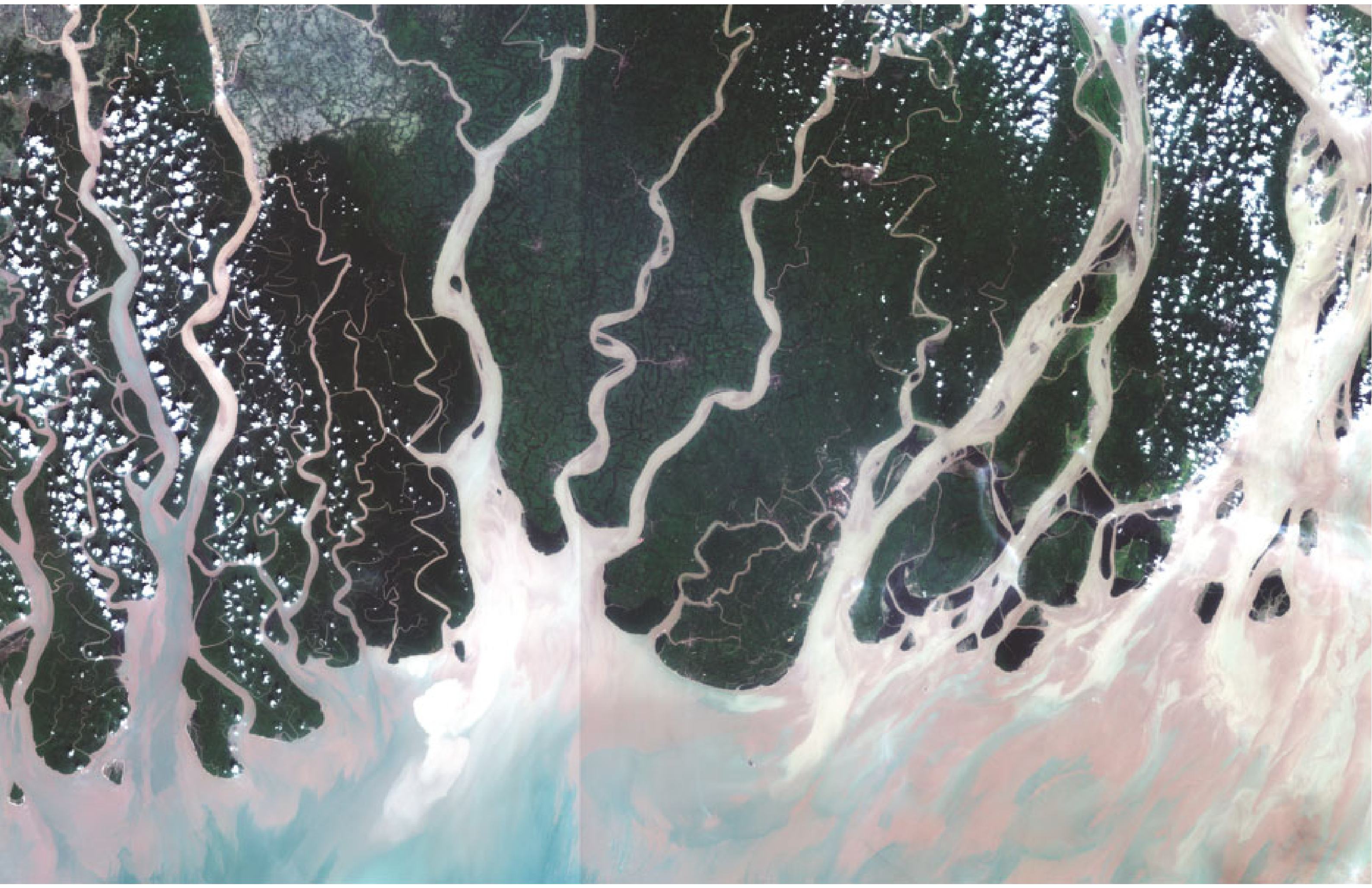
Government of the People's Republic of Bangladesh
Bangladesh Water Development Board (BWDB)

Coastal Embankment Improvement Project



Satellite Image from: ESA, taken at 04:28:29+6

Consultancy Services for Feasibility Studies and Preparation of Detailed Design for the Following Phase (CEIP-2)

Coastal Embankment Improvement Project II

Modelling Assessment: Part A: Embankment Crest Levels
Final Report
December 2022

Table of contents

Appendix A1 **Future Climate Change Analysis**

Appendix A2 **Data from LTM**

Appendix A3 **Comparison of the CEIP-1 and CEIP-2 Storm Surge Modelling Approach**

Appendix A4 **Cyclone Track**

List of Tables

List of Figures Main Report

Abbreviations, Acronyms and Units

AED	Average Annual Expected Damage
ACL	Authorized Crest Level
ADCP	Acoustic Doppler Current Profiler
AHP	Analytical Hierarchy Process
ARIPA	Acquisition and Requisition of Immovable Property Act
ARIPO	Acquisition and Requisition of Immovable Property Ordinance
AsDB	Asian Development Bank
BADC	Bangladesh Agriculture Development Corporation
BARI	Bangladesh Agriculture Research Institute
BBS	Bangladesh Bureau of Statistics
BIWTA	Bangladesh Inland Water Transport Authority
BMD	Bangladesh Meteorological Department
BoB	Bay of Bengal
BoB SAL	Bay of Bengal Salinity
BoQ	Bill of Quantities
BRRI	Bangladesh Rice Research Institute
BTM	Bangladesh Transverse Mercator
BWDB	Bangladesh Water Development Board
BM	Bench Mark
BoBM	Bay of Bengal Model
CBA	Cost-Benefit Analysis
CC	Climate Change
CCL	Cash Compensation Under Law
CDPo	Coastal Development Policy
CDMP	Comprehensive Disaster Management Program
CDS	Coastal Development Strategy
CDSP	Char Development and Settlement Project
CEGIS	Center for Environmental and Geographic Information Services
CEIP	Coastal Embankment Improvement Program / Project
CEIP-1	Coastal Embankment Improvement Program / Project – Phase 1
CEIP-2	Coastal Embankment Improvement Program / Project – Phase 2
CEP	Coastal Embankment Project
CERP	Coastal Embankment Rehabilitation Project
CES	Coastal Embankment System
CPP- I	Cyclone Protection Project - I
CPP- II	Cyclone Protection Project - II
CZ	Coastal Zone
CZE	Coastal Zone Embankment
CZPo	Coastal Zone Policy

CZWMP	Coastal Zone Water Management Program
CSPS	Cyclone Shelter Preparatory Study
DAE	*Department of Agriculture* Extension
DCF	Discounted Cash Flow
D&CSC	Design & Construction Supervision Consultants
DDC	Development Design Consultants
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute Denmark
DISREP	Distribution Sector Recovery Program
DGPS	Differential Global Positioning System
DLR	Director Land Records
DoE	Department of Environment
DoF	Department of Fisheries
DPM	Design Planning & Management
DSM	Digital Surface Model
DTM	Digital Terrain Model
EA	Environmental Assessment
EAP	Environmental Action Plan
ECA	Environmental Conservation Act
ECR	Environmental Conservation Rules
ECRRP	Emergency Cyclone Recovery and Restoration Project
ED	Executive Director
EDP	Estuary Development Program
EEWS	Early Erosion Warning System
EHS	Environmental, Health, and Safety
EIA	Environmental Impact Assessment
EMA	External Monitoring Agency
EMP	Environmental Management Plan
EMF	Environmental Management Framework
EPG	Embankment Protection Group
EPs	Entitled Persons
ES	Embankment Settlers
ESS2	Environmental and Social Standard 2
ESCP	Environmental & Social Commitment Plan
ESF	Environmental and Social Framework
ESS	Environmental Social Standards
FAO	Food and Agricultural Organization
FAP-7	Flood Action Plan-7
FCD	Flood Control & Drainage
FCDI	Flood Control Drainage & Irrigation
FGD	Focus Group Discussion

FFG	Foreshore Forestry Group
FM	Flood Management
FO	Field Office
FREMIP	Flood and Riverbank Erosion Risk Management Investment Program
FWOP	Future-Without-Project
FWIP	Future-With-Project
GBV	Gender Bases Violence
GCC	General Conditions of Contract
GCPs	Ground control points
GDP	Gross Domestic Product
GeoDASH	Geospatial Data Sharing Portfolio
GIS	Geographic Information Systems
GOB	Government of Bangladesh
GO	Government Organization
GPP	Guidelines for People's Participation
GPS	Global Positioning System
GRM	Grievance Redress Mechanism
GRRP	Gorai River Restoration Project
IA	Implementing Agency
IBRD	International Bank for Reconstruction & Development
ICB	International Competitive Bidding
ICZM	Integrated Coastal Zone Management
ICZMP	Integrated Coastal Zone Management Plan
ICZMP	Integrated Coastal Zone Management Program
IDA	International Development Agency
IESCs	Important Environmental and Social Components
IPC & WMPs	Infection Prevention Control and Waste Management Plans
IRR	Internal Rate of Return
INROS	Inros Lackner
IoL	Inventory of losses
IPCC	Intergovernmental Panel on Climate Change
IPSWAM	Integrated Planning For Sustainable Water Management
ITC	Information and Communication Technologies
IUCN	International Union for Conservation of Nature
IWM	Institute of Water Modelling
IEE	Initial Environmental Examination
KJDRP	Khulna Jessore Drainage Rehabilitation Project
KII	Key Informant Interview
KMC	Knowledge Management Consultants
LAPs	Land Acquisition Plans
LGED	Local Government Engineering Department

LGI	Local Government Institution
LMP	Labour Management Procedure
LRP	Land Reclamation Project
MCA	Multi-Criteria Analysis
M&E	Monitoring and Evaluation
MES	Meghna Estuary Studies
MIS	Management information systems
MoEF	Ministry of Environment and Forest
MoFDF	Ministry of Food and Disaster Management
MOWR	Ministry of Water Resources
MoL	Ministry of Land
MSL	Mean Sea Level
NCB	National Competitive Bidding
NEP	National Environmental Policy
NEMAP	National Environment Management Action Plan
NGO	Non Government Organization
NHC	Northwest Hydraulics Consultans
NWMP	National Water Management Plan
OCC	One-stop Crisis Cell
O&M	Operation and Maintenance
OP	Operation Policies
PSC	Project Steering Committee (PSC)
RAP	Resettlement Action Plan
REA	Rapid Environmental Assessment
RMS	Root Mean square
RPF	Resettlement Policy Framework
RTK	Real Time Kinematic
PAP	Project Affected People
PAVC	Property Assessment and Valuation Committee
PBM	Permanent Bench Marks
PD	Project Director
PDC	Polder Development Committee
PIU	Project Implementation Unit
PMU	Project Management unit
POM	Project Operations Manual
PPCR	Pilot Programme for Climate Resilience
PPR	Project Progress Report
PMIS	Polder Management Information System
PVS	Property Valuation Survey
PWD	Public Works Department

PRA	Participatory Rapid Assessment
JV	Joint Venture RHDHV-NHC-INROS
RAP	Resettlement Action Plan
RRA	Rapid Rural Appraisal
RCC	Reinforced Cement Concrete
RHDHV	Royal HaskoningDHV
RoR	Record of Rights
SA	Social Assessment
SCM	Stakeholders Consultation Meeting
SEP	Stakeholder Engagement Plan
SIA	Social Impact Assessment
SLR	Sea Level Rise
SMRPFW	Social Management and Resettlement Policy Framework
SPARSO	Space Research & Remote Sensing Organization
SPMC	Strategic Planning and Management Consultants
SRP	System Rehabilitation Project
SRDI	Soil Resource Development Institute
SSHSMP	Site-Specific Health and Safety Management Plan
SWMC	Surface Water Modelling Centre
SWZ	South Western Zone
SZ	Southern Zone
SOB	Survey of Bangladesh
SWRM	South West Region Model
SEA	Strategic Environmental Assessment
SEAA	Sexual Exploitation and Assault
SMRPF	Social Management & Resettlement Policy Framework
SWRSAL	South West Region Salinity
TRM	Tidal River Management
TBM	Temporary Bench Mark
ToR	Terms of Reference
WARPO	Water Resources Planning Organization
WB	World Bank
WMA	Water Management Association
WMIP	Water Management Improvement Project
WRS	Water Retention Structures
WSIP	Water Sector Improvement Project
WUA	Water Users Association
MWh	Megawatt hour
m	Metre
cm	Centimetre
ha	Hectare

l	Litre
mm	Millimetre
m^3/s	Cubic metres per second
m^3	Cubic metres
km	Kilometre
km^2	Square kilometres
Mt	Mega ton (10^9 kilogram)

1 Introduction

Project Description

The intent of the Coastal Embankment Improvement Project –2 (CEIP-2) is to reduce the flood disaster risk of the Polders within the coastal area of Bangladesh, bringing increased flood security to the communities who live within the Polders. The Polders of Bangladesh are embanked islands surrounded by a complex network of interconnected tidal rivers. The Polders are vulnerable to flooding, which can be caused by irregular cyclone tropical storms. water-logging and annual monsoon flooding. During CEIP-2, flood risk management structures will be designed and constructed, which will mitigate all three types of flooding within the selected Polders.

The following 13 Polders have been selected for flood risk mitigation infrastructure improvement under CEIP-2 (the associated Thana and District has been listed as well, respectively):

Table 1-1: Selected 13 Polders for Next Phase of CEIP (CEIP-2)

Sl. No.	Polder No.	Name of Thana	District
1	P-7/1	Assasuni, Shyamnagar	Satkhira
2	P-7/2	Assasuni	Satkhira
3	P-13-14/2	Koyra	Khulna
4	P-39/1B	Motbaria	Pirojpur
5	P-41/5	Barguna Sadar	Barguna
6	P-45	Taitoli	Barguna
7	P-47/1	Kalapara	Patuakhali
8	P-5	Kaliganj, Shyamnagar	Satkhira
9	P-4	Assasuni	Satkhira
10	P-10-12	Koyra, Paikgacha	Khulna
11	P-39/1C	Motbaria	Pirojpur
12	P-50-51	Rangabali	Patuakhali
13	P-55/2D	Dashmina	Patuakhali

The Polders are situated in two distinct zones: the Shatkira or Southwestern Zone (SW) and the Barguna or Southern/Southcentral Zone (SC). The selected Polders are shown in *Figure 1-1* and *Figure 1-2*, as well as the Polders that were the focus of the first phase of this project, CEIP-1.

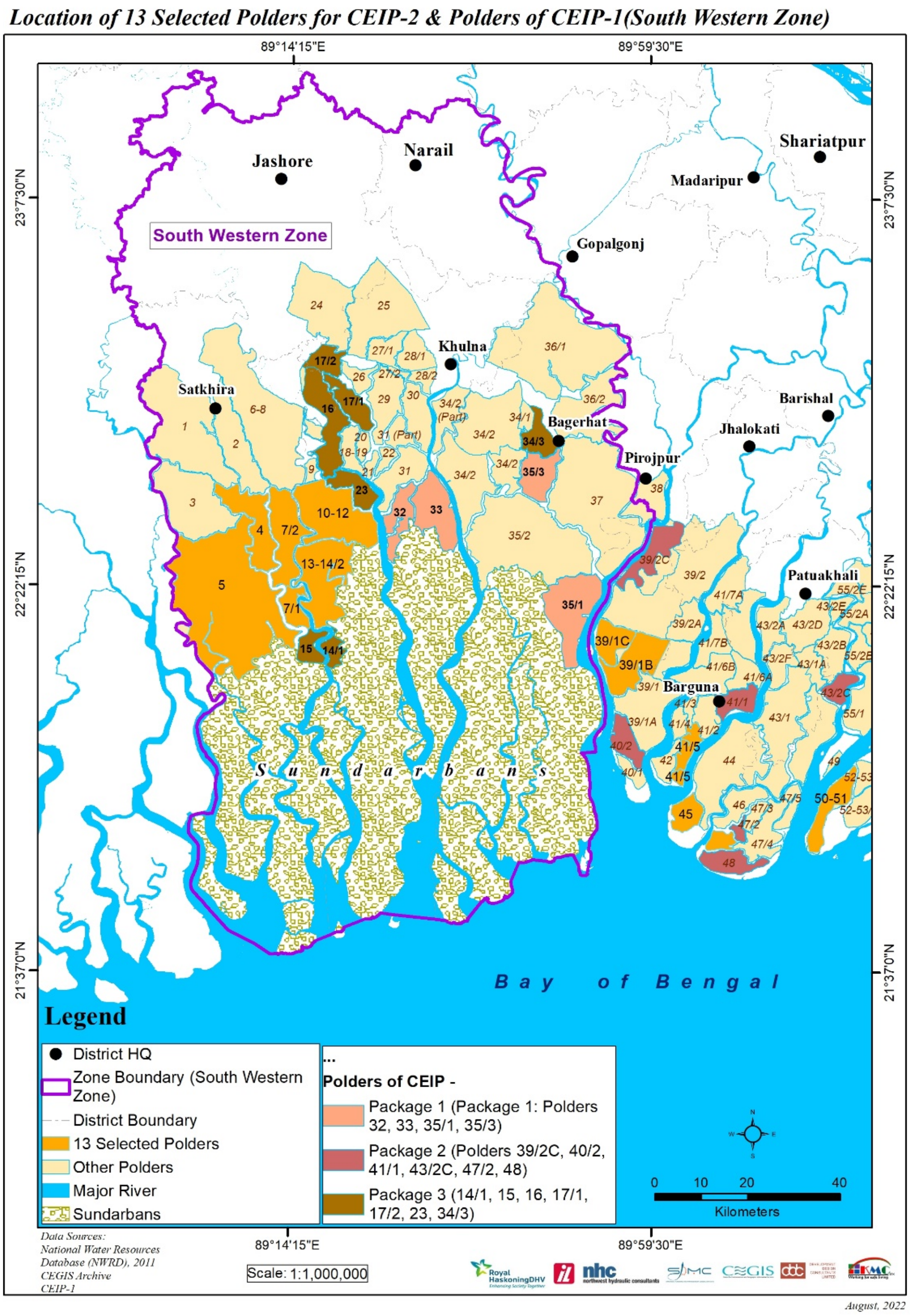


Figure 1-1: Six selected Polders for CEIP-2 in the Southwestern Zone.

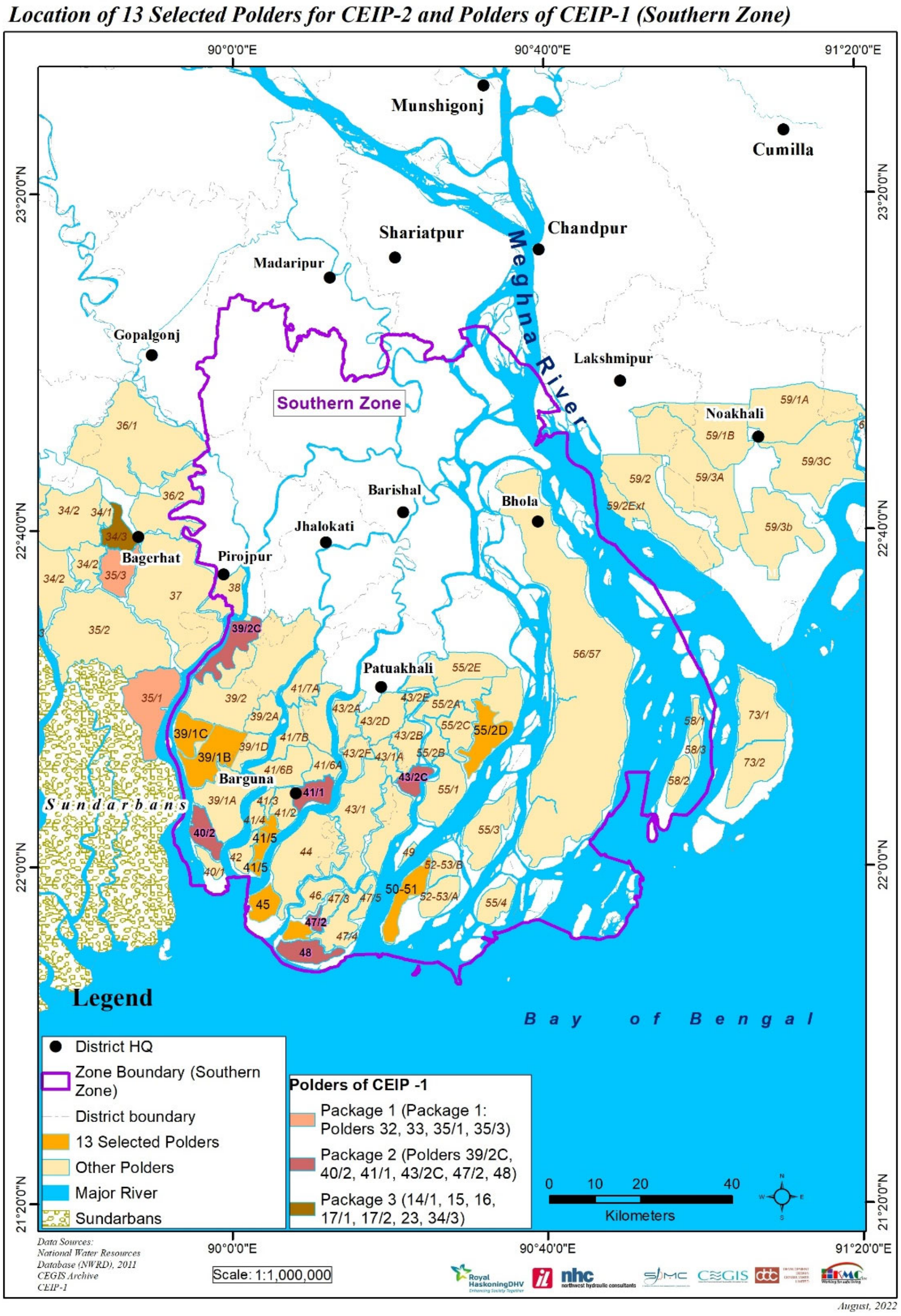


Figure 1-2: Seven selected Polders for CEIP-2 in the Southern Zone.

Purpose and Scope of this Report

This report, along with the Morphological Assessment Report and the Modelling Assessment: Part B Drainage Infrastructure report, is *Deliverable 4: Modelling Reports (Storm Surge Modelling and Polder Morphological Analysis and Polder Drainage Modelling) for max. 13 Polders*. This Deliverable meets *Task 2.1 (c) hydraulic/hydrological analysis/modelling*.

This report is intended to detail the modelling study of monsoon and cyclone flooding and summarize the results. The modelling study of monsoon and cyclone flooding comprises of two main components. First, the storm surge model has been used to simulate the effect of cyclone storms on the study region. To generate wind generated waves and swells in the offshore and coastal areas the Wave Model has been developed. Second, the 1D regional model has been used to simulate the effect of monsoon flooding on the study region. The intent of the modelling study is to determine the design parameters for the design of the flood risk management structures to be constructed during CEIP-2. Specifically, this report provides the recommended embankment crest level, considering monsoon flooding and cyclone storms. Additionally, this report will provide a recommended allowance for subsidence of the embankments.

Outline of this Report

In this report, first an overview of the hydraulic loads considered in the modelling assessment is provided. Next, the selected design scenarios for CEIP-2 are described. The climate change assessment is explained in Section 4, followed by the subsidence analysis. Subsequently, an overview of the modelling approach is detailed in Section 6. In Section 7, the storm surge analysis is presented. And in Section 8, the monsoon flooding analysis is described. Finally, Section 9 presents a summary of the recommended design parameters.

2 Overview of the Hydraulic Loads Considered

The following section summarizes the hydraulic loads that have been considered for the design of the flood mitigation structures.

Nearly every year a cyclone hits Bangladesh's coastal region and on average a severe cyclone strikes the country every three years. Cyclones are low pressure storms, caused by warm ocean temperatures and the Coriolis effect[1]. When cyclones make landfall, they can cause high winds, heavy rainfall, storm surges and large waves. Storm surges are caused by low pressures creating the Inverse Barometer Rise effect, wind set up and, to a lesser extent, wave set up. A storm surge can be visualized as a raised dome of water moving with the cyclone, centred to the right of its path[1]. The severity of a cyclone is dependent on the magnitude of the cyclone, the landfall location and the time of landfall relative to the tides.

Bangladesh is particularly vulnerable to severe cyclone storms; the 1970 and 1991 cyclones are considered two of the deadliest natural disasters of the 20th century. The severity of the cyclones is caused by a number of factors. The triangular shape of the Bay of Bengal funnels sea water pushed by the wind towards the coast, causing surge amplification. Additionally, the wide, shallow continental shelf in the Bay of Bengal creates a large tidal range, especially in the eastern part of the country[2]. Typically, when a cyclone makes landfall at high tide, the potential for storm surge flooding is greater. For example, the 1991 cyclone had much greater inundation extents and a higher death toll than the May 1997 cyclone, despite the two cyclones making landfall at similar locations along the Noakhali-Chittagong coastline and the 1991 cyclone having lower maximum wind speeds (225 km/hr compared to 275 km/hr). The difference between these cyclones was the time of landfall[3]. The 1997 cyclone made landfall at low tide, while the 1991 cyclone made landfall at high tide. The Meghna-estuarine region is vulnerable to some of the highest surge amplifications in the country because of the large tidal range in this area. Finally, low lying topography, high population densities and poor coastal protection systems exacerbates the situation.

The tides along the Bangladesh coast are semi-diurnal. Tidal effects extend approximately 150 km inland (*Figure 2-1*). While tides can impact the intensity of cyclone floods, pure tidal flooding has been largely eliminated since the original construction of the Polders in the 1960s.

---

[1] Klaver, E. N., 2005. *Probabilistic analysis of typhoon induced hydraulic boundary conditions for Suo-nada Bay*, MSc Thesis, Delft University of Technology, Faculty of Civil Engineering and Geosciences.
[2] The largest tidal range is along the Noakhali coast, immediately east of the Lower Meghna estuary. The tidal range declines to the east and west.
[3] Haque, A., Nicholls, R. J., 2018. *Floods and the Ganges-Brahmaputra-Meghna Delta*. In: Nicholls, R., Hutton, C., Adger, W., Hanson, S., Rahman, M., Salehin, M. (eds) Ecosystem Services for Well-Being in Deltas. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-319-71093-8_8

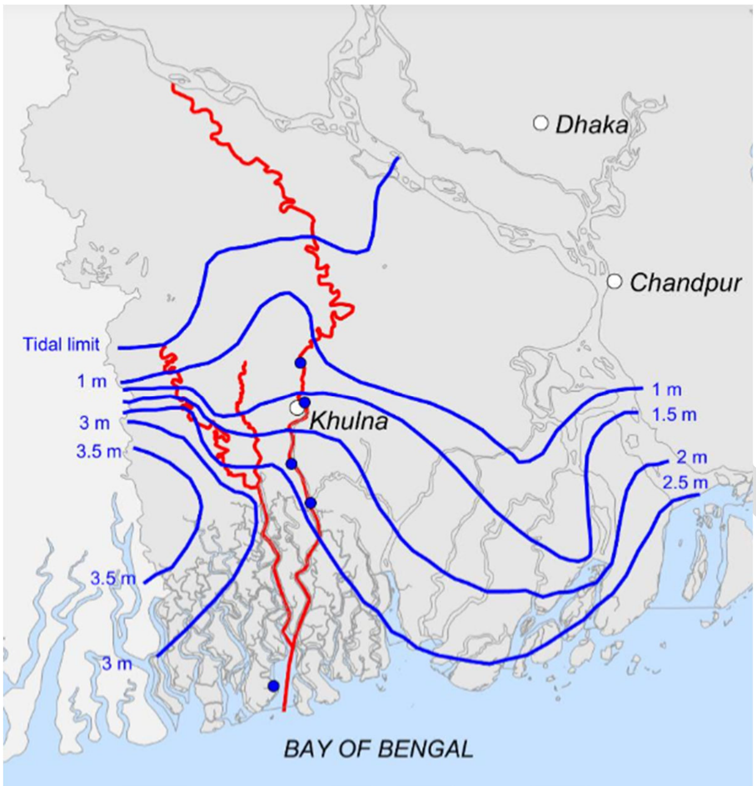


Figure 2-1: Tidal range in the study area. The red lines indicate the Pussur and Sibsa river system. Image from the LTM[4].

The study area is within the Ganges-Brahmaputra-Meghna basin. The large rivers of the basin carry large volumes of water and sediment through the delta, before debouching into the Bay of Bengal. During the monsoon season (June to October), these rivers can spill their banks, and cause severe fluvial flooding. A 100-year flood in the Brahmaputra is ~100,000 m^3/s, while the Ganges is ~70,000 m^3/s (*Figure 2-2*). Typically, the Brahmaputra's dual flood peaks occur earlier than the Ganges single peak. Flows in the Upper Meghna are relatively insignificant compared to the Brahmaputra and Ganges, contributing less than 10% of the total upstream flow[5]. The Kabadak, Bhairab, Gorai and Arial Khan Rivers are four river that carry flows from the Ganges and Padma[6] Rivers to the Southwest and Southern areas.

[4] LTM, 2020a. *Interim Report on the Effect of human interventions on tidal and sediment dynamics in the Pussur-Sibsa basin*. Report prepared by DHI and Deltares in association with IWM and University of Colorado for the Bangladesh Water Development Board.
[5] Haque, A., Nicholls, R. J., 2018. *Floods and the Ganges-Brahmaputra-Meghna Delta*. In: Nicholls, R., Hutton, C., Adger, W., Hanson, S., Rahman, M., Salehin, M. (eds) Ecosystem Services for Well-Being in Deltas. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-319-71093-8_8
[6] The Padma River is downstream of the confluence of the Ganges and Brahmaputra Rivers.

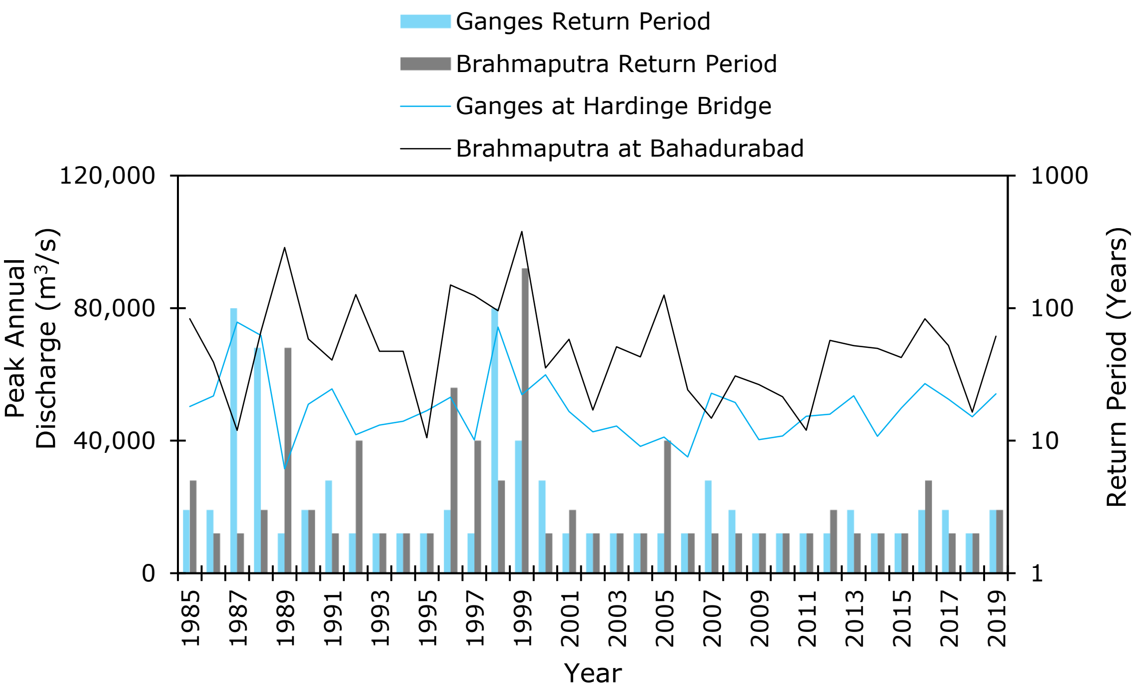


Figure 2-2: Annaul peak discharges and associated return period in the Bramaputra and Ganges Rivers.

Cyclones typically occur in the pre-monsoon (April - May) or post-monsoon (October - November)[7]. Therefore, monsoon floods do not typically coincide with large cyclones. So, depending on the Polder location, embankment crest levels will be determined by *either* monsoon or cyclone water levels, whichever is greater. Cyclone surges decrease in severity as they move inland because once the cyclones make landfall, they lose energy and the storm surge height decreases. Closer to the coast (Southern Zone), flood levels are typically governed by cyclones, while further inland (Southwestern Zone) they are governed by fluvial flooding. These two different flooding mechanisms have been modelled separately (Section 7 and 8, respectively).

