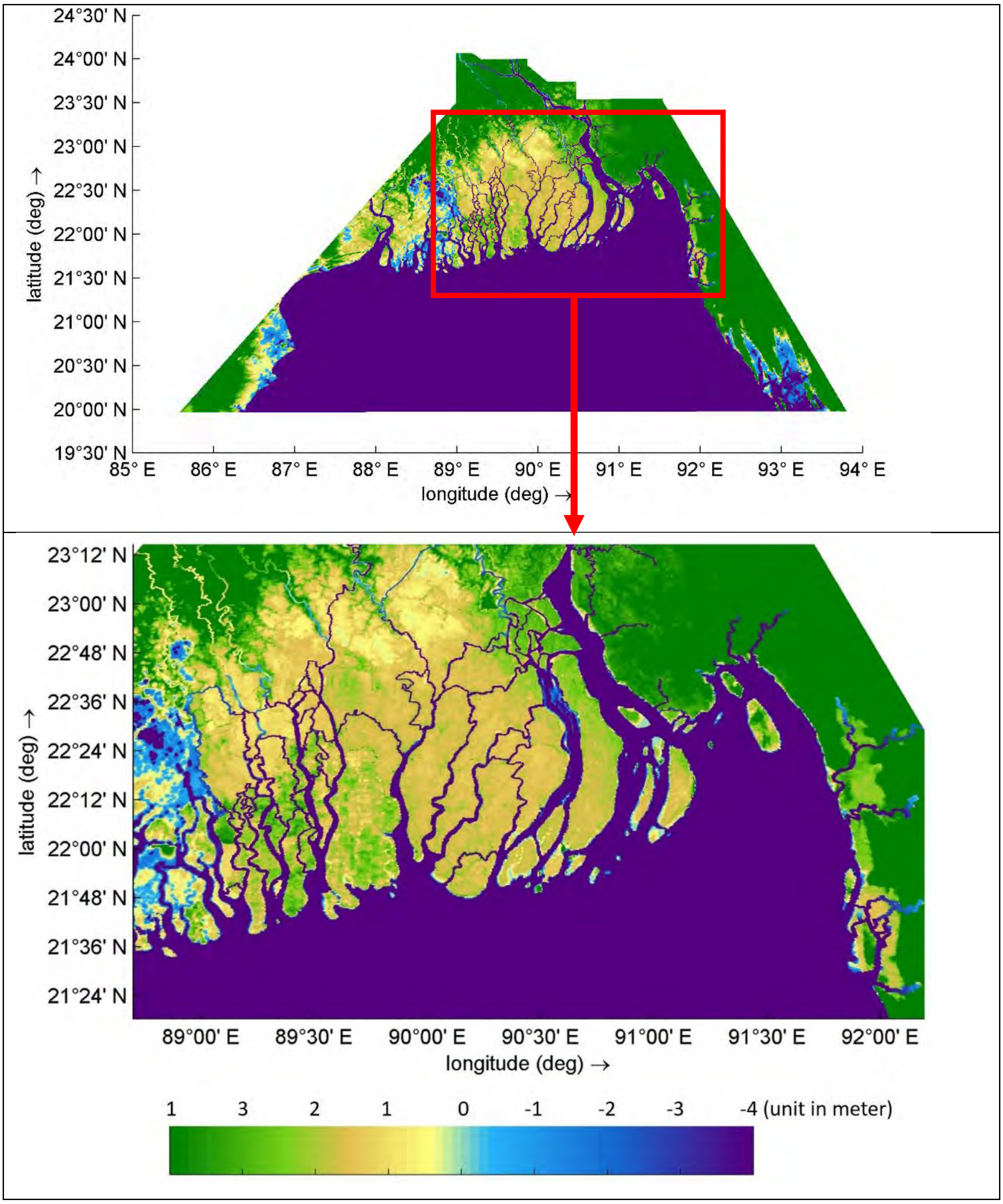


Figure 4.4: Bathymetry of model

4.5. Model Calibration and Validation

River salinity is related with upstream flow and downstream tide of ocean. For the salinity model, constant sea salinity of 35 ppt (Haque *et al*., 2016) for the Bay of Bengal was specified as sea boundary condition and for the upstream boundaries, salinities were assumed to be zero in the same location where freshwater discharge boundaries were specified.

It has been found by analyzing the historical salinity data from the year of 1997 to 2013, that 2011 possess the maximum number of observed stations for measured salinity dataset. To add to, 2011 is considered as dry year which is a crucial fact as impacts of salinity intrusion is the maximum in dry season of a dry year. Salinity intrusion is a time varying event in Bangladesh. Studies suggested that salinity generally increases from late October (post-monsoon) and reach a peak in May (pre-monsoon), with the gradual reduction in the freshwater flow (Dasgupta et al., 2014), (Mahmuduzzaman *et al*, 2014), (Khanom and Salehin, 2012). However, it has been observed through historical data analysis of maximum salinity value in observed locations (Figure 4.5) that in some observed locations, highest salinity magnitude occurred in June, especially up to first 15-20 days of June. Hence, this research includes January to June in dry season. Delft3D salinity model was calibrated using historically observed data at observed locations (Figure 4.5) for the dry season (January-June) of 2011.

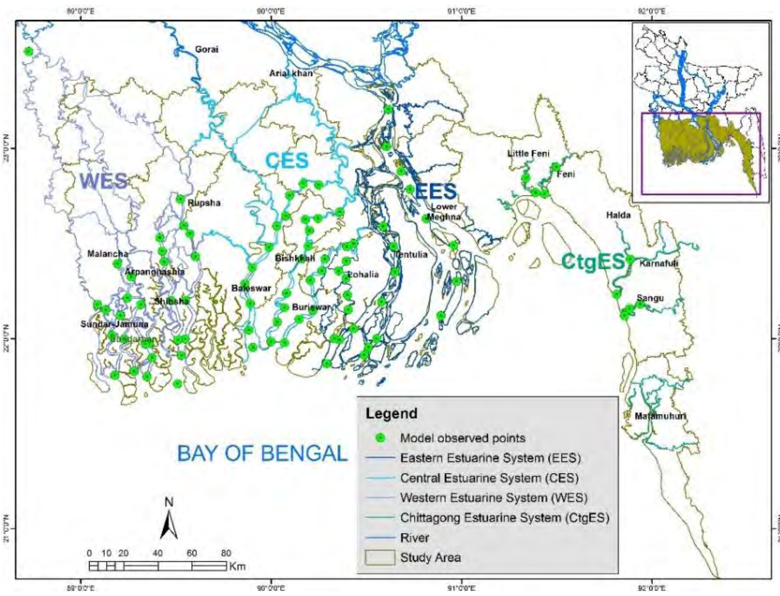


Figure 4.5: Salinity observed station used for model calibration

For model calibration, spatially variable roughness (Manning's roughness coefficient), eddy viscosity and diffusivity (D of salinity Equation 4.29) were used as calibration parameters (Figure 4.6 and Figure 4.7). In estuaries, constant roughness value of 0.025 was used but in downstream or ocean much lower roughness value is used (Figure 4.6). For calibration, the value of eddy viscosity and diffusivity within the estuaries vary by the range of 42 to 700 (approximately) and the value gradually increases from coast to deep sea (Figure 4.7).

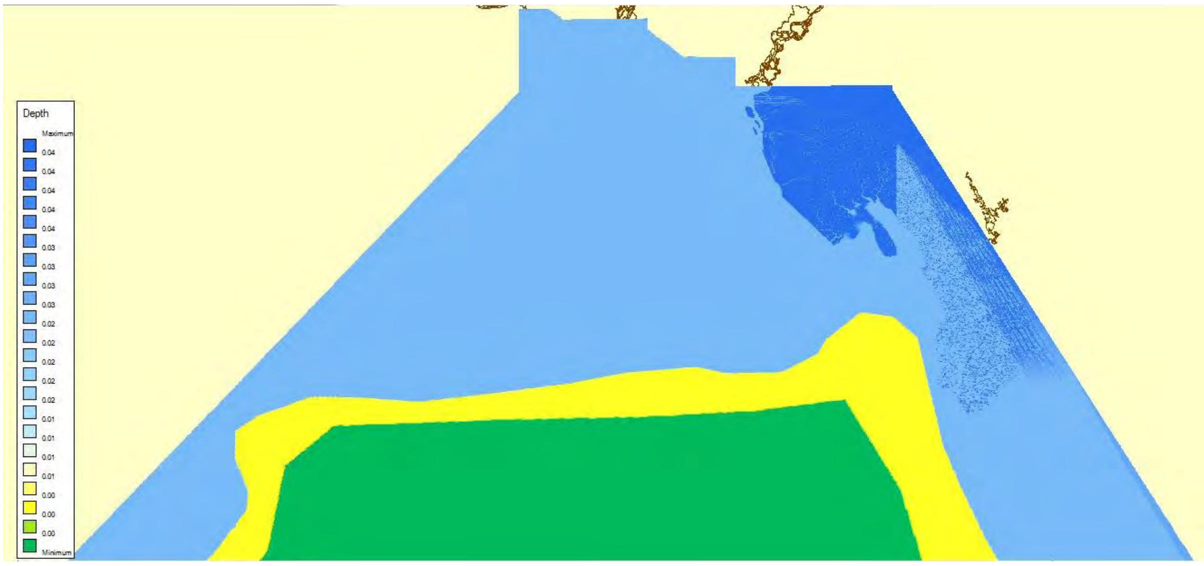


Figure 4.6: Calibrated Manning's roughness value in the model domain

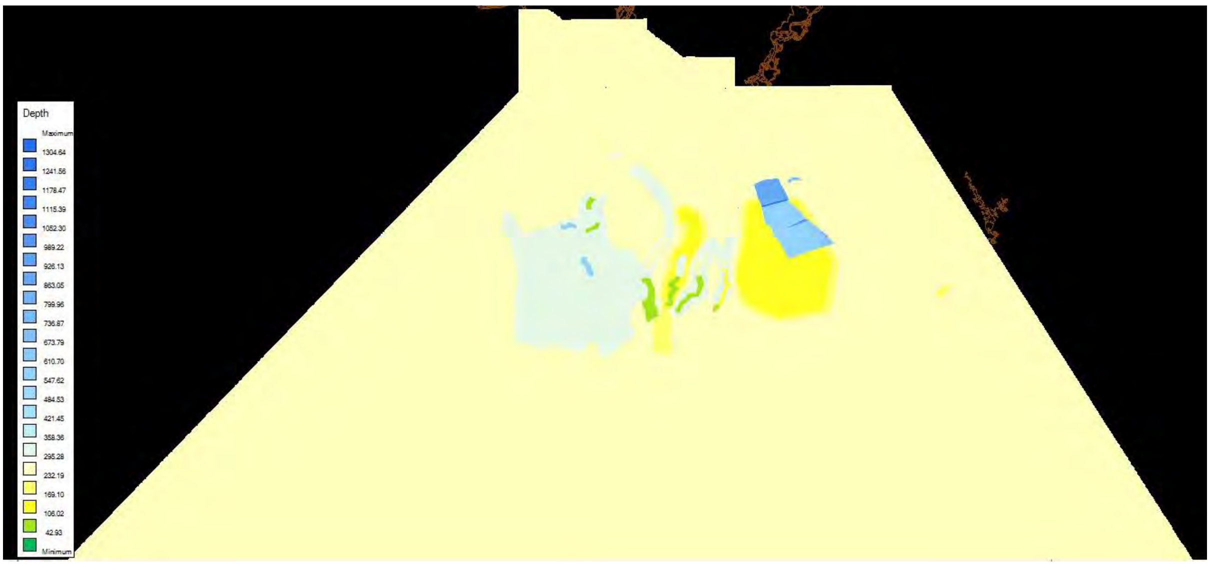
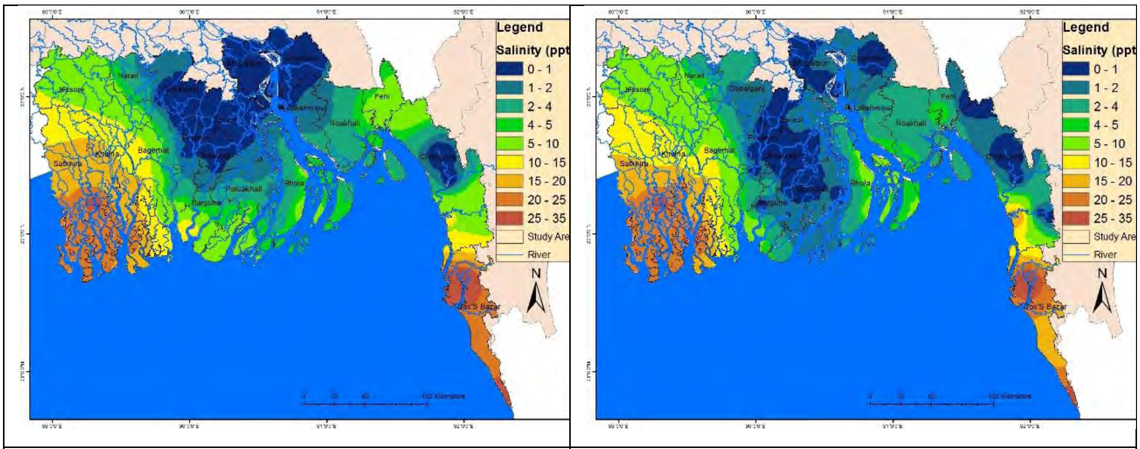


Figure 4.7: Calibrated eddy viscosity and diffusivity values in the model domain

Comparison between model simulation and measurements are shown in Figure 4.8.



(a) Model salinity	(b) Measured salinity

Figure 4.8: Calibration result shows (a) model salinity and (b) measured salinity.

The scatter plot and statistical indicators of the observed and measured values during model calibration is shown in Figure 4.9 and Table 4.2 which indicates a satisfactory performance of model. Values of NMAE and R2 (Table 4.2) indicate satisfactory model performance as the value of former is less than 0.5 and later is greater than 0.5 (Dawson *et al.*, 2007); (Chan and Cannon, 2002).

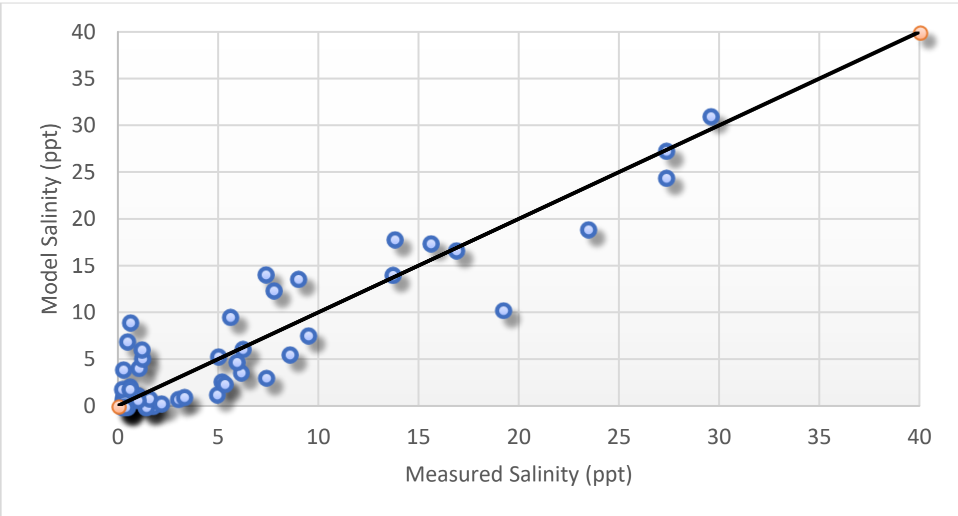


Figure 4.9: Model vs measured salinity

Table 4.2: Statistical indicators showing the model performance during calibration

Normalize Mean Absolute Error (NMAE)	0.39
Co efficient of Determination (R^2)	0.85

4.6. Scenario Description

Scenarios for this research are developed to represent the main drivers of salinity intrusion considering the global climate change which can be represented by events of SLR as well as including the sudden climatic event like cyclonic surge which is capable of propagating large amount of saltwater in upstream within a short time. Two scenarios, associated with sea level rise were considered in this research to predict the future condition. Salinity is affected by Sea Level Rise (SLR) and sudden climatic event like storm surge can exacerbate the situation. Hence these two cases were chosen to develop the scenarios in this research. Descriptions of the scenario along with the base condition is summarized in Table 4.3.

Table 4.3: Scenario description

Scenario names	**Scenario description**	**Upstream boundary condition**	**Downstream boundary condition**
Base condition	A typical dry year in 2011.	Measured data of the year 2011	Nao tide (without any SLR)
SLR scenario	Sea level rise of 1m.	Measured data of the year 2011	GCOMS with 0.54m SLR (Mean Sea Level difference from Nao tide is ~1m)
SLR-Cyc scenario	SIDR-like cyclone in 1m sea level rise scenario.	Measured data of the year 2011	GCOMS with 1m SLR + Cyclone SIDR

4.6.1. SLR scenario

Fifth Assessment Report (AR5) of The Intergovernmental Panel on Climate Change (IPCC) predicted a global rise of mean sea level by 0.52-0.98m by the year 2100 (IPCC, 2014). For sea level rise scenario, simulation result from an ocean model GCOMS (Kay *et al.*, 2015) was used. GCOMS predicted century scale sea level rise using atmospheric and oceanic boundary conditions derived from climate model projections (Kay *et al.*, 2015). GCOMS model simulated three different climate scenarios for the 21st century. These three climate scenarios are all for a medium Business-As-Usual greenhouse gas forcing scenario (the SRES A1B scenario) (IPCC, 2014) but differ in their atmospheric forcing conditions, with these being obtained from alternative atmospheric model projections. The modeled results give a continuous time series of sea surface height at hourly time intervals and at each 0.1˚ model grid point in the region of the GBM delta, for the time period of 1971 to 2099. Three climatic scenarios were named as Q_0, Q_8 and Q_{16}, the key differences between them is the frequency of storm events where Q_0 scenario has the largest number of storm events, characterized by low pressure and high wind speed (Kay *et al.*, 2015). To keep the analysis simple, Q_{16} condition was not analyzed as it focuses on probability of having more storm event. Q_0 and Q_8 had been compared and no significant differences in phases and peaks in data series were found (Figure 4.10).

