STORM SURGE PROPAGATION AND CROP DAMAGE ASSESSMENT IN A COASTAL POLDER OF BANGLADESH

BY

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Md. Gulam Kibria

Dedicated to

The First batch SAWA fellows

for giving colors to my last three years;

for teaching me the meaning of friendship; and

for all the memories we had;

All will be just like treasures till the last day……..

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Abstract

The coastal zone of Bangladesh, characterized by a wide network of river and canal systems, faces frequent cyclonic storms as well as associated surges causing devastation of human lives, crops and other properties. Increasing population density, rising sea level, poor socio-economic conditions and low adaptive capacity to natural disasters are likely to increase the coastal people's vulnerability especially to water related disasters. In the south-west coastal zone, losses and damages due to storm surges in a coastal polder are largely caused by embankment failure which is often the result of human interventions along with natural reasons. This study investigated the storm surge propagation processes into Polder 32 of Dacope upazila of Khulna district and assessed the associated losses and damages, considering Cyclone Aila (2009) as the base event. This study involved the application of a numerical model, called Delft3D, and a mapping tool, called ArcGIS 10.2, to simulate the inundation scenarios associated with polder failure. Primary and secondary information from different sources were analyzed to assess the losses and damages in different sectors including household and agriculture for two modes of embankment failure, namely breaching and overtopping. Primary data were collected using Participatory Rural Appraisal (PRA) tools including social and resource mapping, Focus Group Discussions (FGDs), group discussions, individual interviews and Key Informant Interviews (KIIs). Secondary data were collected from different Government and non-Government organizations and published scientific literatures. The study found that human interventions such as insertion of pipes and holes through the embankment to allow saline water into the shrimp gher aggravated the polder failure during Aila. Results showed that the breaching rate was faster in the earlier period of the event where almost 50% of the total breaching took place within the first 6 hours of the event. Model simulations showed that approximately 25%, 80% and 90% of Polder 32 were inundated due to overtopping, breaching and combined breaching and overtopping, respectively. It was found that 50% of the total impacts were immediate impact, whereas 16% were short term impact. About 58% and 27% of the estimated total impacts in Polder 32 were on agriculture and household sectors, respectively. Crop production dropped down from 4.0-4.5 t/ha to 3.75-4.0 t/ha in the fourth year after Aila though for the first three years the loss was 100%. About 34% of the total impacts in the study area were accounted as long term impact. It was also found that 88% of the long term impacts were only in the agriculture sector. The study concluded that the severity of losses and damages due to Aila was aggravated due to long term inundation inside the polder which was the consequence of breaching of Polder 32, and various human interventions to the polder was a major factor responsible for severe polder breaching.

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ABBREVIATIONS AND ACRONYMS

BBS	Bangladesh Bureau of Statistics
BDT	Bangladeshi Taka
BMD	Bangladesh Meteorological Department
BRAC	Bangladesh Rural Advancement Committee (Former name)
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
CARE	Comprehensive AIDS Resources Emergency
CEGIS	Center for Environmental and Geographic Information Services
CEP	Coastal Embankment Project
DEM	Digital Elevation Model
EPWAPDA	East Pakistan Water and Power Development Board
FGD	Focus Group Discussion
FVCOM	Finite Volume Coastal Ocean Model
GCM	General Circulation Model
GDP	Gross Domestic Product
HH	Household
IDRC	International Development Research Centre
IPCC	Intergovernmental Panel on Climate Change
IWFM	Institute of Water and Flood Management
IWTC	International Workshop on Tropical Cyclones
KII	Key Informant Interview
MCSP	Multi-purpose Cyclone Shelter Project
NGO	Non-governmental Organization
PRA	Participatory Rural Appraisal
PWD	Public Works Department
SAWA	South Asian Water
SLR	Sea Level Rise
SRES	Special Report on Emissions Scenarios
SRTM	Shuttle Radar Topography Mission
SST	Sea Surface Temperature

SWAN	Simulating WAves Nearshore
UNO	Upazila Nirbahi Office
WB	World Bank

CHAPTER ONE
INTRODUCTION

1.1 Background and Rationale

About 324 natural disasters were registered globally in 2014 which caused 140.8 million victims worldwide and estimated economic damages of US$ 99.2 billion (CRED, 2015). Hydro meteorological events are increasing day by day as a result of global climate change (ISDR, 2009). During the last two decades, the greatest number of natural disasters related deaths and associated losses and damages took place in Asia (Cropper and Sahin, 2009). It is reported that Bangladesh, China and India are most likely to experience the greatest number of natural disasters in Asia due to their geographical locations (UNEP, 2002).

Bangladesh is connected to the Indian Ocean through a coastline of 700 km along the north and the north-east part of the Bay of Bengal (Khan & Awal, 2009). The coastal zone of Bangladesh is characterized by a wide network of river and canal system, a dynamic Ganges-Brahmaputra-Meghna estuary shared with India, Nepal, Bhutan and China. The coastal belt is frequently hit by cyclonic storms and associated storm surges causing devastation of human lives, crops and properties. Since 1970, the country has experienced 36 cyclonic storms resulting in over 450,000 deaths and a huge economic loss (UNDP 2010). The trend of cyclonic disasters hitting the coast of Bangladesh is very alarming and increasing at the rate of 1.18 per year from 1950-2000 (Islam and Peterson, 2009). Several studies anticipate increasing number of disastrous events in Bangladesh in the future changed climatic conditions (IPCC, 2007; WB, 2010). Higher population density, poor socio-economic conditions and lower adaptive capacity to natural disasters are likely to increase their vulnerability especially to water related disasters (Agarwala *et al*., 2003).

Surge water rises up to several meters during cyclonic events, which sweeps the coastal region of Bangladesh killing people and livestock, washing household assets and agricultural crops, fisheries and destroying other flora and fauna (Karim, 2005).

Since 1960s coastal embankments have been providing protection to the coastal region against regular tidal inundations of inland areas. But those embankments are capable of preventing surges up to a certain limit, whereas severe events overtop or break through them. A previous study estimated that 13 coastal polders will be overtopped due to 62 cm sea level rise in the year 2080 under A2 scenario, and 45% of the population will experience medium to severe inundation (IWM and CEGIS, 2007).

In the recent past, the coast of Bangladesh was hit by severe cyclones Sidr in 2007 and Aila in 2009. Though, by definition, Aila falls into a ‘weak cyclone’ category in terms of wind speed and also as its landfall occurred outside of Bangladesh. But due to its economic cost and long-term sufferings, the impacts of Aila outweigh those of any cyclone in the past. It severely affected at least 12 out of 19 coastal districts of Bangladesh (Roy *et al.,* 2009). About 2.3 million people were affected by this event and many coastal inhabitants were stranded in the affected area, as they had no safe alternatives to survive. At many points the surge had risen almost three to four meters, which caused overtopping of embankments, breaching at some points, and inundation of households and croplands (Kumar *et al.,* 2010).

Climate change is likely to increase the frequency and magnitude of the natural disasters, including cyclones and storm surges (IPCC, 2007). In case of Bangladesh, the south west coastal region is particularly vulnerable to water related natural disasters. The coastal region is protected by embankments. But during severe cyclonic events, those embankments are likely to fail, causing inland flooding by saline surge water. These inundations that may be stretched up to several years may cause huge economic losses and damages both short term and long term. The magnitude and nature of those impacts largely depend on the mode of embankment failure and duration and depth of inundation. On the other hand, the duration and depth of inundation itself depend on the mode of embankment failure. The embankment failures do not solely depend on the surge height, but also on human interventions. At this stage, it is important to learn how the surge water during a cyclonic storm surge intrudes into a coastal protected area and how the nature and magnitude of losses and damages in different livelihood sectors vary with the mode of embankment failures.

1.2 Objectives

The goal of this study was to assess the storm surge propagation process into a coastal protected area and to determine the associated losses and damages in different livelihood sectors. This study also aimed to assess the sectoral and temporal variation of losses and damages with the modes of embankment failure. The specific objectives of the study were:

(i) to understand the process of storm surge propagation into a coastal polder, and

(ii) to assess possible losses and damages due to polder breaching and overtopping.

1.3 Scope and Limitation of the Study

Almost every year, the south-west coastal region of Bangladesh is hit by different cyclonic storm surges of varying intensity. During those cyclonic events, the embankments which are supposed to protect the coastal settings cannot prevent surge water intrusion into the polders all the time. Sometimes the embankments fail and cause huge losses and damages in different sectors. This study emphasized both of those issues and also determined the sectoral and temporal variations of the impacts. The analysis of failure processes included breaching and overtopping processes. Sectoral assessment of losses and damages involved household, agriculture and embankment with immediate, short term and long term impact analysis on the aforementioned sectors. This study revealed that along with the contributions of surge height on polder overtopping, different human interventions e.g. polder cutting, inserting holes in the existing embankments resulted in subsequent polder breaching. All sectors were not equally affected; rather they depended on the time of occurrence of the cyclonic events and mode of embankment failure. Therefore, it is paramount to control the human interventions to minimize the risk of embankment failures and lessen the subsequent losses and damages. This study also summarized that adaptation strategies should be formulated based on sectoral priorities- which is also an important message to the policy makers.

This study has some limitations as well. There is a direct relationship between climate change and storm surge (Lowe and Gregory, 2005). Due to lack of sufficient water level, discharge, cross section and roughness data this study tried to simplify the model simulation and estimated the gross surge height level. Moreover, high resolution DEM (Digital Elevation Model) data for finer grids were not available which also limits the simulation of the failure scenarios. The polder height was found to be variable and ranged from 3.65 to 4.00 m (PWD). For all of the above reasons the exact field condition was difficult to simulate for different scenarios in the model.

Very limited literature and secondary data on the local level losses and damages were available. So data from the local people, which were collected five years after Cyclone Aila, were the only primary data source. Moreover, there was no documentation of the velocity of the surge water, inundation depth and duration during Aila in the study area. So those data were approximated based on the local people's information and understanding.

The damage assessment was performed based on the data obtained from affected people from limited locations. Data from the entire study area was difficult to obtain in a short span of time. At the same time, access to these remote places was also very difficult.

1.4 Structure of the Thesis

This study has been organized in six chapters. The first chapter provides with relevant background information, rationale of the study, objectives, scope and limitation of the study. The second chapter deals with relevant literatures on the coastal zone of Bangladesh, effects of the major historical storm surge hazards in Bangladesh, impact of climate change on storm surge processes, storm surge modeling, polder failure processes, losses and damages associated with natural disasters, etc.

The third chapter briefly discusses the location, general information on demography, livelihood pattern, land use pattern, socio-economic condition, river system, climate, etc., of the study area. The fourth chapter provides with the methodology of the study, including selection of tools for the study, collection of different primary and secondary data, interpretation of data, assessment of losses and damages, etc. Chapter five deals with the detailed results and discussion on the findings of the study. The last chapter provides the conclusions and recommendations of the study.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Storm surge, polder failures, inland inundation due to storm surge, losses and damages due to storm surge, etc., were the key focuses in this study. Scientific literatures were studied for information on the surge height during Aila, depth and duration of surge water inside the polders, polder failures, inundated area, affected sectors, changes in livelihood and land use, etc. Information about the past cyclonic history, critical disaster seasons in Bangladesh and traditional crop pattern were also studied from different literatures. Various terminologies and issues, including coastal polders of Bangladesh, impact of climate change on storm surge propagation, surge amplification processes along the coast, etc., were reviewed which helped to understand the relevant problems in a better way. It helped to develop an in-depth idea about the coastal settings of Bangladesh and detailed scenarios caused by Aila, which made further field work easier.

2.2 Coastal Zone of Bangladesh

An area where land meets sea or ocean, or a line that acts as the boundary between the land and the ocean is termed as coastline (The Merriam-Webster Dictionary, 2000; The American Heritage Dictionary of the English Language, 2008). Nelson (2007) defines a coastal zone as a dynamic region where the interactions between sea and land are occurred. In many cases the terms ‘coast’ and ‘coastal’ are used interchangeably to describe a geographic location, e.g. New Zealand’s coast, Coastal Bangladesh etc. A coastal profile consists of various segments namely near shore, backshore, foreshore, surf zone, etc., which are illustrated in Figure 2.1.

A precise definition of the coastline is quite difficult due to a coastline paradox. The coastal zone is continuously changing because of the dynamic interaction between ocean and lands.

Lunkapis (1998) described the general concept and detailed profile of the coastal zone as follows;

- It is an area having the dynamic nature of biological, chemical and geological features.
- The area has a growing notion of population migration and a significant role in the urban development.
- It acts as a barrier for urban, peri-urban pollution and discharges to the sea
- Cyclonic storm surges, coastal erosion, accretion, flooding, tsunamis, etc., are the common features of the coastal zone.

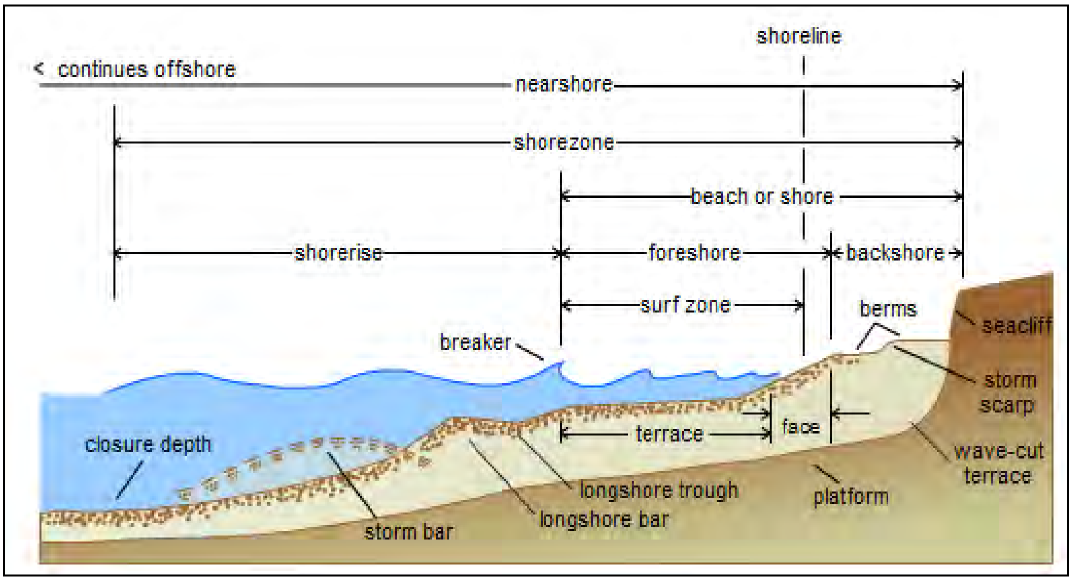


Figure 2.1: Coastal zone profile (*source*: Hogan, 2011).

Along the north and the north-east part of the Bay of Bengal, Bangladesh is connected to the Indian Ocean through a coastline of 700 km (Khan & Awal, 2009). The coastal zone of Bangladesh is characterized by a wide network of river and canal system, a dynamic Ganges-Brahmaputra-Meghna estuary shared with India, Nepal, Bhutan and China. The coastal Zone of Bangladesh consists of 19 districts namely Bagerhat, Barguna, Barisal, Bhola, Chandpur, Chittagong, Cox's Bazar, Feni, Gopalganj, Jessore, Jhalakathi, Khulna, Lakshmipur, Narail, Noakhali, Patuakhali, Pirojpur, Satkhira and Shariatpur (PDO-ICZMP, 2003a). The coastal zone of Bangladesh has an area of 47201 km^2, which is 32% of the total area of

Bangladesh (Khan & Awal, 2009). Moreover, 48 upazilas in the 12 coastal districts are defined as the exposed coast due to their high exposure to the sea and the remaining 99 upazilas are termed as interior coast (PDO-ICZMP, 2003a) (Figure 2.2). In Geo-morphological point of view the coast of Bangladesh is divided into three distinct categories (MCSP, 1993; PDO-ICZMP, 2001) namely west zone, central zone and east zone which are described below in brief.

Western coastal zone is mainly the flood plain of the Ganges river. It encompasses the south-west portion of the country and consists of an interconnected river network of the Sibsa river, the Passur river, the Bishkhali-Buriswar river and the Tetulia river. Sediment flow, land erosion and accretion are relatively low in the rivers of this region. The Sundarbans, the largest mangrove forest is located in this region.

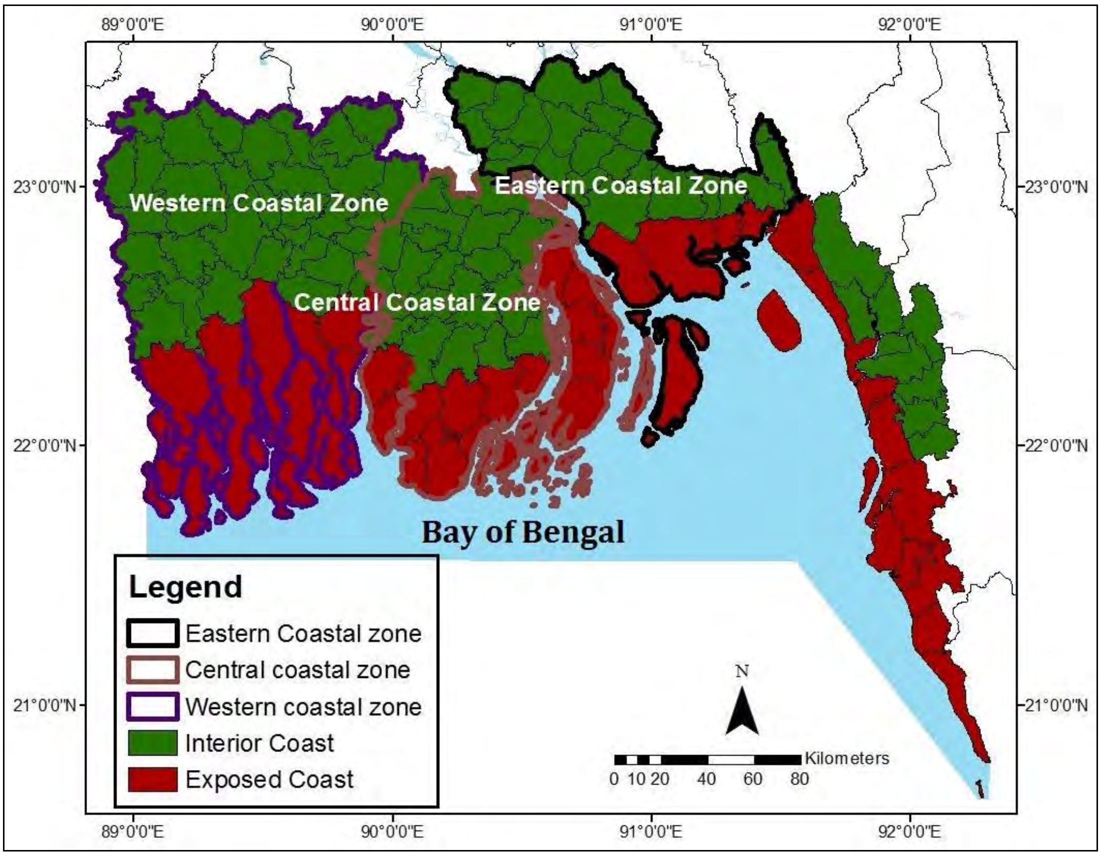


Figure 2.2: Coastal Zone of Bangladesh (*data source*: IWFM, BUET).

Central coastal zone consists of the deltaic region of the Ganges-Brahmaputra-Meghna rivers. The dynamic nature of this zone is defined by a large amount of sediment carrying of the rivers to the Bay of Bengal. Erosion and accretion are dominant in this region. Eastern coastal zone encompasses the Chittagong and Cox's bazaar coast. This is the most stable region of the country which includes the Matamuhuri delta and the Karnaphuli estuary.

2.3 South-western Coastal Polder

Polder, a Dutch term, is an area of low-lying land that has been reclaimed from a body of water and is protected by dikes. According to the encyclopedia, a Polder is a low-lying tract of land enclosed by embankments (barriers) known as dikes that forms an artificial hydrological entity, meaning it has no connection with outside water other than through manually operated devices. There are 139 coastal polders in Bangladesh (Khan, 2014). 49 of the polders are sea facing and all of the polders were constructed in the 1960s under the Coastal Embankment Project (CEP). The project was implemented by Bangladesh Water Development Board (BWDB) between 1961 and 1978 to protect the coast from tidal flooding and reduce salinity incursion.

East Pakistan Water and Power Development Board (EPWAPDA) was established in 1960 on the basis of the Krug mission report set up by the United Nations and the irrigation department was merged with it (Kibria, 2005). A Master Plan formulated in 1964, introduced a new system, e.g. compartmentalized polder or enclosure system in the south-west coastal areas. Almost 1566 kilometers of coastal embankment and 282 sluice gates were constructed under this master plan (Figure 2.3). This project was funded by USAID and done so to prevent intrusion of saline water from the sea and recover more land for agricultural activities in the south-west coastal area. The enclosed polder system isolated the floodplains from the rivers and as a result, many wetlands turned into dry lands in the course of time (Adnan, 2006). Thirty-seven polders were initially constructed in Khulna, Satkhira and part of Jessore district (Ali and Ahmed, 2001). Coastal polders were developed and implemented in line with the "green revolution" paradigms of "grow more food" program. The objective was to improve the cultivation of high yielding variety crops during dry seasons with controlled irrigation when the unavailability of fresh water was a common phenomenon (Adnan, 2006). Moreover, salinity was identified as the main problem for decreasing food production in this area. On completion of the project, paddy production increased, but it was not sustainable.

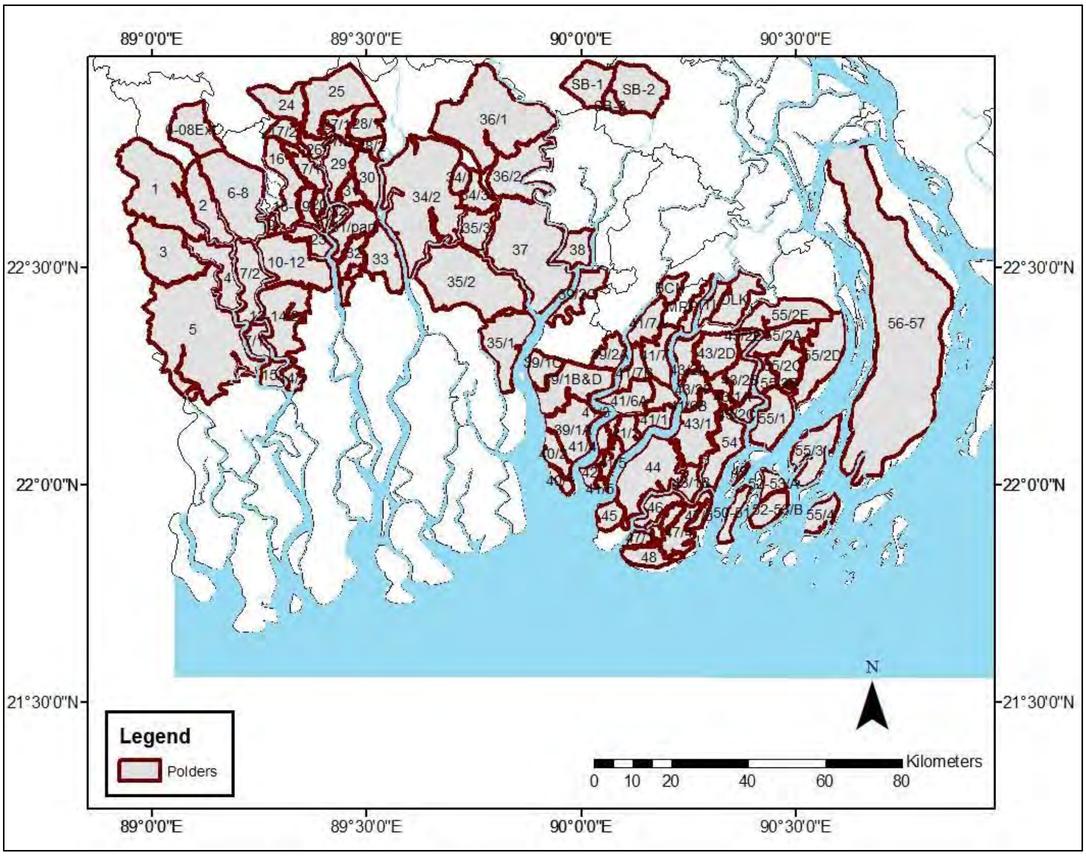


Figure 2.3: Coastal polders in south-west and south-central regions of Bangladesh (*data source:* IWFM, BUET).

A brackish water ecosystem results in a unique ecological and geological combination of the south-west region of Bangladesh. The south-west coastal zone possesses a fragile ecosystem and is highly exposed to tropical cyclones, floods, tidal surges, repeated waterlogging, land degradation etc., that shape the lives and livelihood patterns of people. The polder system was initiated for minimizing those problems in the coastal belts of Bangladesh.

The following issues are related to the polder development and implementation in the south-west coastal zone as identified in PDO-ICZMP, 2002:

- Erosion of the coastal embankments
- Lack of operation and maintenance
- Poor construction and management
- Intervention in the embankment
- Weak structures
- Silting up of the inside canals and outside rivers

2.4 Cyclones and Storm Surges in Bangladesh

Since 1960, approximately 5 million people were killed worldwide in cyclonic disasters and the greatest number of deaths occurred in Asia in the last 20 years (Cropper and Sahin, 2009). The reason behind the above statement is the increasing number of hydro meteorological events due to climate change (ISDR, 2009). Since 1994, two thirds of the recorded tropical cyclonic disasters affected the coastal zone of Bangladesh (UN, 2005). A previous study of Nicholls *et al*. (1995) estimated that in the last two centuries, more than 40% of the 1.9 million disaster related deaths occurred in Bangladesh. A study by WB (2010) also found that vulnerability of Bangladesh to cyclones and cyclonic storm surges may increase in the future as a result of climate change.

2.4.1 Major cyclonic hazards

The strength of a cyclonic disaster mainly depends on rain, strong wind and storm surges (Dube *et al.*, 2009). When tropical cyclones are associated with storm surges, they cause severe damages. Cyclonic events have always been familiar phenomena along the coast of the Bay of Bengal, which have seriously affected the coast of Bangladesh, India, Myanmar and Sri Lanka. Historical evidence highlights that during the past 200 years, 2.6 million people have been affected severely during cyclones and associated surge events (Nicholls, 2003). McBride (1995) stated that every year almost 80 storm surge events with wind speed equal to or greater than 17 m/s take place around the world. Neumann (1993) estimated that 6.5% of the global cyclonic events form in the North Indian Ocean.

Among the tropical cyclones formed in the Bay of Bengal during the period 1877 to 1995, it is seen that Bangladesh is hit by about 1% of the world's total tropical cyclones, India by 3.34%, Myanmar by 0.51% and Sri Lanka by 0.22% (Ali, 1999). A table representing the partial list of severe cyclonic events that caused death toll in excess of 5000 lives is given in Table 2.1. Considering the tropical cyclones with a death toll in excess of 5000, it is found that 16 out of 35 disasters occurred in Bangladesh, 11 in India (Table 2.1).

Among the recent events, Sidr (2007) and Aila (2009) were the most disastrous. Sidr stroke the coast of Bangladesh on November, 2007 and killed almost 3000 people, injured 50000, destroyed 1.5 million homes and affected livelihoods of over 7 million people (BDMIC, 2007; UN, 2007). Aila hit the coast of Bangladesh on 25 May, 2009 and 155 persons was reported dead, 10 missing, 7,108 injured. During the event, about 8,01,602 families were affected and 36,06,116 people became homeless (DMB, 2009). Another source (IFRCRCS, 2009) reported that 2,40,000 homes were completely destroyed and 3,70,000 homes were partially destroyed. Damage of 3,27,406 acres of agricultural lands was reported (IRIN, 2009). In recent years, due to climate change the cyclonic activity in the Bay of Bengal has become more frequent (MoEF, 2009). A brief account of the recent events is given in Table 2.2. In general, it is found that storm surge acts as the key factor for cyclonic disaster in the coastal region of Bangladesh (Chowdhury and Rahman, 1998). Bangladesh is considered to experience 40% of the global storm surges (Murty and El Sabh, 1992). The reasons attributed for these disproportional large impacts on the Bangladesh coast (Ali, 1999) are:

- The phenomenon of recurvature of tropical cyclones in the Bay of Bengal
- Shallow continental shelf
- High tidal range
- Triangular shape at the tip of the Bay of Bengal
- Low lying geography of the Bangladesh coastal land
- High population density and fragile coastal protection system

Table 2.1: Noteworthy tropical cyclonic disasters in the Bay of Bengal (Data up to 1991 from Ali and Chowdhury, 1997 and data after 1991 from Wikipedia).