As mentioned above, the embankments are designed to prevent flooding from both monsoon flooding and cyclone storms. The crest elevation of the embankments is determined from the water level caused by either of these phenomena, termed the still water level (SWL) (*Figure 2-3*). Additionally, a freeboard is added to the crest elevations to prevent excessive overtopping from wave run up[8]. Globally, 50% of earthen dam failures are caused by overtopping[9]. The river- or sea-side embankment slope is determined by location of the embankment (sea or river

[7] Islam, M. S., Alam, R., Khan, M. Z. H., Khan, M. N. A. A., Nur-A-Jahan, I., 2013. *Methodology of Crest Level Design of Coastal Polders in Bangladesh*, 4th International Conference of Water & Flood Management ICWFM
[8] Basson, G., Bosman, E., 2011. *Guidelines on Freeboard for Dams 2011 Volume I Literature Review and Case Studies*, Stellenbosch University.
[9] Marche, C., 2005. *Embankment dam overtopping and collapse: an innovative approach to predict the breach outflow hydrograph*. WIT Transactions on The Built Environment, Vol 84. www.witpress.com ISSN 1743-3509

embankment), geotechnical considerations, and the wave run up criteria. The SWL and wave height have been determined using numerical models. Using these results, the required freeboard considering overtopping has been calculated using analytical calculations. Additionally, over the embankments' design life subsidence will decrease the crest height of the embankment and therefore, recommended crest heights must also consider subsidence.

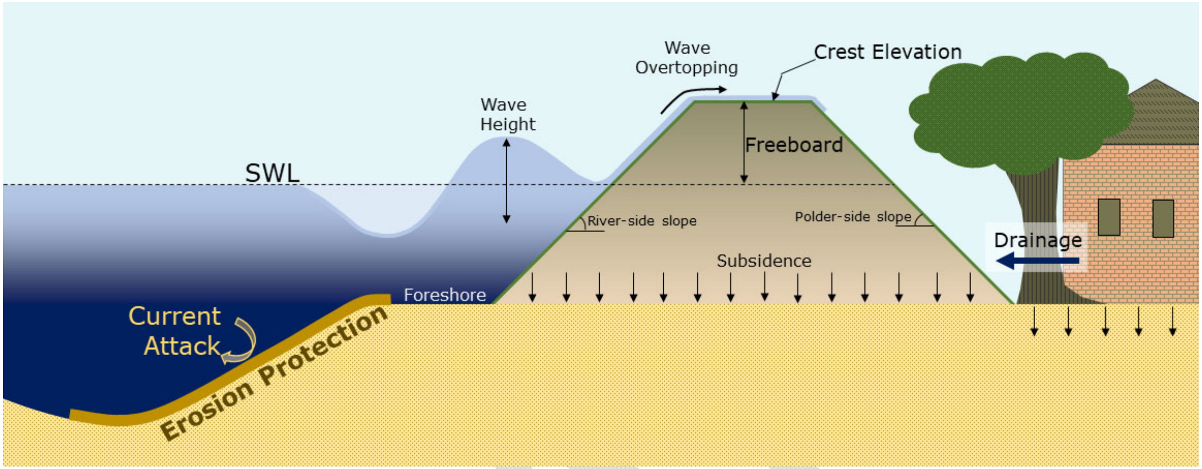


Figure 2-3: Hydraulic loads that must be considered for embankment design.

In addition, watertight embankments, such as the ones that will be constructed for CEIP-2, can cause waterlogging if inadequate drainage systems are installed. Heavy rainfalls occur in the Southern and Southwestern Zone of Bangladesh. If the water from these rainstorms is not drained sufficiently quickly, water logging starts to occur and can cause health problems and damage livelihood. Required Polder drainage rates are dependent on rainfall intensity and duration, as well as the topography and the drainage infrastructure. If gravity drainage no longer works, pumps are required. Furthermore, the drainage structures not only need to be able to have enough capacity to adequately drain the Polder, but they must also be able to withstand the typical head difference and pass peak discharges. The drainage structures and peak discharges were determined from the drainage models. The drainage modelling assessment is not included in this report, but rather the Modelling Assessment Part B report.

3 Selected Design Scenarios for CEIP-2

The typical existing embankment crest levels within the study area provide protection to 5- to 10-year water levels (with 2% wave overtopping)[10]. This design standard will be increased during CEIP-2.

The following conditions are assumed to be the design criteria pertaining to the crest level analysis (*Figure 3-1*):

- Embankments will protect against a 25-year cyclone storm event, including waves generated by cyclone wind velocities
- Embankments will protect against a 25-year river flood event, including waves corresponding to a 25-year monsoon wind velocity
- An overtopping rate of 5 L/m/s is allowed
- Embankments will be designed for a 50-year lifetime
- Embankment design will consider subsidence and river aggradation
- The design of the embankments will consider projected climatic changes over the structures' lifetime

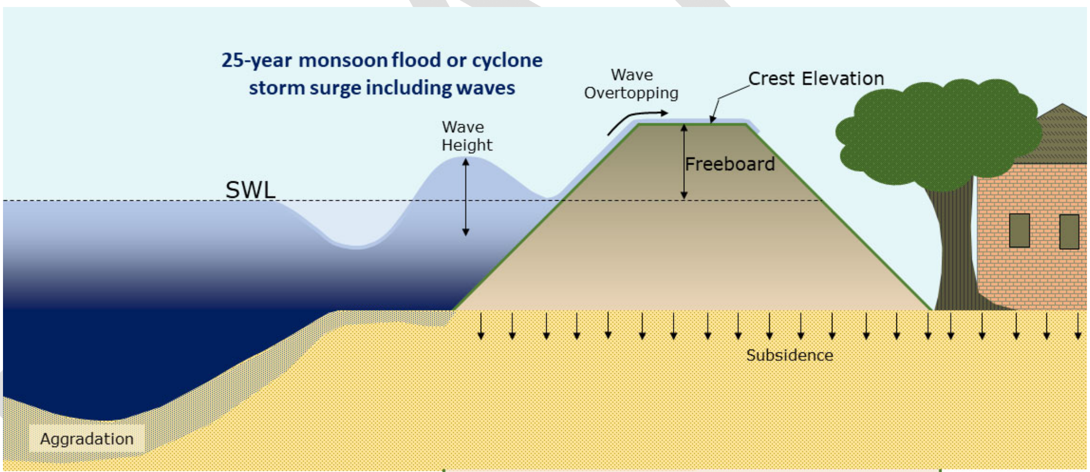


Figure 3-1: Design conditions for CEIP-2 structures.

For comparison, Table 3-1 summarizes design standards for several similar large scale infrastructure projects around the world. When compared to design standards around the world, the embankments of CEIP-2 have a relatively low standard of safety. The lifetime probability of exceedance for the embankments is 87% (*Figure 3-2*). This means that during the embankments' lifetime, the structures have an 87% chance of overtopping beyond the allowable 5 L/m/s. Because

[10] Bangladesh Water Development Board (BWDB), 1983. *Design Manual Procedures for Designs of Polders in Tidal Areas in Bangladesh*, Md. Abdul Quassem, P.F. Raijmakers, J. Burger, Delta Development Project.

of this, other risk mitigation measures should be maintained, such as early cyclone warning systems and use of cyclone shelters.

Table 3-1: Design standards of other flood mitigation structures around the world.

Country	Infrastructure	Design Standard
Bangladesh[11]	Inland embankments on the Jamuna River built during the Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP)	200-year flood without climate change or 100-year flood with climate change Plus 1.5 m of freeboard 30-year design life
	River training works at the Padma River Bridge	500-year flood 100-year design life
	Coastal embankments for CEIP-1	25-year return period
	Coastal embankments for CEIP-2	25-year return period 50-year design life
The Netherlands and Germany[12]	Inland embankments on the Rhine River within Germany	200-year to 500-year flood
	Coastal embankments on the Rhine River in the Netherlands	1,250-year flood
Australia[13] [14]	Embankments	100-year flood 100-year design life
America[15] [16]	Inland embankments on the Mississippi River (in St. Louis)	500-year flood for urban centers 50-year flood for rural areas
	Coastal embankments at the Mississippi River delta	100-year storm event with 0.3 m of freeboard

[11] FRERMIP, 2019. *Feasibility Study for Tranch-2*. Prepared by Institutional Strengthening (ISPMC) and Project Management Consultant for the Bangladesh Water Development Board. August 2019
[12] Linde, A. H. and Aerts, J. C. J. H., 2008. *Simulating flood-peak probability in the Rhine basin and the effect of climate change*, Conference Flood Risk 2008, Oxford, UK, 30 September – 2 October, 2008
[13] Department of Transport and Main Roads (DoTMR), 2020. *Geotechnical Design Standard – Minimum Requirements*. The State of Queensland, Australia.
[14] Department of Environment, Land, Water and Planning (DELWP), 2015. *Levee Management Guidelines*. The State of Victoria, Australia.
[15] Dyhouse, 1995. *Effects of Federal Levees and Reservoirs on 1993 Flood Stages in St. Louis*, http://onlinepubs.trb.org/Onlinepubs/trr/1995/1483/1483-002.pdf
[16] FEMA, 2007. *Risk Management Series Design Guide for Improving Critical Facility Safety*, https://www.fema.gov/sites/default/files/2020-08/fema543_design_guide_complete.pdf, FEMA 543, January 2007

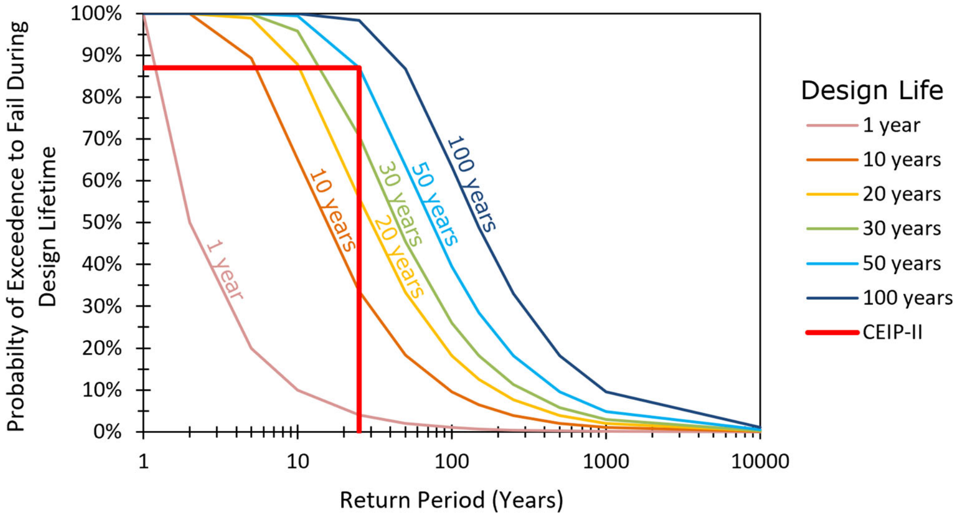


Figure 3-2: Aggregate probability of exceedance for the embankments to fail during their design lifetime. An embankment with a 50-year design life designed to protect against a 25-year water level, has an 87% chance of failing during its lifetime.

4 Climate Change Assessment

Anthropogenic warming of the earth is expected to have significant impacts on the coastal processes of Bangladesh. The designs of CEIP-2 must accommodate the possible changes in future climate conditions, to the best extent possible. There is a high degree of certainty that the average air temperatures will increase in the future; however, the magnitude of this change is uncertain. Furthermore, how increased global temperatures impact specific features of the environment also is uncertain. Additionally, other future anthropogenic changes will also impact the environment. For example, the future Nation River Linking Project, which will connect 44 rivers has been predicted to reduce the Brahmaputra's water and sediment load by 6% and 9-25%, respectively[17]. This may counteract future increases in discharges predicted in climate projections. Therefore, all aspects of climate change impact projections are subject to considerable uncertainty.

The most recent climate change predictions published in the sixth Intergovernmental Panel on Climate Change (IPCC)[18] has projected how various aspects of the environment will respond to increased greenhouse gases emissions. A multinational team of economists, climate scientists, and energy system modelers has developed a number of new "pathways" that look at how society, economy, and demographics may change over the course of the next century. They are referred to as "Shared Socioeconomic Pathways" as a whole (SSPs). The new SSPs present five possible directions for the planet. These scenarios provide a more comprehensive depiction of a "business as usual" world without future climate policies, with global warming ranging from 3.1^{0}C to 5.1^{0}C above pre-industrial levels in 2100.

For the purposes of design, this assessment has considered a high emissions scenario, SSP5-8.5[19] 8.5, projected to 2080 (approximately the end of the 50-year design lifetime). The climate change assessment scenario used in this study has been compared to what has been used in other studies within Bangladesh in Table 4-1. Within this report, the climate change scenario refers to this scenario (SSP5-8.5). Additional climate projections have been assessed; however, these results are contained within the Appendices and are identified as such.

[17] Overeem, I., 2022. *Basin Responses to Human Action and Climate*. International Workshop for the Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone, 11-12 June 2022

[18] IPCC, 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

[19] SSP5-8.5 represents thehigh end of the range of future pathways, corresponding to RCP8.5.SSP stands for Shared Socio-Economic Pathway and RCP stands for Representative Concentration Pathway.

Table 4-1: Comparison of climate change scenarios considered under various projects.

Project	Climate Change Scenario Assessed
CEIP-1[20]	RCP 8.5 Emissions Scenario Taken from the IPCC 6th assessment report
Long Term Monitoring Plan (LTM)[21] [22]	Assessed three periods: Reference period (1951-2005) RCP 4.5 Emission Scenario (2006 – 2099) RCP 8.5 Emissions Scenario (2006-2099) Taken from IPCC 6th assessment report
Delta Plan[23]	Assessed two different climate projections: Business as usual (RCP 4.5) Extreme scenario (RCP 8.5)
FRERMIP[24]	RCP 8.5 Emissions Scenario (2040 and 2100)
LGT Small Scale Projects[25]	RCP 4.5 (2020-2039) RCP 8.5 (2020-2039)

[20] IWM, 2017. *Technical Report on Water Modelling and Climate Resilient Planning for Improvement of Polders*, Prepared for the Bangladesh Water Development Board. 3 February 2017
[21] CEIP-1, 2021. *Climate Change Scenarios: Deliverable 4c*, Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics), Prepared for the Bangladesh Water development Board. June 2021
[22] IPCC, 2013. *Climate Change 2013: The Physical Science Bases. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Stocker*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
[23] General Economic Division (GED), 2018. *Bangladesh Delta Plan 2100*.
[24] FRERMIP, 2021. *Climate Risk and Vulnerability Assessment and Geological Hazard Risk Assessment Final Report*, Prepared by Institutional Strengthening and Project Management Consultant (ISPMC) for the Bangladesh Water Development Board. May 2021
[25] ADB, 2021. *Climate Risk and Adaption Assessment (CRA) Draft Final Report*, ADB Project 53237, Prepared by Northwest Hydraulic Consultants Ltd. and Resource Planning and Management Consultants Ltd for the Bangladesh Government (Local Government Engineering Department). August 5

A summary of how the parameters used in this study vary considering future climate change is presented in Table 4-2. Details on the climate change assessment, including how the values in Table 4-2 were determined, can be found in Appendix A1.

Table 4-2: Summary of climate change considerations for this study. Results are taken from IPCC[26], unless otherwise noted.

Parameter	Remarks	Parameter Variation SSP5-8.5 Scenario in 2080
Average Temperature	Monthly average temperatures are expected to increase.	Average monthly temperature increase varies throughout the year, with a maximum increase in averaged temperatures in December - February of 4.63°C and 4.95°C in the South central and South western region, respectively. Similarly, the annual average temperature will rise by 4 and 4.2°C in the South central and South western region, respectively.
Tropical cyclone wind speed	Tropical cyclone intensity is expected to increase with rising sea temperatures. Due to the increase in intensity, surface winds are expected to increase[27].	Historic rates increased by 10%
Tropical cyclone size and duration	Tropical cyclones are not projected to increase in size nor duration [28].	Unchanged
Sea level rise	The sea level is expected to rise due to, primarily, thermal expansion of the oceans and glacial ice caps melting. The projections are for the global mean sea level rise. This study has assumed that the global mean sea level rise will equal the	Historic sea level increased by 0.65 m (SSP5-8.5, 2080)

[26] IPCC, 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

[27] Knutson, T., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C.-H., Kossin, J., et al., 2020. Tropical Cyclones and 56 Climate Change Assessment: Part II. Projected Response to Anthropogenic Warming. Bull. Am. Meteorol. Soc. 57 101, E303–E322. doi:10.1175/BAMS-D-18-0194.1.

[28] Knutson, T., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C.-H., Kossin, J., et al., 2020. *Tropical Cyclones and 56 Climate Change Assessment: Part II. Projected Response to Anthropogenic Warming*, Bull. Am. Meteorol. Soc. 57 101, E303–E322. doi:10.1175/BAMS-D-18-0194.1.

Parameter	Remarks	Parameter Variation SSP5-8.5 Scenario in 2080
	local sea level rise along the Bangladesh coastline.	
Tidal amplitude and asymmetry	Tidal amplitudes and asymmetries could increase or decrease because of sea level rise. However, other factors, such as loss of intertidal area, can also change tidal characteristics[29]. According to a study by Pickering et al.[30], there are negligible changes in tidal amplitude at the location of the model boundaries. The storm surge model boundaries lie beyond the edge of the Bengal shelf (where the ocean bed levels are significantly shallower), changes in tidal amplitude around the Polders due to sea level rise will inherently be included in the model. In the deep sea, tidal amplitudes are less than in the shallow sections. That being said, anthropogenic or morphologic changes can also impact tidal amplitudes. However, these are difficult to predict and therefore are not included in the model. Therefore, changes in tidal characteristics will in part be included in the modelling results; however, some effects, like bed roughness changes, will not be included.	Unchanged
Rainfall intensity	Extremes in rainfall are expected to increase; this indicates that rainfall events will become more severe.	Monsoon rainfall increased by 11%, and 15% in the South central and Southwestern Zone, respectively
River discharge	With increased rainfall, river discharges are expected to increase.	The expected percent increase in discharge for the Ganges, Brahmaputra, and Upper Meghna is 55%, 29% and 18% respectively

[29] LTM, 2020a. *Interim Report on the Effect of human interventions on tidal and sediment dynamics in the Pussur-Sibsa basin*, Report prepared by DHI and Deltares in association with IWM and University of Colorado for the Bangladesh Water Development Board.

[30] Pickering, M. D., Horsburgh, K. J., Blundell, J. R., Hirschi, J. J.-M., Nicholls, R. J., Verlaan, M., Wells, N. C., 2017. *The impact of future sea-level rise on the global tides*, Continental Shelf Research, Volume 142, 2017, Pages 50-68, ISSN 0278-4343, https://doi.org/10.1016/j.csr.2017.02.004.

Parameter	Remarks	Parameter Variation SSP5-8.5 Scenario in 2080
Salinity	As sea levels rise, salinity extents could increase in the dry season.	Not considered in the analysis
Sediment Flux	With increased rainfall and river discharges, sediment fluxes will increase, however, future sediment fluxes may decrease due to basin wide dynamics[31].	Qualitatively considered

[31] Sarker, M. H., Aketer, J., Ferdous, M. R., Noor, F., 2009. *Sediment dispersal processes and management in coping climate change in the Meghna Estuary, Bangladesh,* Sediment Problems and Sediment Management in Asian River Basin, Workshop held at Hyderbad, India, September 2009, IAHS Publ. 349.

5 Subsidence

What is Subsidence

Subsidence is the gradual, continuous lowering or sinking of the land due to compaction and isostasy[32]. In the Bengal delta, subsidence rates are countered by the accretion of the sediment supply transported from the Himalayan mountains by the rivers and redispersed in the coastal area through tidal forces[33]. Data analysis from 101 water level gauges across the delta reveals that the rate of water level changes in the delta (~3 mm/year) is higher than that of the global mean sea level (~2 mm/year)[34]. In areas without human intervention, such as the Sundarbans, most of the land surface is above the average high tide level during neap tide and below the average high tide level during spring tide[35]. However, after construction of the Polder embankments, the land is no longer flooded and replenished with new sediment supply. Therefore, subsidence has and will continue to gradually lower the land elevation within the Polders. Subsidence must be accounted for when determining the crest levels of the embankments. After Hurricane Katrina hit New Orleans, USA in 2005, local land levels were discovered to have subsided more than 1 m since the embankments were upgraded in the 1960s[36].

Annual subsidence rates vary spatially and temporally across the delta. Along with natural physical processes (glacial or sedimentary isostatic adjustment, tectonics, sediment compaction, sediment load, etc), human-induced processes (land use, withdrawal of groundwater/gas, resources mining, and reduced sediment availability due to interventions upstream, etc) effect the subsidence rates in the Bengal delta. For example, sandier regions typically have lower shallow subsidence rates than muddier regions, in part because of dewatering and decay of organic matter. Likewise, areas around the major cities with significant groundwater extraction can have higher subsidence rates.

Studies on Subsidence in Bangladesh

A number of studies have examined subsidence rates within the Bangladesh delta. The studies have used various methods of estimating subsidence rates, such as measuring historic landmark settlement, studying satellite imagery, or water level data analysis. Reported rates vary substantially, in part due to natural variability of the rates spatially, as well as differences in measurement techniques (including length of time considered) and inconsistencies in defining

[32] LTM, 2020b. *Interim Subsidence Report*. Report prepared by DHI and Deltares in association with IWM and University of Colorado for the Bangladesh Water Development Board.
[33] Sarker, M. H. S., Choudhury, G. A., Akter, J., Kumar, Hore A. K., 2012. *Bengal Delta is not Sinking at a Very High Rate as Indicated by Recent Research: A Pragmatic Assessment based on Archaeological Monuments.* Daily Star, 23 December 2012. https://www.thedailystar.net/news-detail-262153. Accessed 1 April 2019.
[34] Becker, M., Papab, F., Karpytcheva, M., Delebecqueb, C., Kriend, Y., Khan, J.U., Ballua, V., Durandb, F., Le Cozannet, G, Islam, A.K.M.S., Calmantb, S., and Shum, C.K., 2019. *Water level changes, subsidence, and sea level rise in the Ganges–Brahmaputra–Meghna delta*. www.pnas.org/cgi/doi/10.1073/pnas.1912921117. Pp 10.
[35] Sarker, M. H. S., Choudhury, G. A., Akter, J., Kumar, Hore A. K., 2012. *Bengal Delta is not Sinking at a Very High Rate as Indicated by Recent Research: A Pragmatic Assessment based on Archaeological Monuments.* Daily Star, 23 December 2012. https://www.thedailystar.net/news-detail-262153. Accessed 1 April 2019.
[36] Brown, S., Nicholls, R. J., 2015. *Subsidence and human influences in Mega deltas: The case of the Ganges-Brahmaputra-Meghna*, Science of the Total Environment, Science of the Total Environment 527–528, 362–374

subsidence rates (for example, discrepancies in compensation for sedimentation rates and local sea-level rise). A detailed literature review of previous studies on subsidence in the Bengal delta is provided by Akter et al.[37], Becker et al.[38], and LTM[39]. *Figure 5-1* shows the variability in subsidence rates reported by various studies. The values show how the reported subsidence rate would correlate to the necessary increase in crest level for an embankment with a 50-year design life.

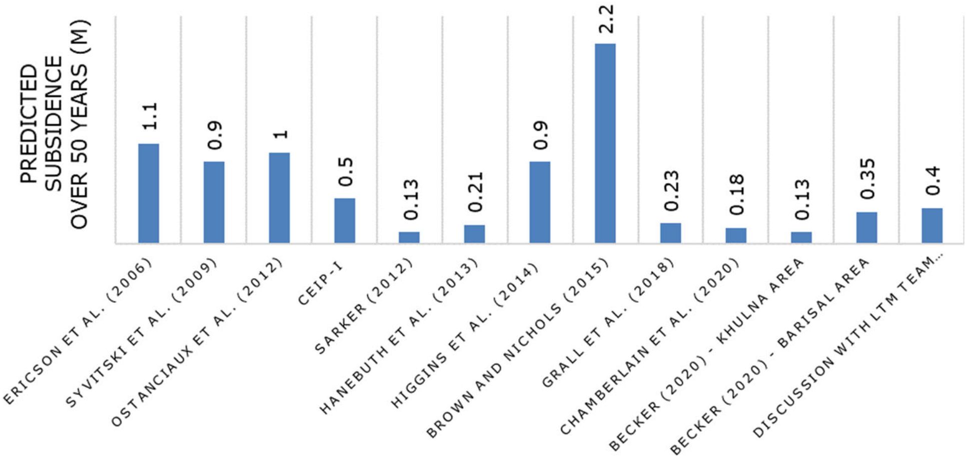


Figure 5-1: Reported subsidence rate over 50 years from previous studies as reported by the LTM Interim Report on Subsidence[39]. (Ranges are presented as the maximum value.)

Figure 5-2 shows the variation of subsidence rates in different studies and recommendations made by Becker et al.[38]. The solid-coloured bars correspond to the significant subsidence rates obtained in that study. They were not able to provide reliable information about the subsidence in the Chattogram region. According to their team, the maximum rate of subsidence for the Southwestern and Southern Zones would not be more than 2.5 mm/year and 7 mm/year respectively.

Grall et al.[40] (*Figure 5-3*) showed a spatial variation of land subsidence showing average subsidence rates over the Holocene (last 10,000 years) derived from radiocarbon dates samples of a suite of over 400 tube wells. The study made an effort to distinguish between components brought on by subsidence, rising sea levels, and sedimentation. The located samples that were impacted by this "river cut" effect and deleted them. Results showed that subsidence rates varied consistently throughout the delta. According to the study, the subsidence rates increase southeast from the Hinge Zone to a maximum of ~4.5 mm/yr. The spatial variation map clearly depicts that at the location of study polders of Southwest Region the land subsidence rate ranges from 3.0–3.5 mm/y.

---

[37] Jakter, J., Sarker, M. H., Popescu, I., Roelvink, D., 2016. *Evolution of the Bengal delta and its prevailing processes*. J. Coast. Res. 321, 1212–1226.
[38] Becker, M., Papab, F., Karpytcheva, M., Delebecqueb, C., Kriend, Y., Khan, J.U., Ballua, V., Durandb, F., Le Cozannet, G, Islam, A.K.M.S., Calmantb, S., and Shum, C.K., 2019. *Water level changes, subsidence, and sea level rise in the Ganges–Brahmaputra–Meghna delta*. www.pnas.org/cgi/doi/10.1073/pnas.1912921117. Pp 10.
[39] LTM, 2020. *Interim Subsidence Report*. Report prepared by DHI and Deltares in association with IWM and University of Colorado for the Bangladesh Water Development Board.
[40] Grall, C., Steckler, M. S., Pickering, J. L., Goodbred, S., Sincavage, R., Paola, C., Akhter, S. H., and Spiess, V., 2018. *A base-level stratigraphic approach to determining Holocene subsidence of the Ganges–Meghna–Brahmaputra Delta plain.* Earth Planet. Sci. Lett., 499 (2018), pp. 23-36, 10.1016/j.epsl.2018.07.008

On the other hand, in the South-Central region the study shows a land subsidence rate of 5.0-6.0mm/y.

The ongoing study under the LTM project has expanded upon earlier research studies. Their study, although not complete[41], has found subsidence values between 4-8 mm/year inside the muddy Sundarbans. Outside the Sundarbans, the rates are around 4-6 mm/year (*Figure 5-4*).

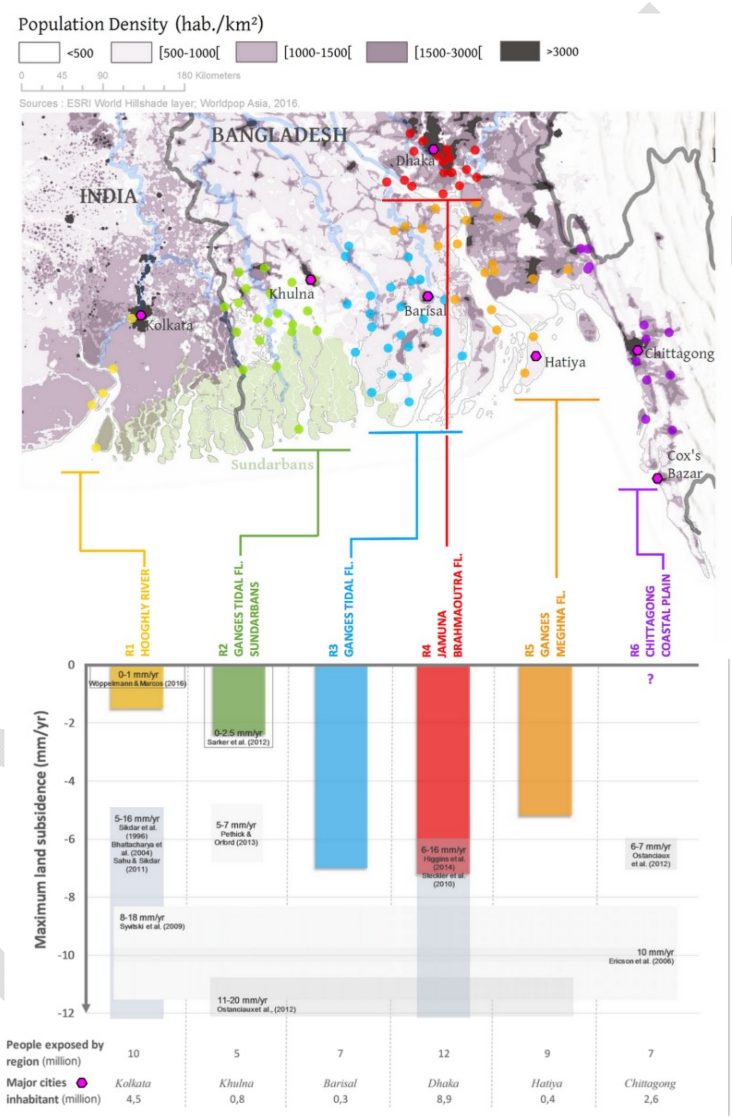


Figure 5-2: Maximum subsidence rates expected over the contemporary period, based on Becker et al.[42].

[41] The LTM research was not complete at the time of this study, November 2021

[42] Becker, M., Papab, F., Karpytcheva, M., Delebecqueb, C., Kriend, Y., Khan, J.U., Ballua, V., Durandb, F., Le Cozannet, G, Islam, A.K.M.S., Calmantb, S., and Shum, C.K., 2019. *Water level changes, subsidence, and sea level rise in the Ganges–Brahmaputra–Meghna delta*. www.pnas.org/cgi/doi/10.1073/pnas.1912921117. Pp 10.

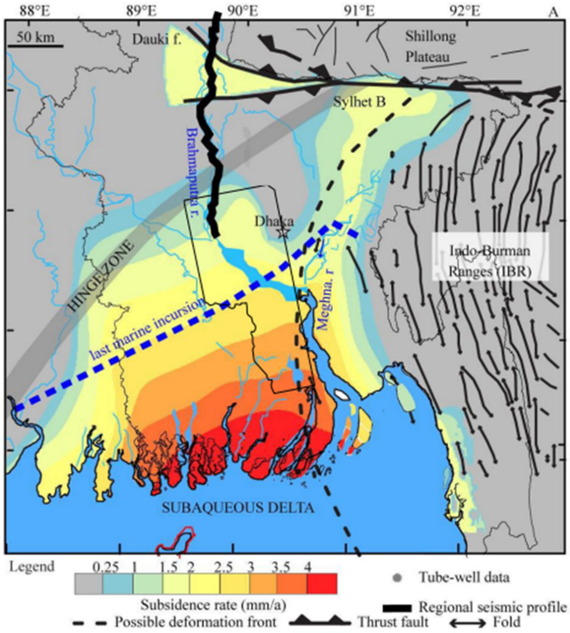


Figure 5-3: Map of Ganges-Brahmaputra Delta from Grall et al., showing average subsidence rates over the Holocene (last 10,000 years) derived from radiocarbon dates samples of a suite of over 400 tube wells and a very high resolution seismic line along the Jamuna River (thick black line)

Figure 5-4: Subsidence rates measured by the latest results of the LTM study at the time of writing this, November 2021. Font size is proportional to the length of the time series and reliability. (From communications with the LTM team.)

Steckler et al[43], (2018) compiled may measurements, which varied in collection technique, around Polder 32. Polder 32 is situated in the south-west region and close to P10-12, P13-14/2. The study discovered long-term subsidence of 2.4–3.2 mm/y.

Recommended Subsidence Rates for CEIP-2

The subsidence rates of CEIP-1 have been refined considering the findings of both historic studies, as well as the most recent findings. The recommended rates also account for compaction of land due to the embankment construction methodology and the lack of recent sediment at the embankment sites, which both cause higher compaction rates in the upper layers of sediment, and therefore lower subsidence rates. Areas with recently deposited sediment typically have a high shallow compaction rates[44]. It should be noted that subsidence rates over the embankments' lifetime may be impacted by future land-use change, which is difficult to predict.

The embankments constructed during CEIP-1 considered a subsidence rate of 10 mm/year. For CEIP-2, the Consultant recommends considering a subsidence rate of 3 mm/year for the Polders located in the Southwestern Zone and 6 mm/year for the Polders located in the Southern Zone. Over the 50-year embankment lifetime, the subsidence allowance will be 15 and 30 cm for the Southwestern and Southern Zones, respectively.