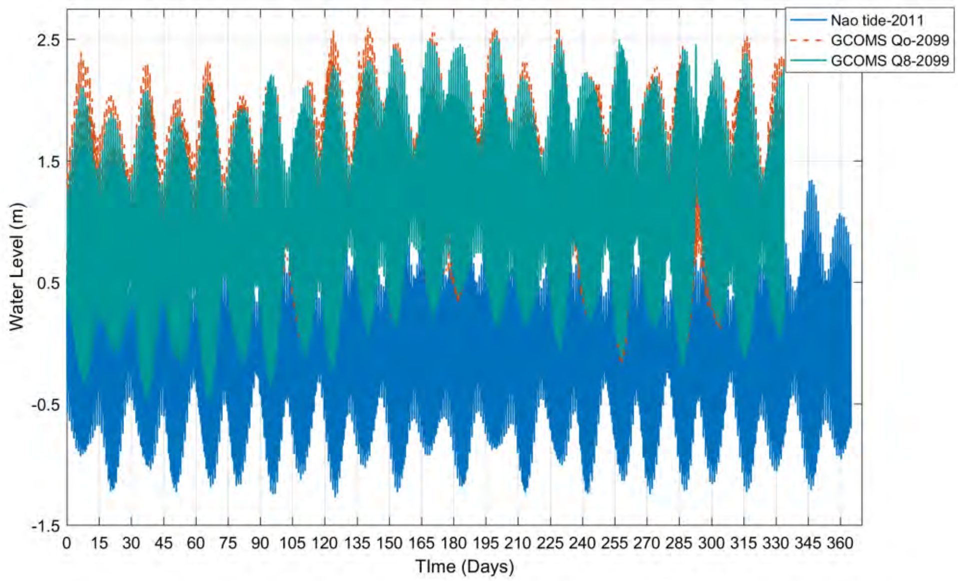


Figure 4.10: Sea level rise scenarios Q0 and Q8 compared to base condition

Hence, Q_0 climatic scenario was selected to produce the SLR scenario by using the ocean data of this climatic scenario. It has been found that Nao tide that was used as base condition (year of 2011) has mean sea level (MSL) at 0m (no SLR). On the other hand, GCOMS Q_0 ocean data which considered 0.54m SLR by the end of century has an average value of MSL of 1.16m for the year 2099. This indicates that there is a 1m SLR (approximately) when MSL is compared between GCOMS (with SLR) and Nao tide (no SLR) (see Figure 4.11).

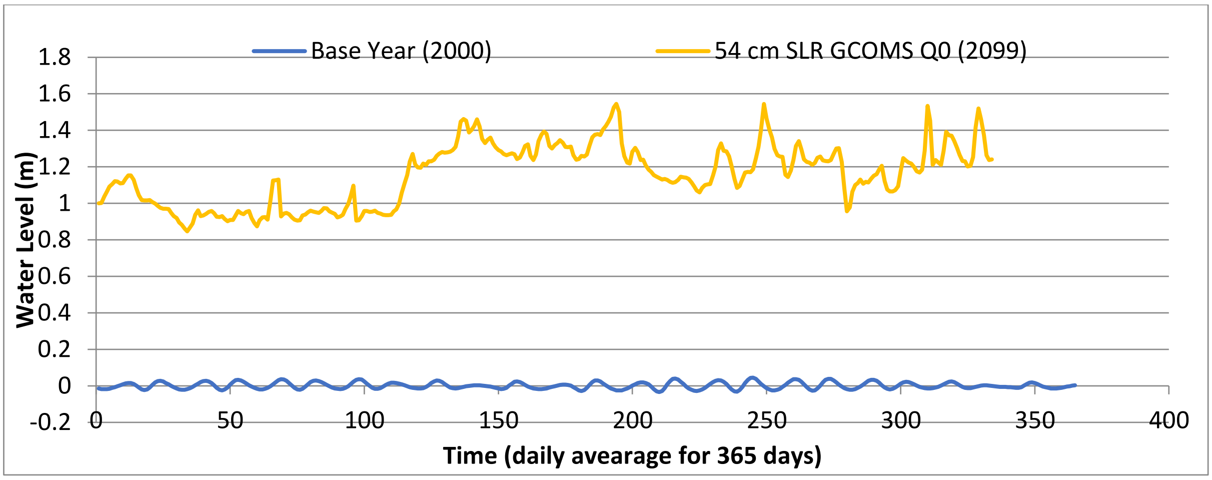


Figure 4.11: Mean sea level (daily) of Naotide and GCOMS Q0

4.6.2. SLR-Cyc scenario

On average, a severe cyclone strikes the country every three years (GOB 2009). Cyclone SIDR (November 2007) is considered a severe cyclone causing storm-surge in Bangladesh coast. In 2007, Cyclone SIDR with an average wind speed of 223 km per hour resulted in 4,234 casualties and 55,282 injuries (EMDAT–CRED, 2012) (Dasgupta *et al*, 2010). Although there are numeral model studies regarding short term to long term damage assessment of SIDR for inundation, soil salinity increase, crop production reduction etc. (Biswas, 2011); (Moni *et al*., 2015), but effects on river salinity are limited mainly due to the lack of data prior and after SIDR. To assess the impact of SIDR like cyclone on salinity hazard in future scenario, cyclone SIDR was chosen as a representative cyclone in sea level rise scenario (named as SLR-Cyc scenario in this research). In SLR-Cyc scenario, the wind speed and pressure were kept same as original SIDR but a SLR of 1m was superimposed.

4.7. Calculation Procedure of RT and NDIS

All the necessary parameters related to RT and NDIS were extracted from simulation results of Delft3D salinity model. Although Delft3D salinity model simulates the entire hydrological year, all calculations in this research were done for dry season as salinity reaches to maximum value in dry season when upstream discharges are low than monsoon season.

Calculation was based on tidal cycles where one tidal cycle was divided into ebb and flood cycles for each cross-section (let giving a name ‘X’ which is located in the mouth of the estuary) of an estuary. Required data was arranged against the date (model simulates the data for every 2 hours interval). In first column, discharge value was kept for the section ‘X’, in second column discharge data of upstream that will be used for river inflow (Q) for section ‘X’, salinity value and column velocity values are kept in third and fourth column respectively to prepare a complete dataset (an example table is shown in Appendix A: T1). Based on the signs of velocity and using the Matlab code (Appendix A: C1), the prepared dataset is divided into tidal periods consisting of ebb and flood cycles and all related variables needed to calculate RT and NDIS were calculated per tidal period (an example table for February month is shown in Appendix A: T2). The value of calculated NDIS were scaled up by multiplying with 10^{10}. To calculate the river inflow (Q) for the section ‘X’, a section from upper sections of the estuary (let name this section ‘Y’) is selected which contributes to section ‘X’. Branching is considered during selection, meaning if an estuary has no branch, the discharge value contributing in extreme upper section will be used as river inflow of section ‘X’. The date wise (2 hours interval data) discharge data of section ‘Y’ was used in another Matlab code (Appendix A: C2) to calculate tidal period wise average river discharge. From the tidal period wise average river discharge data, the minimum river discharge value of section ‘Y’ was selected as river inflow (Q) of the section ‘X’. River inflow (Q) data calculated for base condition was kept same for two scenarios (SLR and SLR-Cyc scenarios).

Density and viscosity for NDIS calculation are calculated from relation represented as a function of salinity and temperature (El-Dessouky and Ettouny, 2002). Salinity values are extracted from model simulation and temperatures of major estuaries were selected from literatures (Hossain *et al*., 2012) (Rahman *et al*., 2013) (GoB, 2013).

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1. Introduction

Salinity assessment depends on governing parameters (Chapter 4) that can be represented by a Non-Dimensional Index for Salinity (NDIS) value. NDIS value represents the condition of estuaries in terms of salinity hazard as a whole incorporating all related dominant salinity parameters. Discharge value (Q) of base condition is kept same for both SLR and SLR-Cyc scenarios. On the other hand, RT and TE are playing important role in assessing the salinity condition of an estuary as they can be linked with ecological health of the estuary (Yuan et al, 2007; Miller and McPherson, 1991) (Zhen-Gang, 2008; Parsa and Shahidi, 2010). Thus, RT and TE are also discussed here. Estuary wise behavior of the parameters will be discussed also to identify the spatial pattern of NDIS value.

5.2. Non-Dimensional Index for Salinity (NDIS) in Base Condition

NDIS is developed to represent salinity hazard through a single index value that contains driving parameters namely residence time (RT), velocity (ν), kinematic viscosity (κ) and discharge (Q) (see Equation 4.25). Formulation and introduction of NDIS are discussed in Chapter 4, Section 4.3.

NDIS value is developed through dimensionless groupings in such a way that physical properties of the parameters are maintained. Equation (4.25) shows that NDIS is a non-linear function of residence time (RT), velocity (ν), kinematic viscosity (κ) and discharge (Q). NDIS directly varies with RT, ν, κ and inversely varies with Q. Though the relation is non-linear, this does not mean that increase of RT, ν and κ or decrease of Q will always increase NDIS. Rather increase or decrease of NDIS with RT, ν, κ and Q depends on complex interaction among these parameters. If in a system, relative importance of combined impacts of ν and κ are less than impact of RT, NDIS in that system will show increased value of the index with the increased value of RT and decreased value of Q. Physically this means that, in an estuary, when residence time of specific salinity magnitude is high and discharge is low, high value of NDIS represents a high salinity hazard condition. The highest value of NDIS for an estuary represents highest salinity hazard of that estuary and vice-versa. If the value of NDIS decreases from highest to lowest in an estuary then salinity hazard also decreases in that estuary from highest to lowest hazard.

For base condition, the calculated value of NDIS along with its associated parameters is shown in (Appendix A:T3, C3), where range of NDIS value varies widely as lowest being less than 30 in EES-CES and highest being greater than 100000 in WES (see Appendix A:T3 and Figure 5.1). The figure is prepared by interpolating data of the Appendix A:T3 and color represents estuaries within the coastal region (a sample figure incorporating polder is given in Appendix A: Figure A1). All the figures in this chapter that are generated by interpolation of NDIS and associated parameters represent NDIS for estuaries within the specific coastal zone.

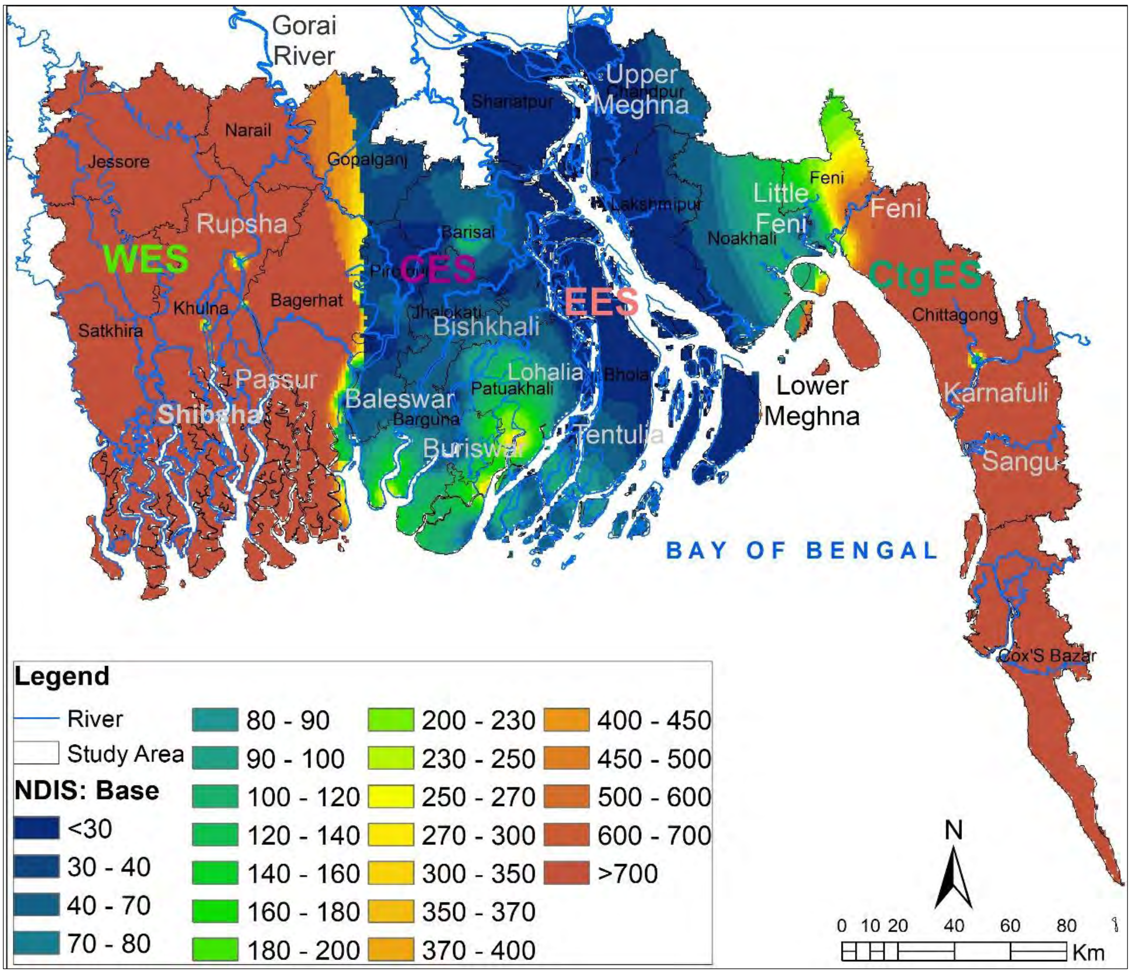


Figure 5.1: NDIS for base condition

In base condition, EES-CES has low salinity hazard as NDIS is lowest here and highest in WES and CtgES (Figure 5.1) because of highest NDIS value. Within EES-CES, Meghna estuary possesses the lowest NDIS value (less than 30) compared to other estuaries of the system. The mouth of Lohalia estuary and CES (Bishkhali, Buriswar and Baleswar estuaries) have higher values of NDIS (100 to 250) compared to upper part of the same system as upper part of these estuaries contains lesser value (30 to 100) than the lower part (Figure 5.1). From Baleswar estuary to WES, NDIS value is at its peak and same pattern is noticeable for estuaries in Chittagong too (greater than 500) (Figure 5.1).

In base condition, an increased salinity hazard is observed in the estuarine mouths of CES. CES is bounded in the west by the highest salinity hazard zone (WES) and the lowest salinity hazard zone (EES) in the east. So, how CES behaves in SLR and SLR-Cyc scenarios will be an interesting fact to be observed.

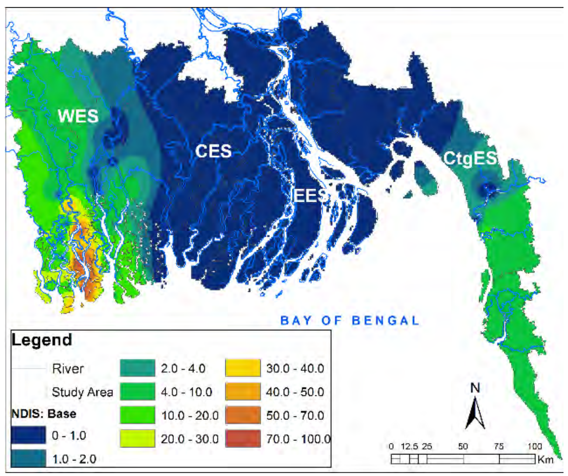
To analyze the reason of having high to low NDIS value, it is necessary to look to the main parameters of Equation (4.25), how they behave and whether their behaviors can explain the pattern of NDIS (Figure 5.1).

To compare the changes in same scale, each parameter of Equation (4.25) was normalized by using Equation (5.1) and converted in 0-100 scale

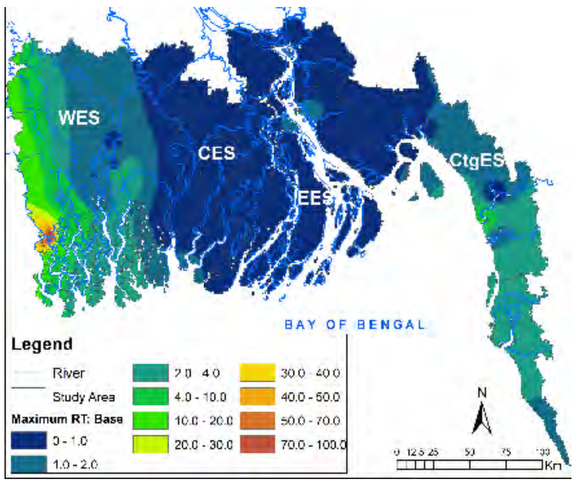
$$Z_i = \frac{X_i - \min(X)}{\max(X) - \min(X)} \quad \text{.....................(5.1)}$$

Where $X_i=(X_1, \ldots, X_n)$ and Z_i is ith normalized data.

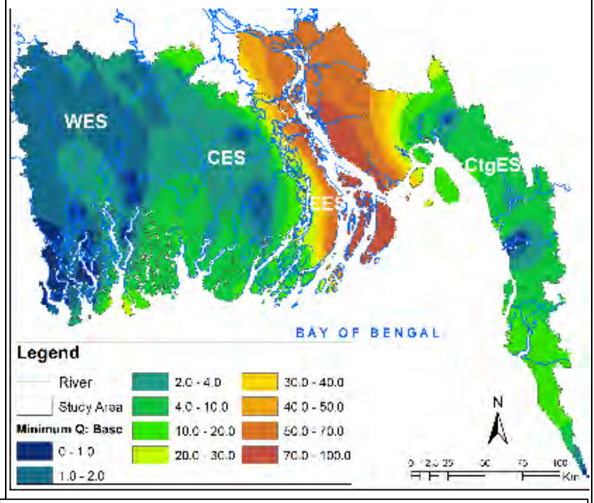
The parameters and NDIS itself are shown in Figure 5.2 in a normalized scale 0-100.



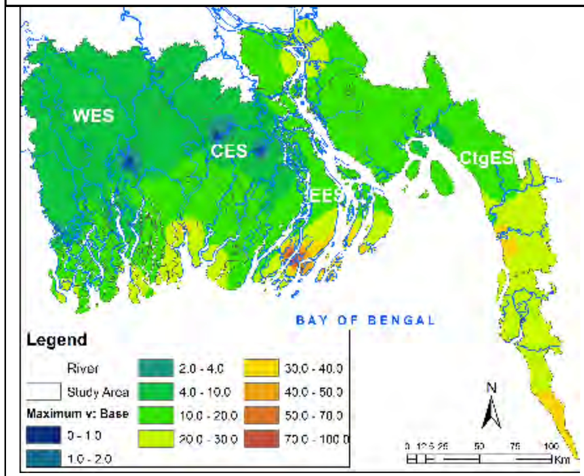
(b) NDIS



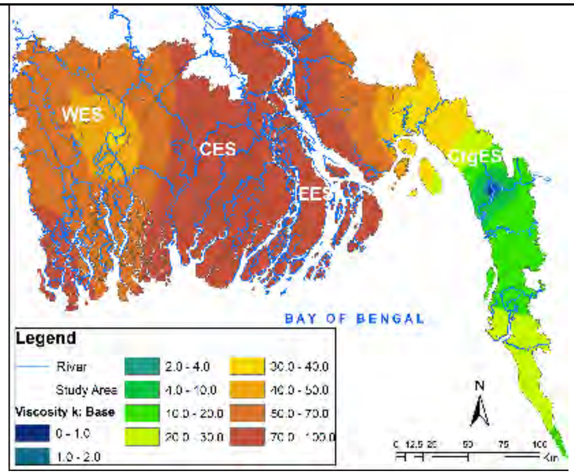
(c) RT



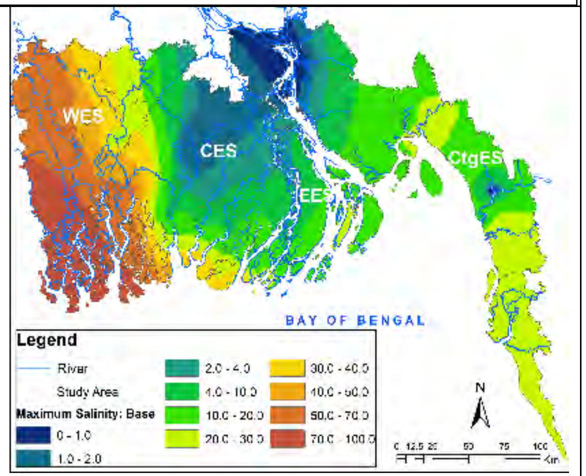
(a) Q



(d) ν



(e) κ



(f) Salinity

Figure 5.2: (a) NDIS and corresponding parameters: (b) RT (c) Q (d) ν (e) κ and (f) maximum salinity magnitude.