Year	Location	Deaths
1584	Bangladesh	2,00,000
1737	India	3,00,000
1779	India	20,000
1822	Bangladesh	40,000
1833	India	50,000
1839	India	20,000
1854	India	50,000
1864	India	50,000
1876	Bangladesh	1,00,000
1895	India	5,000
1897	Bangladesh	1,75,000
1912	Bangladesh	40,000
1919	Bangladesh	40,000
1941	Bangladesh	7,500
1942	India	40,000
1960	Bangladesh	5,149
1961	Bangladesh	11,468
1963	Bangladesh	11,520
1965 (11 May)	Bangladesh	19,279
1965 (31 May)	Bangladesh	12,000
1970	Bangladesh	5,00,000
1971	India	10,000
1977	India	10,000
1985	Bangladesh	11,069
1988	Bangladesh	5,708
1989	India	20,000
1991	Bangladesh	1,38,000
2008	Myanmar	1,38,366

Table 2.2: Chronology of the recent cyclonic events in Bangladesh (1995-2015) (*source*: Wikipedia).

Time	Affected areas	Nature of the phenomena	Damage status
November 21-25, 1995	Cox’s bazar	Cyclonic storm W=210 km/h	Casualty: 650 people, 17,000 cattle.
May 16-19, 1997	Chittagong, Cox's Bazar, Noakhali and Bhola districts	Cyclone, w=225 km/h, s=3.05 m	Casualty: 126 people
May 16-20, 1998	Chittagong, Cox's Bazar, and Noakhali	Cyclonic storm, w=150 km/h, s=1.83-2.44 m	-
November 19-22, 1998	Khulna, Barisal, and Patuakhali	Cyclonic storm, w=90 km/h, s=1.22-2.44 m	-
November 15, 2007	Southern Bangladesh	Cyclone Sidr	Causing over 2,000 deaths and severe damage
October 25, 2008	Barisal coast	Cyclone Rashmi W=85 km/h,	15 people killed, severe damages
April 14, 2009	Chittagong coast	Cyclone Bijli, w=95 km/h, s=2.1-3.0 m	7 people killed, 84 injured, 3825 homes and 3636 acre agricultural land damaged
May 25, 2009	Coastal Bangladesh	Cyclone Aila, w=120 km/h, s=3.0 m	500000 people homeless, severe damages
July 26- August 2, 2015	South-eastern Bangladesh	Cyclonic storm Komen	23 people killed, 130400 people affected

2.5 Impact of Climate Change on Cyclone and Storm Surge Processes

Multiple vulnerabilities to cyclones and storm surges, salinity intrusions, erosion and fragile coastal embankments make the coastal zone of Bangladesh different from the rest of the country (PDO-ICZMP, 2004). Damage causing cyclones occur almost every year. According to Dasgupta *et al.* (2010) and other scientific evidences, vulnerability of Bangladesh to cyclonic storm surges may increase even more as a result of climate change and increased sea surface temperature. Some studies predict an increase in the frequency and intensity of cyclonic storm surges due to climate change and the coast of Bangladesh will experience amplified storm surges (Emanuel, 2005; Webster *et al*., 2005; Bengtsson *et al.*, 2006). The International Workshop on Tropical Cyclones (IWTC) has recently proposed that if the projected rise in sea level due to global warming occurs, then the vulnerability to tropical cyclonic storm surge and flooding will increase and experience a 3-5% increase in wind speed per degree Celsius increase of tropical sea surface temperature (IWTC, 2006; Pielke *et al*., 2005).

2.5.1 Wind speed

Sea surface temperature (SST) of the ocean and the thermal energy of the upper ocean waters highly influence the formation of cyclonic events. Scientific studies show that minimum temperature of 26 to 27^{0}C is required for cyclone formation. An increase in SST is likely to increase the wind speed as a result of convective instability caused by increased SST. Ali (1999) stated that the stress exerted by the wind on the water surface is proportional to the square of the wind velocity. Classification of the cyclones in the South Asia, depending on the wind speed is given in Table 2.3.

Table 2.3: Classification of cyclones based on wind speed (Choudhury, 1992).

Depression	Winds up to 62 km/h
Cyclone Storm	Winds from 63-87 km/h
Severe Cyclone Storm	Winds from 88-118 km/h
Severe Cyclonic Storm of Hurricane Intensity	Winds above 118 km/h

Miller (1958) and Frei *et al.* (2001) suggested that cyclone intensity increases with an increase in sea surface temperature because high temperature instigates more water vapour in the air, which provides more energy to storms and increases the low pressure systems. Emanuel (1987) has established relationships between minimum sustainable central pressure and maximum wind speed considering the change in SST. If the IPCC (2007) standard of a lower bound of 2^0C and an upper bound of 4.5^0C rise in temperature is considered, the corresponding increases in maximum cyclone wind speed using Emanuel's table (Emanuel, 1987) are 10% and 25% respectively, taking the present threshold temperature of 27^0C in the Bay of Bengal (Table 2.4).

Table 2.4: Relationship of maximum wind speed (V_m) in cyclones to sea surface temperature (Emanuel, 1987).

SST (^{0}C)	V_m (ms^{-1})	V_m/V_{27}*
27	72	1.00
28	75	1.04
29	79	1.10
30	83	1.15
31	88	1.22
32	93	1.29
33	99	1.38
34	106	1.47

*V_m/V_{27} is the ratio of maximum wind speed at different temperatures to the maximum wind speed at 27^0C.

Usually, a warmer ocean is likely to intensify cyclone activity and heighten storm surges (Knutson & Tuleya, 2004; Michaels *et al.*, 2005). The impacts are worsened when they are accompanied by strong winds. Some recent scientific studies suggest an increase in the frequency and intensity of tropical cyclones in the last 35 years happened due to the consequences of climate change (Webster *et al.*, 2005; Bengtsson *et al.*, 2006). A study (WB, 2010) showed that a 10-year return period cyclone with an average wind speed of 223 km/h covers 26% of the vulnerable zone which is likely to cover 43% by 2050 due to intense global warming.

2.5.2 Sea level rise

Bangladesh contributes a little to the greenhouse gas emissions in a global context. Several studies suggest that the average change in temperature for Bangladesh over a 100-year period will be as high as 3.6^0C based on Global Climate Models (GCM) - driven scenarios (Ahmed and Alam, 1998; World Bank, 2000). Many scientific researchers consider sea level rise as the main variable of climate change in context of Bangladesh. The effects of SLR are of a particular concern for a low lying delta like Bangladesh (MCSP, 1993). The global sea level is rising due to the warming and thermal expansion of the sea water. Though not conclusive, but the present sea level rise is expected to rise by 1m by the year 2100 (ASCE Task Force Committee, 1992). The reasons for sea level rise on Bangladesh coast are global sea level rising, ice cap melting and the subsidence of the Ganges Delta (Haque, 1997; Mohal *et al.*, 2007; SMRC, 2003; Unnikrishnan *et al.,* 2006). A study (Agarwala *et al.*, 2003) predicted the range 30-100 cm by 2100, while IPCC projected 25-69 cm global SLR under scenario A1F1 (Meehl *et al.,* 2007). According to IPCC (2007), the global sea level rise situation has been listed in Table 2.5 that has been predicted with respect to Special Report on Emission Scenarios (SRES). Scientists suggest that the speed of wave propagation will be increased with the increase in sea water depth. It will amplify the tidal wavelength. The height of the storm surges is also expected to increase. The shoreline is expected to retreat toward inland as a result of sea level rise enhancing the travel distance of the cyclonic storm surges.

Table 2.5: Sea level rise for SRES of AR4 (*source*: IPCC, 2007).

	Scenarios					
	B1	A1T	B2	A1B	A2	A1F1
Temperature (^{0}C)	1.1-2.9	1.4-3.8	1.4-3.8	1.7-4.4	2.0-5.4	2.4-6.4
SLR (m)	0.18-0.38	0.20-0.45	0.20-0.43	0.21-0.48	0.23-0.51	0.26-0.59

2.5.3 Storm surge

Most of the casualties and damages from cyclones in Bangladesh are caused by storm surges. Storm surges combined with high tides can rise sharply and sweep away a whole region (Burroughs, 2003). According to several earlier studies, the vulnerability of the coastal region of Bangladesh depends on several factors, which include population density, disaster preparedness, income level along with a unique combination of high tides and low flat coastal terrain with the severity of the impacts of storm surges (Flierl and Robinson, 1972; Chowdhury and Rahman, 1998). Pressure drop and wind stress are responsible for the generation of storm surges. Atmospheric pressure drop below normal level raises the water surface by a certain amount which is about 1 cm per 1 mb drop of pressure. This process is called "inverted barometer effect" also known as "sucking effect". Wind force implies tangential stresses on the water surface. This tangential stress is responsible for the generation of storm waves (Hussaini, 2005). A study by Halder (2011) showed that if a disaster like Cyclone Aila occurs in the future, the surge height will increase as shown in Table 2.6 due to climate change.

Table 2.6: Projected surge height (Halder, 2011).

Year	Future storm surge height, m (PWD)
2009	6.1
2030	6.9
2050	7.2
2100	7.5

Emanuel (2005), one of the several studies predicted that any increase in SST due to continually changing climate will intensify tropical cyclones. Ali (1999) incorporated SST rise and SLR into a model to show the contribution of the climate change in formation of storm surges.

2.6 Storm Surge Modeling

The region along the Bay of Bengal is threatened by the possibility of severe cyclonic events of varying intensity associated with storm surges. In order to minimize the disaster associated losses and damages and to achieve a greater confidence in predictions of the storm surges a worldwide practice of storm surge modeling is going on. The modeling involves oceanographic parameters, meteorological parameters, hydrological input, basin characteristics, coastal geometry, wind stress, information about astronomical tides etc.; depending on the interest of output.

2.6.1 Storm surges and flooding

Bangladesh is one of the most densely populated country (1,015/sq. km; Economic Report, 2014) and this highly poverty stricken country is one of the worst victims of frequent natural calamities (Ali and Ahmad, 1992). The coastal areas of Bangladesh have a flat terrain and a very low lying geographical settings. The height of the coastal areas is less than 3 m above mean sea level (Alam and Jabed, 2015). About 10 cm of sea level rise will inundate approximately 2% of the country, while 25 cm and 1 m SLR will inundate approximately 4% and 17.5% of the country (WB, 2000). Ali (1996) showed that increase of surge height from 7.6 m to 9.2 m increases the inundation area by about 13% and an increase from 7.6 m to 11.3 m increases inundation by about 31%. Another study quantified that about 11% additional area of the south-west region is likely to be inundated due to 88 cm where about 84% of the Sundarbans area becomes deeply inundated due to 32 cm SLR, and for 88 cm SLR Sundarbans will be lost (PDO-ICZMP, 2005). A study of IWM and CEGIS (2007) showed that about 44% people will be exposed to additional flooding due to sea level rise of 15 cm in 2080 under scenario B1. Under scenario A2, in 2050 (SLR 27 cm) and 2080 (SLR 62 cm) about 47% and 51% people may be victims of coastal storm surge flooding. Flooding in the coastal areas of Bangladesh due to storm surges may be classified as follows (Khan, 2012):

a) Normal coastal flooding: No damage to crops
b) Moderate coastal flooding: very limited damage on crops
c) Moderately high coastal flooding: high damage to crops, but relatively low damage on lives and properties
d) High coastal flooding: large scale damage to crops, lives and properties
e) Severe coastal flooding: severe damage to crops, lives and properties

2.6.2 Surge amplification along the coast of Bangladesh

Tropical cyclones that occur in the Bay of Bengal are likely to travel from east to west considering the general circulation of the atmosphere. But they often travel to the north or north-east and this turning back is known as recurvature. The phenomenon of recurvature is the reason for the disproportionately high percentages of storm surges on the Bangladesh coast (Khan, 2012). The coast line of Bangladesh has a wide continental shelf, especially the eastern region. Storm surges are amplified by this wide shelf as the tangential sea level wind-stress field associated with the tropical cyclone pushes the sea water from the deep water side onto the shelf. Being pushed from the south by the wind stress, the water has nowhere to go but upward; and thus storm surges are formed and amplified (Khan, 2012). The triangular shape at the tip of the Bay of Bengal helps to funnel the sea water pushed by the winds to the coast and causes further amplification of the surge on the Bangladesh coast. The speed of the propagation of a storm surge is a function of the acceleration of the earth's gravity and the local water depth. Hence, the storm surge that has zero amplitude in deep water may quickly build up to several meters' amplitude in shallow continental shelf.

In addition to the above reasons, some local factors contribute to the amplification of a storm surge. The amplitude is inversely proportional to the depth of water which has already been discussed. The Coriolis force which is produced due to the rotation of the earth contributes to the amplification of the surge height. If the surge water moves northward in the northern Bay of Bengal, it will deflect towards the east, thereby increasing surge height along the east coast. Surge height is directly proportional to the convergence (Proudman, 1955). Due to the northward converging nature of the Bay of Bengal, surge water is funneled towards Bangladesh in the north leading to amplification of the surge height. Tidal range in Bangladesh varies in different seasons along the coast. The amplitude shows a gradual increase from the west to the east to reach a maximum at the Meghna estuary and then decreases south-eastward. Pattalo *et al.* (1989) recorded an increased height of 60 cm to 100 cm above the normal height during the monsoon period (October and November). If this high tide level coincides with the storm surge then the impact is worse.

If there were no rivers then the surge height on the coast would be higher (Sinha *et al.*, 1985). Secondly, fresh water discharge through river will affect the sea surface elevation. A number of waterways allow deep inland penetration of surges originating in the bay. Lastly, the surge and tidal water have a backwater effect on river discharge which slows down the discharge rate thus making the flood situation disastrous. Offshore islands play important roles in amplification of storm surge heights. The channels in between the islands confine the water between them and compel them to pass through them causing surge amplification. Moreover, the islands act as barriers to impend surge water, which amplifies the surge height. Surge height is strongly dependent on the cyclone track. Storm surges are stronger to the right of the track. This is because of the occurrence of the maximum wind speed to the right of the cyclone where the forward motion of the cyclone is superimposed on the wind speed (Khan, 2012). Leftward wind drives water away from the coast and produces a negative surge.

2.6.3 Current practices in storm surge modeling

Several numerical models have been developed for storm surge generation and propagation process. Prediction of surge in Bay of Bengal is pioneered by Das (Das, 1972) which was subsequently followed by several more attempts by Das *et al.* (1974), Ghosh (1977), Johns and Ali (1980), Johns *et al.* (1981), Murty and Henry (1983) and Dube *et al.* (1985). Reid and Bodine (1968), Sielecki and Wurtele (1970) and Flather and Heaps (1975) are some of the several studies that developed numerical systems which could simulate the extent of inundation, but not the actual processes of wave propagation. Later on, Lewis and Adams (1983) developed a complicated numerical system for the one dimensional problem. Contributions of Hibberd and Peregrine (1979), Hebenstreit *et al.* (1985) and Kowalik and Bang (1987) are noteworthy for developing numerical algorithm for storm surge analysis. SWAN (Simulating WAves Nearshore) (Booij *et al.*, 1999 and Ris *et al.*, 1999) and time-dependent FVCOM of Chen *et al.* (2003) are widely used in surge applications (e.g. Chen *et al.*, 2007; Huang *et al.*, 2008). Numerical models have been developed for simulating storm surges in the Bay of Bengal along the coast of Bangladesh by Jones and Ali (1980), Ghosh *et al.*, (1983), Qayyum (1983), Dube *et al.*, (1985), Abrol (1987), Flather and Khandaker (1987), Katsura *et al*., (1992), Unnikrishnan *et al.,* (2004), Paul *et al.* (2013), Antony *et al.,* (2014), Debsharma *et al.,* (2014), Kay *et al.* (2015), Rahman *et al.* (2015) etc. The Multi-purpose Cyclone Shelter Project (MCSP, 1993) in Bangladesh modeled storm surge along the Bangladesh coast using GIS. MCSP (1993) prepared a table which showing surge inundation characteristics for cyclones of varying strength in Bangladesh (Table 2.7).

Table 2.7:Typical storm surge inundation characteristics in Bangladesh (MCSP, 1993).

Wind velocity (km/hr)	Storm surge height (m)	Limit to inundation (km) from the coastline
85	1.5	1.0
115	2.5	1.0
135	3.0	1.5
165	3.5	2.0
195	4.8	4.0
225	6.0	4.5
235	6.5	5.0
260	7.8	5.5

Linear variation of storm surge was supported by MCSP. Once the linear surge model was established, two models were used for detailed study of the coastal zone of Bangladesh. The first model assumed that the depth of inundation was equal to the surge height and that land relief was smooth. The second model for mapping risk zones took account of topographical variations by using a DEM (Khan, 2012).

2.7 Polder Failure Process

Embankment failures are of particular concern as the failure of an embankment has the potential to cause more loss and damage than the failure of any other man made structure. The storm surge originated at the ocean approaches towards inland through embankment failures. The power of the wave that is released by the sudden failure of the embankments is likely to cause immense loss and destructions. Traditionally, the embankment crest is kept higher than the design flood level, and thus keeping the probability of overtopping smaller than the design frequency. But waterlogging and intentions to allow saline water for certain purposes lead to slide plane through the embankments or piping which weakens the embankment body, with the sudden failure as a consequence (Kallen *et al.,* 2009). There are more failure mechanisms of embankments that can result in flooding of the polders (Figure 2.4). The experiences in New Orleans proved that other mechanisms rather than overtopping resulted in failure probability of the embankment (Pan *et al.,* 2012). Nowak and Collins (2012) gave more attention to the structural failure of the embankments.

2.7.1 Breaching

Breaching is the occurrence of slope failure and causing a water flow running downwards from the slope (Vlasblom, 2003). For drainage purposes of the arrested water within the polder during rainy season or to allow the entrance of saline water within the polder coastal people insert pipes thorough the embankments. In addition to this, other human interventions, including cutting of embankments for livestock passages, taking embankment soils for various other purposes make the embankments structurally weak (Dasgupta *et al.,* 2010). By the force of the surge the embankments fail at those points. If not controlled, during every high and low tide the breaching points become even wider which ease the further access of water within the polder. In the coastal polders of Bangladesh similar breaching was observed during the Cyclone Aila (2009) which resulted in the severity of the damage levels (Roy *et al.,* 2009; Kumar *et al.,* 2010; Kamal, 2013).

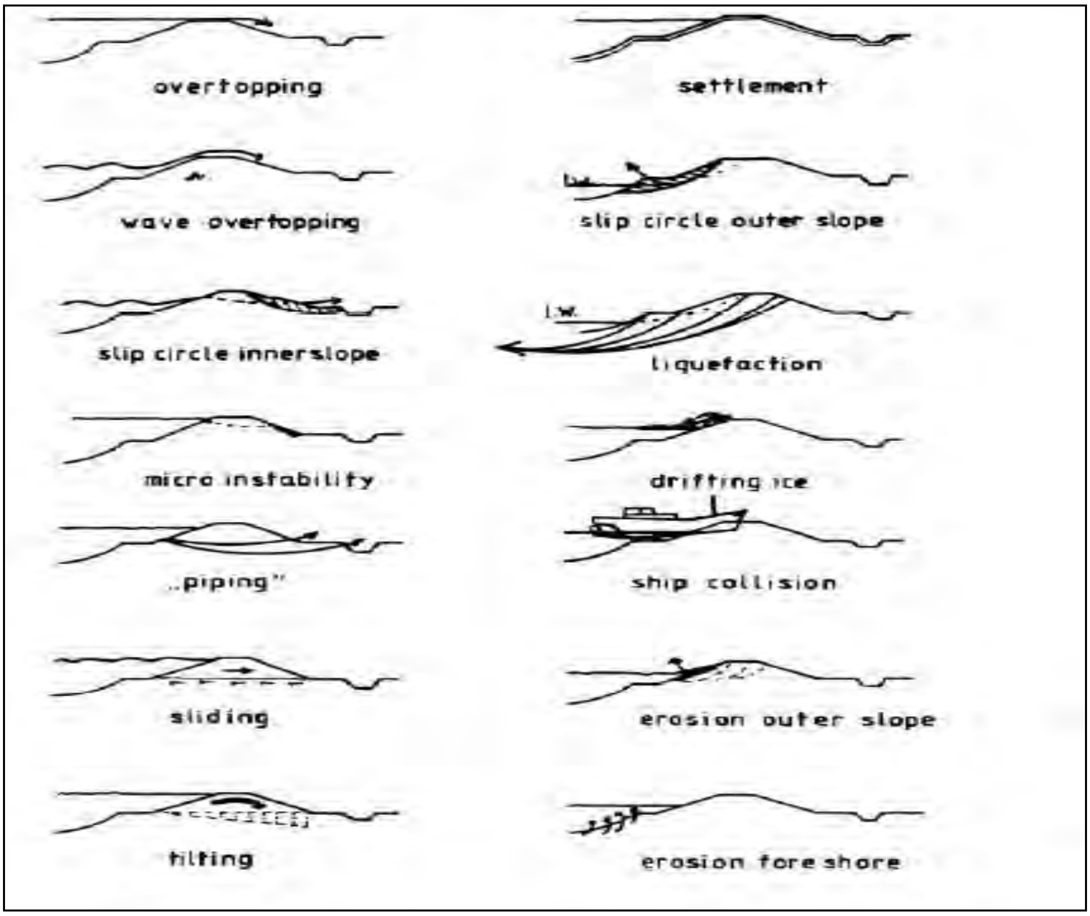


Figure 2.4: Breaching and overtopping modes of embankment (*source*:Vrijling, 1986).

2.7.2 Overtopping

Overtopping of embankments occur when the river channel is inadequate to pass flood waters (Mallick *et al.,* 2011). Any embankment is overtopped if the channel is too small and flood waters rise high enough to flow over the crest of the embankment. Traditionally the embankment crest is kept higher than the expected design flood level. But when the surge height coincides with the astronomical high tide then the amplified surge height exceeds the embankment in some cases (Dasgupta *et al.,* 2010; Chauhan and Gopal, 2013). Moreover, in some cases the design embankment crest level is hardly maintained in the context of Bangladesh. During Cyclone Aila (2009), several places in the coastal polders were identified which were overtopped for 30 minutes to 1.5 hours (Roy *et al.,* 2009).

2.8 Types of Damages Caused by Cyclonic Storm Surges

All the sectors in the affected areas were not damaged equally and in an equal manner during Aila. Several studies (Roy *et al.,* 2009; Kumar *et al.*, 2010; Shamsuddoha *et al.,* 2013) found temporal differences in the losses and damages of the Aila affected areas. Some sectors were damaged immediately and some other sectors experienced no considerable immediate impact but long term impact. So the losses and damages can be categorized under three divisions like immediate, short term and long term damages which has been done on the basis of the field information. The immediate damages were those which were caused immediately after the event. The short term damages were defined as the loss and damages which were caused within a few days or few weeks of the event. The long term impacts included those losses and damages which were caused within a few months to few years. During Aila, households, market places and fishing boats were immediately lost which fall in the first category. Some tin shed houses and livestock were lost or dead after five to fifteen days of the event which fall in the second category. Agricultural lands, ponds, *gher* etc.; were not cultivable even three years after the event which fall in the last category (Dasgupta *et al.,* 2010; Mallick *et al.,* 2011). There were some sectors like agriculture and fisheries which experienced both immediate and long term impacts.

2.9 Sectoral Damage Assessment

A disaster causes sufferings not only to the human lives, but also to the homes and other properties. Compared to the cyclone Sidr that hit Bangladesh in 2007, Aila may not have caused a huge death toll, but the aftermath of the cyclone was beyond description (Dasgupta *et al.,* 2010). It severely damaged the only protection to the coastal belt causing severe breaches which became wider with the daily high and low tides (Debnath, 2014). It left half a million people on the verge of migration due to permanent waterlogged conditions in the affected areas (Roy *et al.,* 2009). Aila caused a huge loss and damage to the agricultural crops, fisheries and other livelihood sector in the affected areas (Rabbani *et al.,* 2013). Damage to households compelled the people to live on the roadside embankments and elevated shelters. Coastal roads and embankments were severely damaged which paralyzed the communication systems of the affected regions (Ahamed *et al.,* 2012). In addition to the schools and madrasas, critical infrastructures like health clinics, power relay centers had to pause their functioning immediately after the event. Damage to the Sundanbans and loss of biodiversity in the wake of Aila was noteworthy (Roy and Hossain, 2015).

2.9.1 Household

In the coastal belt of Bangladesh, most of the houses were made of mud and Golpata. Those houses were very vulnerable to any kind of shocks. According to Cyclone Aila Initial Assessment Report, 1,09,842 households had been affected by Aila in Khulna District (58,499 households fully damaged, 51,343 households partially damaged) (Roy *et al.,* 2009; Mehedi *et al.,* 2010). A survey team found almost 99 percent of earth-made households turned into ruins in the flooded areas immediately after the event (Kumar *et al.,* 2010). The remaining partially affected earth-made households had no chance to stand tall in the waterlogged areas and as a result fell down after a few days (Dasgupta *et al.,* 2010). The following table (Table 2.8) gives the estimates of the damaged households in Dacope upazila after Aila.

Table 2.8: Household Damages in Dacope upazila (*source*: USS, 2009; Cyclone Aila Situation Report).

Affected union	Number of damaged households
Tildanga	2,000
Dacope	1,500
Bajua	1,800
Sutarkhali	2,000
Banishanta	1,300
Pankhali	1,200
Kamarkhola	950
Total	10,750

The table shows that Tildanga and Sutarkhali Unions experienced severe household damages. It was found that in Dacope upazila, 35% of the total houses were damaged (Roy *et al.,* 2009).

2.9.2 Agriculture

Cyclone Aila had the worst impacts on agriculture. According to Initial Assessment Report, damages of 7,392 acres of croplands was reported officially, of which 3412 acres (46%) were fully damaged (Roy *et al.*, 2009; Shamsuddoha *et al.,* 2013). Dacope upazila topped the list of worst affected croplands (3,280 acres, 44% of total standing crop destroyed in Khulna District) with Batiaghata (2080 acres) and Paikgacha (1364 acres) (Kumar *et al*., 2010). The main damaged crops were dry season vegetables, sesame, pulses and *boro* paddy (Dasgupta *et al.,* 2010). The Fisheries Department confirmed a loss of total of 59,045 acres of land under shrimp gher along with 1,074 acres of land under white fish.

2.9.2.1 Crop

After Aila, a thin veneer of salt was deposited on the agricultural fields which reduced the subsequent crop production (Mallick and Vogt, 2014). A previous study (Debnath, 2014) showed that before Aila the rice production was 640-800 kg/ha and it reduced to 320-400 kg/ha after the Cyclone Aila. About 69% of Dacope upazila is cultivable lands (BBS, 2011). Major cops cultivated in the upazila are T. aman, boro, aus, wheat, jute, sugarcane, maize, onion, garlic, green chilli, ginger, turmeric, corianders, sesame, mustard, pulses, potato, sweet potato, watermelon, coconut, mango, banana and different types of winter and summer vegetables (BBS, 2011). During Cyclone Aila, agricultural lands were devastated not only for the single immediate year after Aila but also for three years in a row (Dasgupta *et al.,* 2010). Official reports estimated the following agricultural land damages (Table 2.9) in Dacope upazila from which Sutarkhali and Tildanga unions experienced the most damage.

Table 2.9: Crop land damages in Dacope upazila (*source*: USS, 2009; Cyclone Aila Situation Report).

Affected union	Crops damage (acre)
Tildanga	500
Dacope	400
Bajua	450
Sutarkhali	500
Banishanta	350
Pankhali	300
Kamarkhola	200
Total	2,700

2.9.2.2 Fisheries

Fisheries of Dacope upazila consist of inland open water fisheries and fresh water aquaculture. Homestead pond culture, small scale commercial culture and large scale commercial culture were found in the upazila including rui, catla, mrigal, grass carp, silver carp etc. (BBS, 2011). Most of the area of the upazila was under shrimp cultivation. Saline water intruded into the ponds and shrimp ghers were flooded (Mallick *et al.*, 2011). Fishing boats and nets were lost or damaged, causing a great economic loss (Ahamed *et al.,* 2012). The following table (Table 2.10) shows the number of shrimp ghers in Dacope upazila after Aila.

Table 2.10: Number of lost or damaged shrimp ghers (*source*: USS, 2009; Cyclone Aila Situation Report).