[43] Steckler, M. S., Oryan, B., Wilson, C. A., Grall, C., Nooner, A., L., Mondal, D. R., Akhter, S., H., DeWolf, S., and Goodbred, S. L., 2022 *Synthesis of the Distribution of Subsidence of the Lower Ganges-Brahmaputra Delta*, Bangladesh, Earth-Science Reviews Volume 224, https://doi.org/10.1016/j.earscirev.2021.103887

[44] LTM, 2020. *Interim Subsidence Report*. Report prepared by DHI and Deltares in association with IWM and University of Colorado for the Bangladesh Water Development Board.

6 Overview of Modelling Approach

Outline of Modelling Methodology

The modelling assessment consists of three major components:

1) Cyclone Storm Assessment (Section 7)

   Intent of the assessment: Determine the required embankment crest elevations due to cyclone storms, as well as inundation extents

   What the assessment is: Hindcasting historic storm surge water levels and waves

   Models used: Storm Surge Model and SWAN[45] Model

2) Monsoon Flooding Assessment (Section 8)

   Intent of the assessment: To find the required embankment crest elevations due to monsoon flooding

   What the assessment is: Monsoon flood levels in the peripheral rivers will be determine by modelling the design flood

   Models used: South West and South-Central Regional Models

3) Drainage Model Assessment (in Modelling Report Part B)

   Intent of the assessment: The results will be used for design of the drainage infrastructure

   What the assessment is: Drainage models for each Polders will be used to calculate drainage patterns and flow rates within each Polder

   Models used: South West and South-Central Regional Model and local Polder drainage models (one per Polder)

Notes on Data Availability and Limitations

An extensive data collection exercise was undertaken during CEIP-2. This included collecting both existing and new data. In addition to the data collected during CEIP-2, data has been collected from CEIP-1, the LTM, BWDB, the Bangladesh Meteorological Department (BMD), as well as from CEGIS's own database. A summary of the majority of the LTM data available for this study is detailed in Appendix A2.

A number of surveys will not be collected due to project scheduling and bureaucratic hurtles. These include the Ichamati-Kalindi Indian boarder river and the rivers within the Sundarbans. CEGIS has used the surveyed data which has been collected during 2000. CEGIS worked on the old cross sections and made necessary adjustment based on widths and sinosities, observed from satellite image, as well as slopes taken from Digital Elevation Model (DEM). This will add inaccuracies in the results; however, it is difficult to quantify the additional uncertainty this lack of data introduces to the results.

[45] SWAN is an acronym for Simulating WAves Nearshore

7 Storm Surge and Wave Analysis

Hydrodynamic Model

***Model Overview**:* The 2D hydrodynamic model, known as Bay of Bengal Model, was created using Delft3D Version 4. The Bay of Bengal model has already been used by CEGIS in several government and private projects. In 2017, The model was used to assess the impact of Sea Level Rise in three sectors: water, agriculture and infrastructure of coastal areas of Bangladesh. The study was initiated by Department of Environment (DoE). During 2019, the model was applied to assess the combined effect of sea level rise and storm surge on National and Regional Highways of Chattogram Coastal Zone of Bangladesh. This project was initiated by Roads and Highways Department (RHD) of Bangladesh. In the year of 2021, the model was further simulated to assist in preparation of Water Development Plan (WDP) at Maheshkhali-Matabari Area (MIDI) of Coxsbazar. The model domain contains the entire coastal area of Bangladesh, including approximately 500 m of the Bay of Bengal (*Figure 7-1*). For a realistic simulation of floods in the coastal area and inundation, the Delft3D modelling system contains dynamic simulations of flooding and drying processes. The terrain topography employed in the model also depicts the crest elevations of the existing embankments. The model simulated:

- Upstream river discharges
- Tides
- Storm surges (both pressure and wind set up)
- Predicted future impacts of climate change by raising the sea level by 0.65m and increasing the cyclone wind speeds by 10%
- Wave characteristics generated by cyclone winds (this is modelled by the coupled SWAN model, Version 3)
  - wave refraction over a bottom of variable depth and/or a spatially varying ambient current, depth and current-induced shoaling, wave generation by wind, dissipation by white capping, dissipation by depth-induced breaking, dissipation due to bottom friction, nonlinear wave-wave interactions, wave blocking by flow, transmission through, blockage by or reflection against obstacles and diffraction; details can be found in the Delft3D SWAN Manual[46].

The model did not simulate:

- Sediment transport
- Swells
- Wave overtopping
- Salinity

Generated Grids: The model consisted of variable grid sizes varying from 750-1500 m in the deep sea and 150-200 m in and adjacent to the coastal region. The curvilinear grid contained 864 grid cells in M-direction and 1241 grid cells in N-direction, respectively. The total number of grid

[46] Delft3D-WAVE, 2014. *Simulations of short-created waves with SWAN*, User Manual.

elements was 896,603. The maximum aspect ratio of the grid wass 1.56 which is within the allowable limit specified by 2.0 by Delft3D Manual. On the contrary, orthogonality of the generated grid was 0.05 which is also within allowable limit (0.6) suggested by Delft3D Manual. Therefore, the mesh had adequate aspect ratios and orthogonality.

Open Boundaries: There were four open boundaries in the model: three upstream boundaries and one downstream boundary. The upstream boundaries were located on the Ganges, Jamuna and Upper Meghna rivers. The upstream boundary was assigned a time series discharge at the Ganges, Jamuna and the Upper Meghna Rivers. The upstream discharges were collected from the BWDB daily discharge gauges. The downstream boundary contained timeseries tidal water level data from TPXO 8.0 Global Inverse Tide Model generated using Delft3D Dashboard When considering the effects of sea level rise due to climate change, the downstream water levels was shifted up accordingly. Figure 7-2 shows the boundary location of the model.

Bathymetry and Topography: Surveys collected from CEIP-1, the LTM project, CEGIS internal data sets, as well as those collected during CEIP-2 have been used to create the bathymetry and topography of the rivers and Polders. The bathymetry of the deep sea portion of the Bay of Bengal has been generated using the Open Access General Bathymetric Chart of the Oceans dataset (GEBCO 22). This bathymetry data was from the year 2020 (CEGIS Survey Data) and 2022 (Survey conducted for CEIP II).

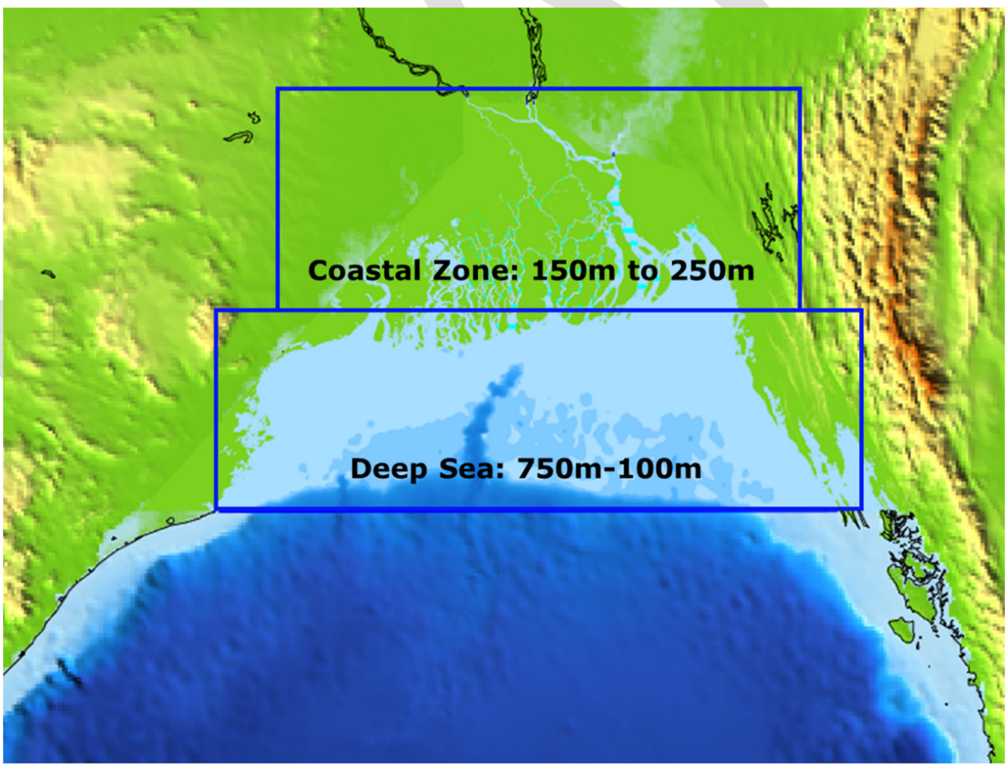


Figure 7-1: Grid size distribution in the model domain.

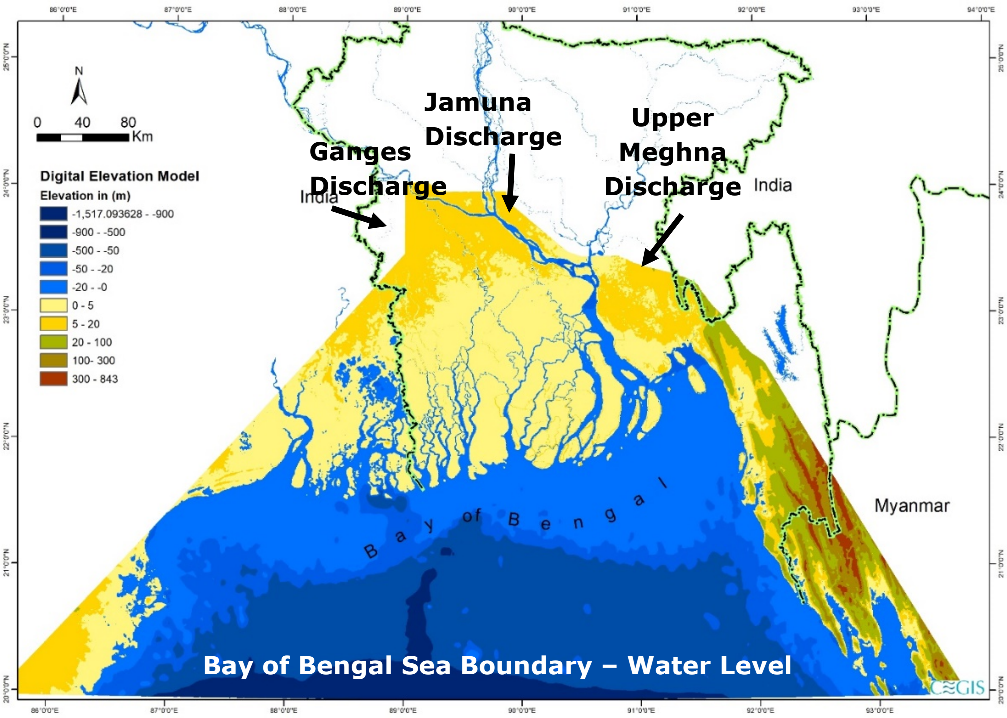


Figure 7-2: Bay of Bengal model domain and boundaries.

Cyclone Induced Storm Surge Model

7.1.1 Approach and Methodology

The existing Bay of Bengal Model has been applied in this study for storm surge modelling. Cyclone and hydrodynamic models are combined to create the storm surge model. Bay of Bengal model based on Delft3D hydrodynamic modelling system has been used to simulate cyclone, cyclone induced storm surge, related flooding and storm surge analysis. The storm surge analysis will determine the water levels at the Polder boundaries due to tides, storm surges and waves. Additionally, inundation extents by overtopping have been determined for the design cyclone storm event. The following methodology has been followed:

1. ***Data Collection:*** Cyclone data was collected for the period of 1960-2021 (61 years). Every year, on average five to six cyclones form in the Bay of Bengal[47]. Major cyclones which made impact at Bay of Bengal Coast have been selected for the analysis. These cyclones are all *severe cyclonic storms* or *super cyclonic storms*, according to the scale of the India Meteorological Department. In total, 33 cyclones have been selected. Characteristic of the

[47] Singh, 2007. *Long-term trends in the frequency of severe cyclones of Bay of Bengal: Observations and simulations*, Mausam, 58, 1, January 2007, 59-66

selected cyclones are summarized in Appendix A4. The models have simulated the landfall of the cyclone in conjunction historic tide levels. The historic cyclones have been simulated both with and without climate change.

2. ***Model Input Parameters:*** Holland Single Vortex theory has been used to create the wind field. Delft3D Dashboard was used to generate spiderweb for the historical cyclones (Figure 7-3) The following facts and information are required by the cyclone model for the description of the wind field and pressure field.
    - Cyclone Track (Including direction)
    - Maximum Wind Speed (V_{max})
    - Central Pressure (P_c)
    - Ambientl Pressure (P_n)
    - Radius of Maximum Winds (R_{max})
    - Holland Parameter, B= 2.0-(Pc-90)/160
    - V_{max}-P_c relation
3. ***Defining Extraction Points:*** A number of extraction points have been identified over the study area (*Figure 7-4*). There are approximately 2-3 points per Polder. After running the Storm Surge model for each of the 33 historic cyclones, at each of the extraction points the water levels over the duration of the storm were extracted (the SWL).
4. ***Storm Surge Model Simulation:*** The storm surge model was simulated for all the 33 cyclones for both base condition and climate change scenario (SSP8.5-2080). The cyclone induced storm surge model was calibrated and validated against water level at specified location where observed data is available during cyclone (Detailed in Section 7.4.2)
5. ***Wave Simulation:*** To simulate the evolution of wind-generated waves in coastal waters (which may include estuaries, tidal inlets, barrier islands with tidal flats, channels etc.) the third-generation SWAN model has been used. This model will be used to hindcast waves generated during historic cyclones to derive time series wave data across the project area. This model will be run *in parallel* to the cyclone model.
6. ***Result Extraction***: At each extraction point, the surge height, significant wave heights, wave period during the entire duration of the storm were extracted.
7. ***Calculating Free Board Requirement***: The freeboard requirement due to wave run up has been calculated analytically for the entire time series for each storm, at each extraction point. If the value was below the minimum freeboard stipulated by BWDB (0.9 m), the minimum freeboard was added.
8. ***Joint Probabilistic Analysis:*** The time series of the SWL and freeboard at each point for each cyclone were added together. This created a time series of the *required crest height* over the duration of each storm. Then, the maximum required crest level was extracted for each time series and a frequency analysis was performed using these maximum required crest elevations. In this way, the assessment considers the joint probability of tides, storm surges and wave effects influencing water levels simultaneously using a continuous simulation approach. *Figure 7-5* shows a schematic of the approach. The assessment accounts for the fact that peak storm surge levels, wave heights and high tides do not always occur simultaneously; if they are assumed to be so, the protection level of embankments will be in fact much higher than the design requirements. As well, the

analysis considers how storm surge severity is spatially variable by analysing each extraction point separately.

9. ***Determining Design Crest Elevation:*** Finally, the 25-year crest elevation was determined from the frequency analysis at each point across the study area.

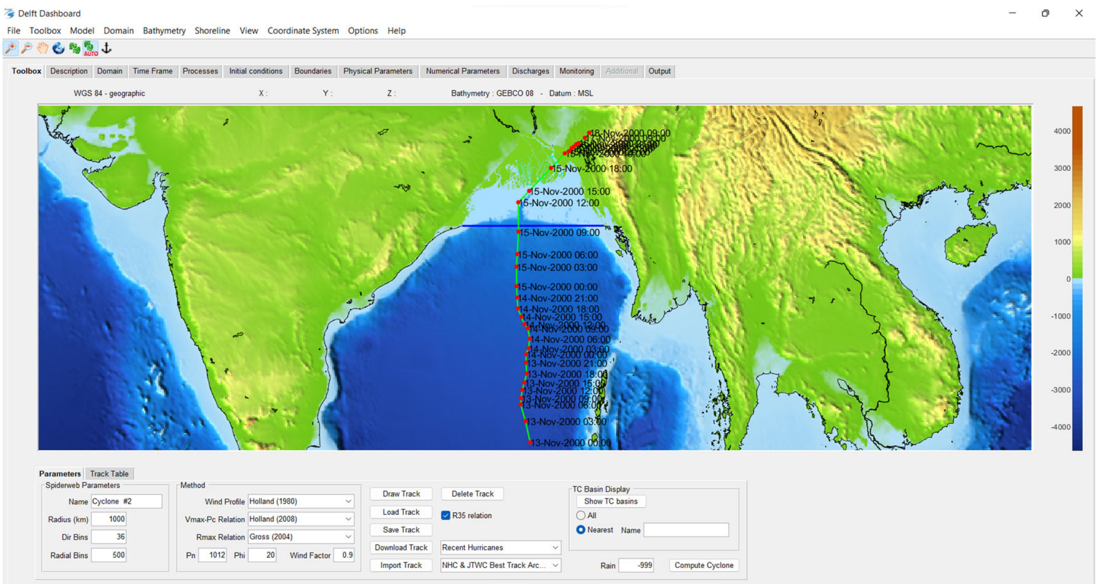


Figure 7-3: Delft3D Dashboard Interface

The methodology of CEIP-2 varies from that of CEIP-1. Appendix A3 summarizes the differences between the two methodologies.

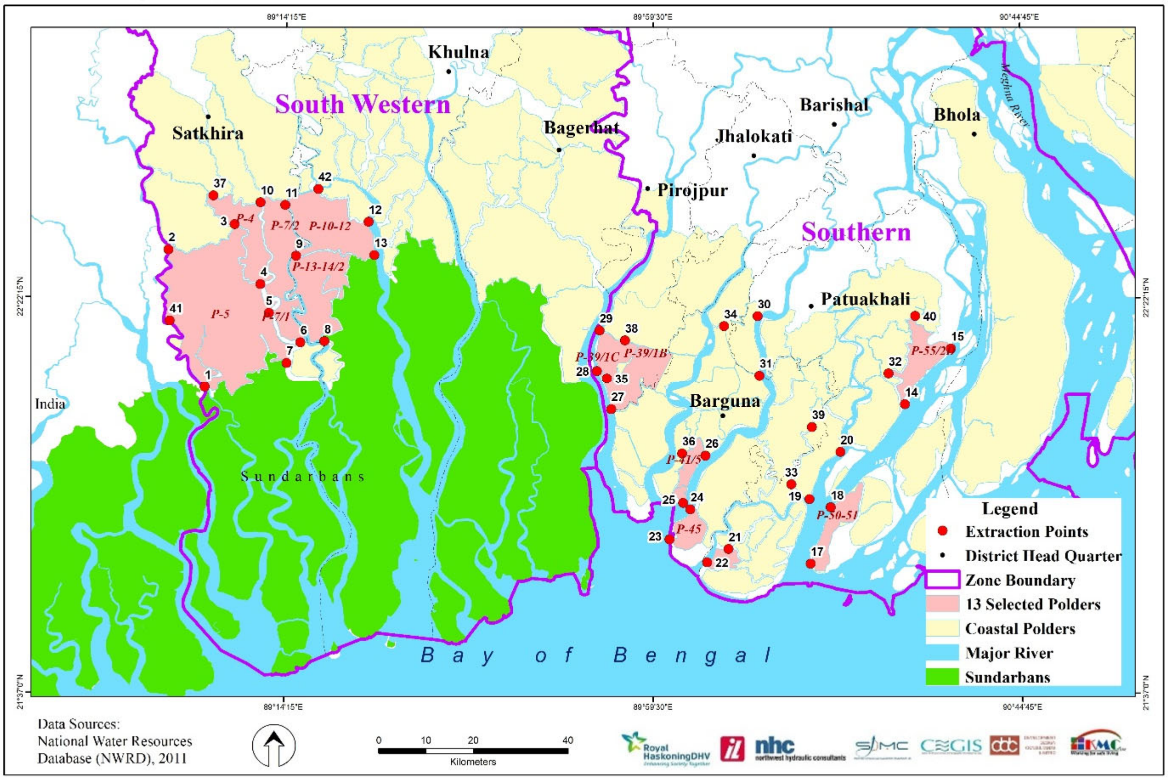


Figure 7-4: Extraction points for the water level and wave height data.

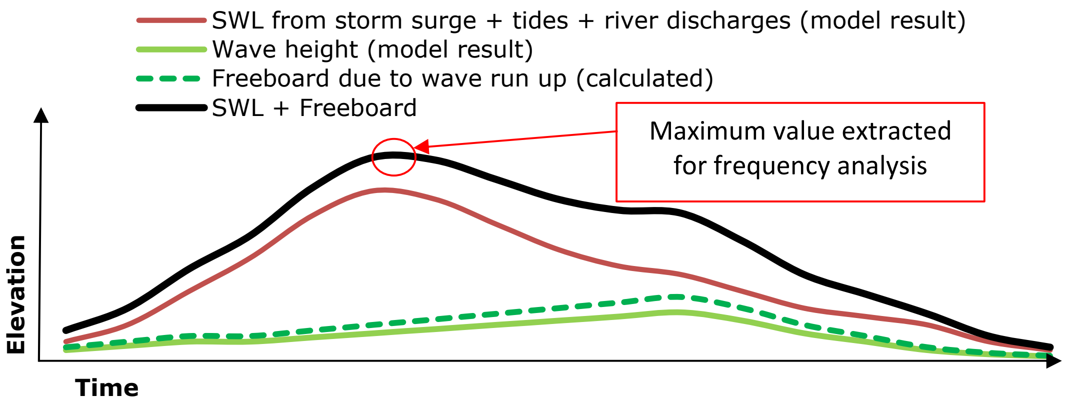


Figure 7-5: Schematic of computed results for one extraction point over the duration of one cyclone storm.

Wave Model Development

The Delft3D-WAVE model (*Figure 7-6*) has been developed to simulate how wind-generated waves change over time in coastal seas. In waters of deep, intermediate, and finite depth, the wave module of Delft3D computes wave propagation, wave generation by wind, nonlinear wave-wave interactions, and dissipation for a given bottom topography, wind field, water level, and current field. Delft3D-WAVE model uses third-generation SWAN model. The stationary second-generation HISWA model was replaced by this SWAN model. The SWAN model is superior to HISWA in a number of ways, and it also substantially outperforms its drawbacks. Some of the notable advantages of SWAN model are: 1) Modern formulations are used to explicitly represent the physics in SWAN, 2) The SWAN model is fully spectral in both directions and frequencies (0 to 360), 3) The fully implicit techniques that have been implemented ensure that the wave computations in SWAN are invariant, 4) The computational grid in SWAN has not to be oriented in the mean wave direction and so the grid can handle all wave directions, 5) SWAN can perform computations on a curvilinear grid (if the FLOW module of Delft3D uses this grid, the coupling between SWAN and FLOW is enabled).

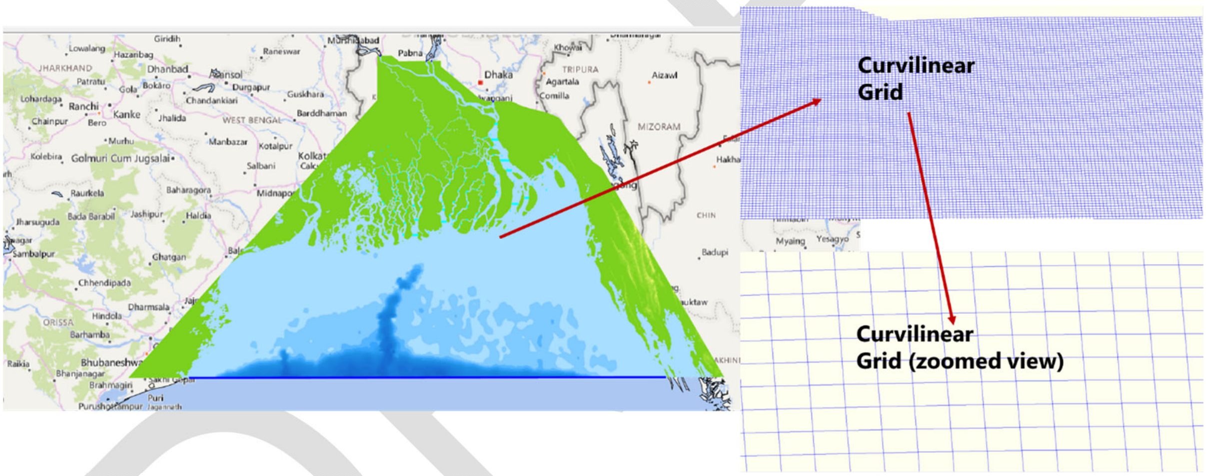


Figure 7-6: Bathymetry and Grid of Wave Model

SWAN calculates the evolution of arbitrary, short-crested waves in shallow, middle, and deep water along coasts. The SWAN model takes into consideration (refractive) propagation due to current and depth and explicitly models non-linear wave-wave interactions (both quadruplets and triads) generated by wind, dissipation due to white capping, bottom friction, and depth-induced wave breaking

CEGIS has wave model developed by Delft3D modelling system to estimate the main wave parameters and some hydrodynamic features. The WAVE module of Deflft3D was used with an online coupling with the FLOW module. Through a two-way wave-current interaction, the two modules in this coupled simulation are dynamically connected. This connection of modules takes into account both the impact of waves on current and the impact of flow on waves.

Three additional boundary conditions along with those used in hydrodynamic and cyclone induced storm surge model: time-varying significant wave height, wave direction and wave period were provided at the southern boundary in Bay of Bengal, from European Centre for Medium-Range Weather Forecasts (ECMWF). Wind speed data were collected from ECMWF as well, at one-degree interval across the whole computational grid.

Calibration and Validation of the Models

7.1.2 Hydrodynamic Model

The updated hydrodynamic model has been calibrated at validated at three locations: Coxsbazar, Khepupara and Hiron Point. Calibration was done for the year 2018 and validation was done for the year 2020. In cased of both calibration and validation, efforts have been made to match the simulated water level with observed water level at the mentioned three locations. *Figure 7-7* shows the geographical location of calibration and validation of hydrodynamic model:

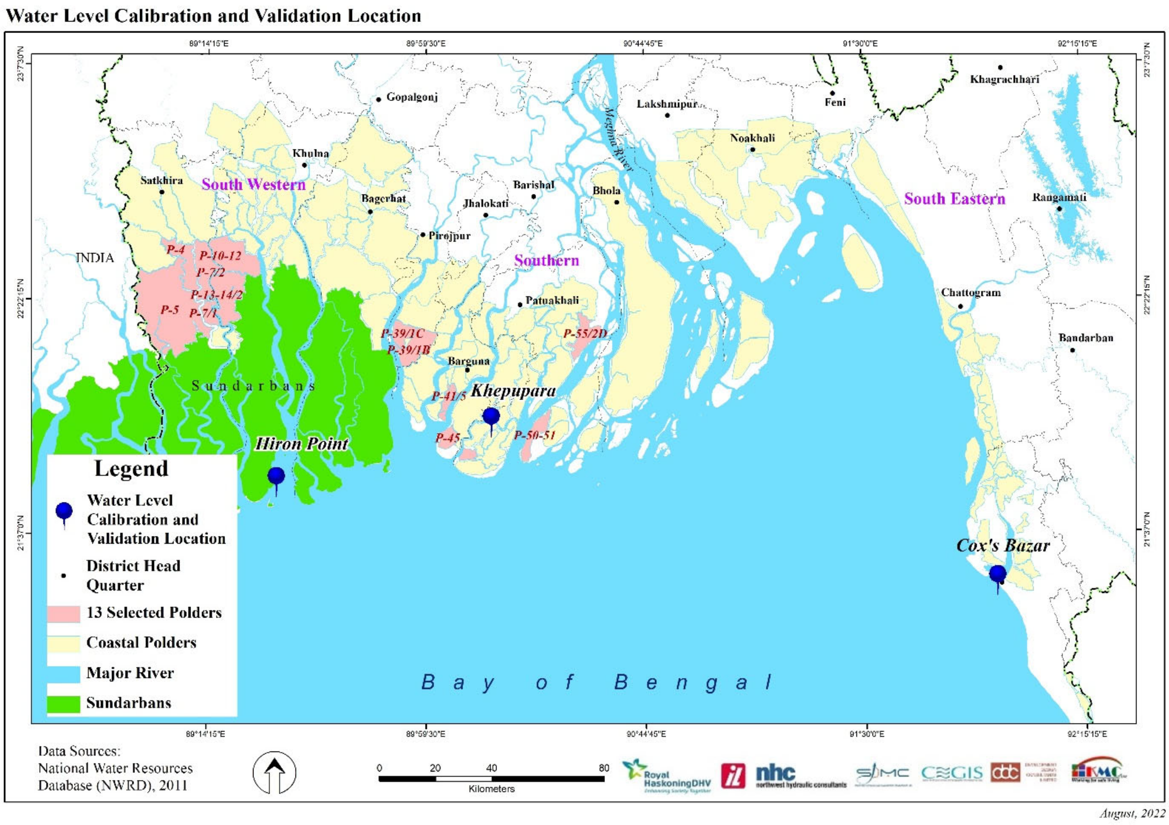


Figure 7-7: Hydrodynamic Model Calibration and Validation Location

Calibration of the Model

The performance of the hydrodynamic model has been evaluated in two ways, (i) visual comparison of observed and simulated water level, and (ii) statistical performance evaluation of results. Statistical performance of the model has been analysed utilising the following parameters: Nash-Sutcliffe Efficiency (NSE), percent Bias (PBIAS), ratio of RMSE and observed data standard deviation (RSR), Pearson's correlation coefficient (r) and coefficient of determination (R^2). In order to achieve satisfactory model performance, the updated and enhanced two-dimensional hydrodynamic model of the Bay of Bengal has been calibrated against water level (simulated and measured) and water flow at various places. The year 2018 has been chosen as the calibration year. The locations of the measured and anticipated data that were used for calibration are depicted in *Figure 7-8* to *Figure 7-10*. From the visual interpretation it has been observed that the model captures the peak water levels well. The result of statistical analysis also shows that the model shows satisfactory performance for all the parameters (see Table 7-1).