The scale of 0 to 100 is classified in 10 categories which later grouped in 3 qualitative classes (Table 5.1) (Appendix A: T4):

Table 5.1: Classification of the value of NDIS and associated parameters

Classification of Value in scale 0-100	Categories of classified value
0-1	Low
1-2	Low
2-4	Low
4-10	Medium
10-20	Medium
20-30	Medium
30-40	High
40-50	High
50-70	High
70-100	High

From the Figure 5.2 and Table T4: Appendix A, it is found that RT and NDIS follow almost the same pattern of change (directly proportional) along the estuaries of the system, whereas discharge shows inverse relation (inversely proportional) with NDIS and RT. But as mentioned before, Equation 4.25 has two more variables, velocity ν and kinematic viscosity κ. In a low discharge section, velocity could be high, and this could reverse the impact of Q. This happens in many estuaries in the region where low discharge and low RT is followed by a low NDIS. But in most of the sections, RT and Q are the most influential parameters of NDIS (Figure 5.2 (a,b,c)).

Variation of average value of NDIS in three estuarine systems along with its driving parameters are shown in Figure 5.3. The results show the variation in same scale (Table T4: Appendix A and Table 5.1).

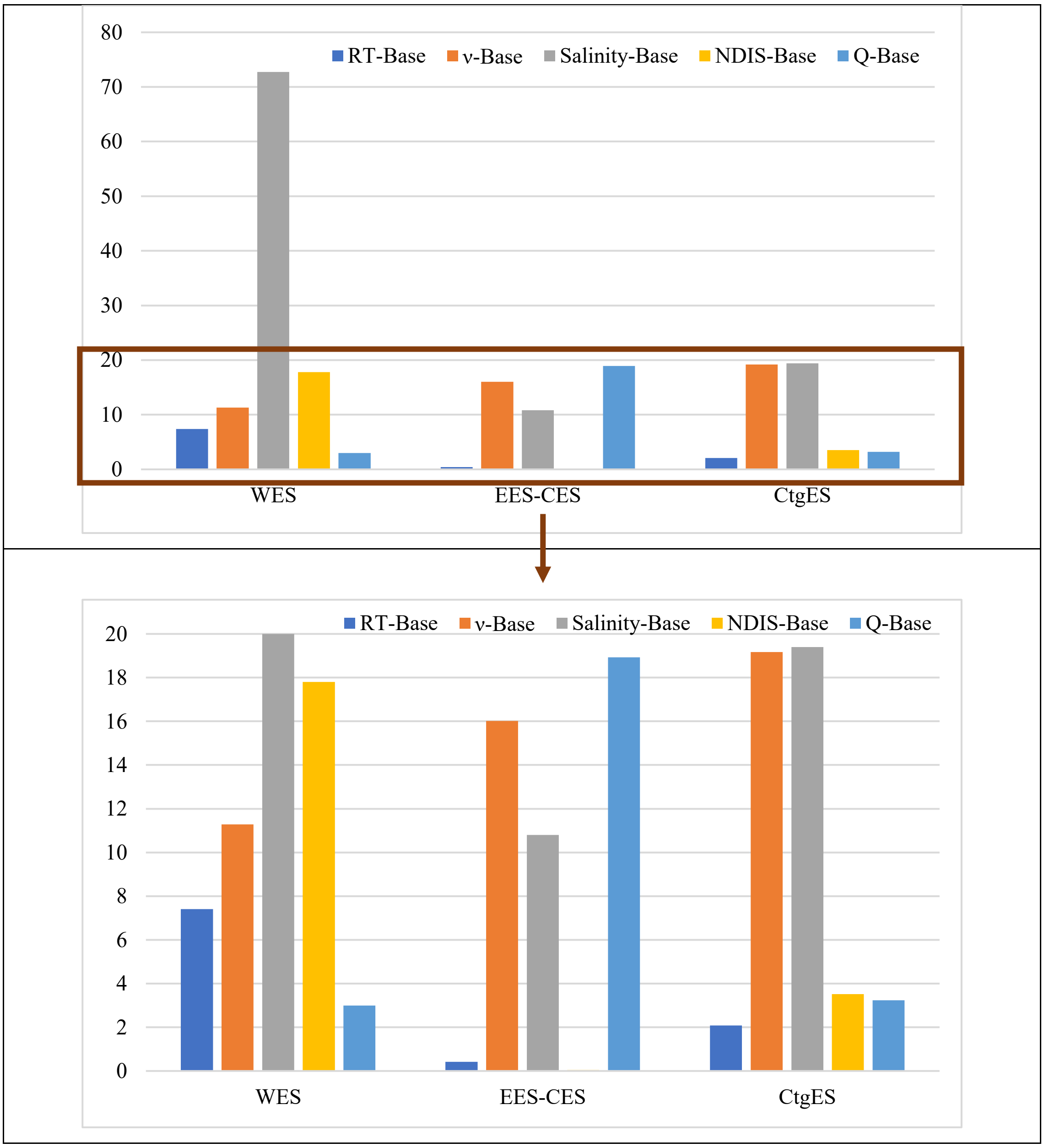


Figure 5.3: Average value of NDIS and associated parameters for three estuarine systems.

Figure 5.3 shows that NDIS is highest in WES and lowest in EES-CES. RT follows the similar trend as NDIS, but Q follows the opposite trend (Figure 5.3). On the other hand, ν does not follow similar trend of either RT or Q. When same Q is to pass suddenly through a shallower & narrower reach or deeper & wider reach of an estuary (for example Arpanghasia estuary of WES (see Figure 3.1 in Chapter 3), ν can create a relation among NDIS, RT and Q which will not follow the expected pattern as explained above. Salinity hazard is low in EES-CES, high in WES and medium in CtgES (Figure 5.3).

In conventional way salinity hazard is measured or represented by salinity magnitude alone but when representing salinity hazard through NDIS, not only salinity magnitude is considered through RT but flow parameters like Q (upstream discharge) and ν (flood velocity) as well as fluid parameters like kinematic viscosity (κ) also incorporated which represent salinity hazard in a better way without compromising the pattern of salinity value. Comparing NDIS with salinity magnitude, it is observed that there are both similarities and dissimilarities when a one-to-one comparison is made (see Figures 5.2a and 5.2f). This shows importance of other drivers of salinity intrusion process in determining salinity hazard. NDIS effectively considers all these drivers.

5.2.1. Residence Time (RT) in Base Condition

As mentioned before, salinity hazard is generally assessed by using the magnitude of salinity. Residence time, on the other hand, is an important parameter, representing the time scale of the physical transport processes of saline water in estuaries (Duarte and Vieira, 2009); (Li, 2010). Because it predicts the time taken to rid a salt mass from a specific location, it can be used as an indicator of ecosystem health too (Yuan et al, 2007; Miller and McPherson, 1991). From the analysis of previous section, it is found that RT and Q play the dominant role for NDIS. RT is a new parameter developed in this research. Its application on assessing salinity hazard as well as how it relates with salinity magnitude needs to be analyzed. In this section, RT will be discussed in detail.

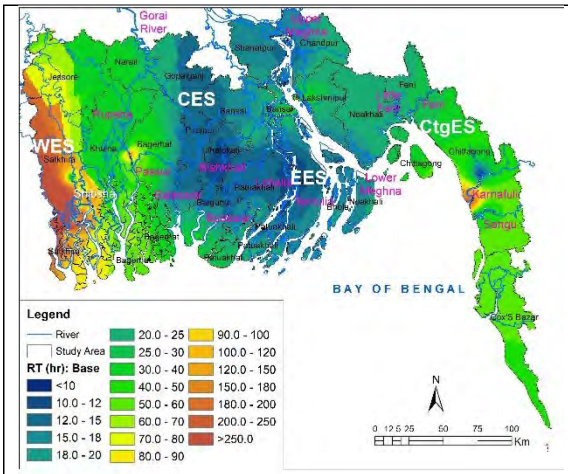
RT is represented as a function of estuary geometry, amount of salt and fresh water volume entering estuary, tidal range and concentration of salinity in Equation (4.20).

Equation (4.20) depicts an inverse relation with upstream discharge (Q) and direct relation with tidal storage (V+P). However, parameters are non-linear in relation and combination of a complex interaction. Equation (4.20) can be re-written as,

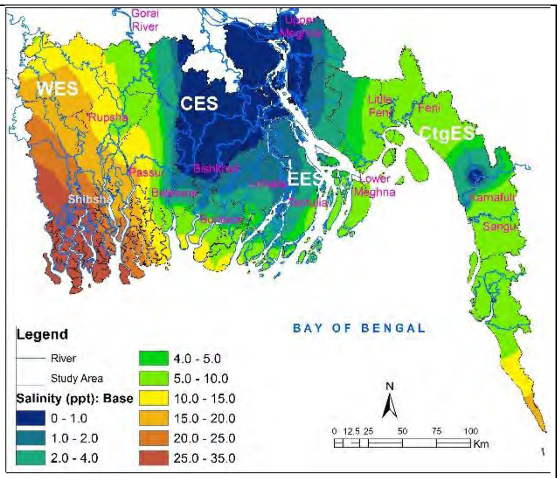
$$RT = A \times B \text{ , where } A = \frac{(V+P)T}{(1-b)P+(1+b)\frac{QT}{2}} \text{ and } B = \frac{2\left\{-QT\left(\frac{S+S_0}{S-S_0}\right)-QTb\right\}-QT(1-b)}{2\left\{-QT\left(\frac{S+S_0}{S-S_0}\right)-QTb\right\}+QT(1-b)} \text{........}(5.2)$$

Here, B represents the salinity magnitude as in the form of ratio with sea salinity (Chapter 4, Equation 4.19). It depicts if the salinity magnitude is high, RT will be high as well.

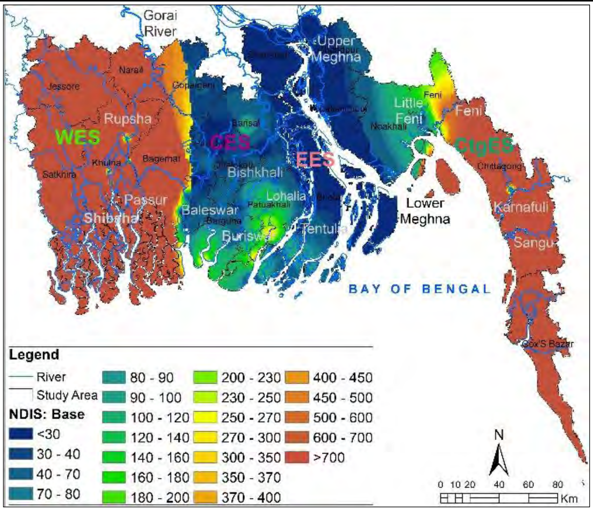
For the base condition, distribution of RT, salinity magnitude and NDIS are shown in Figure 5.4.



(a) RT



(b) Salinity Magnitude



(c) NDIS

Figure 5.4: Distribution of (a) RT (b) Salinity magnitude and (c) NDIS. Distribution shows the values in base condition.

Residence time is calculated per tidal cycle (Chapter 4). Within a tidal cycle, salinity magnitude (which is taken as the maximum salinity value) will take particular time (that is the residence time) to leave the section. From the result, it can be observed that the middle part of EES-CES possesses lowest RT (less than 10 to 12 hours). This means that a particular salinity value in EES-CES for which RT is 10 to 12 hours (see Figure 5.4) will wash out within the tidal cycle, because RT (10 to 12 hours) is less than duration of a semi-diurnal tidal cycle (24 hours 48 minutes). However, in the estuary mouth of CES, RT is higher (20 to 30 hours) (Figure 5.4). This means that salinity will not wash out within a tidal cycle and salinity will 'reside' in the estuary mouth of CES. From Baleswar estuary to WES, RT gradually increases to reach at its peak (Figure 5.4). As WES receives less fresh water and mainly dominated by tides, this estuarine system has high RT. This means intruded salinity resides for longer duration in WES.

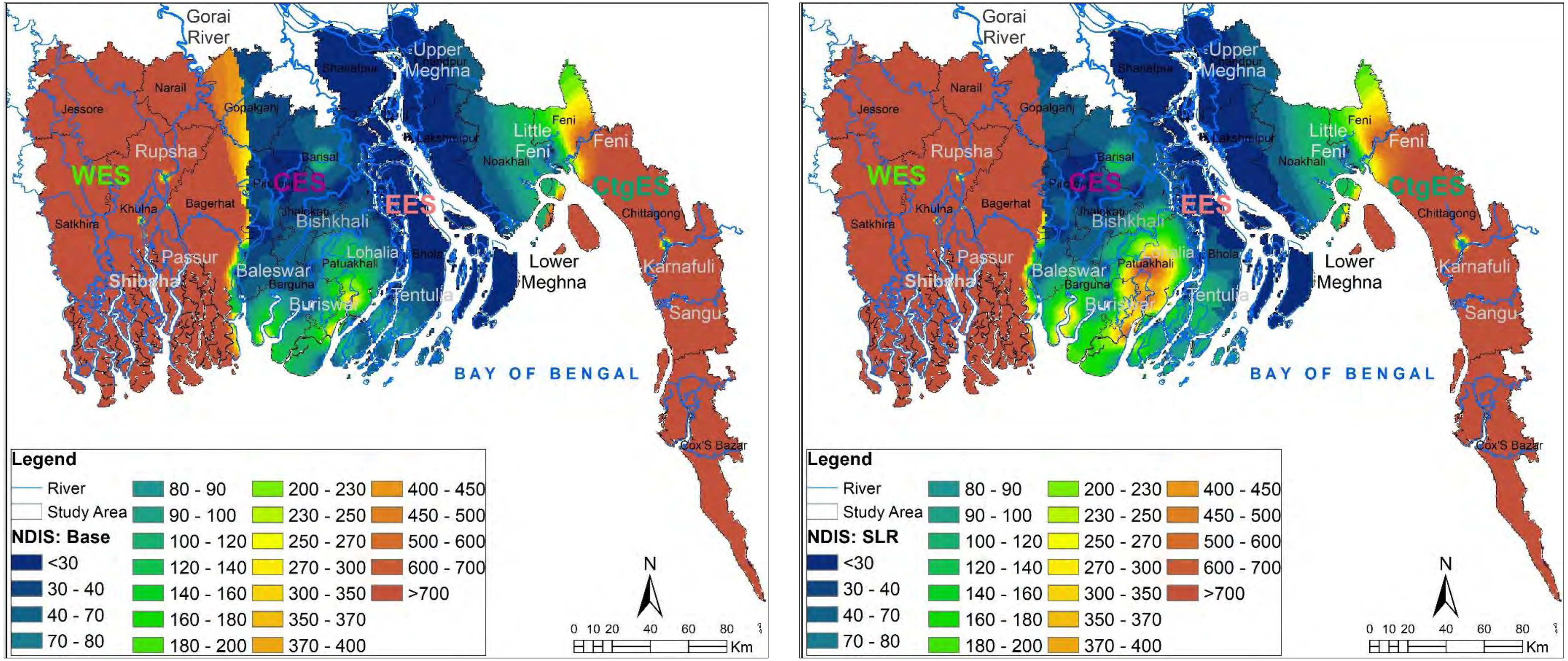
By comparing RT and corresponding salinity magnitude (Figure 5.4a, b), it is found that the relation between the two is not exactly one to one. This means that though salinity magnitude of upper CES is the lowest, the value of RT is not. This variation pattern of RT value in the upper CES is also reflected on the NDIS value of this region (Figure 5.4a, c). Though the overall pattern of RT and NDIS along the estuaries follow the general pattern of salinity magnitude (Figure 5.4b), yet the relation between salinity magnitude and RT (Figure 5.4a, b) or salinity magnitude and NDIS (Figure 5.4b, c) cannot be said as a one to one and seem to vary along the estuaries.

5.3. Application of NDIS to Assess Salinity Hazard in Changing Climate

Global climate change will accelerate sea level rise that will continue to affect Bangladesh coast through increased salinity intrusion of low-lying areas (Akter et al, 2016). The situation becomes more critical when a severe cyclone makes landfall in the coastal region resulting sudden propagation of large volume of landward saline water intrusion through estuaries (Akter et al, 2016). Considering such scenarios, this research developed two scenarios namely SLR which attribute to sea level rise condition and SLR-Cyc which attributes to cyclonic effect in SLR condition. Description of these two scenarios are described thoroughly in Chapter 4, Section 4.6. In the following sections, NDIS is applied to assess salinity hazard in SLR and SLR-Cyc conditions.

5.3.1. Assessing salinity hazard in SLR scenario

For assessing the impact of sea level rise on salinity hazard, 1m sea level rise is considered in this research (Chapter 4, Section 4.6.1). To ensure the impact due to sea level rise only, upstream discharge is kept same as base condition. The effect of sea level rise on salinity hazard is shown in Figure 5.5 below.



(a) Base condition (b) SLR scenario

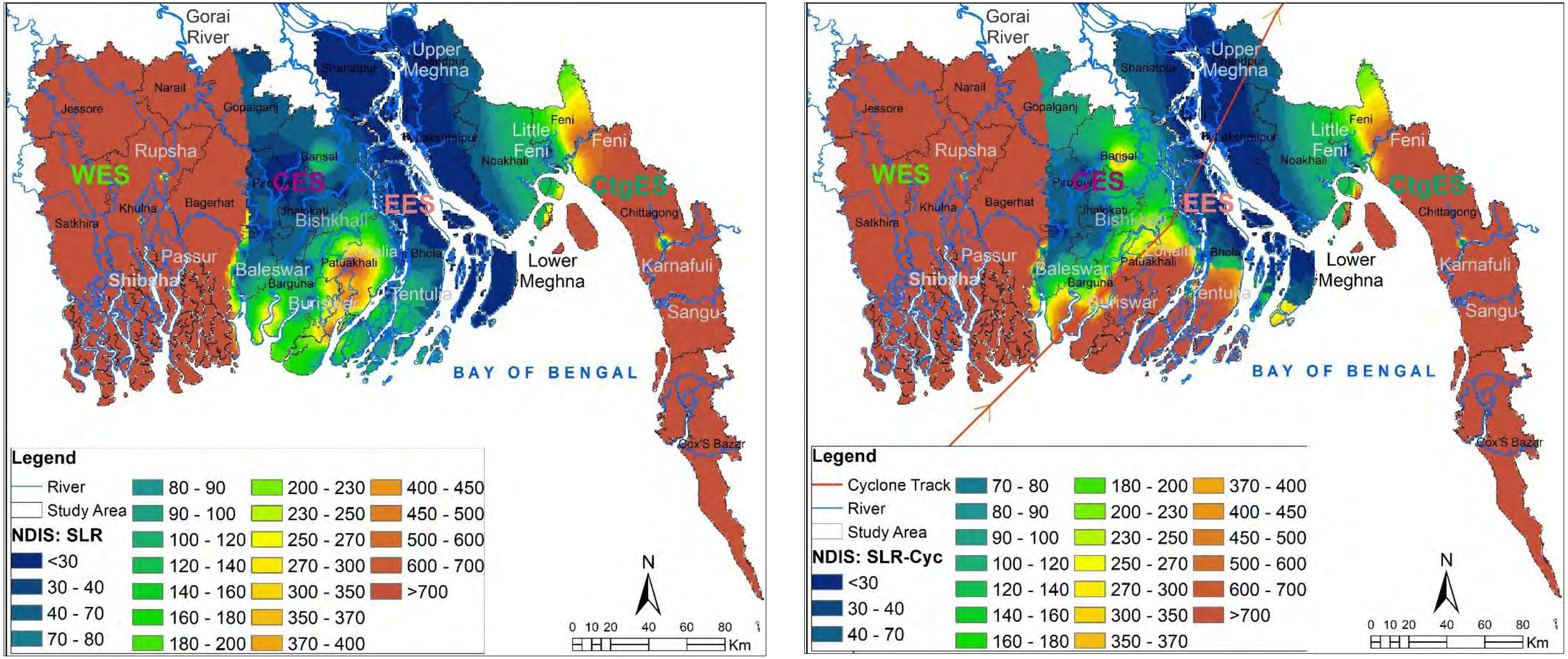
Figure 5.5: Variation of NDIS in (a) base condition (b) SLR scenario

In SLR scenario, upper part of Meghna estuary of EES still has the lowest NDIS value (less than 30) as observed in base condition, but not in the lower part. NDIS value increases in lower part of CES and EES (Meghna and Tentulia Estuaries) (Figure 5.5). However, the estuary mouth of Lohalia, and CES (Bishkhali, Buriswar and Baleswar estuaries) have no change. No changes are also observed in upper part of CES as well. High NDIS (>600) region of WES increased in SLR and the changing direction is toward Baleswar estuary (comparing base with SLR). CtgES also has high NDIS value (>600) in both SLR and base condition (Figure 5.5).