Affected union	Number of damaged shrimp ghers
Tildanga	300
Dacope	200
Bajua	250
Sutarkhali	300
Banishanta	300
Pankhali	150
Kamarkhola	150
Total	1,650

2.9.3 Livestock and miscellaneous

Alia took a heavy toll on livestock in the affected areas (Mallick *et al.,* 2011). According to official estimation 15,785 deaths of livestock in Khulna district were confirmed (Roy *et al.,* 2009). A survey team working on the initial damage assessment estimated about 24,000 deaths of poultry with over 8,00,000 injured immediately after Aila (Roy *et al.,* 2009; Kumar *et al.*, 2010). In Initial Assessment Report of Roy *et al.* (2009), about 33,560 families reported loss of livestock and poultry in Khulna district (Paikgacha: 18,000; Dacope: 8,400; Koyra: 6,500; Dumuria: 600 and Batiaghata: 60). The following table (Table 2.11) shows the estimate of the livestock loss of various kinds in Khulna district.

Table 2.11: Number of different lost or damaged livestock in Khulna district (Compiled from Roy *et al.*, 2009).

Types	Injured	Dead
Cow	1,12,820	322
Buffalo	2,380	-
Goat	45,310	12,017
Lump	23,000	269
Hen	7,54,780	23,313
Duck	77,280	953

Dacope upazila topped the list of death of livestock (6,691) followed by Paikgacha (3,749), Koyra (2,762), Dumria (2,218) and Batiaghata (365) (Kumar *et al.*, 2010). The following table (Table 2.12) shows the dead or missing livestock in Dacope upazila. Tildanga and Sutarkhali had the most losses in the livestock sector.

People lost boats, fish storages, shops etc., during Aila. Marketplaces experienced temporary shutdown to long term losses. Many people lost their money bearing fruit trees. According to Cyclone Aila situation report (2009), 116 tubewell in Dacope upazila were damaged which resulted in drinking water scarcity as the immediate aftermath.

Table 2.12: Number of total dead or missing livestock in Dacope upazila (*source*: USS, 2009; Cyclone Aila Situation Report).

Affected union	Number of dead/missing livestock
Tildanga	400
Dacope	300
Bajua	400
Sutarkhali	400
Banishanta	300
Pankhali	250
Kamarkhola	200
Total	2250

Embankments were breached in several points which cost a huge amount of money to get repaired. All kinds of livelihoods, including both seasonal and regular were temporarily shut down. The mighty Sundarbans in the coastal region of Bangladesh lost many of its resources, both flora and fauna immediately after Aila. The overall biodiversity of the affected areas was threatened after Aila due to intrusion of extreme salinity all over the region (Roy and Hossain, 2015). Out-migration increased sharply after Aila due to loss of income opportunities and damages to local assets and properties (Kartiki, 2011; Mallick and Vogt, 2012).

2.10 Damage Variations with Breaching and Overtopping

The mode of embankment failure is an important factor for the total amount damages or losses. In case of overtopping, certain amount of water escapes over the embankment crest and gets arrested within the polder. The flow velocity and energy slope are small during polder overtopping. The small energy slope imposes low tractive force and thus, erosion of the embankment crest is relatively low unless the embankment is of erodible material (Powledge *et al.*, 1989). The arrested water causes stagnant water body and long term waterlogging in case of inadequate drainage facilities. On the other hand, breaching is a dynamic and complicated embankment failure process. The basic aspects of hydraulics, hydrology, hydrodynamics, sediment transport mechanisms and geotechnical engineering all are involved in the breaching process and eventual embankment failure (Singh and Scarlatos, 1988). During breaching of the embankment, the surge water breaks through the weak points of the embankment with a certain force and high velocity. In this case, all the materials and properties that fall in the face of the thrust of the surge are washed away or get damaged up to a certain extent. So, breaching causes much immediate losses and damages in addition to long term impact. Moreover, once an incipient breach is initiated, the discharging water erodes the breach until the breach resists further erosion (Singh and Scarlatos, 1988). So, the damage level increases with time in the breaching mode of embankment failure.

CHAPTER THREE
STUDY AREA

3.1 Introduction

Polder 32 was selected for this study as this area was closest to the landfall location of Cyclone Aila. This area was one of the worst victims of the past cyclonic events such as Sidr (2007) and Aila (2009). Many cyclones concentrated in the Bay of Bengal left their footprints in the study area through failure of embankments, intrusion of saline water into the polders, loss of household properties, agricultural damages, disruption of traditional livelihoods, etc. Since this study area, Polder 32, represents a typical polder setting in the south-west region, outcome of this study will help understand the storm surge propagation and damages caused by embankment failure in the coastal polders. This understanding will be useful to the policy makers for more pragmatic investment in infrastructure development to attenuate the damages due to any further Aila-like disasters in the coastal region.

3.2 Location

The study was conducted in one of the south-western coastal polders of Bangladesh namely Polder 32, which is located in Dacope upazila of Khulna district. Dacope (located at 22.5722°N and 89.5111°E), has a total area of 991.85 km^2, and is bounded by Batiaghata upazila on the north, the Pashur river on the south, Rampal and Mongla upazilas on the east, and Paikgachha and Koyra upazilas on the west. There are 3 polders in the upazila namely Polder 31, 32 and 33. Polder 32 consists of Kamarkhola and Sutarkhali unions with a combined area of 78.17 km^2 (Figure 3.1). It is bounded by Polder 31 on the north, the Sundarbans on the south, Polder 33 on the east, and Polders 10, 11, 12 and 23 on the west. The polder is surrounded by the Bhadra river on the north and east sides, the Dhaki river on the north-west, the Sibsa (Passur) on the west, and the Sutarkhali (Bhadra) on the south.

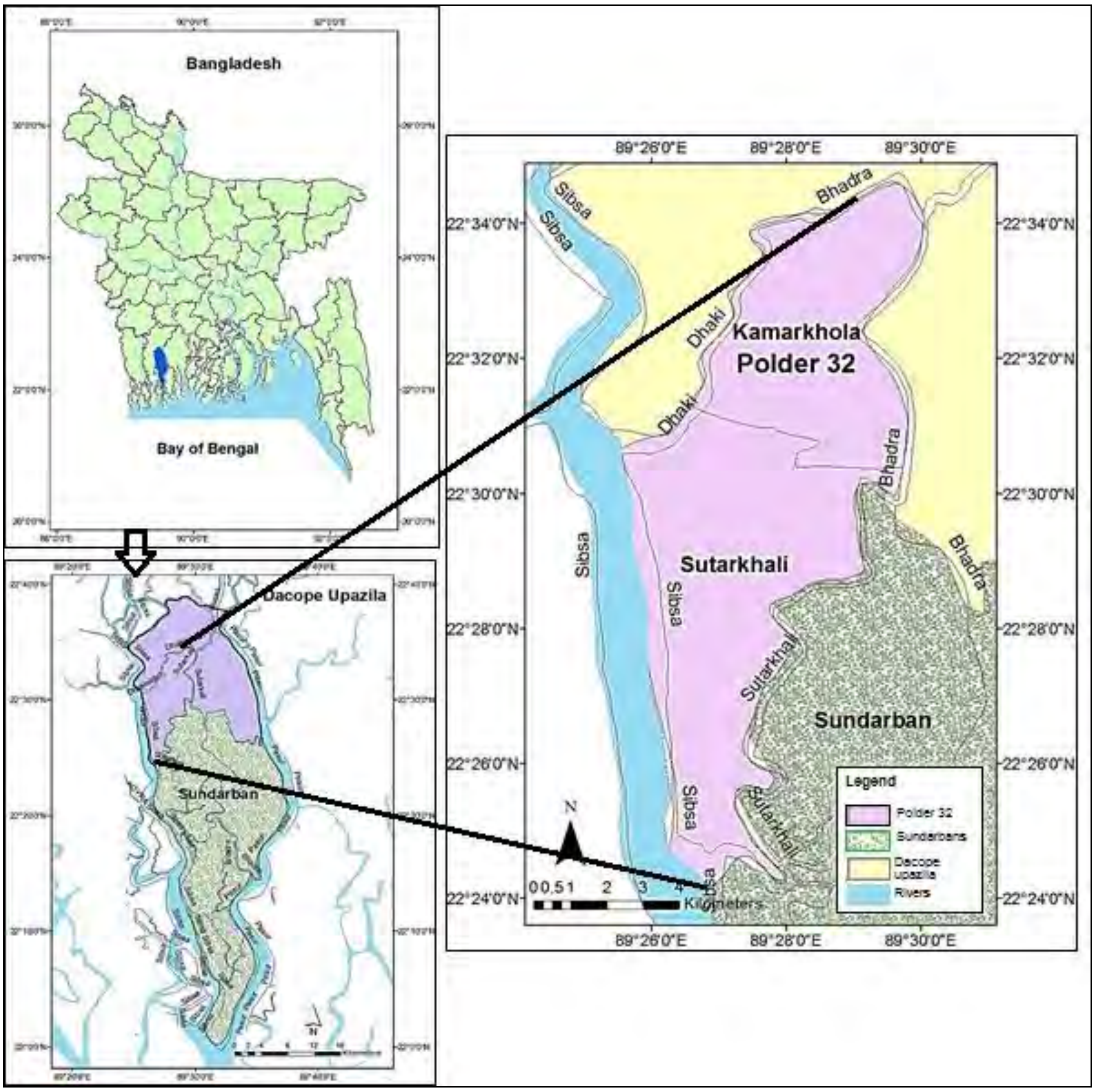


Figure 3.1: Study area location (*data source:* IWFM, BUET).

3.3 General Information

3.3.1 Demography

Demographic information is a guiding factor in the preparation of damage calculations. The estimated population in Dacope upazila is about 1,52,000 of which76,000 are male and 76,000 are female. In Dacope upazila, approximately 56% of the total populations are Hindu, 42% are Muslim and 2% are Christian. There are 36,597 households in the upazila (BBS, 2011). Polder 32 has a total population of 43,749, of which 51% are male and 49% are female. In Sutarkhali, 73.1% of the total populations are Muslim, 26.7% are Hindu and 0.2% are Christian while in Kamarkhola the proportions are 50%, 48.6% and 1.4%, respectively (Table 3.1).

Population densities in Sutarkhali and Kamarkhola are 995 per km^2 and 965 per km^2, respectively. Number of households in the polder is 11,022 (BBS, 2011). Average size of households in Sutarkhali union is 4.0 and that in Kamarkhola is 3.9.

Table 3.1: Demographic information on the study area (*source*: BBS, 2011).

	Sutarkhali	Kamarkhola
Total population	30,060	13,897
Male	15,205	7,103
Female	14,855	6,794
Population density (per km^2)	995	965
Muslim	21,975	6,946
Hindu	8,038	6,758
Christian	47	193

3.3.2 Literacy status

In the study area, the rate of literacy, defined as the percent of population able to write any letter in any language, was assessed for the population of 7 years and above. The overall literacy rate in Sutarkhali is 49.5% where this rate is 56.3% in males and 42.6% in females. In Kamarkhola union, the overall literacy rate is 58.1% where this rate is 65.9% in males and 50.1% in females (BBS, 2011). The literacy rate has increased from 43.2% to 49.5% in Sutarkhali union and from 50.5% to 58.1% in Kamarkhola union over the period 2001-2011. The population aged between 6-10 years attending school and not attending school in Sutarkhali union are 2,892 and 711, respectively, while these proportions in Kamarkhola are 1,225 and 243, respectively (BBS, 2011).

3.3.3 Livelihood pattern

The livelihood pattern in an area normally depends on the resources available at the household level, and local resources and opportunities. Land ownership and access are considered as major factors in determining the livelihood status in the study area. Occupations that characterize the livelihood groups in this area are agriculture, day labor, shrimp gher labor, small farming, fishing, small and medium business, rickshaw/van pulling and Sundanbans resource extraction. In Dacope upazila, 66.07% of the populations are farmers, 4.85% are non-agricultural laborers, 12.86% are businessman, 1.72% are transport and communication related job holders and 4.10% are service holders. Of the total income of the area 0.93% is generated from construction activities, 0.24% from religious services, 0.05% from rent and remittance, and 9.18% from other sources (Banglapedia, 2015).

3.3.4 Land use pattern

The land use of Dacope upazila is dominant in agriculture. Other land use/cover categories include shrimp culture, settlements with homestead forest, water body, river/canal, and infrastructural development (Table 3.2). Though the area is rich in aquatic and terrestrial resources, it is vulnerable to cyclones, storm surges and salinity intrusion. The diversity in land use and resources creates conflicts among the users. The net cultivable land of Sutarkhali and Kamarkhola unions are 25.46 km^2 and 19.0 km^2, respectively, which are 52% and 65% of the respective total area. The permanent fallow land is 0.30 km^2 and 0.40 km^2, respectively, while the temporary fallow land covers are 0.20 km^2 and 0.40 km^2 in these two unions, respectively. Of the 6,228 farmer families, 30% are share croppers in Sutarkhali while this proportion is 25% of the 2,824 families in Kamarkhola. The area of irrigated land is only 3% and 22% of the total land in Sutarkhali and Kamarkhola, respectively, and boro rice is cultivated in a very small scale using surface water irrigation. Major crops are T. aman, boro, sweet potato, pulses and different types of vegetables along with fisheries. The cropping intensity is 107% and 104% in Sutarkhali and Kamarkhola, respectively, which indicates the dominance of single cropped areas (BBS, 2011).

3.3.5 Infrastructure

In Dacope upazila, there are 1 health center/ hospital, 3 family welfare centers, 9 health and family planning centers, and 1 mother and child welfare center. In Sutarkhali union, there are 34 primary schools, 5 high schools and 2 madrasas while these numbers in Kamarkhola union are 26, 4 and 1, respectively. The length of the embankment surrounding the two unions is 50.70 km. There are 61 sluices, inlets and outlets within the polder. The total length of drainage channel within the polder is 47 km. About 6% people of the area have electricity connection. There are almost 80 cyclone shelters in the upazila (Dacope UNO Office).

Table 3.2: Land use pattern of the study area (*source*: MoL, 2011).

	Sutarkhali	Kamarkhola
Total land area (ha)	4896	2921
Net cultivable area (ha)	2546	1900
Agriculture (%)	52	65
Settlement (%)	11	13
Water body (%)	25	15
Fisheries: Bagda and White fish (%)	9	8
Sundarbans	3	-

3.3.6 Socio-economic condition

The overall socio-economic condition of the study area can be described multi-dimensionally by poverty, which restricts them from enjoying a minimum standard of living and the basic necessities of life. The visible results of poverty in the study area are malnutrition, ill health, poor housing condition and illiteracy. The impoverished people are afflicted with unemployment and a lack of access to resources, which restrict their opportunities to income and make them even poorer. The male-dominated interpretations of social and religious norms have placed the women in even more restricted situations as they get very limited ownership and access to resources. There is, however, a strong social coherence shaped by the relationships and networks among the nuclear and extended families, and within and among different communities and groups.

3.4 River System

The area is enriched with natural ecosystems consisting of rivers, khals, beels, etc., which are sources of local livelihood opportunities in several ways. The area is bounded by the Dhaki river on the north, the Bhadra and the Sutarkhali on the east, the Sibsa on the west and the Sutarkhali river on the south (Figure 3.2). There are a number of small rivers and canals within the polder area such as Nalian river, Manki river, Golbunia khal, Jaliakhali khal, Kamarkhola khal, Mistripara khal, Chuna khal, Oramukhi khal and Jugra khal, Bishanbari khal, Mara Pashur river, etc. These rivers and canals are important for local communication, agriculture and sources of income.

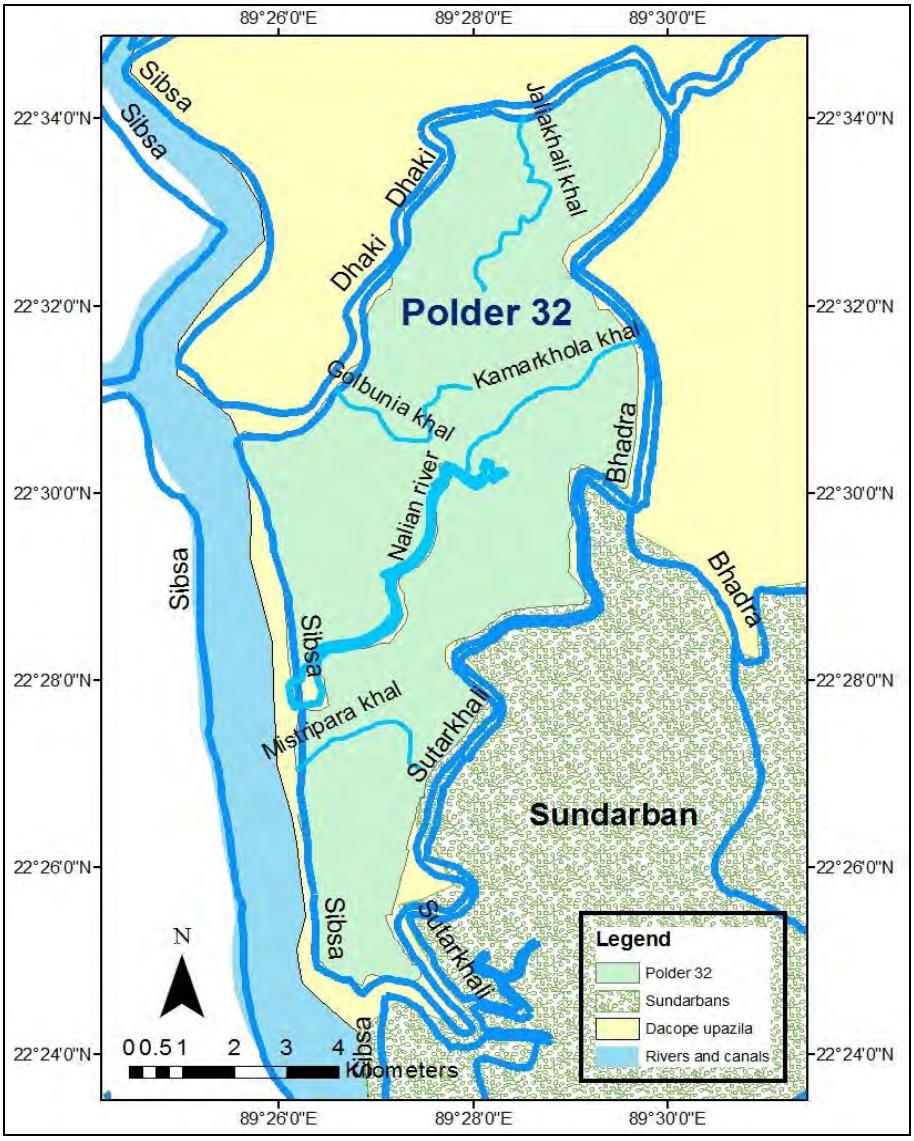


Figure 3.2: River and canal system of the study area (*data source*: satellite image and field information).

3.5 Climate of the Area

The study area is situated in a subtropical monsoon climate with moderate rainfall. There are four main seasons, which are pre-monsoon (March-May), monsoon (June-

September), post-monsoon (October-November) and dry season (December-February). The pre-monsoon season is characterized by high temperature, high evapotranspiration and cyclonic storm surges. The monsoon appears with heavy rainfall, high humidity and cloud cover. The post-monsoon is characterized by hot and humid weather, occasional thunderstorms, cyclones and storm surges. The dry season is characterized by cool, dry and sunny weather. Climatic data of 2013 collected from Bangladesh Meteorological Department (BMD) indicate that the monsoon ranges from late May, averaging 183 mm of rainfall to October, averaging 159 mm of rainfall. The peak rainfall occurs in August averaging 445 mm of rainfall. Rainfall is quite rare in the dry season. The annual average rainfall is 1,764 mm. According to the data collected from the meteorological station in Khulna in 2013, the relative humidity ranges from 18% to 100%. The maximum temperature occurs in April and the minimum temperature in January. According to the data from the meteorological station in Khulna in 2013, the maximum temperature was 38.8^0C in April and the minimum temperature was 11.7^0C in January.

3.6 Storm Surge Hazard

Geographically, the study area is very close to the Bay of Bengal and, therefore, is exposed to the cyclonic storm surges and tidal surges. Historical records indicate that the wind speed during Cyclone Sidr reached up to 223 kmph, which was accompanied by heavy rainfall and causes tidal inundation up to 7 m (Haq *et al.*, 2012). There is evidence that since 1770 to date, at least 25 major cyclones associated with storm surges have hit the general area (MoL, 2011). The super cyclone Sidr hit this area on 15 November 2007, causing immense loss of lives and properties. Due to the lack of adequate funding and efficient planning, necessary rehabilitation of the economy and infrastructure could not take place in time. Just one-and-a-half year after Sidr’s attack, another devastating cyclone, Aila, hit the area. This time, high storm surges washed away polders, human settlements and properties resulting in prolonged sufferings of the inhabitants of the study area. Additionally, the riverine (tidal) floods and their consequences have always been a matter of concern in this coastal belt. The major devastating floods in this region occurred in 1978, 1981, 1987 and 1988 (MoL, 2011).

3.7 Damage Due to Aila

On 25 May 2009, the Cyclone Aila hit this coastal belt, including the study area. The sustained wind speed reached up to 120 kmph. The cyclone sustained over the polder for 2-3 hours, and the associated storm surge overtopped the embankment at several places and caused 3 major breaches. The cyclone disrupted the communication networks, and severely affected human settlements, lives and properties. Saline water intruded vigorously and washed away the homestead properties and agricultural lands. The population of the affected areas took shelter on the roadside embankments, schools, cyclone shelters and other raised platforms. Many people left behind their domestic animals such as cows and goats, and somehow managed to survive. The number of immediately displaced people in Polder 32 was approximately 12,000. The number of destroyed households in the area was estimated as 2,950. The total number of affected people was about 31,000 with 700 acres of crop damage, 600 dead or missing livestock, and 450 shrimp gher damage (USS, 2009). In addition to the immediate impact, Aila inflicted prolonged impact on waterlogging that subsequently affected agricultural production for three years.

CHAPTER FOUR
METHODOLOGY

4.1 Introduction

This study was designed based on different primary and secondary data collection on the super Cyclone Aila that hit the coast of Bangladesh on May 25, 2009. A detailed study was conducted in a specific polder of south-west coastal region of Bangladesh named “Polder 32”. The study investigated the interrelation of the losses and damages to the mode of embankment failure due to a cyclonic disaster. Both quantitative and qualitative data were collected for the study and then analyzed for impact assessment. Although a number of previous study worked on the impact assessment of Aila in broader scale, but very few studies investigated the local level damages in a participatory approach. This study assessed the different types of losses and damages due to Aila in various sectors of the affected areas and linked the assessments to the failure modes of the polder. Information were gathered from scientific literatures, several visits to the study area and relevant organizations. This study provides a noteworthy message to the policy makers regarding future design and implementation of coastal infrastructures and also to the local people about the disastrous effects of the human interventions to the polders. The steps of this study are shown in the methodological framework (Figure 4.1) designed for this research.

4.2 Steps of the Study

4.2.1 Literature review

Tropical cyclones, cyclonic storm surges and other natural disasters are familiar phenomena in the coastal belt of Bangladesh. These are the burning issues in the newspapers, seminars, reports and many other scientific papers. IPCC reports and other scientific research predict that in the future, both the intensity and the severity of the events may increase due to the climate change related issues. The impacts caused by Cyclone Aila may be multiplied by some scales in the future events, if proper policy and strategies are not maintained.

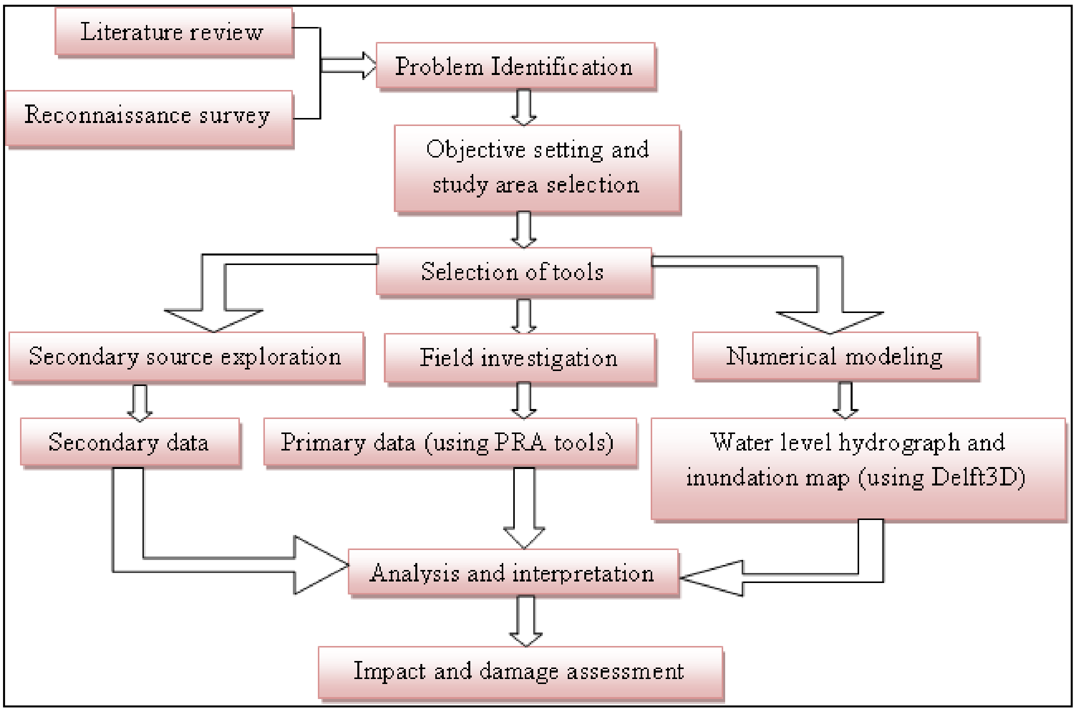


Figure 4.1: Methodological framework of the study.

Various articles on Cyclone Aila were studied for understanding the damage levels, damage processes and the reasons behind the disastrous impacts of Aila. Many reporters, researchers and other officials became very concerned about the Aila issue immediately after the event. A number of official and unofficial reports on an initial assessment of damages of Aila, long term scenarios of damages and impacts of Aila on livelihood pattern changes, land use changes were available online, which were critically reviewed during this study.

4.2.2 Reconnaissance survey

During Aila most of the losses and damages were caused by massive embankment failures. Impacts of Aila included damage to embankments, loss and injury of human lives, damage to crops and fisheries, loss of livestock, etc. The miseries of the coastal communities were magnified by long term inundation of the poldered area. To identify a representative affected area, a reconnaissance survey was carried out during January of 2014 in Dacope upazila of Khulna district. During the survey, local people were interviewed to share their experiences of Cyclone Aila. They defined the event as the most disastrous event in their lifetime. Some affected locations were preliminarily visited, which were damaged during Aila. Some group discussions and Key Informant Interviews (KIIs) were conducted during the reconnaissance survey.

4.2.3 Problem identification

Review of literature indicated that the area experienced both immediate and long term impact during Cyclone Aila. Different sectors such as household, agriculture and fisheries were affected severely though not equally. Many past events took place in the area, but could not cause such level of damages. During past events, the losses and damages in this specific area were less as the embankments did not fail as it did during Aila. Literature review and subsequent field visits helped to understand the problem in details. During consultations with the affected people, they stated that the main factor that triggered the severe damages was the embankment failures during Aila. Surge water intruded into the polder area and washed out as well as inundated living houses, crop lands, fish ponds etc. Long term inundation of crop lands with saline water caused prolonged impacts in the affected areas. The problems associated with the occurrence of Cyclone Aila were identified through reviews of different scientific research works on Aila and its aftermaths along with extensive field visits to the affected areas. Interviews with the officials from different government and non-government organizations associated with the rehabilitation and development of the study area in the post Aila period also helped to identify the problems that accelerated the devastating impact of Aila in the study area.

4.2.4 Definition of objectives

After studying a number of relevant literatures and the first field visit to the Aila affected areas, it was possible to identify the problems which became prevalent in the wake of Cyclone Aila. It helped to make the research questions more specific. The overall aim of the study was selected so as to assess the surge propagation process into a polder, the impacts of storm surge on different sectors, the sectoral and temporal variations of the losses and damages in a coastal polder of Bangladesh. The specific objectives which were defined for this study are:

(i) To understand the process of storm surge propagation in a coastal polder, and

(ii) To assess possible losses and damages due to polder breaching and overtopping

The first objective aimed to understand the process by which the surge water during a storm surge intrudes into a polder area. The second objective included the assessment of the losses and damages due to polder failures in different sectors of a coastal setting.