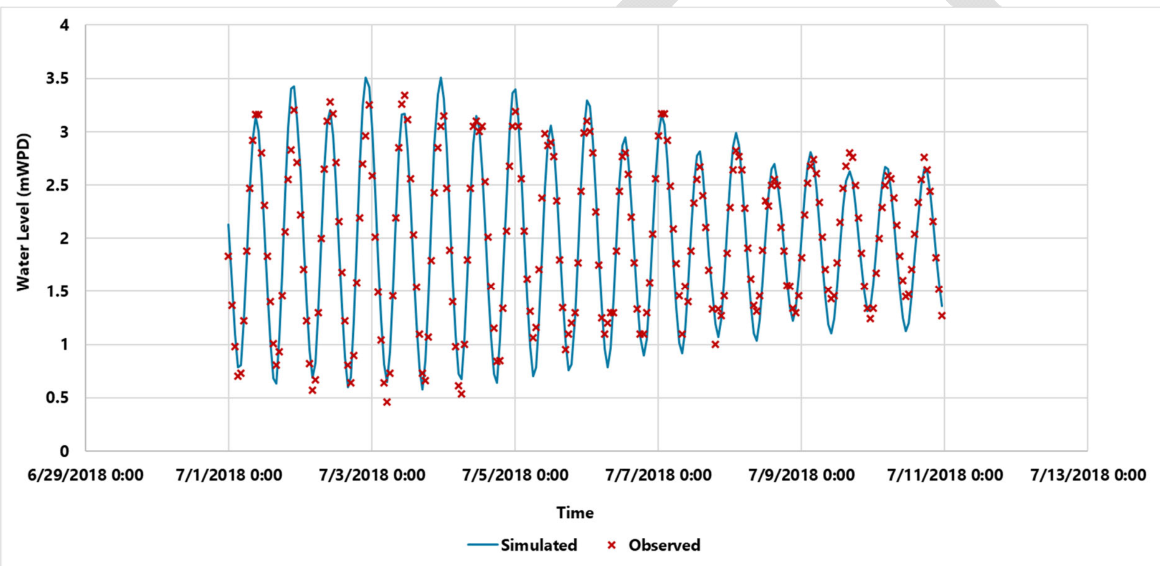


Figure 7-8: Calibration of Water Level at Hiron Point

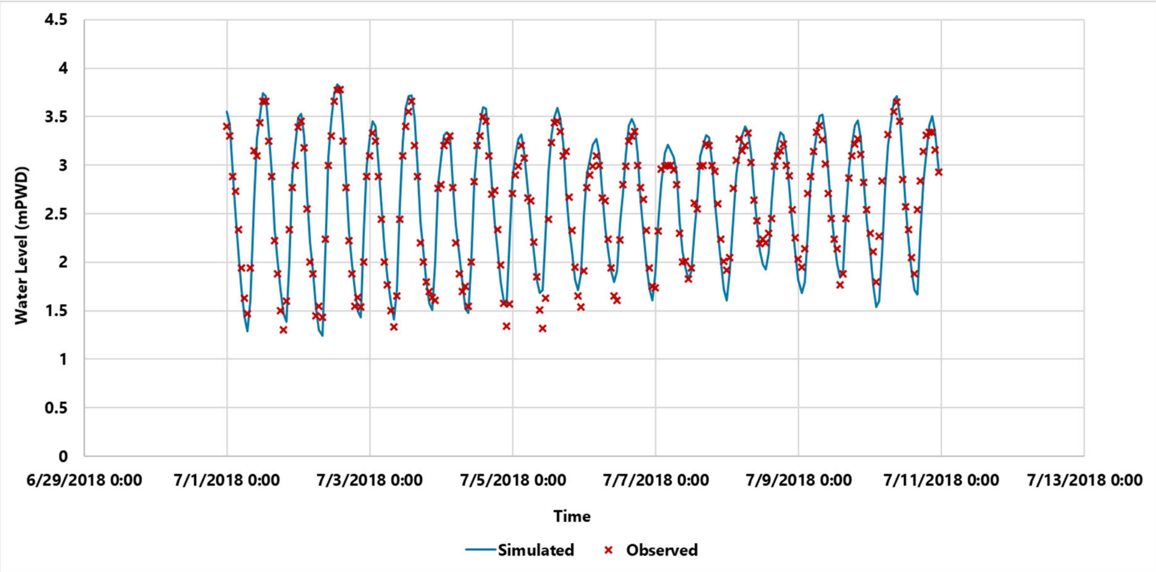


Figure 7-9: Calibration of Water Level at Khepupara

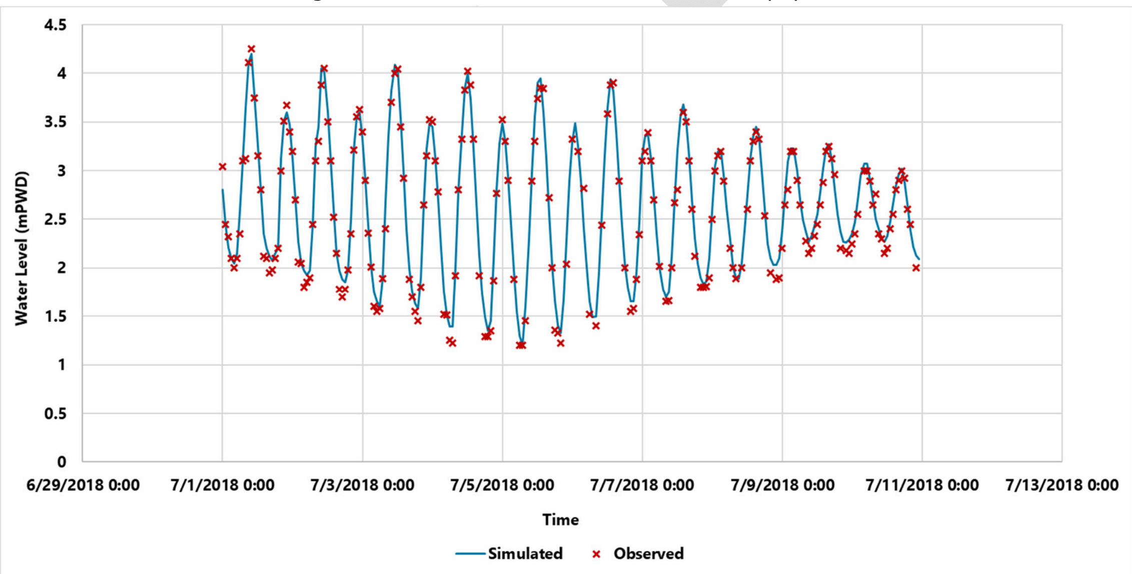


Figure 7-10: Calibration of Water Level at Coxsbazar

Table 7-1: Statistical performance of the Bay of Bengal model for Calibration at Hiron Point, Khepupara and Coxs Bazar

Station Name	Parameter	Value	Status
Coxsbazar	NSE	0.97	Very Good
	PBIAS	2.10	Very Good
	RSR	0.16	Very Good
	R^2	0.98	Very Good

Station Name	Parameter	Value	Status
Khepupara	NSE	0.91	Very Good
	PBIAS	0.54	Very Good
	RSR	0.31	Very Good
	R^2	0.91	Very Good
Hiron Point	NSE	0.91	Very Good
	PBIAS	-0.22	Very Good
	RSR	0.30	Very Good
	R^2	0.91	Very Good

Validation of the Model

To validate the model, other sets of data from different years but at the same locations were compared to the data used in the calibration. Three locations have validated the model for the year 2020. *Figure 7-7* displays the locations for the validations. The results of the validation are displayed from *Figure 7-11* to *Figure 7-13*. From the visual interpretation, it has been observed that, model captures the peak water levels well. The result of statistical analysis also shows that the model shows satisfactory performance for all the parameters (see Table 7-2).

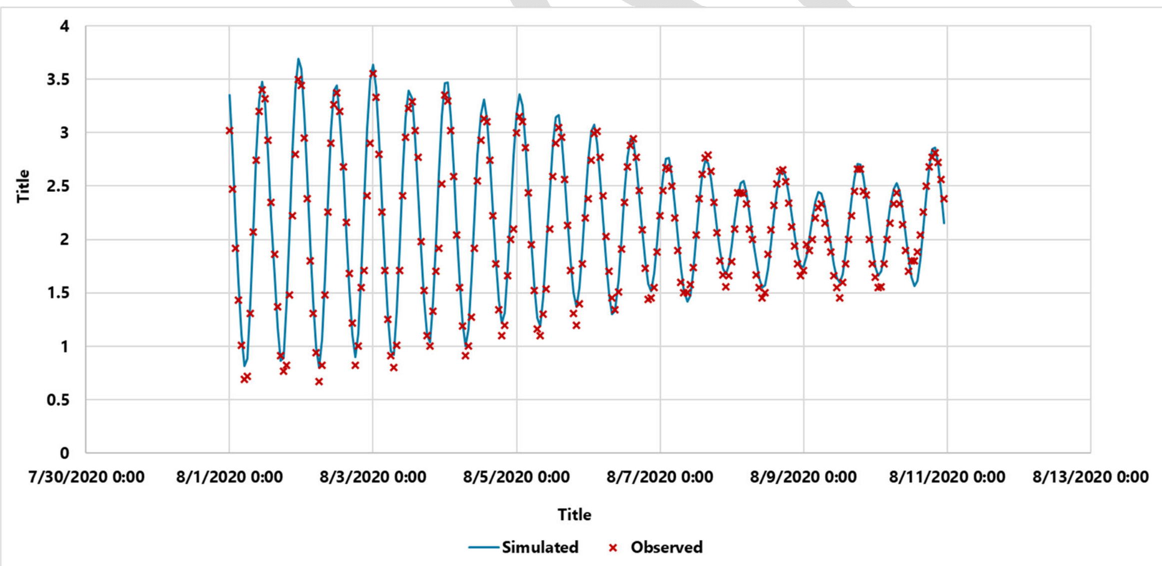


Figure 7-11: Validation of Water Level at Hiron Point

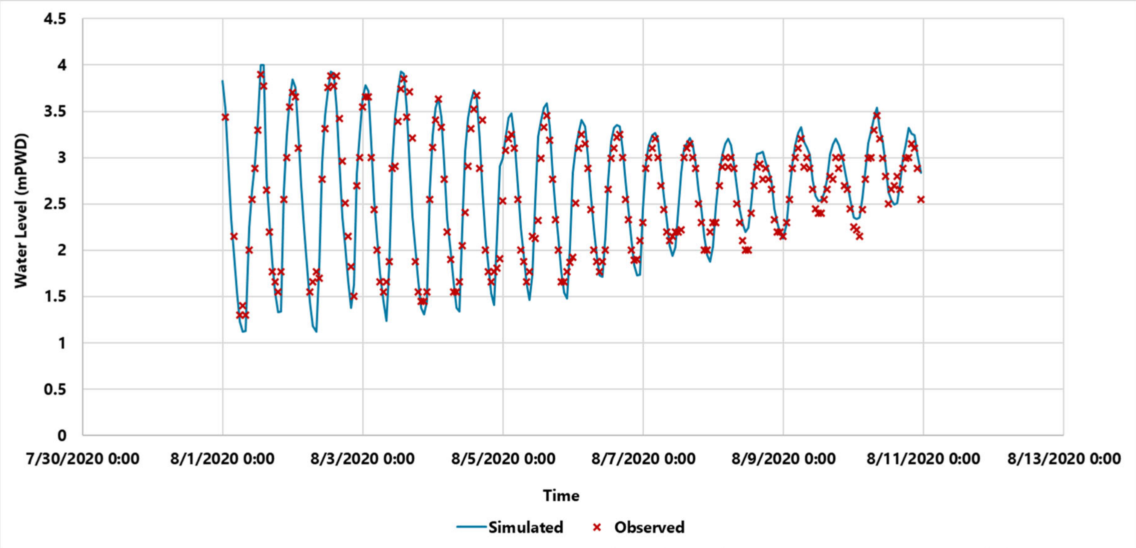


Figure 7-12: Validation of Water Level at Khepupara

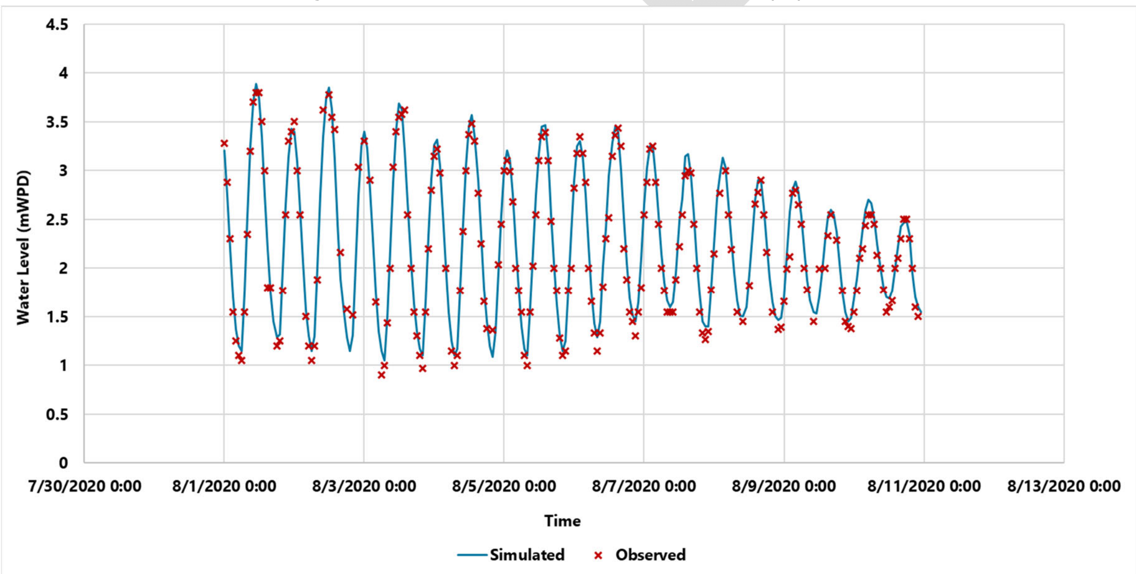


Figure 7-13: Validation of Water Level at Coxsbazar

Table 7-2: Statistical performance of the Bay of Bengal model for Validation at Hiron Point, Khepupara and Coxs Bazar

Station Name	Parameter	Value	Status
Coxsbazar	NSE	0.86	Very Good
	PBIAS	3.96	Very Good
	RSR	0.37	Very Good
	R^2	0.89	Very Good

Station Name	Parameter	Value	Status
Khepupara	NSE	0.87	Very Good
	PBIAS	2.79	Very Good
	RSR	0.36	Very Good
	R^2	0.89	Very Good
Hiron Point	NSE	0.92	Very Good
	PBIAS	4.25	Very Good
	RSR	0.28	Very Good
	R^2	0.94	Very Good

7.1.3 Cyclone Induced Storm Surge Model

The updated storm surge model has been calibrated at validated at three location: CHarchenga, Khepupara and Hiron Point. The location has been selected such way so that storm surge level due to cyclone is available for a particular cyclone. In cased of both calibration and validation, efforts have been made to match the simulated water level with observed water level at the mentioned three locations. *Figure 7-14* shows the geographical location of calibration and validation of Cyclone Induced Storm Surge Model.

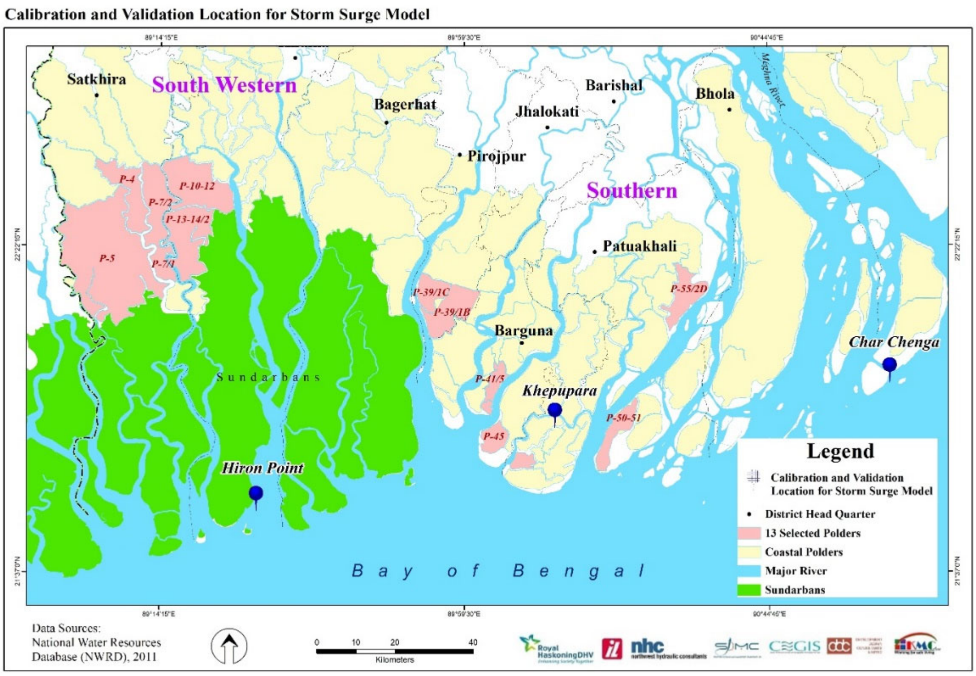


Figure 7-14: Cyclone Induced Storm Surge Model Calibration and Validation Location

The performance of the storm surge model has been evaluated in two ways, (i) visual comparison of observed and simulated water level of a historic cyclone, and (ii) statistical performance evaluation of results. Statistical performance of the model has been analysed utilising the following parameters: Nash-Sutcliffe Efficiency (NSE), percent Bias (PBIAS), ratio of RMSE and observed data standard deviation (RSR), Pearson's correlation coefficient (r) and coefficient of determination (R^2). Calibration has been done by comparing o observed and simulated water level of tropical cyclone Sidr at Khepuppara. Validation has been done by comparing observed and simulated water level of tropical cyclone Sidr at Charchenga and Aila at Hiron Point. *Figure 7-15* to *Figure 7-17*, shows the result of calibration and validation for all the three stations. The model captures the peak water levels well. The result of statistical analysis also shows that the model shows satisfactory performance for all the parameters (see Table 7-3).

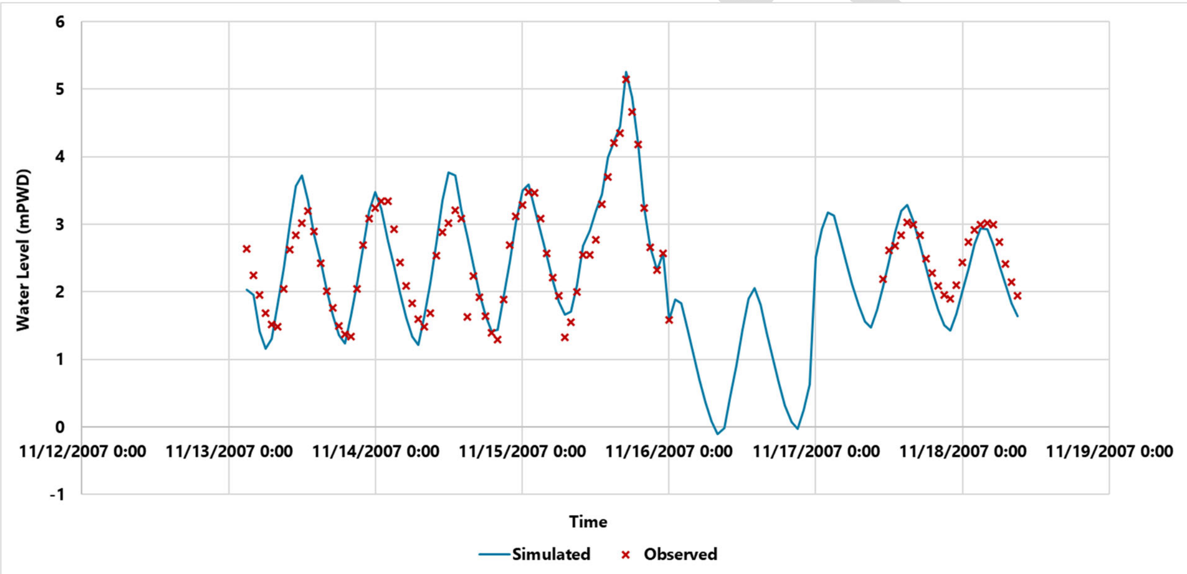


Figure 7-15: Calibration of Water Level at Khepupara for SIDR (Storm Surge Model)

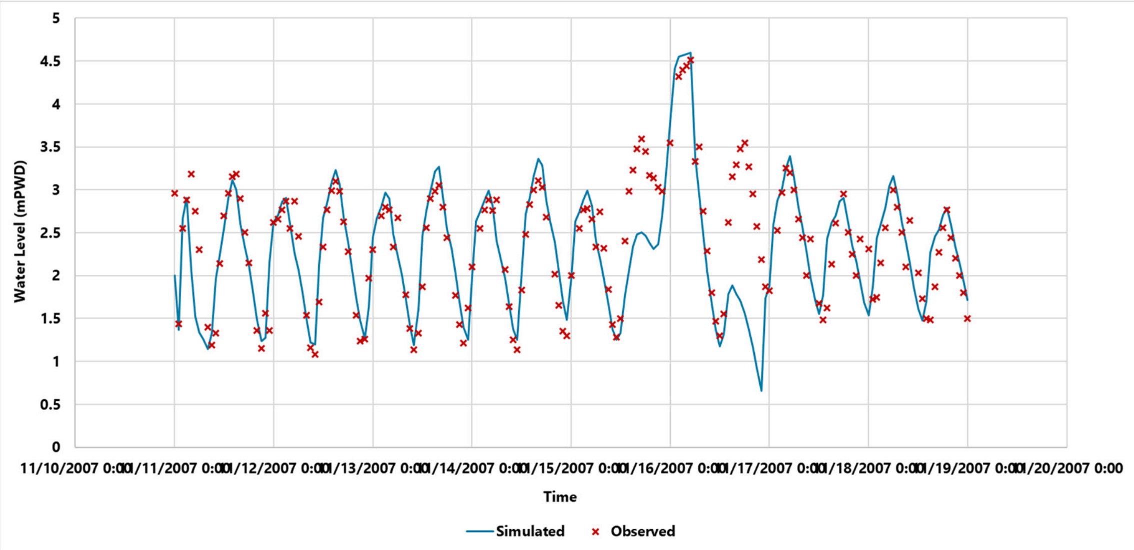


Figure 7-16: Calibration of Water Level at Charchenga for SIDR (Storm Surge Model)

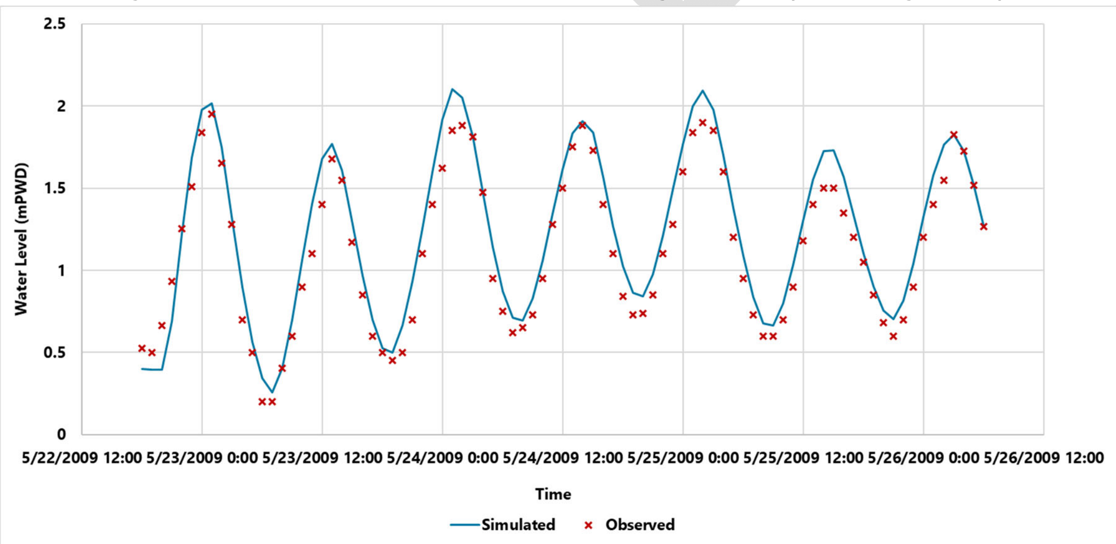


Figure 7-17: Validation of Water Level at Hidron Point for Aila (Storm Surge Model)

Table 7-3: Statistical performance of the Storm Surge Model

Station Name	Parameter	Value	Status
Khepupara	NSE	0.86	Very Good
	PBIAS	-0.28	Very Good
	RSR	0.38	Very Good
	R^2	0.86	Very Good
Charchenga	NSE	0.75	Very Good

Station Name	Parameter	Value	Status
	PBIAS	0.28	Very Good
	RSR	0.50	Very Good
	R^2	0.68	Good
Hiron Point	NSE	0.75	Very Good
	PBIAS	0.28	Very Good
	RSR	0.50	Very Good
	R^2	0.68	Very Good

Comparison to CEIP-1 Results

Because of limited historic data available, the CEIP-2 storm surge model has also been compared to the model results of CEIP-1. In the absence of historic data, confidence in model results can be gained if two separate models create comparable results. Results have been extracted at the same locations as the extracted points for CEIP-1 (*Figure 7-18*). A total of 103 locations have been identified. Three major cyclones have been used for the validation: the 1991 cyclone (landfall at Chattogram Coastal Plain), cyclone SIDR (landfall at Meghna Deltaic Zone) and cyclone AILA (landfall at West Bengal but effected the Ganges Deltaic Plan). The results can be seen in *Figure 7-19* and *Table 7-4*. The results shows that the CEIP-2 model performs well for all the three cyclones both statistically and visually. The CEIP-2 model underestimating the CEIP-1 model outcomes at few locations, see *Figure 7-19*, *(ii)*. Here, the CEIP-1 model shows higher water levels during low tide, compared to those at high tide. Additionally, wind velocities at the points shown in *Figure 7-20* are shown in Table 7-4. There is good agreement between the model velocities.

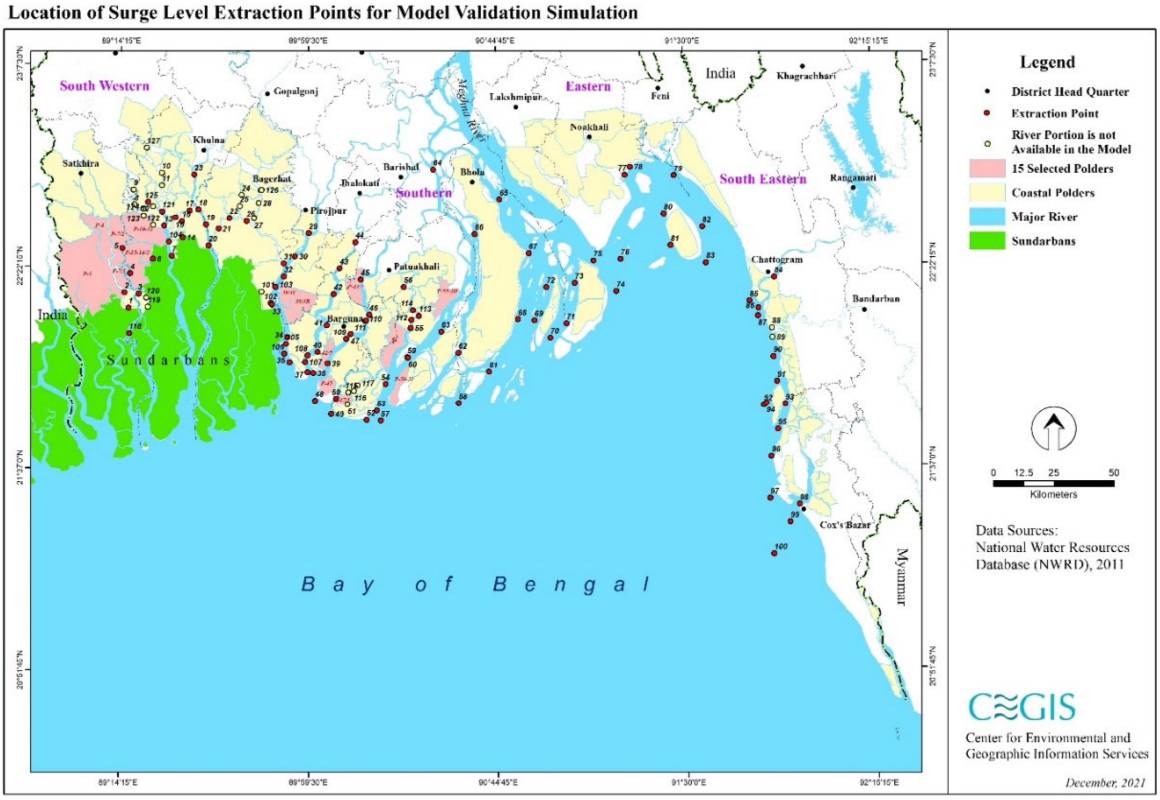
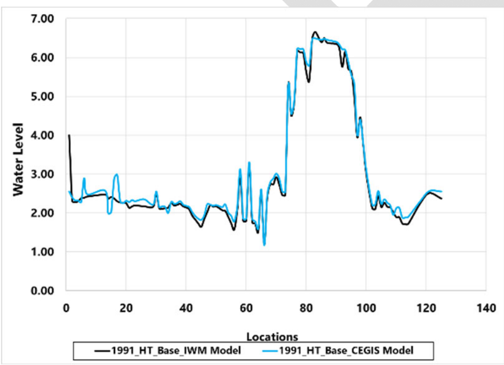
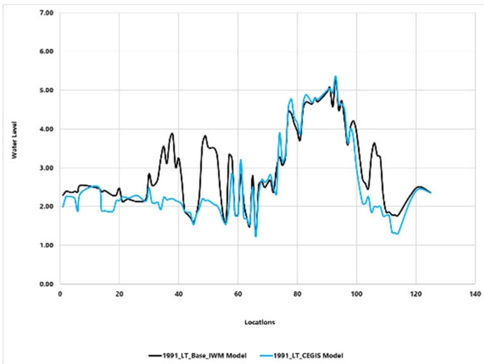


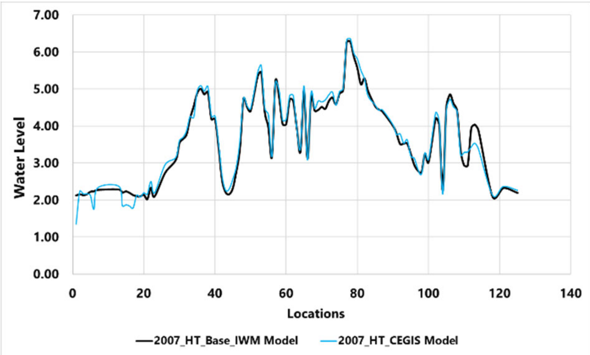
Figure 7-18: Comparison points between the CEIP-1 model and the CEIP-2 model.



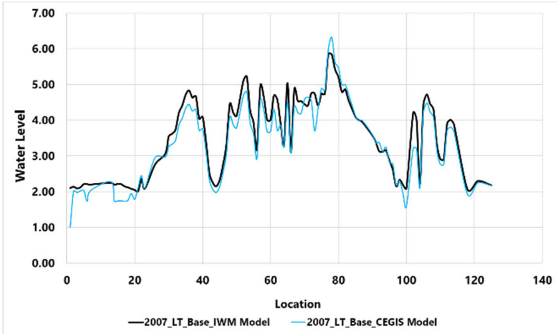
(i) 1991 Cyclone (High Tide)



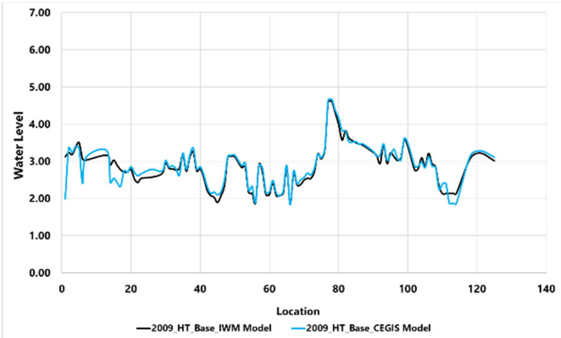
(ii) 1991 Cyclone (Low Tide)



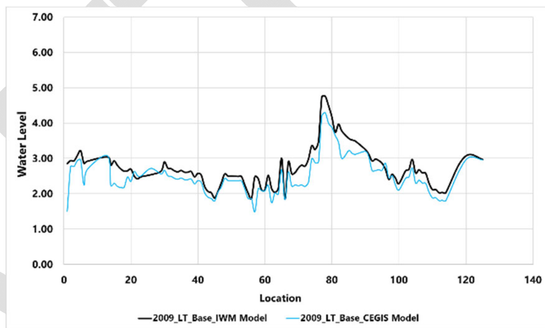
(iii) SIDR Cyclone (High Tide)



(iv) SIDR Cyclone (Low Tide)



(v) AILA Cyclone (High Tide)



(vi) AILA Cyclone (Low Tide)

Figure 7-19: Comparison of water level at various points in the model. The CEIP-1 model is shown with the black line and the CEIP-2 model is shown with the blue line.

Table 7-4: Statistical performance of the CEIP-2 model, compared to the CEIP-1 model.

Cyclone	Parameters	Value (HT)	Status	Value (LT)	Status
1991	NSE	0.80	Very Good	0.57	Satisfactory
	PBIAS	3.50	Very Good	11.26	Good
	RSR	0.35	Very Good	0.65	Satisfactory
	R^2	0.90	Very Good	0.75	Very Good
SIDR (2007)	NSE	0.97	Very Good	0.91	Very Good
	PBIAS	-0.91	Very Good	5.49	Very Good
	RSR	0.17	Very Good	0.31	Very Good
	R^2	0.98	Very Good	0.94	Very Good
AILA (2009)	NSE	0.88	Very Good	0.63	Satisfactory
	PBIAS	-0.42	Very Good	9.29	Very Good
	RSR	0.35	Very Good	0.61	Satisfactory
	R^2	0.89	Very Good	0.84	Very Good

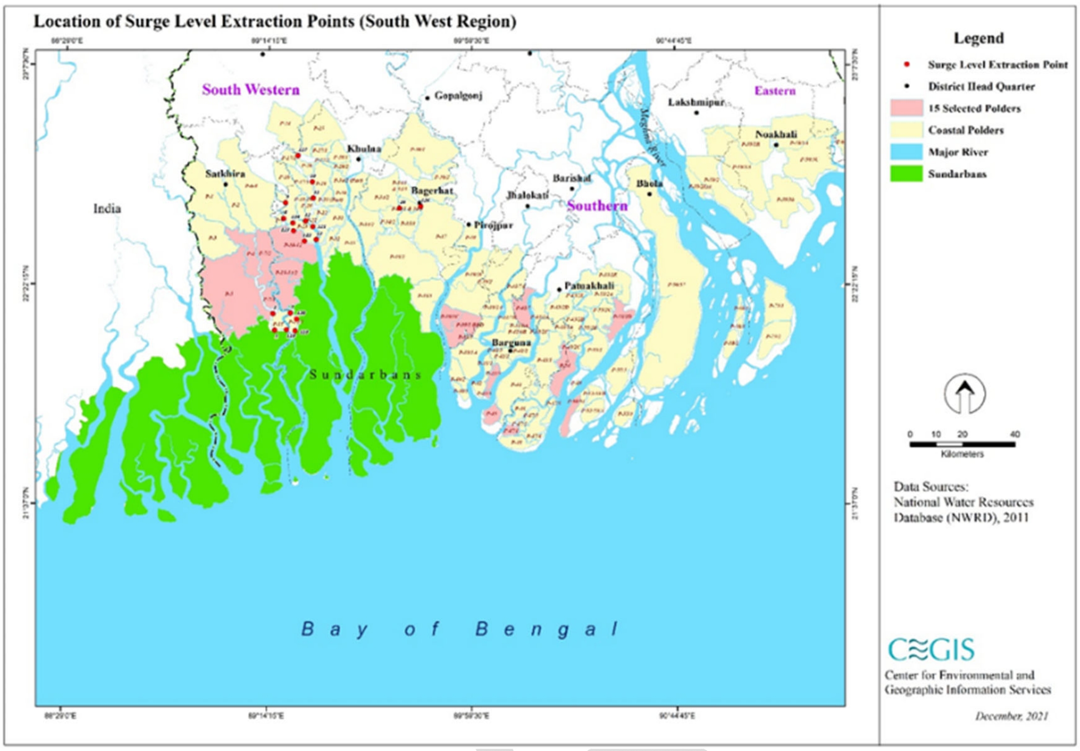


Figure 7-20: Comparison points for the wind speeds.