The effect of SLR on salinity hazard is highest in lower part of EES-CES. This region faces highest salinity intrusion and is affected by SLR condition. Upper part of WES also has increased salinity hazard than base condition. Hence, for SLR scenario, salinity hazard is highest in lower part of EES-CES and upper part of WES.

5.3.2. Assessing salinity hazard in SLR-Cyc scenario

Sudden event like storm surge propagates salt water toward inland and increases salinity magnitude in a particular region within a short time. In this research, salinity intrusion due to storm surge is assessed when SIDR-like cyclone makes landfall in the coast when sea level also rises to 1m. This scenario is named as SLR-Cyc (for scenario description, see Chapter-4, Section 4.6.2).



(a) SLR scenario

(b) SLR-Cyc* scenario

Figure 5.6: Variation of NDIS in (a) SLR and (b) SLR-Cyc* scenario

[*cyclone SIDR]

For SLR-Cyc, highest change is observed along the cyclone track especially in the mouth of EES-CES (Figure 5.6). The estuary mouth faced increased salinity hazard as NDIS value of 160-400 in base condition (Figure 5.6 (a)) reached to 1000 or more (Figure 5.6 (b)) in SLR-Cyc scenario. This indicates that salinity hazard increases in EES-CES for cyclonic condition.

Upper part of CES also faced increased salinity hazard as NDIS value of 30-80 in SLR changed to 90-140 (Figure 5.6). Overall other estuaries are in same pattern as like SLR scenario (Figure 5.6). Hence, for SIDR-like cyclone, highest impact of salinity hazard is observed along the cyclone track (EES-CES) and, also in the upper part of the same (EES-CES) system.

To compare salinity hazards in all estuarine systems, percent change of scaled values of NDIS (see Table 5.1) from base to SLR and SLR-Cyc are compared and is shown in Table 5.2.

Table 5.2: Percentage changes of NDIS from base condition to scenario conditions

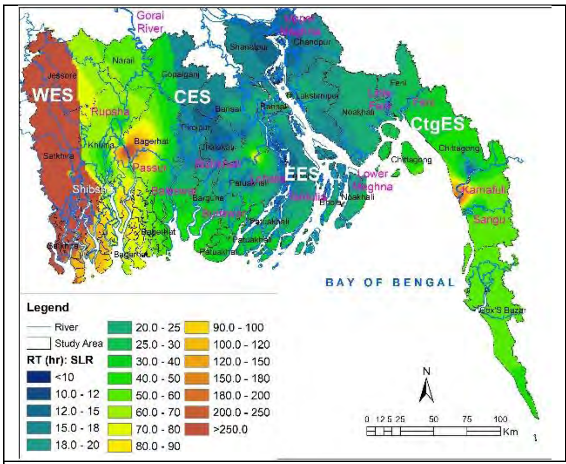
Estuarine Systems	% change from base to SLR condition (NDIS)	% change from base To SLR-Cyc condition (NDIS)
WES	41 (increase)	54 (increase)
EES-CES	44 (increase)	544 (increase)
CtgES	52 (decrease)	3 (increase)

It is observed that (Table 5.2) both in SLR and SLR-Cyc scenarios, maximum increase (from base condition) of salinity hazard is in EES-CES systems. In these systems, salinity increase from base condition is nearly five times in SLR-Cyc scenario compared to increase of nearly half from base condition in SLR scenario. The reason is – cyclone landfall considered in SLR-Cyc scenario (SIDR landfall) is within the EES-CES systems. In CtgES, impact is negative due to SLR only and nearly zero due to SLR-Cyc. In WES, impacts are almost similar due to SLR and SLR-Cyc scenarios. In both scenarios, salinity increases almost half from the base condition.

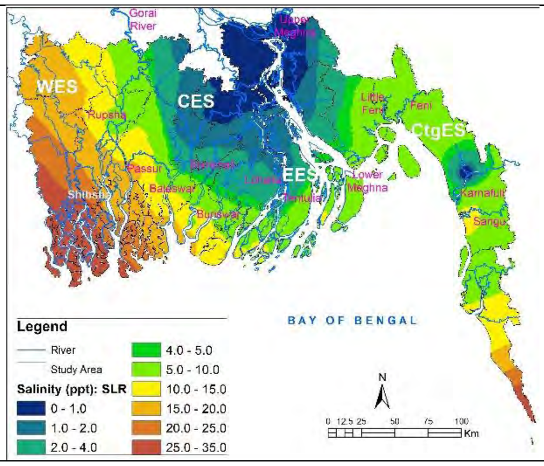
5.4. RT in Changing Climate

The significance of RT in salinity hazard assessment is discussed in Section 5.2.1. In this section, behavior of RT in changing climate scenario is discussed.

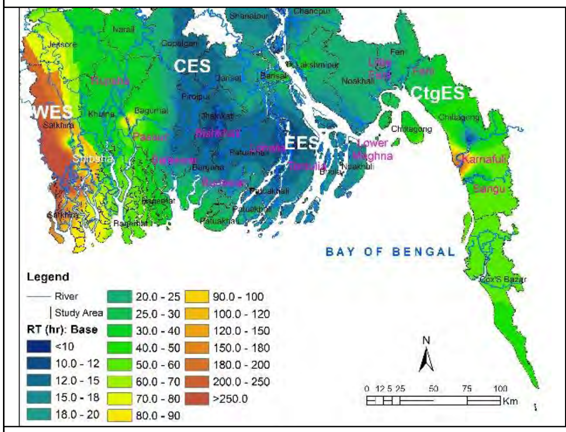
5.4.1. RT in SLR scenario



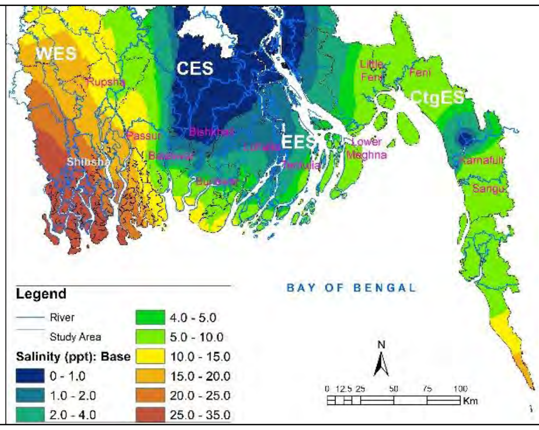
(a) RT in SLR



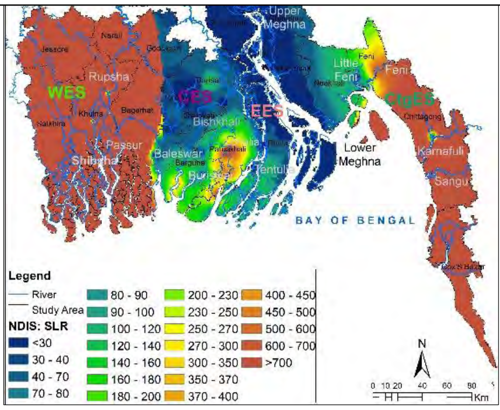
(b) Salinity magnitude in SLR



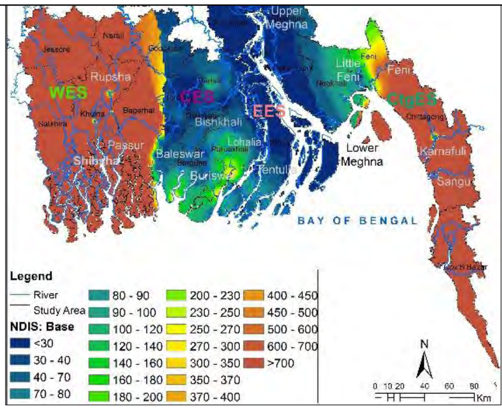
(c) RT in base condition



(d) Salinity magnitude in base condition



(e) NDIS in SLR



(f) NDIS in base condition

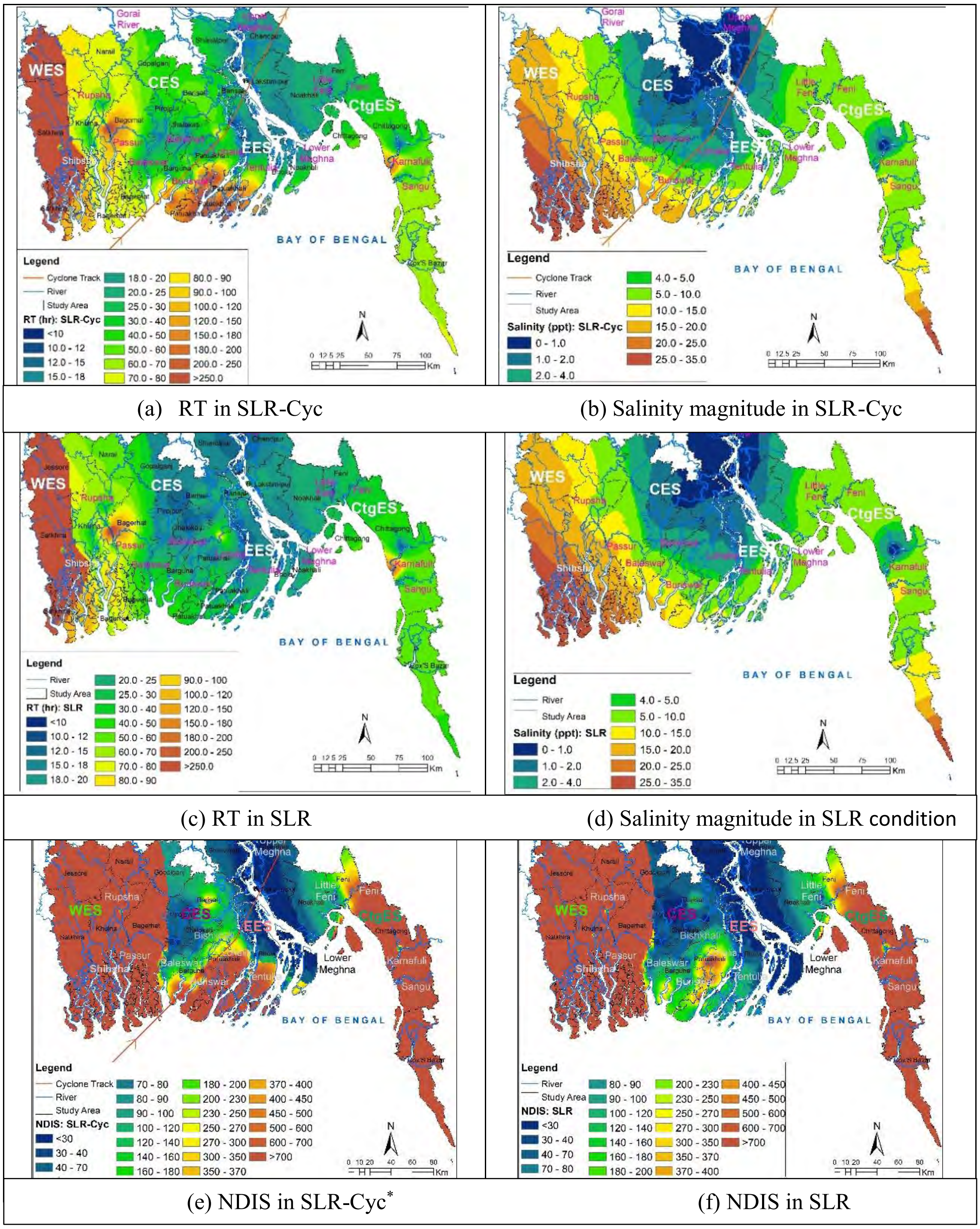
Figure 5.7: Variation of (a) Maximum RT in SLR, corresponding (b) maximum salinity magnitude in SLR (c) Maximum RT in base condition, corresponding (d) maximum salinity magnitude in base condition, and (e) NDIS in SLR (f) NDIS in base condition.

Comparing base condition and SLR, it is observed that salinity intruded through CES as the salinity front pushes in upstream (Figure 5.7b, d). Following the similar pattern of salinity magnitude, RT increased at estuarine mouth of CES as well (20-30 hours changed to 70 hours). RT increased in WES also with a higher magnitude compared to salinity magnitude (70 hours of RT in base condition changed to more than 120 hours). This change in RT is also present in NDIS of SLR (Figure 5.7c, e). Considering RT and salinity magnitude, it is observed that in upper part of CES, salinity magnitude and RT do not change linearly.

From this observation, it can be said that the relation between RT and salinity magnitude follows a non-linear relation and cannot be related directly. It can be also said that increase of salinity magnitude does not necessarily mean that RT would increase too at same rate. A slight change in salinity magnitude might possess longer RT which means that salinity will stay much longer time in a particular estuary. For SLR scenario, RT increased in all estuarine systems except CtgES (remained same as base condition).

5.4.2. RT in SLR-Cyc scenario

In this section, changes of RT in SLR-Cyc scenario is assessed.



(a) RT in SLR-Cyc

(b) Salinity magnitude in SLR-Cyc

(c) RT in SLR

(d) Salinity magnitude in SLR condition

(e) NDIS in SLR-Cyc*

(f) NDIS in SLR

Figure 5.8: Variation of (a) Maximum RT in SLR-Cyc*, corresponding (b) maximum salinity magnitude in SLR-Cyc* (c) Maximum RT in SLR, corresponding (d) maximum salinity magnitude in SLR and (e) NDIS in SLR-Cyc* (f) NDIS in SLR

[*cyclone SIDR]

Salinity magnitude and RT increased in EES-CES comparing SLR condition to SLR-Cyc condition. It is observed that RT in estuary mouth of EES-CES (Tentulia, Lohalia, Buriswar and Bishkhali estuaries) changed from 70 hours to more than 250 hours (Figure 5.8c, a). Such change indicates that SIDR-like cyclone will trap the saline water for a longer period in SLR condition. Additionally, lowest RT (<20) region of upper CES in both base and SLR conditions no longer exist for SLR-Cyc scenario (Figure 5.7c and Figure 5.8c, a). The trend of increased RT value spreading toward central region is also observed here as previously 70 hours RT (SLR scenario) reached to 100 hours or more (Figure 5.8c, a).

In SLR-Cyc, highest change is observed along the cyclone track. In rest of the other regions, salinity magnitude increased by only 1-2 ppt (Figure 5.8b, d). But, RT increased in more greater scale than salinity magnitude as value increases from 30 to 100 or more (Figure 5.8a, c). Such changes of RT are reflected on NDIS as well (Figure 5.8e, f). This indicates that a small change in salinity magnitude can cause salt water to reside for a longer time in a particular location. Without considering the changes of RT, changes of salinity magnitude do not possess significance in expressing changes of salinity hazard in this region. However, changes of RT has added significance regarding the changes of salinity hazard in scenarios compared to base condition. The impact of longer RT is captured in NDIS which depicts that NDIS is more realistic as salinity hazard assessment than salinity magnitude alone.

For SIDR-like cyclone in SLR condition, salinity magnitude changes along the cyclone track but RT changed in other regions as well. Upper part of EES-CES and WES had increased RT but no change in salinity magnitude. Such changes of RT are reflected in NDIS but not in salinity magnitude. This observation depicts that upper part of EES-CES had increased salinity hazard for SLR-Cyc condition that cannot be captured through salinity magnitude alone.

5.5. Tidal Excursion to Assess Salinity Intrusion in Changing Climate

Tidal Excursion (TE) is used as one of the parameters in NDIS that was represented by velocity in Equation (4.25). TE means net excursion of a tracer in a tidal environment during a tidal cycle. In NDIS, tidal excursion during flood tide is considered which represents maximum intrusion length of salinity front during the flood phase of a tidal cycle (Parsa and Shahidi, 2010). TE is calculated by integrating the maximum flood velocity over the tidal period of flood tide. Detail description of TE and related equations are given in Chapter 4, Section 4.2.1. This section discusses the changes of TE in SLR and SLR-Cyc scenarios.

Changes of maximum flood velocity magnitude (directed landward) are studied in different estuarine systems for base condition, SLR and SLR-Cyc scenarios (Figure 5.9). It is seen that in EES-CES systems, compared to base condition, flood velocity changes in SLR and SLR-Cyc. In CtgES and WES systems, these changes are negligible (Figure 5.9).