4.2.5 Study area selection

During Cyclone Aila, 12 out of 19 coastal districts of Bangladesh were affected, including Satkhira, Khulna, Bagerhat, Pirojpur, Barisal, Patuakhali, Bhola, Laksmipur, Noakhali, Feni, Chittagong and Cox's Bazar (Roy *et al.*, 2009). Among the affected districts, Khulna district was one of the severely affected areas. According to different official reports on Cyclone Aila Koyra, Dacope, Paikgacha and Batiaghata upazilas of Khulna district were the worst affected (USS, 2009). According to the local people and other officials from different government and non-government organizations (BWDB, Agriculture Office, BRAC, etc.) Dacope upazila was the worst affected among the upazilas of Khulna district. There are three polders in Dacope upazila namely Polder 31, Polder 32 and Polder 33. During field visits, local people informed that Polder 32 was severely affected having both immediate and long term impact. The sub-divisional engineer from BWDB and an officer from Dacope Agriculture office informed that the impacts were comparatively higher in Polder 32 than other two polders due to severe embankment failures in Polder 32. The changes in land use and livelihood options were more dynamic in Polder 32. Impacts on household asset, crop agriculture and fishery were far reaching and continued for a prolonged period. Having focused on those criteria, this polder was selected as the study area.

4.2.6 Selection of tools

For understanding the storm surge propagation into the polder, an open source model ‘Delft3D’ (v.3.28.50.01) was used. The flow model in Delft3D provided detailed inundation scenarios about polder breaching and overtopping. The simulated hydrographs at selected location were used to assess different situations of polder overtopping and breaching. A series of inundation maps from the flow model were used to assess the contributions of polder breaching and polder overtopping separately for the flooding of the study area. The combined breaching and overtopping effects were also simulated in the flow model. ArcGIS 10.2 (open source) was used to simulate inundation maps, interpreting SRTM DEM data and local water level data.

Data on land use, livelihoods and damages were collected from several field visits through Participatory Rural Appraisal (PRA) tools which included social and resource mapping, Focus Group Discussions (FGDs), Key Informant Interviews (KIIs), group discussions, individual interviews, etc (Appendix B). A semi structured questionnaire approach was followed to collect all information from the local affected people.

4.2.7 Primary and secondary data collection

Different primary data on land use, crop type, cropping pattern, house type, etc., were collected from the local affected people during field visits. Detailed primary data on losses and damages in the household sector, crop agriculture, livestock, fishery, etc., were collected from three different locations of the study area. Data on crop production (production rate, profit), both before and after Aila were collected from the selected locations of the area during field visits. Along with the primary data from the field, a number of secondary data were collected from different organizations and sources. A list of the agencies and sources are given in Table 4.1.

Table 4.1: Agencies and sources of secondary data.

Agencies and sources	Documents
Bangladesh Water Development Board (BWDB)	Books, Scientific journals, Reports, Project report, Online documents.
Bangladesh Meteorological Department (BMD)	
Center for Environmental and Geographic Information Services (CEGIS)	
Upazila Agriculture Office, Dacope	
Upazila Fisheries Office, Dacope	
Local NGOs	
Bangladesh Rural Advancement Committee (BRAC)	
SRTM DEM data	

4.2.8 Data analysis

Data were collected on the number of houses, types of houses, number of lost or damaged houses, number and types of other affected settlements, including shops, fish storages, etc., affected fisheries, crop lands, crop types, production rate, inundation depth and duration, etc. Data were also collected on the approximate cost of each type of houses to translate the household damages into monetary terms. Similarly, information were collected about the type of affected shops, fish storages, small business centers, etc., and their nature of losses and damages to estimate their total losses and damages in monetary terms. Amount of affected shrimp ghers, fish ponds and crop lands were estimated. Total losses and damages were calculated in fisheries and crop production based on the inundation period, missing cropping season, crop types, production rate and the contemporary crop price rate and then total losses and damages were calculated in monetary terms. All data were then analyzed and interpreted to estimate sectoral impacts and temporal effects on the sectoral impacts.

For analysis purposes, water level data were analyzed to calculate discharge at some points of interest using Manning's equation. In those analyses, trapezoidal sections were assumed in the Rupsa and the Sibsa rivers. Appropriate values for Mannings's n, side slope, longitudinal slope, etc., were assumed.

4.2.9 Interpretation of model results

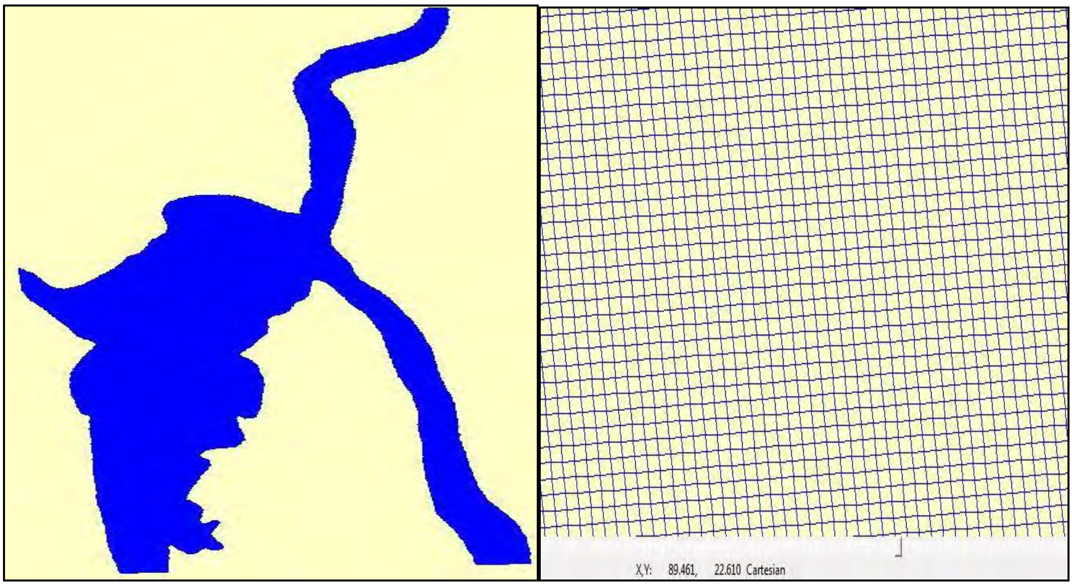
The flow model provided the water level hydrographs at selected locations which ensured the overtopping criteria. The breaching scenario was also simulated in the model. Inundation maps were prepared from model simulation for different conditions of embankment failures such as breaching, overtopping and combined breaching and overtopping. Inundation maps were also prepared interpreting SRTM DEM data (30 m x 30 m) and local water level within polder area using ArcGIS 10.2. Comparisons were made among the inundation maps which were found from model simulations and GIS interpretations.

4.3 Storm Surge Modeling

Delft3D-FLOW is an important and popular component of the Delft3D suite for a multi-disciplinary approach and 3D computations for coastal, river and estuarine areas. It is currently gaining much popularity in simulation of multidimensional hydrodynamic flows, including storm surge analysis and transport phenomena including sediments. A number of tools have been incorporated in this surge model which is very user friendly for storm surge analysis.

4.3.1 Model set up

To set the model for simulation components, including grid, bathymetry and boundary of the domain were specified. The concept of staggered grid was applied in Delft3D-FLOW. In a staggered grid not all quantities, such as the water level, the depth, the velocity components or concentration of substances, are defined at the same location in the numerical grid. The domain of the study area may be divided into some rectangular grids e.g. 30 m x 30 m, 60 m x 60 m and so on. In this specific study, 30 m x 30 m grids were used (Figure 4.2).



(a) (b)

Figure 4.2 : Grid components of the model area, (a) Full area and (b) Partial area.

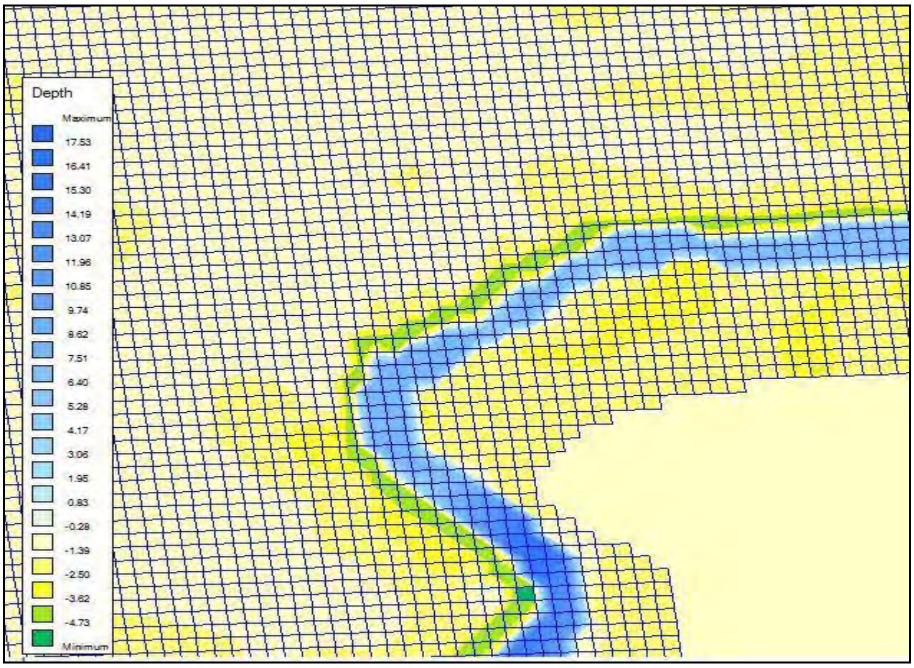


Figure 4.3: Bathymetry of the model area.

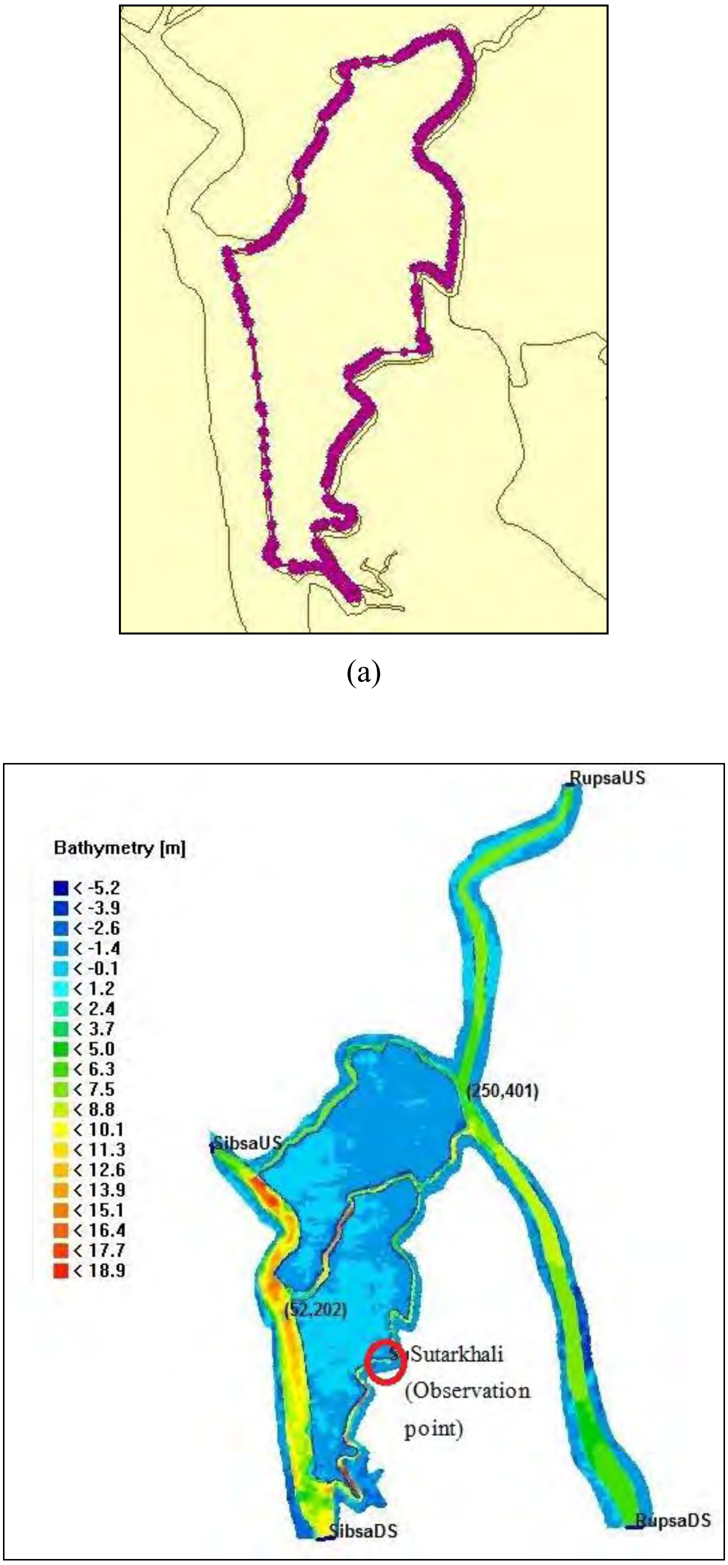
In Delft3D-FLOW, two types of co-ordinate systems are supported, including Cartesian (co-ordinates in metres) and Spherical (co-ordinates are in decimal degrees). The bathymetry may be uniform or non-uniform across the model area. In this study the bathymetry data were collected from CEGIS (Centre for

Environmental and Geographic Information Services) (Figure 4.3). After attributing bathymetry at the known points, triangular interpolation was applied to get bathymetry at the unknown points.

In this study, open boundaries were selected at upstream and downstream of the Rupsha and the Sibsa rivers (Figure 4.4). At an open boundary the flow conditions are required. These conditions represent the influence of the outer world, i.e. the area beyond the model area which is not modeled. The required boundary conditions in the Delft3D-FLOW are water level, velocity, discharge, etc. The choice of the type of boundary condition depends on the phenomena to be studied. In our study, water level at the downstream and discharge at the upstream were used as boundary conditions. Observation points are selected for visualization of the changes in the parameters of interest. In our study, observation point was selected at Sutarkhali river to compare the observed water level hydrographs with model generated water level hydrographs (Figure 4.4).

The important model parameters are gravitational acceleration, air density and water density. Parameters also include roughness (Manning, Chezy, White-Colebrook, etc.) and viscosity (eddy viscosity and eddy diffusivity). In this study, for simplification of the model simulation the Manning's roughness co-efficient was taken as physical variable parameter, skipping the changes of all other physical parameters.

Then the model was calibrated with the observed water level at Sutarkhali. Physical parameter Manning's n was taken as calibration parameter. The calibrated model was also validated with the observed water level at Sutarkhali. In both calibration and validation water level was used, but of different time periods.



(a)

(b)

Figure 4.4: Land boundary of the modeled area, (a) domain area and (b) boundary conditions with observation points.

4.3.2 Selection of failure scenarios

The coastal embankments may fail in case of severe cyclonic events. The failure may occur in a number of ways among which polder overtopping and polder breaching are very common. These two major failure modes were considered in our present study. The embankment height was selected 4.27 m (PWD) throughout the study area as in the design data (BWDB) of embankment. In this case the model results showed that Polder 32 was not overtopped at all in case of Aila like disaster. In the field, the design polder height is not maintained throughout the area and in many locations it was found 3.50-4.00 m (PWD). So, in our model the polder height was reduced to 3.50-4.00 m (PWD) at some points which was selected based on the local peoples' information to simulate the actual overtopping locations. Thus the model was prepared for overtopping condition. Some intentional breaches of varying sizes were created at the actual breaching locations of Aila. In this case, the polder height was kept 4.27 m (PWD) throughout the area. Then the breaching condition was simulated using the model. At last, the combined overtopping and breaching criteria was simulated. In this case, the embankment height was kept variable as in the overtopping case and the intentional breaching was incorporated as well.

4.4 Damage Assessment

Different primary data for detailed assessment of losses and damages caused by Aila were collected through reconnaissance survey and different PRA tools including social and resource mapping, FGDs, group discussions, individual interviews and KIIs.

4.4.1 Social and resource mapping

These mapping tools were used to get information about the position of social institutions and resources of the study area. Social institutions such as school, madrasa, mosque, temple, cyclone shelter, etc.; along with infrastructures, marketplaces were identified in the social map. Crop field, shrimp gher, homestead, brick kiln, pond and other wetland, etc.; were identified in the resource map. Prior to the damage assessment, the probable social institutions and resources of an area were needed to be identified which were likely to be damaged due to a cyclonic event. At first, the objectives of the mapping process were explained to the local people. The resources were identified through discussions with the community people. Participants, including women, farmers and other livelihood holders helped to draw the maps. At first, we initiated the sketch, and then the local people drew by themselves with curiosity. Three maps were prepared at the three major breaching points of Polder 32. The ideas and information of the local people were then interpreted with key informants. The social and resource mapping was carried out in the same paper to manage time. These maps helped to understand and assess the damages that the local infrastructures and resources had experienced during Aila.

4.4.2 Group discussion

Group discussions were conducted rather than individual interviews to gather required information to manage time. A number of group discussions were held during four field visits to the study area (Table 4.2). Most of the group discussions were held informally in the field. In the early field visits, a number of group discussions were held following a semi structured questionnaire which included the amount of an individual's damaged or lost lands, types of crops they used to grow, the amount of crop lands and missing livestock, types of houses they used to live, etc. In the study area, affected people were living in different places without considering the socio-economic classes. So stratification according to caste, religion, livelihood, economy was insignificant during the group discussions. Group discussions were location dependent. At the three major breaching points, group discussions were conducted. The average participants in each group discussions were 8-12 depending on the availability of the people. Every group discussion included at least one third women.

Table 4.2: Schedule of group discussion.

Date	Location	No. of Participants	Types of Participants
30-01-2014	Pankhali	10	Small Farmer, landless farmer, boatman, fisherman, woman
18-02-2014	Sutarkhali	12	Small Farmer, day laborer, woman
19-02-2014	Kamarkhola	11	Small businessman, fisherman, small farmer, woman
20-05-2014	Jaliakhali	10	Farmer, boatman, woman
02-05-2015	Vitevanga	8	Farmer, fisherman, woman
03-05-2015	Nalian	10	Small farmer, fisherman, small businessman, woman

4.4.3 Focus group discussion

Focus Group Discussions (FGDs) were conducted to gather information on different sectoral damages like household, agriculture, fisheries, etc. A number of FGDs were conducted with diverse livelihood groups including farmers, fishermen, day laborers, etc., (Table 4.3). The target groups for FGDs were selected based on the following criteria:

- Identical with respect to habitat
- Livelihoods similar
- Comparable in social status
- Economically almost similar

The participants for FGDs were contacted prior to the meeting through a field facilitator to ensure their presence at the scheduled time. The groups were formed of 10-12 homogenous members. The discussions were held for one hour or less to manage time. The discussions were held in a common place like institutional ground or fallow land. FGDs were conducted with farmers, fishermen which included women to account the impacts of Aila on the community.

Table 4.3: Schedule of Focus Group Discussions (FGDs).

Date	Location	Participants	Target Group
20-05-2014	Jaliakhali	6 M, 4F	Farmer
21-05-2014	Jaliakhali	11 M	Fisherman
02-05-2015	Nalian	7 M, 4 F	Farmer
02-05-2015	Nalian	8 M, 2 F	Fisherman
03-05-2015	Vitevanga	8 M, 2 F	Farmer
03-05-2015	Vitevanga	10 M	Fisherman

M-male, F-Female

4.4.4 Individual interview

A group of people were not always easy to be assembled at a scheduled time. So it was easier to take interviews of individual people. Moreover, the level of damages varied from person to person. For gathering information, victims of Aila were randomly selected for individual interviews. People who had damages in household, agriculture or other livelihood options were selected for the interviews. The interviews were held informally in most cases. Some questions were taken in written format to make the interviews easier and to manage time. The interviews focused on the habitat type, land use, livelihood, livestock, etc. During four field visits, a total of 32 people were interviewed in the three most damaging breaching points (Table 4.4).

Table 4.4: Details of individual interview.

Location	No. of Individual	Types of Individual
Nalian	12	Farmer, fisherman, day laborer, small businessman
Jaliakhali	10	Farmer, fisherman, boatman, day laborer
Vitevanga	10	Farmer, fisherman, small businessman

4.4.5 Key informant interview

Information of an individual may vary from person to person and from place to place due to the difference of their perceptions and understandings. But Key Informant Interview (KII) is an appropriate tool to gather authentic and correct information. It helps to verify the field data. KII was conducted with selected persons from different organizations who were associated with the older rehabilitation and development program from the beginning to the end. Early contacts were made with the key informants prior to the meeting to make the schedule. The participants of the KII are mentioned in Table 4.5.

Table 4.5: Participants of Key Informant Interviews (KIIs).

Serial No.	Designation
1	Upazila Agricultural Officer, Dacope
2	Upazila Fisheries Officer, Dacope
3	Upazila Nirbahi Officer (UNO), Dacope
4	Sub-Assistant Engineer, BWDB, Khulna
5	Sub-Divisional Engineer, BWDB, Khulna
6	Executive Engineer, BWDB, Khulna
7	Manager, BRAC
8	Member of Local Government, 5 No. Nalian Ward
9	Member of Local Government, 2 No. Gunari Ward
10	Member, Gate Operating Committee, Nalian

4.4.6 Crop calendar

Major livelihood option in the study area is agriculture. The agricultural damages vary with the time of the occurrence of a disaster. When the timing of disaster coincides with the cropping season, then the damage becomes maximum. A crop calendar for the study area was prepared during the field visit through focus group discussion with local farmers. This calendar was found identical throughout the study area. During the discussions, the farmers informed the timing of land preparation, seedlings, transplantation, harvesting in term of Bengali month and then they were translated in terms of Julian calendar.

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Introduction

Cyclone Aila hit the coastal belt of Bangladesh on May 25, 2009. The coastal embankments failed at several places throughout the coastal region. The embankments were overtopped at some places and washed away at some other places. The failure process continued during the daily tidal cycles for a long period after Aila. Consequently, a large area of this polder was inundated by saline water. The inundation period extended up to one and a half year, even more at some locations depending on the land types. Agricultural lands were not cultivable until 2012 or more due to residual salinity on the soil surface. This long term agricultural unproductiveness along with the huge immediate losses and damages in household assets, livestock, crops and fisheries resulted in immense long term sufferings of the coastal vulnerable communities. The detailed failure locations, failure processes and damage assessments in different sectors of the study area are discussed in the following sections.

5.2 Embankment Failure Analysis

5.2.1 Failure locations

Cyclone Aila of 2009 affected the coastal belt of Bangladesh submerging the coastal polders through massive embankment failures. Numerous villages were either completely or partially submerged or destroyed by surge water. Several rivers in the coastal region were reported to break through the coastal embankments causing inland submergence. Embankment failures were caused by polder breaching and overtopping. Hundreds of kilometers of the coastal embankments were overtopped throughout 12 coastal districts with several numbers of breaching locations of varying sizes. During this study in a specific polder, BWDB officials who were actively associated with the whole polder rehabilitation work from the early period, informed that in Polder 32 surge water broke through five breaching points of varying sizes. Among these, three major breaching points, namely Nalian, Jaliakhali and Vitevanga were identified as significant from damage point of view (Figure 5.1).

The Dhaki river broke through Jaliakhali and Vitevanga, whereas the Sibsa river broke through Nalian into Polder 32.

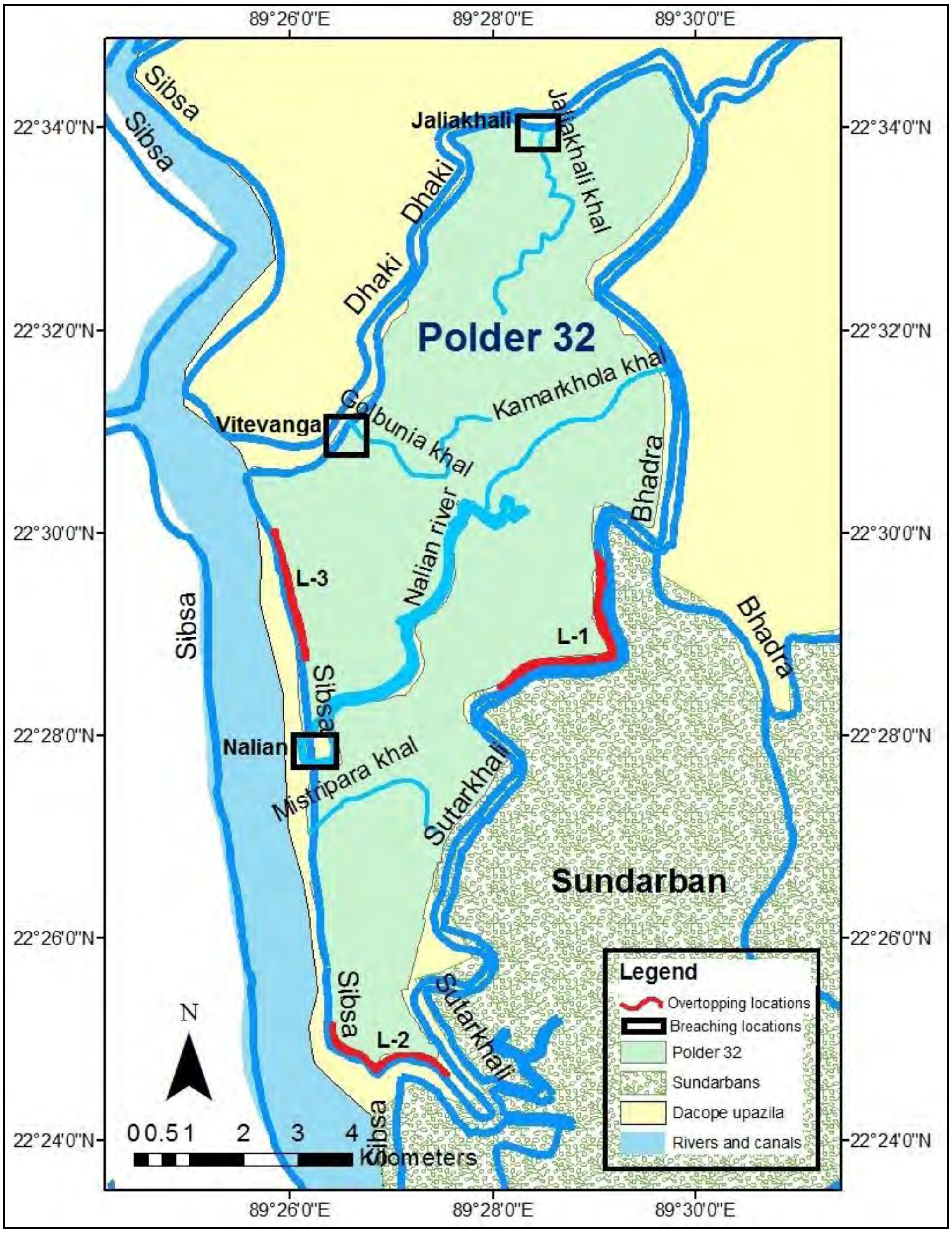


Figure 5.1: Breaching and overtopping locations in Polder 32 during Cyclone Aila (*data source*: satellite image and field visit).

During field visits, affected local people identified the above mentioned breaching points, along with some minor breaching points in Nalian, Joynogor bazar and some other places. According to BWDB authority, damages caused by overtopping of Polder 32 were quite negligible compared to the damages caused by polder breaching. It was reported that polder overtopping might not have caused severe damages, except arresting certain volume of surge water causing short term inundation inside the polder. In this case, the area under inundation would have been relatively small. During field consultations, some overtopping locations were reported. Local people marked some points (Figure 5.1) where Polder 32 was mostly overtopped. According to several local individuals and other officials, overtopping length was approximately 5% of the total length of Polder 32 and some major overtopping locations are mentioned in Table 5.1.

Table 5.1: Major overtopping lengths during Aila in the study area (*source*: field visit).

Name	Location	Overtopping length (m)
L-1	Sutarkhali (U/S)	75
L-2	Sutarkhali (D/S)	35
L-3	Vitevanga	50

5.2.2 Causes of embankment failure

The immediate impacts of Cyclone Aila that were stretched even up to several years after the event were the results of embankment failures including breaching and overtopping. No other previous disasters caused such extent of sufferings in different sectors of lives and livelihoods in Polder 32 as they could not damage the embankments in such manner that Aila could. The breaching of the coastal embankments resulted in washing out and immediate inundation of the coastal settings. The reasons responsible for the massive breaching of Polder 32 that were collected from several field visits to the affected area are given in Table 5.2.

Table 5.2: Causes of embankment breaching during Aila.

Nalian	Jaliakhali	Vitevanga
• Weak embankment (crest level and crest width less than the designed values) • Insertion of pipes through the embankment to allow the access of saline water from the Sibsa river to the Nalian river	• Insertion of pipes • Making holes in the embankment to allow saline water access	• Insertion of pipes

Local people from Nalian informed that insertion of pipes to allow saline water to shrimp gher from the Sibsa river and other human interventions, including cutting of embankments for passage of cows, soil removal from embankment slope for personal use, setting business centers and stationary shops on the embankments, etc.; were responsible for the structural weakness of the embankments that caused subsequent failures during Aila (Photo B3 in Appendix). People used to bring saline water from the Dhaki river to Jaliakhali canal for saline water shrimp culture through a small man-made breach in the embankment at the junction of the river and the canal. At the early period of the event, this narrow breach became devastatingly wide and breaching width further increased with time (Photo B4 in Appendix). At Vitevanga, people created holes and inserted pipes in the polder to allow saline water from the Dhaki river to Gulbonia khal. Polder 32 breached at those weak points immediately during Aila.

According to officials from BWDB, the design crest level for the coastal polders of Bangladesh is 4.27 m (PWD). But the design crest level is not properly maintained throughout the country. BWDB engineers informed that in most of the practical cases the average crest level varies from 3.5-4.0 m (PWD). During field visits, the polder height was measured at several points (Photo B6 in Appendix). The height was found 8 to 10 ft which was equivalent to a crest level of 3.65-4.0 m (PWD) as the average land elevation was 1.0-3.0 m (PWD). The local people also informed that during Aila surge water flowed 1.0 to 1.5 ft above the existing embankment crest depending on locations, which resulted in an approximate water level rise up to 3.80 m (PWD) at some points in the study area. The polder was overtopped at those points, where the polder height was comparatively lower (Figure 5.2). According to local informants, the polder was mainly overtopped in the southern portion of Polder 32 (Figure 5.1) near Sutarkhali where the surge height was observed by them as the highest and the polder height was comparatively lower in those areas. Officials from BWDB also supported local people's information on surge water level and held the low crest level of Polder 32 responsible for overtopping. Some locations near Nalian were overtopped during Aila where the embankment crest was in between 3.50 m (PWD) to 4.00 m (PWD) (Figure 5.2). A similar case happened in all of the overtopping locations in the study area.

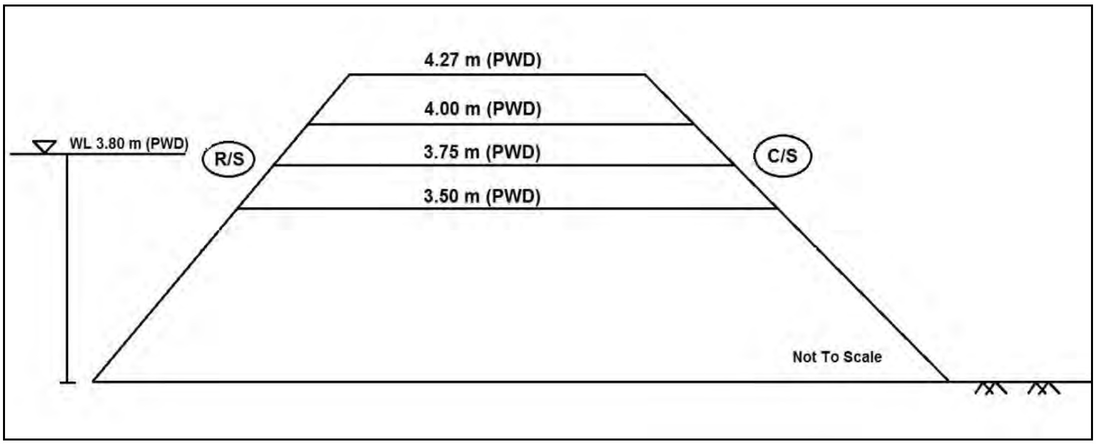
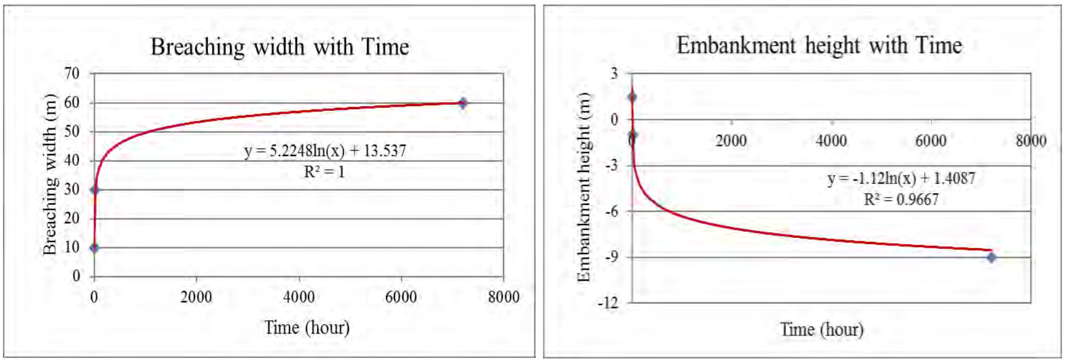


Figure 5.2: Embankment overtopping mechanism during Aila in Polder 32 (*source*: field information).

5.2.3 Failure processes

The failure of the polders is likely to cause indescribable damages and sufferings to the coastal settlers and to the whole coastal settings. Aila bears the example of immense losses and damages caused by massive embankment failures. Surge water during Aila broke into Polder 32 through massive embankment failures. 50 km long embankment was overtopped at some places with major breaching at three points. At some points, the earthen embankments were weaker due to human interventions and some other reasons as already mentioned in the previous section. At the first thrust of

Aila, the polder was breached at three locations. The initial breaching width identified by the local observers was about 10 m, 60 m and 20 m at Nalian, Jaliakhali and Vitevanga respectively, within the first half an hour of Cyclone Aila. The breaching width increased very rapidly after first few hours of the event. Even after Aila, during daily high tide and low tide the breaching width increased until the polder was reconstructed. Not only the breaching width, but also the bed level at the point of the embankment breaching became deeper with time. The bed level dropped down to (-) 16 m (PWD) at some locations where the previous bed level was (-) 2 m to (-) 3 m (PWD). Our analysis was based on the information gathered from local people and technical personnel from BWDB. The progressive breaching width and embankment height in the short and long term showed that the breaching and scouring approximately followed logarithmic trends (Figure 5.3). However, this analysis would be more accurate and reasonable if it was done based on hydraulic theories that include head difference, flow velocity, scouring rate, etc. A Major portion of the breaching width and scouring depth occurred within the early few hours of Aila (Figure 5.3 and Figure 5.4). Almost 50% of the total breaching took place within the first 6 hours of the event. After a certain period the breaching and scouring processes became steady which is represented by the flatter portion of the Figure 5.3.



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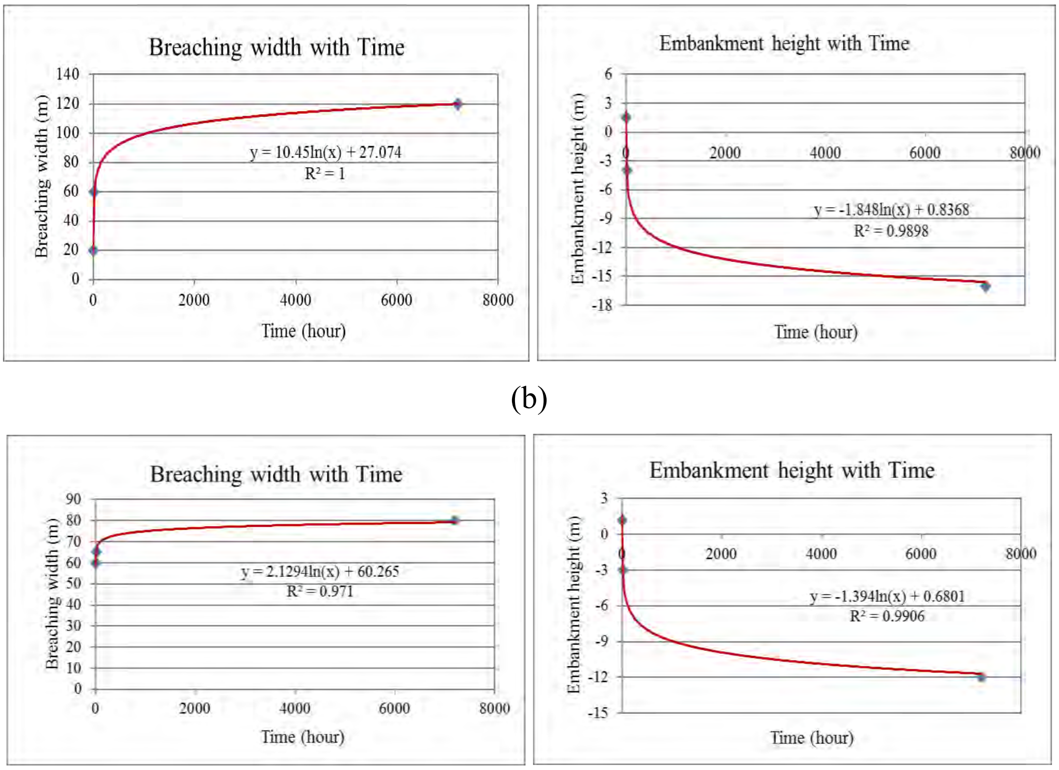


(b)

(c)

Figure 5.3: Breaching and scouring process (a) Nalian (b) Jaliakhali (c) Vitevanga (*data source*: field information).

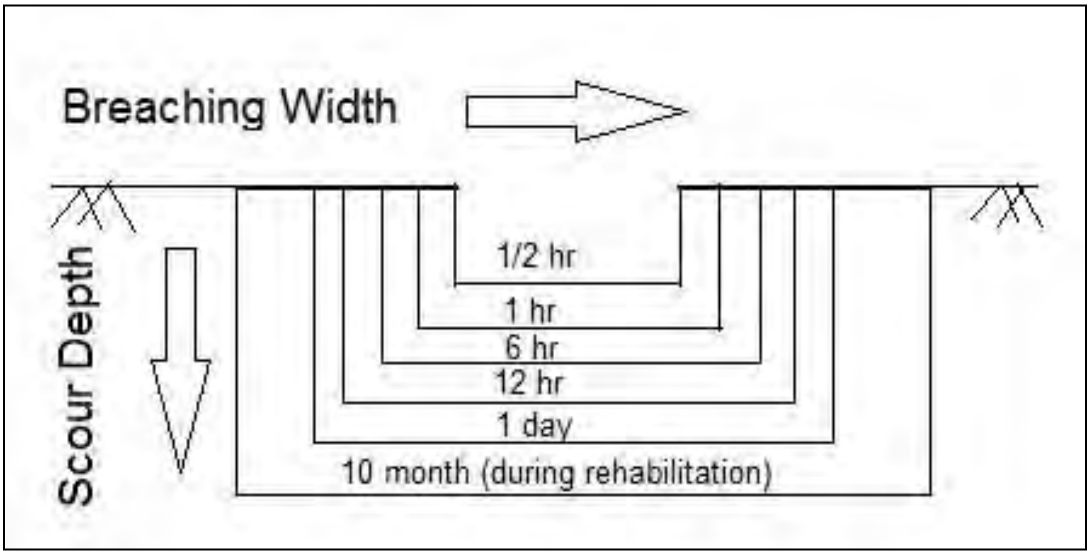
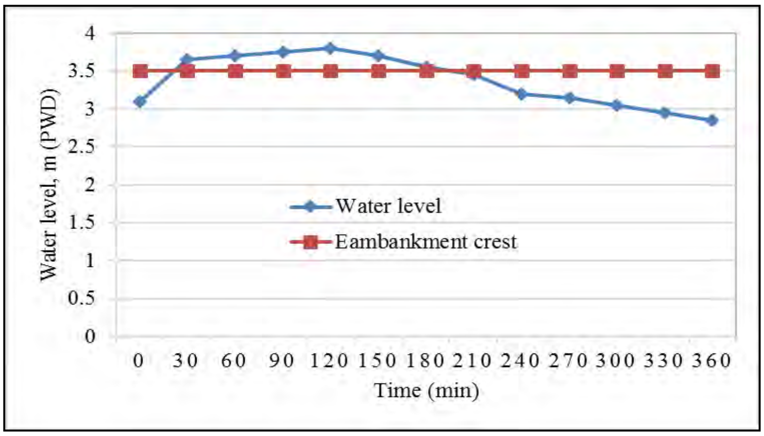


Figure 5.4: Schematic diagram showing increasing breaching width and scouring depth with time in Polder 32 (*data source*: field information).

Breaching is a complex process; whereas overtopping is a quite simple process occurred by a significant rise in water level. Overtopping occurs when the water level in the vicinity of the embankment exceeds the crest level of the embankment. Polder 32 was overtopped at some points during Cyclone Aila among which three overtopping locations were identified during this study, namely L-1, L-2 and L-3 as mentioned earlier in Figure 5.1. At those locations the embankment crest was 3.65 to 3.70 m (PWD). The water level rose to almost 3.80 m (PWD) at those points during Aila. The detailed overtopping process has been illustrated in Figure 5.5. In the figure water level for the first six hours immediately after Aila has been plotted against time and summarized in Table 5.3.



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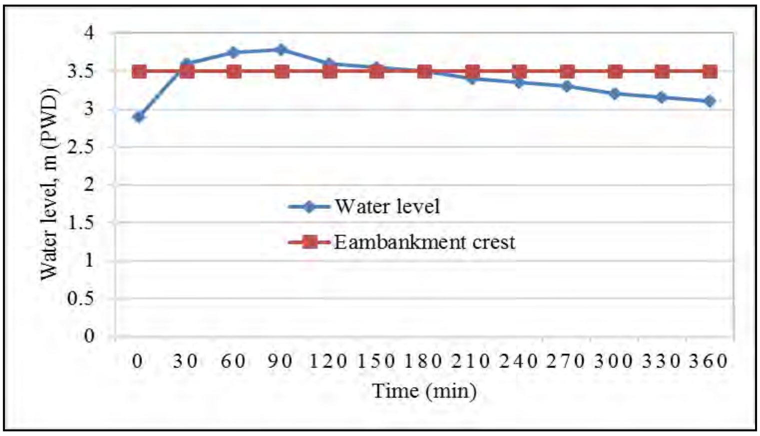

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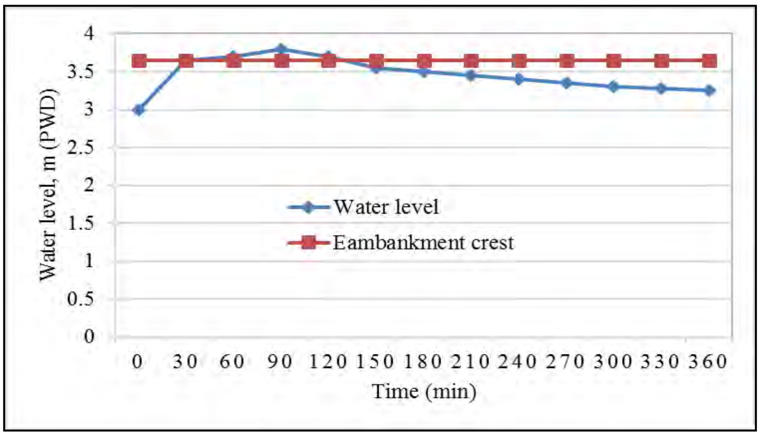


(c)

Figure 5.5: Overtopping process at three locations (a) L-1, (b) L-2 and (c) L-3 (*data source*: field information).

Table 5.3: Overtopping durations during Aila in Polder 32.

Locations	Surge WL (m, PWD)	Embankment crest (m, PWD)	Overtopping duration (hr)
L-1	3.80	3.50-4.00	2.50
L-2	3.85		2.00
L-3	3.75		1.50

5.3 Estimated Storm Surge Levels

There was a sharp rise in the river water level during Cyclone Aila. The variation in river water level was estimated using a numerical model “Delft3D”. The water level was observed at Sutarkhali water level station. The model was calibrated and validated prior to the final simulation of breaching and overtopping scenarios. The model generated water level hydrographs were compared with the observed water level hydrographs for calibration and validation purposes.

5.3.1 Model calibration and validation

Different input parameters including discharge of the river at the upstream boundary, water level at downstream boundary, Manning’s n for the river channel, etc., were used in the simulation of failure scenarios in Delft3D. For our analysis, Manning’s n was used as calibration parameter in the model. The model was calibrated by taking a number of values for Manning's n. Comparisons were made between the model results and the known water level at Sutarkhali point for calibrating the model. Observed water level and model results of November and December of 2009 were used for calibrating the model. Then the model was tested for a gradual change in the values of Manning's n. The observed water level hydrograph at Sutarkhali is shown in Figure 5.6. A series of hydrographs were developed for different values of n ranging from 0.02 to 0.08 and the best calibration was found for n value of 0.025 which has been used in this study as final calibration and shown in Figure 5.7. It was observed that the model conveyed better results as the Manning's n value was decreased and the results became more congruent with the observed values. After setting a value for Manning's n the model was validated with the water level of the Sutarkhali river (Figure 5.8). Observed water level and model results of October, 2009 were used for validation of the model.

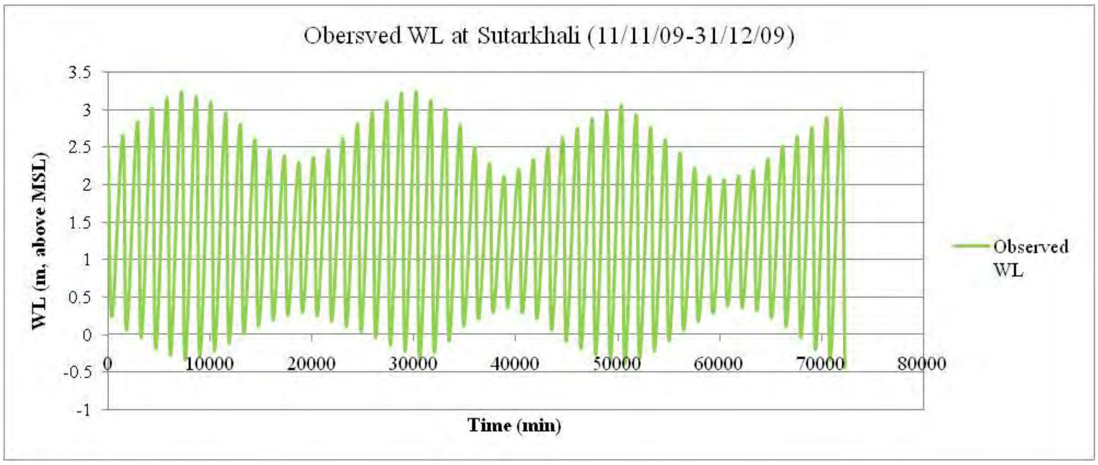


Figure 5.6: Observed water level hydrograph at Sutarkhali station during 11-11-2009 to 31-12-2009 (*source*: BWDB).

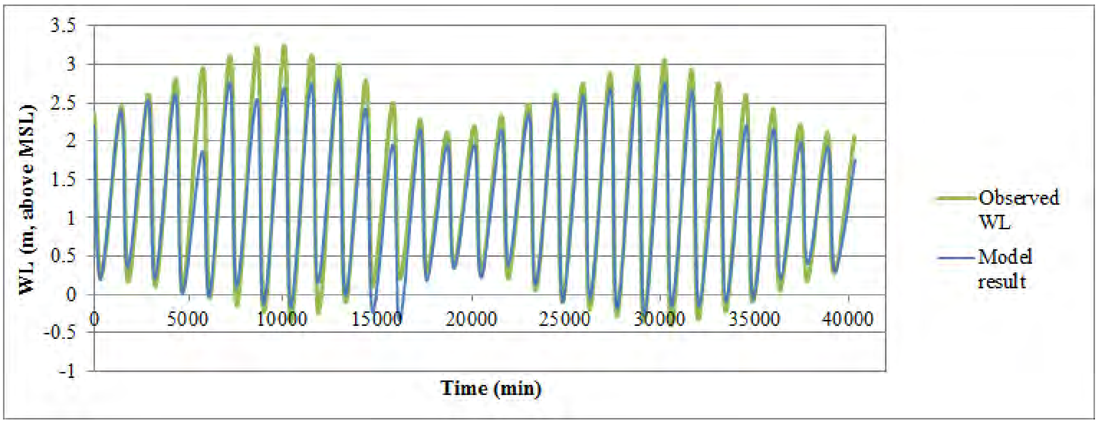


Figure 5.7: Comparison between the model generated and observed hydrographs during model calibration (from 15-11-2009 to 15-12-2009) for Manning's n value of 0.025 (calibration plot).

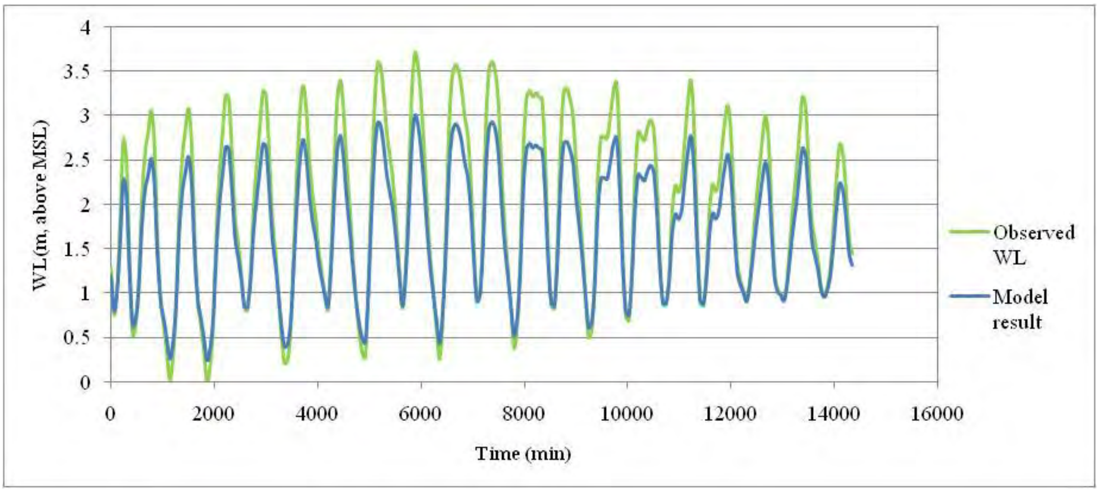


Figure 5.8: Model generated water level hydrograph from 01-10-2009 to 10-10-2009 (validation plot).

5.3.2 External water level variation

The model generated water level hydrograph at Sutarkhali river at the time of occurrence of Cyclone Aila is shown in Figure 5.9 and Figure 5.10. Using the data from BWDB at the boundary of the model, water level hydrographs at the time of Aila were generated to observe the water level variation at Sutarkhali station. It was found that on May 25, 2009 when Aila occurred, the water level sharply rose up to 3.80 m (PWD) (Figure 5.9). From hourly hydrograph of May 25 (Figure 5.10), it was found that from 2 PM of that day the water level started to rise. Between 3 PM to 6 PM, the water level exceeded the embankment crest which made it to overtop the embankment. A similar scenario was observed in a number of places where overtopping of polder took place.

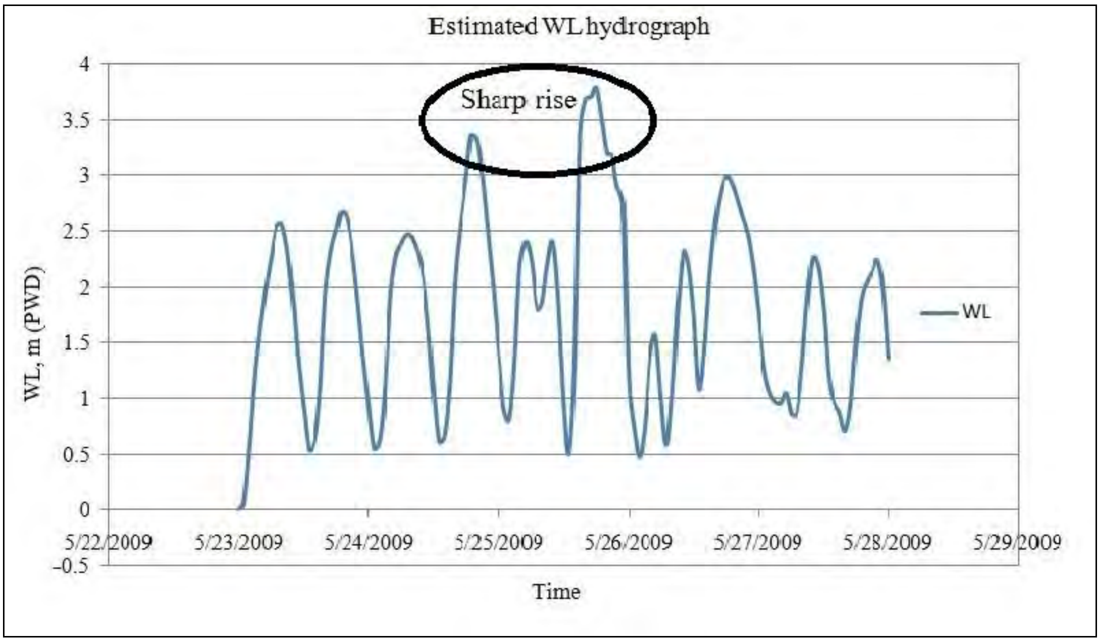


Figure 5.9: Estimated water level hydrograph during Aila (*source*: model result).

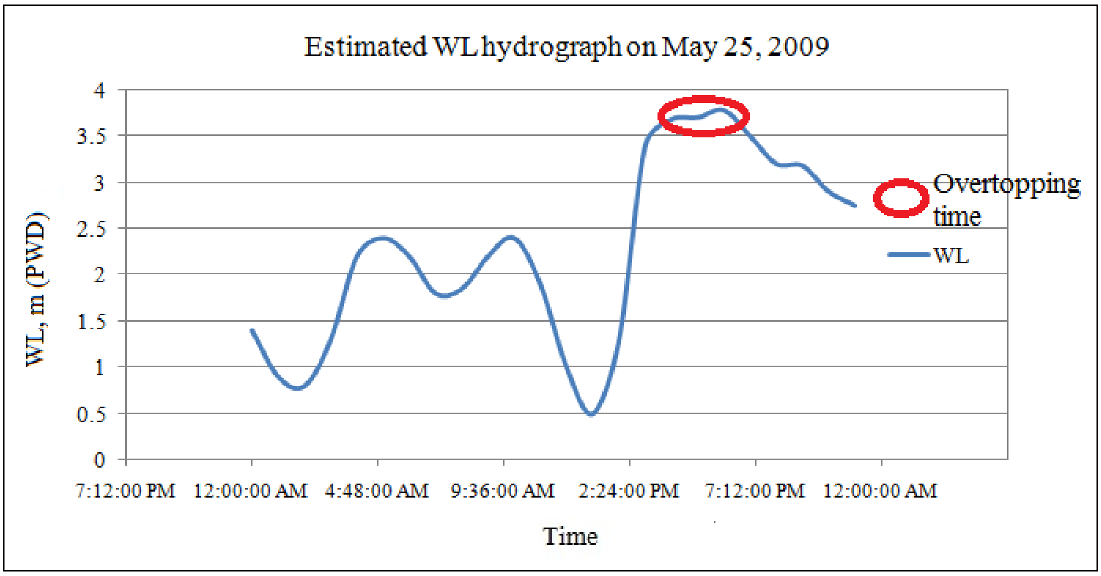


Figure 5.10: Estimated water level hydrograph on May 25, 2009 (*source*: model result).

5.4 Polder Inundation

5.4.1 Inundation due to overtopping

The model result showed that during Cyclone Aila surge water intruded into Polder 32 by overtopping and resulted in the inundation of the inland area (Figure 5.11). According to the model result, approximately 25% of Polder 32 was inundated due to overtopping. The water level rose up to 2.50 m above mean sea level inside the polder due to overtopping (Figure 5.11). Field information showed that Polder 32 was overtopped in some locations and among them three major locations were noteworthy which have been discussed in earlier sections. According to the local people, the contribution of polder overtopping in the total inundation of the polder was comparatively lower. The embankments were overtopped for the first one to two hours of the event. The water flowed 0.3 to 0.5 m above the embankment crest.

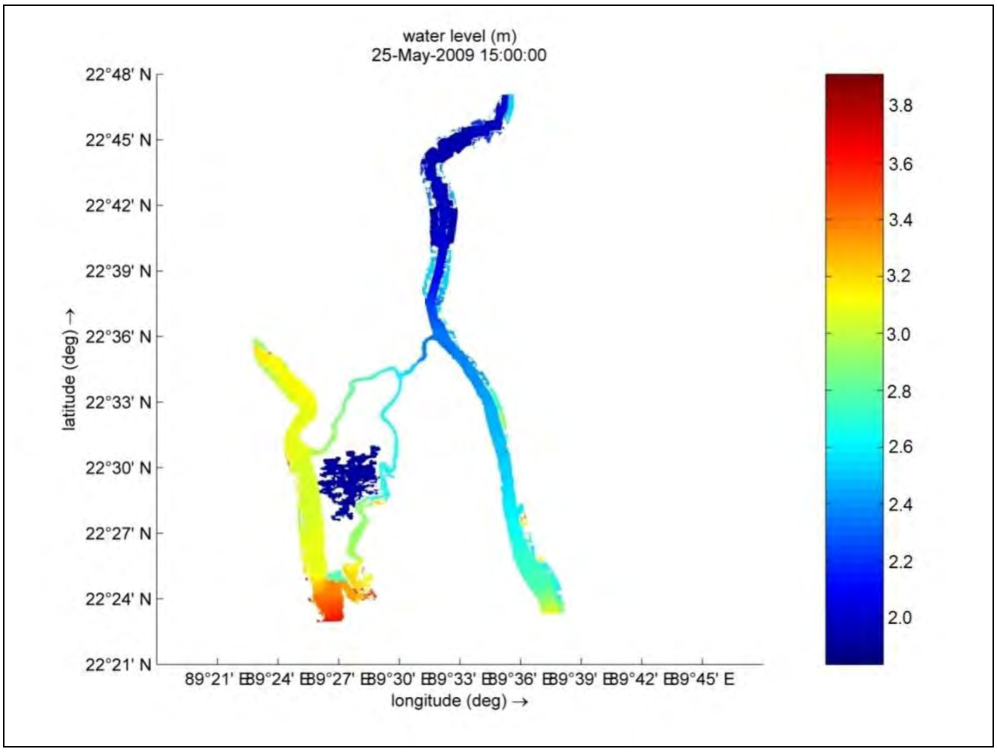


Figure 5.11: Inundation due to embankment overtopping (*source*: model result).

5.4.2 Inundation due to breaching

During Aila, most of the area of Polder 32 was inundated by surge water. The inundation was caused by massive embankment breaching at three major locations. Model result showed that more than 80% of the area was inundated due to polder breaching (Figure 5.12). The water level rose up to 2.20 m above mean sea level inside most of the polder. In some small area the water level even rose up to 2.60 m. During field visits the local people also informed that most of the inundation inside the polder was caused due to polder breaching.

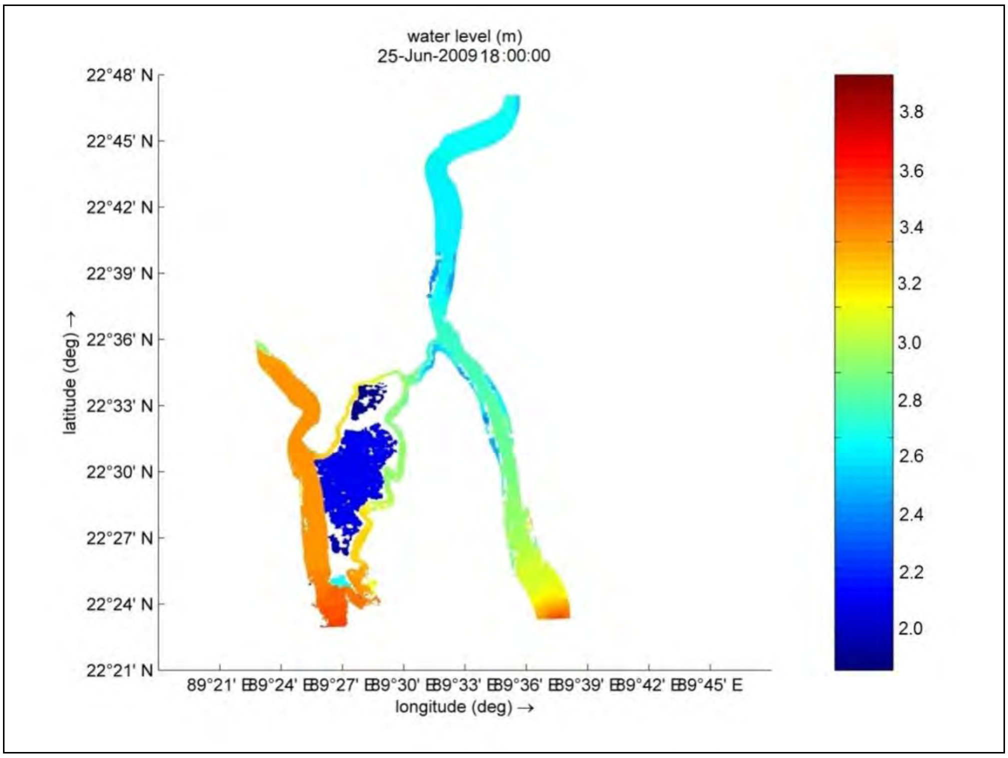


Figure 5.12: Inundation due to embankment breaching (*source*: model result).

5.4.3 Inundation due to combined breaching and overtopping

During Aila, massive embankment failures both breaching and overtopping occurred in Polder 32. Model result showed that approximately 90% of the area inside Polder 32 was inundated by surge water during Cyclone Aila (Figure 5.13). The water level rose up to 2.90 m above mean sea level inside the polder due to combined breaching and overtopping. During field visits, several individuals also informed that the water depth reached up to 2.0 m after Aila inside the polder. Using the local water depth, which was collected during field consultations, analyses were done using ArcGIS 10.2 (Figure 5.14). It showed that approximately 85% of the area inside Polder 32 was inundated. The inundation depth ranged from 1.20 to 2.50 m.

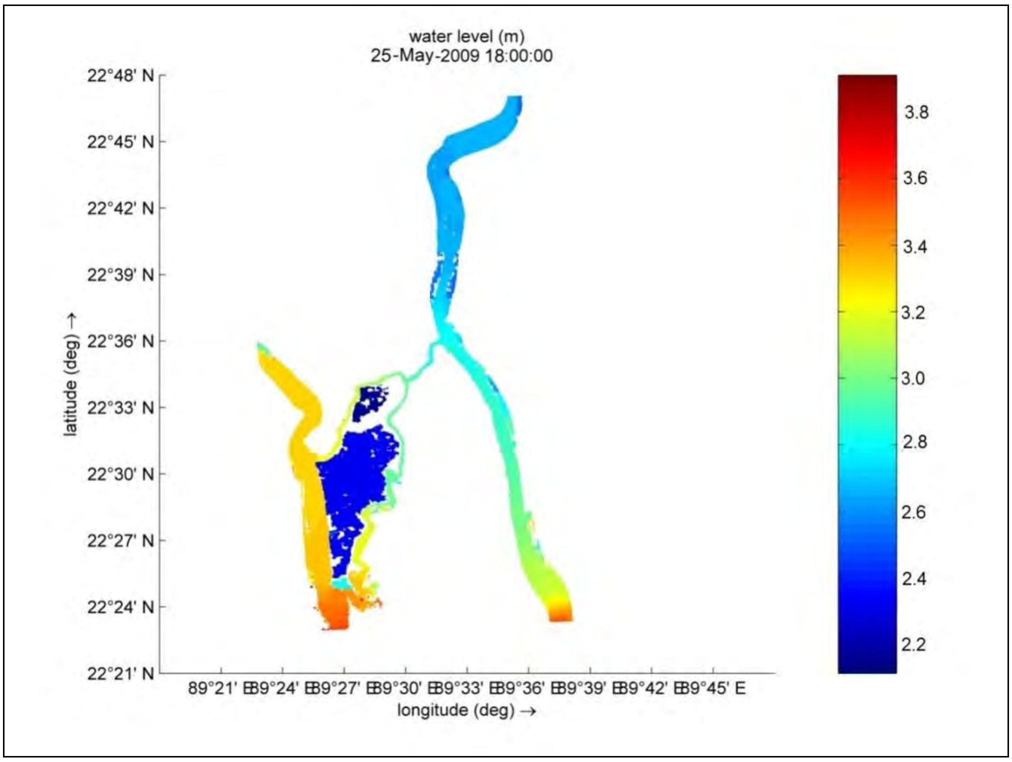


Figure 5.13: Inundation due to breaching and overtopping (*source*: model result).

5.5 Impact and Damage Assessment

Cyclone Aila inflicted a heavy damage to Polder 32 of Dacope upazila of Khulna district. The failure of the embankment of the polder was more responsible than the strength of the cyclone for the wreckage condition of the whole area. The breaching and overtopping of the polder caused both short and long term inundation in the area. But the inundation became severe when the surge water intruded into the polder area through embankment breaching. For inundation criteria and subsequent losses and damages, land elevation of the area, internal drainage routes, and dead water bodies played a significant role which was taken into consideration during damage assessment in this study. Most of the land in the study area ranged from low to medium highlands which were likely to be flooded with moderately high cyclonic events. Analysis showed that 63% of the area had an elevation of less than 3 m and 15 % area had an elevation ranging from 4-5 m above mean sea level (Figure 5.15). As a result, the maximum local water level of 4.25 m above mean sea level during Cyclone Aila inundated more than 85% of the area (Figure 5.16).

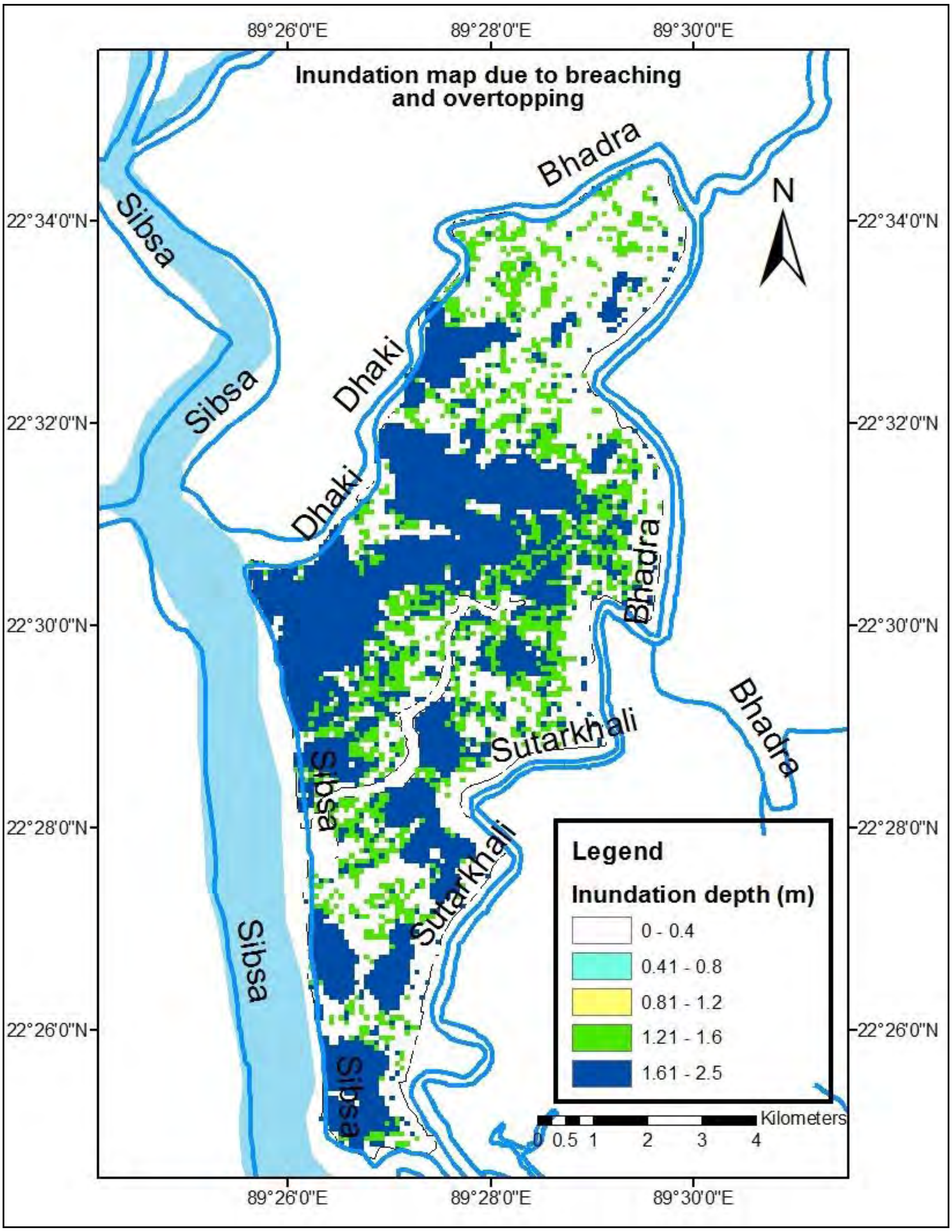


Figure 5.14: Inundation due to embankment failure (map generated from water level reported by local people).

Three major breaching points became free for water flow during regular high and low tides. These three points along with other internal drainage routes resulted in regular changes in inundation depth in the area for more than the first one year after

Aila. The drainage routes acted as flow channels giving passage to the regular cyclic tidal water that resulted in long term inundation of the area (Figure 5.17). After a year of the event, surge water receded from most of the areas through the drainage routes except some dead water bodies (Figure 5.18). In those water bodies, saline water was logged for some more years that worsened the prolonged impacts (Kabir *et al*., 2016). The broader impacts were assessed in three major breaching points, namely Nalian, Jaliakhali and Vitevanga of Polder 32. The total losses and damages of some typical affected people of the study area have been presented in Table 5.4 which gives an idea about the relative impacts of the event in three different breaching points. This assessment was performed based on the information provided by the affected people from the area. Information were collected on some selected sectors which were severely damaged and then gross losses and damages were calculated in monetary terms. Our detail damage assessment showed that Nalian was comparatively higher sufferer than other two points. The detailed sectoral and temporal impacts have been assessed in Polder 32 and discussed in the following sections including Appendix A.

Table 5.4: Sectoral damages at three locations (based on reports by 10 typically affected people from each location).

Sectors	Nalian (BDT, million)	Jaliakhali (BDT, million)	Vitevanga (BDT, million)
Household	2.73	0.605	0.61
Agriculture	5.075	1.4	1.85
Livestock	0.0924	0.065	0.178
Other properties	1.2	0.305	0.37
Total	9.0974	2.375	3.008

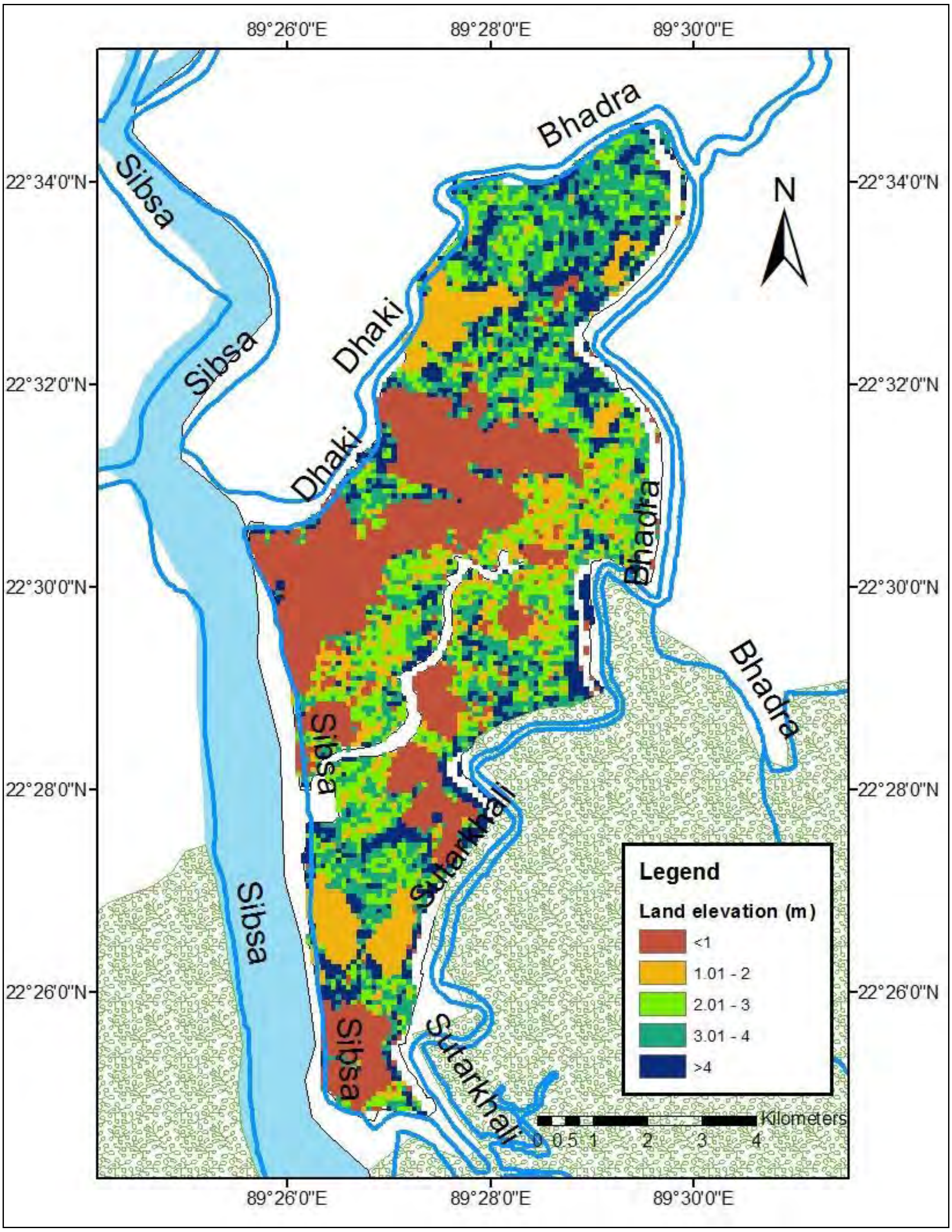


Figure 5.15: Land elevation in the study area (*data source*: IWFM, BUET).

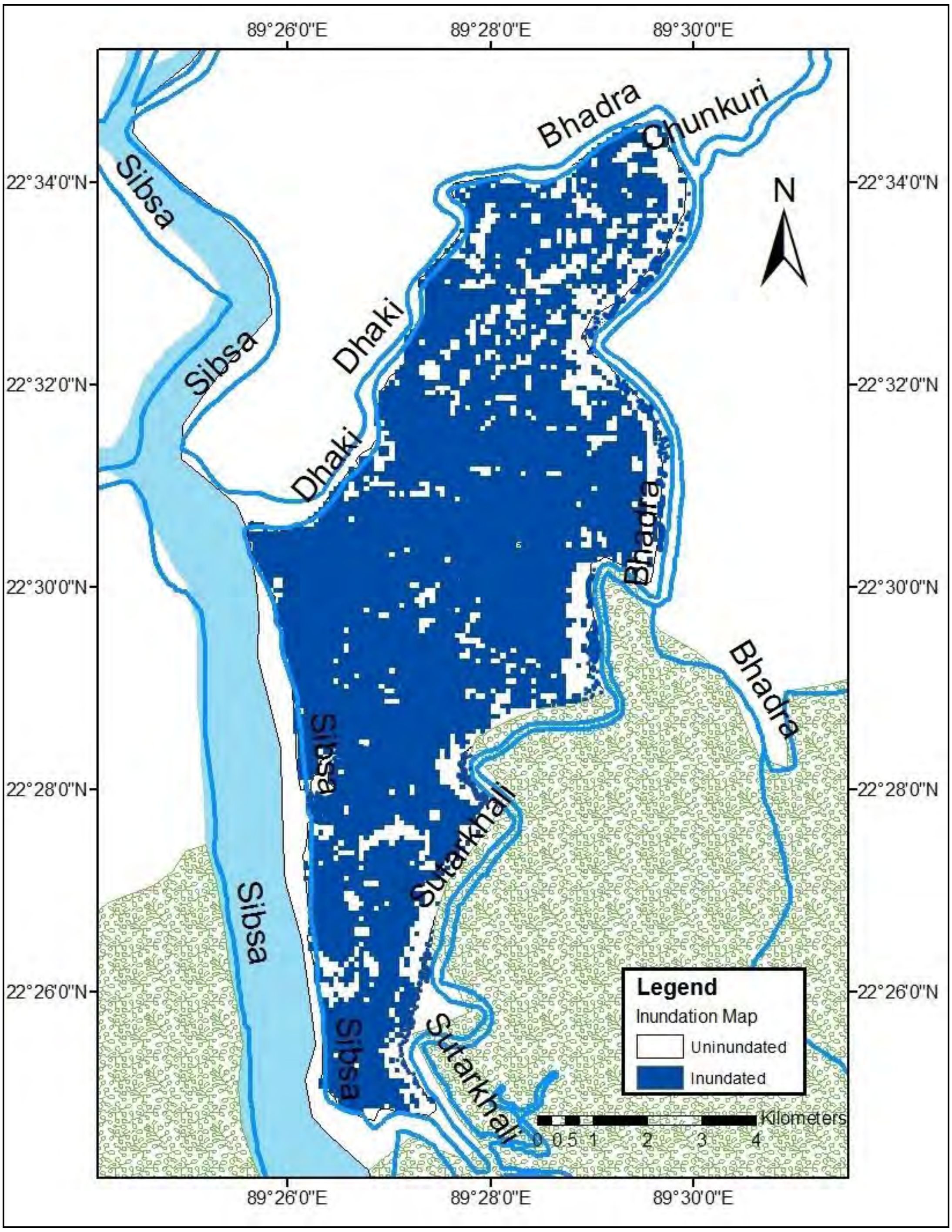


Figure 5.16: Inundation map of the study area (immediately after Aila) (*source*: Local people's information).

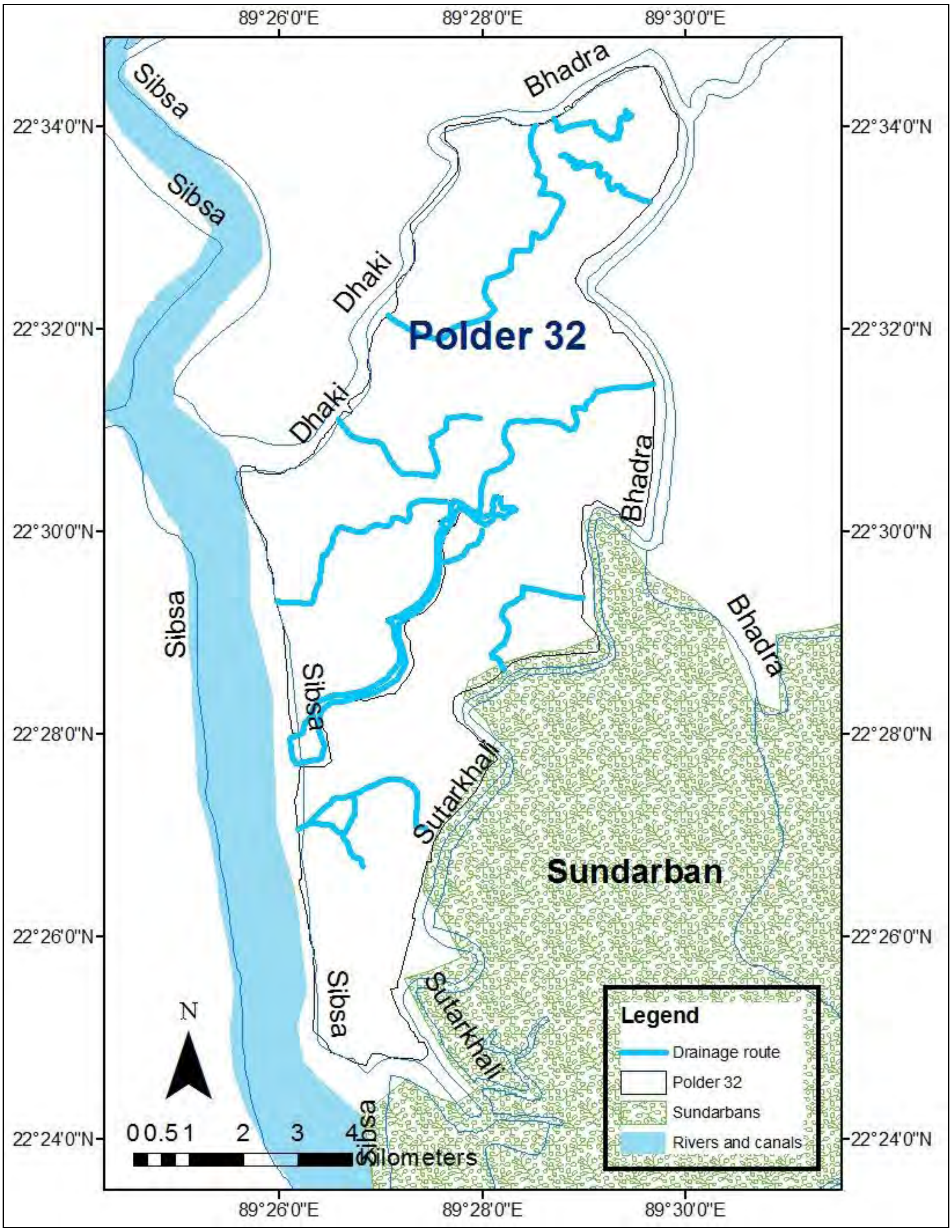


Figure 5.17: Drainage routes in the study area (*source*: satellite image and field information).

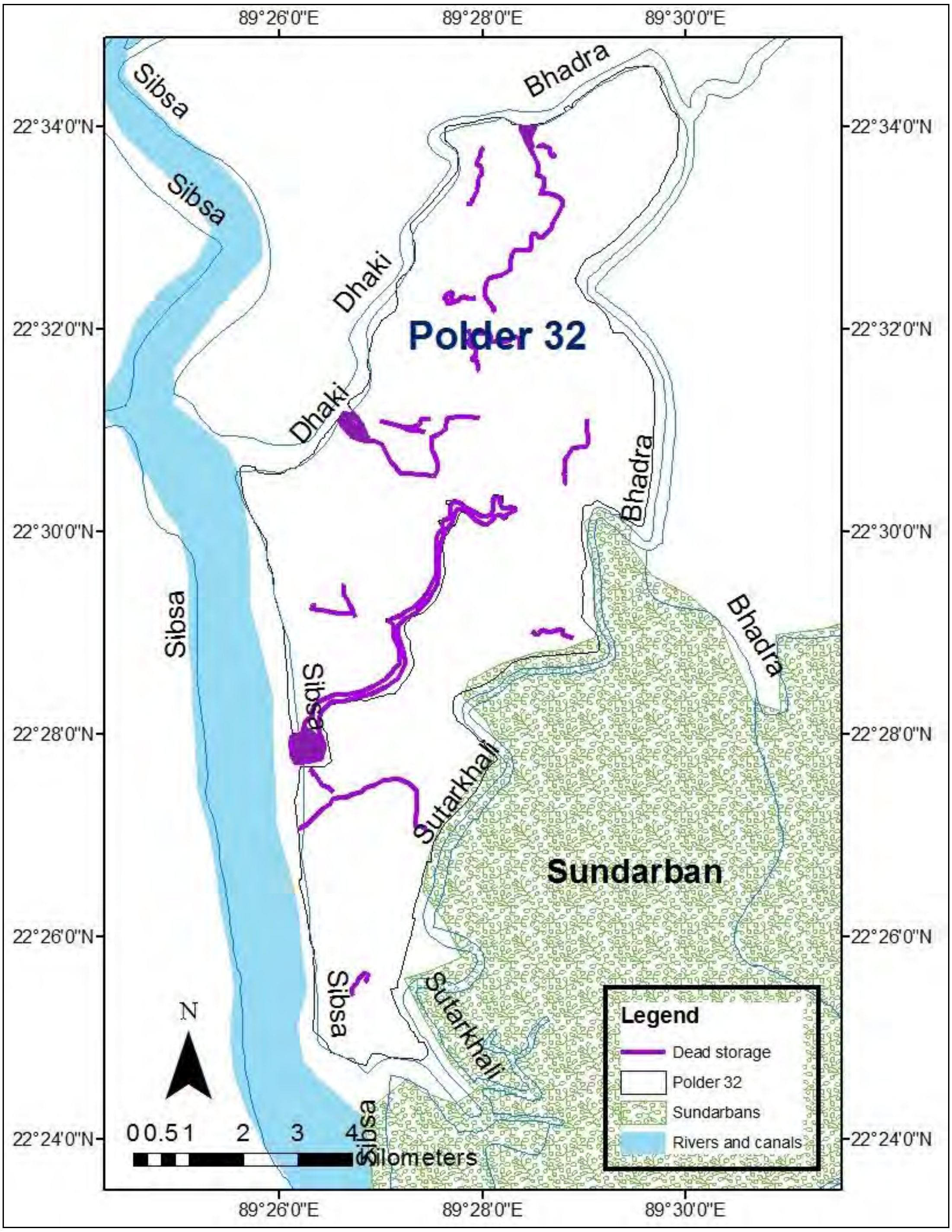


Figure 5.18: Dead water storages in the study area (*source*: satellite image and field information).