Table 7-5: Results of the comparison between the CEIP-1 and CEIP-2 wind results.

Point	SIDR (CEIP-1)	SIDR (CEIP-2)	AILA (CEIP-1)	AILA (CEIP-2)
1	40.56	40.2	23.94	24.22
2	38.79	37.1	24.29	24.12
3	39.38	38.47	23.78	23.55
8	31.52	31.22	22.86	22.98
9	30.54	31.04	22.74	22.65
10	29.45	29.12	21.52	21.45
11	30.42	30.33	21.68	21.56
12	31.94	32.23	22.37	22.65
13	33.52	33.65	22.00	22.34
24	33.65	33.76	19.45	19.22
118	42.80	42.99	24.13	24.39
119	41.57	41.94	22.95	22.75

Point	SIDR (CEIP-1)	SIDR (CEIP-2)	AILA (CEIP-1)	AILA (CEIP-2)
120	40.37	40.67	22.82	22.65
121	32.46	32.31	21.91	21.55
122	33.52	33.08	22	21.89
123	32.97	32.52	22.44	22.48
124	31.94	31.75	22.37	22.31
125	31.94	31.50	22.37	22.25
126	34.27	33.79	18.79	19.10

7.1.4 WAVE Model

The performance of the wave model has been evaluated in two ways, (i) visual comparison of observed and simulated significant wave height and (ii) statistical performance evaluation of results. The ERA5 atmospheric reanalysis, which covers the period from January 1950 to the present, is the fifth generation of the ECMWF. The Copernicus Climate Change Service (C3S) at ECMWF creates ERA5. A significant number of atmospheric, land, and oceanic climate variables are provided hourly estimates by ERA5. ERA5 replaces the ERA-Interim reanalysis. Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. Reanalysis does not have the constraint of issuing timely forecasts, so there is more time to collect observations, and when going further back in time, to allow for the ingestion of improved versions of the original observations, which all benefit the quality of the reanalysis product.

ERA5 provides hourly estimates for a large number of atmospheric, ocean-wave and land-surface quantities. An uncertainty estimate is sampled by an underlying 10-member ensemble at three-hourly intervals. ERA5 is updated daily with a latency of about 5 days. In case of serious flaws are detected in this early release (called ERA5T), this data could be different from the final release 2 to 3 months later. In case that this occurs, users are notified.

The data set presented here is a regridded subset of the full ERA5 data set on native resolution. Data has been regridded to a regular lat-lon grid of 0.25 degrees for the reanalysis and 0.5 degrees for the uncertainty estimate (0.5 and 1 degree respectively for ocean waves). There are four main sub sets: hourly and monthly products, both on pressure levels (upper air fields) and single levels (atmospheric, ocean-wave and land surface quantities).

The WAVE model was calibrated against two locations where the data from ERA5 is available. One location is located at Sibsa River close to Hiorn Point (defined as Location-1) and another is located at Bishkhali River close to Charduani (defined as Location-2). Calibration was done at at Bishkhali River close to Charduani against the observed significant wave height for SIDR cyclone and validation was done at Sibsa River close to Hiorn Point for Amphan Cyclone. *Figure 7-21* illustrates the location of Calibration and Validation location graphically. *Figure 7-22* and *Figure 7-23* shows the calibration and validation location of the Wave Model. Statistical performance of the model has been analysed utilising the following parameters: Nash-Sutcliffe Efficiency (NSE), percent Bias (PBIAS), ratio of RMSE and observed data standard deviation (RSR), Pearson's correlation coefficient (r) and coefficient of determination (R^2).

The model captures the peak wave heights well. The result of statistical analysis also shows that the model shows satisfactory performance for all the parameters (see Table 7-6).

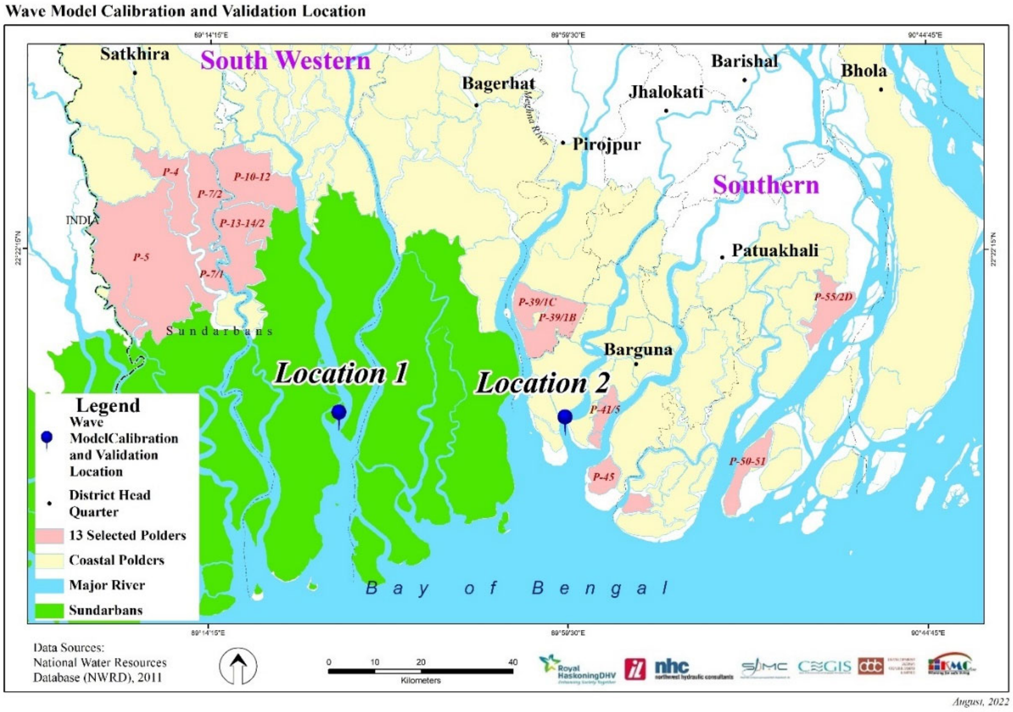


Figure 7-21: Calibration and Validation Location of Wave Model

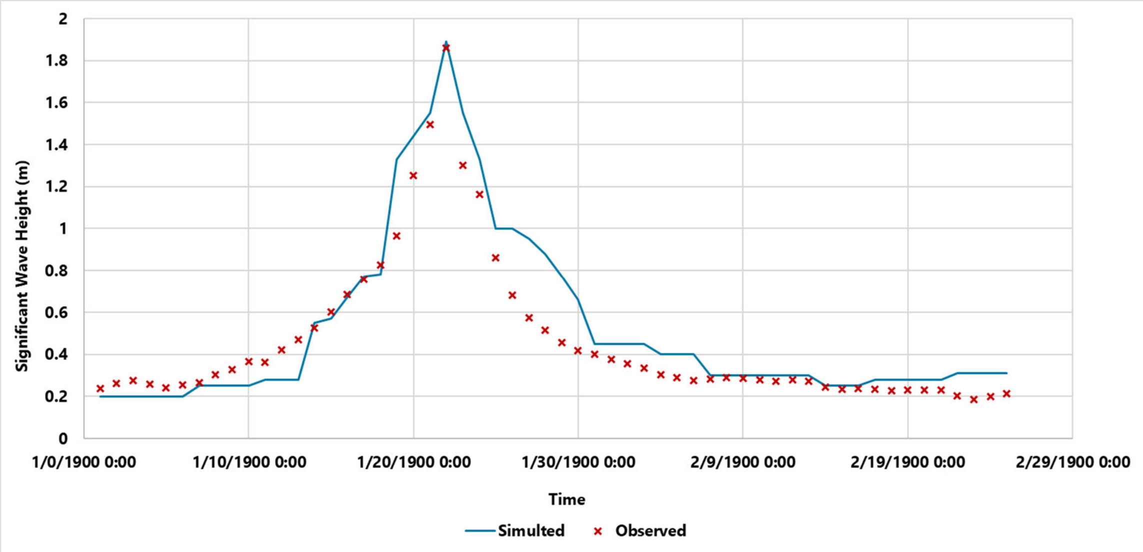


Figure 7-22: Calibration of Significant Wave Height at Location-2 for SIDR

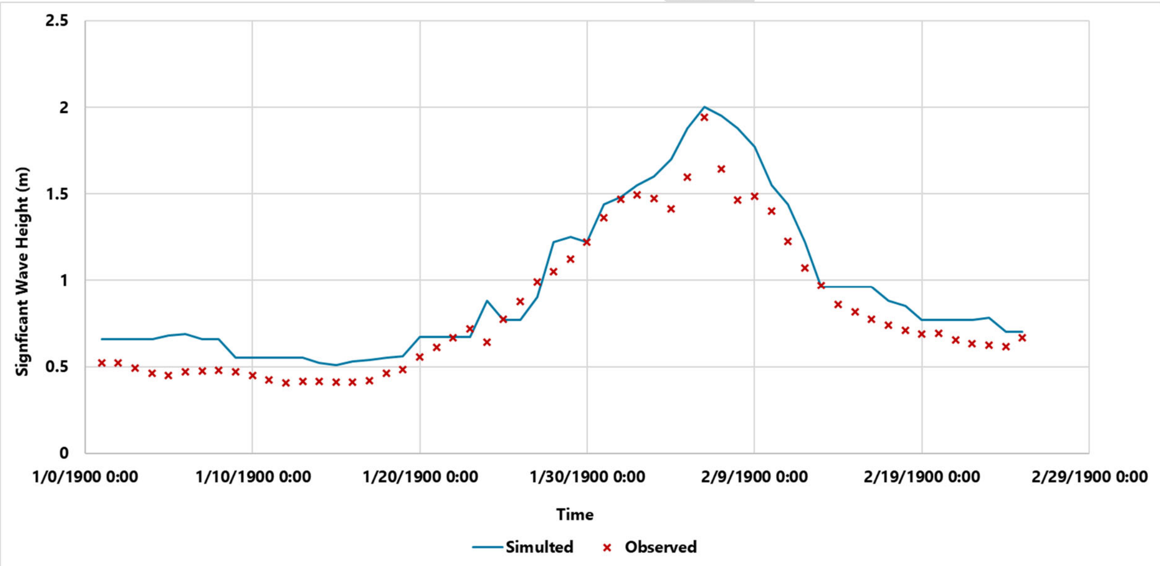


Figure 7-23: Validation of Significant Wave Height at Location-1 for Aila

Table 7-6: Statistical performance of the Wave Model

Station Name	Parameter	Value	Status
Location-1	NSE	0.87	Very Good
	PBIAS	12.98	Good
	RSR	0.36	Very Good
	R^2	0.95	Very Good
Location-2	NSE	0.89	Very Good

Station Name	Parameter	Value	Status
	PBIAS	11.22	Good
	RSR	0.34	Very Good
	R^2	0.92	Very Good

Hydrodynamic, Storm Surge and Wave Model Simulations

Table 7-7 summarizes the simulation runs of the Storm Surge and Wave Model.

Table 7-7: Hydrodynamic, Storm Surge and Wave Model model simulations.

Type of Model	Upstream boundary	Downstream Boundary		Cyclone Winds	Cyclone Track	No. of Runs	Remarks
		Sea Level	Astronomical Tides				
Hydrodynamic	Time Series Unsteady Discharge Hydrograph	N/A	Histroic tidal levels	N/A	N/A	1	Model Calibration and Validation
Cyclone Induced Storm Surge Coupled with Wave	Time Series Unsteady Discharge Hydrograph	Present day sea level	Histroic tidal levels during cyclone	Historic winds during cyclones	Historic Track	33	
Cyclone Induced Storm Surge Coupled with Wave	Time Series Unsteady Discharge Hydrograph	Present day sea level plus 0.65 m due to climate change	Histroic tidal levels during cyclone	Historic winds plus 10% to account for climate change	Historic Track	33	
					Total	**67**	

Freeboard Calculation

Wave run-up will cause overtopping of the embankment. A small amount of overtopping will not cause damage to the embankments; however, excessive overtopping may cause flooding and erosion of the embankment slopes. Overtopping rates from wave run-up will vary spatially and temporally, depending on both the wave and embankment characteristics. The embankments of CEIP-2 will include a freeboard which will limit the average overtopping rate to 5 L/m/s for the design event. Wind effects are neglected in the wave run up calculations as per Eurotop[48] recommendations.

[48] Eurotop, 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application, Volume 2. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.

The methodology for determining overtopping is based on the analytical methodology outlined in Eurotop[48]. The 2018 Eurotop manual updates the overtopping equations presented in the 2007 manual[49]. The required freeboard, R_c, has been determined by the following equation:

$$\frac{q}{\sqrt{gH_{m0}^3}} = \frac{0.026}{\sqrt{tan\alpha}} \gamma_b \, \xi_{m-1,0} \, exp\left[-\left(2.5 \, \frac{R_c}{H_{m0} \, \gamma_b \, \xi_{m-1,0} \, \gamma_f \, \gamma_\beta \, \gamma_v}\right)^{1.3}\right]$$

with a maximum of,

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.1035 \, exp\left[-\left(1.35 \, \frac{R_c}{H_{m0} \, \gamma_f \, \gamma_\beta \, \gamma_*}\right)^{1.3}\right]$$

where,

Variable		Value	Units	Note
R_c	Embankmenk crest freeboard	variable	[m]	Calculated
q	average wave overtopping discharge	5	[l/m/s]	BWDB design guidelines
g	acceleration due to gravity	9.81	[m/s²]	Constant
H_{m0}	Estimated significant wave height from spectral analysis at the toe of the dike	variable	[m]	Output from model
γ_b	Correction factor for a berm	1	[-]	Embankment outer slopes are simple slopes - assume no berm
γ_f	Correction factor for the permeability and roughness of or on the slope	0.8/1.0	[-]	Both a rough (armoured) and smooth (grass slopes) embankment slope have been considered in the calculations. Friction factors of $\gamma_f = 0.8$ and $\gamma_f = 1.0$, respectively, have been used.
γ_v	Correction factor far a vertical wall on the slope	1	[-]	There is no floodwall on the embankment
γ_*	Factor for storm wall or promenade	1	[-]	No prominent prominade or storm wall
α	Angle between overall structure slope and horizontal	variable	[°]	1V:5H – Riverside Embankment 1V:7H – Sea Embankment
γ_β	Correction factor for oblique wave attack		[-]	Wave attack has conservatively been

[49] Eurotop, 2007. Wave Overtopping of Sea Defenses and Related Structures: Assessment Manual. Die Küste, 1-178

	Variable	Value	Units	Note
				assumed to be normal to the embankment, $\beta = 0$
	For wave overtopping			$\gamma_\beta = 1 - 0.0033\lvert\beta\rvert, \beta \leq 80$ $\gamma_\beta = 0.736,\ \beta > 80$
	For wave run up			$\gamma_\beta = 1 - 0.0022\lvert\beta\rvert,\ \beta \leq 80$ $\gamma_\beta = 0.824,\ \beta > 80$
$\xi_{m-1,0}$	Breaker parameter based on so $\xi_{m-1,0} = \frac{tan\alpha}{\sqrt{H_{mo}/L_{m-1,0}}}$ where $L_{m-1,0}$ = deep water wave length, $L_{m-1,0} = \frac{gT_{m-1,0}^2}{2\pi}$ where $T^2_{m-1,0}$ is the average wave period		[-]	

These equations are recommended for design and include a safety factor in the results (one standard deviation). However, the BWDB embankment design manual recommends a minimum freeboard of 0.9 m. If the calculated freeboard based on the overtopping calculations is lower than 0.9 m, then the minimum value of 0.9 m is recommended. The required freeboard has been calculated at every point, over the duration of each cyclone.

Storm Surge and Wave Model Results

7.1.5 Analysis of Storm Surge Level

In order to assess the effectiveness of the current coastal embankment, frequency analysis has been used to determine the storm surge level for various return periods along the embankment. Under the present study, time series storm surge levels in the peripheral rivers of coastal polders at different locations have been generated from simulation results. These surge level values are analyzed to determine the different return period for all the locations. Statistical analysis of surge level is carried out using Extreme Value Analysis (EVA). The return period analysis was conducted for both base period and climate change scenario (65cm SLR and 10% increase in cyclone intensity). Table 7-8 shows the storm surge elevation for different return period for both base and climate change scenarios.

Table 7-8: Storm Surge Depth (in meters) for Different Return Period for Both Base and Climate Change Scenarios

Location (CEIP-2)	Sidr	Aila	Amphan	Return Period (Years) Without Climate Change				Return Period (Years) With Climate Change				Polder No
				10	25	50	100	10	25	50	100	
1	2.12	3.45	3.80	2.66	3.13	3.47	3.81	3.23	3.58	3.80	4.00	5
2	2.17	3.15	3.55	2.43	2.89	3.23	3.57	2.93	3.38	3.71	4.03	5
3	2.16	2.83	3.52	2.46	3.00	3.41	3.85	2.92	3.40	3.76	4.12	4,5
4	2.14	3.13	3.62	2.57	3.04	3.39	3.73	3.07	3.51	3.83	4.14	4,5
5	2.12	3.18	3.78	2.68	3.20	3.59	3.99	3.32	3.88	4.30	4.71	7/1, 5
6	2.08	3.15	3.82	2.79	3.23	3.56	3.89	3.25	3.69	4.01	4.31	7/1, 5
7	2.00	3.22	3.95	2.85	3.35	3.72	4.10	3.31	3.75	4.06	4.37	5
8	2.36	3.22	3.67	3.06	3.63	4.05	4.46	3.30	3.88	4.25	4.77	5
9	2.25	3.07	3.55	2.75	3.16	3.45	3.74	3.17	3.55	3.82	4.20	7/2, 13-14/2
11	2.20	2.77	3.35	2.59	2.85	3.02	3.17	3.00	3.28	3.46	3.61	7/2, 10-12
12	2.18	2.97	3.15	2.86	3.41	3.82	4.22	3.26	3.78	4.17	4.56	10-12
13	2.29	3.10	3.30	2.96	3.52	3.94	4.36	3.35	3.90	4.31	4.71	10-12
14	3.80	2.10	2.83	3.06	3.43	3.67	3.89	3.46	3.83	4.06	4.67	55/2D
15	3.70	1.85	2.45	2.45	2.76	2.95	3.13	3.01	3.38	3.61	3.83	55/2D
17	5.48	2.65	3.34	3.55	4.47	5.23	6.08	4.21	5.62	6.67	7.77	50-51
18	4.05	2.16	3.03	2.73	3.74	4.21	4.70	3.85	4.56	5.13	5.72	50-51
19	4.02	2.13	3.15	2.90	3.74	4.21	4.70	3.85	4.56	5.13	5.72	54
20	3.93	2.18	3.05	2.83	3.29	3.62	4.01	3.10	3.86	4.19	4.49	54
21	3.82	2.82	3.17	3.00	3.62	4.18	4.72	3.58	4.35	4.88	5.12	47/1
22	4.42	3.08	3.47	3.35	3.95	4.39	4.83	4.01	4.70	5.21	5.72	47/1
23	4.66	3.00	3.55	3.39	4.00	4.45	4.90	4.06	4.96	5.27	5.78	45
24	4.12	2.77	3.35	3.15	3.70	4.11	4.51	3.77	4.55	4.95	5.22	45
25	4.11	2.74	3.33	3.15	3.70	4.11	4.51	3.77	4.55	4.95	5.22	41/5
26	3.45	2.13	2.65	2.77	3.24	3.58	3.92	3.39	3.90	4.28	4.66	41/5
27	4.51	2.75	3.22	3.28	3.90	4.37	4.82	3.89	4.54	5.02	5.49	39/1B
28	4.28	2.65	3.01	3.08	3.64	4.06	4.55	3.63	4.22	4.66	5.10	39/1B, 39/1C
29	3.74	2.55	2.63	2.84	3.35	3.72	4.30	3.45	4.01	4.43	4.85	39/1C
30	2.40	1.89	1.80	2.20	2.49	2.69	2.89	2.68	2.95	3.14	3.32	41/7
31	2.85	2.17	2.00	2.44	2.82	3.10	3.38	2.96	3.25	3.44	3.62	41/7
35	3.52	2.60	3.05	2.92	3.42	3.79	4.16	3.45	3.96	4.35	4.73	39/1B, 39/1C
36	3.65	2.13	2.56	2.86	3.35	3.71	4.07	3.41	3.89	4.25	4.61	41/5
41	2.15	3.30	3.73	2.54	2.85	3.05	3.23	2.74	3.06	3.26	3.45	5

7.1.6 Analysis of Significant Wave Height

Significant wave height extracted from wave model was analysed to obtain the 10-, 25-, 50- and 100-years return period significant wave height. Statistical analysis of significant wave height is carried out using Extreme Value Analysis (EVA). Table 7-9 contains the significant wave height for different return period under climate change scenario.

Table 7-9: Significant Wave Height (in meters) for Different Return Period for Climate Change Scnearios

Location	Aila	Amphan	Sidr	Return Period (CC)			
				10	25	50	100
1	1.83	2.07	0.68	1.1	1.2	1.8	2.2
2	1.4	1.67	0.64	0.88	0.94	1.48	1.81
3	1.48	1.61	0.63	0.86	0.95	1.52	1.89
4	1.55	1.66	0.6	0.88	0.95	1.50	1.85
5	1.57	1.7	0.6	0.95	1.07	1.67	2.06
6	1.61	1.82	0.68	1.03	1.17	1.77	2.17
7	1.63	1.91	0.7	1.06	1.18	1.76	2.14
8	1.63	1.85	0.7	1.07	1.21	1.81	2.22
9	1.29	1.7	0.69	0.97	1.09	1.68	2.06
11	1.15	1.6	0.69	0.90	0.97	1.51	1.85
12	1.1	0.95	0.43	0.93	1.07	1.68	2.09
13	1.35	0.95	0.68	1.03	1.18	1.80	2.23
14	1.03	0.94	2.4	1.98	2.61	3.15	3.75
15	0.83	0.89	2.2	1.80	2.37	2.86	3.42
17	2.3	1.01	4.45	3.38	4.34	5.04	5.75
18	2.05	0.94	4.2	3.13	4.03	4.70	5.37
19	2.05	0.94	4.2	3.13	4.03	4.70	5.37
20	0.79	0.88	2.38	1.82	2.45	3.02	3.68
21	1.21	1.34	1.6	1.77	1.93	2.05	2.16
22	1.6	1.47	2.05	3.16	3.97	4.58	5.18
23	2.46	1.88	3.95	3.1	3.9	4.5	5.1
24	2.21	1.51	3.7	2.85	3.60	4.16	4.72
25	2.21	1.51	3.7	2.85	3.60	4.16	4.72
26	2.01	0.98	3.5	2.63	3.35	3.88	4.40
27	1.5	1.43	2.6	2.48	3.12	3.60	4.07
28	1.05	1.09	2.15	1.80	2.47	3.09	3.81
29	1.65	1.08	1.95	1.81	2.12	2.32	2.50
30	1.61	0.72	3.1	1.93	2.55	3.05	3.59
31	1.81	0.87	3.3	2.43	3.10	3.60	4.10
35	1.05	0.89	2.15	1.79	2.48	3.12	3.89
36	0.87	0.97	2	1.87	2.10	2.27	2.44
41	1.2	1.75	0.6	0.93	1.01	1.56	1.91

Summary of Storm Surge Assessment Results

Table 7-10 shows the results of the storm surge assessment.

Table 7-10: Overview of recommended crest elevations based on the storm surge analysis; results include climate change

Polder	Point	Recommended slope[1] (1V:XH)	25-year crest level – rough[2] (mPWD)	25-year crest level – smooth[2] (mPWD)
4	3	2	4.0	4.4
	4	3	4.0	4.5
	10	Not extracted from cyclone model[3]		
	37	Not extracted from cyclone model[3]		
5	1	3	4.9	5.4
	2	3	4.2	4.6
	3	2	4.0	4.4
	4	3	4.0	4.5
	5	3	4.1	4.5
	7	3	4.4	4.8
	41	3	4.6	5.1
7/1	5	3	4.1	4.5
	6	3	4.3	4.8
7/2	4	3	4.0	4.5
	9	3	4.1	4.7
	10	Not extracted from cyclone model[3]		
	11	2	3.3	3.7
10-12	9	3	4.1	4.7
	11	2	3.3	3.7
	12	3	4.1	4.3
	13	3	4.4	4.7
	42	Not extracted from cyclone model[3]		
13-14/2	8	3	4.5	4.9
	9	3	4.1	4.7
39/1B	27	5	5.5	6.0
	28	5	5.1	5.7
	35	2	4.6	5.0
39/1C	28	5	5.1	5.7
	29	5	4.9	5.3
	35	2	4.6	5.0
	38	2	4.1	4.5
41/5	25	7	5.8	6.3
	26	5	5.1	5.6
	36	2	4.5	5.0

Polder	Point	Recommended slope[1] (1V:XH)	25-year crest level – rough[2] (mPWD)	25-year crest level – smooth[2] (mPWD)
47/1	21	5	4.9	5.1
	22	7	6.2	6.7
45	23	7	6.2	6.7
	24	7	5.8	6.3
50-51	17	7	6.4	6.9
	18	7	5.6	6.3
55/2D	14	3	5.2	5.8
	15	3	4.8	5.2
	32	2	3.8	4.2
	40	2	3.6	4.0

Notes:

[1]Riverside slope

[2] Includes the required freeboard, calculated from wave run up

[3] Crest elevations will be governed by monsoon water levels

8 Monsoon Flooding with Regional Model

Regional Model Development

Model Overview: CEGIS has updated the existing Regional Model for the South-west and South-central hydrological regions. SOBEK was used to develop the 1-dimensional regional model. The model simulated:

- river discharges
- tidal forcing
- future impacts of climate change by raising the sea level and increasing the river discharges

The model did not simulate:

- Cyclone forcing
- Sediment transport
- Waves (including wave overtopping)
- Salinity
- Storm surges (both pressure set up and wind set up)

8.1.1 Software Package

For simulating flow within the South-west and South-central region, the 'SOBEK' modelling suite developed by Deltares of the Netherlands is being utilized in this study. SOBEK is an integrated software package for river, urban or rural water management. SOBEK is an implicit, finite difference model for computation of unsteady flows, where advanced computational modules are included for description of flow. Specifically, coupling of three modules of SOBEK model can be used to assess both hydrologic and hydraulic phenomena of the study area, including rainfall-runoff, flooding and drainage condition. The three modules are: SOBEK-Rural 1D Flow, SOBEK-RR and SOBEK Overland Flow (2D). SOBEK-RR module estimates surface runoff for design storm event. SOBEK-Rural 1D, simulates the dynamics of flow in channels, drains or rivers. SOBEK Overland Flow (2D) module generates flood depth and extent maps. All the modules are necessary for flood and drainage modelling.

The 1D and 2D modules are implicitly coupled and solved simultaneously based on momentum balance and mass conservancy between separate computational layers while both layers use finite difference formula based on a staggered grid approach. The RR, 1D and 2D modules can be run either simultaneously or separately. For this particular study, the 1D module of SOBEK is being used to simulate flow, water levels and salinity concentrations within the different major river systems within the SW and SC regions.

8.1.2 Approach of the Model

A multi-model approach was taken to produce the crest level for the concerned polders of the study. The 13 polders that are considered in the study are spread across both the Southwest and Southcentral Hydrological Regions of Bangladesh. Table 8-1 presents the region-wise divided list of polders, which is also illustrated in *Figure 8-1*. Given the complexity of incorporating each and every peripheral river bordering the polders, separate models for the SW and SC regions are required. But this again gives rise to the necessity of assigning boundaries at appropriate locations along the mid portion of both the regions. Four (4) locations adjacent to tidal meeting points were identified for these downstream water level boundary locations. For assigning time-series boundary data for the locations, a combined regional model was developed for the SW-SC regions and was calibrated and validated at key locations.

Table 8-1: List of Polders and their respective Regional Models

Sl	Name	Upazila	Area (sqkm)	Hydrological Region
1	Polder-10-12	Koyra, Paikgacha	0.0147	SW
2	Polder-13-14/2	Koyra	0.013604	SW
3	Polder-4	Assasuni	0.009045	SW
4	Polder-41/5	Barguna Sadar	0.003273	SC
5	Polder-41/7	Mirganj	0.006459	SC
6	Polder-45	Amtali	0.003473	SC
7	Polder-47/1	Kalapara	0.001818	SC
8	Polder-5	Kaloganj, Shayamnagar	0.047904	SW
9	Polder-50-51	Galachipa	0.003897	SC
10	Polder-54	Kalapara, Amtali, Galachipa	0.008755	SC
11	Polder-55/2D	Dashmania	0.006922	SC
12	Polder-7/1	Assasuni, Shaymnagar	0.003171	SW
13	Polder-7/2	Assasuni	0.009608	SW
14	Polder-39/1B	Patharghata, Mathbaria, Bamna	0.009155	SC
15	Polder-39/1C	Mathbaria	0.004525	SC

Since the separate models are to be simulated for at least 30 years duration, the combined model has been simulated for 31 years, from 1990-2020, to generate 30 years boundary data for the separate models and these models, fully schematized with polder adjacent rivers, were each simulated for three separate scenarios (Base, SSP5-8.5(2080)), 31 years each from 1990 to 2020 to generate water levels for the peripheral rivers, from which, yearly maximum water level values were extracted. These levels represent the Still Water Level (SWL), phased year-wise from 1990-2020 and used both directly for designing embankment, as well as for calculating crest height of embankment. Yearly maximum water depth values were also extracted and used for calculating appropriate freeboard for calculating crest levels.

8.1.3 Updating of the 1D Regional Model

A combined one dimensional (1-D) hydrodynamic model has been developed for the SW-SC regions and has been calibrated and validated for the rivers of the South-west and South-central regions of Bangladesh. As mentioned before, this model has been used to calculate boundary data for four (4) specific locations along the mid-portion of the regions (*Figure 8-1*). Upon calibration and validation, this model has been detached to produce separate models for South-west and South-central regions. This has been done to both increase model accuracy in generating design parameter values, and significantly reduce simulation times. Boundary at split channel points has been generated using combined model.

The regional models have been updated using both historic cross section data, specifically for the Raimangal system, as well as pertinent latest data from CEGIS database, the Long-term Monitoring (LTM) and most importantly the ongoing survey for CEIP-II. As mentioned, this update includes cross-section data and water level data of selected river systems. Since survey was not possible for the westernmost system i.e., the Raimangal System adjacent to the Sundarbans and Bangladesh-India border; and also given the fact that recent data is not available for this system, historic cross-section data from CEGIS's archives. Model upstream and downstream boundaries have been updated with latest discharge and water level data. The models have been calibrated and validated using latest water level data.

For fixing the crest level for polders, the separated regional models have been simulated both for base and with climate change (CC) considerations. Three separate scenarios were thus generated; a base scenario for representing current conditions, and a scenario for SSP5-8.5(2080) for representing a 50-year climate change impact. This means that both in upstream discharge boundaries and downstream water level boundaries, influence of futuristic climate chance implications has been factored in. For the upstream boundaries, changes in discharge due to climate change implications have been used. For downstream boundaries, the effect of sea level rise (SLR) due to climate change has been factored in. The SSP5-8.5 high emissions scenario (2080) is considered as CC impacted water levels, assuming a 50-year design life for polders.

8.1.4 Model Domain

The models encompass the extent of the Southwest (SW) and Southcentral (SC) hydrological regions. The models have been schematized, preliminarily simulated and has been calibrated & validated for key locations. The models include the following river systems presented in Table 8-2. *Figure 8-1* illustrates the model domains and *Figure 8-2* presents the schematic of major river systems within the models.