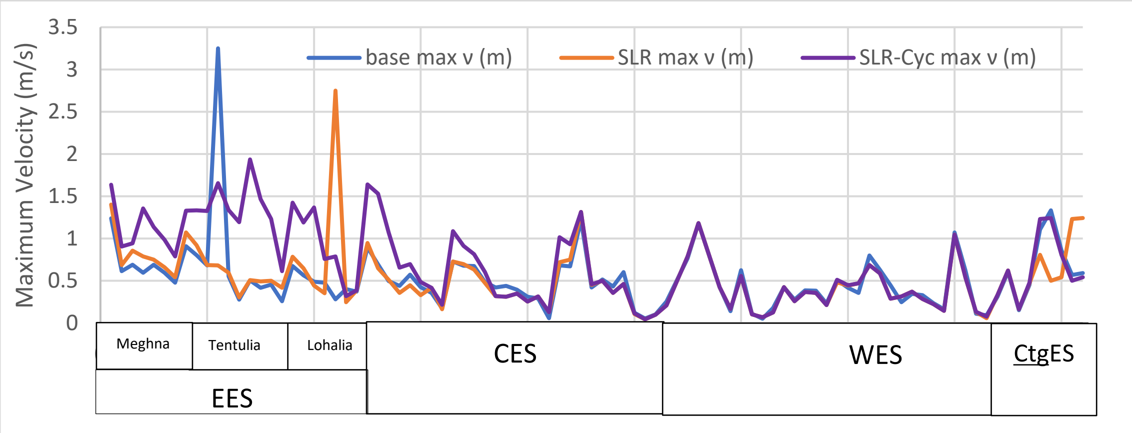
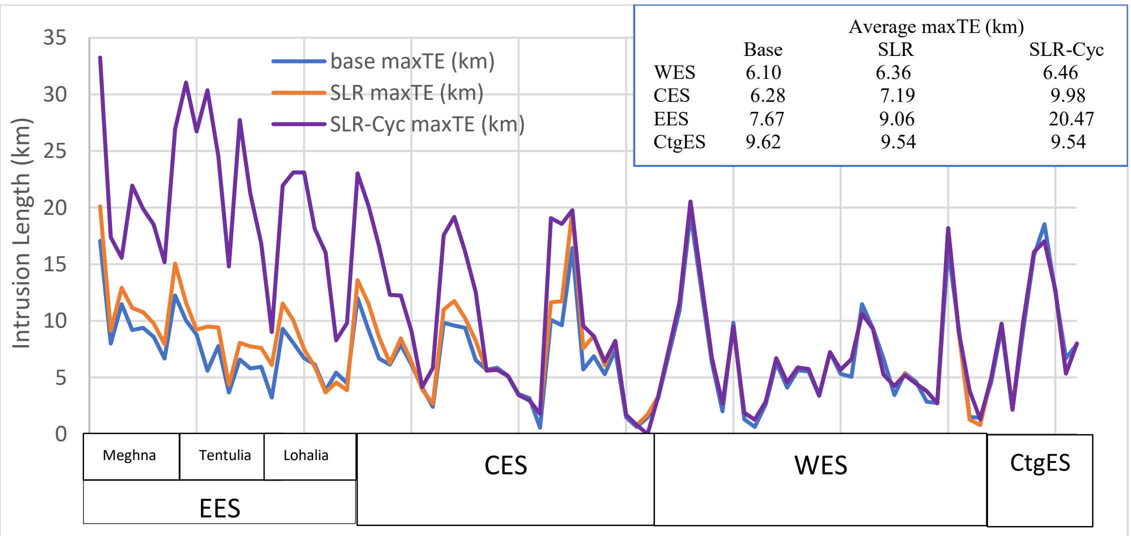


Figure 5.9: Variations of maximum flood velocities along different estuarine systems. The variations are shown for base condition, SLR and SLR-Cyc scenarios.

As TE is dependent on velocity magnitude and direction (Equation 4.3, Chapter 4: Section 4.2.1), changes of TE follows a similar pattern as that of flood velocity (Figure 5.10).



Average maxTE (km)

	Base	SLR	SLR-Cyc
WES	6.10	6.36	6.46
CES	6.28	7.19	9.98
EES	7.67	9.06	20.47
CtgES	9.62	9.54	9.54

Figure 5.10: Variations of tidal excursions along different estuarine systems. The variations are shown for base condition, SLR and SLR-Cyc scenarios.

Figure 5.10 shows that both in base condition and SLR scenario, average magnitude of tidal excursion is almost same for WES and CtgES and approximately 1-1.5 km change in EES-CES. But due to SLR-Cyc scenario, relative increase of TE in EES-CES systems is more compared to WES system. To observe these relative increase, differences of TE of SLR and SLR-Cyc scenarios from the base condition is shown in Figure 5.11. In SLR scenario, average magnitude of TE in all the estuarine systems is 0.74 km longer than the base condition. For SLR-Cyc scenario, this trend remains similar in WES, but not in EES-CES. In EES this increases to 12.8 km, and in CES it is 3.7 km.

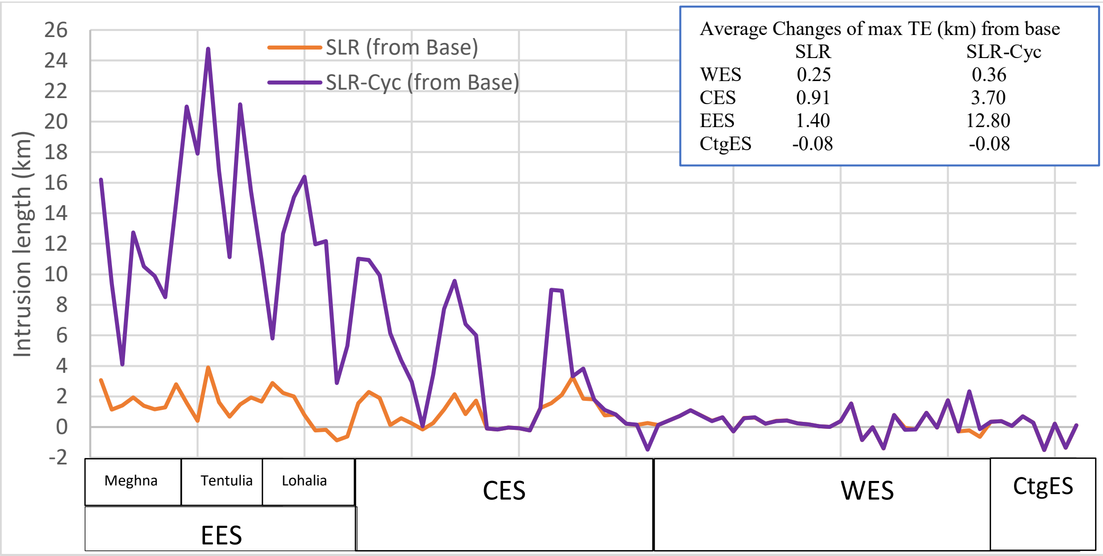


Figure 5.11: Changes in TE length (km) from base condition to scenario conditions (SLR and SLR-Cyc)

These results show that due to 1m sea level rise only, on average, saline front in all the estuarine systems intrudes 0.74 km inland. Due to a SIDR-like cyclone in 1m sea level rise condition, this intrusion length increases into 4.76 km in all the estuarine systems and especially increases in EES. EES faces 4 to 5 times more intrusion length in SLR-Cyc scenario. On the other hand, WES remains almost same as SLR scenario.

5.6. Implication of Residence Time (RT) for a particular Salinity Magnitude

In literature, magnitude of salinity was considered to assess the salinity hazard as magnitude of salinity plays a vital role in livelihood, life of human and ecosystem of the environment of brackish water (Kamal and Khan, 2009). Salinity magnitude has a list of detrimental effect on human and environment based on the scale of salinity magnitude. The water is not usable for domestic purposes if salinity is higher than 1ppt though it is still favourable for crop and livestock agriculture unless salinity exceeds 2ppt (Palash *et al*., 2014). Some of the freshwater aquaculture is still possible when the salinity is below 4ppt (Palash et al, 2014). Agriculture and irrigation is affected vigorously if salinity value is more than 7 ppt (BARC, 2013) (Haque et al., 2016). Normal forestry and fishery are affected if value of salinity exceeds 8 ppt and 10 ppt respectively and in case of more than 10 ppt salinity value, specifically when salinity exceeds 15 ppt, only specialized brackish ecosystem can survive in such saline environment (Hossain *et al*., 2014) (Hossain *et al*., 2013); (Hossain *et al*., 2012).

No study in the past reveals the information on residence time of a particular salinity magnitude. So, it can not be stated with certainty how and to what extent residence time can affect the estuarine ecosystem and human life. To know the effect of RT of a particular salinity value, it requires development of a proper methodology for data collection as well as long term data assessment which is beyond the scope of this research.

As part of a preliminary investigation, a field visit was carried out in February 2017 to understand the combined impact of salinity magnitude and RT. The field visit was made in Dumuria and Shoronkhola Upazila of Khulna and Bagerhat districts (Figure 5.12) of WES. These areas were also under the influence of cyclone SIDR in 2007.

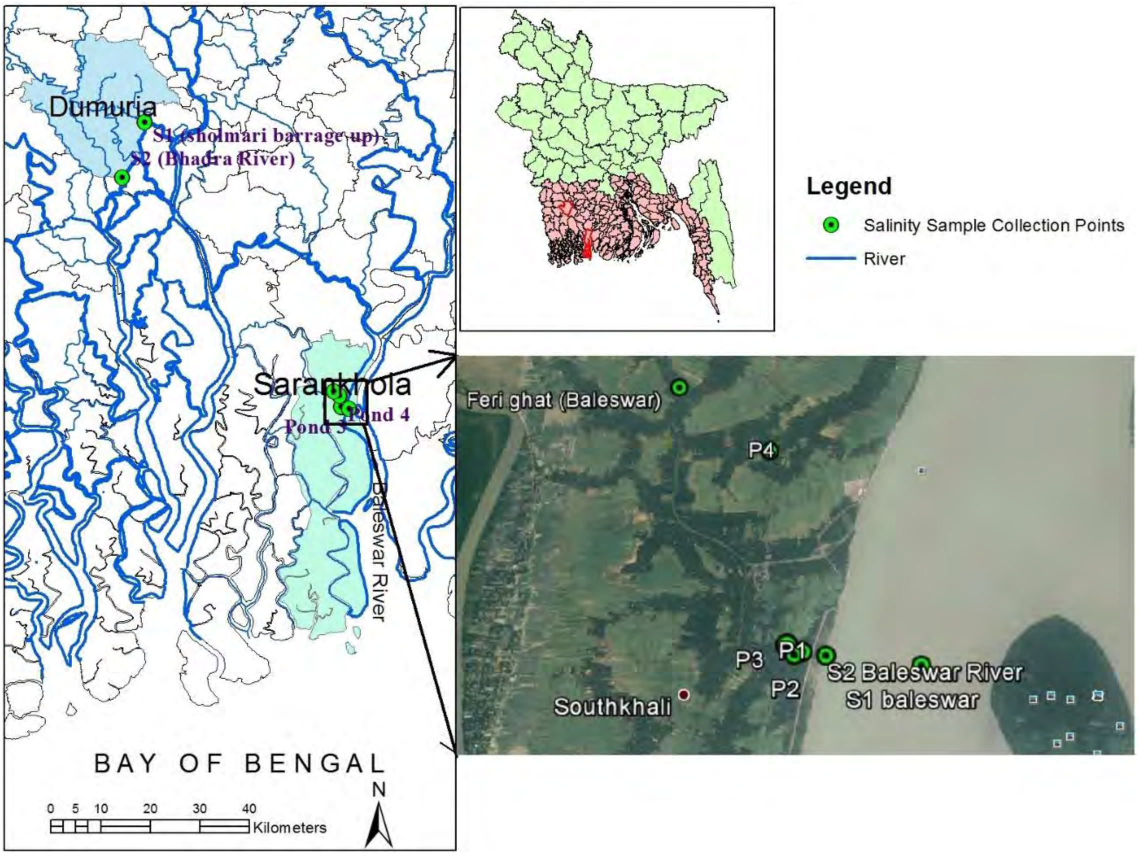


Figure 5.12: Location map of the field visit area

To protect the area from saline water intrusion, there are polders in Dumuria Upazila (Figure 5.12). According to local people, during the high tide in April/May 2015, one of the polder (polder 29) in the study area was breached. This event carried saline water directly inside the polder area and the whole area was waterlogged by saline water for more than a year. Total duration of saline water residence time (RT) was 365 days (determined as the time required to flash out the trapped saline water by natural drainage and evaporation process). Although the processes of salinity intrusion and flash out were different from a normal tidal cycle (intrusion due to polder breaching and flash out due to natural drainage and evaporation), the source of saline water is same of what is simulated in the model (the Shibsha-Passur estuary). Hence, the effect of RT can be observed from this incident.

During field visit (Checklist: Appendix B) to Dumuria and Shoronkhola Upazila of Khulna and Bagerhat districts (Figure 5.12), local people stated that their houses, trees, crops, livelihoods and day to day life were hampered miserably due to salinity. Fishes are not as abundant as it was prior to cyclone SIDR (November 2007) and AILA (May 2009). Trees and crops were also damaged due to prolong trapped salt water intrusion inside the polder (Field Visit, February, 2017). There were barren fields without even a trace of grasses, except the thin white layer of dried out salt patches (Figure 5.13). Fruits had fallen out from the trees due to the long-time water logging of saline water. The agricultural fields were occupied with the dry season's vegetables which do not grow nowadays; the fields were just left barren (Figure 5.13).

Figure 5.13: Barren fields having white salt layers

Source: Field visit, 2017

Trapped saltwater for a long period can cause huge impacts on building materials, roads and concrete infrastructures (Lubelli et al, 2004). Premature deterioration of concrete structures in the form of cracking, spalling of concrete and corrosion of reinforcements in coastal areas is a common feature due to salt crystallization (Bosunia and Chowdhury, 2001). This would enhance the loss of cohesion at the surface of the bricks (Lubelli et al, 2004). During Field visit, damages like 'efflorescence' (migration of salt to the surface of a porous material, where it forms a coating) effect and cracks or blisters were found in the building structures (Figure 5.14 and Figure 5.15).

Figure 5.14: Salt patches and damage of the bricks and plasters

Figure 5.15: Blistering in plaster and crack effects due to surge water of cyclone SIDR

CHAPTER 6

CONCLUSIONS

6.1. Introduction

Salinity intrusion in estuaries of Bangladesh coast is a complex and dynamic process. Salinity is higher in dry season and lower in monsoon. This research defines salinity hazard through a newly developed dimensionless index named NDIS that incorporates the governing parameters of salinity intrusion process. As one of the parameters of NDIS, this research also develops a new parameter related to salinity intrusion process - the residence time of salinity, named as RT.

6.2. Conclusions

Major findings of the study are:

- A new method of assessing salinity hazard is introduced by developing a new indicator named NDIS (Non-Dimensional Index). NDIS incorporates dominant parameters associated with salinity intrusion and represent salinity hazard more rationally than salinity magnitude alone.
- As one of the parameters of NDIS, a new equation is developed to compute the residence time of salinity magnitude which is also a dominant parameter of salinity hazard. Residence time does not follow direct relation with salinity magnitude. But follows a more direct relation with salinity hazard index (NDIS).
- In base condition, salinity magnitude is lowest in the eastern region and in upper part of the central region. Salinity gradually increases from central-east coast to west coast and reaches maximum in western region and Chittagong region. Sea level rise affects estuary mouths of central region and causes saline front to intrude further inland. Cyclonic condition affects the estuaries which are around the landfall location of the cyclone and all along the cyclone track.
- For base condition, salinity washed out within a tidal cycle in middle part of eastern and central region of the coast. Hence, saline water could not reside in this region. Residence time gradually increases from east to west coast and east to Chittagong coast. This pattern is similar to the salinity magnitude pattern along the coast.

- Residence time of salinity showed an interesting phenomenon in cyclonic condition. Along the cyclone track, significant increase in residence time in western coast is observed. But for the same coast, salinity magnitude did not change in similar extent.
- Tidal Excursion (TE) is found to be another important parameter to assess salinity hazard. It represents the landward distance travelled by saline front during a flood tide. In base condition, Meghna estuary has low salinity magnitude and lowest salinity hazard but highest tidal excursion. During a cyclonic condition, saline front travelled almost 4 to 5 times more distance in east coast compared to base condition.
- For base condition, salinity hazard is highest in west coast and lowest in middle and east coast. Sea level rise affects the estuary mouths of eastern, central and upper western regions of the coast. When a SIDR-like cyclone is considered with a sea level rise of 1m, salinity hazard increased in a greater extent along the cyclone track and, also in previously affected region due to sea lever rise.
- Climatic scenarios reveal that compared to base condition, estuary mouths of eastern and central coast faced the highest salinity hazard than other part of the coast. Due to SIDR-like cyclone, significantly increased salinity hazard is noticed along the cyclone track and along the mouths of the estuarine systems.

To date, impact of salinity on irrigation, plant life and ecological health are assessed by using salinity magnitude only (Fipps, 2003), (Singh *et al.*, 2008). However, there are other parameters driving the salinity intrusion that can cause detrimental effect and should be considered when salinity hazard is assessed. This research shed light on this, where not only salinity magnitude but also other governing parameters are incorporated in calculating salinity hazard through NDIS. It might happen that NDIS is beneficial to assess salinity hazard than salinity magnitude only but that cannot be said certainly at this moment because it will require long term assessment of governing parameters following a properly developed methodology to collect data (for example residence time of salinity) and identify the range of NDIS value that represents low, medium and high salinity hazard. It could be an interesting topic of further exploration. However, this can be said certainly that salinity hazard that is defined through NDIS in this research, captures additional information than other researches that represent salinity hazard through salinity magnitude only.

6.3. Limitations of the study

The study developed an analytical equation of RT and formulated NDIS by incorporating all governing parameters of salinity intrusion process to assess salinity hazard. During application of RT and NDIS in coastal region of Bangladesh, following limitations are identified:

1. River discharge Q of base condition, sea level rise and cyclone condition were kept same.
2. The range of NDIS values for which salinity hazard can be qualitatively classified as low, medium and high are not known as it will require long time data collection in the study area.
3. Due to lack of measured data, field validation of RT all along the coast was not possible.

6.4. Recommendations

1. It has been found from field visit and literatures that Residence Time of salt water has a detrimental effect on structures. Hence, value of RT can be incorporated in building codes in coastal areas.

2. Detail research on the threshold values of NDIS (instead of salinity magnitude) and corresponding impacts should be carried out so that NDIS can be used in future by planners and policy makers.