5.5.1 Immediate impacts

During Aila surge water intruded into Polder 32 through both breaching and overtopping. According to local people, there were no noteworthy immediate impact to their household assets, agricultural crops caused by polder overtopping during Aila. But, in case of breaching the surge water broke through the embankment with high velocity, which took away all the belongings that it found in its course during travelling. The settlements and the properties close to the breaching points were the immediate victims. In all the three major breaching points, households, homestead properties, marketplace, livestock were the immediate victims of the event. Analysis based on the information gathered from field visits showed the detailed picture of the immediate impacts of Aila in the study area. Based on more than 30 individual interviews with affected people of the study area, Figure 5.19 represents that 50% of the total impacts were immediate impact in the study area. High immediate impacts occurred due to the breaching of Polder 32. Figure 5.20 shows the sectoral distribution of the immediate impacts on different sectors in Polder 32. Sectoral distribution of immediate impacts demonstrates that household and agriculture were the worst immediate victims. A major portion of the households situated at the breaching locations and surrounding areas were immediately washed away by the surge water. Immediate damages in agricultural sector included homestead vegetables and fisheries both carp fishes and shrimp gher. A huge amount of ponds and shrimp ghers were immediately flooded with surge water, which allowed the fishes to escape and freshwater fishes died due to saline water intrusion. A good number of livestock was washed away by the surge water immediately after Aila. Other properties, including boats, shops and fish storages were immediately washed away, which constitute a considerable percentage of total immediate impacts. Figure 5.21 provides location specific damage status based on individual interviews of the affected people. The distribution of immediate, short and long term impacts of Cyclone Aila in three major breaching points is shown in Figure 5.21. The comparative analysis shown in Figure 5.21 provides that all the three locations experienced higher immediate impact with respect to short and long term impact. The higher share of immediate impacts was due to immediate washing out of households, agricultural lands, fish ponds, shrimp ghers etc., in all of the locations.

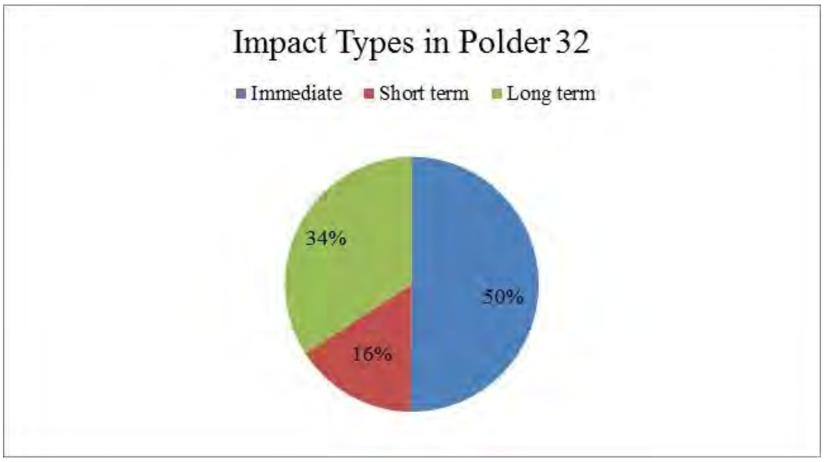


Figure 5.19: Impact types in Polder 32.

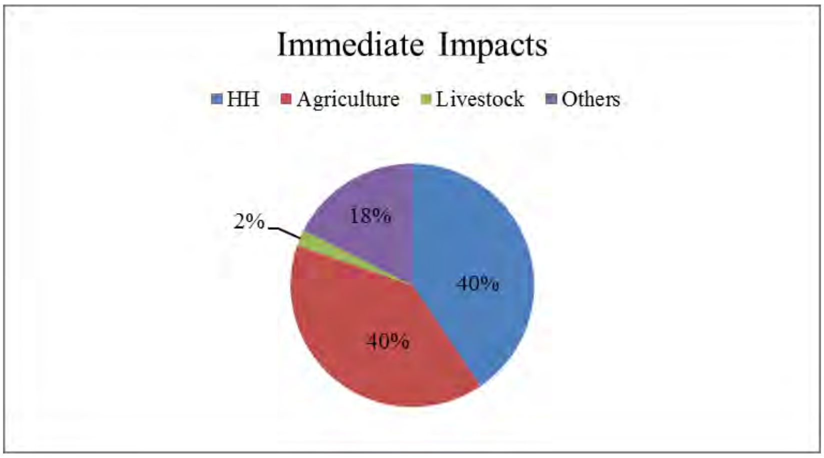


Figure 5.20: Sectoral distribution of immediate impacts in Polder 32.

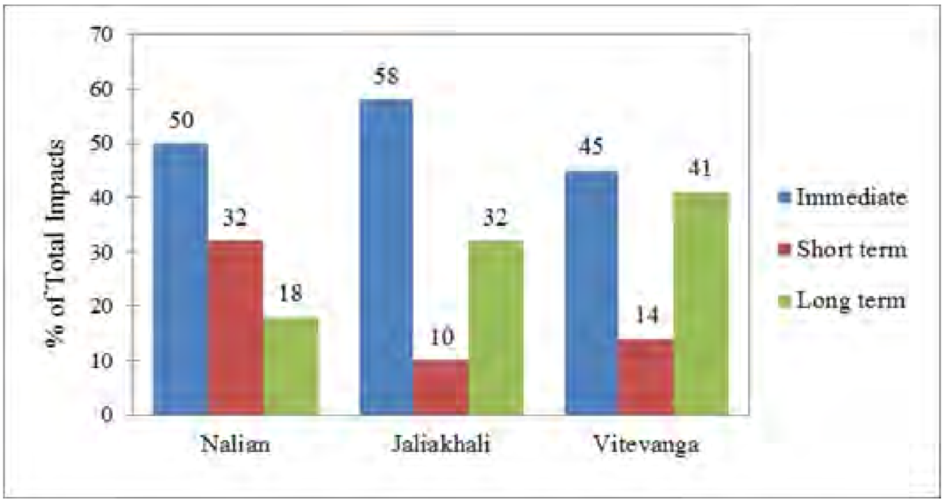


Figure 5.21: Immediate, short and long term impact distribution in three locations of Polder 32 based on individual interviews.

Information gathered from nine Focus Group Discussions (FGDs) were analyzed to show a comparative distribution of immediate, short and long term impacts in three breaching locations (Figure 5.22). This distribution showed a slight difference from the distribution attained from individual interviews. This variation was attributed as the reasons for the difference in the individual peoples' perceptions and understanding of the damages to those of a group of people.

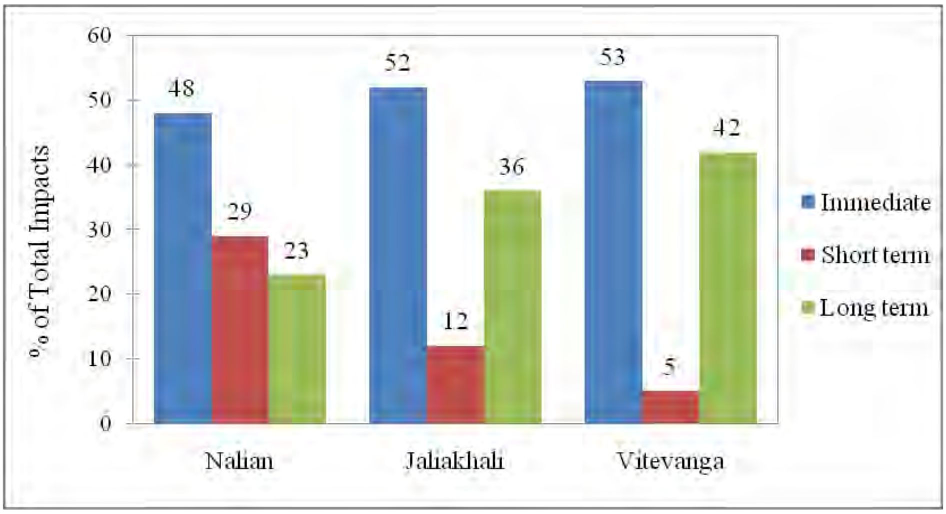


Figure 5.22: Immediate, short and long term impact distribution in three locations of Polder 32 based on FGDs.

Based on the information gathered from local people during individual interviews, analyses were performed to show the distribution of the immediate impacts over different sectors in three major breaching locations (Figure 5.23). In Nalian, households were the worst immediate victims of Cyclone Aila. Agriculture was the worst victim of immediate impact in both Jaliakhali and Vitevanga. The comparative analysis also shows that in all locations households\ and agriculture constitute the major portions of the total immediate impacts. The sectoral distribution of the immediate impacts based on FGD's slightly varies from the distribution obtained from individual interviews (Figure 5.24). But still household and agriculture are the worst victims in all of the three locations.

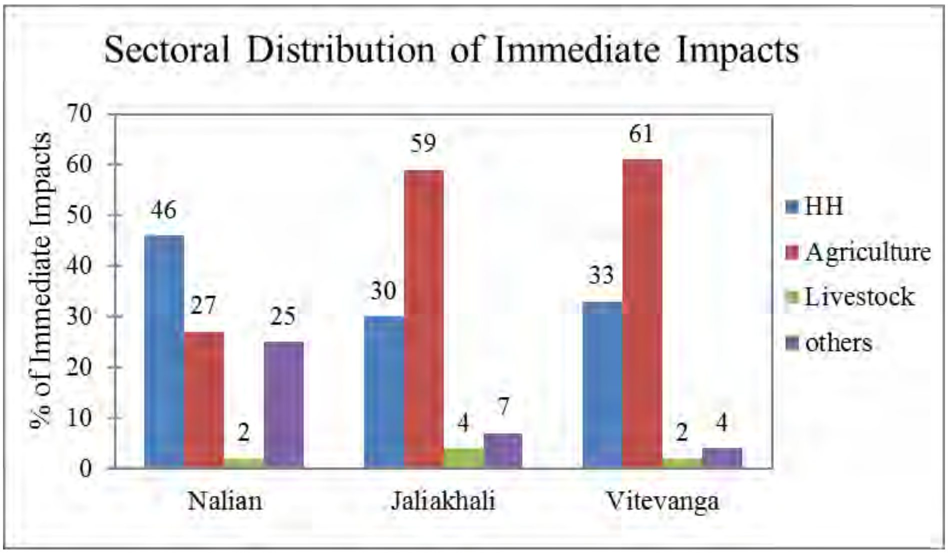


Figure 5.23: Sectoral distribution of immediate impacts in three major breaching locations based on individual interviews.

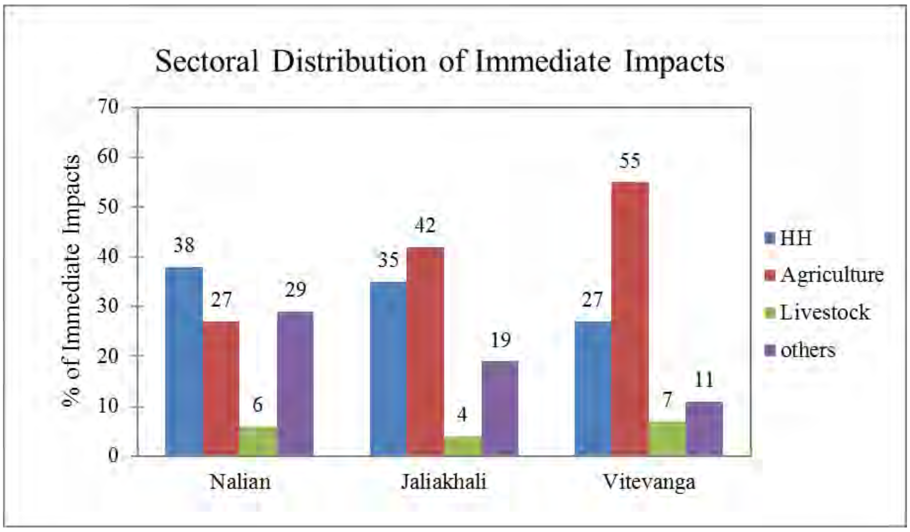


Figure 5.24: Sectoral distribution of immediate impacts in three major breaching locations based on FGDs.

5.5.2 Short term impacts

After the intrusion of the surge water into the polder, water was logged within the polder for a long period. Most of the houses within the polder were earthen made. Being waterlogged, the earthen houses could not manage to stand tall more than a week. Livestock like ducks, hens, cows, goats led a miserable life in a situation of waterlogging and faced extreme food scarcity. Most of the livestock those somehow survived the first stroke of the disaster eventually died on later period in devoid of food. As stated in the previous section (Figure 5.19), 16% of the total losses and damages within Polder 32 were identified as short term impact. It was also found that out of the total impacts 32%, 10% and 14% were short term impacts in three major breaching locations namely Nalian, Jaliakhali and Vitevanga respectively (Figure 5.21). The distribution of the short term impacts over different sectors within Polder 32 is shown the Figure 5.25. Agriculture sector experienced the most short term impact followed by household. The submergence of the local ponds with saline water resulted in death of a huge amount of sweet water fishes within a few days after Cyclone Aila. Some homestead agricultural crops and many trees, both fruit trees and timber trees died within a few days after the event. Earthen houses became weak due to submergence with saline water and failed after a short period of the event. Other impacts included the temporary shutdown of the local market and associated losses and loss in working opportunities of local day laborers, which cumulatively account for 6% of the total short term impacts. The distribution of the short term impacts on different sectors in three major breaching locations is shown in Figure 5.26. The analysis was performed based on the individual interviews of the affected people. Agriculture experienced the most short-term impact in Nalian but in two other locations household sector had the most of short term impact.

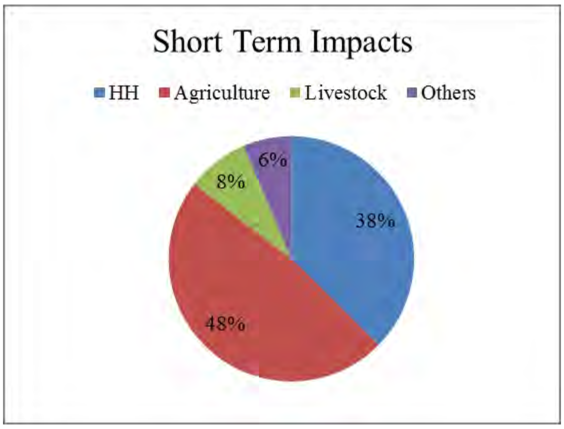


Figure 5.25: Sectoral distribution of short term impacts in Polder 32.

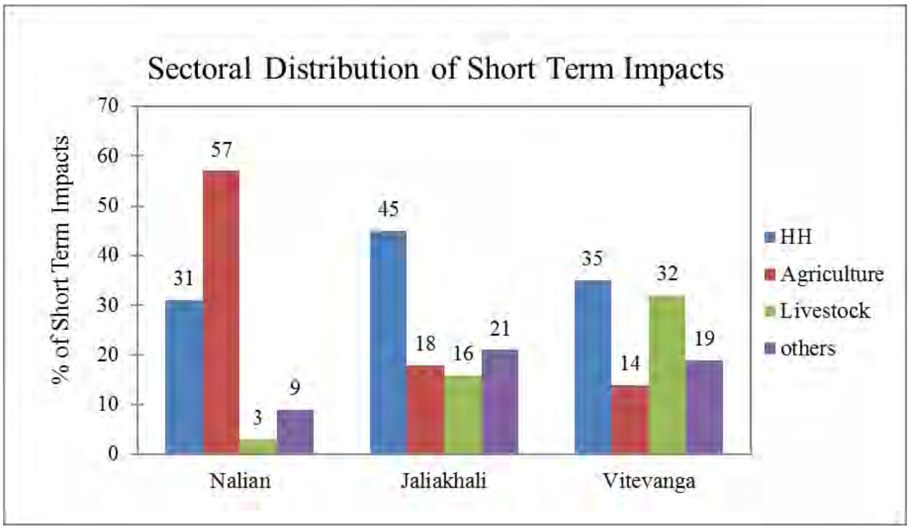


Figure 5.26: Sectoral distribution of short term impacts in three locations based on individual interviews.

5.5.3 Long term impacts

The immediate aftermaths of Aila continued for a prolonged period, causing immense sufferings to the lives and livelihoods of the affected people. The possible damages to household, livestock, crops and fisheries occurred within the first fifteen or some more days of the event. But the impacts continued in agriculture sectors, both crops and fisheries for even a longer period. Saline water remained logged within the polder for more than one year, which made any kind of agricultural productivity impossible. Even when the water receded, due to the residual salts in the soil, agricultural production was not possible for one more year until the washing out of the salts from the soil. The three years of unproductiveness at a row made the farming based area economically paralyzed. Apart from agricultural productivity, affected people suffered from lack of accommodations and sanitations for two long years during the time of their temporary residence at cyclone shelters and elevated roadside embankments. As a consequence of the event, people faced a scarce situation of various livelihood opportunities for a longer period. Analysis based on individual interviews of the affected people showed that 34% of the total impacts in the study area were long term impacts (Fig 5.19). Figure 5.27 shows that agriculture was the major sector to be affected for a longer period. Even after the drain out of the surge water people had to wait until the wash out of the salts that was left by the surge water on the soil surface. During field visits, the local people also informed that the surge water also brought a lot of sandy sediments into the polder. Until the removal of the sediments from the agricultural lands, no crops were possible to grow on those sandy sediments. But the removal of the sediments was expensive enough for the already wretched people. It was seen during field visits that even after five years of the event, some people were unable to grow any crops in their lands for their inability to remove sediments from the lands which increased the long term impacts. Analysis was performed for the sectoral distribution of the long term impacts in three major breaching locations (Figure 5.28). In all locations, agriculture was the worst victim of long term impacts due to long term saline water inundation and associated agricultural unproductiveness. Some other long term impacts included long term unemployment of day laborers, boatmen and small other businessmen which constitute some percentage of the long term impacts.

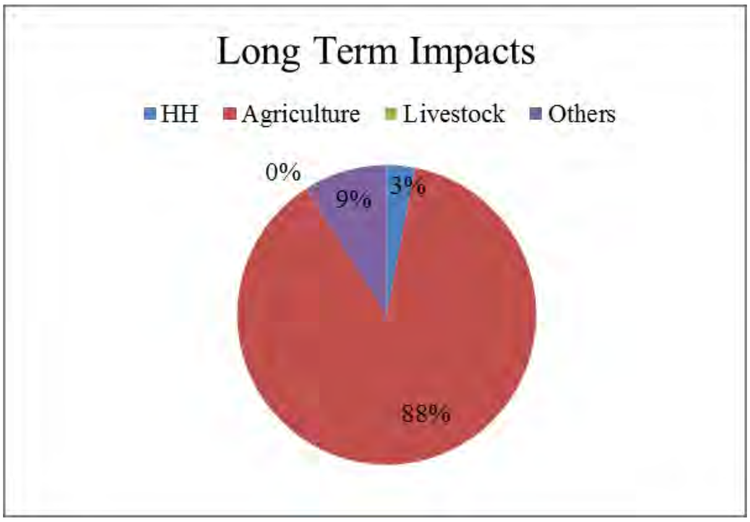


Figure 5.27: Sectoral distribution of the long term impacts in Polder 32.

5.6 Sectoral Impacts

Super Cyclone Aila of 2009 affected the whole coastal settings, all the sectors related to coastal lives and livelihoods of the south west coastal region of Bangladesh. Affected people stated that their long life savings and ancestral houses were lost in this disastrous event. Though a lot of sectors related to the coastal system were affected, but the broad assessment was carried out for infrastructure (embankment), household and agriculture sector as those sectors held the major percentage of the total impacts.

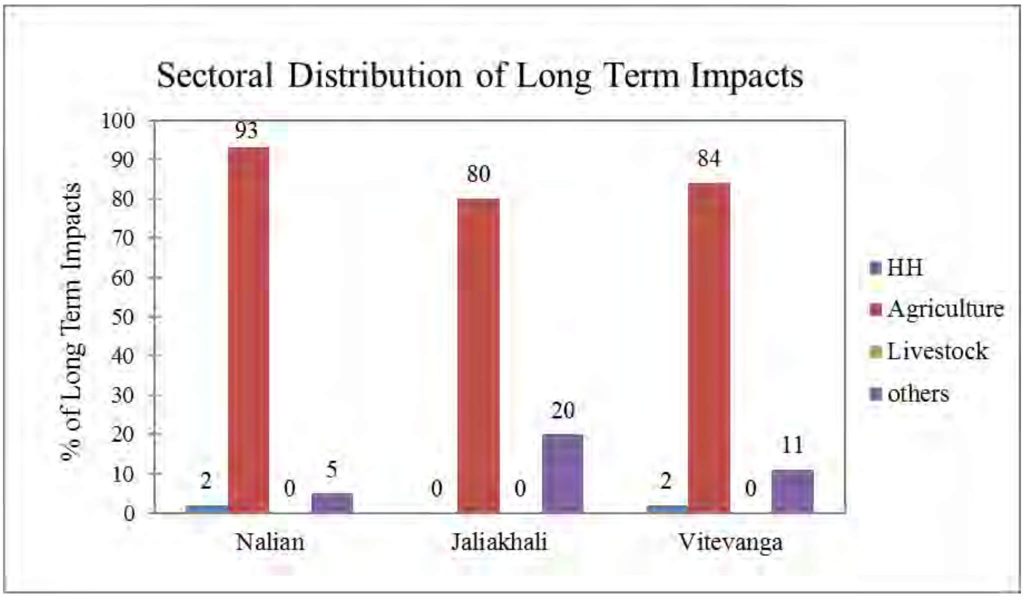


Figure 5.28: Sectoral distribution of long term impacts in three locations based on individual interviews.

5.6.1 Embankment

The failure of the embankment during Aila aggravated the situation causing both immediate and prolonged losses and damages (Photo B1 in Appendix). Failure of the embankment occurred through polder overtopping and breaching. Some part of Polder 32 was overtopped in Sutarkhali union, mainly the area in the southern portion of the union which was close to the Sundarbans. The embankment at those overtopping locations was relatively lower as stated by the local people. The embankment was washed away at those points and became narrower. The losses and damages due to overtopping were relatively lower compared to those caused by the breaching of the polder at three major points. A key informant, sub-assistant engineer of BWDB who had been working in Khulna division since Aila until the rehabilitation of the polder gave us the detail picture of the polder breaching (Table 5.5). They also suggested strengthening of the polders to reduce losses due to cyclonic events.

Table 5.5: Breaching width and scour depth at three locations (*source*: field information).

Breaching Point	Initial width (m)	Width during repairing (m)	Bed elevation (m, PWD)
Vitevanga	20	120	(-) 15 to (-) 16
Jaliakhali	60	80	(-) 12
Nalian	10	60	(-) 8 to (-) 9
	2	40	
	1.5	20	

It was also found that the polder rehabilitation could not start until the natural drain out of the surge water from the polder area that took it almost one year to start the rehabilitation work. The average bed level at the Nalian river, Gulbonia khal at Vitevanga and Jaliakhali khal was (-) 2.0 to (-) 3.0 m (PWD) but after breaching at the face of the breaching the bed level went up to (-) 15.0 to (-) 16.0 m (PWD) which compelled the authority to shift the embankments from the previous positions due to depressions at the faces. In some other places, the embankment had to be repaired. According to the respective authority from BWDB, Khulna the shifting of embankment cost BDT 60,00,000/km, whereas repairing cost BDT 20,00,000/km. The detailed status of the shifting and repairing of 50 km long Polder 32 is shown in Table 5.6.

It is noteworthy that the overtopping locations mainly required repairing and in some cases shifting, whereas the breaching locations required shifting. The shifting of the 39 km embankment cost about BDT 234 million where the repair of 39 km would cost about BDT 78 million. The breaching and subsequent shifting required additional BDT 156 million.

Table 5.6: List of reconstructed embankments with cost in Polder 32 (*source*: BWDB).

Points	Length (km)	Status	Cost (Taka, million)	Authority
South Kalabagi	1.2	Shifted	7.2	CARE
Mistripara	3	Shifted	18	BWDB
Gunari	5.5	Shifted	33	BWDB
Kalibari	2.5	Shifted	15	BWDB
Upside of Kalibari	2.5	Shifted	15	BWDB
Jaliakhali	2	Shifted	12	BWDB
Nalian	22.5	Shifted	135	BWDB
Other	33	Repaired	66	BWDB

5.6.2 Household

About 35 million, which accounts for 28% of the country's total population, live in the coastal region in Bangladesh (Khan and Awal, 2009). According to BBS (2008), there were more than eight thousand households in Polder 32. Most of the houses were earthen made; some were made of golpata where others were tin-shed. Local people informed that household was the first sector to be affected by Aila. On the first thrust of the surge, numerous houses were washed away. The houses which somehow could survive the first phase, most of them could not stand tall for a longer period. The earthen houses being waterlogged for a few days, the plinth became structurally weak and failed eventually. Based on field information, it was found that 27% of the estimated total impacts in Polder 32 occurred in the household sector (Figure 5.29). Impacts on the household sector included immediate washing out of the houses and household properties, gradual failure of the earthen houses in the wake of Aila and unsuitability of some other houses for further living due to long term submergence with saline water. It was also found that 75% of the total impacts in household sector were immediate, whereas 21% and 4% were short term and long term impact (Figure 5.30). It implied that most of the houses and household properties were lost in the early period of Aila. Some 21% of the houses and other household assets were lost within a few days after Aila. In the long term, there occurred no considerable damages in the household sector.

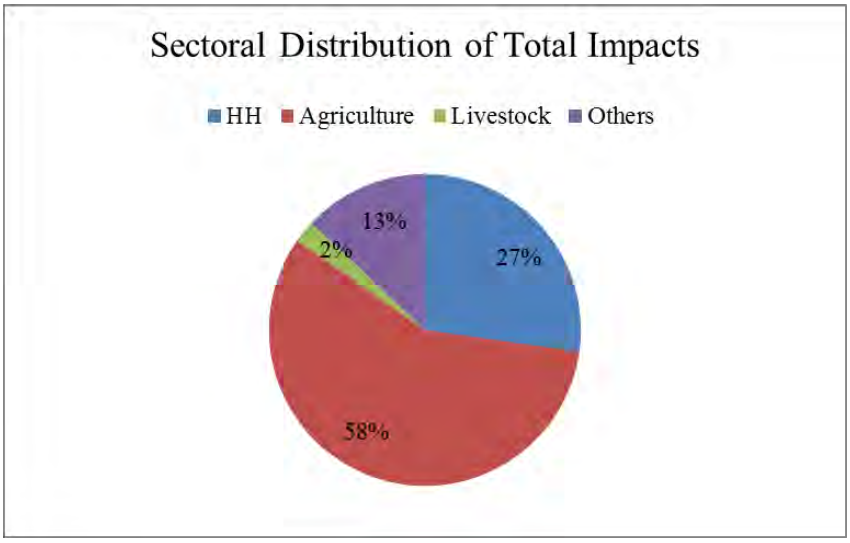


Figure 5.29: Sectoral distribution of the estimated total impacts in Polder 32.

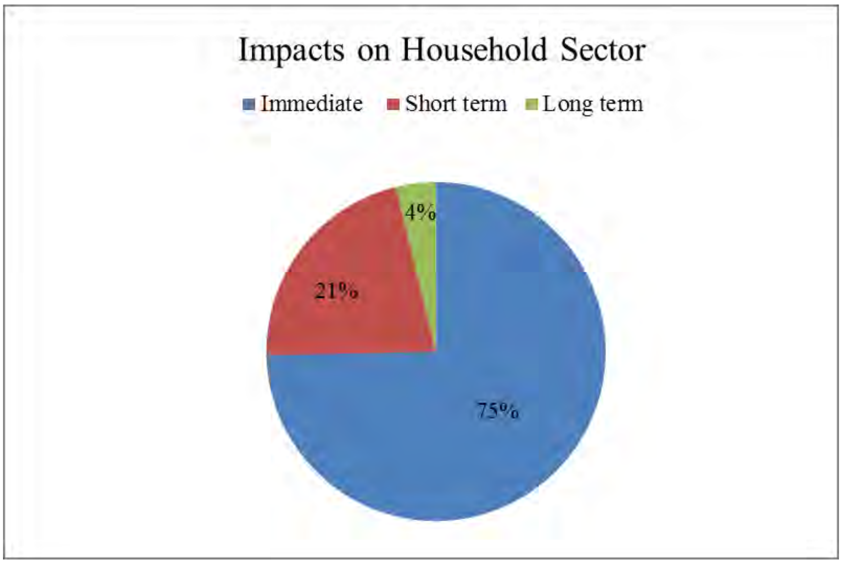


Figure 5.30: Immediate, short term and long term impact in household sector.

5.6.3 Agriculture

Total area of Polder 32 is 7,817 ha and about 60% of the land is cultivable (BBS, 2011). Agriculture is the major livelihood in the area. Most of the people are landless and small scale farmers. More than 90% people of the study area are directly or indirectly dependent on agriculture. So damages in the agriculture sector are likely to aggravate the total losses, damages and sufferings in the study area. During the occurrence of Aila on May, 2009 there were no crops in the field as it was the sowing time of *aman* rice. So there were less immediate damages in crop agriculture. But the fisheries, both freshwater and saline water were devastatingly damaged. The ponds and shrimp ghers were flooded with saline water which allowed the fishes to escape in flood plains which resulted in a considerable amount of immediate impact (35%) in the agriculture sector (Figure 5.31). The long term impact in agriculture sector was far reaching compared to the other sectors (Figure 5.28). The ponds remained polluted with saline water for more than two years, which made fish cultivation impossible for three consecutive years. Shrimp farming could not be practiced until the reconstruction of the gher. The residual salts on the soil surface along with sand deposition in the crop land after Aila inhibited crop production three years or even more after Aila in some places. The crop fields did not become saline free until the fourth year of Aila. Most of the agricultural damages were long term as the farmers could not go back to their production for three long years after Aila until the natural washing out of the salts from the fields by rainwater. Delay in embankment rehabilitation was also an important factor which enhanced the long term crop damages. Delay in embankment repair resulted in long term inundation of crop fields by regular tidal actions.

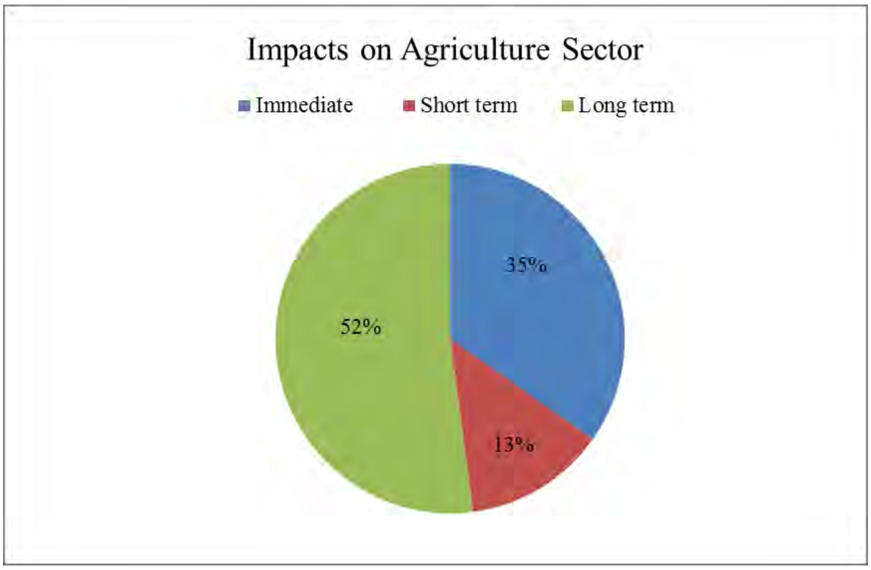


Figure 5.31: Immediate, short term and long term impact in agriculture sector.

During field visits, it was found that some agricultural lands were still uncultivable even six years after Aila. Two to three-inch layer of sands in the crop land made those lands unsuitable for further cultivation. Removal of sands from the lands required a good amount of money, which the already wretched farmers could not bear. This long term unproductiveness resulted in a huge long term impact on agriculture sector. Moreover, some agricultural lands were lost in the river forever due to the breaching of the polder. It implied that agricultural lands became part of the river in course of time with regular breaching of the polder that was initiated in the early phase of Aila. Key informants from the Dacope Agriculture office and BWDB office of Khulna gave us the detail picture of the agricultural land losses which are mentioned in Table 5.7.

Table 5.7: Permanent loss in agricultural land (*source*: field information).

Breaching Point	Initial width (m)	Width during repairing (m)	Area lost (ha)	Production lost (ton/year)	Loss (BDT, million/year)
Vitevanga	20	120	51	210	4
Jaliakhali	60	80	2	4	0.2
Nalian	10	60	17	71	1.3
	2	40			
	1.5	20			

It was found that in the three major breaching points, namely Nalian, Jaliakhali and Vitevanga almost 70 ha land had become part of river after Aila of 2009. About 85% of the mentioned areas were agricultural land and 15 % were human settlements and bare land. This resulted in a loss of about 286 ton aman productions every year which is equivalent to BDT 5.5 million. In addition to the above quantity, 10.5 km long new embankment (locally known as Ring) was constructed along the Nalian river (Photo B2 in Appendix). In between the Nalian river and the ring, there lies almost 540 ha land which are partly river portion and still gets regular inundation during high tide and spring tide. This accounts for an additional loss of 2,240 ton of aman rice every year, which is worth BDT 42 million.

Though short term impacts on agricultural crops were not severe in the study area, the long-term residual impacts were far-reaching and caused profound negative impacts on local crop production. For instance, aman rice harvests significantly decreased in consecutive years following cyclone Alia (Table 5.7) due to the sudden and drastic increase in soil and water salinity that resulted from surge water. This whipped the already affected poor people since there was no agricultural production for three years at a stretch. Typical local farmers informed that before Aila they used to get 4.0-4.5 tons of aman rice/ha. For the first three years after Aila, the loss was 100%, and in the fourth year they were able to cultivate some lands which were relatively high and got 3.75-4.0 t/ha only after reduced salinity in the agricultural land. The reduction of aman rice production has been mentioned in Table 5.7. The analysis was performed based on the information gathered from interviews with more than 20 local farmers. The results from interviews with five typical farmers from Kamarkhola are mentioned in Table 5.8. In Sutarkhali union the farmers could return to crop production in 2013.

Table 5.8: Aman rice production before and after Aila (*source*: field information).

	Amount of land (ha)	Before Aila (2008) (ton/ha)	During 2009, 2010, 2011	During 2012[1] (ton/ha)	During 2013[2] (ton/ha)
Farmer-1	0.12	4.50	No Crops	3.75	5.80
Farmer-2	0.40	4.35	No Crops	3.85	5.75
Farmer-3	0.40	4.20	No Crops	3.80	6.10
Farmer-4	0.60	4.10	No Crops	3.75	6.00
Farmer-5	0.80	4.40	No Crops	3.65	5.80

[1] Aman production with the same variety which people used to produce before Aila

[2] Aman production with improved rice variety.

We attributed the sediment deposition after Aila within the poldered area, initiation of improved rice variety for increased crop production in 2014.

5.7 Sectoral and Temporal Damage Variation

The devastating Cyclone Aila was classified as Category-1 (Saffir-Simpson scale) cyclone for its sustained wind speed of 120 km/hr. Official reports showed that the death toll stood on 45 as of 3 June, 2009 (USS, 2009) but its chain of loss and damage stayed active for a longer period even up to three years after the event. The amount of losses and damages and their nature were not same throughout the coastal areas. Losses and damages varied from place to place depending on the depth and duration of inundation and types of land use. Local people informed that Polder 31 was waterlogged only for 17 days after Aila. Due to short term saline water inundation, only one cropping season was missed in that polder. But in Polder 32, water was stagnant in many places for more than a year. After rehabilitation, water receded from most of the polder after one year except some natural depression type areas. But long term inundation resulted in deposition of salts and sandy sediments in agricultural lands. Hence, agricultural crop production was missed for three to four long years in Polder 32.

For a better understanding of damage nature and variations, a detailed study was conducted in three major breaching points, namely Nalian, Jaliakhali and Vitevanga in Polder 32. In the study area, aman rice was the major crop during the monsoon. From consultations with local farmers, it was found that damages due to inundation is a function of two factors e.g. (a) whether the water is fresh or saline and (b) whether the depth of inundation is greater or less than the plant height. If the water is fresh, then for any depth less than the plant height and for duration of less than 3 days there are no considerable damages to aman rice (Table 5.9). But, for ripened crop there are some losses for the above mentioned depth and duration. If the depth is greater than the plant height or the duration is above 3 days, then in all stages of the plant growth there is a considerable amount of losses. Local farmers concluded that if the plant height is around 4 ft, then the plant is vulnerable to a depth above than 4 ft and duration of more than 3 days.

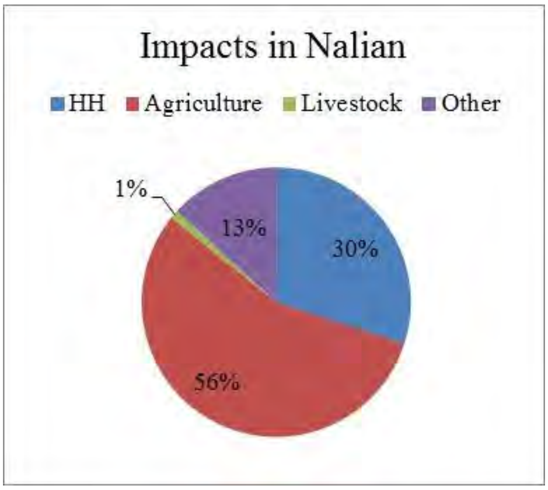
Table 5.9: Relation of aman rice production with depth and duration of inundation (*source*: field information).

Depth	Duration	Results
2 ft	2 days	Seedlings: will be damaged for full submergence for quite a long time Matured: no damage Ripened: damage increases with submergence time
4 ft	3 days	Matured: No considerable losses Ripened: considerable losses
Above 4 ft	Above 3 days	Considerable losses in all growth stages

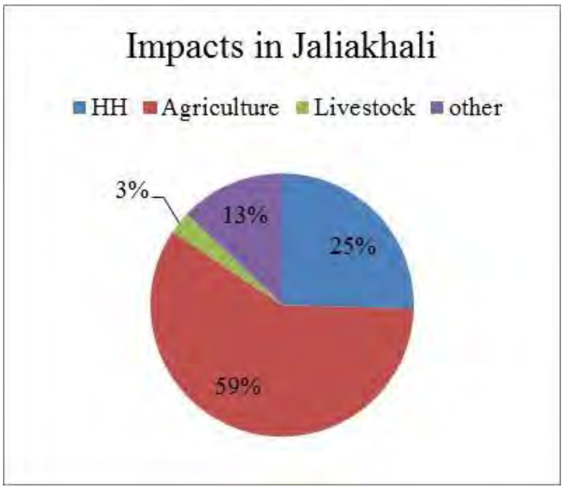
But in case of saline water, irrespective of the duration and depth, even if saline water resides for 1 hour, then there will be heavy losses as aman rice is very sensitive to salts. After Aila, farmers could not grow any aman rice or any other crops due to salinity in the soil and water of the study area. This phenomenon resulted in a huge long term loss in agriculture sector of the affected areas.

Most of the earthen houses were damaged in the early period of the event. The earthen houses which were submerged in saline water could not stand tall any longer than 5-7 days. Local people informed that those houses which were submerged above the plinth level failed within the first week after the event. The marketplaces which were under submergence of less than 2 ft were operational during the emergency situation i.e. immediately after Aila. But, the marketplaces which were under submergence of more than 2 ft or was under threat of being washed away, remained closed for a few days until the recession of the surge water from the marketplaces. It was found that all the sectors of an affected area were not equally affected by Aila. Based on the interviews of the affected people, the distributions of the total losses and damages in the different sectors of the study area in some selected points were assessed (Figure 5.32). It showed that agriculture, household, livestock, etc.; were not equally affected by Aila (Kibria *et al.,* 2016). The assessment also showed that overall impacts in agriculture sector were far reaching compared to other sectors. In the vicinity of Nalian breaching point, there were human settlements along with agricultural lands. So, agriculture was the worst victim along with considerable amount of losses in household properties in Nalian and surrounding areas. But, in Jaliakhali and Vitevanga, there were mainly agricultural lands with sparse human settlements at a small distance from the breaching face. As a result, the impacts on agriculture in those areas were far reaching compared to household and other sectors. Agriculture seemed to be the worst victim in all the locations due to long term inundation of agricultural lands which were comparatively lowlands than those of homesteads.

The study also found that the nature of the occurrence of the damages in different sectors varied from sector to sector. Some of the sectors experienced much immediate impacts while some other sectors did not exhibit much immediate impacts but had huge long term impacts. The details have been illustrated in Table 5.10. Our qualitative analysis showed that immediate impacts of Aila on household, fisheries and livestock were very high while the long term impacts were very high on agriculture.



(a)



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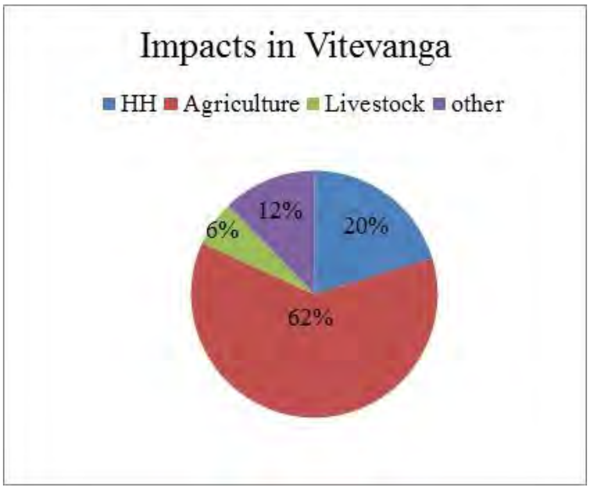

(c)

Figure 5.32: Difference in sectoral distribution of impacts in (a) Nalian (b) Jaliakhali and (c) Vitevanga.

Table 5.10: Nature of the impacts during Aila in different sectors of the study area (*source*: field information).

Sector	Immediate impact	Short term impact	Long term impact
Household	++	+	- -
Crop	-	-	++
Fisheries	++	-	+
Livestock	++	+	- -

Note: + for high, ++ for very high, - for low, -- for very low.

It was found that all the locations in Polder 32 were not equally affected. In this study, we assessed the total losses and damages of 30 interviewed people from the study area and then we ranked the degree of impacts (Table 5.11). Considering Nalian to be the base, the degrees of impacts are 1, 0.26 and 0.33 for Nalian, Jaliakhali and Vitevanga, respectively. So it is obvious that the severity of Aila was the highest in Nalian followed by Vitevanga and Jaliakhali in the study area.

Table 5.11: Ranking of the degree of impact based on the information of local people.

Sectors	Nalian (BDT, million)	Jaliakhali (BDT, million)	Vitevanga (BDT, million)
Household	2.73	0.605	0.61
Agriculture	5.075	1.4	1.85
Livestock	0.0924	0.065	0.178
Other properties	1.2	0.305	0.37
Total	9.0974	2.375	3.008
Scale	1	0.26	0.33

5.8 Damage Variation with Crop Calendar

The south west coastal region of Bangladesh is very much vulnerable due to its frequent experience of natural hazards. The dense poor communities living in this region increase its susceptibility to hazards. During field visits, local aged people informed that migration of working people to the southern part is noteworthy in the month of April, May, October and November since the distant past. The reason they put forward is these are the favorable months for securing jobs in aman fields. The details of crop calendar and aman production are mentioned in Table 5.12 and Table 5.13. But, the above mentioned months coincide with the two cyclone seasons as illustrated in Figure 5.33. Most of the cyclones occur during these four months. Previously, there was only one cropping season in the coastal region of Bangladesh. So, coincidence of the aman season with the cyclone season used to have devastating results. From field observations and local people's experiences, it was found that damages to the households and other sectors except agricultural crops would be the same for an event of any time of the year. But the damages to the agricultural crops, more specifically the immediate losses to crops would vary depending on the time of occurrence of the event. Field observations showed that Aila hit the coastal belt of Bangladesh on May 25, 2009 which was the sowing time of aman rice (Table 5.13). Most of the lands were fallow at the time of the landfall of Aila. So, the immediate impacts of Aila on crop production were not much. But, the net cultivable land in polder 32 was almost 4,450 hectares, according to BBS (2011). Dacope Agriculture office informed that in more than 80% of the cultivable land, farmers used to produce aman during the monsoon. So, in the aman season any event like Aila would result in an immediate loss of 18,460 tons of rice only in Polder 32 which was worth BDT 34.50 million.

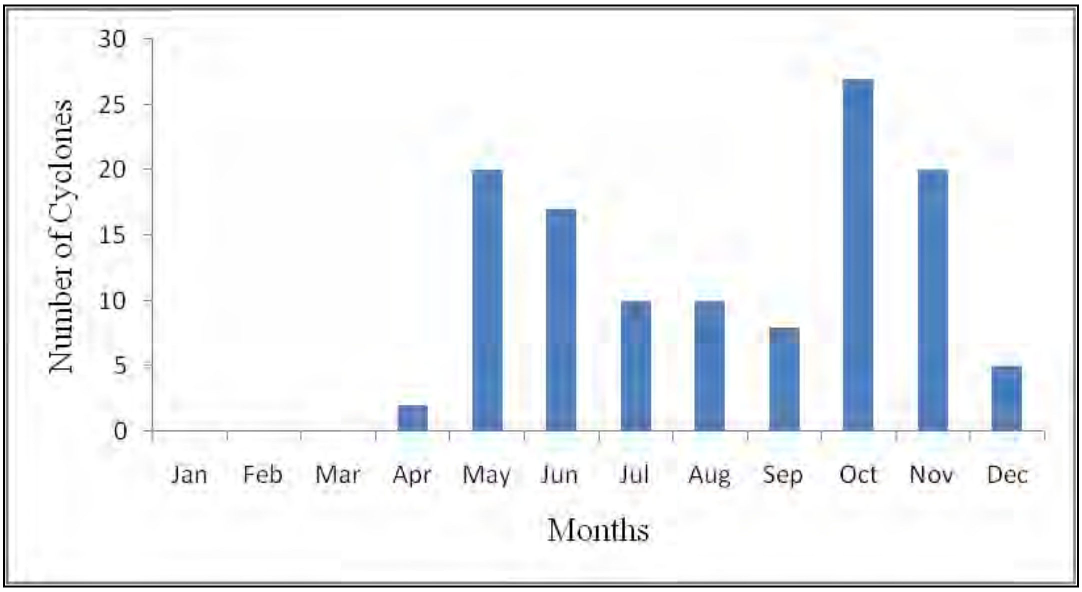

Figure 5.33: Monthly distribution of the cyclonic events in Bangladesh (compiled from Islam and Peterson, 2009; Dasgupta *et al.*, 2010).

Table 5.12: Crop calendar of the study area (*source*: field information).

Season	Month	Previous Crop	Present Crop
Kharif-1 (Pre-monsoon)	Mid April-July	Fallow	Fallow
Kharif-2 (Monsoon)	Mid July-Mid November	Aman	Aman
Rabi/winter crops (Post-monsoon)	Mid January-Mid May	Fallow (Small scale homestead vegetable)	Rabi crops (Sunflower, sesame etc.)

Table 5.13: Cropping period of aman rice (*source*: field information).

Month	April-May	June-July	November
Activity	Sow seeds	Seedlings	Harvesting

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study investigated the modes of embankment failure, the locations of embankment failure, the processes of embankment failure and associated losses and damages in Polder 32 of Dacope upazila during Cyclone Aila. It was found that there were three major breaching points in Polder 32 during Cyclone Aila, namely Nalian, Jaliakhali and Vitevanga. The Dhaki river broke through Jaliakhali and Vitevanga whereas the Sibsa river broke through Nalian into Polder 32. This study also found that less than 5% of Polder 32 was overtopped during Aila. It was found that insertion of pipes to allow saline water to shrimp ghers and some other human interventions were responsible for the structural weakness of the embankments that caused subsequent failures during Aila. During field visits, the measured crest level of embankments at several points in Polder 32 was found to be only 3.65-4.0 m (PWD). The local people informed that the water level rose up to 3.80 m (PWD) at the overtopping locations of the study area.

Analysis showed that the progressive magnitude of breaching and scouring in Polder 32 during Aila followed approximately logarithmic trend. Almost 50% of the total breaching took place within the first 6 hours of the event. It was found that the polder was overtopped for 2.0-2.5 hours depending on the location.

Model results showed that water level rose up to 3.80 m (PWD). Hourly analysis of water level of 25 May, 2009 when Aila hit, showed that the polder was overtopped between 3 PM and 6 PM. Model results also showed that approximately 25%, 80% and 90% of Polder 32 was inundated due to overtopping, breaching and combined breaching and overtopping, respectively, and water depth rose up to 1.80 m inside the polder. Local data showed that the water depth inside the polder reached up to 2.0 m. ArcGIS analysis using local data showed that 85% of Polder 32 was inundated during Aila.

Analysis showed that 63% of the area had an elevation of less than 3 m and 15% area had an elevation ranging from 4-5 m above the mean sea level. As a result, the maximum local water level of 4.25 m above the mean sea level during Cyclone Aila inundated more than 85% of the area. Our detailed damage assessment at three different breaching points showed that the damage level at Nalian was relatively higher than the other two points, approximately 3.8 times higher than Jaliakhali and 3 times higher than Vitevanga.

It was found that 50% of the total impacts were immediate impact in the study area. Sectoral distribution of immediate impacts demonstrated that household (40%) and agriculture (40%) were the worst immediate victims. Location specific damage analysis showed that all the locations experienced higher immediate impact with respect to short and long term impact. About 16% of the total losses and damages within Polder 32 were identified as short term impact. It was also found that out of the total impacts 32%, 10% and 14% are short term impact at three major breaching locations, namely Nalian, Jaliakhali and Vitevanga, respectively. The sectoral distribution of short term impacts showed that agriculture sector (48%) experienced the most short term impact followed by household (38%). About 34% of the total impacts in the study area were long term impact. It was found that 88% of the long term impacts occurred only in agriculture sector. About 27% of the estimated total impacts in Polder 32 occurred in the household sector.

The average bed level at the Nalian river, Gulbonia khal at Vitevanga and Jaliakhali khal was originally (-) 2.0 to (-) 3.0 m (PWD) but after breaching, at the face of the breaching the bed level went up to (-) 15.0 to (-) 16.0 m (PWD), which compelled the authority to shift the embankments from the previous positions due to depressions at the faces. It is noteworthy that the overtopping locations mainly required repairing and in some cases shifting, whereas the breaching locations required shifting. During Aila the ponds and shrimp ghers were flooded with saline water which allowed the fishes to escape to floodplains resulting in considerable immediate impacts (35%) in agriculture sector. The residual salts on the soil surface along with sand deposition in the crop land after Aila inhibited crop production even four years after Aila resulting in long term (52%) impact. Before Aila farmers used to get 4.0-4.5 ton aman rice per ha. For the first three years after Aila in Kamarkhola, the loss was 100%, and in the fourth year they were able to cultivate some lands, which were relatively high, and got 3.75-4.0 t/ha only after reduced salinity in the agricultural land.

It was found that crop damages due to inundation are a function of two factors, e.g. (a) whether the water is fresh or saline and (b) whether the depth of inundation is greater or less than the plant height. The coincidence of the aman season with the cyclone season is likely to cause devastating results. It was found that damages to household and other sectors except agricultural crops would be the same for an event at any time of the year. But the immediate losses to crops would vary depending on the time of occurrence of the event. In the aman season, any event like Aila is likely to result in an immediate loss of 18,460 tons of rice only in Polder 32 which is worth BDT 34.50 million.

6.2 Recommendations

Based on this study, the following recommendations are made:

- The breaching process during a storm surge can be further studied based on hydraulic theories;
- Future studies should investigate the ways and means to enhance the adaptive and coping capacities of the coastal people to reduce losses and damages;
- Future studies should also consider the climate change impacts on storm surge severity;
- A study can be conducted on vulnerability minimization by proper operation and maintenance of the existing polders;
- A study can be conducted on how human interventions such as placing pipes through embankments reduce the structural strength of the embankments.
- A study should include the performance of the strengthening of the polders at vulnerable locations to reduce the risk of embankment failures.

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APPENDIX A

LOSS AND DAMAGE DATA

Table A1: Damages to Houses in 5 No. Nalian Ward and 2 No. Gunari ward ('Ward' is a sub-division of a union)

House Type	Average cost of a house (BDT, thousands)	No. of house	Total cost (BDT, thousands)
Earthen wall with roof of Golpata	15-18	20-22	360
Earthen wall with tin shed	40-42	10-12	420
Wall and roof both Golpata	15-20	30-35	600
Golpata wall but tin shed roof	40-45	5-6	225
Brick wall with tin shed	100-150	1	150
Brick built	400-500	1	500

Table A2: Information on losses and damages from individual interviews in Nalian

	Informant-1	I-2	I-3	I-4	I-5	I-6	I-7	I-8
Occupation	Small business	Housewife	Business	Farmer	Shopkeeper	Shopkeeper	Farmer	Farmer
Household properties	2 (1 tin shed, 1 Golpata) + properties (BDT 1 lakh)	3 (1 brickwall, 1 tin shed, 1 golpata) + properties (BDT 4-5 lakh)	4 (1 brick, 2 tin shed, 1 golpata) + properties (BDT 5-6 lakh)	2 (1 earthen, 1 Golpata) + properties (BDT 1 lakh)	2 (1 tin shed, 1 golpata) + properties (BDT 80,000)	2 (1 tin shed, 1 golpata) + properties (BDT 80,000)	4 (1 tinshed, 3 Golpata) + Properties (BDT 1 lakh)	4 (2 tin shed, 2 Golpata)
Type of damage/loss	Immediate loss	Immediate	Immediate	Short term	Short term	Immediate	Short term	Short term
Loss/damage (BDT)	1,90,000	13,00,000	33,50,000	1,40,000	1,00,000	40,000	1,10,000	1,50,000
Agricultural land	50 decimal	1800 decimal	700 decimal	100 decimal	-	100 decimal	400 decimal	300 decimal
Type of practice	Rice and fish	Rice and fish	Rice and fish	Rice and fish	-	Rice	Rice and fish	Rice and fish
Type of damage/loss	Short term and long term loss	Immediate, short term and long term loss	Immediate and long term loss	Short term and long term loss	-	Immediate and long term loss	Immediate and long term loss	Immediate and long term loss

Loss/damage (BDT)	1,23,500	26,00,000	10,72,000	1,20,000	-	1,10,000	6,00,000	4,50,000
Livestock	Duck, hen, goat	Cow, swan, hen, duck	Cow, goat, hen, duck	Goat, swan, hen	Goat, duck, hen	-	Cow, goat, hen, duck	-
Type of damage/loss	Immediate loss	Immediate	Immediate	Short term	Short term	-	-	-
Loss/damage (BDT)	21,000	4,400	50,000	15,000	2,000	-	-	-
Other properties	1 fish storage, 1 large boat, 4 small boats	1 shop	1 fish storage	1 shop	1 shop	1 shop	-	-
Type of damage/loss	Immediate loss	Immediate	Immediate	Immediate	Short term	Immediate	-	-
Loss/damage	4,30,000	1,50,000	3,50,000	55,000	15,000	1,50,000	-	-
Notes	WL:10-12 ft, one family member died	WL:8-10 ft, worst victim	WL: 9-10 ft, worst victim	WL: 7-8 ft	Shut down shop for 3 days	Resettled shop in higher land	Still has unsuitable land	Still settling on polder

APPENDIX B

PHOTOGRAPHS

Photo B1: Damages to embankment by Aila.

Photo B2: Ring embankments undergoing rehabilitation after Aila.

Photo B3: Breaching caused by Aila at Nalian sluice.

Photo B4: A small canal turned into a river by Aila.

Photo B5: Group discussion at Nalian.

Photo B6: Measurement of Polder height during field visit.

Photo B7: Individual interview at Jaliakhali.

Photo B8: Focus Group Discussion at Kamarkhola.

Photo B9: Key Informant Interview with BWDB Engineer.

Photo B10: Key Informant Interview with SRDI Official.

Photo B11: Key Informant Interview in Blue Gold office.

Photo B12: Social and resource map preparation.