Table 8-2: Major River Systems Incorporated within the Model Domain

Major River System	Region
Gorai-Modhumati Hishna-Mathabanga Chandana-Barasia Rupsa-Sibsa-Passur Malancha-Arpangasia etc.	Southwest
Arial Khan Tentulia Bishkhali Barisal-Buriswar Baleswar Lower Meghna etc.	Southcentral

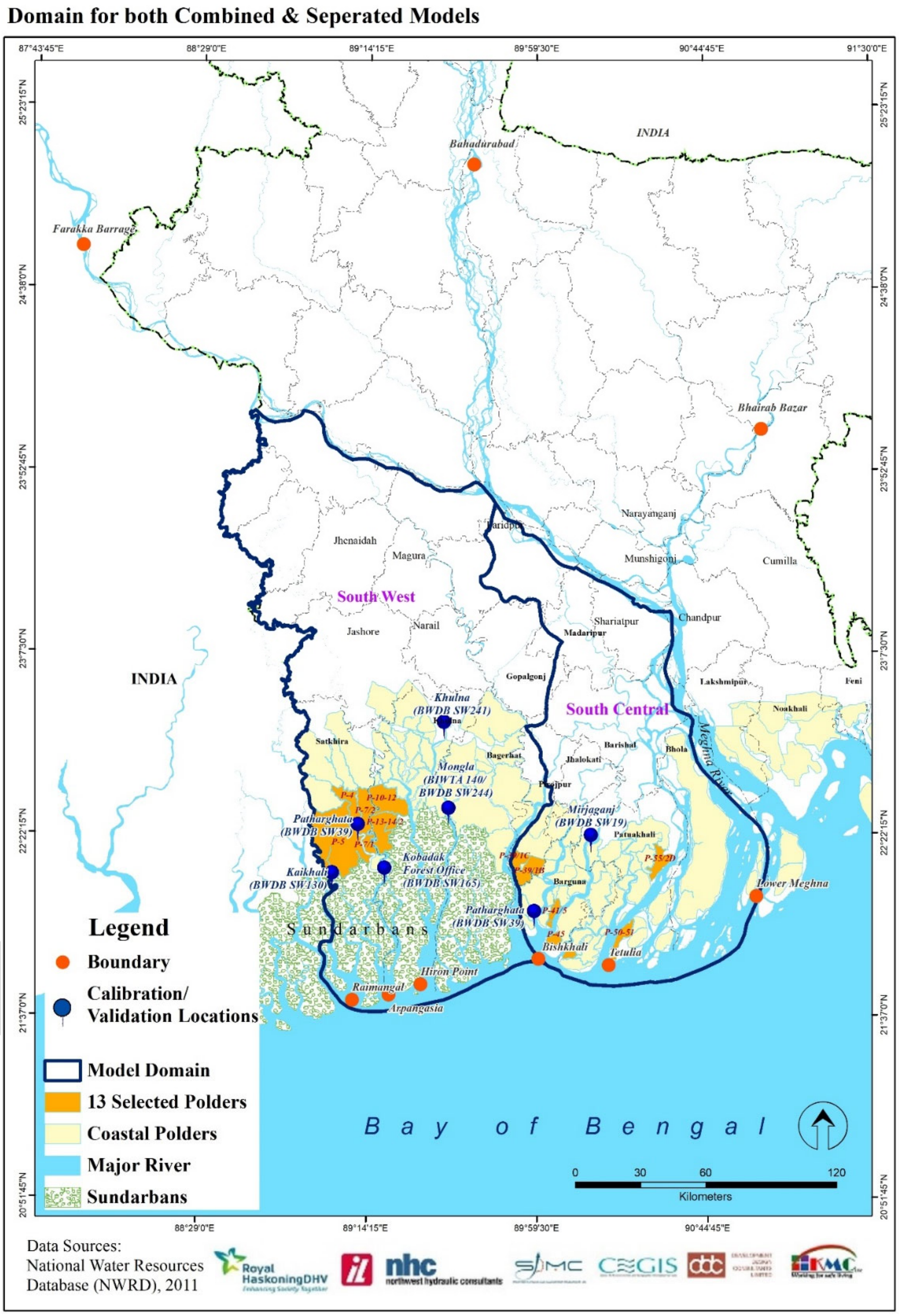


Figure 8-1: Domain for combined and separated models

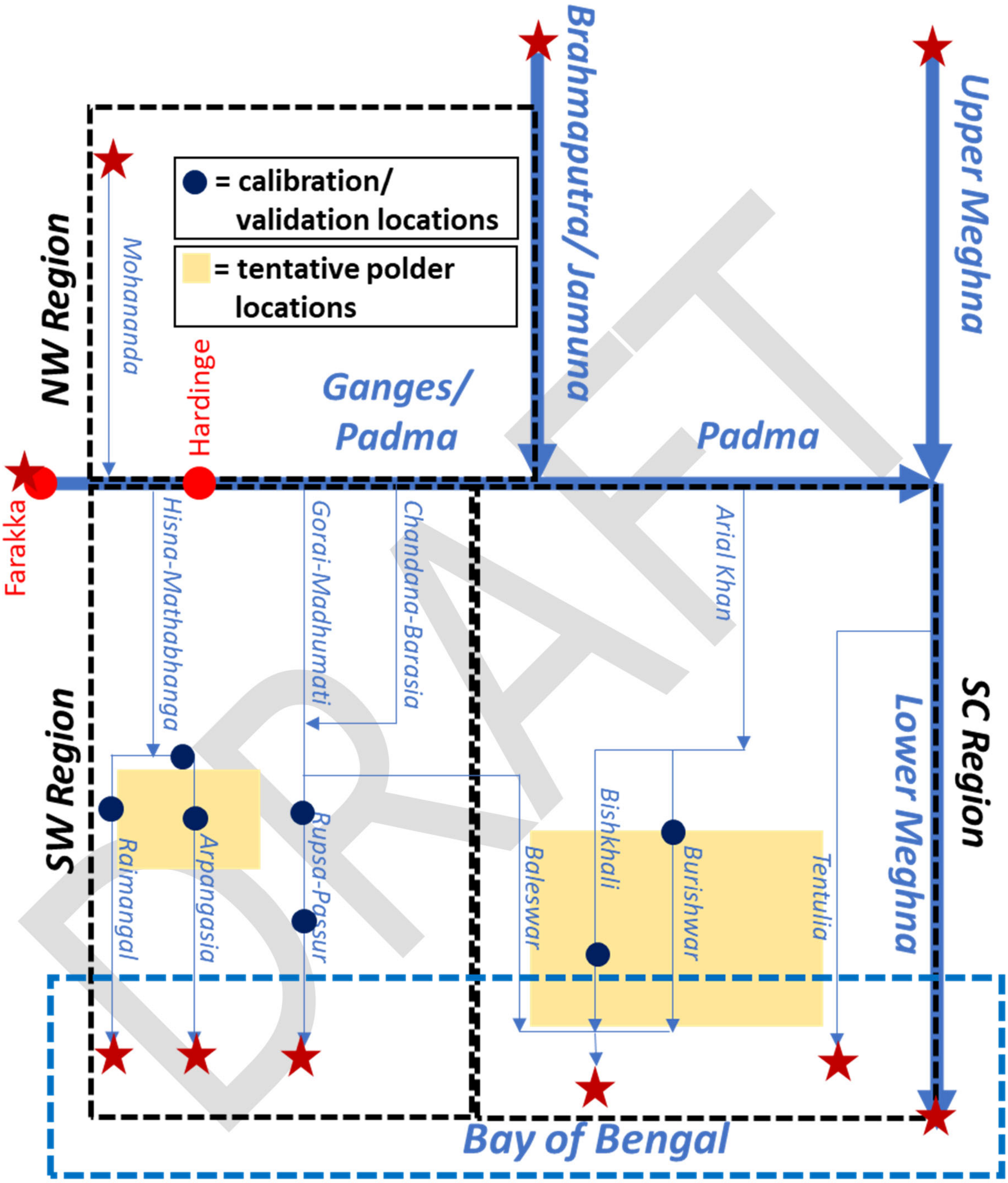


Figure 8-2: Major river systems within model domains

8.1.5 Model Input Data

Data requirements concerned with model development includes data for assigning boundary conditions, model calibration/ validation and model schematization. Hydrological data such as discharge and water levels will be required for assigning the northern and southern model boundaries and subsequently for model calibration and validation for selected time periods. Bathymetry data such as river cross-sections as well as a varying degree of GIS layer data will be required for model schematization purposes. Table 8-3 lists the data requirements for model development.

Table 8-3: Data Requirements for 1D Hydrodynamic Modeling

Data	Type	Purpose	Source
Discharge	Hydrology	Boundary assign, model calibration/ validation	BWDB, BIWTA, Model
Water Level	Hydrology	Boundary assign, model calibration/ validation	BWDB, BIWTA, Field Survey, Model
Cross-section	Bathymetry	Model schematization	BWDB, CEGIS database, Field Survey, LTM
River system, location of hydrological stations, Hydrological Regions, Cross-section locations	GIS	Model schematization	NWRD, Field Survey

8.1.6 Model Schematization

The schematized model domains are bounded to the north-northeast by the Ganges and the Padma, to the northeast-east by the lower Meghna, to the west by the Ichamati_Kalindi-Raimangal system and to the south by the Bay of Bengal. The in-built NETTER GIS interface has been utilized to digitize the river systems and cross-sections within the model schematization. For the separated models, the combined model has been severed through appropriate locations along the middle portion to create two models for SW and SC regions. These separate models have been updated with polder specific data such as incorporation of peripheral rivers and khals, associated cross-sections etc. These two models have been separately checked for stability and have been separately calibrated and validated. Figure 8-3 illustrates the schematized model within the SOBEK NETTER interface.

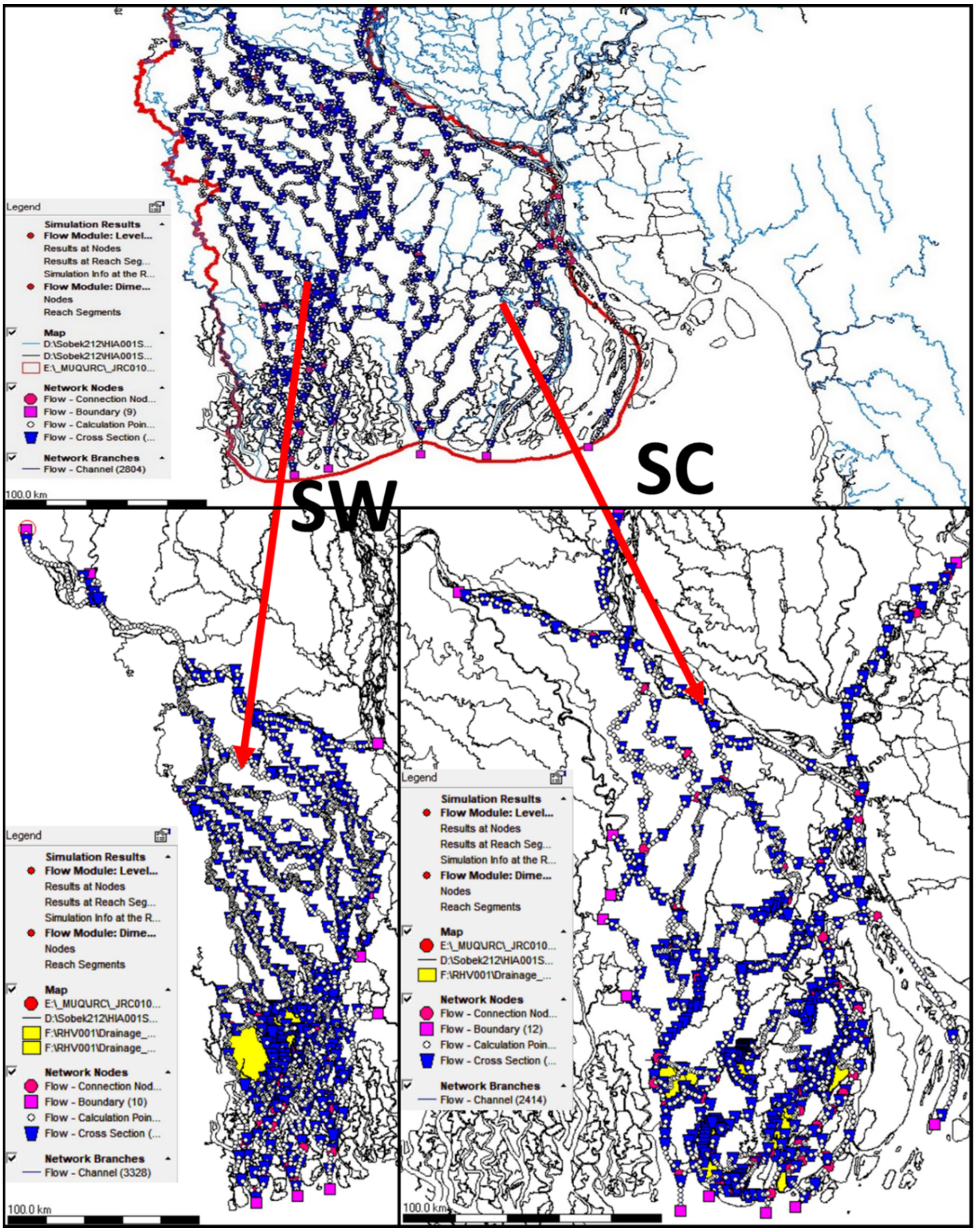


Figure 8-3: Model Schematization within SOBEK NETTER GIS Interface

8.1.7 Boundary Condition

At its present state, there are nine (9) boundary conditions defined within the combined model schematization. Of these, four (4) are upstream boundaries and five (5) are downstream boundaries. The upstream boundaries consist of daily discharge data for the Farakka point which is prepared from the available data, Chapai Nawabganj Station at Mohananda, Bahadurabad Station at Brahmaputra-Jamuna and Bhairab Bazar Station at Upper Meghna. Kazipur, Hardinge Bridge and Bahadurabad stations are at Mathabhanga, Ganges and Brahmaputra/ Jamuna Rivers respectively. Time periods for discharge data input is varied depending on the data availability but data from 1997-2019 i.e., for simulation period is kept common. Double staged rating curves have been generated to estimate daily discharge values using water level values for the same stations from the observed weekly discharge for the mentioned time periods. Downstream sea facing boundaries have been defined using global ocean model data collected/ generated from the Delft Dashboard interface. Initially, data for the period of 1990-2020 have been collected. The five boundaries include Arpangasia, Passur, Baleswar-Buriswar-Bishkhali, Tentulia and the lower Meghna. For Arpangasia and Passur, data adjacent to the location of the Hiron Point station have been collected. For the other three eastern locations namely the Baleswar-Buriswar-Bishkhali, Tentulia and the lower Meghna, BWDB observed data has been used. These data have then been corrected for phase, amplitude and datum with respect to relevant BWDB tidal water level data. Raimangal System has been added as an addition for the SW model. Interim model boundaries exist for the separated SW & SC models. Table 8-4 describes and illustrates the model boundary condition data.

Table 8-4: Specified Boundary Conditions

Boundary Locations			Date Type	Time Period
River	**Station**			
Farakka **Ganges (SC)** **Jamuna** **Mohananda** **Upper Meghna**	• BWDB Observed Data • Combined Model Simulated Data	Source: BWDB; Model Data	Discharge	1990-2020
Ganges (SW) **Raimangal** **Arpangasia** **Passur** **Baleswar-Buriswar-Bishkhali** **Tentulia** **Lower Meghna** **Severance points (SW & SC Models)**	• Global Model Data • BWDB Observed Data • Combined Model Simulated Data	Source: Observed data of BWDB; Model Data	Water Level	1990-2020

8.1.1 Model Simulation

For fixing the crest height for Polders due to monsoon flooding, the separated regional models will be simulated with climate change considerations. The upstream discharges will be increased accordingly. In case of sea level rise the existing tidal water level at downstream boundaries have been increased by 0.65m considering SSP5-8.5 (2080) climate change scenario.

The model simulated a 30-year period of historic monsoon floods with climate change. The water level adjacent to polder periphery will be extracted from the model. The extraction points are the same points that were used in the storm surge model (Figure 7-4). A frequency analysis will be done to ascertain the 25-year return period water level unique to each extraction point in order to fix the crest height.

Table 8-5: Simulation of the 1D Regional Model

Region		Upstream boundary	Downstream Boundaries[1]	No. of Runs
Southwestern Model		30 years of historic discharge data (1990 – 2020)	30 years of historic water levels including tidal forcing (1990 – 2020)	30
		30 years of historic discharge data (1990 – 2020) with climate change (increased upstream discharges)	30 years of historic water levels including tidal forcing (1990 – 2020) with climate change (sea level +0.65 m)	30
Southern Model		30 years of historic discharge data (1990 – 2020)	30 years of historic water levels including tidal forcing (1990 – 2020)	30
		30 years of historic discharge data (1990 – 2020) with climate change (increased upstream discharges)	30 years of historic water levels including tidal forcing (1990 – 2020) with climate change (sea level +0.65 m)	30
			Total	**120**

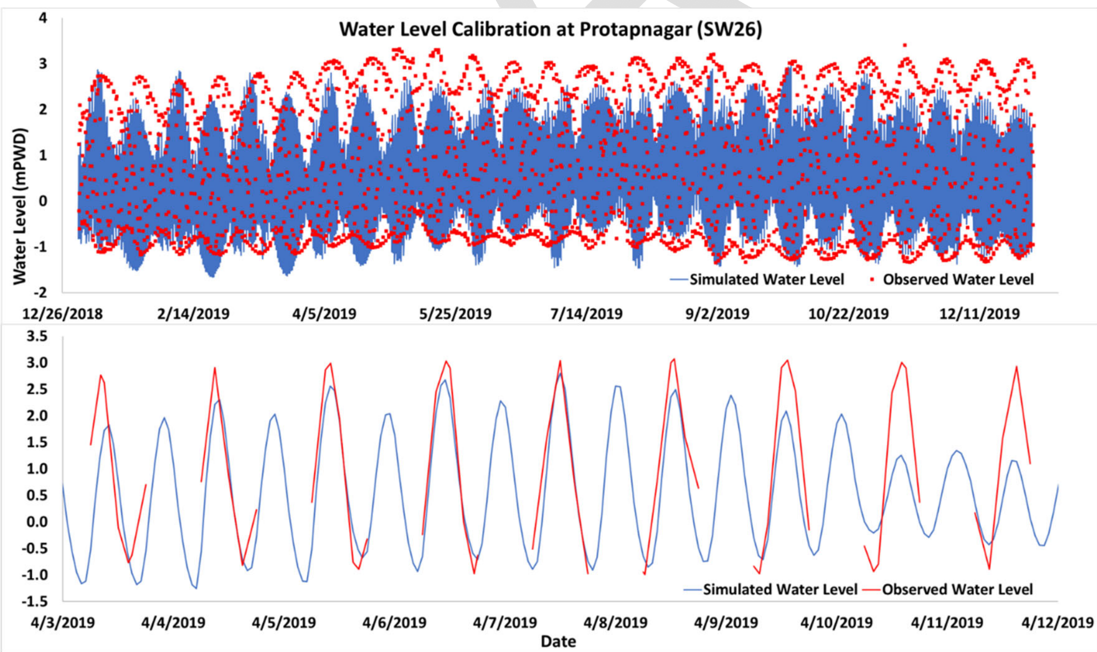
8.1.2 Model Calibration and Validation

Once the models were setup, they have been simulated for different time periods to assess model stability. Once stable, the model has been calibrated and validated against the observed data to determine its ability to reproduce the actual phenomena observed in the field. The resistance parameter is the major controlling calibration parameter for the hydrodynamic model. As such, Manning's 'n' was chosen as a resistance parameter for the flow model and dispersion coefficient has been used for salinity model. After calibration, the model was validated both at other locations and with another set of observed data different from model calibration. Table 8-6 presents the calibration and validation location and other details. *Figure 8-4* to *Figure 8-10* presents the model calibration plots. *Figure 8-11* to *Figure 8-18* contains the model validation plots:

Table 8-6: Calibration and Validation Locations

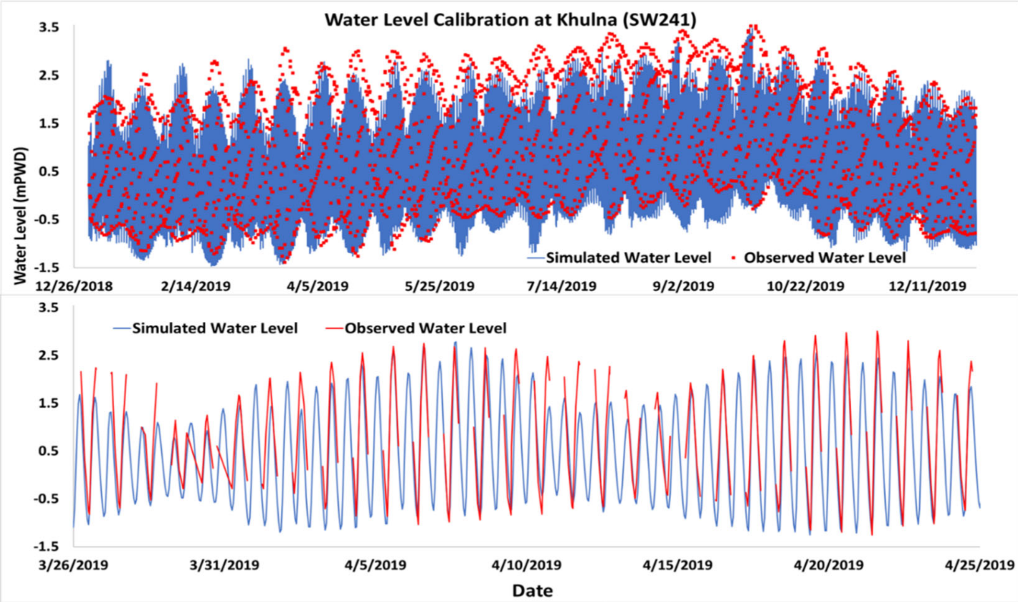
Parameter	Location/ Station	River/ System	Calib (Model & Year)	Valid (Model & Year)
Water Level	Protapnagar (SW26)	Betna-Kholpetua	Combined (2019);	Combined (2018); SW (2019)
	Khulna (SW241)	Rupsa-Passur	Combined (2019)	SW (2019)
	Mirjaganj (SW19)	Barisal-Buriswar	Combined (2019); SC (2019)	SC (2020)
	Mongla (BIWTA 140 & BWDB SW244)	Rupsa-Passur	SW (2012)	Combined (2018)
	Patharghata (SW39)	Bishkhali	SC (2019)	Combined (2018); SC (2020)
	Kobodak Forest Station (SW165)	Kobodak	SW (2015)	-
	Kaikhali (SW130)	Ichamati-Kalindi	SW (2019)	SW (2018)

Calibration of the Combined Model



Note – The break in observed data is due to the fact that no data is recorded during night time.

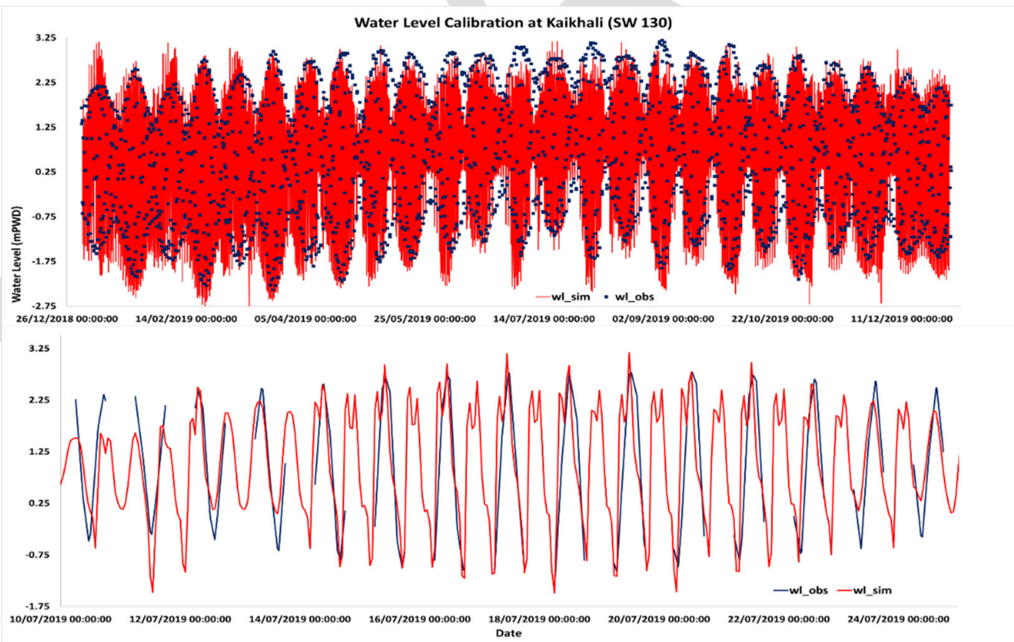
Figure 8-4: Water Level Calibration at Protapnagar (SW26)



Note – The break in observed data is due to the fact that no data is recorded during night time.

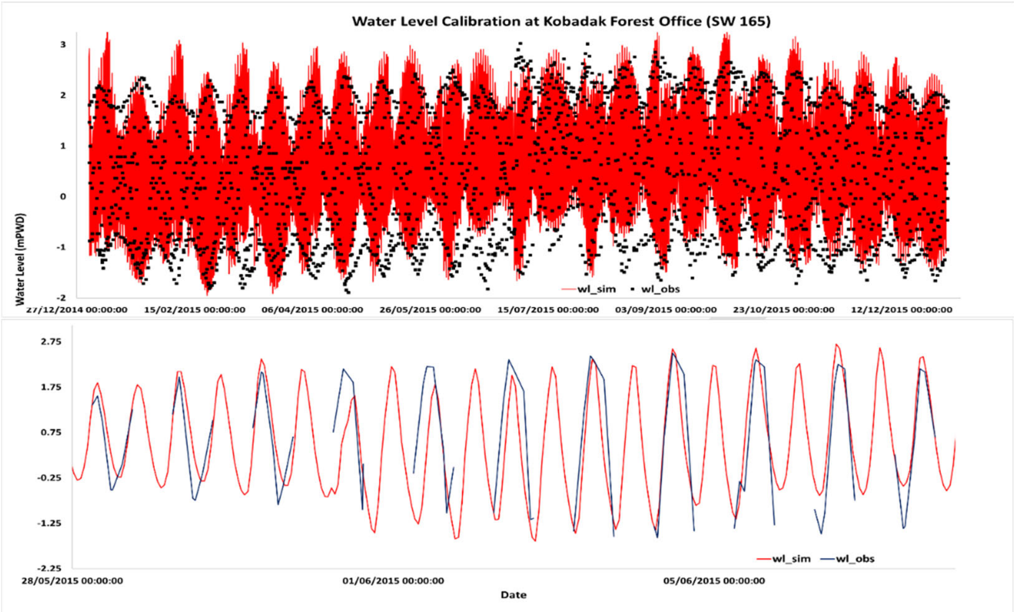
Figure 8-5: Water Level Calibration at Khulna (SW241)

Calibration of the South West Model



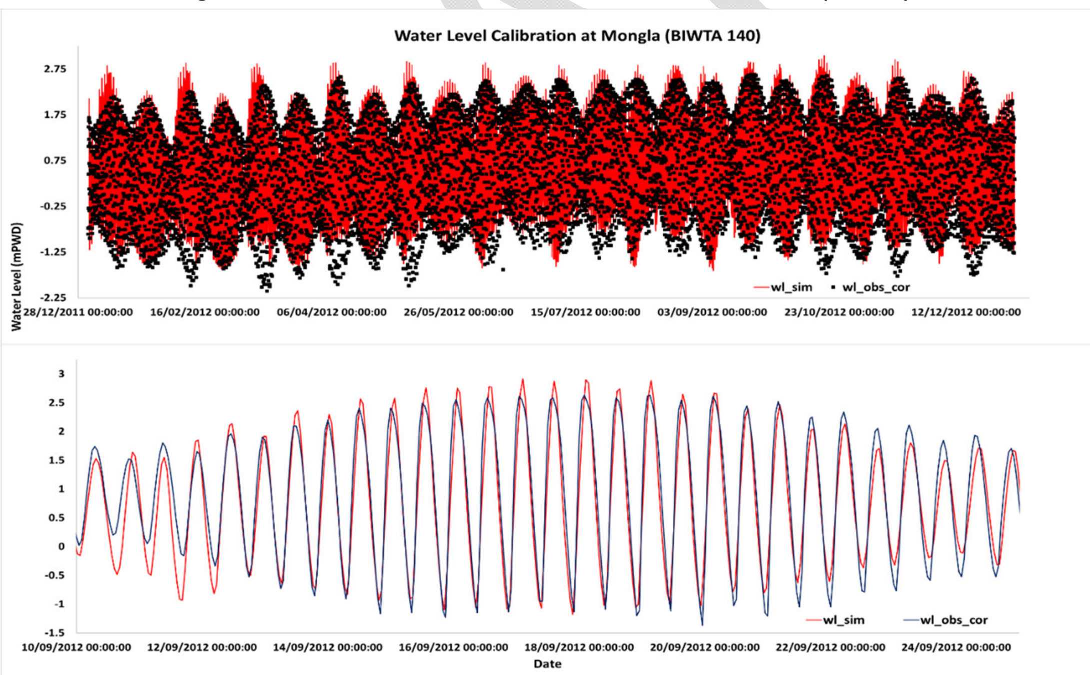
Note – The break in observed data is due to the fact that no data is recorded during night time.

Figure 8-6: Water Level Calibration at Kaikhali (SW130)



Note – The break in observed data is due to the fact that no data is recorded during night time.

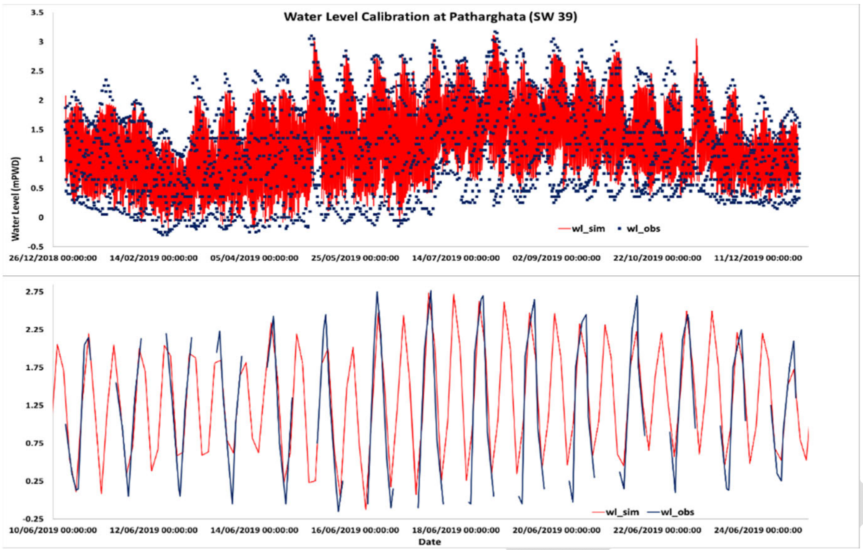
Figure 8-7: Water Level Calibration at Kobadak Forest Office (SW165)



Note – The break in observed data is due to the fact that no data is recorded during night time.

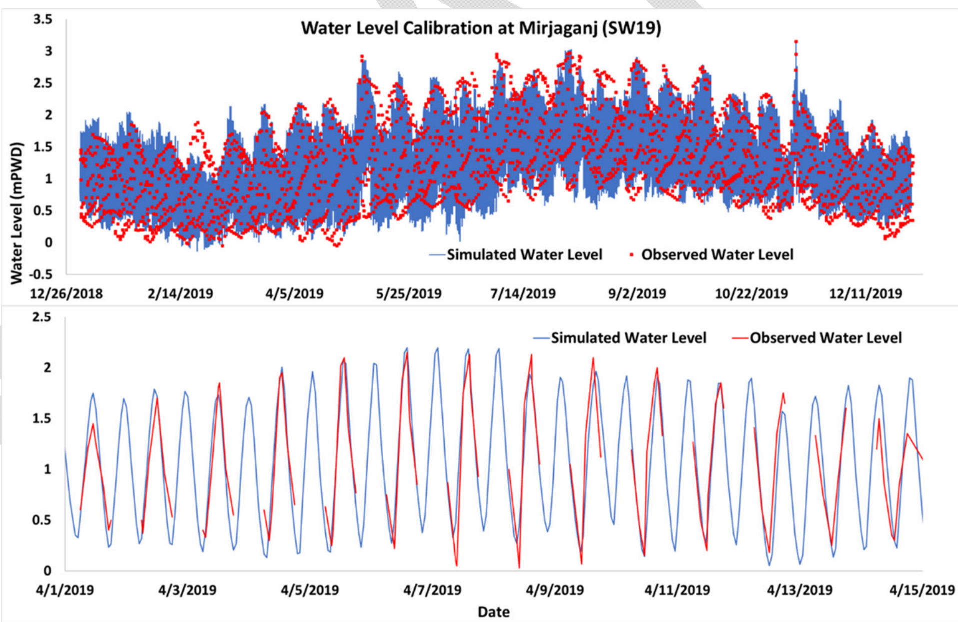
Figure 8-8: Water Level Calibration at Mongla (SW140)

Calibration of the South Central Model



Note – The break in observed data is due to the fact that no data is recorded during night time.

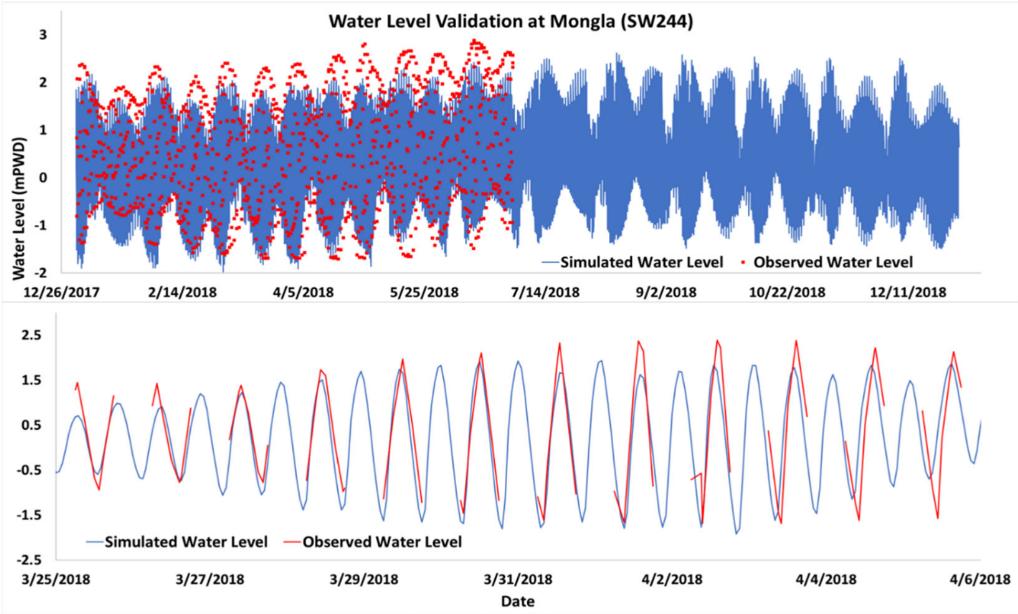
Figure 8-9: Water Level Calibration at Patharghata (SW39)



Note – The break in observed data is due to the fact that no data is recorded during night time.

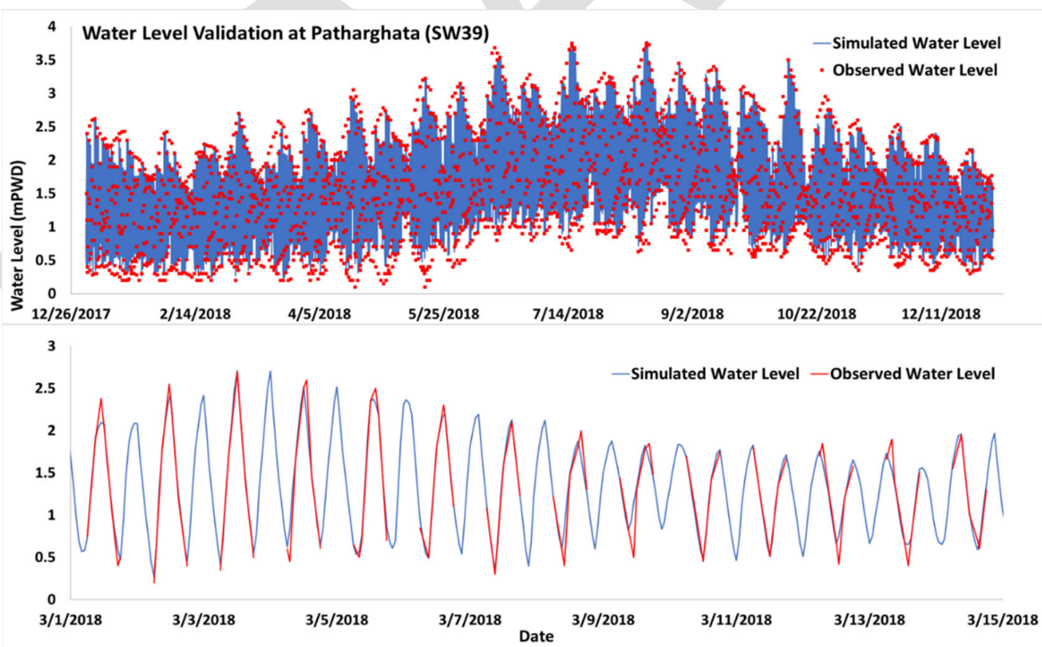
Figure 8-10: Water Level Calibration at Mirjaganj (SW19)

Validation of Combined Model



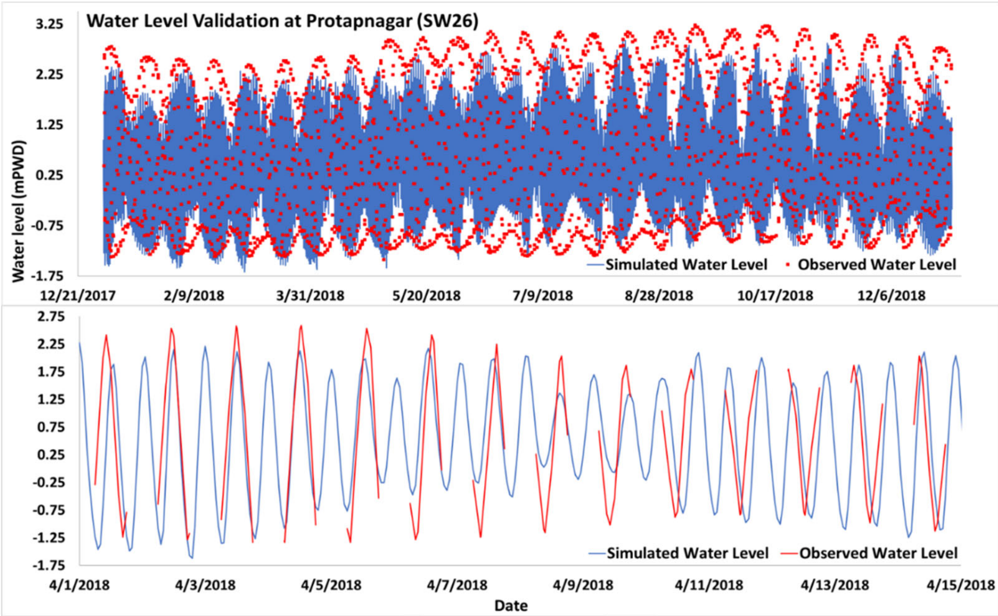
Note – The break in observed data is due to the fact that no data is recorded during night time.

Figure 8-11: Water Level Validation at Mongla (SW244)



Note – The break in observed data is due to the fact that no data is recorded during night time.

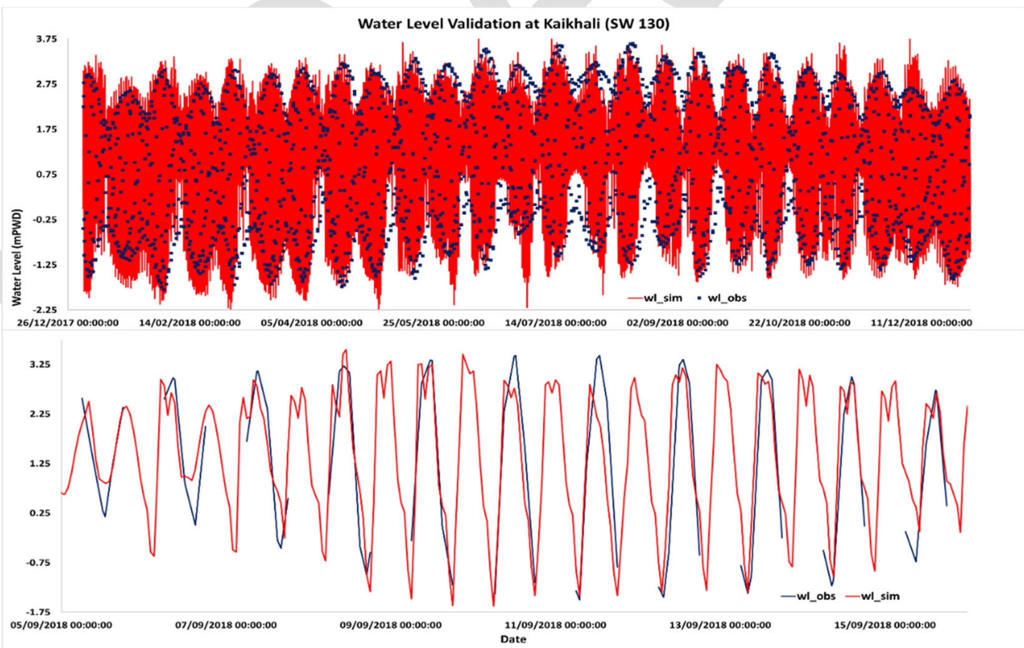
Figure 8-12: Water Level Validation at Pathatghata (SW39)



Note – The break in observed data is due to the fact that no data is recorded during night time.

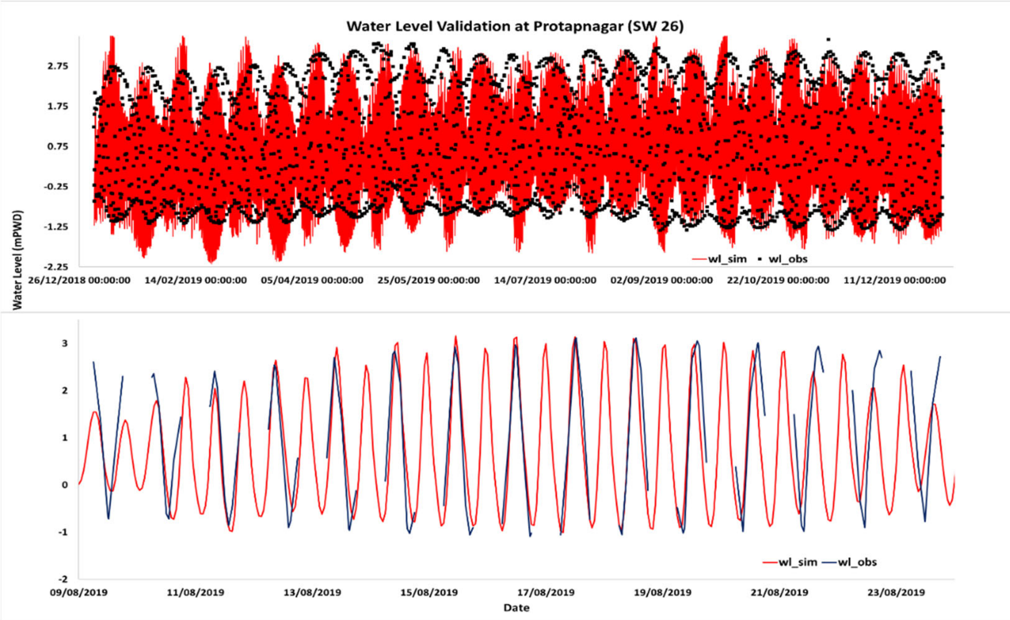
Figure 8-13: Water Level Validation at Protapnagar (SW26)

Validation of SW Model



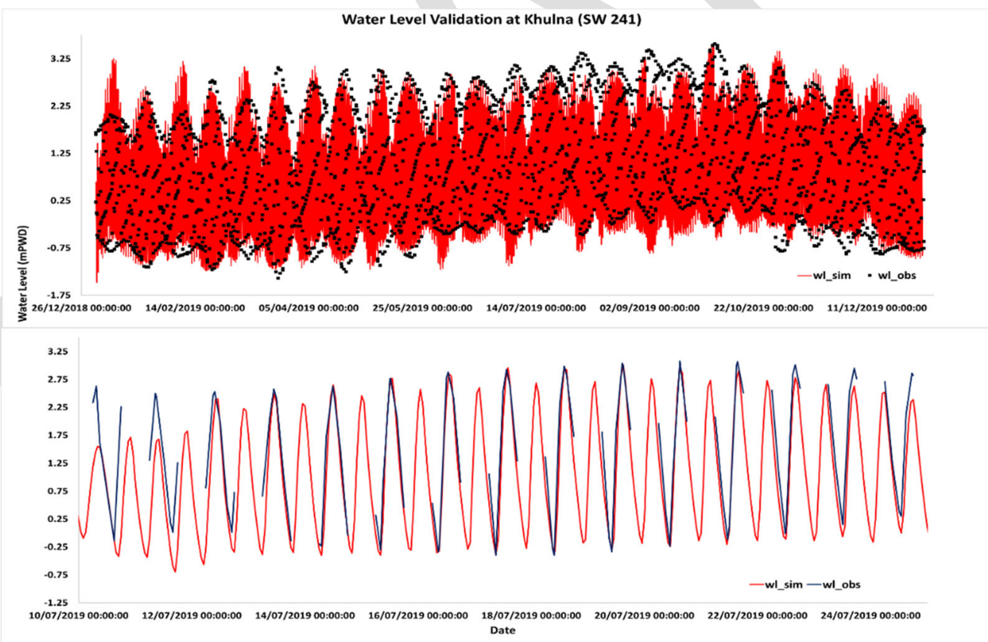
Note – The break in observed data is due to the fact that no data is recorded during night time.

Figure 8-14: Water Level Validation at Kaikhali (SW130)



Note – The break in observed data is due to the fact that no data is recorded during night time.

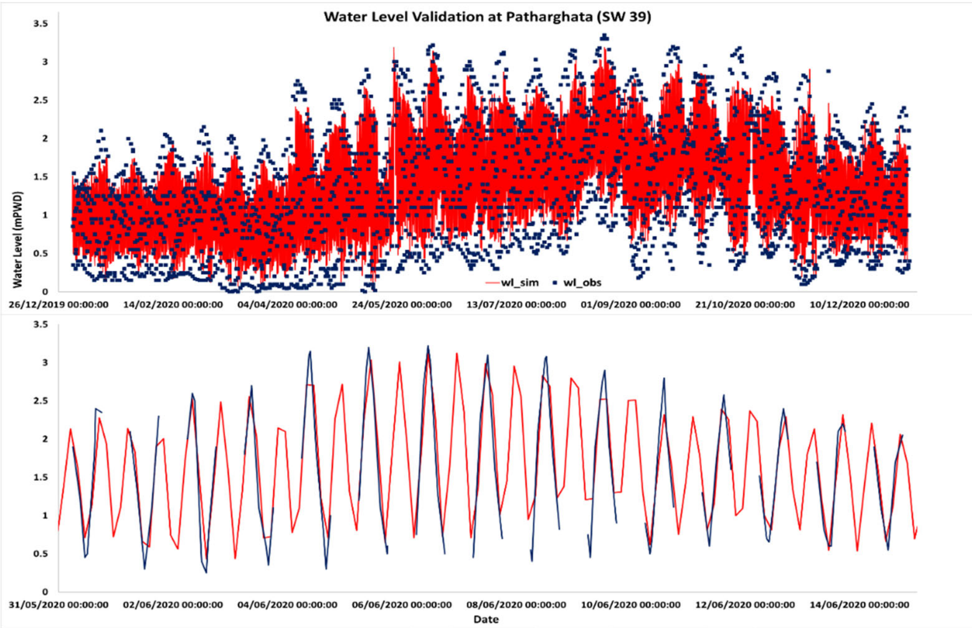
Figure 8-15: Water Level Validation at Protapnagar (SW26)



Note – The break in observed data is due to the fact that no data is recorded during night time.

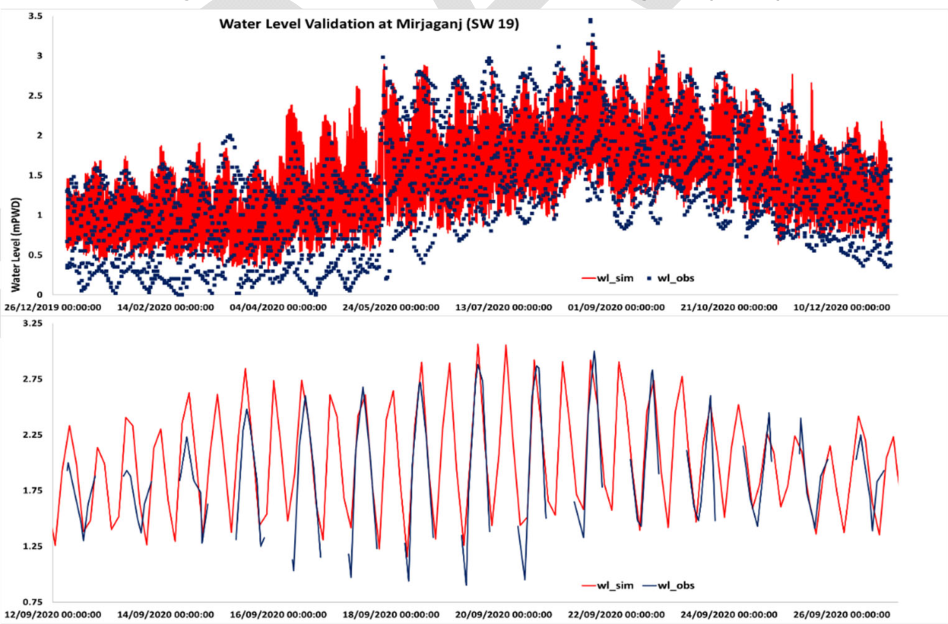
Figure 8-16: Water Level Validation at Khulna (SW241)

Validation of SC Model



Note – The break in observed data is due to the fact that no data is recorded during night time.

Figure 8-17: Water Level Validation at Patharghata (SW39)



Note – The break in observed data is due to the fact that no data is recorded during night time.

Figure 8-18: Water Level Validation at Mirjaganj (SW39)

Wave Height and Overtopping Calculations

8.1.3 Wind Speed

In order to determine monsoon wave height monsoon wind is used. Frequency analysis of monsoon wind is carried out for the wind of Khulna Meteorological station. Annual maximum monsoon wind speed from 1990-2020 was analyzed for frequency distribution. Frequency distribution of monsoon wind considering climate change impacts has also been carried out.

Wind Speed Analysis of Patuakhali

Annual maximum monsoon wind speeds at Patuakhali station from 1990 to 2020 are given in Table 8-7.

Table 8-7: Annual maximum Monsoon Wind Speed (m/s) at Patuakhali for different year

Year	Max wind speed (m\sec)
1990	9.3
1991	14.4
1992	10.3
1993	30.9
1994	10.3
1995	21.6
1996	10.8
1997	30.9
1998	22.6
1999	8.2
2000	20.6
2001	9.3
2002	11.8
2003	7.7
2004	9.3
2005	7.7
2006	11.3
2007	15.4
2008	12.9
2009	7.7
2010	11.3
2011	11.8
2012	13.4
2013	25.7
2014	5.1
2015	15.4

Year	Max wind speed (m\sec)
2016	14.0
2017	8.0
2018	10.0
2019	9.8
2020	11.0

Figure 8-19, shows the wind rose diagram, showing the governing direction of wind in Patuakhali with distribution of wind speed. The wind at this station has a tendency of blowing at North Direction.

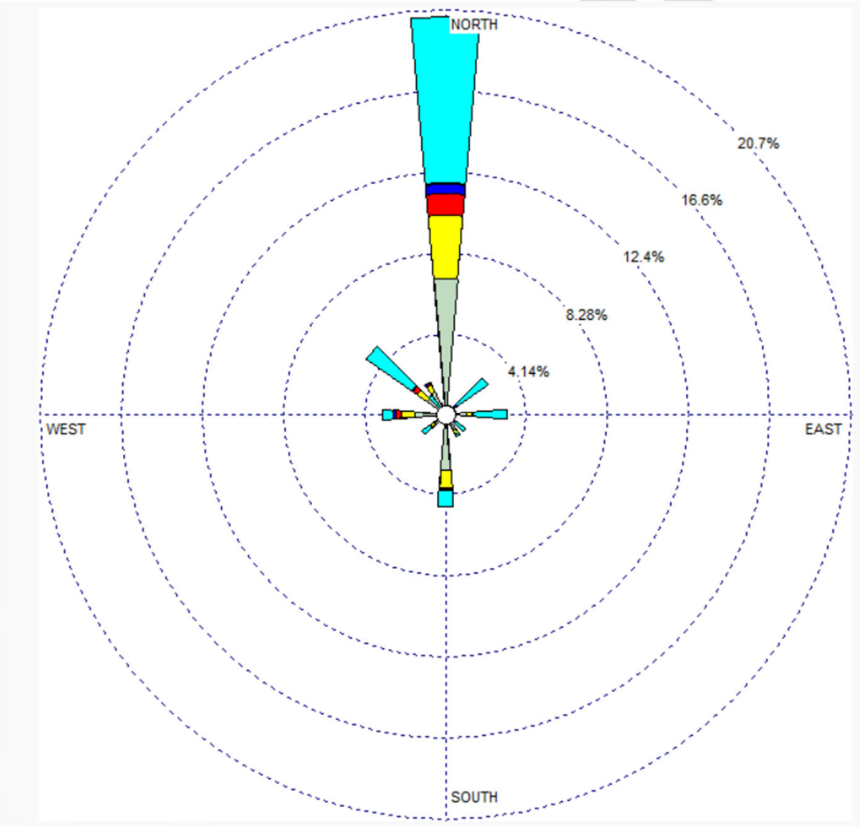


Figure 8-19: Wind Rose Diagram of Patuakhali

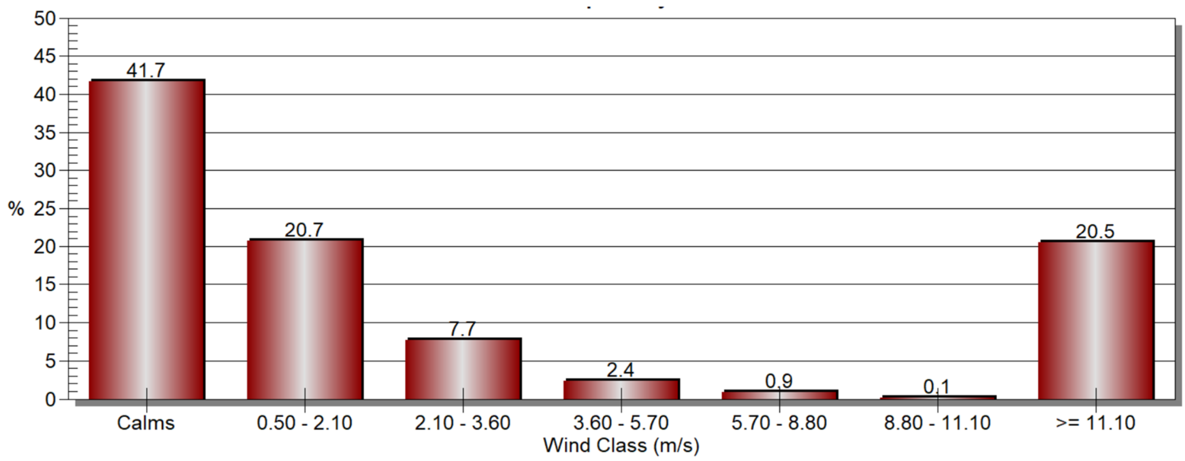


Figure 8-20: Wind Class Frequency Distribution of Patuakhali

Monsoon wind speed for 10-, 25-, 50- and 100-year return period with and without climate change condition are shown in Table 8-8

Table 8-8: Monsoon wind speed for different return period

Return Period (Years)	Monsoon Wind Speed (m/s)	Monsoon Wind Speed (m/s) with climate change + 8% increase
10	21.3	23.0
25	26.1	28.2
50	29.8	32.2
100	33.5	36.2

Wind Speed Analysis of Shatkhira

Annual maximum monsoon wind speeds at Patuakhali station from 1990 to 2020 are given in Table 8-9:

Table 8-9: Annual maximum monsoon wind speed at Patuakhali for different years

Year	Max wind speed (m\sec)
1990	12.9
1991	18.0
1992	10.3
1993	13.4
1994	15.4
1995	8.2
1996	7.2
1997	7.7
1998	9.3
1999	7.7
2000	14.4

Year	Max wind speed (m\sec)
2001	6.2
2002	6.2
2003	15.4
2004	8.2
2005	7.7
2006	5.1
2007	12.3
2008	8.2
2009	13.4
2010	5.1
2011	11.3
2012	6.7
2013	8.2
2014	5.1
2015	7.7
2016	7.0
2017	5.0
2018	12.9
2019	18.0
2020	12.9

Figure 8-21, shows the wind rose diagram, showing the governing direction of wind in Patuakhali with distribution of wind speed. The wind at this station has a tendency of blowing at North Direction

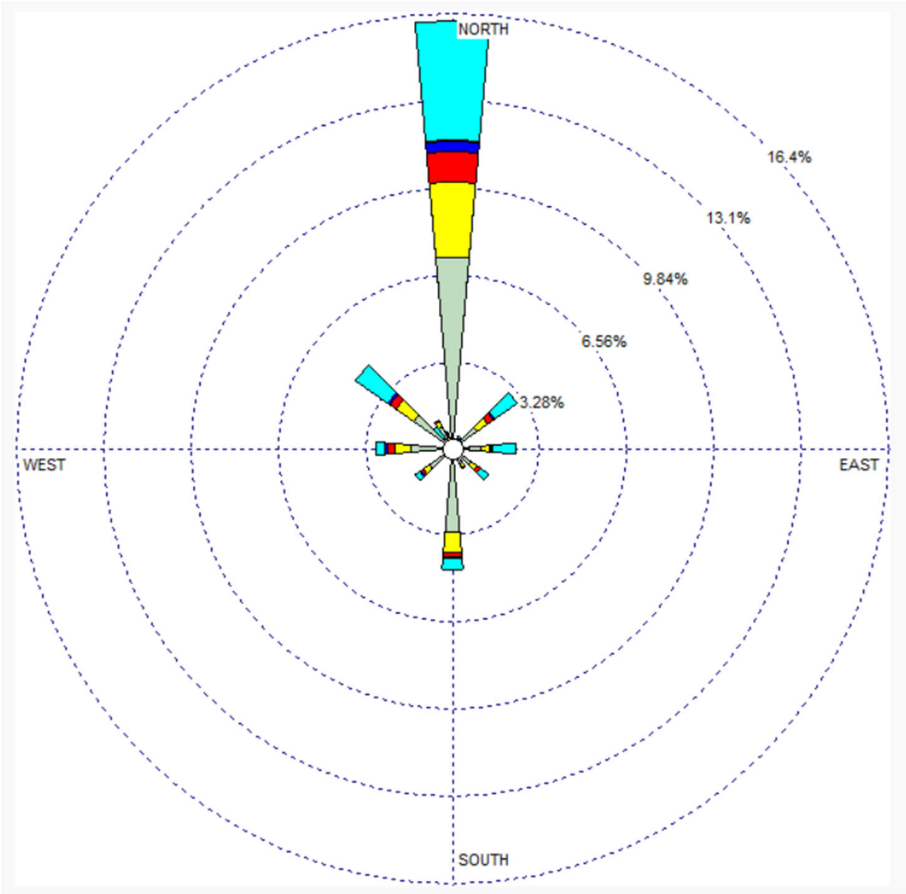


Figure 8-21: Wind Rose Diagram of Shatkhira

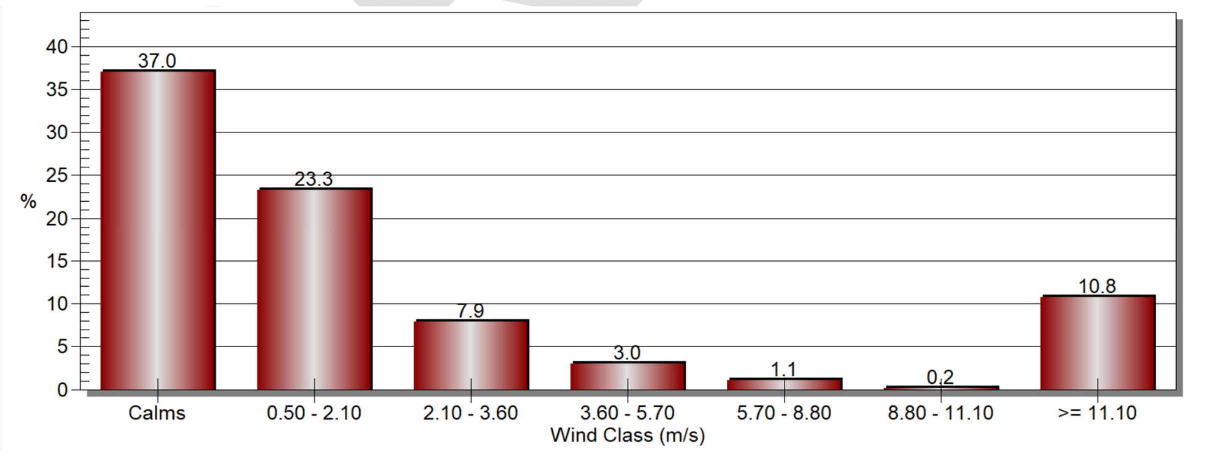


Figure 8-22: Wind Class Frequency Distribution of Shatkhira

Monsoon wind speed for 10-, 25-, 50- and 100-year return period with and without climate change condition are shown in Table 8-10

Table 8-10: Monsoon Wind Speed (m/s) for different return period (Shatkhira)

Return Period (Years)	Monsoon Wind Speed (m/s)	Monsoon Wind Speed (m/s) with climate change + 8% increase
10	15.1	16.4
25	18.2	19.7
50	20.5	22.2
100	22.8	24.6

8.1.4 Wave Height and Overtopping Calculations

Cyclone storms typically do not typically occur during the monsoon season (June to September) (*Figure 8-23*). However, monsoon storms can still create strong winds and, consequently large waves. To determine the freeboard required for the embankments considering monsoon storms, a similar methodology was followed to the methodology presented in Section 7.6. However, the significant wave height was calculated analytically, rather than using the SWAN model, as the 2D wave model will be time consuming for simulating for a longer time period. The 25-year wind speed was determined by converting wind speed at z elevation to elevation at 10 m above the surface. For conversion wind speed of both base and climate change of Khulna and Shatkhira have been used. The below equation was applied for the conversion:

$$U_{10} = U_Z \cdot \left(\frac{10}{z}\right)^{1/7}$$

Here, U_{10}= wind speed 10 m above the surface, U_z= wind speed z m above the surface, z= ground elevation. The average ground elevation (z) was calculated for each polder from the Digital Elevation Model prepared from the topographic survey data.

Next the significant wave height was calculated using the methodology presented by Mathiesen [50] .Using the methodology presented in Section 7.6, the required freeboard was calculated. This freeboard was added to the 25-year still water level, calculated from the monsoon modelling results.

[50] Mathiesen, J. 2022. *Wave Forecasting on the Big Rivers of Bangladesh*. Master of Science from the Technische Universitat Braumschweig.

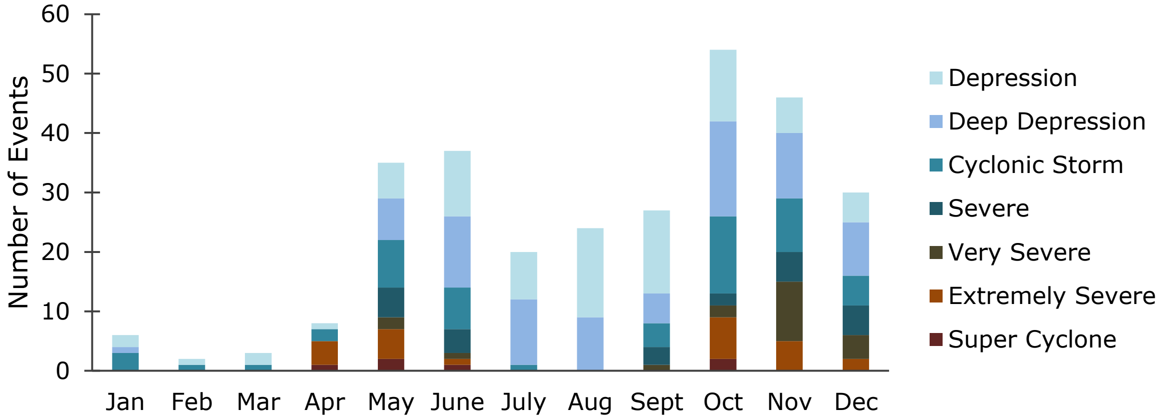


Figure 8-23: Number of incidences of storm events in the North Indian Ocean[51].

Summary of Regional Assessment Results

The following table shows the results of the monsoon model assessment.

Table 8-11: Results of the monsoon model; results include climate change

					Rough Embankment			Smooth Embankment		
Polder	Point	Recommended slope[1] (1V:XH)	Design water elevation, SWL (m PWD)	Design wave height (m)	Calculated freeboard (m)	Recommended freeboard[2] (m)	Crest elevation for monsoon floods[3] (m PWD)	Calculated freeboard (m)	Recommended freeboard[2] (m)	Crest Elevation for monsoon floods[3] (m PWD)
4	3	2	3.9	0.2	0.2	0.9	4.8	0.3	0.9	4.8
	4	3	4.1	0.4	0.5	0.9	5.0	0.6	0.9	5.0
	10	3	3.9	0.3	0.3	0.9	4.8	0.3	0.9	4.8
	37	2	3.5	0.3	0.4	0.9	4.4	0.5	0.9	4.4
5	1	3	3.9	0.3	0.3	0.9	4.8	0.4	0.9	4.8
	2	3	4.1	0.2	0.2	0.9	5.0	0.3	0.9	5.0
	3	2	3.9	0.2	0.2	0.9	4.8	0.3	0.9	4.8
	4	3	4.1	0.4	0.5	0.9	5.0	0.6	0.9	5.0
	5	3	3.9	0.4	0.5	0.9	4.8	0.6	0.9	4.8
	7	3	3.9	0.2	0.2	0.9	4.8	0.2	0.9	4.8
	41	3	4.2	0.2	0.2	0.9	5.1	0.2	0.9	5.1
7/1	5	3	3.9	0.4	0.5	0.9	4.8	0.6	0.9	4.8
	6	3	3.9	0.4	0.5	0.9	4.8	0.6	0.9	4.8
7/2	4	3	4.1	0.4	0.5	0.9	5.0	0.6	0.9	5.0

[51] data source: https://en.wikipedia.org/wiki/North_Indian_Ocean_tropical_cyclone

					Rough Embankment			Smooth Embankment		
Polder	Point	Recommended slope[1] (1V:XH)	Design water elevation, SWL (m PWD)	Design wave height (m)	Calculated freeboard (m)	Recommended freeboard[2] (m)	Crest elevation for monsoon floods[3] (m PWD)	Calculated freeboard (m)	Recommended freeboard[2] (m)	Crest Elevation for monsoon floods[3] (m PWD)
	9	3	3.8	0.3	0.2	0.9	4.7	0.2	0.9	4.7
	10	3	3.9	0.3	0.3	0.9	4.8	0.3	0.9	4.8
	11	2	3.8	0.3	0.3	0.9	4.7	0.4	0.9	4.7
10-12	9	3	3.8	0.3	0.2	0.9	4.7	0.2	0.9	4.7
	11	2	3.8	0.3	0.3	0.9	4.7	0.4	0.9	4.7
	12	3	4.0	0.4	0.5	0.9	4.9	0.6	0.9	4.9
	13	3	3.9	0.4	0.6	0.9	4.8	0.7	0.9	4.8
	42	3	3.9	0.3	0.4	0.9	4.8	0.4	0.9	4.8
13-14/2	8	3	4.0	0.3	0.4	0.9	4.9	0.5	0.9	4.9
	9	3	3.8	0.3	0.2	0.9	4.7	0.2	0.9	4.7
39/1B	27	5	3.8	0.5	0.5	0.9	4.7	0.7	0.9	4.7
	28	5	3.8	0.4	0.7	0.9	4.7	0.9	0.9	4.7
	35	2	3.3	0.2	0.3	0.9	4.2	0.5	0.9	4.2
39/1C	28	5	3.8	0.4	0.7	0.9	4.7	0.9	0.9	4.7
	29	5	3.8	0.4	0.8	0.9	4.7	1.0	1.0	4.8
	35	2	3.3	0.2	0.3	0.9	4.2	0.5	0.9	4.2
	38	2	3.2	0.3	0.4	0.9	4.1	0.6	0.9	4.1
41/5	25	Not extracted from monsoon model[4]								
	26	5	3.8	0.4	0.3	0.9	4.7	0.4	0.9	4.7
	36	2	3.0	0.2	0.3	0.9	3.9	0.5	0.9	3.9
47/1	21	5	3.3	0.3	0.3	0.9	4.2	0.4	0.9	4.2
	22	Not extracted from monsoon model[4]								
45	23	Not extracted from monsoon model[4]								
	24	Not extracted from monsoon model[4]								
50-51	17	Not extracted from monsoon model[4]								
	18	7	3.7	0.6	0.9	0.9	4.7	1.3	1.3	5.0
55/2D	14	3	3.8	0.5	0.5	0.9	4.7	0.7	0.9	4.7
	15	3	3.8	0.5	0.6	0.9	4.7	0.8	0.9	4.7
	32	2	3.2	0.2	0.3	0.9	4.1	0.5	0.9	4.1
	40	2	3.3	0.3	0.4	0.9	4.2	0.6	0.9	4.2

Notes:

[1]Riverside slope

[2]A minimum freeboard of 0.9 m is stipulated by the BWDB

[3]Crest elevation is equal to the design water elevation, SWL, plus the recommended freeboard; the results include subsidence

[4]Crest elevations will be governed by storm surge water levels

9 Summary of Recommended Design Parameters

The following table provides a summary of the recommended crest elevation for all 13 polders. These recommended crest elevations are based on the critical event. The critical event is determined by whichever event results in higher water levels at the embankment, storm surge or monsoon floods.

Table 9-1: Summary of recommended crest elevations; results include climate change

					Rough Embankment		Smooth Embankment	
Polder	Point	Allowance for subsidence (m)	Recommended slope[1] (1V:XH)	Critical event[2] (monsoon / cyclone)	Recommended crest elevation [3] (m PWD)	Peak crest elevation allowing for subsidence [3] (m PWD)	Recommended crest elevation [3] (m PWD)	Peak crest elevation allowing for subsidence [3] (m PWD)
4	3	0.15	2	monsoon	4.8	5.0	4.8	5.0
	4	0.15	3	monsoon	5.0	5.2	5.0	5.2
	10	0.15	3	monsoon	4.8	5.0	4.8	5.0
	37	0.15	2	monsoon		0.2	4.4	4.6
5	1	0.15	3	cyclone	4.9	5.1	5.4	5.6
	2	0.15	3	monsoon	5.0	5.2	5.0	5.2
	3	0.15	2	monsoon	4.8	5.0	4.8	5.0
	4	0.15	3	monsoon	5.0	5.2	5.0	5.2
	5	0.15	3	monsoon	4.8	5.0	4.8	5.0
	7	0.15	3	monsoon	4.8	5.0	4.8	5.0
	41	0.15	3	monsoon	5.1	5.3	5.1	5.3
7/1	5	0.15	3	monsoon	4.8	5.0	4.8	5.0
	6	0.15	3	monsoon	4.8	5.0	4.8	5.0

Polder	Point	Allowance for subsidence (m)	Recommended slope[1] (1V:XH)	Critical event[2] (monsoon / cyclone)	Rough Embankment: Recommended crest elevation [3] (m PWD)	Rough Embankment: Peak crest elevation allowing for subsidence [3] (m PWD)	Smooth Embankment: Recommended crest elevation [3] (m PWD)	Smooth Embankment: Peak crest elevation allowing for subsidence [3] (m PWD)
7/2	4	0.15	3	monsoon	5.0	5.2	5.0	5.2
	9	0.15	3	monsoon	4.7	4.9	4.7	4.9
	10	0.15	3	monsoon	4.8	5.0	4.8	5.0
	11	0.15	2	monsoon	4.7	4.9	4.7	4.9
10-12	9	0.15	3	monsoon	4.7	4.9	4.7	4.9
	11	0.15	2	monsoon	4.7	4.9	4.7	4.9
	12	0.15	3	monsoon	4.9	5.1	4.9	5.1
	13	0.15	3	monsoon	4.8	5.0	4.8	5.0
	42	0.15	3	monsoon	4.8	5.0	4.8	5.0
13-14/2	8	0.15	3	monsoon	4.9	5.1	4.9	5.1
	9	0.15	3	monsoon	4.7	4.9	4.7	4.9
39/1B	27	0.30	5	cyclone	5.5	5.8	6.0	6.3
	28	0.30	5	cyclone	5.1	5.4	5.7	6.0
	35	0.30	2	cyclone	4.6	4.9	5.0	5.3
39/1C	28	0.30	5	cyclone	5.1	5.4	5.7	6.0
	29	0.30	5	cyclone	4.9	5.2	5.3	5.6
	35	0.30	2	cyclone	4.6	4.9	5.0	5.3
	38	0.30	2	cyclone	4.1	4.4	4.5	4.8
41/5	25	0.30	7	cyclone	5.8	6.1	6.3	6.6
	26	0.30	5	cyclone	5.1	5.4	5.6	5.9

					Rough Embankment		Smooth Embankment	
Polder	Point	Allowance for subsidence (m)	Recommended slope[1] (1V:XH)	Critical event[2] (monsoon / cyclone)	Recommended crest elevation [3] (m PWD)	Peak crest elevation allowing for subsidence [3] (m PWD)	Recommended crest elevation [3] (m PWD)	Peak crest elevation allowing for subsidence [3] (m PWD)
	36	0.30	2	cyclone	4.5	4.8	5.0	5.3
47/1	21	0.30	5	cyclone	4.9	5.2	5.1	5.4
	22	0.30	7	cyclone	6.2	6.5	6.7	7.0
45	23	0.30	7	cyclone	6.2	6.5	6.7	7.0
	24	0.30	7	cyclone	5.8	6.1	6.3	6.6
50-51	17	0.30	7	cyclone	6.4	6.7	6.9	7.2
	18	0.30	7	cyclone	5.6	5.9	6.3	6.6
55/2D	14	0.30	3	cyclone	5.2	5.5	5.8	6.1
	15	0.30	3	cyclone	4.8	5.1	5.2	5.5
	32	0.30	2	cyclone	3.8	4.1	4.2	4.5
	40	0.30	2	cyclone	3.6	3.9	4.0	4.3

Notes:

[1]Riverside slope

[2] The recommended crest elevations are based on the critical event, which is the event that produces the highest 25-year water levels, either monsoon floods or storm surges

[3] Includes the required freeboard, calculated from wave run up

A1 Future Climate Change Analysis

A1.1 Future Climate Change Scenario

Assessment of future climate change is of great importance for a sustainable planning of water resources and disasters. Global climate change is impacting the temperature, rainfall and overall hydrologic cycle. So, the assessment of future climate change for water related hazards is essential for long term future planning.

The assessment of future climate change is done by IPCC through the Coupled Model Inter-comparison Project (CMIP). A set of Global Circulation Models (GCM) simulate plausible future climate conditions based of different scenarios. Recently, IPCC released its 6th Assessment Report that utilizes CMIP6 GCMs. In this report, IPCC has introduced the Shared Socioeconomic Pathways (SSPs) scenarios.

Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. The SSPs are based on five narratives describing broad socioeconomic trends that could shape future society. These are intended to span the range of plausible futures. They include: a world of sustainability-focused growth and equality (SSP1); a "middle of the road" world where trends broadly follow their historical patterns (SSP2); a fragmented world of "resurgent nationalism" (SSP3); a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5).

These narratives describe alternative pathways for future society. They present baselines of how things would look in the absence of climate policy, and allow researchers to examine barriers and opportunities for climate mitigation and adaptation in each possible future world when combined with mitigation targets. SSP1 and SSP5 envision relatively optimistic trends for human development, with "substantial investments in education and health, rapid economic growth, and well-functioning institutions". They differ in that SSP5 assumes this will be driven by an energy-intensive, fossil fuel-based economy, while in SSP1 there is an increasing shift toward sustainable practices.

For the present study, SSP5 based outputs will be used for future climate change assessment as this scenario represent the higher extreme of the future climate.

A1.1.1 Overall Methodology

The assessment of local climate change impact demands downscaling of General Circulation Model (GCM) data which are very coarse in resolution (approximately 100-300 km) to capture local phenomena. Two types of downscaling techniques are available i.e. dynamic downscaling and statistical downscaling, having pros and cons in both techniques. However, future projections through either dynamically or statistically downscaled GCM datasets have proven evidences to generate high resolution, dependable and appropriate local level climate change information.

Downscaling is the process through which finer resolution climate information is generated from GCM outputs, considering the dynamics of local physical processes. The following figure shows general approach of downscaling.

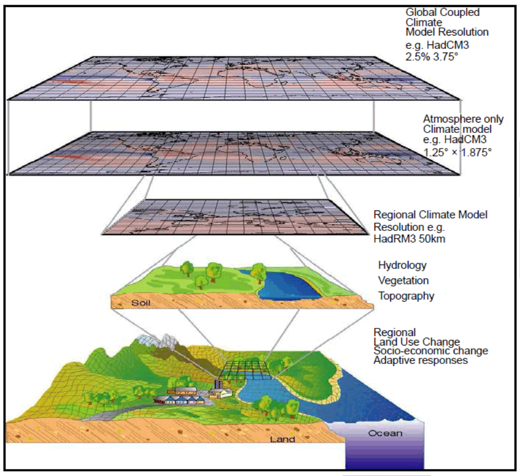


Figure xx: General approach of downscaling

The GCM and dynamically downscaled RCM outputs contain significant system biases with respect to the actual scenario during historical simulation. IPCC (2015) identified the significance of bias correction in regional climate projections and their use in impacts and risk analysis studies with possible guidelines to correct biases. There are many available bias correction methods particularly for correction of rainfall and temperature data, e.g., linear scaling, distribution-based scaling, quantile mapping, ISI-MIP, cumulative distribution function etc. Choice of methods varies with the purpose of bias correction and aim of the climate modelling output analysis.

The climate change assessment following the new SSP scenario based projection utilizes the CHELSA dataset. CHELSA is a mechanistical statistical downscaling of GCM data following Karger et al. (2021)[1]. The dataset utilizes Inter sectoral Impact Model Inter comparison Project (ISI-MIP) suggested trend-preserving bias correction method[2]. The downscaling exercises and future climate change anomalies assessment has been done for Temperature and Rainfall (precipitation) for SSP585 scenario of CMIP6 dataset for mid-century, i.e., 2050s (2035-2065) and end of century, i.e., 2085s (2071-2100). In accordance with IPCC practice, the base period for the climate change analysis has been considered from 1981 to 2010.

[1] Karger, D.N., Wilson, A.M., Mahony, C., Zimmermann, N.E., Jetz, W. (2021): Global daily 1km land surface precipitation based on cloud cover-informed downscaling. Scientific Data. doi.org/10.1038/s41597-021-01084-6.

[2] Lange, S. (2019): Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0), Geosci. Model Dev., 12, 3055–3070, https://doi.org/10.5194/gmd-12-3055-2019.

The future projection of sea level rise has been estimated based on IPCC AR6 GCM ensemble for the Bay of Bengal near Hiron Point, sea level rise estimates has been assessed for future climate change for SSP 585 during two time slices.

The future changes in wind speed has been estimated from the IPCC AR6 GCM ensemble data for the nearby locations of the study area (polders and surrounding rivers).

A1.2 Future Climate Change Projection

A1.2.1 Temperature

The following tables present the plausible changes in Temperature during 2050s and 2085s in South West (SW) and South Central (SC) regions of Bangladesh. (DJF = December, January, February; MAM = March, April, May; JJAS = June, July, August, September; ON = October, November)

Average Temperature during base period (1981-2010) °C

Region	annual	DJF	MAM	JJAS	ON
South Central Zone	25.85	20.55	27.96	28.33	25.70
South West Zone	25.83	19.99	28.29	28.60	25.35

Changes in Temperatures (^{0}Celcius) for Future Climate Change (2050s)

Region	SSP5-8.5(2050s)				
	annual	DJF	MAM	JJAS	ON
South Central Zone	1.86	2.00	1.70	1.75	2.11
South West Zone	1.89	2.07	1.76	1.77	2.06

Changes in Temperatures (^{0}Celcius) for Future Climate Change (2080s)

Region	SSP5-8.5(2080s)				
	annual	DJF	MAM	JJAS	ON
South Central Zone	3.99	4.63	3.82	3.52	4.25
South West Zone	4.21	4.95	4.01	3.69	4.45

A1.2.2 Rainfall

The following tables present the plausible changes in rainfall during 2050s and 2085s in South West (SW) and South Central (SC) regions of Bangladesh . (DJF = December, January, February; MAM = March, April, May; JJAS = June, July, August, September; ON = October, November)

Average Rainfall during base period (1981-2010) (mm)

Region	annual	DJF	MAM	JJAS	ON
South Central Zone	2380	45	431	1670	235
South West Zone	1826	52	312	1286	177

Percent Change in Rainfall for Future Climate Change (2050s)

Region	SSP5-8.5(2050s)				
	annual	DJF	MAM	JJAS	ON
South Central Zone	3.12	0.30	3.05	4.49	4.73
South West Zone	3.95	0.53	4.92	4.37	6.79

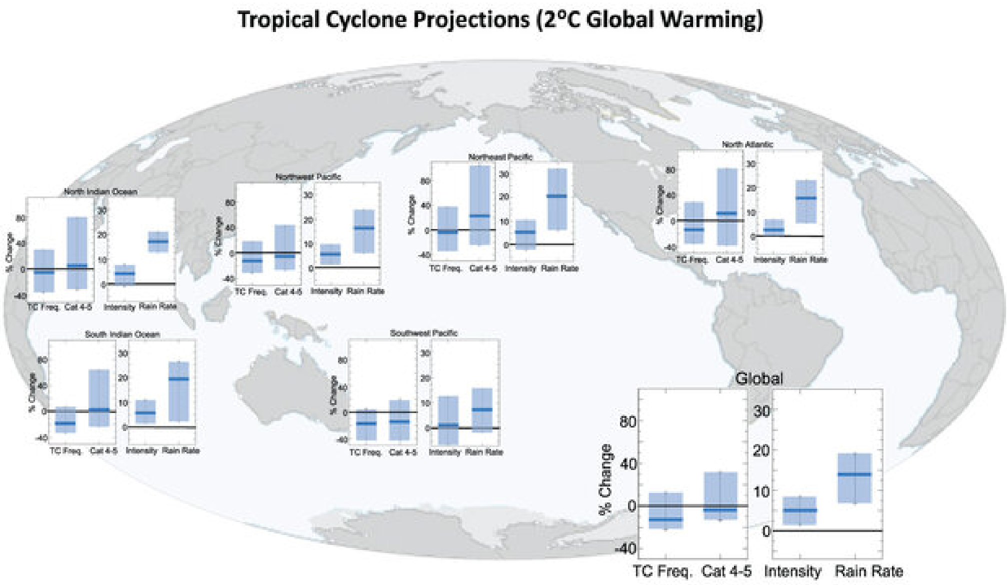
Percent Change in Rainfall for Future Climate Change (2080s)

Region	SSP5-8.5(2080s)				
	annual	DJF	MAM	JJAS	ON
South Central Zone	6.70	-1.10	4.52	14.71	5.66
South West Zone	5.85	-1.09	6.55	10.52	5.89

A1.2.3 Wind Speed

Based on the IPCC AR6 GCM data for wind speed, in SSP 585 scenario, for end of century period, it was found that an average of 8% increase in monsoon wind speed is projected. This has been incorporated in the monsoon modelling.

In the North Indian basin, Mohapatra et al. (2015) find, based on observations over 1951-2010 (monsoon and post-monsoon seasons), that the probability of cyclonic disturbances intensifying into tropical cyclones has increased in the Arabian Sea in association with decreased vertical wind shear. They further report that the probability of tropical cyclones intensifying into severe tropical cyclones has increased over the Bay of Bengal in association with increased low-level cyclonic vorticity. For the Arabian Sea, model simulations suggest that recent increases in the occurrence of extremely severe tropical cyclones in the post-monsoon season are likely due in part to anthropogenic forcing (Murakami et al., 2017). For tropical cyclone intensity, a +2°C warming scenario is projected to yield a +5% (+1 to +10%) increase in maximum wind speed (Knutson et al., 2020), resulting in greater potential damage per storm.



Summary of projected regional and global changes in tropical cyclones (TC) assuming a 2° Celsius (3.6° Fahrenheit) global warming scenario

For this study, in case of cyclone, a 10% increase in intensity has been considered as it is predicted that there may be increase of $+4^0$C temperature based on SSP8.5-5 scenario which is more than 2^0C.

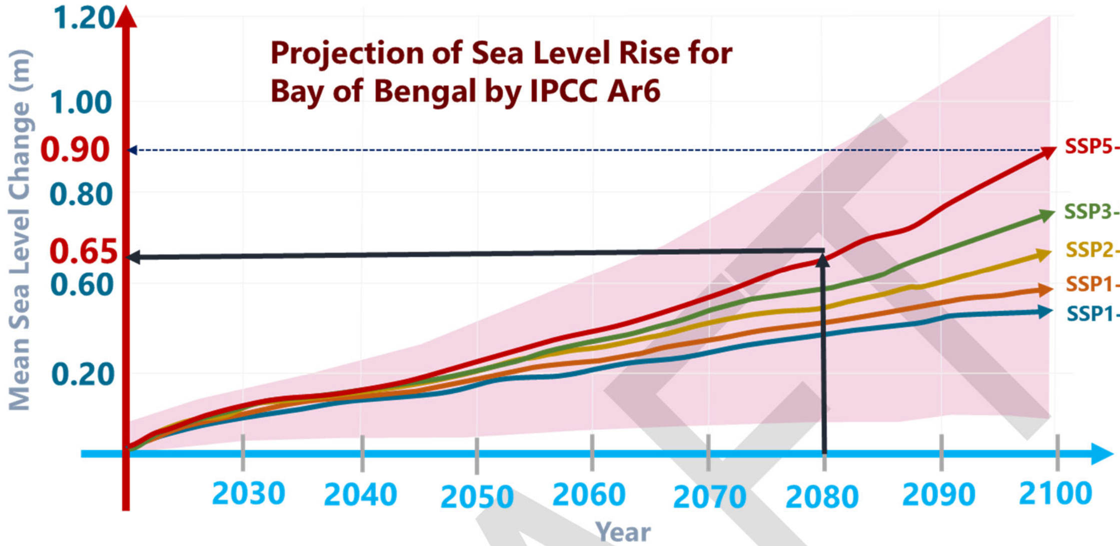
A1.3 Sea Level Rise

(IPCC) 6th Assessment Report estimates for the Bay of Bengal[3]. In this study, sea level rise scenario for the region was based on projections for Hiron Point, produced for the IPCC 6th Assessment Report (AR6). The geographically varying projections in the AR6 were created using an ensemble of 20 general circulation models from the Coupled Model Intercomparison Project Phase 6 (CMIP6), together with modelling of glaciers and ice sheets. The sea level rise projections include thermal expansion, the effect of atmospheric loading, sterodynamic sea level, glaciers, Greenland and Antarctica ice sheet, Land water storage and vertical land motion.

For SSP585, the median sea level change is 0.27 meter and 0.65 m for 2050s and 2080s relative to a 1995-2014 baseline. The sea level rise projections in the IPCC AR6 GCMs show quite some variations with a wide range of uncertainties. Under these circumstances, for the present study, SSP 5-8.5 (2080) projections for sea level rise has been utilized to ensure higher emission

[3] IPCC, 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

scenarios are covered. As there is also quite some variation among the GCMs for the SSP585, the present study uses the median projection values that is most plausible.



A1.4 Increase in Upstream River Discharges

CEGIS has a basin model developed using ArcSWAT. SWAT is a physically based distributed hydrological model, which operates on a daily time step. It simulates hydrological processes at high spatial resolution by dividing the catchment into hydrological response unit (HRU) based on land use/cover, soil and slope.

Climate Change Impact on the Percentage Change of Availability of Surface Water			
Basin	**Annual Average Flow (1981-2010)**	**SSP5-8.5**	
		2050s	**2085s**
Ganges (average annual flow)	11,928	28	55
Brahmaputra (average annual flow)	17,503	5	29
Meghna (average annual flow)	4,827	4	18

A2 Data from LTM

This Appendix lists the data from the LTM available for the CEIP-2 Polder assessment.

Name	Data Type	Available Information	Co-ordinates
		Bathymetric Survey Data	
BoB Model Elevations	Point Shapefiles	Elevation of Deep Sea Part of IWM BoB Model in mPWD	WGS84
BoB Model Contours	Contour Lines	Elevation of Deep Sea Part of IWM BoB Model in mPWD	WGS84
Xsection_River	Poly Lines Shapefiles	Baleswar River (Approx 5km from DS)	WGS84
		Bishkhali River (Approx 5km from DS)	
		Lohalia River (Beside Polder 55/1)	
		Bhola (Bagerhat) river (Beside Polder 35/1)	
		Pussur river (Beside Polder 35/2, 34/2)	
		Sibsa (Beside Polder 32, 31,23,9)	
		Chunkuri (Beside Polder 32,33)	
		Kurulia RIver (Beside Polder 23)	
		Teliganga/Ghengrail River (Beside Polder 17/1)	
		River parts besude polder 14/1 and 15 (Kobadak, Kholpetua)	
		Peripehral River of Polder 40/2, 40/1, 43/2C (Lohalia River)	
		Soil Data	
Soil Types and Class	Polygon Layers	Soil Types and Classes	WGS84
Lithology	Point Shapefiles	Soil Depth	WGS84
		Existing Structures	
Hydraulic Structures	Point Shapefiles	General Information, No of Vent, Size of Vent, Vent Height & Width, Vent Diameter, Area, condition of structure Collected in 2016	WGS84
Embankment Height	Point Shapefiles	Height of the Embankments in mPWD	WGS84
Embankment	Shapefile (Polygon)	Polderwise Population, Land use Statistiscs, Socio Economic Statistics, Average, Maximum and Minimum Height of Embankment	WGS84
Xsection_Embankment	Poly Lines Shapefiles	Available for Polder 23, Polder 17/1, 18-19 (Partially), 15, 14/1, 35/1, 34/1 & 34/3 Only GIS layer is available	WGS84

A3 Comparison of the CEIP-1 and CEIP-2 Storm Surge Modelling Approach

The current study has improved upon the CEIP-1 approach of the storm surge modelling. The differences between the CEIP-1 and CEIP-2 methodology are summarized in in the table below.

Parameters	CEIP-1	CEIP-2
Dimension	2D	2D
Software	MIKE 21M	Delft3D Flow 4.0
Grid Type	Unstructured Curvilinear	Structured Curvilinear
Boundary Conditions	*Upstream (Time Series Discharge):* 1) Upper Meghna River at Bhairab 2) Padma River at Baruria *Downstream (Global Tide Model):* 1) Southern Bay of Bengal	*Upstream (Time Series Discharge):* 1) Upper Meghna River at Bhairab 2) Padma River at Hardinge 3) Brahmaputra at Bahadurabad *Downstream (TPXO 8.0 Global Inverse Tide Model):* 2) Southern Bay of Bengal
Boundary for Cyclones	Parameters related to pressure field imposed on water surface: 1) Radius of maximum winds 2) Maximum wind speed 3) Cyclone track location and direction 4) Central Pressure 5) Neutral Pressure 6) Holland Parameters	Parameters related to pressure field imposed on water surface: 1) Radius of maximum winds (calculated by model during creation of spiderweb) 2) Maximum wind speed (Input) 3) Cyclone track location and direction (Input) 4) Central Pressure (Input) 5) Neutral Pressure (Input) 6) Holland Parameters (Equation is there in the Model) Cyclone is generated using spiderweb generation tool in the model.
Climate Change Scenario Considered	50 cm Sea Level Rise: According to RCP 8.5m, Global MSL by 2100 is 0.52 to 0.98m. Increase in maximum wind speed of cyclone by 8%.	Based on latest IPCC Ar6 Report and the latest Shared Socioeconomic Pathways (SSPs) scenarios will be considered. The scenario which has been planned to considered is SSP5-8.5 (2050) , SSP5-8.5 (2080). Sea level at Hiron Point of Bay of Bengal is projected to increase 0.25m [0.05-0.5m] by 2050, 0.65m [0.1-0.9m] by 2080 and 0.90m [0.15-1.2 m] by 2100. 0.65m considered for this study. Maximum wind speed increase by 10%.

Parameters	CEIP-1	CEIP-2
Approach of the Overall Model	1) Model updating using recent bathymetry 2) Base model simulation 3) Model calibration and validation 4) Simulation of total 19 cyclones; each cyclone was modelled twice, once for the original tidal phase and once for the opposite tidal phase from base scenario (historic cyclone data collected between 1960-2009, 51 years) 5) Statistical analysis of surge levels for different return period with and without climate change 6) Statistical analysis of wind speed for different return period with and without climate change 7) Statistical analysis of wave height for different return period with and without climate change 8) Embankment crest height was determined by adding the maximum storm surge level with the maximum wave height for the required return period.	1) Model updated using recent bathymetry 2) Base model simulation 3) Model calibration and validation 4) Simulation for total 33 cyclones for original tidal phase with and without the effect of climate change (historic cyclone data collected between 1960-2021, 61 years) 5) In parallel to step 4, run wave model 6) Surge Height, Surge Level, Significant Wave Height, Wave Period as outcomee of the model 7) Calculate the additional freeboard required from wave run up 8) Identification of maximum crest level required for each storm at each location, considering the joint occurance of waves and storm surge 9) Statistical analysis of required crest levels with and without climate change 10) Identification of the return period for the design.

Comparison of methodology with and without joint probability: The results of Point 17 have been used to test the effects of the joint probability methodology on the recommended crest elevations. The below table shows the results for a rough embankment with an assumed wave period of 6 seconds. The joint probability methodology reduces the height of the embankment at this location by 1.3 m.

	Without Joint Probability	With Joint Probability
25-year significant wave height (m)	4.3	Not directly calculated
25-year freeboard (m)	3.4	Not directly calculated
25-year storm surge height (m)	5.6	Not directly calculated
Recommended crest height (m)	9.0	7.7

A4 Cyclone Data

The following cyclones have been simulated. The cyclone data has been collected from the Indian Meteorological Department (IMD), Joint Typhoon Warning Center (JTWC) and the Bangladesh Meteorological Department (BMD), based on availability.

SL no.	Date of Occurrence	Name[1]	Nature of Phenomenon	Landfall Area	Maximum wind speed (km/hr)	Direction of the Max. Wind Speed	Tidal Surge Height (ft)	Central Pressure (mbs)
1	11.10.60		Severe Cyclonic Storm	Chittagong	160	SE	6	-
2	31.10.60		Severe Cyclonic Storm	Chittagong	193	SE	15	-
3	09.05.61		Severe Cyclonic Storm	Chittagong	160	SE	20	-
4	30.05.61		Severe Cyclonic Storm	Chittagong (Near Feni)	160	SSE	8-10	-
5	28.05.63		Severe Cyclonic Storm	Chittagong-Cox's Bazar	209	SE	6-15	-
6	11.05.65		Severe Cyclonic Storm	Chittagong-Barisal Coast	160	SSE	8-12	-
7	05.11.65		Severe Cyclonic Storm	Chittagong	160	SE	12	-
8	15.12.65		Severe Cyclonic Storm	Cox's Bazar	210	SE	8-12	-
9	01.11.66		Severe Cyclonic Storm	Chittagong	120	SE	8-10	-
10	23.10.70		Severe Cyclonic Storm of Hurricane intensity	Khulna-Barisal	163	SW	20-22	-
11	12.11.70		Severe Cyclonic Storm with a core of hurricane wind	Chittagong	224	SE	-	-
12	28.11.74		Severe Cyclonic Storm	Cox's Bazar	163	SE	10-33	-
13	10.12.81		Cyclonic Storm	Khulna	120	SW	9-17	989
14	09.11.83		Severe Cyclonic Storm	Cox's Bazar	136	SE	-	986
15	24.05.85		Severe Cyclonic Storm	Chittagong	154	SE	5	982
16	29.11.88		Severe Cyclonic Storm with a core of hurricane wind	Khulna	160	SW	15	983
17	18.12.90		Cyclonic Storm (crossed as a depression)	Cox's Bazar Coast	115	SE	2-14.5	995
18	29.04.91		Severe Cyclonic Storm with a core of hurricane wind	Chittagong	225	SE	5-7	940

SL no.	Date of Occurrence	Name[1]	Nature of Phenomenon	Landfall Area	Maximum wind speed (km/hr)	Direction of the Max. Wind Speed	Tidal Surge Height (ft)	Central Pressure (mbs)
19	02.05.94		Severe Cyclonic Storm with a core of hurricane wind	Cox's Bazar-Teknaf Coast	220	SE	12-22	948
20	25.11.95		Severe Cyclonic Storm	Cox's Bazar	140	SE	5-6	998
21	19.05.97		Severe Cyclonic Storm with a core of hurricane wind	Sitakundu	232	SE	10	965
22	27.09.97		Severe Cyclonic Storm with a core of hurricane wind	Sitakundu	150	SSE	15	-
23	20.05.98		Severe Cyclonic Storm with core of hurricane winds	Chittagong Coast near Sitakunda	173	SSE	10-15	
24	15.11.07	SIDR	Severe Cyclonic Storm with core of hurricane winds (SIDR)	Khulna-Barisal Coast near Baleshwar river	223	SW	9.8	942
25	16.05.13	MAHSEN	Cyclonic Storm (Mahasen)	Noakhali-Chittagong Coast	100	SSE	6.6	-
26	21.05.16	ROANU	Cyclonic Storm (Roanu)	Barisal-Chittagong Coast near Patenga	128	WSW	7	992
27	30.05.17	MORA	Severe Cyclonic Storm (Mora)	Chittagong-Cox's Bazar Coast near Kutubdia	146	SE	4 to 5	998
28	08.10.2018	Titli 2018	Very Severe Cyclonic Strom	Khulna-Satkhira	148	SE	3.3	1004
29	05.11.2019	Bulbul 2019	Very Severe Cyclonic Strom	Khulna_Barishal area	139	SE	5-7	1004
30	26.04.2020	Fani 2020	Extremely Severe Cyclonic Strom	Khulna area	213	SSW	5	1000
31	16.05.2020	May 2020	Super Cyclonic Strom	Khulna area	241	SSW	-	1002
32	22.11.2020	Nivar 2020	Very Severe Cyclonic Strom		120		5	1002
33	23.05.2021	Yaas 2021	Very Severe Cyclonic Strom	Khulna area	139	SE/SW	20	996

Notes: [1]Before 2004 cyclones were not named.