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APPENDIX A

C1:

```
[FileName,PathName] = uigetfile({'*.csv';'*.csv';'*.*'},'Select the Excel file');
RawData = importdata(strcat(PathName,'\',FileName));
DateData = RawData.textdata(2:end,1);
Data = RawData.data;


dt = 2;
SCIdx = 1;
SDate = [];
Volume = [];
MaxTide = [];
MaxTideTime = [];
MaxSal = [];
Sgn = [];
DischargeSum = [];
Velocity = [];



for i = 2 : length(Data(:,1))
  if sign(Data(i-1)) ~= sign(Data(i))
     SCIdx = [SCIdx,i];
  end
end
SCIdx = [SCIdx,i];


for j = 1 : length(SCIdx)-1
   SDate = [SDate; DateData(SCIdx(j))];


   if SCIdx(j) == SCIdx(j+1)-1
```

```
    Volume = [Volume; Data(SCIdx(j))*dt*3600];
    TemporaryD = Data(SCIdx(j),2);
     TemporaryD = TemporaryD(TemporaryD <0);%%%
    if isempty(TemporaryD) == 1;
        TemporaryD = 0;
    end
    c = 0;
else
    Volume = [Volume; trapz(Data(SCIdx(j):SCIdx(j+1)-1,1))*dt*3600];
    TemporaryD = Data(SCIdx(j):SCIdx(j+1)-1,2);


    TemporaryD = TemporaryD(TemporaryD <0);%%%
    if isempty(TemporaryD) == 1;
        TemporaryD = 0;
    end


    c = 1;
end


if (Data(SCIdx(j))) > 0
    [MValue, MIdx] = max(Data(SCIdx(j):SCIdx(j+1)-1,1));
    MSal = max(Data(SCIdx(j):SCIdx(j+1)-1,3));
    Sgn = [Sgn; 1];
else
    [MValue, MIdx] = min(Data(SCIdx(j):SCIdx(j+1)-1,1));
    MSal = max(Data(SCIdx(j):SCIdx(j+1)-1,3));
    Sgn = [Sgn; 0];
end


        if c == 1
```

```
            DischargeSum = [DischargeSum; trapz(TemporaryD*dt*3600)];
        else
            DischargeSum = [DischargeSum; TemporaryD*dt*3600];
        end

    if (Data(SCIdx(j))) > 0
        Velocity = [Velocity; max(Data(SCIdx(j):SCIdx(j+1)-1,4))];
    else
        Velocity = [Velocity; min(Data(SCIdx(j):SCIdx(j+1)-1,4))];
    end

    MIdx = SCIdx(j) + MIdx - 1;
    MaxTide = [MaxTide; MValue];
    MaxTideTime = [MaxTideTime; DateData(MIdx)];
    MaxSal = [MaxSal; MSal];
end

FData = table(SDate, Volume, DischargeSum, Velocity, MaxTide, MaxTideTime,
MaxSal,Sgn);
OutN = ['V-Out ',FileName,'.csv'];
writetable(FData,OutN,'Delimiter',',');
```

C2:

```
[FileName,PathName] = uigetfile({'*.csv';'*.csv';'*.*'},'Select the Excel file');
RawData = importdata(strcat(PathName,'\',FileName));
DateData = RawData.textdata(2:end,1);
Data = RawData.data;

dt = 2;
SCIdx = 1;
SDate = [];
```

```
DischargeSum = [];
Avg = [];



for i = 2 : length(Data(:,1))
  if sign(Data(i-1)) ~= sign(Data(i))
     SCIdx = [SCIdx,i];
  end
end
SCIdx = [SCIdx,i];

for j = 1 : length(SCIdx)-1
   SDate = [SDate; DateData(SCIdx(j))];

   if SCIdx(j) == SCIdx(j+1)-1
      TemporaryD = Data(SCIdx(j),1);
       TemporaryD = TemporaryD(TemporaryD <0);%%%
      if isempty(TemporaryD) == 1;
         TemporaryD = 0;
      end
      c = 0;

   else
      TemporaryD = Data(SCIdx(j):SCIdx(j+1)-1,1);

      TemporaryD = TemporaryD(TemporaryD <0);%%%
      if isempty(TemporaryD) == 1;
         TemporaryD = 0;
      end
```

```
        c = 1;
    end

        if c == 1
        DischargeSum = [DischargeSum; trapz(TemporaryD*dt*3600)];
        Avg = [Avg; mean(TemporaryD)];
        else
          DischargeSum = [DischargeSum; TemporaryD*dt*3600];
          Avg = [Avg; mean(TemporaryD)];
        end

end

FData = table(SDate, DischargeSum,Avg);
OutN = ['QrOut2 ',FileName,'.csv'];
writetable(FData,OutN,'Delimiter',',');

DischargeSum(DischargeSum==0) = min(DischargeSum);
[mx,idx]=max(DischargeSum);

disp(SDate(idx));
disp(mx);
```

T1: Dataset of estuary mouth section of Buriswar estuary for model Input

Date	Discharge	River inflow (Q)	Salinity	velocity
2/1/2011 0:00	141.157	-2773.02	4.827	0.011879
2/1/2011 2:00	5468.27	-2350.92	5.12598	0.351755
2/1/2011 4:00	4315.25	848.761	6.04737	0.281714
2/1/2011 6:00	-2383.83	2779.61	6.33131	-0.15428
2/1/2011 8:00	-6127.01	1031.98	5.6889	-0.41644
2/1/2011 10:00	-5620.64	-1581.3	4.93726	-0.39639
2/1/2011 12:00	617.195	-2689.72	4.45047	0.045203
2/1/2011 14:00	7631.31	-2331.03	4.86214	0.489023
2/1/2011 16:00	8776.05	1159.3	6.20378	0.54677
2/1/2011 18:00	1134.26	3908.96	7.32379	0.079409
2/1/2011 20:00	-5568.83	3190.61	6.95309	-0.36565
2/1/2011 22:00	-6935.59	-535.263	6.03047	-0.4763
2/2/2011 0:00	-3741.5	-2752.23	5.20273	-0.25771
2/2/2011 2:00	3709.03	-3170.65	5.02391	0.244651
2/2/2011 4:00	7071.87	-877.057	5.89617	0.448849
2/2/2011 6:00	906.29	2579.14	6.82899	0.067688
2/2/2011 8:00	-5694.57	2737.79	6.47203	-0.37896
2/2/2011 10:00	-7020.83	-476.481	5.59195	-0.49065
2/2/2011 12:00	-3233.3	-2542.11	4.80818	-0.2249
2/2/2011 14:00	5285.02	-3042.41	4.74569	0.34782
2/2/2011 16:00	10532.1	-541.763	5.91083	0.650618
2/2/2011 18:00	5118.55	3342.2	7.54135	0.334882
2/2/2011 20:00	-4227.25	4420.74	7.72124	-0.26803
2/2/2011 22:00	-7704.04	936.347	6.75397	-0.51924
2/3/2011 0:00	-6606.71	-2371.38	5.74387	-0.46616
2/3/2011 2:00	1210.59	-3441.67	5.12585	0.085594
2/3/2011 4:00	7881.45	-2783.33	5.69572	0.49731
2/3/2011 6:00	4933.8	1514.59	7.01522	0.321133
2/3/2011 8:00	-3973.58	3664.51	7.19379	-0.25756
2/3/2011 10:00	-7726.56	861.9	6.2741	-0.52933
2/3/2011 12:00	-6430.15	-2135.61	5.32124	-0.46075
2/3/2011 14:00	2308.67	-3245.26	4.80318	0.15966
2/3/2011 16:00	10659.6	-2553.48	5.59642	0.661588
2/3/2011 18:00	9280.08	2075.56	7.45086	0.584054
2/3/2011 20:00	-1620.89	4952.23	8.30674	-0.08982
2/3/2011 22:00	-7949.05	2612.99	7.44655	-0.52357
2/4/2011 0:00	-7989.96	-1675.23	6.32214	-0.56133
2/4/2011 2:00	-1447.98	-3492.84	5.37329	-0.09409
2/4/2011 4:00	7273.43	-3635.05	5.5276	0.462255
2/4/2011 6:00	8267.3	14.0088	6.94215	0.517346
2/4/2011 8:00	-1531.85	3809.69	7.73438	-0.09026
2/4/2011 10:00	-7817.02	2375.74	6.9381	-0.52361
2/4/2011 12:00	-7813.67	-1463.4	5.86719	-0.55691
2/4/2011 14:00	-708.108	-3232.22	5.00283	-0.04368

2/4/2011 16:00	9413.81	-3448.05	5.32971	0.592795
2/4/2011 18:00	11943.1	424.762	7.15469	0.735224
2/4/2011 20:00	1349.1	4810.09	8.62846	0.107646
2/4/2011 22:00	-7584.04	4110.52	8.06646	-0.4873
2/5/2011 0:00	-8807.58	-653.437	6.87127	-0.60816
2/5/2011 2:00	-5508.92	-3360.84	5.74683	-0.38797
2/5/2011 4:00	4863.57	-3972.94	5.42694	0.318563
2/5/2011 6:00	9947.45	-1455.97	6.67943	0.61133
2/5/2011 8:00	1452.79	3307.72	8.02068	0.109375
2/5/2011 10:00	-7277.09	3711.15	7.5378	-0.47612
2/5/2011 12:00	-8613.53	-509.748	6.39191	-0.60236
2/5/2011 14:00	-5009.09	-3050.55	5.34565	-0.35562
2/5/2011 16:00	6317.31	-3738.49	5.15372	0.410781
2/5/2011 18:00	13033.7	-1110.59	6.70473	0.79002
2/5/2011 20:00	4646.22	4039.95	8.66475	0.318224
2/5/2011 22:00	-6466.57	5243.94	8.57863	-0.40415
2/6/2011 0:00	-9332.62	598.528	7.35823	-0.62951
2/6/2011 2:00	-7828.31	-3056.11	6.13812	-0.56166
2/6/2011 4:00	2328.47	-4096.93	5.4062	0.160719
2/6/2011 6:00	10554.6	-3267.28	6.29513	0.644953
2/6/2011 8:00	5036.64	2213.69	8.01711	0.338873
2/6/2011 10:00	-5708.83	4544.36	8.03489	-0.36258
2/6/2011 12:00	-9123.86	667.021	6.87701	-0.6228
2/6/2011 14:00	-7534.53	-2687.91	5.7291	-0.54549
2/6/2011 16:00	3282.97	-3822.91	5.09434	0.223581
2/6/2011 18:00	12949.1	-3085.07	6.18517	0.780886
2/6/2011 20:00	8747.2	2684.1	8.39234	0.557413
2/6/2011 22:00	-4132.58	5736.41	8.92972	-0.2454
2/7/2011 0:00	-9576.08	1995.68	7.76571	-0.63125
2/7/2011 2:00	-8758.78	-2490.41	6.48312	-0.62348
2/7/2011 4:00	-309.78	-4055.93	5.44009	-0.01246
2/7/2011 6:00	10080.8	-4041.91	5.87184	0.620103
2/7/2011 8:00	8753.4	688.259	7.72142	0.558843
2/7/2011 10:00	-3122.48	4732.09	8.37228	-0.18453
2/7/2011 12:00	-9132.41	2072.33	7.31332	-0.60651
2/7/2011 14:00	-8489.61	-2098.92	6.09504	-0.60743
2/7/2011 16:00	265.764	-3763.7	5.13904	0.026141
2/7/2011 18:00	11739.9	-3866.52	5.6933	0.715758
2/7/2011 20:00	11995.4	953.328	7.87534	0.735618
2/7/2011 22:00	-1148.54	5532.74	9.06618	-0.04883
2/8/2011 0:00	-9282.26	3361.89	8.09682	-0.59866
2/8/2011 2:00	-9296.17	-1694.67	6.77179	-0.6507
2/8/2011 4:00	-3758.84	-3895.02	5.57741	-0.25728
2/8/2011 6:00	7596.79	-4297.68	5.49557	0.47906
2/8/2011 8:00	11032.7	-698.136	7.19763	0.68219
2/8/2011 10:00	-1.02104	4339.12	8.47055	0.023398

2/8/2011 12:00	-8601.58	3494.76	7.69009	-0.55763
2/8/2011 14:00	-9033	-1189.38	6.42965	-0.63226
2/8/2011 16:00	-3662.85	-3546.72	5.32014	-0.25197
2/8/2011 18:00	8445.07	-4095.43	5.31603	0.531088
2/8/2011 20:00	13219.1	-535.677	7.1949	0.79982
2/8/2011 22:00	1870.47	4789.36	8.93075	0.145912
2/9/2011 0:00	-8416.01	4592.92	8.32536	-0.53187
2/9/2011 2:00	-9652.32	-638.035	6.99132	-0.66112
2/9/2011 4:00	-7297.05	-3585.31	5.74502	-0.52375
2/9/2011 6:00	4436.07	-4338.4	5.22253	0.292913
2/9/2011 8:00	11599	-2440.13	6.52201	0.707234
2/9/2011 10:00	3359.06	3328.93	8.27129	0.239136
2/9/2011 12:00	-7132.4	4620.52	7.9781	-0.45181
2/9/2011 14:00	-9328.28	11.6961	6.73064	-0.63667
2/9/2011 16:00	-7004.61	-3122.16	5.56408	-0.50112
2/9/2011 18:00	4764.19	-4077.51	5.10162	0.313704
2/9/2011 20:00	12732.5	-2412.34	6.46215	0.770441
2/9/2011 22:00	5099.52	3478.56	8.49891	0.347687
2/10/2011 0:00	-6534.27	5287.55	8.44427	-0.40457
2/10/2011 2:00	-9695.28	633.293	7.15495	-0.65006
2/10/2011 4:00	-8327.07	-3076.94	5.89757	-0.59809
2/10/2011 6:00	1599.67	-4196.14	5.06305	0.114328
2/10/2011 8:00	11002.3	-3652.86	5.82813	0.669722
2/10/2011 10:00	7195.28	1826.94	7.74051	0.471272
2/10/2011 12:00	-4271.11	4912.43	8.12782	-0.25974
2/10/2011 14:00	-9068.88	1487.38	6.99963	-0.60346
2/10/2011 16:00	-7951.06	-2421.69	5.82406	-0.5655
2/10/2011 18:00	1691.41	-3854.07	5.04081	0.119592
2/10/2011 20:00	11253.4	-3585.45	5.80186	0.684191
2/10/2011 22:00	8479.63	1721.16	7.7935	0.54226
2/11/2011 0:00	-3552.9	5076.31	8.39439	-0.21022
2/11/2011 2:00	-9175.92	1950.64	7.27181	-0.60438
2/11/2011 4:00	-8566.78	-2309.99	6.03521	-0.6077
2/11/2011 6:00	-1193.26	-3891.65	5.026	-0.07489
2/11/2011 8:00	8819.39	-3937.65	5.25491	0.551349
2/11/2011 10:00	10000.8	181.038	6.96326	0.627426
2/11/2011 12:00	-606.512	4464.08	8.04555	-0.02002
2/11/2011 14:00	-7913.34	3001.1	7.25459	-0.51519
2/11/2011 16:00	-8144.67	-1318.9	6.11225	-0.56691
2/11/2011 18:00	-1546.69	-3425.45	5.16423	-0.10026
2/11/2011 20:00	8080.88	-3770.54	5.34563	0.507613
2/11/2011 22:00	9910.64	-14.8412	6.95777	0.618329
2/12/2011 0:00	-347.962	4216.33	8.11112	-0.00252
2/12/2011 2:00	-7878.17	3149.93	7.35438	-0.51121
2/12/2011 4:00	-8480.46	-1200.66	6.18138	-0.59006
2/12/2011 6:00	-4955.57	-3393.77	5.14866	-0.34801

2/12/2011 8:00	4916.33	-3829.56	4.90109	0.322864
2/12/2011 10:00	10220.6	-1194.28	6.10081	0.628599
2/12/2011 12:00	3295.19	3306.32	7.64039	0.225276
2/12/2011 14:00	-5493.86	4094.98	7.50842	-0.35124
2/12/2011 16:00	-7696.51	272.071	6.47371	-0.52098
2/12/2011 18:00	-5342.6	-2666.49	5.51297	-0.37188
2/12/2011 20:00	3466.9	-3518.28	5.18136	0.229707
2/12/2011 22:00	8921.34	-1747.92	6.14413	0.552763
2/13/2011 0:00	3217.4	2638.42	7.54587	0.213292
2/13/2011 2:00	-5328.08	3750.19	7.41907	-0.34381
2/13/2011 4:00	-7889.81	193.124	6.38937	-0.5374
2/13/2011 6:00	-6549.62	-2594.49	5.40287	-0.46612
2/13/2011 8:00	1088.29	-3458.29	4.80983	0.078285
2/13/2011 10:00	8396.78	-2729.49	5.35348	0.530628
2/13/2011 12:00	7733.44	1493.37	6.83887	0.484982
2/13/2011 14:00	-857.505	4076.54	7.63957	-0.04896
2/13/2011 16:00	-6278.47	2319.18	6.9822	-0.41419
2/13/2011 18:00	-6304.58	-1274.04	6.07073	-0.43393
2/13/2011 20:00	-861.73	-2941.92	5.36897	-0.05545
2/13/2011 22:00	5837.74	-2978.74	5.55252	0.373579
2/14/2011 0:00	6394.16	236.758	6.66699	0.405539
2/14/2011 2:00	-1076.51	3114.62	7.34168	-0.06352
2/14/2011 4:00	-6242.75	1999.95	6.72493	-0.41518
2/14/2011 6:00	-6724.98	-1205.89	5.83	-0.46951
2/14/2011 8:00	-3442.34	-2799.46	5.05495	-0.23936
2/14/2011 10:00	4135.73	-3016.92	4.91861	0.274773
2/14/2011 12:00	8699.59	-642.592	5.86971	0.547743
2/14/2011 14:00	5195.63	2831.14	7.27883	0.3326
2/14/2011 16:00	-2346.12	3831.9	7.6643	-0.14906
2/14/2011 18:00	-6014.01	1264.92	6.93208	-0.40109
2/14/2011 20:00	-5668.44	-1778.02	6.08189	-0.39194
2/14/2011 22:00	11.7615	-2909.02	5.47883	0.003621
2/15/2011 0:00	5759.62	-2579.83	5.78448	0.368735
2/15/2011 2:00	4943.23	771.165	6.83238	0.319433
2/15/2011 4:00	-1967.87	2927.52	7.24224	-0.12503
2/15/2011 6:00	-6144.85	1330.44	6.57763	-0.41414
2/15/2011 8:00	-6296.73	-1469.45	5.73592	-0.44399
2/15/2011 10:00	-1486.82	-2749.04	5.03997	-0.1004
2/15/2011 12:00	6160.58	-2775.5	5.15261	0.400908
2/15/2011 14:00	9694.77	162.39	6.4102	0.60297
2/15/2011 16:00	4136.39	3537.22	7.95413	0.266969
2/15/2011 18:00	-3838.68	4000.49	8.08624	-0.24699
2/15/2011 20:00	-7004.48	707.631	7.15869	-0.47224
2/15/2011 22:00	-6215.7	-2288.1	6.17691	-0.43638
2/16/2011 0:00	888.808	-3245.43	5.54618	0.06343
2/16/2011 2:00	7151.1	-2635.78	6.05957	0.453489

2/16/2011 4:00	5061.75	1352.23	7.34603	0.328085
2/16/2011 6:00	-3110.55	3403.15	7.645	-0.20052
2/16/2011 8:00	-7194.81	1078.83	6.78012	-0.49036
2/16/2011 10:00	-6711.68	-1892.98	5.8153	-0.48063
2/16/2011 12:00	624.317	-3088.25	5.13211	0.047517
2/16/2011 14:00	9487.78	-2873.89	5.64816	0.598058
2/16/2011 16:00	10829.8	1186.2	7.49348	0.669924
2/16/2011 18:00	1183.35	4722.33	8.93535	0.091296
2/16/2011 20:00	-6847.28	3743.24	8.38003	-0.44359
2/16/2011 22:00	-8273.83	-673.918	7.19619	-0.57191
2/17/2011 0:00	-5403.55	-3186.36	6.07559	-0.38098
2/17/2011 2:00	4251.32	-3735.98	5.72574	0.280651
2/17/2011 4:00	9337.78	-1436.07	6.91181	0.579028
2/17/2011 6:00	2053.83	3040.9	8.33663	0.143457
2/17/2011 8:00	-6482.27	3691.92	7.97359	-0.42544
2/17/2011 10:00	-8341.58	-219.428	6.82403	-0.58227
2/17/2011 12:00	-5970.14	-2828.31	5.74423	-0.43047
2/17/2011 14:00	4919.02	-3593.04	5.38602	0.327039
2/17/2011 16:00	13009.7	-1735.58	6.78891	0.78879
2/17/2011 18:00	7357.35	3506.01	9.05523	0.478319
2/17/2011 20:00	-4626.38	5578.86	9.42681	-0.28153
2/17/2011 22:00	-9184.34	1594.33	8.21437	-0.61102
2/18/2011 0:00	-8432.93	-2612.48	6.89893	-0.60322
2/18/2011 2:00	144.084	-3979.56	5.86805	0.017879
2/18/2011 4:00	9968.74	-3818.11	6.40428	0.61512
2/18/2011 6:00	8108.37	1002.04	8.32085	0.519905
2/18/2011 8:00	-3390.93	4663.75	8.90576	-0.20548
2/18/2011 10:00	-8985.81	1869.07	7.79287	-0.60245
2/18/2011 12:00	-8390.21	-2125.41	6.52697	-0.60537
2/18/2011 14:00	384.89	-3707.55	5.52587	0.03425
2/18/2011 16:00	12221.6	-3778.71	6.1427	0.744984
2/18/2011 18:00	13037.6	1043.74	8.55773	0.790957
2/18/2011 20:00	-379.18	5790.45	9.97587	0.001523
2/18/2011 22:00	-9213.26	3819.36	9.03376	-0.59106
2/19/2011 0:00	-9526.32	-1476.17	7.62123	-0.66445
2/19/2011 2:00	-5246.59	-3896.26	6.29317	-0.36835
2/19/2011 4:00	6937.59	-4386.75	6.04023	0.441218
2/19/2011 6:00	11635.1	-1131.4	7.81727	0.712586
2/19/2011 8:00	772.277	4253.81	9.3188	0.074335
2/19/2011 10:00	-8668.57	3907.93	8.57534	-0.55969
2/19/2011 12:00	-9418.9	-981.517	7.20305	-0.65864
2/19/2011 14:00	-5824.86	-3541.27	5.94815	-0.41633
2/19/2011 16:00	7704.1	-4219.42	5.71334	0.490539
2/19/2011 18:00	14959.1	-1223.1	7.72161	0.889483
2/19/2011 20:00	3826.49	4796.31	9.94699	0.270294
2/19/2011 22:00	-8152.45	5558.92	9.56951	-0.50567

2/20/2011 0:00	-10221.4	81.1553	8.13652	-0.68922
2/20/2011 2:00	-8652.55	-3528.86	6.71848	-0.62664
2/20/2011 4:00	3238.89	-4532.63	5.85508	0.219399
2/20/2011 6:00	12557.1	-3640.14	7.06224	0.753742
2/20/2011 8:00	5118.48	2750.18	9.17422	0.351018
2/20/2011 10:00	-6869.96	5251.25	9.09638	-0.42813
2/20/2011 12:00	-10092.6	553.553	7.7134	-0.68107
2/20/2011 14:00	-8502.42	-3099.97	6.36338	-0.61706
2/20/2011 16:00	3464.95	-4287.73	5.53335	0.235297
2/20/2011 18:00	14422.6	-3685.3	6.80824	0.859161
2/20/2011 20:00	8658.53	2859.99	9.36305	0.550266
2/20/2011 22:00	-5439.12	6157.3	9.78384	-0.32239
2/21/2011 0:00	-10442.6	1747.44	8.43077	-0.68412
2/21/2011 2:00	-9370.38	-2807.06	6.99308	-0.66806
2/21/2011 4:00	-360.237	-4424.63	5.77901	-0.0144
2/21/2011 6:00	11541.9	-4397.33	6.28686	0.695461
2/21/2011 8:00	9826.62	752.309	8.50348	0.617715
2/21/2011 10:00	-3508.24	5313.65	9.2479	-0.20132
2/21/2011 12:00	-9966.3	2220.07	8.03125	-0.65227
2/21/2011 14:00	-9154.45	-2331.75	6.64711	-0.65083
2/21/2011 16:00	-391.46	-4089.77	5.51105	-0.01778
2/21/2011 18:00	12218.3	-4291.28	5.99936	0.734802
2/21/2011 20:00	12444.6	676.496	8.39862	0.754606
2/21/2011 22:00	-1737.93	5780.93	9.62458	-0.08241
2/22/2011 0:00	-9902.83	3324.29	8.52206	-0.63375
2/22/2011 2:00	-9689.86	-1872.77	7.09272	-0.67599
2/22/2011 4:00	-4534.38	-4126.71	5.80062	-0.31284
2/22/2011 6:00	8007.2	-4521.79	5.67178	0.501016
2/22/2011 8:00	11952.5	-853.091	7.54867	0.730241
2/22/2011 10:00	249.969	4602.91	9.00681	0.042642
2/22/2011 12:00	-9039.97	3793.01	8.16976	-0.57793
2/22/2011 14:00	-9475.56	-1254.15	6.80563	-0.65699
2/22/2011 16:00	-4992.44	-3726.25	5.60771	-0.34772
2/22/2011 18:00	7838.47	-4352.34	5.47117	0.493014
2/22/2011 20:00	13064.2	-934.549	7.33521	0.789474
2/22/2011 22:00	1639.78	4652.05	9.12804	0.133185
2/23/2011 0:00	-8669.54	4578.07	8.45979	-0.54548
2/23/2011 2:00	-9803.58	-740.732	7.07618	-0.66949
2/23/2011 4:00	-7547.12	-3654.81	5.80778	-0.54182
2/23/2011 6:00	4430.98	-4416.21	5.26869	0.29236
2/23/2011 8:00	11790.2	-2602.7	6.57621	0.718206
2/23/2011 10:00	3654.33	3339.44	8.44555	0.260455
2/23/2011 12:00	-7073.99	4779.39	8.18388	-0.44405
2/23/2011 14:00	-9415.13	109.448	6.8978	-0.63694
2/23/2011 16:00	-7278.02	-3150.29	5.71571	-0.51858
2/23/2011 18:00	4102.14	-4145.46	5.19745	0.27192

2/23/2011 20:00	11972.9	-2707.28	6.41942	0.725519
2/23/2011 22:00	4681.93	3129.42	8.38593	0.322546
2/24/2011 0:00	-6427.01	4978.83	8.30376	-0.39977
2/24/2011 2:00	-9479.53	508.116	7.01757	-0.63663
2/24/2011 4:00	-8029.47	-3022.6	5.80425	-0.57521
2/24/2011 6:00	1748.79	-4114.1	5.05022	0.123629
2/24/2011 8:00	10696.9	-3494.69	5.80618	0.653674
2/24/2011 10:00	7009.16	1884.26	7.68317	0.459443
2/24/2011 12:00	-4024.55	4784.89	8.09782	-0.24563
2/24/2011 14:00	-8706.18	1473.67	6.98605	-0.57864
2/24/2011 16:00	-7618.12	-2345.84	5.8513	-0.53838
2/24/2011 18:00	1421.91	-3755.9	5.12067	0.101004
2/24/2011 20:00	10037.8	-3441.14	5.78825	0.617384
2/24/2011 22:00	7270.82	1534.96	7.57736	0.471942
2/25/2011 0:00	-3626.89	4551.54	8.07336	-0.22053
2/25/2011 2:00	-8588.58	1605.42	6.9862	-0.5707
2/25/2011 4:00	-7900.43	-2227.83	5.84355	-0.56017
2/25/2011 6:00	-433.256	-3673.95	4.99293	-0.02311
2/25/2011 8:00	8591.54	-3590.45	5.32253	0.540059
2/25/2011 10:00	8971.43	546.647	6.93077	0.562635
2/25/2011 12:00	-905.828	4255.8	7.91137	-0.04531
2/25/2011 14:00	-7378.13	2686.93	7.12893	-0.48436
2/25/2011 16:00	-7421.07	-1343.96	6.06369	-0.51571
2/25/2011 18:00	-944.667	-3252.84	5.24375	-0.05968
2/25/2011 20:00	7279.8	-3428.51	5.47392	0.46115
2/25/2011 22:00	8141.05	199.257	6.87785	0.507152
2/26/2011 0:00	-1160.95	3740.28	7.77444	-0.066
2/26/2011 2:00	-7282.11	2464.99	7.00688	-0.48151
2/26/2011 4:00	-7498.34	-1349.99	5.95672	-0.52451
2/26/2011 6:00	-2576.37	-3151.64	5.10665	-0.17539
2/26/2011 8:00	5660.8	-3376.19	5.1026	0.368007
2/26/2011 10:00	8917.59	-390.204	6.29263	0.556796
2/26/2011 12:00	1865.37	3334.2	7.57326	0.128747
2/26/2011 14:00	-5307.49	3429.19	7.30275	-0.34608
2/26/2011 16:00	-6720.43	-159.079	6.36023	-0.45766
2/26/2011 18:00	-3371.17	-2573.58	5.5581	-0.23031
2/26/2011 20:00	3825.65	-3106.98	5.43388	0.251121
2/26/2011 22:00	7134.33	-826.101	6.3484	0.450561
2/27/2011 0:00	1139.04	2583.22	7.37345	0.081873
2/27/2011 2:00	-5330.28	2815.41	7.04809	-0.35083
2/27/2011 4:00	-6716.72	-393.113	6.14859	-0.46201
2/27/2011 6:00	-4136.95	-2492.95	5.35678	-0.28805
2/27/2011 8:00	2694.31	-2991.03	5.10791	0.182035
2/27/2011 10:00	7471.58	-1234.56	5.83754	0.476182
2/27/2011 12:00	4819.48	2185.93	7.07137	0.311593
2/27/2011 14:00	-2114.14	3416.39	7.43449	-0.13532

2/27/2011 16:00	-5433.22	1160.48	6.7672	-0.36338
2/27/2011 18:00	-4359.03	-1612.84	6.03298	-0.2982
2/27/2011 20:00	712.618	-2602.22	5.64158	0.04913
2/27/2011 22:00	5045.85	-1913.36	6.01834	0.325207
2/28/2011 0:00	3306.65	1058.74	6.89039	0.217626
2/28/2011 2:00	-2507.47	2511.82	7.06588	-0.1637
2/28/2011 4:00	-5380.44	651.483	6.43569	-0.36392
2/28/2011 6:00	-4585.95	-1582.3	5.74482	-0.31852
2/28/2011 8:00	-35.1767	-2443.52	5.31176	-0.00053
2/28/2011 10:00	5099.89	-1929.48	5.57245	0.333496
2/28/2011 12:00	6101.52	783.343	6.51676	0.391827
2/28/2011 14:00	1649.6	2809.34	7.38148	0.111112
2/28/2011 16:00	-3034.91	2449.31	7.30871	-0.20001
2/28/2011 18:00	-4398.9	-49.3526	6.70271	-0.29654
2/28/2011 20:00	-2787.42	-1861.76	6.14417	-0.18936
2/28/2011 22:00	1400.66	-2193.15	5.93772	0.093797

T2: Model output of T1 table

Date	Volume (V)	Maximum Velocity	Maximum Salinity	Tidal cycle
2/1/2011 6:00	-7.3E+07	-0.41644	6.33131	ebb
2/1/2011 12:00	1.24E+08	0.54677	7.32379	flood
2/1/2011 20:00	-8.3E+07	-0.4763	6.95309	ebb
2/2/2011 2:00	67532616	0.448849	6.82899	flood
2/2/2011 8:00	-8.3E+07	-0.49065	6.47203	ebb
2/2/2011 14:00	1.13E+08	0.650618	7.54135	flood
2/2/2011 20:00	-9.4E+07	-0.51924	7.72124	ebb
2/3/2011 2:00	78866244	0.49731	7.01522	flood
2/3/2011 8:00	-9.3E+07	-0.52933	7.19379	ebb
2/3/2011 14:00	1.18E+08	0.661588	7.45086	flood
2/3/2011 20:00	-1.3E+08	-0.56133	8.30674	ebb
2/4/2011 4:00	55946628	0.517346	6.94215	flood
2/4/2011 8:00	-1.2E+08	-0.55691	7.73438	ebb
2/4/2011 16:00	1.25E+08	0.735224	8.62846	flood
2/4/2011 22:00	-1.1E+08	-0.60816	8.06646	ebb
2/5/2011 4:00	94360536	0.61133	8.02068	flood
2/5/2011 10:00	-1.1E+08	-0.60236	7.5378	ebb
2/5/2011 16:00	1.33E+08	0.79002	8.66475	flood
2/5/2011 22:00	-1.2E+08	-0.62951	8.57863	ebb
2/6/2011 4:00	1.03E+08	0.644953	8.01711	flood
2/6/2011 10:00	-1.1E+08	-0.6228	8.03489	ebb
2/6/2011 16:00	1.37E+08	0.780886	8.39234	flood
2/6/2011 22:00	-1.5E+08	-0.63125	8.92972	ebb
2/7/2011 6:00	67803120	0.620103	7.72142	flood
2/7/2011 10:00	-1.1E+08	-0.60743	8.37228	ebb

2/7/2011 16:00	1.29E+08	0.735618	7.87534	flood
2/7/2011 22:00	-1.5E+08	-0.6507	9.06618	ebb
2/8/2011 6:00	67066164	0.68219	7.19763	flood
2/8/2011 10:00	-1.4E+08	-0.63226	8.47055	ebb
2/8/2011 18:00	1.32E+08	0.79982	8.93075	flood
2/9/2011 0:00	-1.3E+08	-0.66112	8.32536	ebb
2/9/2011 6:00	1.12E+08	0.707234	8.27129	flood
2/9/2011 12:00	-1.2E+08	-0.63667	7.9781	ebb
2/9/2011 18:00	1.27E+08	0.770441	8.49891	flood
2/10/2011 0:00	-1.2E+08	-0.65006	8.44427	ebb
2/10/2011 6:00	1.11E+08	0.669722	7.74051	flood
2/10/2011 12:00	-1.1E+08	-0.60346	8.12782	ebb
2/10/2011 18:00	1.18E+08	0.684191	7.7935	flood
2/11/2011 0:00	-1.4E+08	-0.6077	8.39439	ebb
2/11/2011 8:00	67752684	0.627426	6.96326	flood
2/11/2011 12:00	-1.2E+08	-0.56691	8.04555	ebb
2/11/2011 20:00	64769472	0.618329	6.95777	flood
2/12/2011 0:00	-1.4E+08	-0.59006	8.11112	ebb
2/12/2011 8:00	1.03E+08	0.628599	7.64039	flood
2/12/2011 14:00	-9.4E+07	-0.52098	7.50842	ebb
2/12/2011 20:00	88297128	0.552763	7.54587	flood
2/13/2011 2:00	-1E+08	-0.5374	7.41907	ebb
2/13/2011 8:00	92215044	0.530628	6.83887	flood
2/13/2011 14:00	-9.7E+07	-0.43393	7.63957	ebb
2/13/2011 22:00	44034840	0.405539	6.66699	flood
2/14/2011 2:00	-1.1E+08	-0.46951	7.34168	ebb
2/14/2011 10:00	96229944	0.547743	7.27883	flood
2/14/2011 16:00	-7.2E+07	-0.40109	7.6643	ebb
2/14/2011 22:00	59307233	0.368735	6.83238	flood
2/15/2011 4:00	-1E+08	-0.44399	7.24224	ebb
2/15/2011 12:00	1.07E+08	0.60297	7.95413	flood
2/15/2011 18:00	-8.7E+07	-0.47224	8.08624	ebb
2/16/2011 0:00	72909929	0.453489	7.34603	flood
2/16/2011 6:00	-8.7E+07	-0.49036	7.645	ebb
2/16/2011 12:00	1.53E+08	0.669924	8.93535	flood
2/16/2011 20:00	-1E+08	-0.57191	8.38003	ebb
2/17/2011 2:00	89930556	0.579028	8.33663	flood
2/17/2011 8:00	-1E+08	-0.58227	7.97359	ebb
2/17/2011 14:00	1.38E+08	0.78879	9.05523	flood
2/17/2011 20:00	-1.1E+08	-0.61102	9.42681	ebb
2/18/2011 2:00	1.01E+08	0.61512	8.32085	flood
2/18/2011 8:00	-1.1E+08	-0.60537	8.90576	ebb
2/18/2011 14:00	1.36E+08	0.790957	8.55773	flood
2/18/2011 20:00	-1.6E+08	-0.66445	9.97587	ebb
2/19/2011 4:00	1.12E+08	0.712586	9.3188	flood
2/19/2011 10:00	-1.2E+08	-0.65864	8.57534	ebb

2/19/2011 16:00	1.49E+08	0.889483	9.94699	flood
2/19/2011 22:00	-1.3E+08	-0.68922	9.56951	ebb
2/20/2011 4:00	1.2E+08	0.753742	9.17422	flood
2/20/2011 10:00	-1.3E+08	-0.68107	9.09638	ebb
2/20/2011 16:00	1.47E+08	0.859161	9.36305	flood
2/20/2011 22:00	-1.6E+08	-0.68412	9.78384	ebb
2/21/2011 6:00	76926672	0.695461	8.50348	flood
2/21/2011 10:00	-1.5E+08	-0.65227	9.2479	ebb
2/21/2011 18:00	88786440	0.754606	8.39862	flood
2/21/2011 22:00	-1.6E+08	-0.67599	9.62458	ebb
2/22/2011 6:00	1.16E+08	0.730241	9.00681	flood
2/22/2011 12:00	-1.2E+08	-0.65699	8.16976	ebb
2/22/2011 18:00	1.28E+08	0.789474	9.12804	flood
2/23/2011 0:00	-1.3E+08	-0.66949	8.45979	ebb
2/23/2011 6:00	1.14E+08	0.718206	8.44555	flood
2/23/2011 12:00	-1.2E+08	-0.63694	8.18388	ebb
2/23/2011 18:00	1.18E+08	0.725519	8.38593	flood
2/24/2011 0:00	-1.2E+08	-0.63663	8.30376	ebb
2/24/2011 6:00	1.09E+08	0.653674	7.68317	flood
2/24/2011 12:00	-1E+08	-0.57864	8.09782	ebb
2/24/2011 18:00	1.04E+08	0.617384	7.57736	flood
2/25/2011 0:00	-1.3E+08	-0.5707	8.07336	ebb
2/25/2011 8:00	63226692	0.562635	6.93077	flood
2/25/2011 12:00	-1.1E+08	-0.51571	7.91137	ebb
2/25/2011 20:00	55515060	0.507152	6.87785	flood
2/26/2011 0:00	-1.2E+08	-0.52451	7.77444	ebb
2/26/2011 8:00	91300860	0.556796	7.57326	flood
2/26/2011 14:00	-8E+07	-0.45766	7.30275	ebb
2/26/2011 20:00	69240060	0.450561	7.37345	flood
2/27/2011 2:00	-8.2E+07	-0.46201	7.04809	ebb
2/27/2011 8:00	80845020	0.476182	7.07137	flood
2/27/2011 14:00	-6.2E+07	-0.36338	7.43449	ebb
2/27/2011 20:00	50799485	0.325207	6.89039	flood
2/28/2011 2:00	-8.1E+07	-0.36392	7.06588	ebb
2/28/2011 10:00	68229108	0.391827	7.38148	flood
2/28/2011 16:00	-5.3E+07	-0.29654	7.30871	ebb
2/28/2011 22:00	37512360	0.25558	6.95228	flood

T3: Estuary wise calculated value of NDIS and related parameters

X	Y	Estuary name	Cross section name	Maximum Residence Time RT (hr)	Maximum Velocity ν (m)	Minimum Discharge Q (m^3/s)	Maximum Salinity (ppt)	NDIS base	Kinematic Viscosity κ
90.89	22.12	Meghna (downstream to upstream)	01meghna1	20.29	1.24	17993.945	8.276	7.622	0.00083
90.97	22.30		02meghna1_1_2	16.95	0.61	17993.945	7.215	2.854	0.00083
90.96	22.49		03meghna2	14.6	0.69	17993.945	4.692	2.465	0.00082
90.81	22.63		04meghna3	15.77	0.59	17993.945	3.127	1.970	0.00082
90.73	22.78		05meghna4	14.29	0.69	17252.028	1.547	1.916	0.00082
90.68	22.88		06meghna4_1_5	57.79	0.59	15347.355	0.73	6.075	0.00082
90.61	23.01		07meghna5	13.84	0.48	12040.753	0.053	1.450	0.00082
90.62	23.20		08meghna6	12.36	0.91	12367.568	0.003	2.097	0.00082
90.49	21.91	Tentulia	10tentulia4	22.81	0.8	2286.503	8.226	34.680	0.00083
90.51	21.95		11tentulia4_1_3	21.54	0.68	1362.470	5.378	41.201	0.00083
90.55	22.00		12tentulia4_2_3	13.37	3.25	1362.470	3.337	108.654	0.00082
90.36	21.99		14tentulia0_1	17.11	0.55	1540.439	4.582	26.634	0.00082
90.43	22.05		15tentulia1	9.862	0.28	2516.400	2.209	4.527	0.00082
90.58	22.19		17tentulia2	10.2	0.5	4259.087	1.073	5.213	0.00082
90.65	22.35		18tentulia5	10.22	0.42	4259.087	1.106	4.221	0.00082
90.64	22.48		19tentulia5_1_6	10.19	0.45	4259.087	1.152	4.437	0.00082
90.59	22.59		20tentulia6	13.41	0.26	2993.193	1.18	4.404	0.00082
90.29	21.87	Lohalia	23lohalia1	28.76	0.67	2648.509	13.96	36.667	0.00083
90.33	22.00		25lohalia2_1_3	24.71	0.56	179.233	6.499	394.464	0.00083
90.41	22.15		26lohalia3	21.69	0.49	179.233	5.213	317.813	0.00083
90.40	22.23		27lohalia3_1_4	17.43	0.48	179.233	4.396	231.761	0.00082
90.39	22.32		28lohalia3_2_4	13.49	0.28	179.233	3.189	102.152	0.00082
90.36	22.36		29lohalia4	11.78	0.4	151.065	1.966	147.187	0.00082
90.40	22.41		30lohalia5	12.48	0.37	151.065	1.474	144.609	0.00082
90.07	21.98	Buriswar	32buriswar1	27.65	0.89	1189.547	11.46	99.080	0.00083
90.15	22.10		33buriswar1_1_2	18.07	0.69	1189.547	5.531	44.926	0.00083
90.22	22.15		34buriswar2	13.24	0.5	1189.547	2.657	25.817	0.00082
90.21	22.31		35buriswar2_1_3	11.29	0.44	1189.547	2.009	20.464	0.00082
90.27	22.36		36buriswar3	13.97	0.57	472.186	1.817	80.533	0.00082
90.28	22.42		37buriswar3_1_4	14.49	0.42	290.047	1.522	99.244	0.00082
90.40	22.48		38buriswar3_2_4	13.36	0.36	265.461	1.328	79.549	0.00082
90.43	22.50		39buriswar3_3_4	11.38	0.17	415.539	1.178	20.093	0.00082

90.00	21.98	Bishkhali	41bishkhali1	38.35	0.73	501.258	14.18	297.396	0.00083
90.03	22.09		42bishkhali1_1_2	26.48	0.68	501.258	8.055	179.646	0.00083
90.07	22.16		43bishkhali2	17.51	0.67	501.258	4.061	89.954	0.00082
90.08	22.24		44bishkhali2_1_3	12.32	0.48	501.258	1.044	55.763	0.00082
90.16	22.42		45bishkhali2_2_3	11.04	0.42	501.258	0.712	42.305	0.00082
90.20	22.49		46bishkhali3	11.07	0.44	501.258	0.672	43.747	0.00082
90.20	22.57		47bishkhali3_1_4	10.1	0.4	501.258	0.686	35.089	0.00082
90.18	22.63		48bishkhali4	11.18	0.31	462.636	0.7	32.951	0.00082
90.25	22.63		49bishkhali4_1_5	13.64	0.29	462.636	0.733	37.340	0.00082
90.36	22.67		50bishkhali4_2_5	26.19	0.06	462.636	0.808	14.843	0.00082
89.91	21.95	Baleswar	52baleswar1	40.26	0.68	2030.433	15.6	71.810	0.00084
89.88	22.04		53baleswar2	28.54	0.67	2030.433	9.685	46.340	0.00083
89.89	22.18		54baleswar3	18.73	1.22	2030.433	5.182	47.678	0.00083
89.86	22.29		55baleswar3_1_4	14.84	0.42	2030.433	2.781	14.611	0.00082
89.90	22.37		56baleswar4	12.98	0.51	942.824	1.58	30.379	0.00082
89.99	22.48		57baleswar5	11.93	0.43	942.824	0.625	22.264	0.00082
90.03	22.59		58baleswar6	13.53	0.6	661.057	0.474	54.992	0.00082
90.08	22.64		59baleswar7	14.63	0.12	386.229	0.398	20.236	0.00082
90.10	22.75		60baleswar7_1_8	11.61	0.06	386.229	0.38	7.300	0.00082
90.17	22.81		61baleswar8	12.25	0.1	386.229	0.368	13.737	0.00082
90.25	22.81		62baleswar8_1_9	19.35	0.25	148.598	0.386	132.573	0.00082
89.51	21.76	Shibsha-Rupsha	66Shib-Rup1	44.44	0.77	6708.528	27.91	28.378	0.00082
89.53	21.91		67Shib-Rup2(Rupsha1)	50.96	1.18	2060.022	24.78	159.053	0.00081
89.55	22.00		68Rupsha1	69.03	0.42	9.711	21.26	15736.743	0.00081
89.55	22.20		69Rupsha2	58.13	0.14	9.711	18.94	4337.012	0.00081
89.60	22.43		70rupsha3	55.12	0.63	9.711	18.38	12168.985	0.00081
89.57	22.55		71rupsha3_1_4	109.6	0.11	9.711	13.41	6004.455	0.00080
89.54	22.59		72rupsha4	13.68	0.05	265.566	13.75	12.274	0.00080
89.53	22.73		73rupsha5	22.87	0.18	171.573	7.681	101.275	0.00079
89.51	21.99		75Shibsha1	49.27	0.42	780.076	21.68	181.397	0.00081
89.48	22.20		76shibsha2	43.64	0.28	780.076	19.03	78.530	0.00081
89.44	22.40		77shibsha3	34.31	0.39	780.076	17.56	84.629	0.00080
89.43	22.46		78shibsha3_1_4	32.53	0.38	780.076	16.68	79.276	0.00080
89.42	22.53		79shibsha3_2_4	26.42	0.23	780.076	16.03	38.255	0.00080
89.35	21.80	Arpanghasia	83sundar1	90.89	0.51	2.248	28.55	114607.027	0.00082
89.38	21.90		85sundar0_1	86.98	0.42	2.248	27.59	85108.745	0.00082
89.36	21.98		86Sundar4	82.56	0.36	2.248	25.91	65497.990	0.00081

89.34	21.97		88sundar5	72.89	0.8	2.248	26.61	131319.070	0.00082
89.32	22.18		89sundar6	69.15	0.63	2.248	27	95043.923	0.00082
89.27	22.32		90sundar8	58.4	0.45	2.248	23.91	56500.592	0.00081
89.28	21.83	Malancha	84sundar3	79.88	0.25	364.528	30.27	288.790	0.00082
89.23	22.00		92sundar1_1	77.43	0.34	364.528	29.29	357.996	0.00082
89.21	22.12		93sundar2_1	51.63	0.33	364.528	28.36	224.921	0.00082
89.25	22.21		94sundar3_1	44.81	0.24	364.528	27.65	139.966	0.00082
89.19	22.39		95sundar5_2	37.26	0.16	364.528	24.72	81.918	0.00081
89.18	21.81	Sundarban-Jamuna	97sundar1_2	91.44	1.07	33.619	31.77	17277.146	0.00082
89.16	22.02		98sundar2_2	83.77	0.62	33.619	31.8	8220.839	0.00082
89.13	22.15		99sundar3_2	1859	0.11	33.619	32.56	30931.629	0.00082
89.09	22.18		100sundar4_2	706.6	0.09	33.619	32.69	9969.129	0.00082
91.39	22.77	Little Feni	102littlefeni	23.52	0.31	988.878	7.001	38.318	0.00079
91.34	22.84		103little feni	17.72	0.61	988.878	5.971	51.627	0.00079
91.44	22.76	Feni	105feni	29.23	0.15	110.471	7.152	213.274	0.00079
91.50	22.90		106feni	28.4	0.45	110.471	7.049	576.467	0.00079
91.86	22.12	Sangu	114sangu5	38.54	1.11	14.312	10.4	12594.131	0.00078
91.88	22.16		115sangu3_1_4	33.73	1.33	14.312	9.187	16552.258	0.00078
91.94	22.18		116sangu3_2_4	36.09	0.86	14.312	9.143	11437.616	0.00078
91.81	22.23	Karnafuli	108haldasangu	215.4	0.57	2534.829	1.184	61.733	0.00077
91.89	22.42		112halda3	9.584	0.59	472.775	2E-07	6.848	0.00077

T4: Estuary wise classification of NDI and related parameters

NDI	RT	Q	ν	S_{max}	κ	**Estuary name (d/s to u/s)**
Low	Low	High	High	Medium	High	**Meghna**
Low	Low	High	Medium	Medium	High	
Low	Low	High	Medium	Medium	High	
Low	Low	High	Medium	Medium	High	
Low	Low	High	Medium	Medium	High	
Low	Low	High	Medium	Low	High	
Low	Low	High	Medium	Low	High	

Low	Low	High	Medium	Low	High	
Low	Low	Medium	Medium	Medium	High	**Tentulia**
Low	Low	Medium	Medium	Medium	High	
Low	Low	Medium	High	Medium	High	
Low	Low	Medium	Medium	Medium	High	
Low	Low	Medium	Medium	Medium	High	
Low	Low	Medium	Medium	Low	High	
Low	Low	Medium	Medium	Low	High	
Low	Low	Medium	Medium	Low	High	
Low	Low	Medium	Medium	Low	High	
Low	Low	Medium	Medium	High	High	**Lohalia**
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Medium	Medium	High	High	**Buriswar**
Low	Low	Medium	Medium	Medium	High	
Low	Low	Medium	Medium	Medium	High	
Low	Low	Medium	Medium	Medium	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Low	Low	High	
Low	Low	Low	Medium	High	High	**Bishkhali**
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Low	Medium	Low	High	
Low	Low	Low	Medium	Low	High	
Low	Low	Low	Medium	Low	High	
Low	Low	Low	Medium	Low	High	
Low	Low	Low	Medium	Low	High	
Low	Low	Low	Medium	Low	High	
Low	Low	Low	Low	Low	High	
Low	Low	Medium	Medium	High	High	**Baleswar**

Low	Low	Medium	Medium	Medium	High	
Low	Low	Medium	High	Medium	High	
Low	Low	Medium	Medium	Medium	High	
Low	Low	Medium	Medium	Medium	High	
Low	Low	Medium	Medium	Low	High	
Low	Low	Low	Medium	Low	High	
Low	Low	Low	Low	Low	High	
Low	Low	Low	Low	Low	High	
Low	Low	Low	Low	Low	High	
Low	Low	Low	Medium	Low	High	
Low	Low	High	Medium	High	High	**Shibsha-Rupsha**
Low	Low	Medium	High	High	High	
Medium	Low	Low	Medium	High	High	
Low	Low	Low	Low	High	High	
Medium	Low	Low	Medium	High	High	
Medium	Medium	Low	Low	High	High	
Low	Low	Low	Low	High	High	
Low	Low	Low	Medium	Medium	High	
Low	Low	Medium	Medium	High	High	
Low	Low	Medium	Medium	High	High	
Low	Low	Medium	Medium	High	High	
Low	Low	Medium	Medium	High	High	
Low	Low	Medium	Medium	High	High	
High	Medium	Low	Medium	High	High	**Arpanghasia**
High	Medium	Low	Medium	High	High	
High	Low	Low	Medium	High	High	
High	Low	Low	Medium	High	High	
High	Low	Low	Medium	High	High	
High	Low	Low	Medium	High	High	
Low	Low	Low	Medium	High	High	**Malancha**
Low	Low	Low	Medium	High	High	
Low	Low	Low	Medium	High	High	
Low	Low	Low	Medium	High	High	
Low	Low	Low	Low	High	High	
Medium	Medium	Low	High	High	High	**Sundarban-Jamuna**
Medium	Medium	Low	Medium	High	High	

Medium	High	Low	Low	High	High	
Medium	High	Low	Low	High	High	
Low	Low	Medium	Medium	Medium	High	**Little Feni**
Low	Low	Medium	Medium	Medium	High	
Low	Low	Low	Low	Medium	High	**Feni**
Low	Low	Low	Medium	Medium	High	
Medium	Low	Low	High	High	Medium	**Sangu**
Medium	Low	Low	High	Medium	Medium	
Medium	Low	Low	Medium	Medium	Medium	
Low	Medium	Medium	Medium	Low	Low	**Karnafuli**
Low	Low	Low	Medium	Low	Low	

Appendix A

C3:

$$T = \frac{(V+P)T}{(1-b)P + (1+b)\frac{QT}{2}} \times \frac{S}{S_0}$$

Sample calculation

We have

$$T = \frac{(V+P)T}{(1-b)P + (1+b)\frac{QT}{2}} \times \frac{2\left\{-QT\left(\frac{S+S_0}{S-S}\right) - QTb\right\} - QT(1-b)}{2\left\{-QT\left(\frac{S+S_0}{S-S}\right) - QTb\right\} + QT(1+b)}$$

……………….………….. (4.20)

$NDI = \frac{\kappa \times v \times RT}{Q}$…………………..(4.25)

let,

For a tidal cycle in any particular cross-section of an estuary,

Low tide Volume, V= 2000 m^3/s

Tidal storage (between ebb and flood tide), P= 4000 m^3/s

Tidal period, T= 12 hours

Maximum salinity, S= 7 ppt and Ocean Salinity, S_0= 35 ppt

Maximum flood velocity, ν= 0.75 m/s

Kinematic viscosity, κ= 0.00085

River inflow, Q= 1000 m^3/s

Return flow factor, b=0.5

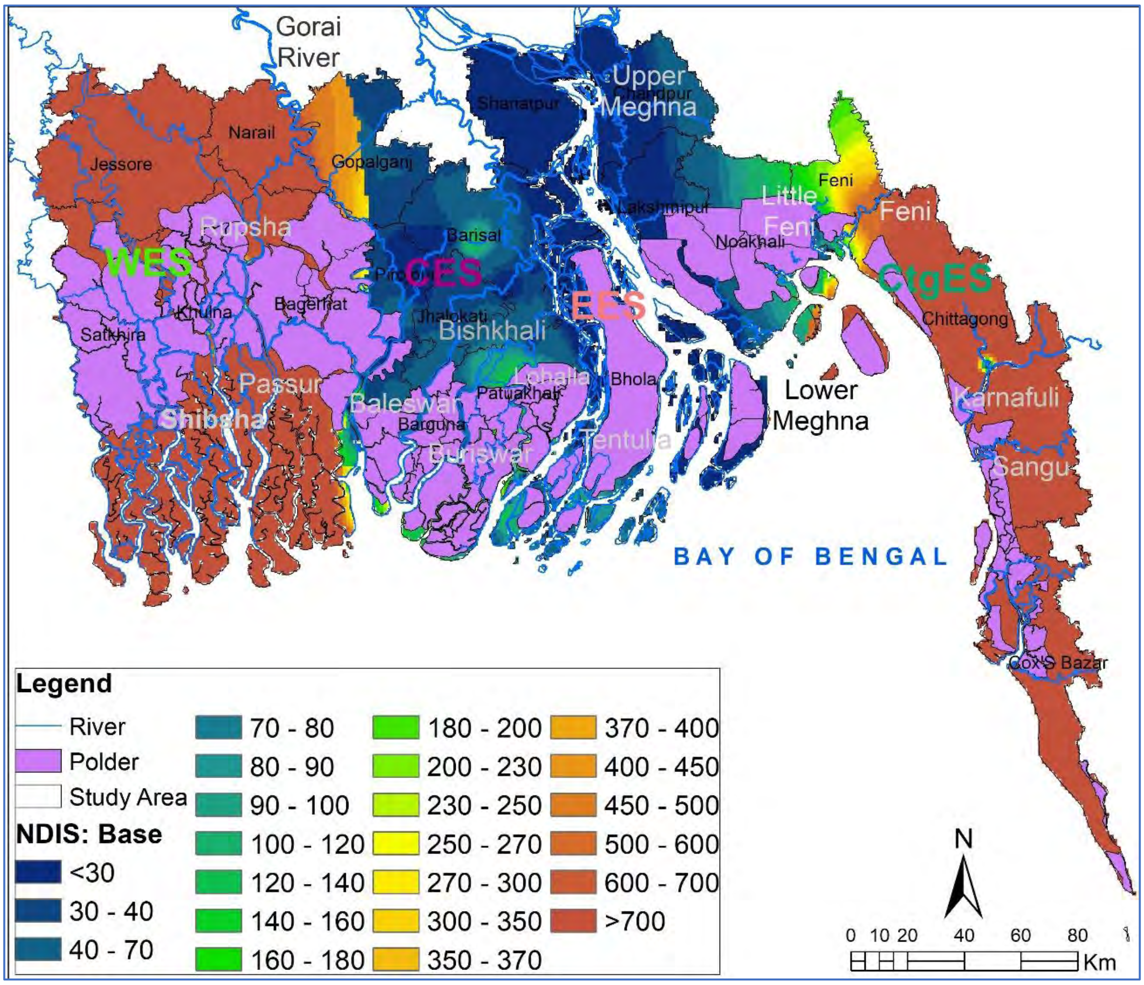
Hence, from Equation (4.20),

$$RT = \frac{(2000+4000)\times 12\times 3600}{(1-0.5)4000 + (1+0.5)\frac{1000\times 12\times 3600}{2}} \times \frac{2\left\{-1000\times 12\times 3600\left(\frac{7+35}{7-35}\right) - 1000\times 12\times 3600\times 0.5\right\} - 1000\times 12\times 3600(1-0.5)}{2\left\{-1000\times 12\times 3600\left(\frac{7+35}{7-35}\right) - 1000\times 12\times 3600\times 0.5\right\} + 1000\times 12\times 3600(1+0.5)}$$

= 17.63 hours

And from Equation (4.25),

$$NDIS = \frac{0.00085\times 0.75\times 17.63\times 3600}{1000} = 0.0405$$



Appendix A-Figure A1: NDIS of Base condition excluding the poldered area

APPENDIX B

To collect the information regarding surface water salinity hazard, a checklist was prepared before.

<u>Checklist to collect field information:</u>

Type of salt water inundation:

☐ Tidal flooding from estuary water salinity

☐ Trapped saline water (storm surge/polder breach)

☐ Other (specify):

Frequent inundated areas within Upazila (by saline water)

Time of salt water residence, duration: **(if location exists, collect sample)**

total…………………………………………..hours/days/months

Starting time:

Ending time:

Impact on Fisheries

Top Fish species:

Fishes that come in wet season but leave in dry season:

Irrigation Water from estuary:

Trees affected by salt water:

Type of house:

☐Pacca ☐ Semi-Pacca ☐Kacha ☐Jhupri ☐ Others

Foundation of the house:

Type: Depth: Materials:

Wall of the house:

Type: Depth: Materials:

Roof of the house:

Type: Depth: Materials:

Problems due to salt water residence time (RT) on building: **(photograps of problem)**

Any other view from the local people: