

STORM SURGE INUNDATION MODELLING FOR AMPHAN IN BANGLADESH PART



By

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A thesis submitted in partial fulfilment of the requirements for the degree of
MASTER of SCIENCE in Civil Engineering

Department of Civil Engineering

CHITTAGONG UNIVERSITY OF ENGINEERING AND TECHNOLOGY

October 2024

Declaration

I hereby declare that the work contained in this thesis has not been previously submitted to meet the requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the Thesis contains no material previously published or written by another person except where due reference is cited. Furthermore, the Thesis complies with PLAGIARISM and ACADEMIC INTEGRITY regulation of CUET.

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Dedication

I dedicate my thesis to my parents and beloved wife for their endless love, support and encouragement throughout my pursuit of this journey.

List of Publications

Journal Article

Pollen C. and Aysha A. (2021). Flood Mapping in the Coastal Region of Bangladesh Using Sentinel-1 SAR Images: A Case Study of Super Cyclone Amphan. Journal of the Civil Engineering Forum (JCEF). Vol. 7 No. 3 . pp. 267 – 278. <https://doi.org/10.22146/jcef.64497>

Approval by the Supervisor

This is to certify that Pollen Chakma has carried out this research work under my supervision and that he has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology so that he is qualified to submit the following Thesis in the application for the degree of MASTER of SCIENCE in Civil Engineering. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulations of CUET.

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Acknowledgement

The author would like to extend his deepest gratitude and sincere thanks to his esteemed supervisor, Dr. Aysha Akter, Professor, Chittagong University of Engineering & Technology (CUET), Department of Civil Engineering, for her appropriate direction, priceless advice, and unceasing supervision throughout this research project. Throughout the thesis study, the author is grateful for her kind support, boundless creativity, and useful collaboration. Her genuine effort is also greatly appreciated by the author, as it greatly aided in the writing of this thesis. Furthermore, the writer would like to extend his sincere gratitude and debt of gratitude to his parents, friends, and family for their love, support, encouragement, and tolerance. Their encouragement and support served as a constant source of inspiration for my work.

Lastly, the this study was made possible through the use of data provided by the Bangladesh Water Development Board(BWDB), Bangladesh Inland Water Transport Authority (BIWTA) and Bangladesh Meteorological Department (BMD).

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Abstract

During a Cyclone storm surge related forecasting and warnings in Bangladesh are provided by Bangladesh Meteorological Department (BMD) by giving forecasting and warning of the expected storm surge height during a cyclone. This forecasting does not give any forecasting regarding areas that might be inundated due to the storm surge. This study focuses on developing a storm surge inundation model using Delft3D using current state of the art in storm surge inundation modelling. This research is based on the super cyclone Amphan, which made landfall on May 20, 2020, across the Sundarbans from the west Bengal-Bangladesh coast. Its wind speed ranged from 155 to 165 kmph with gusts up to 185 kmph.

At first the tide model is developed. Then after the calibration and validation of the tide model it is run using atmospheric forcing generated from the cyclone model. Cyclone model is run by using IMD and JTWC best track data of cyclone Amphan. Then calibration and validation of the cyclone model shows that the pressure field and wind field data produced using JTWC best track data shows better R^2 and NSE values as compared to IMD. Due to this reason pressure field and wind field data produced using JTWC best track data is used to force the storm surge inundation model to simulate cyclone Amphan. Then water levels at four BIWTA water level stations are calibrated and validated. Finally inundation scenario is also compared with two inundation maps for the validation of the inundated area produced by the storm surge inundation model. One is produced by NAWG by survey during Amphan and another one is inundation map produced using Sentinel-1 SAR images during Amphan. There are some findings related to challenges and different aspects in different stages of storm surge modelling in a data scarce region like Bangladesh that will help researchers to help storm surge inundation related studies in future.

বিমূর্ত

ঘূর্ণিঝড়ের সময় বাংলাদেশের আবহাওয়া অধিদপ্তর দ্বারা জলোচ্ছ্বাসের প্রত্যাশিত উচ্চতা সম্পর্কে পূর্বাভাস প্রদান করে বাংলাদেশে ঝড়বৃষ্টি সম্পর্কিত পূর্বাভাস এবং সতর্কতা প্রদান করা হয়। এই পূর্বাভাসে উপকূলীয় অঞ্চলের যেসব এলাকা জলোচ্ছ্বাসের কারণে প্লাবিত হতে পারে তার কোন নির্দেশনা নেই। তাই এই গবেষণাটি Storm Surge Inundation মডেলিং এ বর্তমানে ব্যবহৃত অত্যাধুনিক পদ্ধতি ব্যবহার করে Delft3D ব্যবহার করে একটি Storm Surge Inundation Model তৈরির উপর গুরুত্ব আরোপ করা হয়েছে। এই গবেষণাটি সুপার সাইক্লোন আফ্রানের উপর যা 20 মে, 2020 তারিখে পশ্চিমবঙ্গ-বাংলাদেশ উপকূলে সুন্দরবন জুড়ে আঘাত করেছিল। এর বাতাসের গতিবেগ ছিল 155 থেকে 165 কিমি প্রতি ঘণ্টা এবং ঝোড়ো হাওয়ার সাথে 185 কিলোমিটার পর্যন্ত।

প্রথমে Tide Model তৈরি করা হয়। তারপরে Tide Model এর Calibration এবং Validation এর পরে এটি ঘূর্ণিঝড় মডেল থেকে সৃষ্ট এটমোস্ফেরিক ফরসিং প্রয়োগ করে রান করা হয়। সাইক্লোন মডেল IMD এবং JTWC সাইক্লোন আফ্রানের বেস্ট ট্র্যাক ডেটা ব্যবহার করে চালিত হয়। তারপর Cyclone Model এর Calibration এবং Validation এ দেখায় যে JTWC বেস্ট সেরা ট্র্যাক ডেটা ব্যবহার করে উৎপাদিত উইন্ড ফিল্ড এবং প্রেশার ফিল্ড ডেটা IMD এর তুলনায় ভাল R^2 এবং NSE মান দেখায়। এই কারণে JTWC সেরা ট্র্যাক ডেটা ব্যবহার করে উৎপাদিত উইন্ড ফিল্ড এবং প্রেশার ফিল্ড ডেটা ঘূর্ণিঝড় আফ্রানের অনুকরণে ঝড়ের জলোচ্ছ্বাসের মডেলকে রান করতে ব্যবহৃত হয়। তারপর চারটি BIWTA ওয়াটার লেভেল স্টেশনে ওয়াটার লেভেল এর মাধ্যমে Calibration এবং Validation করা হয়। অবশেষে জলোচ্ছ্বাস দ্বারা উৎপাদিত প্লাবিত এলাকার Validation জন্য দুটি Inundation Map এর সাথে তুলনা করা হয়। একটি আফ্রানের সময় জরিপ দ্বারা NAWG দ্বারা তৈরিকৃত এবং অন্যটি আফ্রানের সময় Sentinel-1 SAR চিত্রগুলি ব্যবহার করে সৃষ্ট Inundation Map। এখানে বাংলাদেশের মতো ডেটার ঘাটতি অঞ্চলে Storm Surge Inundation মডেলিংয়ের বিভিন্ন পর্যায়ে চ্যালেঞ্জ এবং বিভিন্ন দিক সম্পর্কিত কিছু অনুসন্ধান রয়েছে যা গবেষকদের ভবিষ্যতে Storm Surge Inundation মডেলিং সম্পর্কিত গবেষণায় সাহায্য করবে।

Table of Contents

Abstract	VI
বিমূর্ত	VII
Table of Contents	VIII
List of Figures	XI
List of Tables.....	XV
Nomenclature	XVI
Chapter 1: INTRODUCTION	1
1.1 Background	1
1.2 Context	4
1.3 Aims and Objectives	5
1.4 scope of the study	6
1.5 Thesis Outline	6
Chapter 2: LITERATURE REVIEW	10
2.1 Tropical Cyclone.....	10
2.5.1 Classification of Tropical Cyclone	10
2.5.2 Tropical Cyclone Structure and its Formation.....	12
2.5.3 Formation of Tropical Cyclone.....	13
2.2 Storm Surge	14
2.5.1 Genesis of Storm Surge/ Physical Processes of Cyclone Induces Storm Surge.....	14
2.5.2 Factors Contributing to Storm Surge Height	15
2.3 Wave.....	19
2.4 Tide	20
2.5.1 Generation of Tide.....	22
2.5.2 Tidal Predictions.....	26
2.5.3 Characteristics of Tide Along Bangladesh Coast.....	31
2.5 Coastal Flooding.....	32
2.6 Storm Surge and Bangladesh Coast.....	33
2.5.1 The Coastal Zone of Bangladesh.....	33
2.5.2 Characteristics of Northern Bay of Bengal	36
2.5.3 Cyclone and Storm Surge scenario in the Northern Bay of Bengal	37
2.7 Coastal Polders	39

2.8	Modelling of the Physical Processes	40
2.5.1	Cyclone Model	40
2.5.2	Previous storm surge study in the BoB	42
2.9	SUMMARY AND IMPLICATIONS.....	49
Chapter 3: THEORETICAL BACKGROUND.....		50
3.1	Theoretical Background of the Hydrodynamic Model	50
3.2	Theoretical Background of the Wind Setup.....	53
3.3	Wave Model	54
3.4	Flood Inundation Map using Sentinel-1 SAR Images	56
3.5	Performance Evaluation of The Model.....	58
3.5.1	Coefficient of determination (R^2)	59
3.5.2	The Nash–Sutcliffe Efficiency (NSE)	60
3.6	Summary.....	61
Chapter 4: MODEL SETUP, CALIBRATION AND VALIDATION		64
4.1	Delft3D	64
4.2	STUDY AREA	66
4.3	Tropical Cyclone used for VALIDATION: Amphan (2020).....	66
4.4	Model Setup	69
4.5.1	Model Grid Development.....	70
4.5.2	Bathymetry and Topography	72
4.5.3	Time Step.....	73
4.5.4	Boundary Condition	74
4.5.5	Model Forcing.....	76
4.5	Model Calibration and Validation	78
4.5.1	Calibration and Validation of the Tide Model.....	80
4.5.2	Calibration and Validation of the Cyclone Model	88
4.5.3	Calibration and Validation of the Storm Surge Model.....	95
4.5.4	Validation of the Inundation Area.....	100
Chapter 5: DISCUSSION		108
5.1	Tide model.....	108
5.2	Cyclone Model	110
5.3	Storm surge Inundation model	111

Chapter 6: CONCLUSIONS	114
6.1 Key Findings	114
6.2 Limitation of the Study	115
6.3 Practical Implication.....	116
6.4 Recommendation for Further Study	117
Bibliography	118
Appendices	124

List of Figures

Fig. 1.1 Contour showing depth of different location of the Bay of Bengal (Garzanti, 2019))	2
Fig. 1.2 Thesis Outline.....	8
Fig. 2.1 A Schematic of Tropical Cyclone structure and its different components (iLearncana,2020)	13
Fig. 2.2 Tidal Patterns along earths coastline (a) Diurnal (b) Semidiurnal (c) Mixed Semidiurnal (NOAA).....	21
Fig. 2.3 Spatial distribution of different tidal patterns along earths coastline (NOAA).....	22
Fig. 2.4 Bulging of earths water at 0° and 180° position due to moons gravity.....	24
Fig. 2.5 Moon lags behind 50min every day after the earth make one rotation in 24 hours	25
Fig. 2.6 Central solid red circle as earth having two solid ellipses representing the tidal force envelopes produced by the moon in different positions and the dashed ellipse is representing the tidal force envelop produced by the sun	26
Fig. 2.7 Tide analysis of San Diego, California showing tidal curve for different constituents.	30
Fig. 2.8 Example of global tide model(TPXO 9) showing real time water level variation due to astronomical tide. Adopted from: Egbert and Eroffeeva (2002)	31
Fig. 2.9 Morphological zones of coastal area of Bangladesh	36
Fig. 2.10 Coastal Polders in the Coastal Zone.....	40

Fig. 2.11 Spider web grid. Adopted from DELFT3D flow manual	42
Fig. 3.1 Definition of water level, depth and total depth (b) σ grid. Adapted from Deltares (2018)	51
Fig. 3.2 An example of a vertical grid consisting of six equal thickness of σ layers (Delaures 2013)	52
Fig. 3.3 Schematization of a single wave with relevant parameters displayed	55
Fig. 4.1 Model Bathymetry in the computational domain.....	73
Fig. 4.2 Generated Pressure filed during the approaching of super cyclone Amphan using parametric model.....	77
Fig. 4.3 Generated wind filed during the approaching of super cyclone Amphan using parametric model.....	78
Fig. 4.4 Water Level Stations.....	81
Fig. 4.5 Water level Calibration of the tide model at (a) Kutubdia, (b) Tojumuddin (c) Kuakata (d) Sadarghat(ctg)	83
Fig. 4.6 On the left relationship between the simulated and observed water level at (b) Kutubdia (c) Tojumuddin (e) Kuakata (g) Sadarghat in optimum space varying manning roughness condition are shown along with their respective R2 and NSE on the left. On the right relationship between the simulated and observed water level at (b) (d) (f) (h) in fixed manning roughness condition are shown along with their respective R ² and NSE.	85
Fig. 4.7 Water level validation of the tide model at (a) Kutubdia, (b) Tojumuddin (c) Kuakata (d) Sadarghat	86

Fig. 4.8 Relationship between the simulated and observed water level at station (a) Kutubdia (b) Tojumuddin (c) Kuakata (d) Sadarghat along are shown with their goodness of fit indices.....	87
Fig. 4.9 Observed Air pressure and simulated air pressure in millibar(or mbar) for JTWC and IMD best track for Amphan shown in time series at station (a) Khulna (b) Patuakhali (c) M Court	89
Fig. 4.10 BMD Observation Stations for the validation of the cyclone model.....	90
Fig. 4.11 Relationship between the simulated and observed air pressure are shown at station (a) Khulna (c) Patuakhali (e) M Court with their goodness of fit indices in the left. , Relationship between the simulated and observed wind speed are shown at station (b) Khulna (d) Patuakhali (f) M Court with their goodness of fit indices in the right.....	91
Fig. 4.12 Observed wind speed and simulated wind speed in kmph for JTWC and IMD best track for Amphan shown in time series at station (a) Khulna (b) Patuakhali (c) M Court.....	92
Fig. 4.13 Relationship between the simulated and observed wind speed are shown at station (a) Khulna (c) Patuakhali (e) M Court with their goodness of fit indices in the left. , Relationship between the simulated and observed wind speed are shown at station (b) Khulna (d) Patuakhali (f) M Court with their goodness of fit indices in the right.....	93
Fig. 4.14 Water level validation of the storm surge model at (a) Kutubdia, (b) Tojumuddin.....	96
Fig. 4.15 Water level validation of the storm surge model at (a) Kuakata (b) Sadarghat.....	97

Fig. 4.16 Relationship between the simulated and observed water level at station (a) Kutubdia (b) Tojumuddin (c) Kuakata (d) Sadarghat.....	99
Fig. 4.17 Inundation map of the flooding caused by cyclone Amphan generated from simulation of the storm surge model	100
Fig. 4.18 Inundation map based the validation survey by NAWG, Bangladesh.	101
Fig. 4.19 Inundation map of the flooding caused by cyclone Amphan in the coastal region of Bangladesh generated from the Sentinel-1 SAR image taken on May 22, 2022.....	101
Fig. 4.20 Comparison between model generated inundation area and satellite derived inundation area in (a) Patuakhali (b) Barguna (c) Bhola during cyclone Amphan.....	103
Fig. 4.21 Comparison between model generated inundation area and satellite derived inundation area in (a) Barisal (b) Jhalokati (c) Pirojpur during cyclone Amphan.....	105
Fig. 4.22 Comparison between model generated inundation area and satellite derived inundation area in (a) Bagerhat (b) Khulna (c) Satkhira during cyclone Amphan.....	106

List of Tables

Table No.	Table Caption	Page No.
Table 2.1.	A summary of the list of influencing factors affecting storm surge.	17
Table 2.2.	List of 37 tidal harmonic constituents used for tidal prediction with their common name and description(Pugh and Woodworth, 2014).....	27
Table 2.3	Maximum surge height records along the Bangladesh coasts	38
Table 2.4	A summary of the preveious storm surge study in the BoB	43
Table 4.1	Topography and bathymetry sources.....	72
Table 4.2	Applied Manning’s roughness coefficient, n in the Bay of Bengal..	81
Table 4.3	Model Goodness-of-fit indices for tide model at different station for space varying mannings n	87
Table 4.4	Model Goodness-of-fit indices for the calibration and validation of the wind model at three BMD station.....	94
Table 4.5	Evaluation of Goodness-of-fit indices for storm surge model at different station.....	99

Nomenclature

Symbols

α	:	Local upslope drainage through a certain point per unit contour length
β	:	Local slope in radians
E	:	East Longitudes
e	:	Margin of error
km/hr	:	Kilometre Per Hour
m	:	Meters
m/km	:	Meters Per Kilometre
mm/year	:	Millimetres Per Year
N	:	North Latitudes
Z	:	Level of Significance
°	:	Degree
'	:	Minutes
"	:	Seconds
°C	:	Degree Celsius

Acronyms and Abbreviations

BoB	:	Bay of Bengal
BMD	:	Bangladesh Meteorological Department
GEE	:	Google Earth Engine
IMD	:	Indian Meteorological Department
JMA	:	Japan Meteorological Agency
MSL	:	Mean Sea Level
TC	:	Tropical Cyclone
TCP	:	Tropical Cyclone Programme
WMO	:	World Meteorological Organization
DDB	:	Delft Dashboard
DSM	:	Digital Surface Model

Chapter 1: INTRODUCTION

1.1 BACKGROUND

Coastal flooding caused by storm surges are considered as one of the most destructive natural hazards along coastlines worldwide. According to Bouwer and Jonkman (2018), storm surges caused an annual average of over 8,000 fatalities. 1.5 million individuals got affected globally over the past century. The Bay of Bengal, located in the northern Indian Ocean, is among the most dangerous basins for storm surges.

On an average there are five surge events took place every decade having surge height over 5m, it often experiences the highest surges worldwide (Needham, Keim and Sathiaraj, 2015). The most intense storm to ever be recorded in the Bay of Bengal was found on May 18, 2020, when a super-cyclone by the name of Amphan reached a sustained wind speed of over 240 km/h (130 knots) and a maximum wind gust of 260 km/h in just one minute. Amphan made landfall on the beaches of Bangladesh and West Bengal two days later on May 20, 2020. With sustained wind speeds of 112 km/h and gusts of 190 km/h, the storm caused enormous damage and claimed hundreds of lives. (IMD, 2020). According to IMD cyclone best track data, cyclone Amphan(2020) is the third super cyclone originating in the Bay of Bengal(BoB) in the last two decades, with 128 casualties. The other two were the 1999 Odisha Supercyclone and the 1991 Bangladesh Cyclone. It shows how the cyclone scenario in the BoB has been getting more severe recently.

According to Needham et al. (2015), the Bay of Bengal exhibits a unique pattern of cyclone activity when compared to other oceanic basins. According to Bhardwaj and Singh (2019), this basin has a unique bi-modal allocation of

cyclonic occurrence activity. One peak taking place during the pre-monsoon season during April–May. And another during the post-monsoon season during the month of October–November. This result implies that cyclone activity in the Bay of Bengal is different from that in other basins and emphasises the need for more investigation into the elements that lead to this unique pattern.

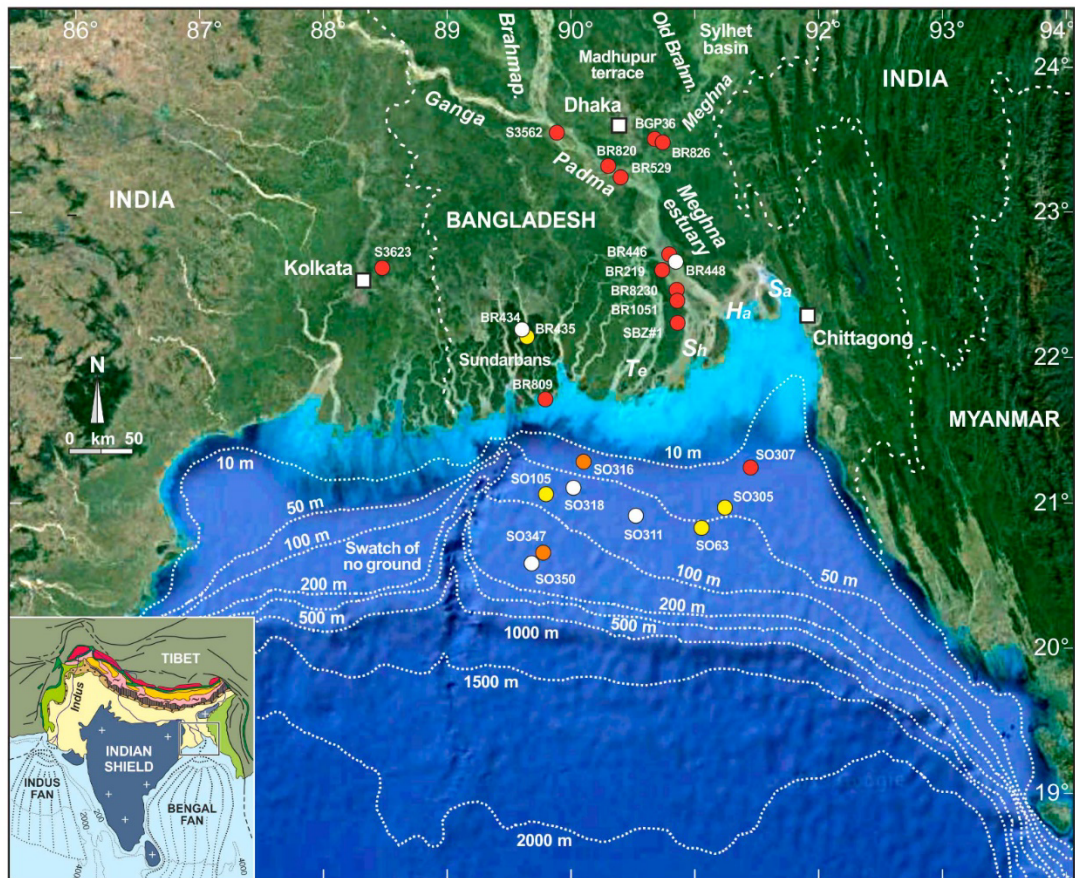


Fig. 1.1 Contour showing depth of different location of the BoB (Garzanti, 2019))

Figure 1.1 depicts the Bay of Bengal, a small semi-enclosed region that is home to just 6% of all cyclones worldwide. Over the past century, this region has accounted for over 70% of global cyclone-related deaths and the storm surges they generate (Ali, 1999). In the Bengal Delta region of Bangladesh and India, more than 150 million individuals live below 5 meters above mean sea

level (MSL), where numerous fatalities have been recorded (Alam and Dominey-Howes, 2014). Previous studies indicate a strong correlation between storm surge height and the number of fatalities in this area (Seo and Bakkensen, 2017). Significant cyclones that have impacted the delta include the 1970 Bhola cyclone, which resulted in approximately 300,000 deaths (Frank and Husain, 1971), and the 1991 Gorky cyclone, which claimed around 150,000 lives (Khalil, 1993). However, in recent decades, the number of fatalities has significantly decreased. For example, Cyclone Sidr in 2007, classified as a category five cyclone on the Saffir-Simpson scale, caused 3,406 deaths (Paul, 2009). Despite this reduction in fatalities, the financial costs of damage have soared (Alam and Dominey-Howes, 2014; Emanuel, 2005; Schmidt et al., 2009). In an effort to mitigate the effects of these natural disasters, the governments and voluntary organizations of Bangladesh and India evacuated millions to cyclone shelters prior to the storm's arrival (Paul and Dutt, 2010). Enhanced communication, an increase in shelters, and improved numerical predictions of storm tracks and intensity have all played vital roles in facilitating this effective coordination.

storm surge forecasting has seen significant global advancements in recent years, evolving in tandem with improvements in weather and storm prediction technologies (Bernier and Thompson, 2015; Daniel et al., 2009; Flowerdew et al., 2012; Lane et al., 2009; Verlaan et al., 2005). Today, operational surge forecasting systems are typically deployed on high-performance computing infrastructures. These systems are designed to function either according to a pre-planned schedule or in response to specific operational triggers. They generally maintain a horizontal resolution of 3.7 km and can operate continuously for up to ten years (Dube et al., 2009).

In particular, the Bangladesh Meteorological Department (BMD) employs the IIT-D model as a crucial component of its efforts under the Tropical Cyclone

Program (TCP) established by the World Meteorological Organisation (WMO). This collaboration allows for enhanced accuracy in storm surge forecasting, enabling more effective disaster preparedness and response strategies. The integration of advanced modeling techniques has been instrumental in providing timely and reliable surge predictions, which are vital for safeguarding communities in vulnerable regions. As such, the ongoing development and implementation of these forecasting systems represent a significant step forward in managing the impacts of cyclones and their associated storm surges.

1.2 CONTEXT

Over the past century, numerous numerical models have been created to predict storm surges in the BoB . While these models have effectively forecasted storm surge heights, most have primarily focused on predicting peak surge heights along the Bangladeshi coastline. Only a few studies have attempted to include surge height inundation predictions in their modelling efforts. The Bangladesh Meteorological Department (BMD) employs various numerical and regression models to provide operational forecasts of maximum surge heights and cyclone tracks. Although early warning systems and increased access to cyclone shelters have helped reduce loss of life, effectively mitigating the impact of storm surges still relies on accurate predictions of inundation in coastal areas. While BMD's models offer valuable information about the timing and locations of maximum wave heights and surges, predictions of storm surge inundation remain underdeveloped. Therefore, there is a pressing need to explore storm surge inundation prediction systems that can enhance emergency planning and create a robust warning system aligned with BMD forecasts.

Storm surge forecasting system in this region are still based on storm surge height. But flooding and the extent of the flooding is also an important

part of the storm surge. This study focuses on developing a storm surge inundation model to storm surge forecasting by modelling the inundation scenario due to storm surge. So that forecasting due to storm surges can be given based on the storm surge height as well as the extent of flooding in the coastal areas. The Study focuses on developing a storm surge inundation model in the Bay of Bengal using Delft 3D software. The model domain also includes the coastal region of Bangladesh. The hydrodynamic model files are developed by using Delft Dashboard software which makes the model development faster due to its ease of operation and easy user interface.

1.3 AIMS AND OBJECTIVES

This study aims on developing a storm surge inundation model to storm surge forecasting by modelling the inundation scenario due to storm surge. This research aims to create an innovative inundation prediction system that can enhance the storm surge forecasting system in Bangladesh. To achieve this objective, the sub-objectives are:

- To develop a tide model of the Bay of Bengal using Delft 3D software
- To develop a storm surge inundation model by coupling the previously developed tide model and wave model based on the scenario of cyclone Amphan

Thus, the goal of the research work is to create a storm surge inundation model to facilitate the storm surge forecasting system in Bangladesh by giving insights about predicting storm surge height and extent of the inundation.

1.4 SCOPE OF THE STUDY

The focus of the study is to develop a storm surge inundation model in the Bay of Bengal for Bangladesh part using Delft3D software. For the development of the storm surge inundation model at first the tide model which is basically the hydrodynamic model is developed. After the calibration and validation of the model tide model is coupled with the wave model the generate the storm surge during the cyclone Amphan. This study will assess the storm surge height during cyclone Amphan and identify the inundated area in the coastal region of Bangladesh using the storm surge inundation model . The study will cover 315 thousand square km area including the northern Bay of Bengal and 14 coastal districts of Bangladesh. For calibration and validation of the model water level in 4 tidal gage data from BIWTA will be used during the Month of May in 2020. The study also utilizes best track data of cyclone Amphan from IMD and JTWC to generate the wind field and velocity field during the time of cyclone Amphan. The study also uses Sentinel-1 SAR imagery to produce the inundation map during Amphan and to compare it with the model generate inundation scenario. Due to the lack of wave observation data the inundation model is run without the calibration and validation of the study.

This study will help to understand the coastal dynamics. It also help to point out the challenges of storm surge inundation modelling in data scarce region like Bangladesh.

1.5 THESIS OUTLINE

The thesis is structured into six distinct chapters, each addressing various aspects of the research. Chapter one provides an in-depth background of the study, placing particular emphasis on both historical and contemporary cyclonic events. This chapter not only examines the occurrence and impact of

these cyclones but also discusses the rationale behind the research. It articulates the specific problems and limitations associated with existing storm surge modeling approaches, highlighting the gaps in current knowledge and methodologies. Furthermore, this chapter meticulously outlines the principal objectives of the study, as well as its scope, ensuring that readers have a clear understanding of the research focus and its intended contributions to the field. Overall, this introductory chapter sets the stage for the subsequent analysis and findings presented throughout the thesis.

In chapter two, the past and present storm surge scenario is presented in the northern bay as well as in the Bangladesh coast. This chapter also outlined different modelling approaches and techniques associated with storm surge modelling. A comparative study of different storm surge modelling approaches along the Bangladesh coast is also presented in this chapter. Furthermore, a brief description of the coastal regions of Bangladesh is also given.

In chapter three, the methodology used in this study is discussed. Also, how and what performance indices will be used to evaluate the model is discussed

In chapter four, implementation of the storm surge model using Delf3D and Delft Dashboard software is discussed. This chapter consist of developing different models to construct the final storm surge inundation model. It is followed by calibration and validation of these different models. Then the validation of the final storm surge model by using SAR imagery is discussed. Then at the end of the chapter vulnerable polders classification based on depth

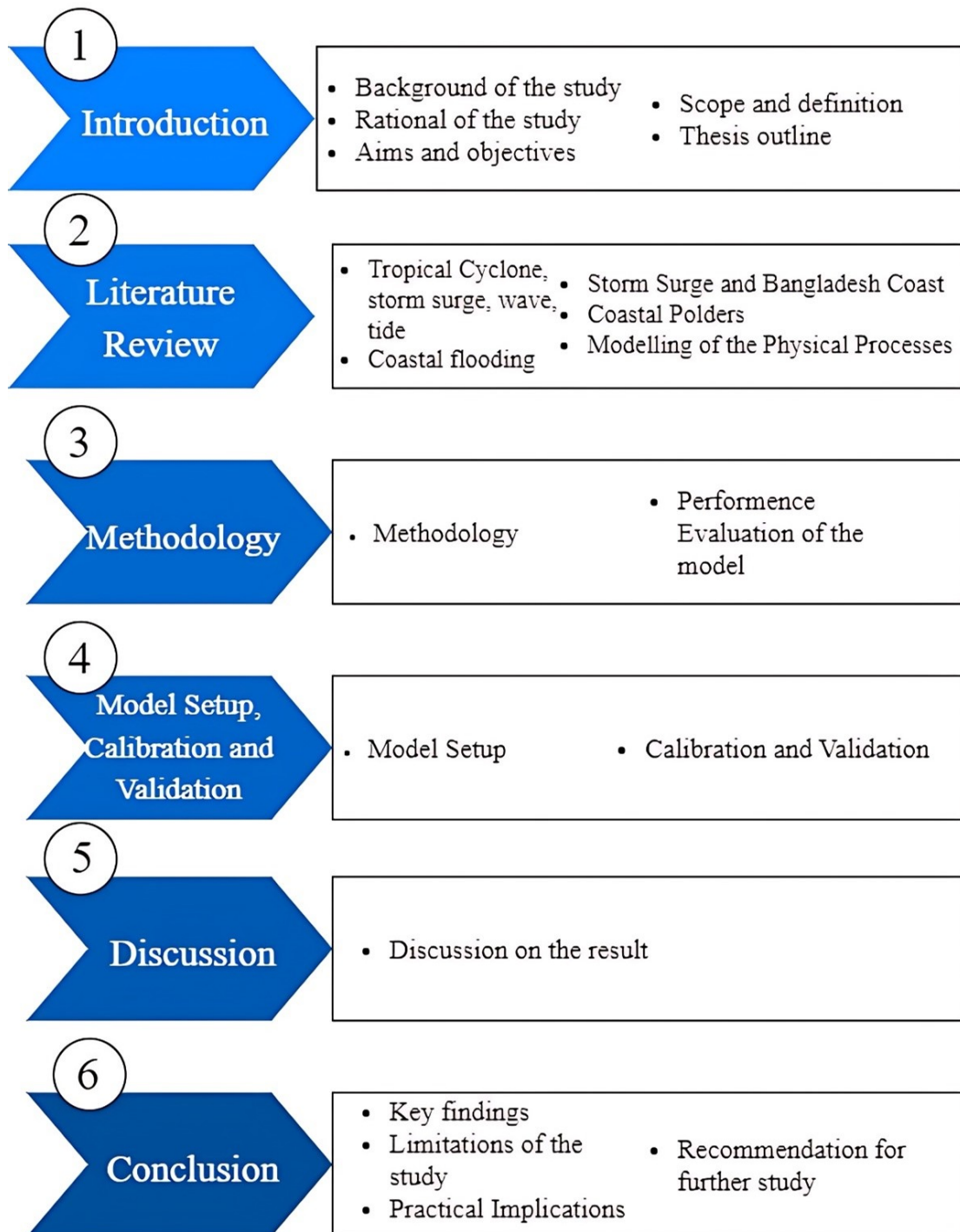


Fig. 1.2 Thesis Outline

of inundation in different SLR condition found from the validated storm surge inundation model is discussed.

In chapter five, results derived from the storm surge model are discussed.

Finally in chapter six, conclusions are made based on the results. Future recommendations are provided to improve the model outcome and to overcome the limitations of this study.

After the conclusions references are provided in the bibliography section.

Then in Appendix A, Google Earth Engine (GEE) codes that used to find the inundated area during Amphan are given.

Chapter 2: LITERATURE REVIEW

Gaining a comprehensive understanding of the physical processes that govern storm surge-induced flooding in coastal regions is a fundamental prerequisite before engaging in any modeling activities. Consequently, this chapter encompasses essential concepts pertaining to tropical cyclones, storm surges, waves, tides, and coastal flooding. A significant focus is placed on the specific study area, where the chapter examines the current dynamics of cyclone-induced storm surges and the related flooding scenarios within the context of Bangladesh. By analyzing historical and recent events, the chapter aims to provide a clearer picture of the vulnerabilities faced by this region.

Moreover, the chapter offers a detailed description of the current state-of-the-art methodologies employed in storm surge-induced flood modeling. It highlights a variety of modeling suites and approaches that are widely utilized in the field, each with its own strengths and limitations. This exploration of different modeling techniques is crucial for understanding how they can be applied to accurately simulate the complexities of storm surge phenomena and their impacts on coastal communities. By laying this groundwork, the chapter prepares the reader for the subsequent discussions on the implementation and refinement of these models in addressing storm surge-related challenges.

2.1 TROPICAL CYCLONE

2.4.1 Classification of Tropical Cyclone

In tropical regions, the formation of large-scale, warm-cored rotary storms occurs over warm ocean waters, driven by heat transfer from the ocean's surface. These significant meteorological phenomena are classified as tropical

cyclones (Emanuel, 2003). Tropical cyclones are characterized by their association with strong winds, low atmospheric pressure, heavy rainfall, and the occurrence of thunderstorms. Importantly, these storms are designated by different names depending on their geographical location; in the Atlantic Ocean, they are referred to as hurricanes, while in the Pacific Ocean, they are known as typhoons. In the Indian Ocean, these systems are simply called tropical cyclones or cyclones.

The classification of tropical cyclones is determined based on five distinct intensity scales that assess both the maximum sustained wind speeds and the specific oceanic basin from which the cyclone originates. In the case of cyclones that develop in the North Indian Ocean, the classification adheres to the tropical cyclone intensity scale provided by the Indian Meteorological Department (IMD). This particular scale categorizes cyclones into seven distinct classes, which are defined according to the estimated maximum sustained wind speeds measured over a three-minute interval.

The lowest classification, known as "Depression," encompasses sustained wind speeds ranging from 17 to 27 knots (20–31 mph; 31–49 km/h). If the sustained wind speed increases to between 28 and 33 knots (32–38 mph; 50–61 km/h), the storm is then categorized as a "Deep Depression." When sustained wind speeds reach between 34 and 47 knots (39–54 mph; 62–88 km/h), the system is classified as a "Cyclonic Storm." For storms classified as "Severe Cyclonic Storms," the sustained wind speeds must be between 48 and 63 knots (55–72 mph; 89–117 km/h). The classification progresses to "Very Severe Cyclonic Storm" when wind speeds range from 64 to 89 knots (73–102 mph; 118–166 km/h). Finally, storms exhibiting sustained wind speeds of 90 to 119 knots (104–137 mph; 166–221 km/h) are designated as "Extremely Severe

Cyclonic Storms." The most intense category, referred to as "Super Cyclonic Storm," includes systems with sustained wind speeds exceeding 120 knots (138 mph; 222 km/h) (Secretariat of the World Meteorological Organization, 2007). This comprehensive classification system is crucial for understanding the potential impact of these powerful storms on coastal regions and for developing effective preparedness and response strategies.

2.4.2 Tropical Cyclone Structure and its Formation

Tropical cyclone structure is very complex and has been studied by the researchers extensively. These studies has been conducted by means of satellites, radars, airplanes and through numerical simulations (Emanuel, 2003). A TC has three major components: storm-scale structure, inner-core and spiral rainbands. Storm-scale structure corresponds to the who cyclonic structure with sustained wind speed higher than 15m/s. Inner core includes the eye of the storm and the eyewall. The center of the TC is called the eye. It is the calmest part of the TC compared to the rest of the storm. Well-developed TCs have well defined eye which can be easily seen and distinguished form the rest of the storm. The eye is not generally well defined in case of TCs with lower intensity. Eyewall is a ring of very deep convective cloud with highest winds and precipitation. It is also associated with severe thunderstorm. It extends outwards form the edge of the eye. Usually 20-50 km outwards form the edge of the eye. It controls the shrinking and the growth of the eye. Then rainbands are the most outer component of a cyclone structure. It can extent up to 150km from they eye base on the size of the TC. Rainbands are arranged in a spiral fashion(Wang and Wu, 2004). An schematic of a TC structure with its major components are shown in Figure 2.1

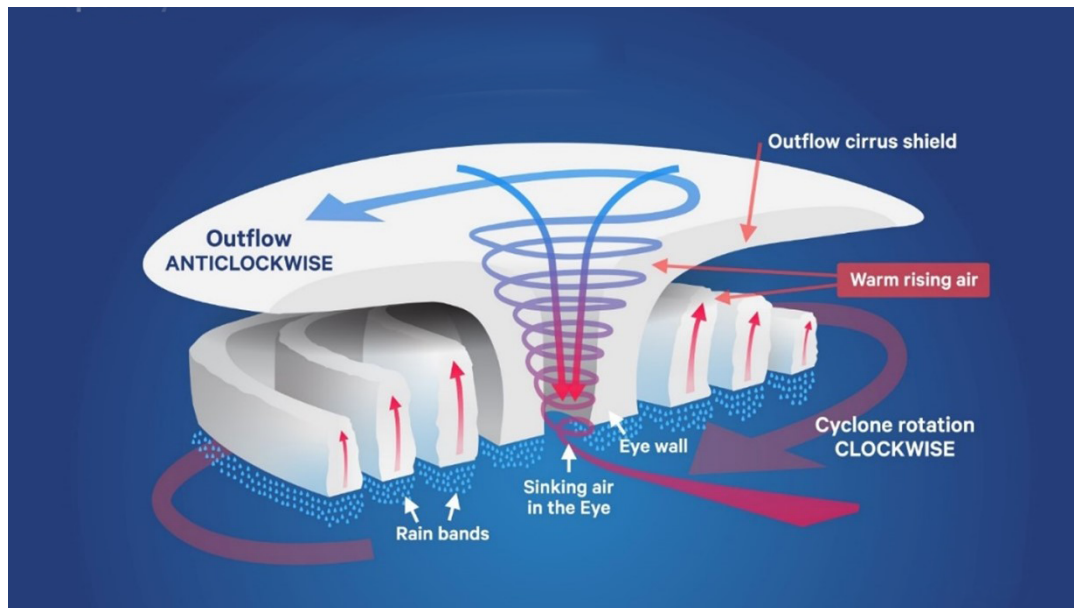


Fig. 2.1 A Schematic of Tropical Cyclone structure and its different components
(iLearncana,2020)

2.4.3 Formation of Tropical Cyclone

Tropical cyclones start to form in the ocean when the ocean surface temperature rises significantly in association with lower air pressure. The formation of tropical cyclone is called cyclogenesis. There are five climatological conditions that are responsible for the formation of TC's, high sea surface temperature, a deep surface based layer of conditional instability, enhanced values of cyclonic low level absolute vorticity, organized deep convection in an area with high to mid level humidity and weak to moderate vertical wind shear. When sea surface temperature increases the warm ocean water get evaporated. Then it starts to develop TC. TC gains strength and intensity form the head of the ocean. Gradually vapour forms cloud by condensation. Vorticity in air or the clockwise or anticlockwise movement of air assists TC formation. For sustainable cloud formation and thunderstorm TC requires humidity. So high to mid-level humidity favours TC formation. Vertical wind shear is the difference in speed and direction of wind at two different heights in the atmosphere. TC develops under low to moderate vertical wind shear condition.

2.2 STORM SURGE

Storm surge is defined as the water being pushed towards the land causing an abnormal temporary rise of sea level from the predicted astronomical tide due to a TC. This abnormal rise in sea level during a TC causes inundation in the coast damaging infrastructures, extensive property loss with lots of casualties. Storm surge is mainly generated in the deep sea. Drag effect of wind is the main driving force of storm surge. There are few more contributing factors that are associated with the genesis of storm surge which are discussed in the Section 2.2.1. Damage associated with a storm surge is governed by many factors and height of the storm surge is the most influential of all. There are many factors that are responsible for the significant rise of the height of the storm surge. These factors are discussed in Section 2.2.2.

2.4.1 Genesis of Storm Surge/ Physical Processes of Cyclone Induces Storm Surge

There are five main physical processes that are responsible for the genesis of the storm surge during a TC. They are effect of low atmospheric pressure, shear stress developed by the dragging effect of wind, Coriolis effect, effect of wave and effect of rainfall (Harris, 1964). The genesis of the storm surge initiates during the formation of TC when it is in the deep sea. Air pressure is low at the centre of the cyclone. This low air pressure causes a slight bulging of the sea surface reported to have approximately 1cm rise in the water level due to 1hPa pressure drop the eye of the cyclone (McInnes *et al.*, 2002).

After the formation of the cyclone, it develops and approaches towards the coast. During its approaching towards the coast the depth of the water gradually decreases. The volume of water builds up by the bulging of the sea surface at the eye of the cyclone can not disperse in the low water depth due to the presence of the shallow sea bed. Also this water is pushed towards the coast due to the swirling motion of the wind causing rise of the sea level generating storm surge. There are many factors such as the topography, bathymetry, forward

speed, central pressure, and angle of approach that influence the height of the storm surge. Some of them have major influence on storm surge and some of them have minor influences on the height of the storm surge. In Section 2.3.2 influencing factors of storm surge height are discussed.

2.4.2 Factors Contributing to Storm Surge Height

TCs associated with property damage and loss of life in the coast. It comes with heavy rainfall, thunderstorm, very violent winds, high waves, and destructive large storm surges. Despite having its many destructive effect in the coast the classification system that are currently available for tropical cyclone are based only on the wind speed value. But storm surge is considered to have the most life-threatening effects on the coast. Water level rise caused by storm surge causes severe flooding in the coastal region. Its effect amplifies when storm surge coincides with astronomical tides, heavy rainfall in the coastal regions and with other many influencing factors. Table 2.1 describes the influencing factors of storm surges, details are:

Astronomical tides: Astronomical tide is the periodic rise and fall of the sea level due to the gravitational influence of the sun and moon on the earth. Tide-surge plays an important role in the storm surge level. In literature, effect of tide on total storm surge is termed as Tide-Surge Interaction which is basically the addition height of water due to tide. Study shows that tidal phase have a direct impact on the storm surge height and time of surge peak. Generally, it is expected to have higher storm surge during a high tide and lower surge height during a low tide. But study have found the relationship between tidal phase and the storm surge height to be non-linear. Thus lower storm surge in a particular area could be observed during a high tide than a surge height during a low tide depending on different parameter of the cyclone and these are approaching angle of the cyclone, wind speed and direction, proximity to the cyclone track etc (Azad et al., 2018). In another study on the

tide-surge interaction it is found that influence of tidal phase on storm surge height and time of surge peak is dependent on the storm surge and tidal modulation which are related to the parameters of the cyclone track (Zhang *et al.*, 2019). Further research in this field continues to enhance our understanding of these interaction phenomena, aiding in more accurate coastal risk assessments and better-informed disaster preparedness efforts.

Effect of Wave: In the past the effect of wave was not considered in storm surge modelling. But the current state of art considers the effect of wave by considering wave setup. Wave setup refers to the additional height gained due to the effects of waves. Momentum is transferred from wind to wave in the area where the wave is generated. Then wave conveys momentum to the shore. During the process momentum is transferred to the water column. This momentum transfer creates a shoreward push on the water which causes the water surface to rise. Wave setup is small as compared to the overall surge height but begins to rise in the surf zone due to the moment transfer mechanism. Shoreline with steeper bottom slope and large and long period swells are susceptible to large wave setup due to the accumulation of more water column during approaching towards the shoreline (Guill, 2020). Recognizing the significance of wave setup in storm surge modelling, we gain a deeper understanding of the interaction between meteorological and oceanographic forces, enabling us to better predict and prepare for the complex dynamics of storm surge .

Table 2.1. A summary of the list of influencing factors affecting storm surge.

Authors	Study Area	Influencing Factors	Findings
(Terry, Kim and Jolivet, 2013)	South West Indian Ocean	Angle of approach towards coast, Spatial pattern of the TC track	• TC approaching perpendicular to the shore tend to produce more surge than TC approach at an oblique angle. • Curvature in the cyclone track controls cyclone intensity
Poulose et al. 2017(Poulose, Rao and Bhaskaran, 2018)	West Coast of India	Shape, width, slope, and length of the continental shelf	• Continental shelves with wide and gentle slope produces higher storm surge as compared to narrow and steep sloped continental shelves • Shallower and longer continental shelves produce higher storm surge
Antony and Unnikrishnan, 2013(Antony and Unnikrishnan, 2013)	East Coast of India, Bay of Bengal	Effect of tide	• Surge peak distribution can be explained by phase alteration due to surge and surge modulation by tide. • Detailed numerical study is suggested to find the factors affecting tide surge interaction.
Chenguang Zhang and Chunyan Li (Zhang and Li, 2019)	An idealized numerical simulation with simplified hypothetical region	Cyclone forward speed (V) and approaching angle (θ)	• TC with higher moving speed produces higher surges. • Continental shelves with sloped bathymetry maximum surge height occurs at a specific acute approach angle. • Optimal value of V and θ for maximizing the storm surge for semi circular ocean is a function of bathymetry.

Rainfall: Extreme rainfall during and ahead of TC landfall can cause rise of the river water level. Which can aggravate the overall surge height caused by a TC. Effect of river discharge caused by heavy rainfall is Natural and manmade levees along the riverbank

Table 2.1. A summary of the list of influencing factors affecting storm surge(Cont'd)

Authors	Study Area	Influencing Factors	Findings
Li et al. 2022(Li et al., 2022)	Hangzhou Bay, East coast of China	Effect of tide, wind stress, atmospheric pressure drop in the eye of the TC, effect of Wave	• Tide-surge interaction contributes 50% of the total surge • Wind stress has the most dominated effect on storm surge, then followed by effect of low atmospheric pressure. Wave having the smallest amount of effect on storm surge.
Luo et al. 2021(Luo et al., 2021)	Pearl River Estuary, Hong Kong	Effect of wave, rainfall, tide	• Storm surge simulation is minimally affect by wave setup up to 8% • River-surge interaction is dominant, storm surge height increases with runoff increase • Storm surge and wave setup increased during spring tide and decreased during neap tide
Zhang et al. 2019(Zhang et al., 2019)	South Yellow Sea	Effect of tide , TC tracks	• Tidal phase effects depends on storm surge modulation and tidal modulation which are related to TC track parameters.

Central Pressure: Since lower air pressure at the eye of the tropical cyclone initiates the generation of storm surge by the bulging of the sea surface approximately of 10 mm rise per 1 hPa pressure drop. So higher pressure drop will lead to higher storm surge level.

Intensity of the TC: Intensity refers to how strong the wind during a cyclone is in terms of the speed of the wind. TC with higher intensity will produce higher level surge as compared to low intensity TC.

Shape of the Coastline: Funnel shaped coasts are more sensitive to storm-tides as compared to other shapes(Li et al., 2022)

Table 2.1. A summary of the list of influencing factors affecting storm surge(Cont'd)

Authors	Study Area	Influencing Factors	Findings
Azad et al. 2018(Alauddin Al Azad <i>et al.</i> , 2018)	No Bay of Bengal	Effect of tide, different TC track parameters e.g. approaching angle of TC, wind speed and direction, proximity to the TC track	• A particular area it is possible to have lower storm surge during a high tide than a surge during a low tide depending on different parameter of the cyclone such as approaching angle of the TC, intensity and direction of TC, proximity to the cyclone track etc.
Musinguzi and Akbar 2021(Musinguzi and Akbar, 2021)	Gulf of Mexico	Cyclone forward speed, wind intensity (wind speed) and atmospheric pressure drop in the eye of the TC	• The biggest influence on storm surges comes from wind intensity, which is followed by surface pressure and TC's forward speed. • Storm with slower moving speed have higher inland surges and lower nearshore surges. Faster storms create higher nearshore surges but lower inland surges.
Khan et al. 2020(Khan <i>et al.</i> , 2020)	Bay of Bengal, Bangladesh	Effect of tide, effect of wave	• Interactions between Tide-surge and wave-setup contributes about 10% and 10-15% of the overall storm surge height.

2.3 WAVE

Waves are generated by the local wind fields in the open ocean. Waves are irregular and random. Direct analysis and spectral energy density analysis are the two methods that characterize the irregular records of wave. Both these

methods result in a wave height parameter. At the generation area, the waves are generally steep and short-crested. The parameters that influence the wave characteristics are the wind field, fetch and local water depth. The wave height is represented in many forms i.e. significant wave height, root mean square height and mean wave height. Among these three, significant wave height is most common of them. Which is defined as the average wave height of the highest 1/3 of the waves by Eq 2.1.

$$H_{\frac{1}{3}} = \frac{1}{N/3} \sum_{j=1}^{N/3} H_j \quad (2.1)$$

When it comes to describing the motion of waves Navier Stokes and continuity equations are used. Solving these equations is difficult. For solving these difficulties linear wave theory is used. Linear wave theory is used to describe different wave characteristics such as wave height, wave speeds, wave periods etc. in different depth conditions. Wave propagation speed is dependent upon the depth of water as per linear wave theory. As wave propagates from deep to shallow water the propagation speed gradually decreases. As a result the wave height increases. It is known as shoaling. When a TC forms and moves towards the coast, waves generated by the wind field carry energy and momentum along with it. When these waves reach near the coast wave setup is added to the surge causing water level to rise even more due to momentum transfer by the wave.

2.4 TIDE

Tides are long waves which move through the ocean caused by the gravitational pull exerted by the moon and the sun. These long waves are formed in the ocean and propagate towards the coastline where they appear as the regular rise and fall of the sea water level. There are three basic tidal pattern

is observed along the Earth's shorelines. They are diurnal, semidiurnal, and mixed diurnal. Diagrams Shown in Figure 2.2 the sea level variation over time for different tidal patterns. Shorelines experiencing one high and one low tide every lunar day is called diurnal tides. Many areas in Gulf of Maxico experiences diurnal tides. Most shorelines have two tidal cycles. That means two high tides and two low tides having tidal period of approximately half a day. The two highs and the two lows are about the same height. This tidal pattern is called a semidiurnal tide. Tidal pattern in the Bay of Bengal is semidiurnal. When shorelines experiences two high and two low tides but with different height, then it is called mixed diurnal (*NOAA's, 2022*). A spatial distribution of these three basic tidal patterns along different coast is shown in Figure 2.2. Diurnal, semidiurnal and mixed semidiurnal tidal pattern are marked as yellow, red and blue in the Figure 2.3.

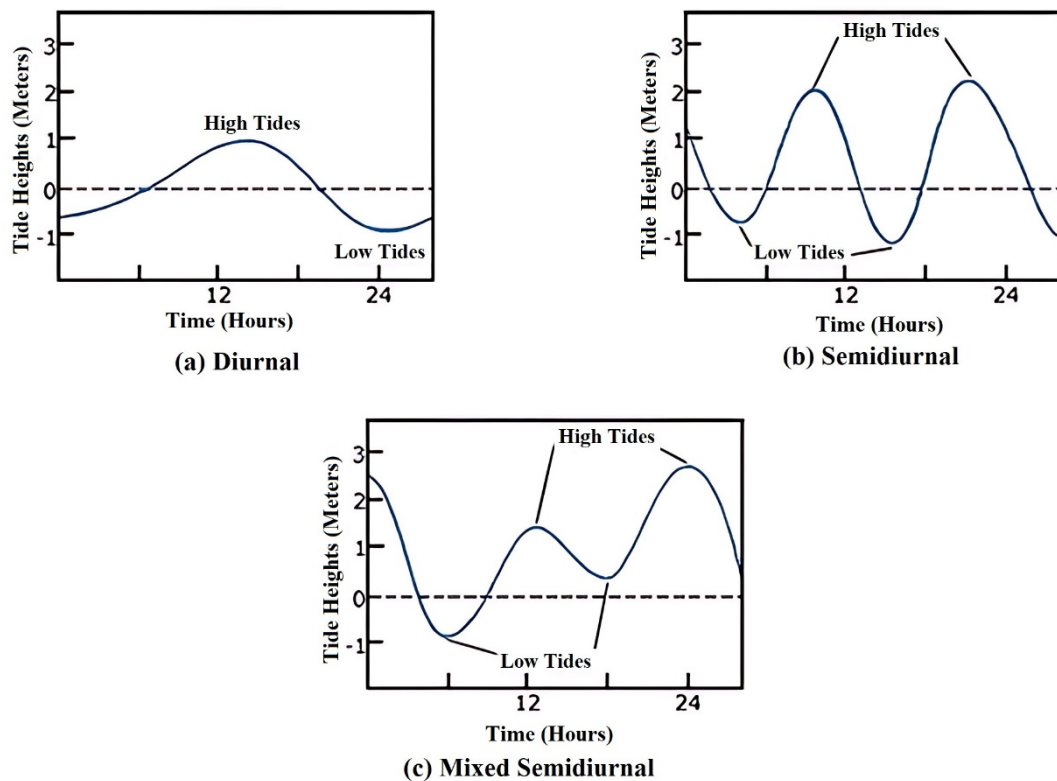


Fig. 2.2 Tidal Patterns along earths coastline (a) Diurnal (b) Semidiurnal (c) Mixed Semidiurnal (NOAA)

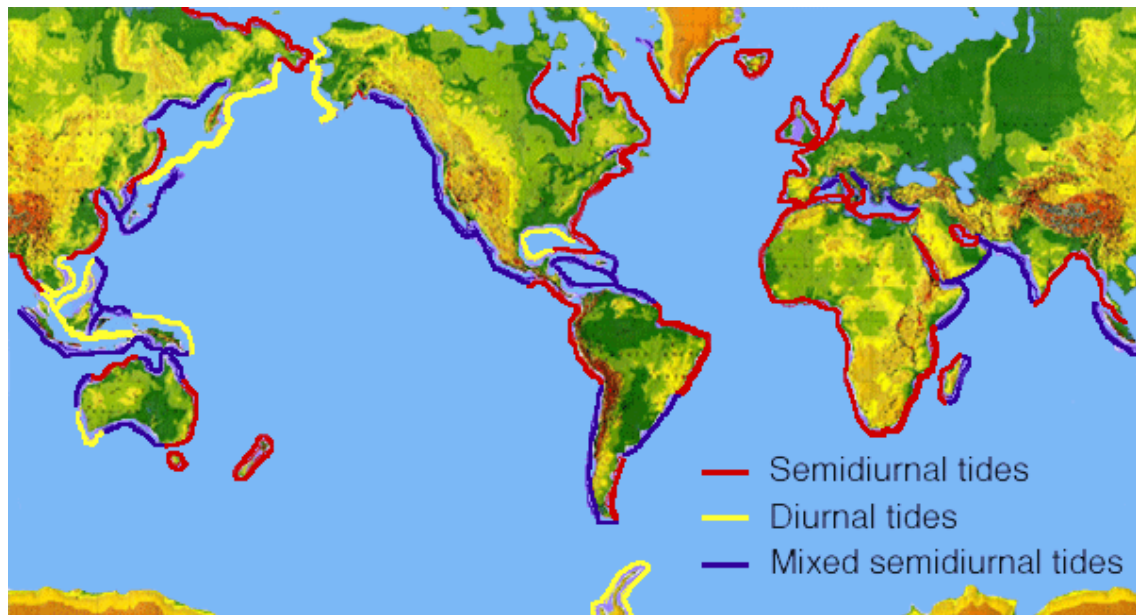


Fig. 2.3 Spatial distribution of different tidal patterns along earths coastline (NOAA)

2.4.1 Generation of Tide

Isaac Newton is the first who explained the generation of tides in the ocean is called the equilibrium theory of tides. There are the few assumptions are required for this theory. They are, the forces that generate tides produces an instant response of the ocean water, there is no friction, and the earth is entirely covered with water. These are the assumptions Newton made in this equilibrium theory of tides.

For tidal generation, The moon's and the sun's gravitational influence on ocean water is crucial. The orbit of the earth around the sun is round. In a similar manner, the moon travels in a circle around the earth. The centripetal force of gravity sustains this circular motion. This gravitational attraction between two things is inversely proportional to the square of their distance apart and immediately relates to the product of their masses. This gravitational formula makes it evident that there will be a stronger gravitational attraction between two objects the more mass they have and the closer they are. The moon and sun's gravitational force on the ocean's water is very significant. The earth travels in a circle around the sun. The moon likewise travels in a circle around

the earth. Gravity acts as a centripetal force to sustain this circular motion. The gravitational force exerted by two objects is proportional to their product of masses and inversely relates to the square of their distance from one another. This gravitational formula makes it evident that an object's mass and distance from another object both increase with their respective gravitational force. (NOAA, 1994). That means moon is the major contributor of the forces generating earth's tides. Though tide is the combined effect of both the sun and the moon. This combined effect is caused by the difference in the gravitation pulling by the sun and the moon on the ocean water masses which is termed as differential pull. Tide generating forces are the strongest on the side of the earth facing the moon. Which creates bulges on the ocean water facing the moon. On other hand the gravitational pull is less on the opposite side of the moon due to the distance from the moon. In this side centrifugal force on the ocean water exceeds the gravitational force due to the moon. This centrifugal force on the ocean water is produced by the revolutions of the earth and the moon around their common centre of gravity(mass) or barycentre. Which moves the water away from the earth creating bulges on the opposite side of the earth. Due to the combination of gravitational pull by moon and the inertia of the rotating earth two bulges of water form on earth at the same time. One at the location where Earth and the moon are the closest and another one forms where they are the furthest away from each other. That means, when a location on earth is located in such a way that the moon makes an angle of 0 degree or 180 degrees in relation to the earth centre. Then low tide occurs at that location when this angle is 90 degree or 270 degrees. Where centrifugal force and gravitational pull on the ocean water is equal and opposite balancing each other. Which results in the net tidal force to be zero in these locations causing water level to reduce due to the bulges created in the 0 degree (front side) and 90 degree (opposite side). And water level moves up and down from the level of high tide and low tide as the moon transitions between these angles.

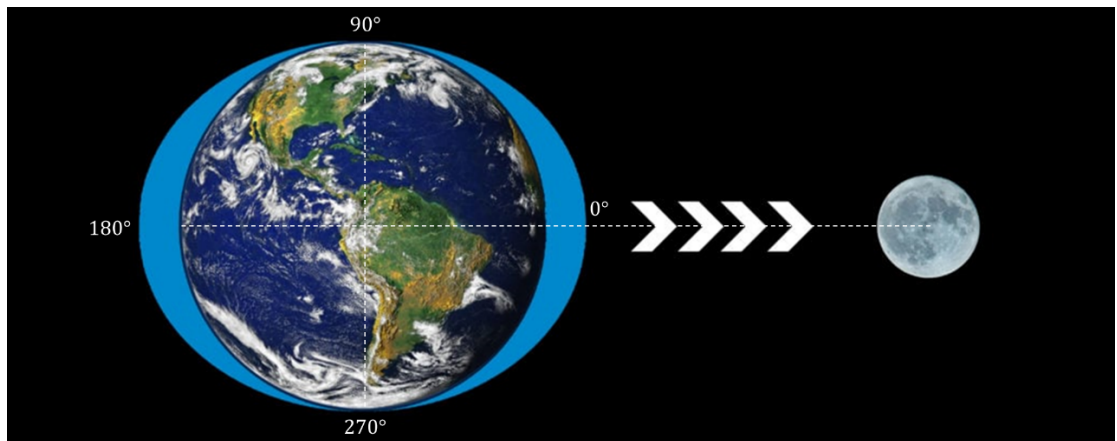


Fig. 2.4 Bulging of earth's water at 0° and 180° position due to moon's gravity.

The earth takes 24 hours to make one rotation or full 360 degree spin about its own axis, which is called solar day. On the other hand during that 360 degree spin moon has moved around 12 degrees on its orbit around the earth from A to B as shown in Figure 2.5. That will require an extra 50 minutes by a particular location on earth to realign with the moon. These 24 hours 50 minutes is called a lunar day. It means in a particular location moon rises 50 minutes later each day. If lunar cycle is divided into 4 equal stages each having 90-degree rotation, then each stage will be of 6 hours and 12.5 minutes. That means there will be 6 hours and 12.5 minutes time difference between a high tide and a low tide. Similarly, the time difference between two high tide or two low tides will be around 12 hours and 25 minutes. In most of the coastal areas tide as described which is semidiurnal where tidal cycle is approximately 12 hours and 25 minutes (Dongerren and Ormond, 2016; Zhang *et al.*, 2019).

There are two special tides that occur on certain special position of the sun, earth and the moon. During the full moon and new moon the earth sun and the moon stays nearly in a straight line as shown in the Figure 2.5. In both conditions gravitational pull of the sun is added to the gravitational pull produced by the moon on the earth. Which creates a bulge more than usual. In

this case high tides are a little bit higher and low tides are a little bit lower than usual. These are called spring tides. This occurs twice each month.

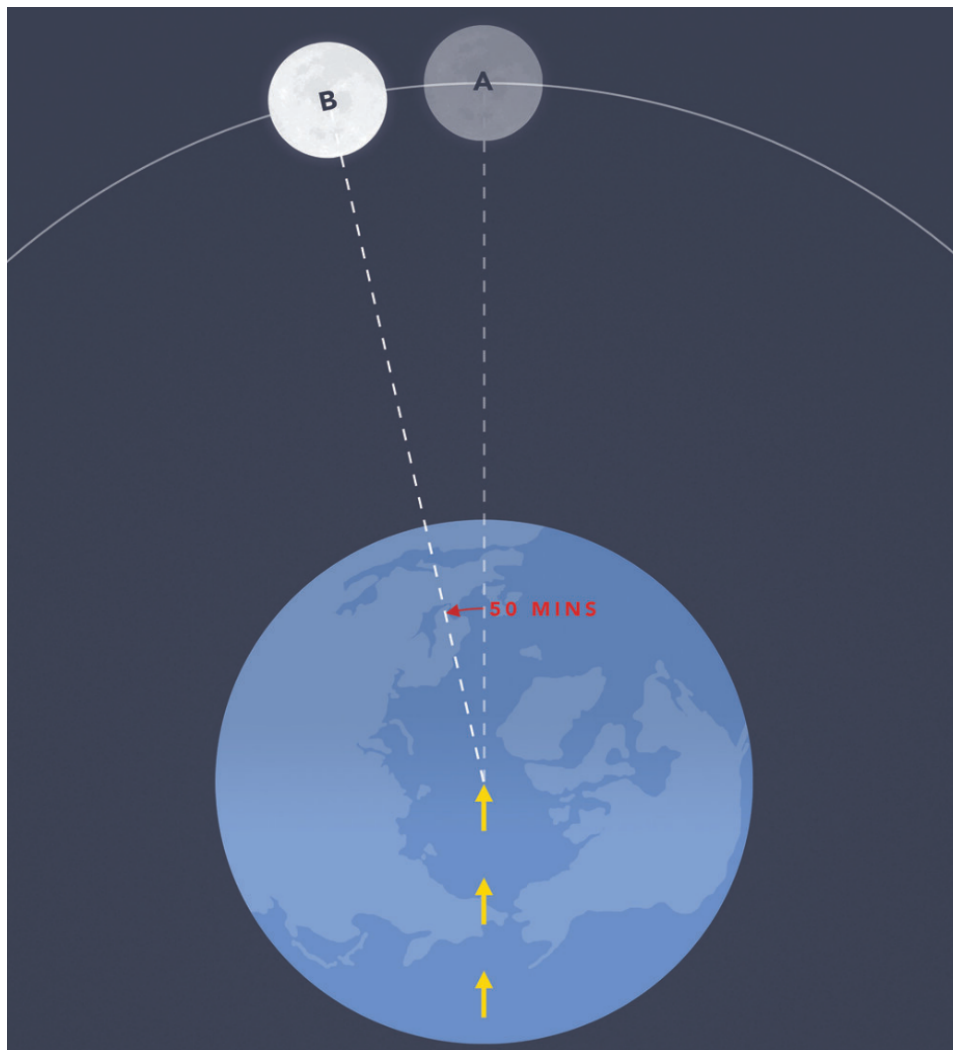


Fig. 2.5 Moon lags behind 50min every day after the earth make one rotation in 24 hours

Also there is another special tide that occurs seven days after a spring tide when the sun and the moon are at 90 degrees with each other as shown in the Figure 2.6. In the ocean, the moon's and the sun's gravitational attraction is greatly significant. Earth's orbit is round, centred on the sun. The moon travels in a similar circle around the earth. Because gravity acts as a centripetal force, the motion remains circular. The product of the masses of the two objects and the square of their distance from one another determine the direct and inverse

gravitational pull between them. The gravitational pull between two objects is directly proportional to their mass and distance from one another, as demonstrated by this gravitational formula.

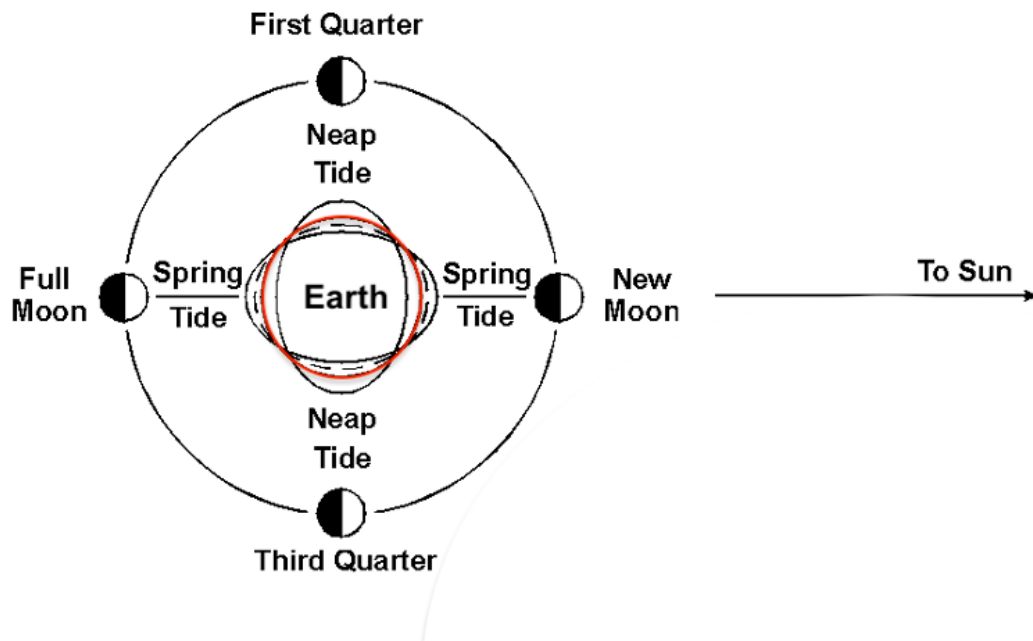


Fig. 2.6 Central solid red circle as earth having two solid ellipses representing the tidal force envelopes produced by the moon in different positions and the dashed ellipse is representing the tidal force envelop produced by the sun

2.4.2 Tidal Predictions

The moon's and sun's gravitational influence on the ocean's water is crucial. The earth orbits the sun in a circle. In a similar manner, the moon travels in a circle around the planet. Gravity acts as a centripetal force to sustain this circular motion. The gravitational attraction between two objects is inversely proportional to their squared distance apart and directly relates to the product of their masses. This gravitational formula makes it obvious that there will be a stronger gravitational attraction between two objects the more mass they have and the closer they are.

Table 2.2. List of 37 tidal harmonic constituents used for tidal prediction with their common name and description (Pugh and Woodworth, 2014)

Sl. No.	Name	Description
1.	M2	Principal lunar semidiurnal constituent
2.	S2	Principal solar semidiurnal constituent
3.	N2	Larger lunar elliptic semidiurnal constituent
4.	K1	Lunar diurnal constituent
5.	M4	Shallow water overtides of principal lunar constituent
6.	O1	Lunar diurnal constituent
7.	M6	Shallow water overtides of principal lunar constituent
8.	MK3	Shallow water terdiurnal
9.	S4	Shallow water overtides of principal solar constituent
10.	MN4	Shallow water quarter diurnal constituent
11.	NU2	Larger lunar evectional constituent
12.	S6	Shallow water overtides of principal solar constituent
13.	MU2	Variational constituent
14.	2N2	Lunar elliptical semidiurnal second-order constituent
15.	OO1	Lunar diurnal
16.	LAM2	Smaller lunar evectional constituent
17.	S1	Solar diurnal constituent
18.	M1	Smaller lunar elliptic diurnal constituent
19.	J1	Smaller lunar elliptic diurnal constituent
20.	MM	Lunar monthly constituent
21.	SSA	Solar semi-annual constituent
22.	SA	Solar annual constituent
23.	MSF	Lunisolar synodic fortnightly constituent
24.	MF	Lunisolar fortnightly constituent
25.	RHO	Larger lunar evectional diurnal constituent
26.	Q1	Larger lunar elliptic diurnal constituent
27.	T2	Larger solar elliptic constituent
28.	R2	Smaller solar elliptic constituent
29.	2Q1	Larger elliptic diurnal
30.	P1	Solar diurnal constituent
31.	2SM2	Shallow water semidiurnal constituent
32.	M3	Lunar terdiurnal constituent
33.	L2	Smaller lunar elliptic semidiurnal constituent
34.	2MK3	Shallow water terdiurnal constituent
35.	K2	Lunisolar semidiurnal constituent
36.	M8	Shallow water eighth diurnal constituent
37.	MS4	Shallow water quarter diurnal constituent

They are also known as tidal constituents. These tidal harmonic constituents generate the pure tides caused by the astronomical forces. This tide doesn't include the influence of the wind and wave on tides. There is total 37 tidal harmonic constituents identified which have the greatest effect on tides (Table 2.4). By knowing these tidal constituents' tide can be predicted in a particular location on earth on a particular time. These constituents for a certain location on earth can be found by analysing tidal data from physical observations. Today, these tidal constituents are available for all oceanic waters (NOAA, 2022).

The abbreviated form of the common term for the tidal constituents is referred to as the constituent's name. The subscript also denotes the quantity of cycles that occur each day. For instance, M2 stands for the greatest lunar constituent, which has to do with the Moon's direct gravitational influence on tides. And every twenty-four hours and fifty minutes, this produces a tidal signal with two peaks. Likewise, S2 is the principal solar component responsible for the two peaks of the tidal signal that occur every 24 hours and 50 minutes, SA refers to solar annual constituents having annual effect in every 365.25 days etc. These constituents can be classified as diurnal, semidiurnal, annual etc based on their periodic effect in a lunar day. For example K1, O1, S1, P1, Q1, J1 is known as diurnal constituents of tide since these constituents result in 1 peak or have 1 cycles per lunar day. Each constituent listed in Table 2.2 can be represented as a Cosine curve as shown in Figure 2.7 The value of the curve refers to the amplitude and phase difference of that constituent. By summing up these 37 Cosine curve for a particular location the tide at that location can be predicted. Since this tide only has astronomical influences, it is also known as astronomical tides (Figure 2.8). Water level due to this astronomical tides caused by the harmonics constituents can be described by Eq. 2.2:

$$\eta(t) = a_0 + \sum_{n=1}^{N=37} a_n \cos (\omega_n t - \alpha_n) \quad (2.2)$$

Where,

$\eta(t)$ = Tidal level

a_0 = Mean height of water level

a_n = Amplitude of nth tidal constituent

ω_n = Angular velocity of the nth tidal constituent

α_n = Phase angle of nth tidal constituent

t = Time

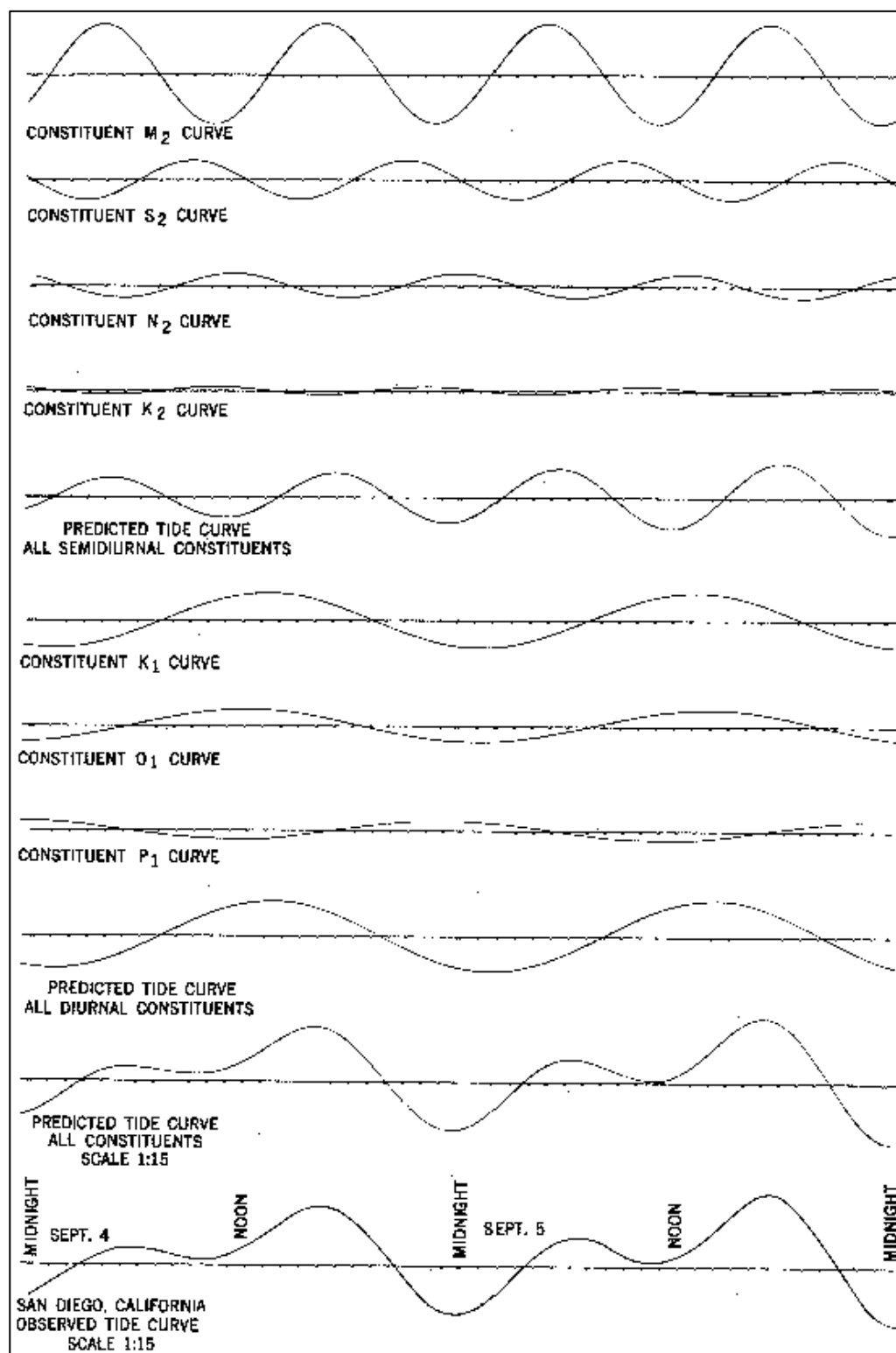


Fig. 2.7 Tide analysis of San Diego, California showing tidal curve for different constituents.

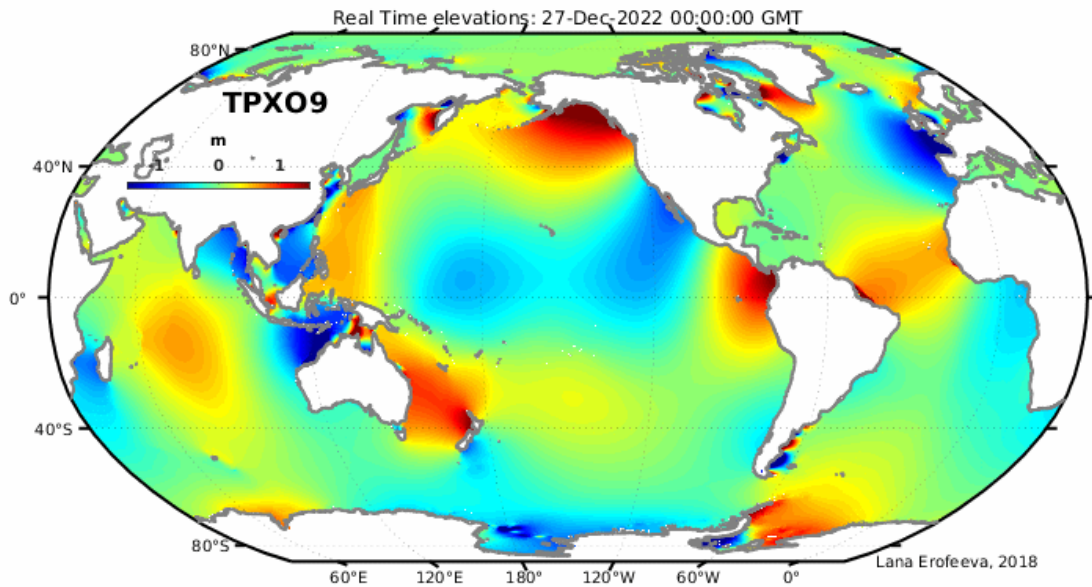


Fig. 2.8 Example of global tide model(TPXO 9) showing real time water level variation due to astronomical tide. Adopted from: Egbert and Eroffeeva (2002)

2.4.3 Characteristics of Tide Along Bangladesh Coast

As mentioned earlier tides Bay of Bengal is dominated by semi-diurnal tides. Hence, tides along Bangladesh coast are semi-diurnal. This indicates that Bangladesh's coastal regions see two high tides and two low tides per day. The 18.6-year lunar nodal cyclone has no effect on the tides near Bangladesh's coastline. However, a 4.4-year lunar perigean cyclone affects this region's tides by 4 cm.(Sumaiya, 2017) . M2 and S2 are the two most dominant constituents of tides in this region(Khan *et al.*, 2012; Sumaiya, 2017). Tidal amplitude and range are not same along the coast. The tidal range is maximum along the Noakhali coast and decreases to the east and the west(Ahmed and Louters, 1997). The variation in water level between high tide and low tide is known as the tidal range. Around 7 meters is the mean tidal range close to the Noakhali shore near Sandwip.. then it the west it decreases to around 3 m at Hiron Point near Sundarbans(Commander and Firoz, 2016). Bangladesh And to the east it decreases

to 3.6 m at Cox's Bazar. Tides propagate up to 100 km inland through the coastal river estuaries.

2.5 COASTAL FLOODING

Storm surges can trigger coastal flooding, posing a significant threat to low-lying coastal areas. The consequences include damage to infrastructure, displacement of communities, and environmental impact. Mitigation strategies, like coastal defenses and early warning systems, are crucial for managing the risks associated with coastal flooding. Rising sea levels due to climate change further amplify the vulnerability of coastal regions to flooding. Insufficient protection against tropical cyclones can result in severe coastal flooding due to storm surges. This threat isn't confined solely to coastal areas but extends to inland communities as well. Even regions located many miles away from the coastline can be impacted by the far-reaching effects of storm surges. There are several factors that can impact the quantity, extent and consequences of flooding caused by tropical cyclones :

Antecedent Precipitation: Due to recent rainfall occurred in the coastal region the soil pores might get saturated decreasing the soil infiltration capacity. It increases the runoff as well as the flooding impact.

The speed of the cyclone's movement: Speed of cyclone movement is a significant factor; a slower forward speed allows the storm surge to stay longer time at the coastline for a more extended period, resulting in greater flooding effects.

Orographic enhancement: occurs in elevated regions, where additional moist air is lifted, leading to increased precipitation.

Hydrology: Coastal hydrology plays significant role in coastal flooding. Narrow river basins are more susceptible to flooding than wider, flatter ones.

Land use: Especially in urban areas, influences flooding, as building foundations can reduce soil filtration and increase runoff volumes. Impermeable soil materials exacerbate runoff and flooding, while soil stability is enhanced by vegetation cover on hill slopes.

In Bangladesh, along with these factors coastal embankments plays an important role in the coastal flooding caused by storm surge. Every year when a cyclone hit, it is seen that coastal areas get flooded due to high water level caused by the storm surge. Sometime these overtops the embankments due to inadequate crest levels of the embankments and sometimes due the breaching of the embankments by the storm surge. Breaching occurs mainly to the damaged embankments in previous cyclones that are poorly repaired or reconstructed by the local people. Thus, proper design as well as regular maintenance of these coastal embankment can reduce flooding caused by storm surge.

2.6 STORM SURGE AND BANGLADESH COAST

2.4.1 The Coastal Zone of Bangladesh

Bangladesh's coastal regions are among the most vulnerable to natural disasters. Bangladesh is regarded as the nation most vulnerable to the effects of climate change, including rising sea levels, more precipitation, and an increase in the frequency of Cat-5 cyclones. The coastal zone makes for 32% of Bangladesh's total land area. It is divided into 19 administrative districts, or 147 upazillas. Eleven of them share a shoreline with the Bay of Bengal and are coastal districts. These are the following: Cox's Bazar, Satkhira, Bagerhat, Barguna, Patuakhali, Bhola, Lakshmipur, Noakhali, Feni, and Khulna. "Exposed Coast" is the designation given to these districts. Since the remaining eight districts do not have direct access to the Bay of Bengal, they are classified as "Interior Coast." Pirojpur, Barisal, Jhalokati, Gopalganj, Jessore, Narail, Shariatpur, and Chandpur are these districts. (Barnes and Barnes, 2014). These

districts do not have direct influence of the Bay of Bengal, but they are significantly influenced by coastal processes like daily astronomical tide, salinity intrusion, tropical cyclone and associated storm surges.

Coastal zone of Bangladesh is a very diverse area with many distinctive morphological, topographical and ecological features. Based on these physical characteristic differences coastal Bangladesh is divided into three distinctive zone. These zones have very significant different with each other in terms of their physical characteristics. This classification was proposed by both Pramanik (Islam, 2001) and (ESCAP/UN, 1987) as eastern, western and central coastal region.

Western coastal region consists of three coastal districts Satkhira, Khulna and Bagerhat. It comprises of the active floodplains of the Ganges. It is also known as the Ganges tidal plain. These are often called as simply tidal plains since these floodplains mostly near to the coastline are inundated twice daily by astronomical tides due to its semidiurnal tidal nature. It lies about 0.9 to 2.1 m above the mean sea level. This region consists of river flood plains with very low gradient and flat topography. Low gradient of the lands in this region is generally ranging from 1.5 inch/mile to 1 inch/mile in the central coastal zone. Due to this flat topography this zone extends upto 195 km inland (book chapter) These flood plains are associated with an intricate network of tidal creeks and tributaries.. The Sundarbans mangrove forest is one of this region's most notable features. The world's largest mangrove forest is called Sundarbans. The Bay of Bengal cyclone and the storm surges it causes are repelled by the Sundarbans. It is thought to act as a biological barrier that is natural against cyclones. By absorbing the initial thrust of the strong cyclonic wind and accompanying storm surge, it lessens the impact of the cyclone. In the last decade Sundarbans played an important role by defending against many significant cyclones like Sidr(2007) and Amphan(2009). The mangrove forest

also gives protection to the land against coastal erosion. It also helps to gain land by helping in the sediment accretion process (Warrick and Ahmad, 1996).

Eastern coastal region is located in the east coast of Bangladesh. It consists of two coastal districts Chittagong and Cox's Bazar. This zone is relatively narrow and straight in shape. Its location is in between the Bay of Bengal coastline and a series of small hills running parallel to this zone is known as Chittagong Hill Tracts. This zone is very different from the other two zones due to its distinguishing characteristics. Unlike the other two zones, the gradient of the land in this region is much steeper. Due to its steeper land gradient eastern zone extends up to only 30-40km inland. This area is thought to be the one least impacted by sea level rise. This zone is dominated more by marine processes than by fluvial processes, in contrast to the other two zones. Mudflats and buried sandbars shield the shore, much like the Sundarbans do in the west. Sand beaches are one of this region's most distinctive features. In this area, there are two beaches: Patenga Beach and Cox's Bazar Beach. The longest natural sea beach in the world, Cox's Bazar Sea Beach, stretches 155 kilometres from Cox's Bazar to Teknaf.

The zone that is thought to be least impacted by sea level rise is this one. Unlike the other two zones, this one is primarily dominated by marine processes as opposed to fluvial activities. Mudflats and sandbars that are submerged provide coastal protection, much like the Sundarbans in the west. The sandy beach in this area is one of its most distinctive features. Here are two beaches: Patenga Beach and Cox's Bazar Beach. The world's longest natural sea beach, measuring approximately 155 kilometres, extends from Cox's Bazar to Teknaf. Along with this, erosion and attrition are also very common phenomena that are very prominent in this region. These characteristics result in formation of new islands, continuous changing of the outline of these islands,

bank erosion of rivers and islands and channel instability. The topography of this region is flat, and the gradient of the land is as low as 1 inch/mile.

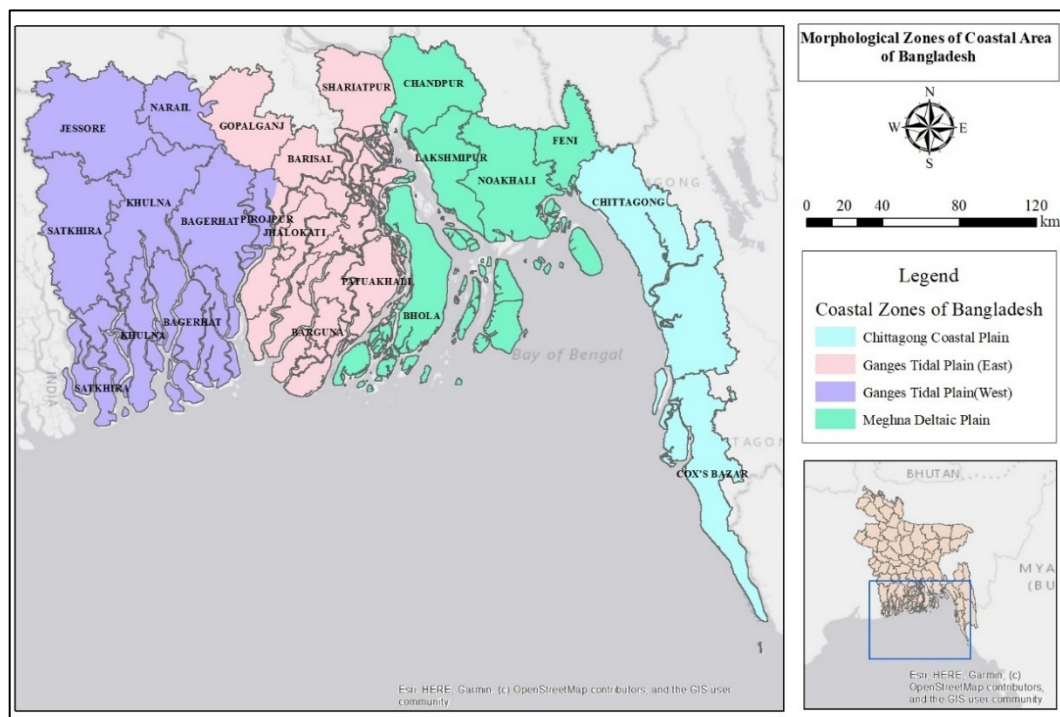


Fig. 2.9 Morphological zones of coastal area of Bangladesh

2.4.2 Characteristics of Northern Bay of Bengal

Covering 2.2 million square kilometres of area, BoB is world largest bay and reaches maximum depth up to 5528 m (Antony, Unnikrishnan and Woodworth, 2016) Extending from GBM mega delta, BoB located around 20°N latitude to south 7°S, with a maximum width 1000 km around 15°N latitude. The northern BoB receives enormous freshwater inflow from Indian subcontinent river basin and a large sediment budget from the GBM basin. The sea floor gradually decreases its bathymetry from north to south. The Swatch of No Ground, a deep sea canyon situated 45 km south of Sundarbans plays an eminent role in sediment discharge in BoB. Overall, the morphological development of the Bengal fan is controlled by the hydrodynamics of GBM and the northern BoB. A northward, clockwise ocean circulation observed during January to October. The remainder of the year experiences a counterclockwise circulation flowing

southwestward. These residual circulation patterns have strong influence on cyclone track. Harmonic constituents of tide vary significantly over the BoB. A number of small and large rivers discharge into BoB influence on the hydrological and morphological process of the bay. The tide fluctuates in the BoB in a range between 0.2~3 m (Sindhu and Unnikrishnan 2013). The lower Meghna estuary near Char Gazaria is micro-tidal in nature having tidal fluctuations of 0.2 m (Sindhu and Unnikrishnan, 2013). The tidal range gradually increases at Chittagong, Bhola and Hatia taking a form of meso-tidal estuary with 2~4 m tidal fluctuations (Krien *et al.*, 2016a). But, area around Sandwip channel take form of macro-tidal estuary with tidal fluctuations of 3~6m (Wolf and Islam, 2016).

2.4.3 Cyclone and Storm Surge scenario in the Northern Bay of Bengal

A tropical cyclone ended with landfall over a particular coast, it affects the adjacent area by storm surge, tropical cyclone induced heavy rainfall and coastal flooding. During eighteenth century, BoB experiences only 21 tropical cyclones which increased by 90 events during nineteenth century and 169 tropical cyclones during last century (Alam and Howes 2015). Frequent tropical cyclone occurrence poses a great concern and accurate prediction is necessitated to minimize devastating casualties. The preparedness in Indian coast is notable from observing the reported casualties of two same category (category-5) cyclones namely super cyclone 1999 and cyclone Phailin 2013 at same landfall location. Both cyclones made landfall at Odisha coasts but the death toll reduced from 10000 to 22 people in later cyclone (Table 2.5). However, from the Bangladesh perspective two category-5 tropical cyclones i.e., cyclone 1991 and Sidr 2007 caused the death toll of respectively 140,000 and 4234 (Alam and Howes 2015).

Table 2.3 Maximum surge height records along the Bangladesh coasts

Date of the event	Landfall locations	Central pressure (mb)	Wind speed (km/hr)	Observed surge height (mMSL) and location
8-11 Oct 1960	Meghna estuary	993.5	160	5.7 m at Meghna estuary
28-31 Oct 1960	Chittagong	967	193	6.1 m at Kutubdia, 5.49 m at Banshkhali, 3.7-4.9 m at Sandwip
5-9 May 1961	Barisal and west of the Meghna estuary	976	160	5.65 m at Khepupara, 4.42 m at Patuakhali, 6.62 m at Galachipa
25-29 May 1963	Chittagong-Cox's Bazar	935	193	2.44-3.66 m at landfall location
7-15 Dec 1965	Cox's Bazar		210	4.58 m at Companigonj (Comilla), 3.64 m at Sandwip
27 Sep -01 Oct 1966	Khulna	980	145	5.57 m at Noakhali 4.48 m at Cox's Bazar
8-13 Nov 1970	Chittagong	966	224	3.69 m at Cox's Bazar, 3.75 m at Chittagong, 5.19 m at Noakhali, 5.76 m at, Companiganj, 6.0 m at Char Jabbar, 2.67 m at Patharghata 4.09 m at Chandpur
22-25 May 1985	Chittagong coast	982	154	4.6 m at landfall location
23-30 Nov 1988	Khulna coast	983	160	Observed surge height was reported 0.61-4.42 m
24-30 Apr 1991	Chittagong	940	225	Surge height 3.66-6.71 m
29 Apr- 2 May 1994	Cox's Bazar-Teknaf coast	948	215	3.64-4.85 m at landfall
15-19 May 1997	Sitakundu of Chittagong	965	232	4.6 m at landfall
23-27 Sep 1997	Sitakundu of Chittagong	-	150	3.03-4.55 m at Bhola 1.52-2.12 m at Galachipa
11-16 Nov 2007 (Cyclone Sidr)	South-western coast of Bangladesh	942	224	4.57 m at landfall
25-26 May 2009 (Cyclone Aila)	West Bengal of India	974	112	4 m at Sundarban area, 1.5 m at Hiron point, 0.6 m at Chittagong and Charchanga
11-16 May 2013 (Cyclone Mahasen)	Patuakhali	990	121	1-1.1 m at landfall
20 May, 2020 (Amphan)	Sundarbans	-	-	3 m at Chittagong, Sadarghat 2.5 m at Kutubdia, 2.5 m at Kuakata

Cyclone Amphan (2020), which had 128 fatalities, is the third super cyclone to originate in the Bay of Bengal (BoB) in the past 20 years, according to IMD cyclone best track data. The other two were the Bangladesh Cyclone of 1991 and the Odisha Supercyclone of 1999.

2.7 COASTAL POLDERS

Being a disaster-prone area, coastal zone of Bangladesh also faces issues like salinity intrusion, land erosion, tidal flood, frequent cyclonic storm surge and scarcity of freshwater. To solve these issues and to protect the land during 1960s to early 1970s about 139 coastal polders are constructed under the Coastal Embankment Project (CEP) (Figure 2.10). Polder are low lying land areas enclosed by embankments. At the beginning these polders were meant for protecting the low-lying areas in the coast from tidal effects. There is no consideration of wind wave and cyclonic storm surges effects in the initial design. A study estimated that existing storm surge polders have a return period of only 6 years (BWDB, 2013). These polders have been protecting the coastal region in many ways until climate change effects have started to appear. Due to increased cyclonic event and climate change effect some coastal polders are hit, overtopped and damaged frequently in the last decade. The necessity of the redesigning of the polders became an emergency when cyclone SIDR (November 2007) and AILA(May 2009) hit the coast. To improve the present scenario Coastal Embankment Improvement Project-Phase 1(CEIP-1) has been undertaken (Bangladesh Delta Plan, 2020). Under the CEIP-1 selected 17 coastal polders are redesigned for the storm surges with the design return period of 25 years along with other design parameters(monsoon flood level, freeboard, subsidence etc. (BWDB, 2013)

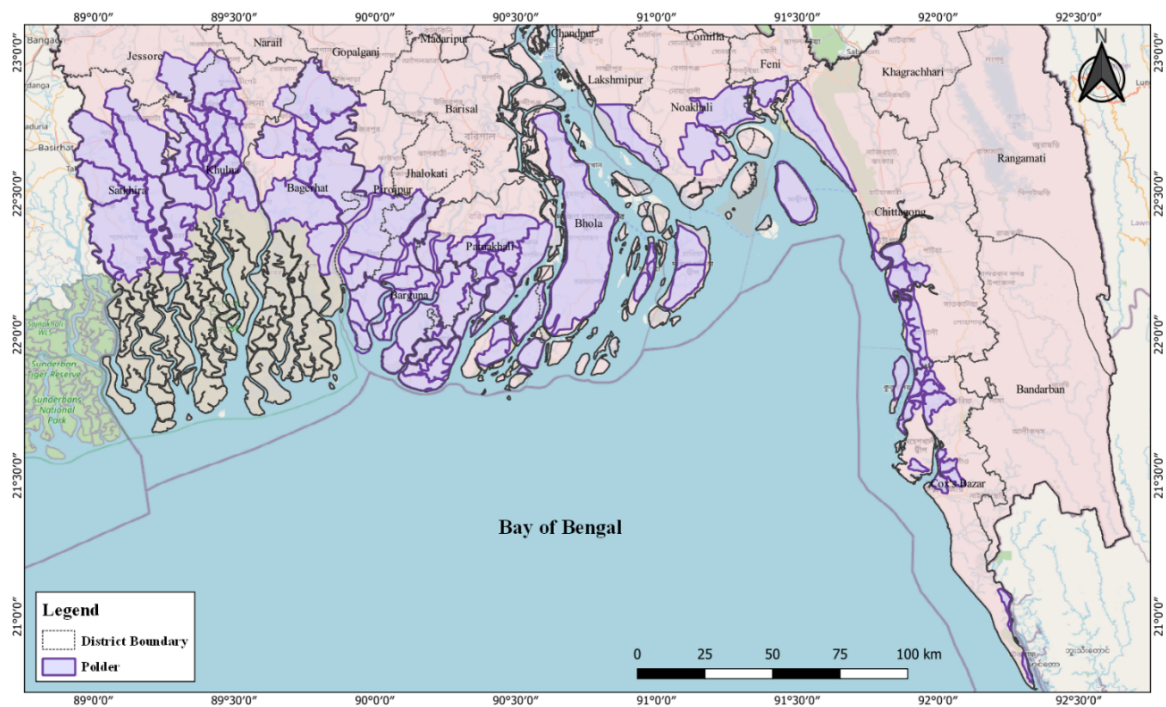


Fig. 2.10 Coastal Polders in the Coastal Zone

2.8 MODELLING OF THE PHYSICAL PROCESSES

2.4.1 Cyclone Model

A tropical cyclone is characterised as a rotating large air mass with inward-spiralling winds around a zone of low atmospheric pressure at the centre. A tropical cyclone's computer model can only be built with high-quality meteorological data from previous cyclonic episodes. It can serve as the foundation for the model's constituent parts. However, there is a finite quantity of data available for a cyclone. Organisations like the IMD and JTWC offer the greatest track data, which includes details about the tropical cyclone's centre sea level pressure, maximum sustained wind speed, and coordinated position of the eye. One such collection of best track data created by NOAA is the IBTrACS database. As was previously noted, substantial cyclone data is needed to create an accurate complete physics mesoscale model; however, recorded cyclone data is constrained by specific factors. Parametric relationships are therefore required in order to construct the complete shape of the cyclone. The

correlations between pressure drop and maximum wind (Holland, 2008) and the radius of maximum wind (RMW or R_{max}), pressure drop, and latitude (Vickery and Wadhera, 2008; Holland, Belanger and Fritz, 2010) are examples of such parametric relationships. We refer to these models of cyclones as parametric wind models. Because parametric wind models require relatively little data, they are frequently employed in storm surge investigations worldwide. These parametric models use cyclone information from the best track data provided by the different organization and it created cyclonic wind field and pressure field. Then these wind and pressure field is used as an meteorological input in the storm surge model. These time and space varying wind and pressure field of a cyclone are generally provided on a spider wave grid in polar coordinates as shown in Figure. 2.11. Each point of this grid contains information about the wind speed, wind direction and pressure drop at that point. The origin of the this spiderweb grid is the coordinates of the centre of the cyclone. The grid cell sizes depend on the the number of radial bins, tangential bins and the total radius of the grid. The higher the number of radial and tangential bins, the smaller the grid size or the higher the resolution of the wind and pressure field data. Holland wind model is one of the most commonly used wind model specially in the storm surge studies in the northern BoB (Krien *et al.*, 2016b, 2017; Tanim and Akter, 2019a; Khan *et al.*, 2020). The output is the space and time varying wind speed, direction and air pressure field which is used as input in the hydrodynamic model or the storm surge model.

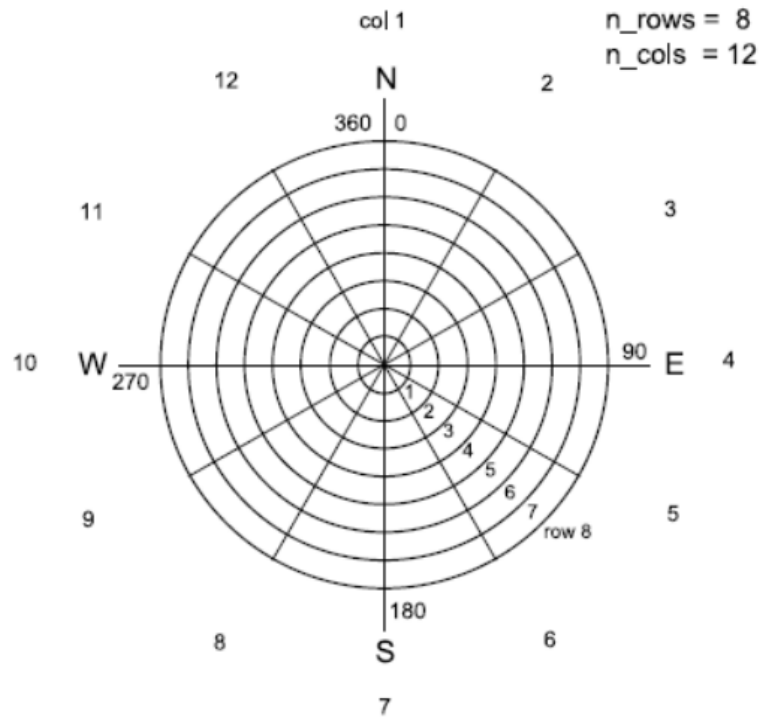


Fig. 2.11 Spider web grid. Adopted from DELFT3D flow manual

2.4.2 Previous storm surge study in the BoB

Earlier study comprises of astronomical tide, meteorological forcing(wind filed and pressure field) is generated using a analytical cyclone model . Only river and estuarine bathymetry is used since model setup consist of river networks only. Ocean bathymetry often remain ignored (Table 2.6). Later a DEM consisting of river and estuarine bathymetry and land topography maps were used for calculated flooded area. Flooded area is computed separately in GIS software using maximum water level (Karim and Mimura, 2008). Debsarma (2009) handled coarser data with the 1 km grid which perform faster storm surge prediction. The wave current interaction was not considered. The model had no consideration of tide and wave interaction. Maximum surge height could be predicted from such robust method. Therefore, the linear assumption is not valid for all phases of tide-surge interaction.

Table 2.4 A summary of the previous storm surge study in the BoB

Authors	Model used	Bathymetry	Forcing type	Methods	Calibration and Validation	Limitations
Madsen and Jakobsen (2004)	MIKE 21	C-Map of Hydrographic Survey of UK, Further improved with different field survey.	Astronomical tide, meteorological forcing(wind filed and pressure field)	Air pressure and wind fields were applied to 2D hydrodynamic tide model.	No calibration and validation information. Model simulations are compared with observed data	Moreover, the pressure field and wind field was not validated. .
Karim and Mimura(Karim and Mimura, 2008)	Newly developed 1D numerical hydrodynamic model	Only river and estuarine bathymetry is used since model setup consist of river networks only. No ocean bathymetry.	Astronomical Tide, meteorological forcing is introduced as a time series storm surge height in seaward water level boundary	Model is run for synthetic storm surge by considering different SLR condition.	Hydrodynamic model is validated using water level	No validation of the inundation model(flooded area)

Table 2.4 A summary of the previous storm surge study in the BoB

Authors	Model used	Bathymetry	Forcing type	Methods	Calibration and Validation	Limitations
Debsarma (2009)	IIT Storm surge Model	Earth-topography-two-minute Module (ETOPO2).	Astronomical tide elevations and cyclone model.	Modified IIT-D model	Robust simulation model due to large grid size of models.	Coarser grid resolution i.e., 3.7 km provides fewer details for the northern BoB. This model provides fewer details regarding storm surge.
Dube et al. (2009)	IIT-D Storm surge model	Earth-topography-two-minute module(ETOPO2)	Astronomic tides with high values of wind stress.	Non-linear storm surge model that can adopt wind stress formulation over sea surface.	Simulates series of cyclones including Gwa 1982, Mala 2006, Nargis 2008, Cyclone 1991, Sidr 2007.	

Table 2.4 A summary of the previous storm surge study in the BoB

Authors	Model used	Bathymetry	Forcing type	Methods	Calibration and Validation	Limitations
Lewis et al., (2013)(Lewis <i>et al.</i> , 2013)	IIT-D Model and LISFLOOD-FP inundation model	Processed SRTM for land topography, river channel depths were estimated using hydraulic geometry theory, estuary depth are assumed to be within 0 to 9 m	Predicted water levels at the coast from the IIT-D model were used as the coastal boundary condition to force the LISFLOOD-FP model for inland flooding		Validation of storm surge height is performed, validation of inundation area is performed using ENVISAT Advanced Synthetic Aperture Radar (ASAR) image	Tide-surge interaction, wave setu-up, wind drag coefficient is not introduced during simulation.

Table 2.4 A summary of the previous storm surge study in the BoB

Authors	Model used	Bathymetry	Forcing type	Methods	Calibration and Validation	Limitations
Murty et al. (2016)	ADCIRC and SWAN	GEBCO and near Andhra Pradesh coast reconstructed from surveyed bathymetry.	Wave and tide coupling. Developed modified Jelesnianski wind envelope for reasonable wind estimation.	High resolution model wave flow couple simulation with consideration of wave current non-linear interactions.	Surge height, wave set up and SWH.	The models bathymetry was not improved for the northern BoB. The model provides reliable information including depth averaged currents, storm surge and net water level, although to simulate non-linear wave interaction super computation environment is required.
Deb and Ferreira (2016)	ADCIRC and SWAN	GEBCO data	Astronomical tide elevations and cyclone model.	Simulated Cyclone 1991 and Sidr 2007 in high	Bottom friction and roughness coefficient sensitivity in	Bathymetry in nearshore was derived from GEBCO.

Table 2.4 A summary of the previous storm surge study in the BoB

Authors	Model used	Bathymetry	Forcing type	Methods	Calibration and Validation	Limitations
				performance computing environment.	nearshore zone can improve the surge height prediction.	Wave, tide and surge interaction was considered with unstructured mesh grid. The nearshore bathymetry was suggested for improved surge height prediction.
Krien et al. (2017)(Krien <i>et al.</i> , 2017)	SCHISM	GEBCO data with improved recent bathymetry.	Astronomic tides and cyclone model.	SCHISM-WAVEWATCHIII hindcast and developed wave flow couple model with unstructured grid.	Improved bathymetric dataset of northern BoB. Wave set up can be termed out for the region. Large tide-surge interaction was found.	The drag coefficient based on the implicit relationship between surface roughness and wind. This model is most reliable due to it focuses on the hydrodynamics of the northern BoB.

Table 2.4 A summary of the previous storm surge study in the BoB

Authors	Model used	Bathymetry	Forcing type	Methods	Calibration and Validation	Limitations
						The study well-documented the tide-surge interaction. Axisymmetric parametric cyclone model Holland (1980) can be improved for accurate cyclone simulation.
Tanim and Akter, (2019)(Tanim and Akter, 2019a)	Delft3D and SWAN	GEBCO data with improved recent bathymetry.	Astronomic tides and cyclone model.	SCHISM-WAVEWATCHIII hindcast and developed wave flow couple model	Hydrodynamic model is validated using water level No validation of the inundation model(flooded area)	River discharge is not considered.

2.9 SUMMARY AND IMPLICATIONS

Understanding the genesis, strength, and trajectory of cyclones as well as the unfavourable weather conditions that they are linked with—heavy rainfall, gale winds, storm surges, and coastal inundation—is essential to reducing the destruction and difficulties caused by storm surges. Thorough comprehension of these procedures is essential for timely identification and precise evaluation of risks. Strategies for cyclone disaster mitigation in Bangladesh include coastal embankments, cyclone shelters, post-cyclone relief and rehabilitation, and cyclone forecasting and warning.

Numerical models are now widely used in cyclone forecasting, greatly improving our capacity to forecast the formation of cyclones, monitor their motion, predict storm surges that coincide with them, and ascertain the depth and breadth of inundation. The last five years have seen the development of sophisticated computer resources, which has made storm surge modelling an essential tool for predicting storm impacts and helping with response planning—particularly the evacuation of vulnerable coastal communities. Moreover, retrospective modelling of storms is instrumental in assessing risk, devising mitigation strategies, and facilitating coastal restoration efforts globally (Dietrich *et al.*, 2013). As the Bay of Bengal faces the need for accurate cyclone prediction, numerous modelling applications have been proposed. These applications aim to prevent or minimize loss of life and property damage by providing comprehensive insights into cyclone behaviour, thereby facilitating informed decision-making in disaster management and response planning. The integration of cutting-edge modelling technologies underscores the ongoing commitment to enhancing our preparedness and resilience against the coastal challenges posed by cyclones in the Bay of Bengal region.

Chapter 3: THEORETICAL BACKGROUND

3.1 Theoretical Background of the Hydrodynamic Model

The Delft3D-FLOW software allows for the execution of either 2D (depth-averaged) or 3D (unsteady flow and transport) simulations, encompassing a broad spectrum of natural occurrences such as tidal and astronomical influences. The 2D option employs depth-averaged equations, prioritizing horizontal variations and proving effective for modeling tidal waves, surges, and tsunamis, where vertical changes hold less significance. On the other hand, the 3D approach is beneficial for scenarios involving substantial vertical variations, making it suitable for addressing transport issues like salt intrusion, waste water dynamics, sediment movement, river water discharges, and similar complex flow problems. Both the 2D and 3D models operate on versions of the shallow water equations derived from the underlying three-dimensional Navier-Stokes equations (Deltares, 2018).

Rather than using flat xyz coordinates, Delft3D adopts orthogonal curvilinear coordinates, allowing for curved coordinate lines. The software offers two types of coordinate systems: Cartesian or spherical. Moreover, it employs a vertical grid referred to as σ , characterized by two non-horizontal planes that follow the bathymetry and free surface, enabling a more accurate representation of the vertical dimension in simulations.

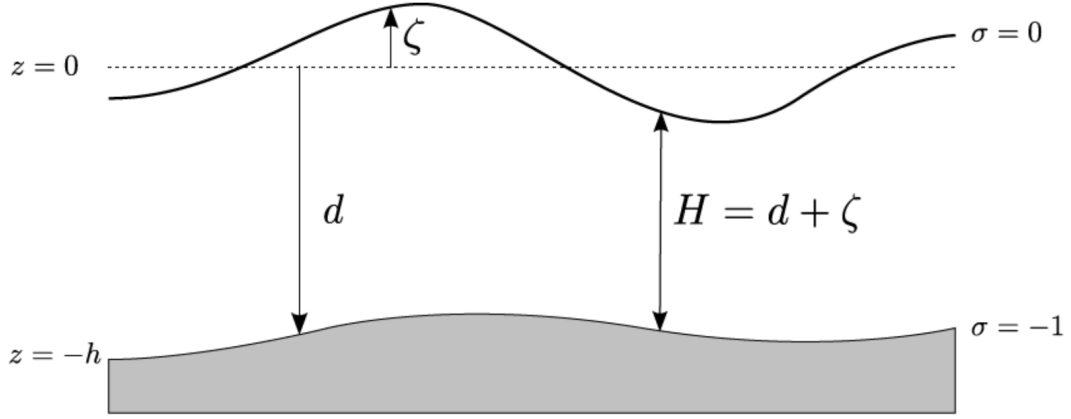


Fig. 3.1 Definition of water level, depth and total depth (b) σ grid. Adapted from Deltares (2018)

the shallow water equations are given by the momentum equations in horizontal direction (Equations 3.1 and 3.2) and the continuity equation (Equation 3.3). The equations are displayed in the form of the curvilinear grid coordinates (ξ and η).

$$\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}} \frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}} \frac{\partial u}{\partial \eta} + \frac{\omega}{d + \zeta} \frac{\partial u}{\partial \eta} - \frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - fv = -\frac{1}{\rho_0 \sqrt{G_{\xi\xi}}} P_\xi + F_\xi + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left(\nu_v \frac{\partial u}{\partial \sigma} \right) + M_\xi \quad (3.1)$$

$$\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}} \frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}} \frac{\partial u}{\partial \eta} + \frac{\omega}{d + \zeta} \frac{\partial u}{\partial \eta} + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} + \frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} + fu = -\frac{1}{\rho_0 \sqrt{G_{\eta\eta}}} P_\eta + F_\eta + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left(\nu_v \frac{\partial u}{\partial \sigma} \right) + M_\eta \quad (3.2)$$

$$\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial (d + \zeta)u\sqrt{G_{\eta\eta}}}{\partial \xi} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \omega}{\partial \sigma} = (d + \zeta)(q_{in} - q_{out}) \quad (3.3)$$

In these equations, u and v denote the depth-averaged horizontal flow velocities, while w represents the vertical velocity. The variable ν_v stands for the vertical viscosity coefficient, P refers to the pressure gradient, F accounts for horizontal Reynolds stresses, and M signifies contributions stemming from external sources. Among the foundational assumptions of the shallow water equations lies the hydrostatic pressure assumption, which simplifies the vertical momentum equation into a distribution based on hydrostatic pressure.

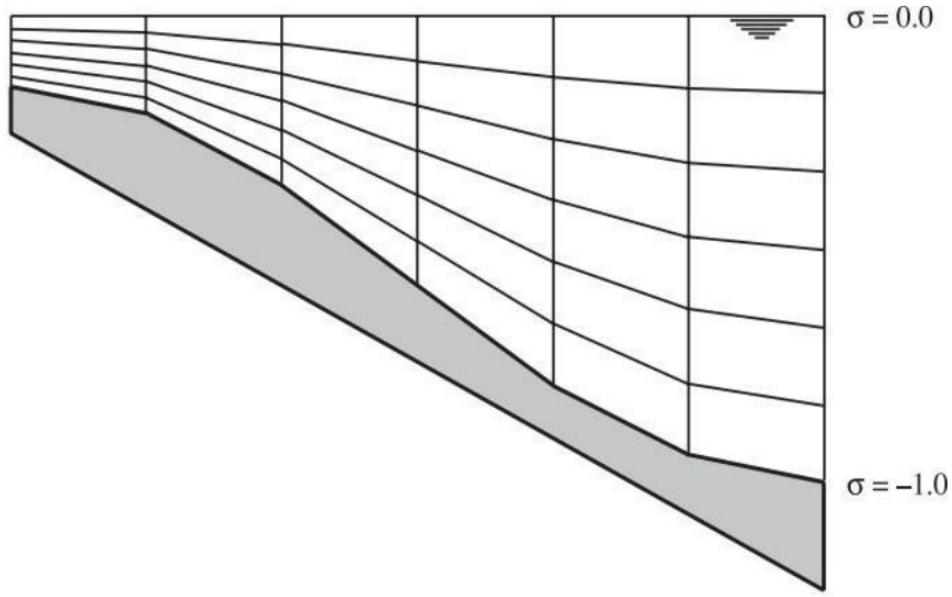


Fig. 3.2 An example of a vertical grid consisting of six equal thickness of σ layers
(Deltres 2013)

$$\frac{1}{\rho_0 \sqrt{G_{\xi\xi}}} P_{\xi} = \frac{g}{\sqrt{G_{\xi\xi}}} \frac{\partial \zeta}{\partial \xi} + \frac{1}{\rho_0 \sqrt{G_{\xi\xi}}} \frac{\partial P_{atm}}{\partial \xi} \quad (3.4)$$

$$F_{\xi} = \frac{1}{\sqrt{G_{\xi\xi}}} \frac{\partial \tau_{\xi\xi}}{\partial \xi} + \frac{1}{\sqrt{G_{\eta\eta}}} \frac{\partial P_{\tau_{\xi\eta}}}{\partial \eta} \quad (3.5)$$

$$M_{\xi} = q_{in}(\hat{U} - u) \quad (3.6)$$

The flow equations within Delft3D are a set of partial differential equations. Resolving this mathematical challenge involves imposing a series of initial and boundary conditions. These conditions are categorized as either closed or open boundaries. Open boundaries, applied to the 'water' boundaries, serve to delimit the computational area. Additionally, boundary conditions can be established vertically, encompassing factors like free surface and seabed specifications. In the context of depth-averaged 2D flow, the bed shear stress induced by turbulent flow adheres to the quadratic friction law, leveraging the Chézy coefficient. It plays a crucial role in expressing the relationship between bed shear stress and flow in the computational model. This coefficient can be derived from formulations such as Chézy, Manning, or White-Colebrook, which is a widely utilized to incorporate friction effects.

$$\vec{\tau}_b = \frac{\rho_0 \vec{U} |\vec{U}|}{C_{2D}^2} \quad (3.7)$$

The open boundary conditions are applied along the domain's edges, introducing external influences into the model, such as tidal forcing. Delft3D offers various types of open boundary conditions, each serving specific purposes within the simulation. They are,

- a. Water Level: $\zeta = F_\zeta(t) + \delta_{atm}$
- b. Velocity: $U = F_U(t)$
- c. Discharge: $Q = F_Q(t)$
- d. Neumann: $\frac{\partial \zeta}{\partial n} = f(t)$
- e. Riemann Invariant: $U \pm \zeta \sqrt{\frac{g}{d}} = F_R(t)$

3.2 Theoretical Background of the Wind Setup

Shear stress is exerted on the water surface by the moving air that can be described by

$$\tau_{wind} = C_d \rho_a W^2 \quad (3.8)$$

C_d represents the wind drag coefficient, ρ_a denotes air density, and W signifies the wind speed atop the water's surface. As a result of shear stress, the water surface initiates movement aligned with the wind. When the wind blows shoreward, it prompts a coastal current in the upper layers. The coastline acts as a barrier, hindering the inland flow. To offset this inward movement, a counter-directed water mass transport occurs in the lower layers. Consequently, a setup or setdown of water level happens along the coast to counterbalance the shear stresses induced by the wind. The wind-induced water level alteration can be articulated through the equation

$$\rho gh \frac{d\eta}{dx} = \tau_{wind,x} \quad (3.9)$$

$$\eta(x) = \int_0^L \frac{\tau_{wind,x}}{\rho gh} dx \quad (3.10)$$

The equation indicates that water level buildup inversely correlates with water depth. This suggests that in shallow coastal areas, water levels can surge to significant heights during storms (known as storm surges). Walton and Dean's 2009 study examined the impact of storm-driven wind setup on different beach shapes. Their findings emphasized wind setup as the primary factor driving the rise in still water levels. Additionally, they highlighted how gentle slopes can result in remarkably elevated water levels at the boundary between land and water.

3.3 Wave Model

The linear wave theory finds frequent application in coastal and oceanic engineering to delineate the features of wind-generated waves. Derived from the Navier-Stokes and continuity equations, as explained earlier, this theory is briefly outlined in this section without delving into its derivation. The image below illustrates a singular wave alongside key components of the linear wave theory.

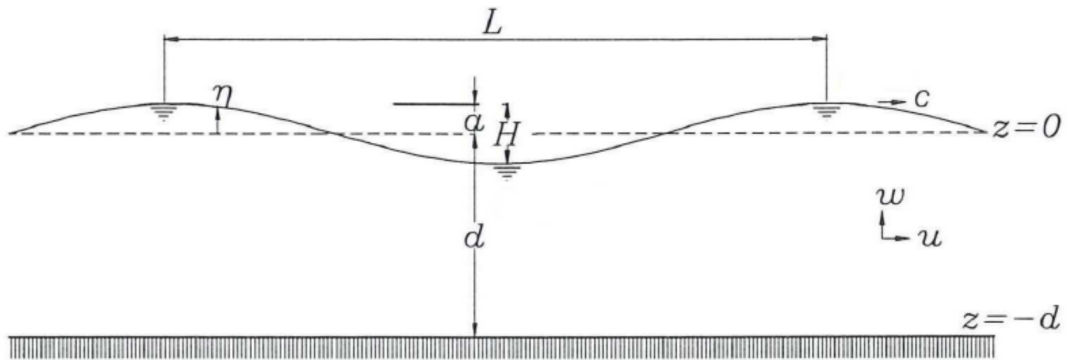


Fig. 3.3 Schematization of a single wave with relevant parameters displayed

The displacement of the water surface can be described by means of the angular frequency ω and the wave number (k)

$$\eta(x, t) = a \sin (\omega t - kx + \alpha) \quad (3.11)$$

$$\omega = \frac{2\pi}{T} \quad (3.12)$$

$$k = \frac{2\pi}{L} \quad (3.13)$$

The wave's displacement relies on the water depth, and in the linear wave theory, waves can exist in shallow, deep, or transitional waters. Shallow-water waves propagate their motion right down to the seabed, whereas in deep water, the wave motion doesn't reach the bed. Determining whether water is deep or shallow relies not only on water depth but also on wavelength. Put simply, if the water depth exceeds roughly half the wavelength, it's categorized as deep water.

For Shallow water $h/L < 1/20$, for deep water: $h/L > 0.5$ and for transitional water: $1/20 < h/L < 0.5$. The dispersion relationship holds significant importance within the realm of linear wave theory. It establishes a connection between a wave's wave number and length with its frequency, offering a means to ascertain both phase and group velocity

$$\omega^2 = \left(\frac{2\pi}{T}\right)^2 = gk * \tanh (kh) \quad (3.14)$$

For deep water the dispersion relation reduces to $\omega^2 = gk$. The wavelength becomes: $L = \frac{gT^2}{2\pi}$ and for shallow water the wave length becomes; $L = T * \sqrt{gh}$

Energy plays a crucial role in characterizing waves within a wave field. This energy can be partitioned into potential and kinetic components. The water surface's displacement correlates with potential energy, while the orbital movement corresponds to kinetic energy. The total energy per unit surface area can be computed using the following equation:

$$E = \frac{1}{8} \rho g H^2 L \quad (3.15)$$

3.4 Flood Inundation Map using Sentinel-1 SAR Images

Change detection technique in remote sensing images involves comparing and analysing two or more images captured at different times of the same area to extract information about changes in the landscape. Change detection involves comparing SAR images taken before and after a flood event to identify areas that have undergone significant changes. SAR is sensitive to changes in surface roughness and can detect the presence of water. Flooded areas typically exhibit different backscattering properties compared to dry surfaces, enabling the detection of inundated regions. Through thresholding techniques, researchers can establish precise thresholds using variations in backscatter values to differentiate between areas affected by flooding and those that are not. This methodological approach aids in precisely outlining the boundaries of the flood extent. This technology finds extensive applications in diverse fields such as land planning (Kamel, 2020), urban growth assessment (Kundu, Halder and Mandal, 2020), disaster evaluation, agricultural studies, scene categorization, and ecological monitoring. In this study a combined methodology using change detection and thresholding is used for detecting flooded areas. A workflow diagram is given in Figure 3.3 which shows all the steps involved in

methodology that is applied in this study. At first images are filtered from the Sentinel-1 Dataset based on date, acquisition mode and polarisation. The reference image which is basically the non-flooded image is calculated using images filtered from the dataset dated from 1st May 2020 to 21st May 2020. This time period is chosen as there was heavy rainfall in the study area before the landfall of the cyclone Amphan. So, the land was moisten in some places due to the absorption of rain water. If the reference image is chosen based on the driest season of the year (Singha et al. 2020) there is possibility that those regions might appear as flooded in the difference image the flooded image is compared with the reference image. Proper selection of reference image plays a great role in the accuracy of detecting flooded areas using SAR data (Hostache, 2012). The final reference image is created by taking the median from the images during the non-flooding time period. For the flood image, an image is found on 22nd May just one day after the cyclone Amphan hit the land. Then a filter is applied to the reference image and the flood image to remove the speckle from these images. It makes the images smoother which helps to process the images for accurately. In this study a radius of 50 to apply this speckle filter is selected. After applying the filter to these images the difference image is generated. The difference image is generated based on the variations in the backscattering differences between the images before and after the event (Clement, Kilsby and Moore, 2018). A threshold value is applied to the difference image so that it extract the areas that have more probability of inundation. According to Long et al (Oluwatobi Oke *et al.*, 2014):

$$PF < (\{\mu[D] - fc \times \{\sigma[D]\}) \quad (3.16)$$

Where, PF are the flooded pixels, $\mu[D]$ and $\sigma[D]$ the mean and standard deviation of the difference image, and fc is a coefficient whose optimal value

was suggested to be 1.5(Oluwatobi Oke *et al.*, 2014). In this way flood inundation may due to cyclone Amphan is generated and used for the validation of the flood map generated from the Delft3D model.

3.5 Performance Evaluation of The Model

The purpose of models is to simulate the physical processes that they are designed to represent. It is important to select best goodness of fit index for the model. Values less than optimal values of the goodness-of-fit index do not necessarily indicate that the model is inaccurate. In fact, they may be due to the inappropriate use of the goodness-of-fit index. Therefore, it's crucial to have reliable goodness-of-fit index in the modelling process. A goodness-of-fit index is intended to provide information about the predictive accuracy of the calibrated model. Thus, the choice of the indices is crucial to ensure that it accurately reflects the specific aspect of the model's performance that it is meant to capture(McCuen, Knight and Cutter, 2006). For evaluating the performance of the model two statistical indices are used in this study. One is standard regression statistics which represents how strong the linear relationship between the simulated and the measured data. On the other hand, the error indices represents the deviation of the simulated data from the measured data. In this case coefficient of determination, R^2 is used as a standard regression statistical parameter and Nash–Sutcliffe efficiency (NSE) index is used as error index to evaluate to performance of the model.(Legates and McCabe, 1999). Where R^2 is a measure of probability of likelihood of a data falling withing the predicted outcomes or falling on the regression line. These two indices are widely used in many past storm surge modelling studies and hydrologic modelling studies.

QWEQWE

3.4.1 Coefficient of determination (R^2)

Coefficient of determination is a measure of assessing the ability of a model to predict an outcome. It indicates the proportion of the variance or percent variation in predicted data explained by linear regression and measured data. For example, if $R^2 = 0.40$, it represents 40 percent of the variation in the predicated data can be explained using the regression line or 40 percent of the predicated data will fall in the regression line. Higher value indicated more strong linear relationship or more predicted data will fall in the regression line hence less error variance. It value ranges from 0 to 1 (i.e. 0 to 100% variation in predicated data can be explained using regression line). Generally 0.5 is considered as an acceptable value for R^2 and it is a widely used parameter for evaluating performance of a model (Legates and McCabe, 1999; D. N. Moriasi *et al.*, 2007). Between 0.6 and 0.75 is considered satisfactory, 0.75 and 0.85 is good and values above 0.85 is considered very good in terms of goodness of fit of the model. The coefficient of determination (R^2) is a derived index from the correlation coefficient, r . Both are similar, while the correlation coefficient measures the strength of a linear relationship between the predicted and observed data, the coefficient of determination measures how well a linear regression model fits the data and explains the variation in the predicted data. R^2 is the square of the correlation coefficient, r .

Correlation Coefficient (r):

$$r = \frac{n(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[n \sum X^2 - (\sum X)^2][n \sum Y^2 - (\sum Y)^2]}} \quad (3.1)$$

Where, X is the measured or observed data, Y is the simulated data and n is the number of observations.

3.4.2 The Nash–Sutcliffe Efficiency (NSE)

The Nash–Sutcliffe efficiency index (NSE) is a widely utilized metric for evaluating the performance and goodness-of-fit of hydrologic models (McCuen, Knight, and Cutter, 2006). This normalized statistic provides a comparative assessment of the residual variance, or the discrepancies between simulated and observed data. Specifically, the NSE quantifies how well the modeled values replicate the actual measurements, offering insights into the model's predictive accuracy. A higher NSE value indicates a better fit, reflecting a smaller ratio of residual variance to the variance of the observed data, thus highlighting the model's ability to explain variability in the data. Conversely, an NSE value less than zero suggests that the mean of the observed data may provide a better predictor than the model itself. This efficiency index is crucial for hydrologists and modelers seeking to improve the reliability and credibility of their predictive simulations.

$$NSE = 1 - \frac{\sum(X - Y)^2}{\sum(X - \bar{X})^2} \quad (3.2)$$

Where, X is the measured or observed data, Y is the simulated data and $\bar{X}$ is the mean of the observed data. The index evaluates the agreement between the observed values (measurements) and the predicted or simulated values, represented by a 1:1 line, with a range of values from $-\infty$ to 1. The resulting Nash-Sutcliffe Efficiency (NSE) value indicates the degree of closeness between the two sets of values. A value closer to 1 indicates a better agreement between the observed and simulated values which is acceptable. NSE value greater than 0.75 is considered to represents a very good quality acceptable model whereas less than 0.5 is considered unsatisfactory. (Motovilov *et al.*, 1999; D. N. Moriasi *et al.*, 2007). NSE value equal to 1 corresponding to a perfectly matched model with the observed data, NSE equals to 0 represents the predicated data of the

model are as accurate as the mean of the observed data or the mean of the observed data is as accurate as model predictions and a negative NSE value represents the mean of the observed data predicts better than the model which required rearranging parameters of the model depending on the objective.

In summary R^2 is the probability of a new predicated data falling on the line or ability to find the likelihood of an observed data from an event failing within the predicted outcome. On the other hand, NSE indicated how well the plot of observed vs predicted values fits the 1:1 line which quantitatively describes the predictive accuracy of the model.

3.6 SUMMARY

Delft3D hydrodynamic model is used in this study to model storm surge due to cyclonic activity in BoB. It is a powerful and widely used hydrodynamic modeling suite, particularly popular for coastal modeling. Several storm surge study has been conducted with this modelling suite in the Bay of Bengal (Rezaie, 2015; Jisan, 2016; Nahiduzzaman, 2018; Tanim and Akter, 2019b) and in many other coastal areas around the world.

Being open source, which means it's accessible to a wide community of researchers and practitioners. It is versatile, offering a range of modules for different purposes within coastal modeling, including hydrodynamics, sediment transport, morphology, water quality, and ecology. This versatility allows for comprehensive and integrated modeling of various coastal processes. It employs physics-based algorithms to simulate complex hydrodynamic processes, making it suitable for studying tides, currents, waves, and sediment transport in coastal environments. Its coupling capability allows coupling different processes, enabling the study of interactions between hydrodynamics,

sediment transport, and other factors affecting coastal dynamics such as wind and wave. Which is the fundamental of storm surge modelling.

In this study, change detection and thresholding techniques are employed to generate inundation maps during Cyclone Amphan, utilizing Sentinel-1 Synthetic Aperture Radar (SAR) satellite images for several compelling reasons. One key aspect of this approach is its application in validating the storm surge inundation model. SAR images are particularly advantageous as they capture variations in the backscattering properties of the Earth's surface over time, which is crucial for identifying changes associated with flooding. One of the primary benefits of SAR technology is its ability to acquire data independent of weather conditions or cloud cover. This characteristic enables continuous monitoring, even during adverse weather scenarios that would typically obstruct optical sensors. As a result, SAR images provide reliable and timely information, which is essential for effective flood assessment and management.

Thresholding techniques play a critical role in this analysis by allowing researchers to establish specific thresholds based on changes in backscatter values. These thresholds are used to differentiate between flooded and non-flooded areas, providing a quantitative framework for accurately delineating the extent of inundation. By applying this systematic approach, researchers can effectively identify flood-affected regions with greater precision.

Moreover, these methodologies offer an objective means of detecting flood-impacted areas based on predefined thresholds, thereby minimizing subjective interpretation of the satellite data. This objectivity is crucial in enhancing the reliability of the results and ensuring that the inundation maps generated reflect true conditions on the ground. Ultimately, the integration of change detection and thresholding techniques using SAR data significantly contributes to the understanding of flood dynamics and the effectiveness of storm surge inundation models.

Both the coefficient of determination R^2 and the Nash–Sutcliffe efficiency index (NSE) are widely recognized and employed across a range of scientific disciplines, serving as essential tools for evaluating model performance. Their widespread acceptance is largely due to their ability to provide a standardized framework for assessment, which enhances consistency in evaluation methodologies across various studies. This standardization not only facilitates uniformity in how model performance is gauged but also allows for more straightforward comparisons of results between different research projects, fostering collaboration and knowledge sharing within the scientific community.

The R^2 value is particularly intuitive, as it quantifies the proportion of the variance in the observed data that is accounted for by the model. This straightforward interpretation makes it easy for researchers to understand how well the model captures the variability inherent in the actual measurements. A higher R^2 indicates a better fit, suggesting that the model effectively represents the data.

In contrast, the NSE provides a complementary perspective by offering an easily interpretable assessment of the relative magnitude of the residual variance in relation to the variance of the observed data. This means that NSE not only considers how well the model fits the data but also highlights the importance of the model's predictive accuracy relative to the observed variability. By examining both R^2 and NSE, researchers can gain a comprehensive understanding of model performance, helping to identify strengths and weaknesses in predictive capabilities. This dual approach ultimately enhances the robustness of scientific analyses, leading to more informed decision-making in fields such as hydrology, environmental science, and engineering.

Chapter 4: MODEL SETUP, CALIBRATION AND VALIDATION

In this chapter all the aspects regarding modelling storm surge in the Bay of Bengal using Delft3D as discussed. Delft 3D model has been widely used and verified for various river, coasts and estuaries all around the world as stated earlier. In the first part of the chapter the model setup is discussed. This section also subdivided based on the different stages involved in the modelling setup. After discussing about the model setup calibration and validation of the storm surge model is discussed. The validation of the storm surge model is done for super cyclone Amphan.

4.1 DELFT3D

Delft3D is a hydrodynamic model, has undergone validation across a wide spectrum of physical conditions, encompassing storm surge, as per the quality assessment criteria. Nonetheless, the precision of simulation outcomes relies on the suitability of available data, the choice of model by the end user, and the specified model parameters. As highlighted, achieving accurate and beneficial results for a specific application necessitates not only the utilization of high-quality modelling tools but also other factors.

The aim in employing Delft3D is to create a well calibrated and validated storm surge model to design crest level for coastal embankments for different SLR scenario (Figure 4.1). This chapter's objective is to establish and validate the surge model. This involves simulating a historical event using Delft3D and comparing the resulting storm surge with observed data collected during the actual event. Cyclone Amphan has been selected for this validation process.

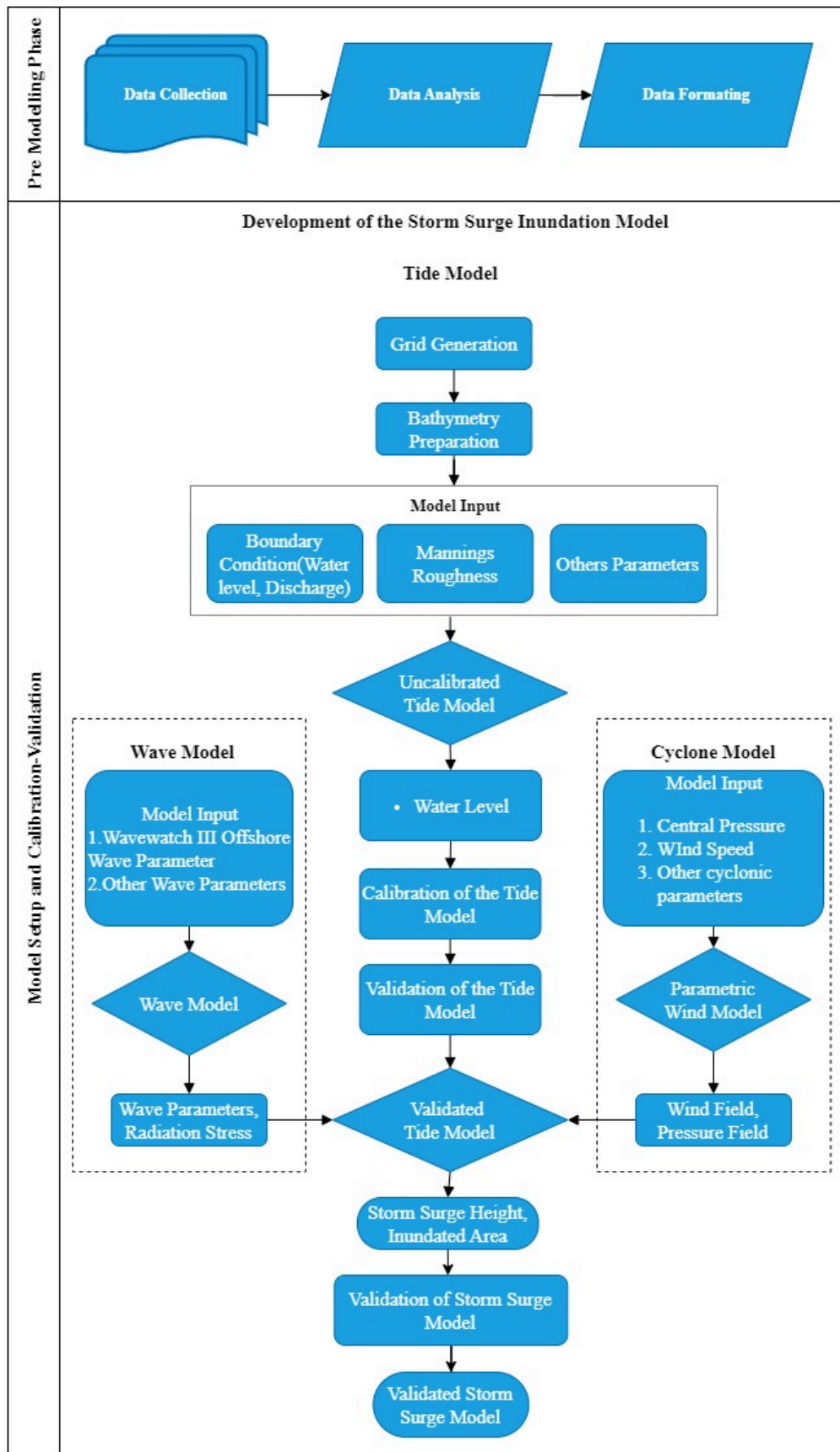


Figure 4.1: Delft3D model setup

4.2 STUDY AREA

For study area coastal region of Bangladesh is selected. Since Amphan hit India Bangladesh border near Sundarbans. Figure 4.2 shown the model domain of the storm surge inundation model. The model domain is set by including the northern part of the Bay of Bengal and the coastal regions of Bangladesh. The model domain covers around 315 thousand square km area. There are 14 coastal districts in the model domain. The downstream open boundary is situated in Bay of Bengal. Average distance of this open boundary is about 330 km away from the coast of Bangladesh.

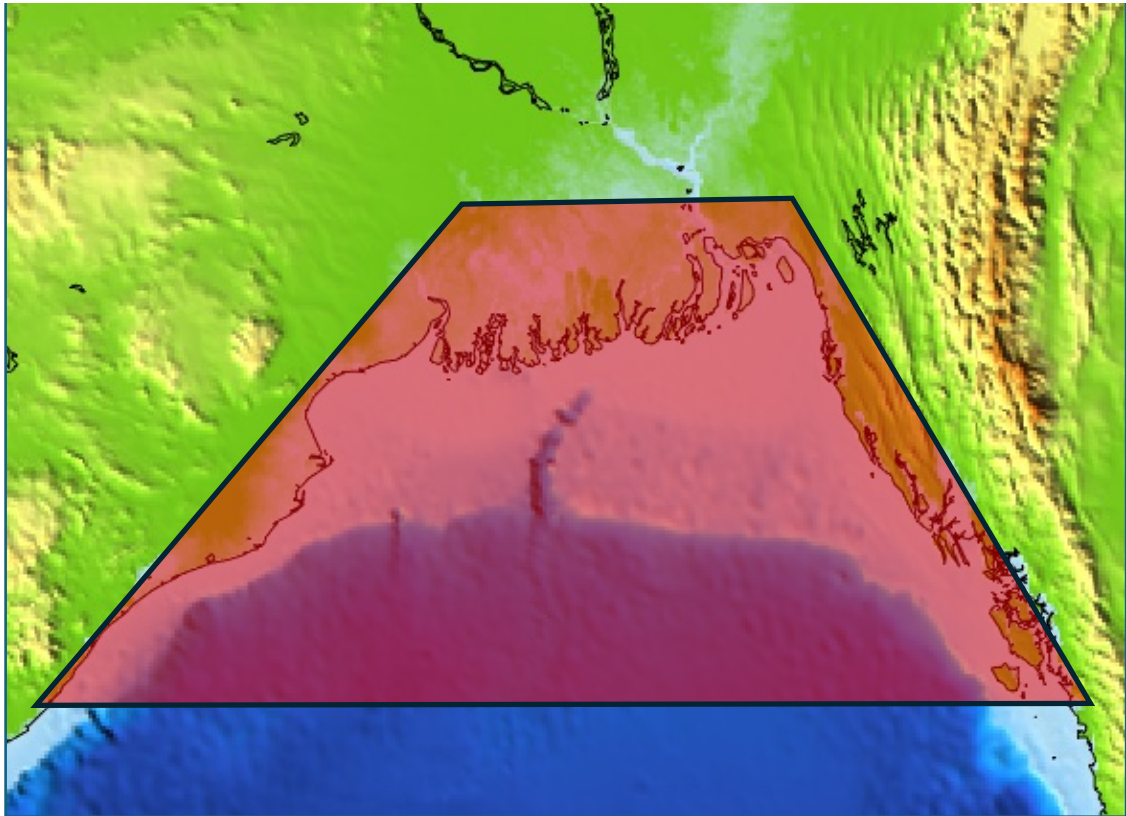


Figure 4.2: Study area

4.3 TROPICAL CYCLONE USED FOR VALIDATION: AMPHAN (2020)

On May 13, 2020, a low-pressure system lingered in the northern Bay of Bengal, positioned approximately 300 kilometers east of Sri Lanka. By the end of May 15, both the Indian Meteorological Department (IMD) and the Joint Typhoon Warning Centre (JTWC) had classified this system as a tropical depression. As the situation progressed, by May 16 at around 18:00 UTC, the

depression had shifted northward and transformed into Cyclonic Storm Amphan. Initially, there was little change in intensity over the next twelve hours. However, beginning at 12:00 UTC on May 17, Amphan entered a phase of rapid intensification, with its wind speeds soaring from 140 km/h to 215 km/h within just six hours. This rapid increase in wind speed qualified it as an extremely severe cyclonic storm, categorized as a Category 4 on the Saffir-Simpson scale.

As the storm continued to develop over the next twelve hours, it reached unprecedented wind speeds of 260 km/h, with a central pressure plummeting to 907 millibars. This made Amphan the most powerful cyclone ever recorded in the Bay of Bengal. During this period, the cyclone demonstrated the phenomenon of dual eye-wall formation, which is commonly associated with strong cyclonic activity.

However, the storm's strength began to decline significantly over the following day due to an eye-wall replacement cycle combined with considerable vertical wind shear ranging from 30 to 40 km/h. This deterioration was further exacerbated by easterly shear and the intrusion of mid-level dry air, although the vertical wind shear remained moderate throughout this period. The cyclone made landfall between 8:00 and 10:00 UTC at coordinates approximately (88.35°N, 21.65°E), coinciding with mid-tide conditions. At the time of landfall, Amphan's maximum wind speed was reported to be between 150 and 160 km/h, with a central pressure recorded at 965 millibars. By May 21, the system had weakened further and ultimately dissipated as it moved inland.

In an extended range forecast released on May 7, the IMD projected a low likelihood of cyclogenesis occurring between May 8 and May 14. Global and regional models began forecasting a major storm in the Bay of Bengal as early as May 12, which was eight days prior to the cyclone's impact and four days before the tropical depression's actual formation. Both the National Oceanic and Atmospheric Administration (NOAA) and the IMD activated their operational Hurricane Weather Research and Forecasting (HWRF) systems in response to the developing low-pressure system. However, this analysis specifically concentrates on the forecasts generated by the NOAA HWRF, utilizing the outputs from the Automated Tropical Cyclone Forecasting System (ATCF). Figure 3 provides a visual representation of selected forecast cyclone tracks issued sequentially from NOAA-HWRF.

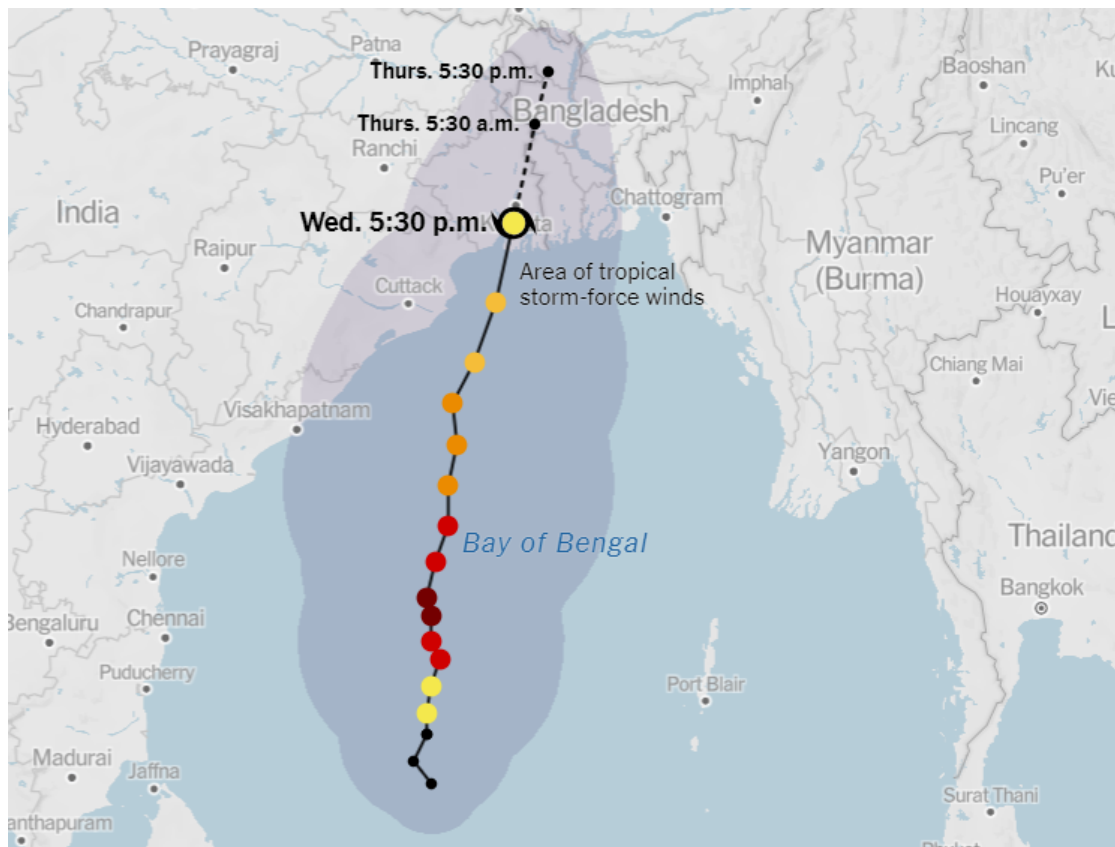


Fig. 4.2 Cyclone Amphan(2020) track

The best track depicted in Fig. 4.2 convergence in the anticipated location of landfall. Three days prior to landfall on May 17, the forecast tracks coincided with the observed track. One day prior to landfall on May 18, the projected error for the storm's track location had dropped to about 50 km. On the other hand, compared to the trajectory, the predicted accuracy for wind speed and centre pressure was lower. Although the first projections were accurate in terms of the amount of intensification, they were not able to account for the sudden increase in intensity that was seen on May 17–18. In a similar vein, the quick weakening of the system that happened prior to landfall on May 19–20 was not anticipated by later forecasts that were started on May 17 and May 18. Overall, the predicted accuracy for wind speed was only within 1 m/s during a 24-hour period.

4.4 Model Setup

The anticipated tracks coincided with the observed track as early as May 17, three days prior to impact. The anticipated error in the storm track position has dropped to about 50 km by May 18, the day before landfall. On the other hand, compared to trajectory forecasting, wind speed and central pressure forecast accuracy was lower. Although the early estimates were accurate in terms of the intensity, they were not able to account for the sudden intensification that was witnessed on May 17–18. Similar to the previous forecasts, the quick weakening of the system that transpired prior to landfall on May 19–20 was not anticipated by the forecasts started on May 17 and May 18. The predicted accuracy for wind speed over a 24-hour period was limited to 1 m/s overall. DDB offers users to define computational domain, grid generation, bathymetry assignment on base maps. Delft Dashboard has toolboxes that helps user to generate and assign boundary conditions (Tide, wind, waves) with ease. Tropical Cyclone Toolbox is one of the toolboxes which enables user to generate input files for Delft3D for modelling the impact of physical process of tropical

cyclone in storm surge generation by using multiple parametric cyclone models such as Vickery and Waldhera (2008), Holland (2010), Kees Nederhoff, Ap van Dongeren and Ormond, (2016). Because of the ability of setting up a model in a single platform and ease of use DDB is used in this study to set up the Delft3D storm surge model (Fig. 4.3). In this section setting up the storm surge is discussed sequentially in different subsections based on the stages involved in the setup process.

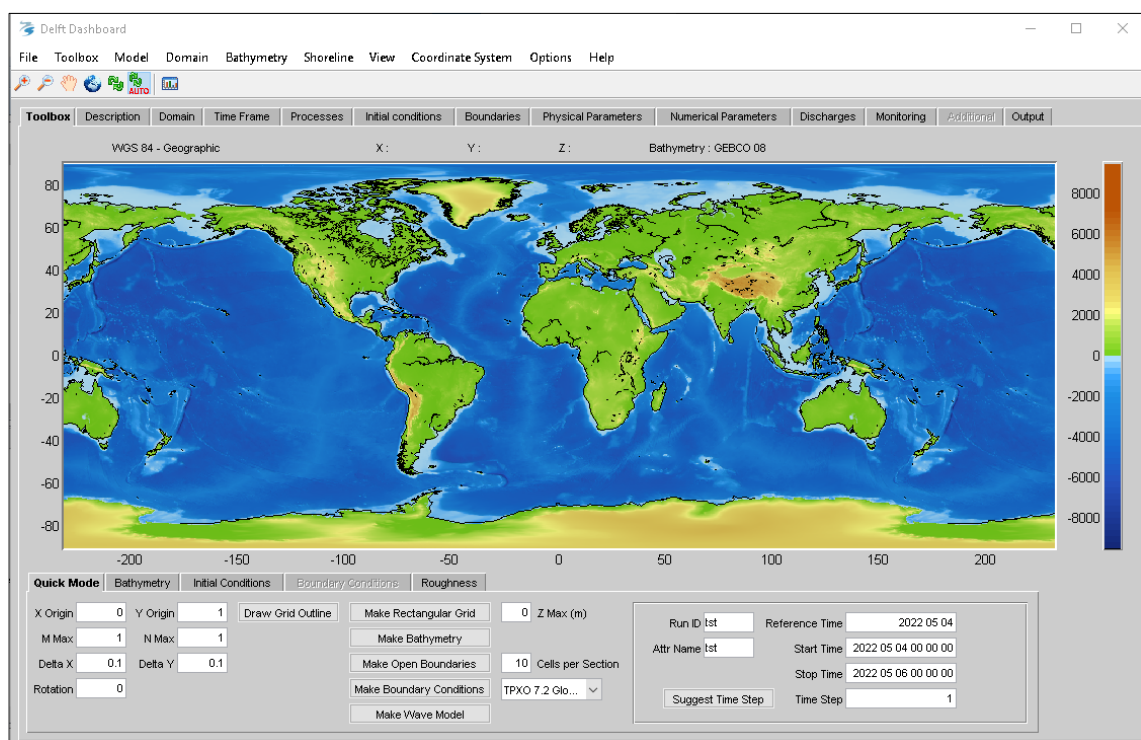


Fig. 4.3 Delft Dashboard User Interface

4.4.1 Model Grid Development

As stated earlier model computational grid is generated in DDB. There is also a grid generation tool developed by Deltares which comes with the Delft3D modelling suite. But due to the ease of use and working flexibility in DDB is preferred in this study. There is a limitation of DDB. It doesn't allow user to make curvilinear grid. It can only generate rectangular grid. Although it allow users to work with curvilinear grid. Therefore, this model grid has only

rectangular grid. The grid extent , orthogonality and size of the grid cells significantly influence the performance of the model result. Since tropical cyclones have larger size and longer travel distances, the extent of the grid should be large enough to cover its huge size and travel path from its generation to landfall. Grid size depends on the desired resolution of the model. In case of a storm surge model, it is desired to have higher resolution or smaller grid size in shallow water and estuarine area to accurately reproduce the shallow water bathymetry due to frequent changes in bathymetry near coastline. To model the inundation due to storm surge it required to have higher resolution in the coastal topography as well. On the other hand in open sea bathymetry changes are very gradual in nature. Therefore lower resolution or larger grid sizes can be used to reproduce these gradual changes in deep water bathymetry. Model with smaller grid size requires much computational time than larger grid size although it offers more accurate result. Delft3D allow users to divide the study area in multiple subdomains to based on the different grid resolution required in different location of the domain. This technique is called domain decomposition. In DDB there is a toolbox called Domain Decomposition to perform this operation. Initially a rectangular grid outline is drawn covering the land and the Bay of Bengal to make low resolution rectangular grid (Figure 4.4). This low-resolution larger domain has grid cell size of 1km×1km. Maximum elevation for grid generation is set to 10m, so that no grid is generated inside the rectangular grid outline where land elevation is above 10m. Then a smaller subdomain with higher resolution is created to reproduce the shallow water bathymetry and coastal land topography. This subdomain has grid cell size of 10m×10m.

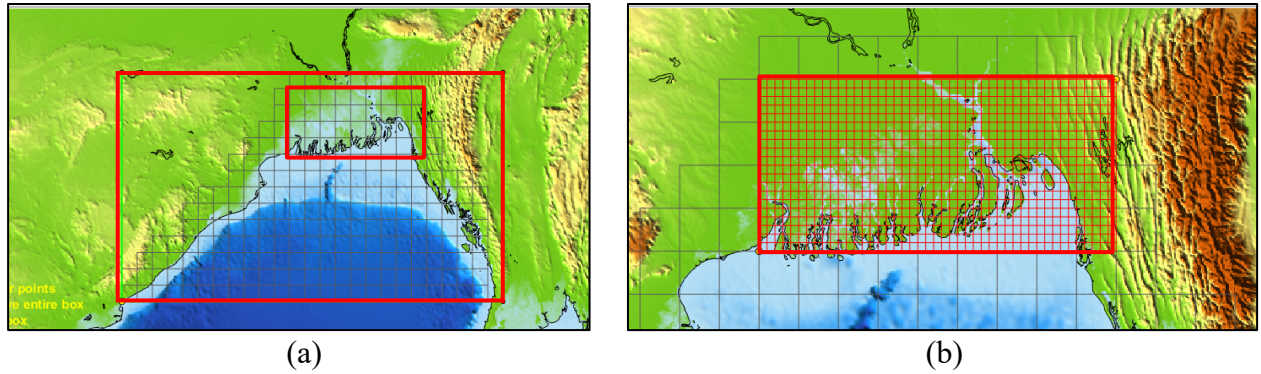


Fig. 4.4 Model Computational Grid (a) Low Resolution Open Sea Grid (b) High Resolution Shallow Water Grid

4.4.2 Bathymetry and Topography

Data on the topography and bathymetry for the area of interest are collected from different sources. For bathymetry of the Oceanic waters, the General Bathymetry Card Of Oceans (GEBCO19) is used. This database provides up to 500 m accurate bathymetry and land cards by using different measurements and estimations (Table 4.1).

Table 4.1 Topography and bathymetry sources

Datasets	Coordinate system	Reference level
GEBCO19	EPSG:4326	Mean Sea Level
River Cross Sectional Data	EPSG:4326	Mean Lower Low Water (1.45m below MSL)
SRTM topography	EPSG:4326	Mean Sea Level

Before the data sets can be used to create the Delft3D model, some source must be transformed and edited. This is due to the fact the different coordinate systems and reference levels are used. The data with different coordinate systems and reference levels are all transformed to EPSG:4326 and MSL. The original topography cards are in 5m resolution. This very high resolution is not needed for the model since the main focus is not on inland flooding. To improve the computational speed, the topography data accuracy is reduced to 100m. Furthermore, some of the data overlap each other and need to be filtered

out. The data filtering ensures that the most accurate data is used, and the overlapping points are deleted. The local topography and bathymetry sources are significantly more accurate than the global Gebco19 database. The points from the GEBCO database that overlap any of the points from the other sources are deleted. All the points from the GEBCO database that represent lands with an altitude higher of 30m are also filtered out and deleted. Finally, the transformed and edited sources are combined in one .xyz file that can be used in Delft3D. To make the bathymetry suitable as input for Delft3d, it must be adapted to the computational grid. With QUICKIN the bathymetry points are averaged or interpolated over the grid to obtain bed levels at the grid cell corners.

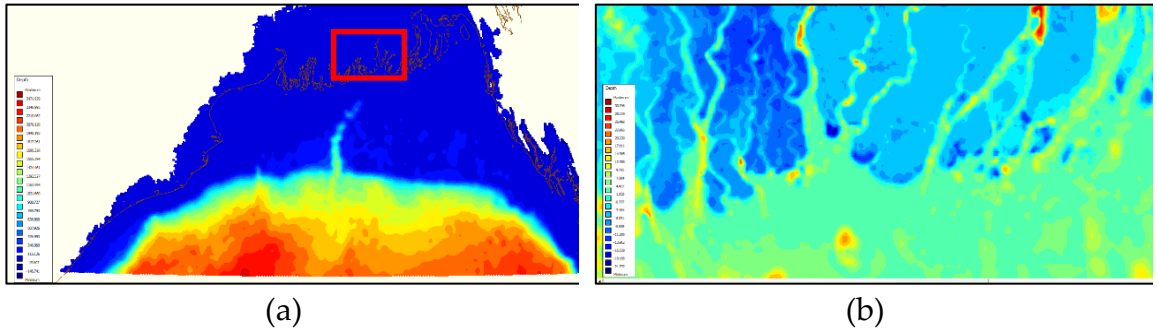


Fig. 4.1 Model Bathymetry in the computational domain

4.4.3 Time Step

Selection of time step is mostly associated with the accuracy of the model result. Sometimes stability of the model is also associated with it. But most of the cases stability is not an issue. It is recommended to select time step so that Courant-Friedrichs-Lewy number (CFL) doesn't exceed 10. Courant-Friedrichs-Lewy number is defined by

$$CFL = \frac{\Delta t \sqrt{gH}}{\{\Delta x, \Delta y\}}$$

where Δt is the time step (in seconds), g is the acceleration of gravity, H is the (total) water depth, and $\{\Delta x, \Delta y\}$ is the value of the characteristic (in many cases

the minimal value) of the grid spacing in either direction. CFL number can be taken larger in some special cases where there is a small variation in space and time or where stability is an issue (Deltares, 2014). Initially, $\Delta t = 30s$ is considered. Which results in the abnormal shut down of the flow module. It means the model is unstable due to higher CFL. Finally $\Delta t = 15s$ is set as time step with maximum CFL of 17.

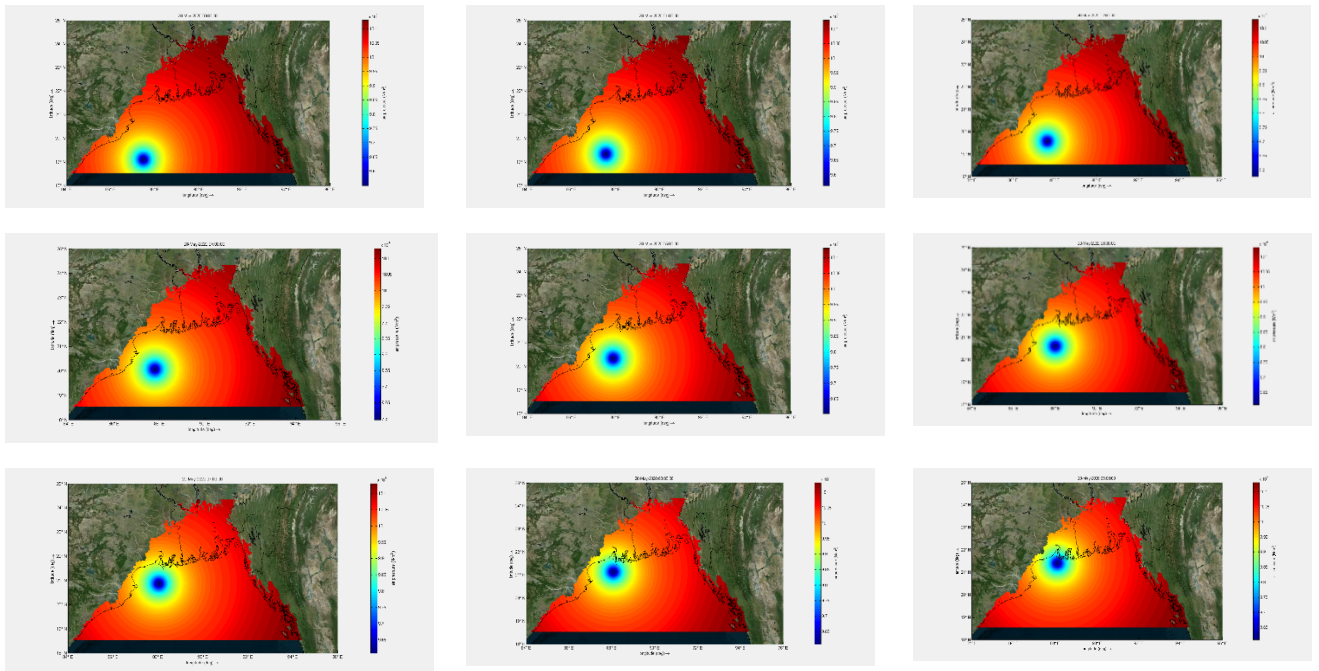
4.4.4 Boundary Condition

Depending on the type of external forcing on the model domain from the outside, it is required to impose boundary conditions at the open boundaries of the computational grid to model the effects of these external forcing on the model. There are two open boundary locations in the computational domain of this storm surge model. One is at the Bay of Bengal, downstream and another is at the upstream of the computational domain grid at Meghna. In Delft3D, user can use 5 different types of boundary condition based on the external forcing types and the physical process to be studied. They are water level, current (velocity), Neumann, Discharge or flux and Riemann boundary conditions. Discharge or flux type boundary conditions are used to model the inflow from upstream into the model domain. Modelling tidal flow in a large basin or in large coastal model water levels are recommended as boundary conditions since water levels data are the most reliable data as compared to other types of boundary conditions (Deltares, 2014). Because in most cases water level in the sea is governed by the astronomical tidal constituents as stated earlier in chapter three. It is also required to define hydrodynamic forcing in the model as boundary forcing. In Delft3D, hydrodynamic forcing can be prescribed using astronomic components, harmonic components, as time series or as Q-H relationship. For storm surge simulation at open ocean boundaries water level type boundary condition with astronomical forcing is recommended (Deltares,

2014). Each astronomical component has a amplitude and a phase value associated with it. By using amplitude and phase value of all the astronomical components it is possible to measure water level changes due to tidal forcing. As it is stated earlier that water level changes at sea due to astronomical tidal forcing can be determined from the astronomical constituents at the open ocean boundaries. There are multiple tide models available today to provide this data in different resolution. At different grid resolution these models have a unique set of astronomical constituents for each grid which can be used for the boundary conditions. Some of these tidal models are TPXO6.2, TPXO7.2, TPXO8.0, TPXO9.0, FES2014. DDB provides access to some of these tide models and allow users to make boundary conditions instead of using other open-source platforms. In this study TPXO 8.0 tidal model is used to generate boundary conditions for the storm surge model. There is also an open boundary at the upstream of the model domain at Meghna River. At this boundary time series discharge data are provided as boundary condition to model the river inflow coming into the model computational domain. The GI approach provides a dynamic and optimum solution of Laplace tidal equation to apply in a global scale at 0.25°-degree resolution. Twelve major harmonic elements, namely T2, K1, K2, M2, N2, O1, P1, Q1, S2, 2N2, NU2, and MU2, were identified by Krien et al. (2016) in the northern BoB and were subsequently pushed into the Delft3D-FLOW domain. Tide level is most influenced by semi-diurnal elements at the top of the BoB (0.3-0.7-day periods). MSF, one of the fortnightly elements of tidal rivers, likewise exhibits increased dominance during spring or neap tide. Furthermore, due to non-linear interactions long period constituents significant in shallow water but insignificant in offshore deep water (Rose and Bhaskaran, 2017). In this study all the major and minor constituents are used as forcing. Delft dashboard is used to generate these tidal constituents using TPXO 8.0 global tide model.

4.4.5 Model Forcing

For storm surge simulations, the wind input is the most important forcing factor in the model. As discussed in Section 2.5 in this thesis the observed wind speeds and pressure can be used in a parametric wind model to describe the wind and pressure field of the TC throughout its life cycle. Data from historical TC's all around the world are stored in the IBTrACS database from the national oceanic and atmospheric administration (NOAA). The database contains information on the location, maximum wind speed, pressures and other relevant parameters for the duration of the TC. The TC track data is used as input for a MATLAB script that applies the wind model as discussed in Section 2.5. The applied wind model creates a file with the wind speed and pressure fields on a moving spiderweb grid. This spiderweb file is used as the TC forcing in the model. Figure 4.5 shows that reproduction of the wind field and pressure field in Delft3D during the approaching of super cyclone Amphan.



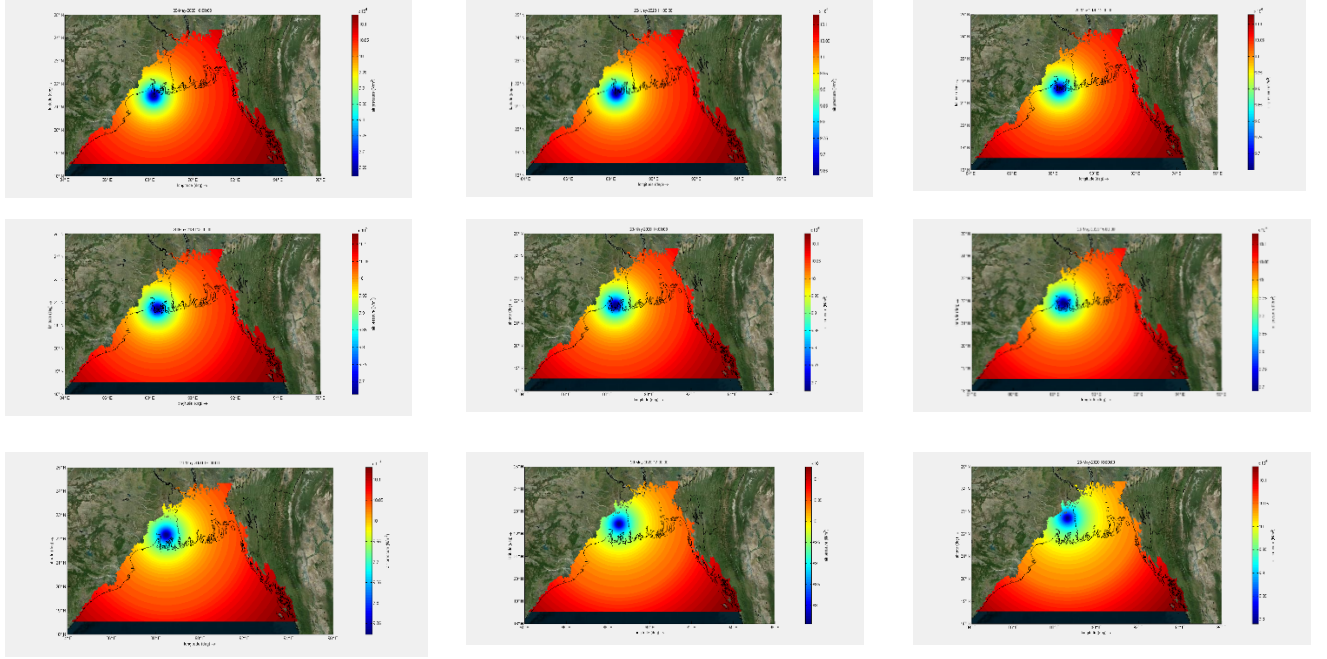
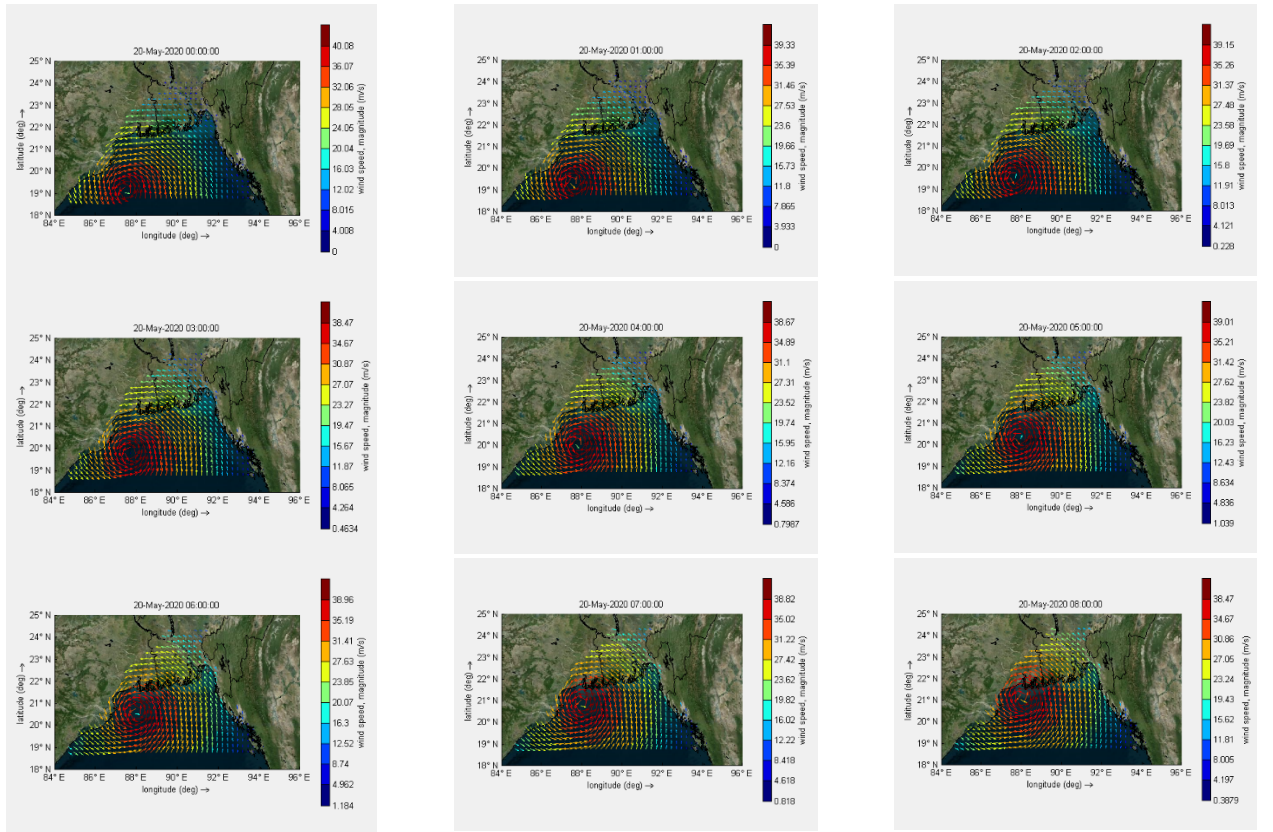


Fig. 4.2 Generated Pressure field during the approaching of super cyclone Amphan using parametric model.



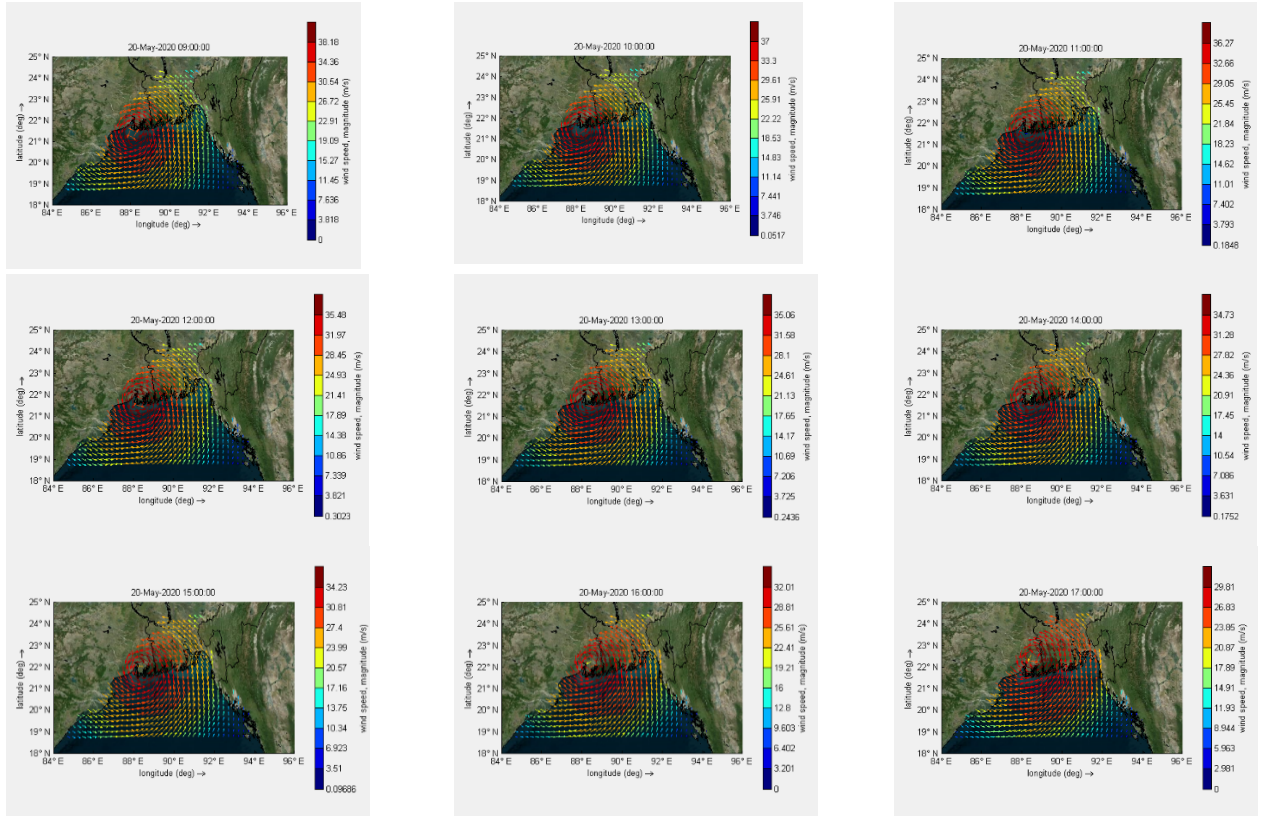


Fig. 4.3 Generated wind filed during the approaching of super cyclone Amphan using parametric model.

4.5 Model Calibration and Validation

Calibration is an important step in modelling because it ensures that the model is a reliable tool for making predictions and guiding decision-making. Calibration of a model involves adjusting its parameters to make the model output match observed data as closely as possible. The purpose of calibration is to improve the accuracy of the model's predictions by reducing errors and uncertainties in the model. To calibrate a hydrodynamic model, it is required to compare the model's predicted data with actual measurements or observations such as water levels, flow rates, or other hydrodynamic variables in the system being modelled. a calibration parameter is a model parameter that can be adjusted during the calibration process to improve the agreement between the model output and observed data. Calibration parameters are typically variables that affect the behaviour of the system being modelled but are difficult to

measure directly or are subject to uncertainty. Calibration is typically an iterative process that involves running the model multiple times, adjusting the parameters, and comparing the results with observations until an acceptable level of agreement is reached. The goal is to improve the match between the model's output and the measured data. Calibration parameters are critical for ensuring that hydrodynamic models accurately represent the behaviour of the system being modelled. By adjusting these parameters, modelers can improve the accuracy and reliability of the model and make better predictions of future behaviour in the system.

Calibration of the model is followed by validation of the model which involves testing its predictive capabilities against independent, real-world data that were not used during the model's development or calibration. The purpose of validation is to evaluate the accuracy and reliability of the model's predictions and to assess its performance under a range of conditions. The validation process is like the calibration process in that it involves comparing the model's predictions with observed data, but it differs in that the data used for validation must be independent of the data used for model development and calibration. Validation is typically a one-time process that is conducted after the model has been developed and calibrated. Validation is an important step in hydrodynamic modelling because it provides an objective assessment of the model's performance and helps to identify any limitations or weaknesses in the model. A well-validated model can be used with confidence to make predictions and inform decision-making related to water resources management, flood forecasting, environmental impact assessments, and other applications.

Storm surge modelling consist of coupling of different models as discussed earlier. That means it will require multistage validation of different

models to produce the actual scenario. In this section multistage validation of different models are discussed in detailed.

4.5.1 Calibration and Validation of the Tide Model

The foundation of storm surge modelling is the tide model. The tide model, which is essentially a hydrodynamic model, needs to be thoroughly validated in order to develop a storm surge model. The output from the other models is utilised as distinct input parameters for the storm surge model after the tide model has been validated. Therefore, the tide model's accuracy is the primary determinant of the model's accuracy.

A 15-day run with solely tidal forcing is scheduled from May 1, 2020, to May 15, 2020, for the purpose of calibrating the tide model. In order to align the water level determined by the tide model with the observed water level data recorded by the BIWTA during these 15-day simulation periods, Manning's roughness, n , is employed as a calibration parameter. For the calibration of the tide model 5 observation stations are selected for comparing the simulated and the observed data. Location of these 4 stations is shown in Figure 4.7. BIWTA water level data are measured by considering MSL as datum. In Delft3D simulated water level data are also referenced to MSL. Hence water levels data are kept unchanged and all the water level data used in this study are with reference to the MSL considering it as datum.

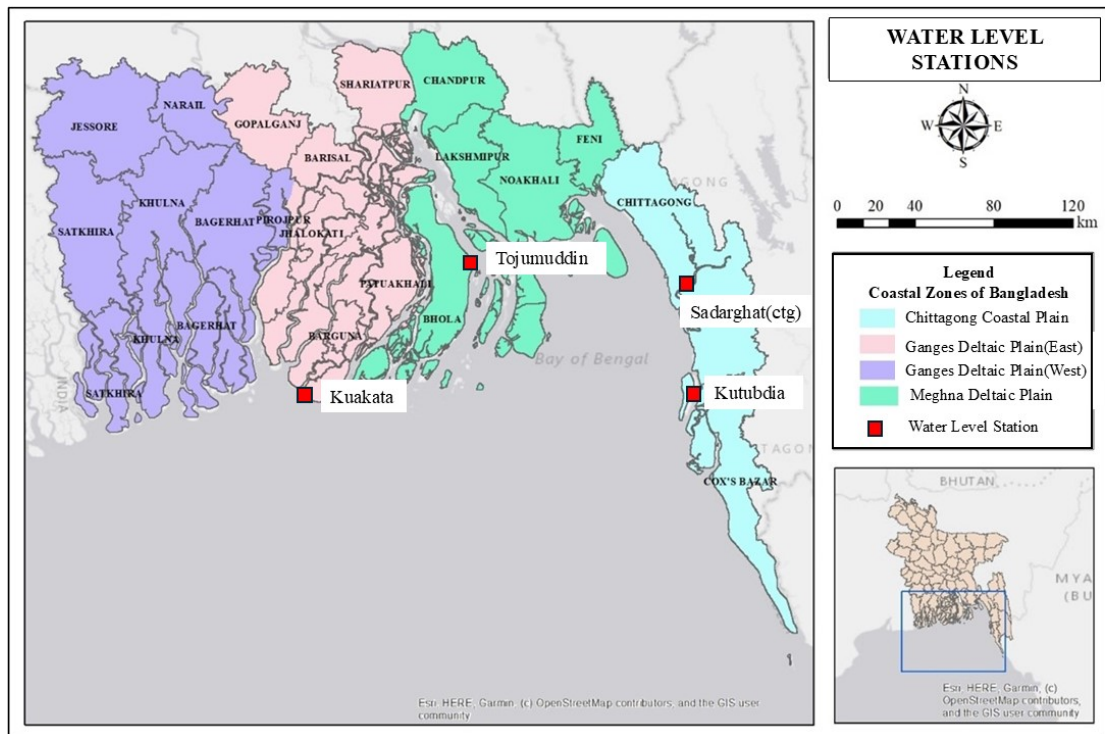


Fig. 4.4 Water Level Stations

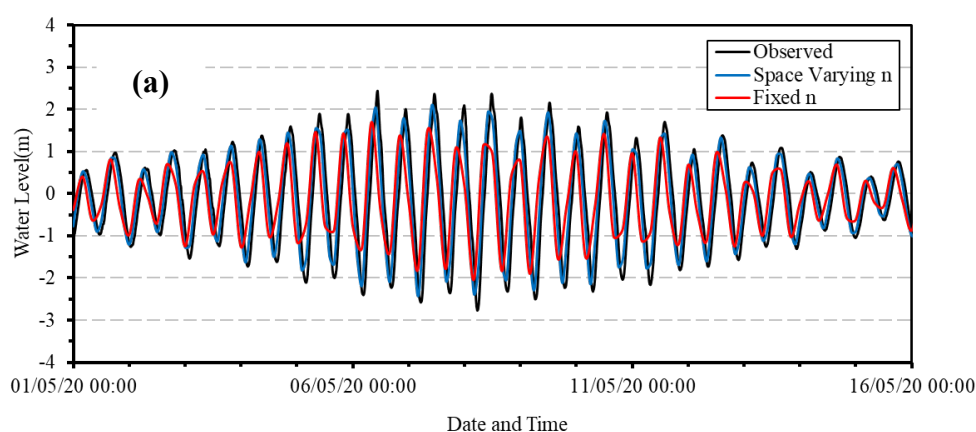
Number of simulations were performed in various combination of 'n' for land, mangrove, and sea. Initially fixed 'n' value of 0.08 for land and 0.024 for sea is considered as it was the default roughness value in Delft Dashboard. Next, depending on the depth of the water and the cover of the land, manpower with spacing variation (n) is employed. Storm surge is discovered to be significantly impacted by sea surface roughness. (Bertin *et al.*, 2015). And inland bottom roughness also has significant impact on flooding(Krien *et al.*, 2017). From the previous research findings, it is clear that selection of optimum roughness value is crucial for storm surge inundation modelling. Space varying manning roughness are assumed for different trials are based on the roughness value considered in the previous storm surge studies in the Bay of Bengal. Table 4.2 shows a list of manning's roughness, n used in previous storm surge studies.

Table 4.2 Applied Manning's roughness coefficient, n in the Bay of Bengal.

Description	Manning's n	References
Land	0.05	(Lewis <i>et al.</i> , 2013)

	0.07	(Krien <i>et al.</i> , 2017)
Mangrove	0.08	(Deb and Ferreira, 2016)
Depth below 20m	0.013	(Krien <i>et al.</i> , 2017)
Depth larger than 20 m	0.02	(Krien <i>et al.</i> , 2017)

After number of trial simulations, optimum Space varying Manning's roughness, n value is fixed and for land it is 0.065, for mangrove it is 0.08, for river, estuarine and sea depth below 20m it is 0.015 and depth larger than 20m it is 0.02. Calibration results at 5 stations are shown in Figure. 4.8 comparing simulated water level with the observed water level for the optimum space varying Manning's n and fixed n value. Only by visual inspection it is evident that space varying Manning's n have significantly improved the model outcome as compared to with fixed n value for land and sea. Model evaluation indices at different stations are found to be good enough for the tide model at the calibration stations for considering it as a well calibrated model. R^2 and NSE indices for the optimum n and fixed n condition are shown in table 4.8. Figure 4.9 shows the relationship between the simulated and observed water level along with their R^2 and NSE indices at 5 observation stations.



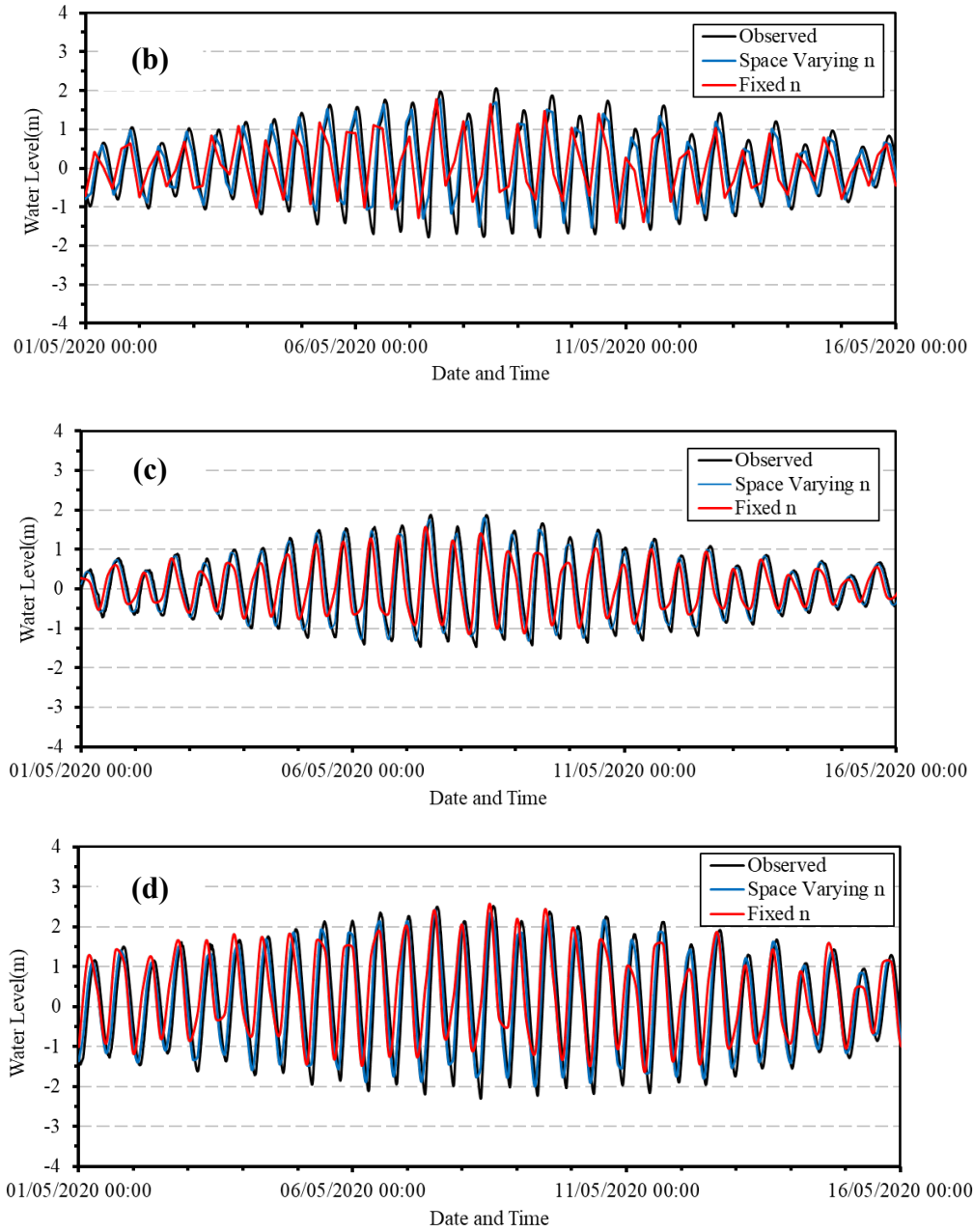


Fig. 4.5 Water level Calibration of the tide model at (a) Kutubdia, (b) Tojumuddin (c) Kuakata (d) Sadarghat(ctg)

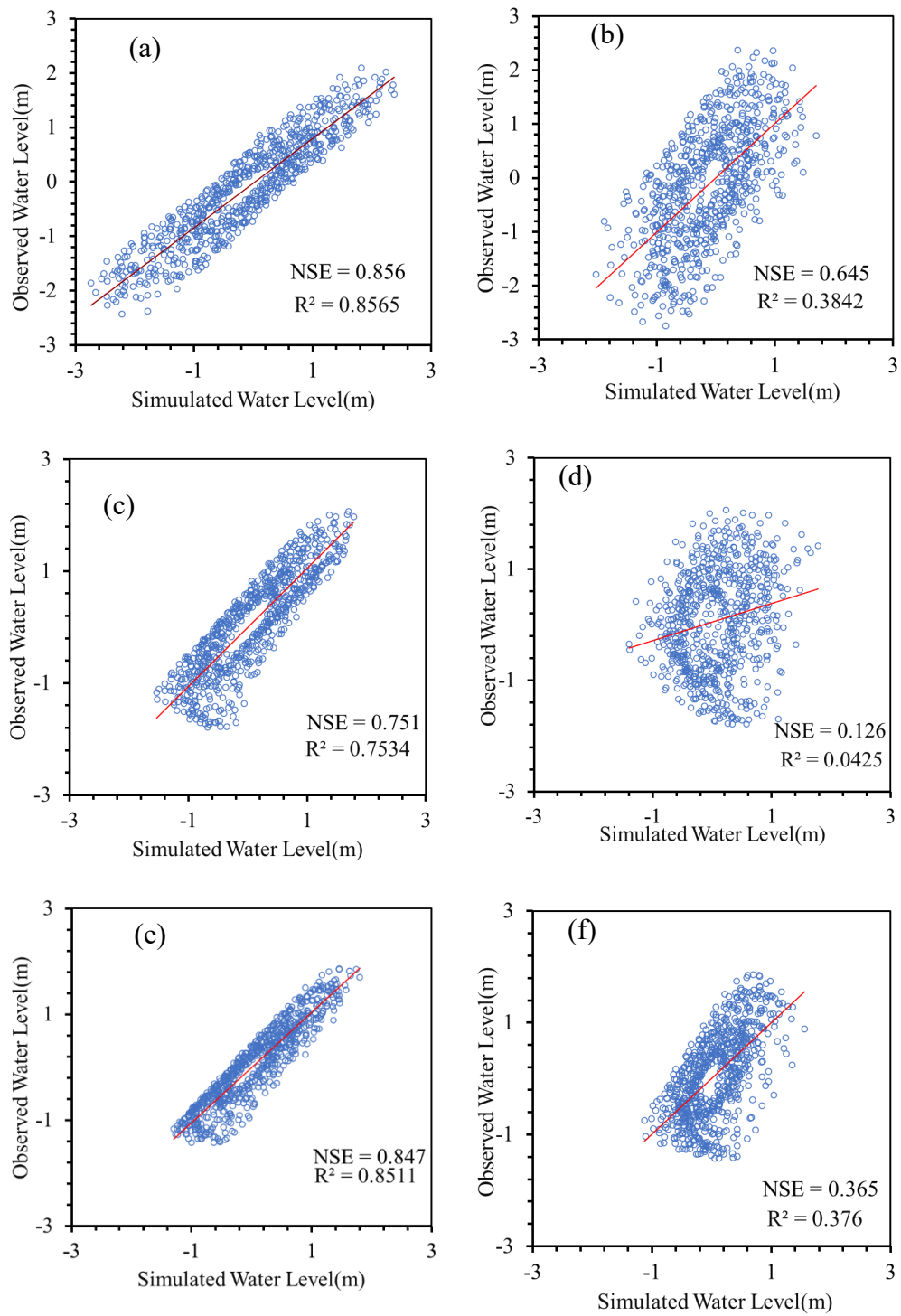


Fig. 4.9 On the left relationship between the simulated and observed water level (Cont'd)

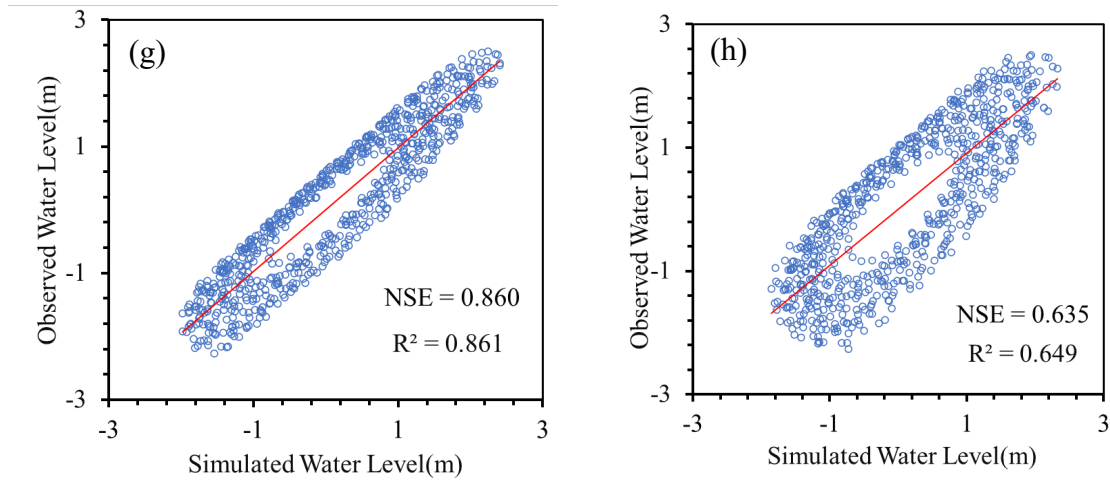


Fig. 4.6 On the left relationship between the simulated and observed water level at (b) Kutubdia (c) Tojumuddin (e) Kuakata (g) Sadarghat(ctg) in optimum space varying manning roughness condition are shown along with their respective R^2 and NSE on the left. On the right relationship between the simulated and observed water level at (b) (d) (f) (h) in fixed manning roughness condition are shown along with their respective R^2 and NSE.

For the validation of the tide model, a 7-day simulation period is set from 25 May, 2020 to 31 May, 2020 after the event. During this validation period, five observation stations' time series of simulated and observed water levels are displayed in Fig. 4.9. With a 2 to 2.5 hour phase difference between the observed and simulated tide, a visual comparison of the simulated and observed water levels at these sites demonstrates that the model has successfully represented the tidal pattern. The observation stations' tidal ranges are little less than the real tidal ranges. Chapter 5 goes over a more thorough discussion of the model validation results. Despite this, the tide model's water level simulations are noticeably better than the observed water levels, according to the model goodness-of-fit indices. In Figure 4.10 observed water level vs simulated water level are shown with their respective goodness of fit indices at different observation stations. These indices are shown in a tabular form in Table 4.11 .

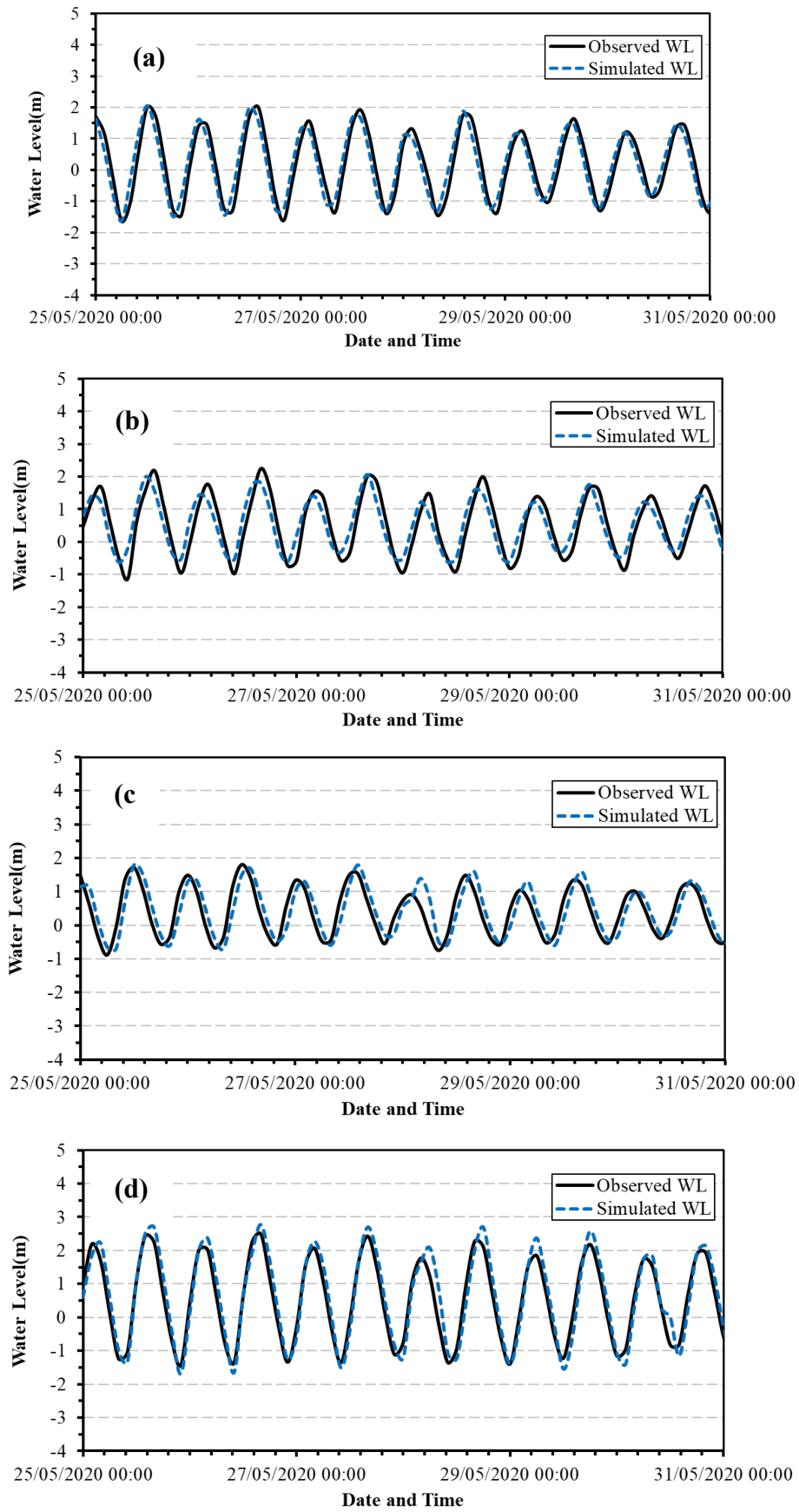


Fig. 4.7 Water level validation of the tide model at (a) Kutubdia, (b) Tojumuddin (c) Kuakata (d) Sadarghat(ctg)

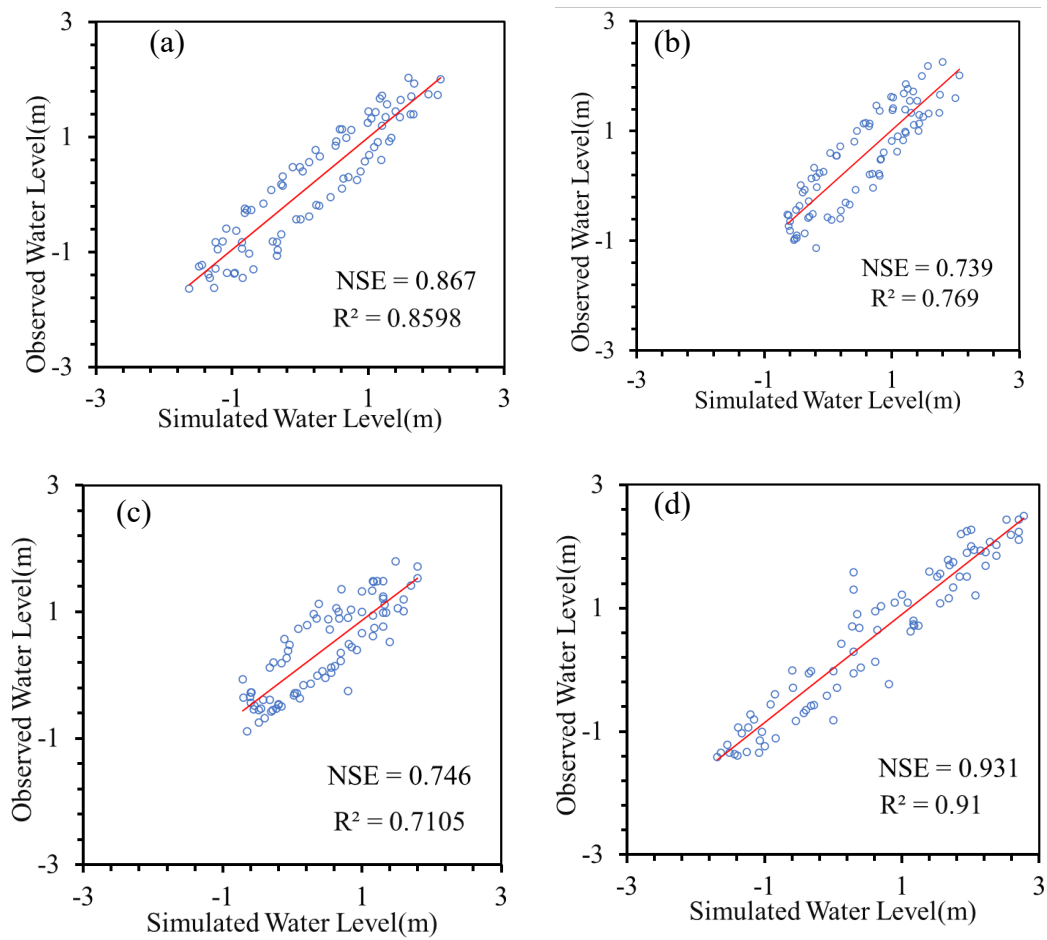


Fig. 4.8 Relationship between the simulated and observed water level at station (a) Kutubdia (b) Tojumuddin (c) Kuakata (d) Sadarghat (ctg) along are shown with their goodness of fit indices.

Table 4.3 Model Goodness-of-fit indices for tide model at different station for space varying mannings n

		R^2	NSE
Stations			
Tide Model Calibration (01/05/2020 to 16/05/2020)	Kutubdia	0.856	0.856
	Tojumuddin	0.753	0.751
	Kuakata	0.851	0.847
	Sadarghat(Ctg)	0.861	0.860
	Mean	0.831	0.828
Tide Model Validation (25/05/2020 to 31/05/2020)	Kutubdia	0.860	0.867
	Tojumuddin	0.769	0.739
	Kuakata	0.711	0.746
	Sadarghat(Ctg)	0.910	0.931
	Mean	0.812	0.821

4.5.2 Calibration and Validation of the Cyclone Model

As mentioned earlier the cyclone model used for simulating the super cyclone Amphan is a parametric wind field model. Holland wind model is a well-known parametric wind field model. In this study Holland wind field model is used to generate wind field around the centre position of the storm. Outputs from this wind model are the wind field and pressure field on a 2D spider web grid as shown in Figure 4.11. Model setups are used as meteorological input in the tide model to simulate the tropical cyclone. Since tide model is well developed and validated, proper validation of the cyclone model is essential for reliable and more accurate storm surge modelling. For the calibration of the cyclone model best-fit cyclone track data for Amphan from IMD and JTWC are used in the Holland wind field model as calibration parameters. Wind field and pressure field generated from these two best-fit tracks are compared with the observed data at different location. For the observed data three BMD stations are selected for both calibration and validation based on the availability of the data during the event of Amphan. Location of these three BMD stations is shown in Figure 4.3. There is another way of comparing wind speed and direction with satellite data. ERS and QuickSCAT satellites uses scatterometer data for deriving wind data. Since getting wind data over the ocean is hard to get, comparing model wind data with the observed data over the ocean has to rely on the satellite data. Although in this study comparison of model data is only done using ground observations at three BMD stations.

Holland cyclone model is run using the Amphan best track record data from JTWC and IMD. For both best track data the model run time is set to 7 days from May 16,2020 to May 22,2020 based on the lifeline of the Amphan found from the best track data. The whole process is done with the help of cyclone toolbox in delft dashboard. Simulation outputs, space varying air pressure and wind speed data generated by the best track data from the two sources are

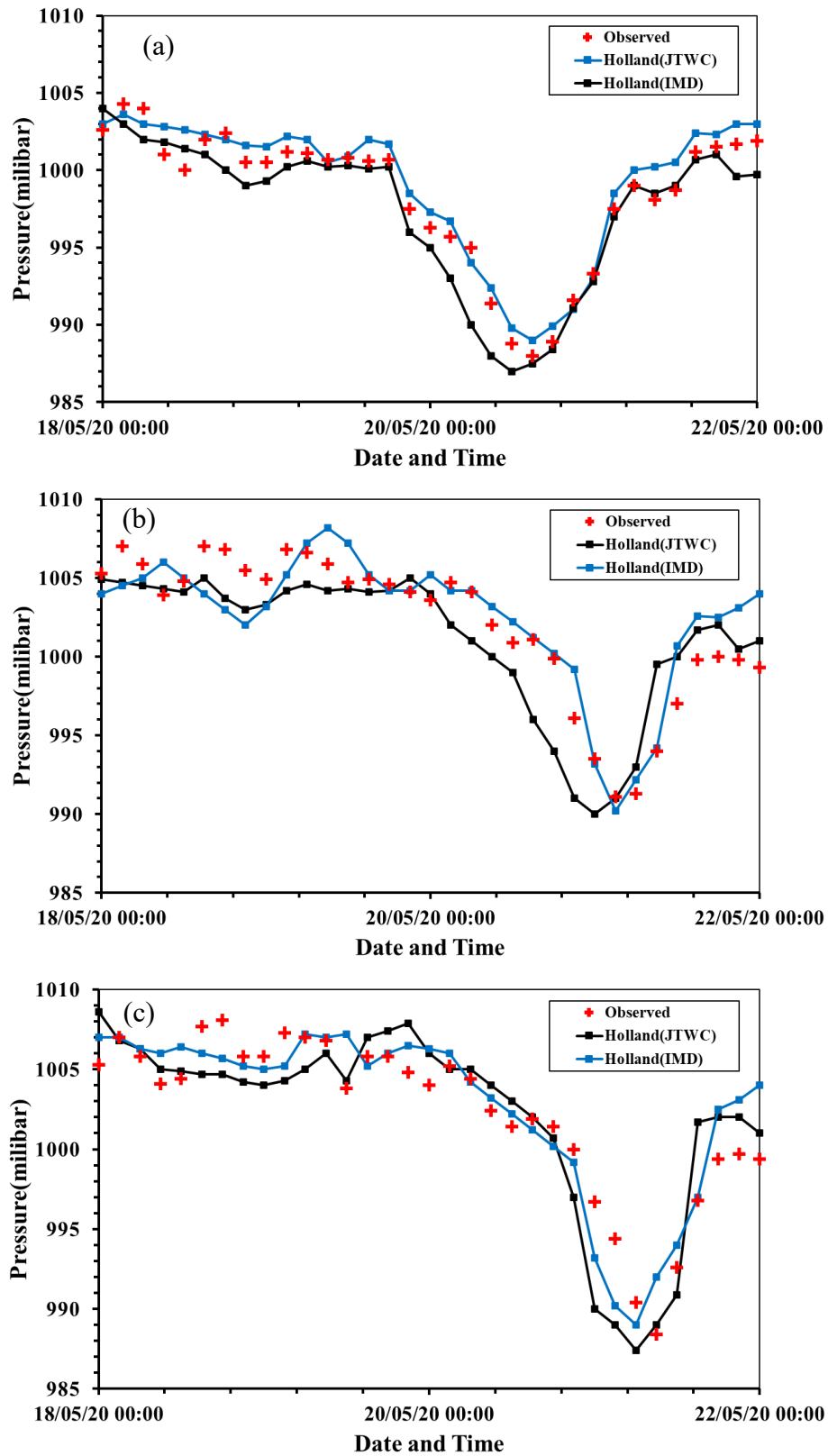


Fig. 4.9 Observed Air pressure and simulated air pressure in millibar(or mbar) for JTWC and IMD best track for Amphan shown in time series at station (a) Khulna (b) Patuakhali (c) M. Court

analysed for selecting the most suitable cyclone track that will produce the same effect similar to the super cyclone Amphan. In Figure 4.12 and Figure 4.13, simulated air pressure and wind speeds at 3 BMD observation stations are compared and are plotted in time series to compare the result with the ground observation data at these stations.

For selecting the best track of Amphan for final storm surge model simulation based on the goodness-of-fit indices, these R^2 and NSE are calculated and compared. In Table 4.3 all the indices are shown for air pressure and wind speed for the two best track dataset. Figure 4.14 shows the relationship between observed and simulated air pressure and wind speed data. It is clear from the calculated R^2 and NSE indices that IMD best track data is giving much more near closer air pressure and wind speed values at the 3 observation stations (Figure 4.15).

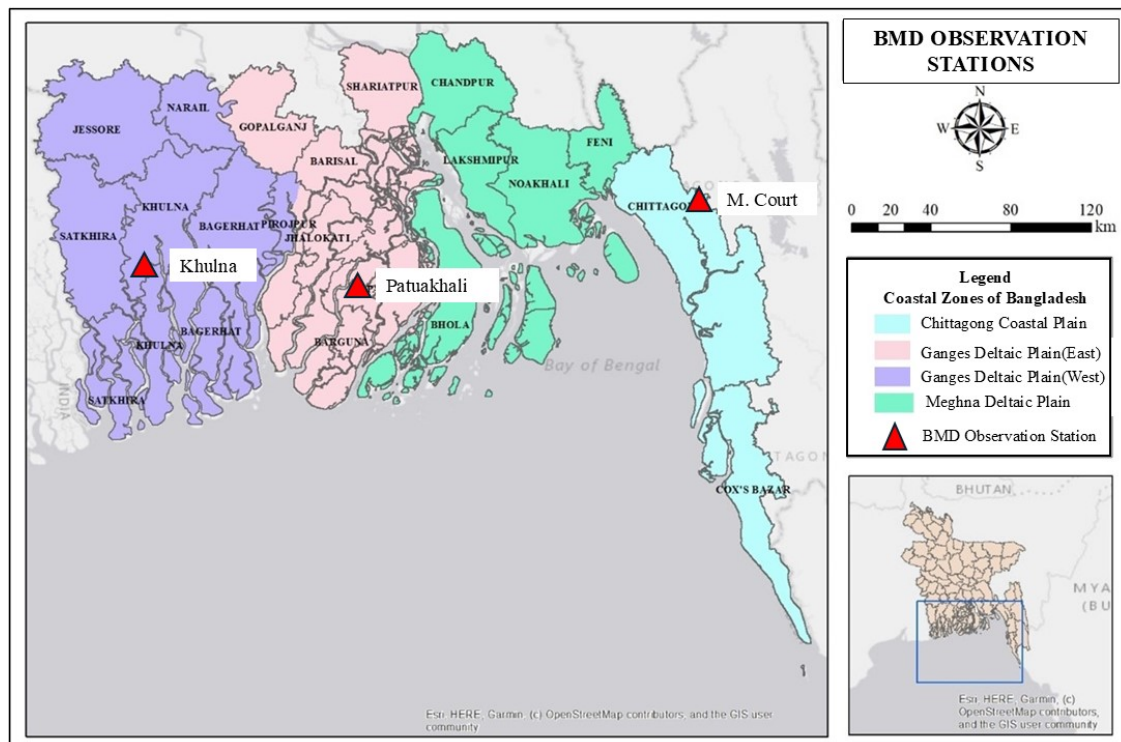


Fig. 4.10 BMD Observation Stations for the validation of the cyclone model

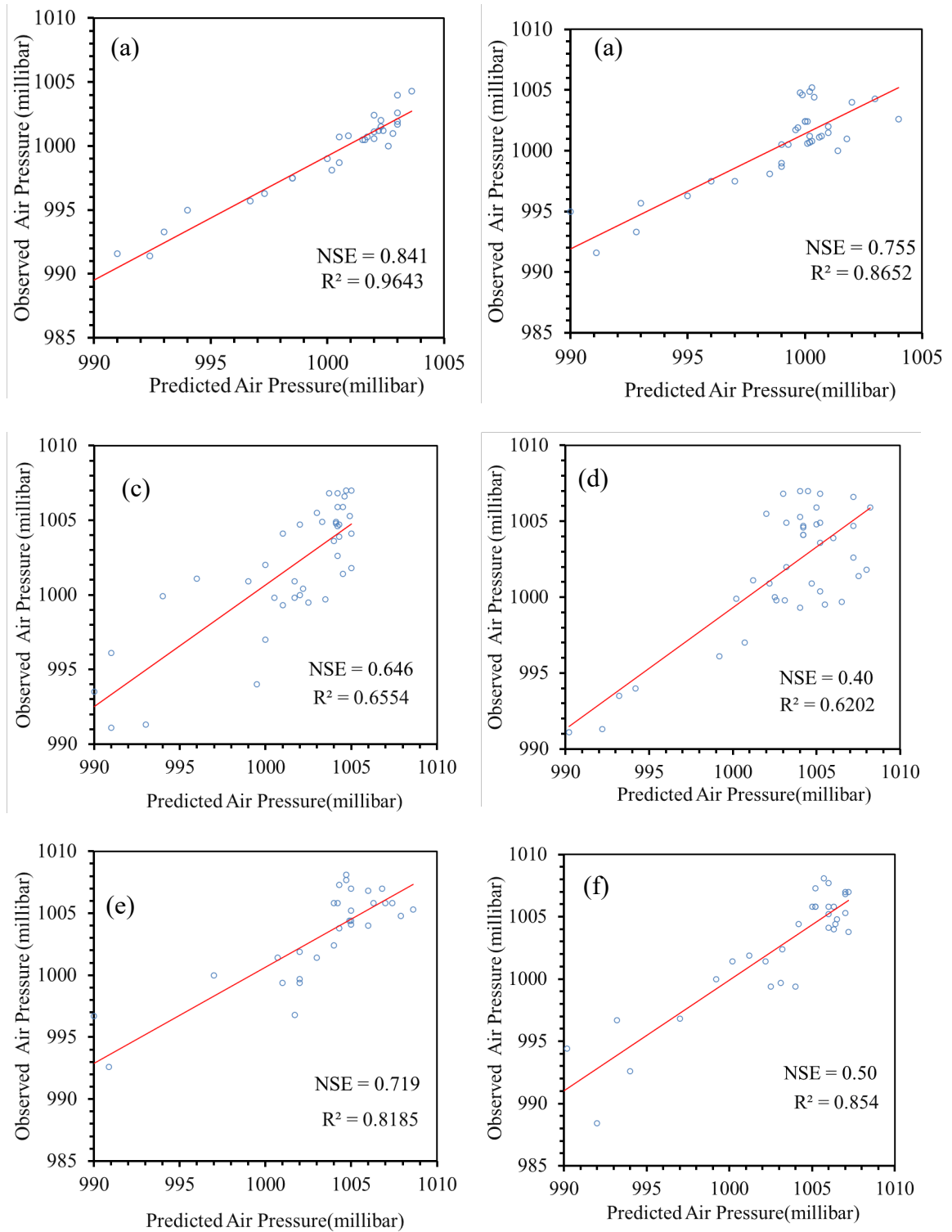


Fig. 4.11 Relationship between the simulated and observed air pressure are shown at station (a) Khulna (c) Patuakhali (e) M. Court with their goodness of fit indices in the left. , Relationship between the simulated and observed wind speed are shown at station (b) Khulna (d) Patuakhali (f) M Court with their goodness of fit indices in the right.

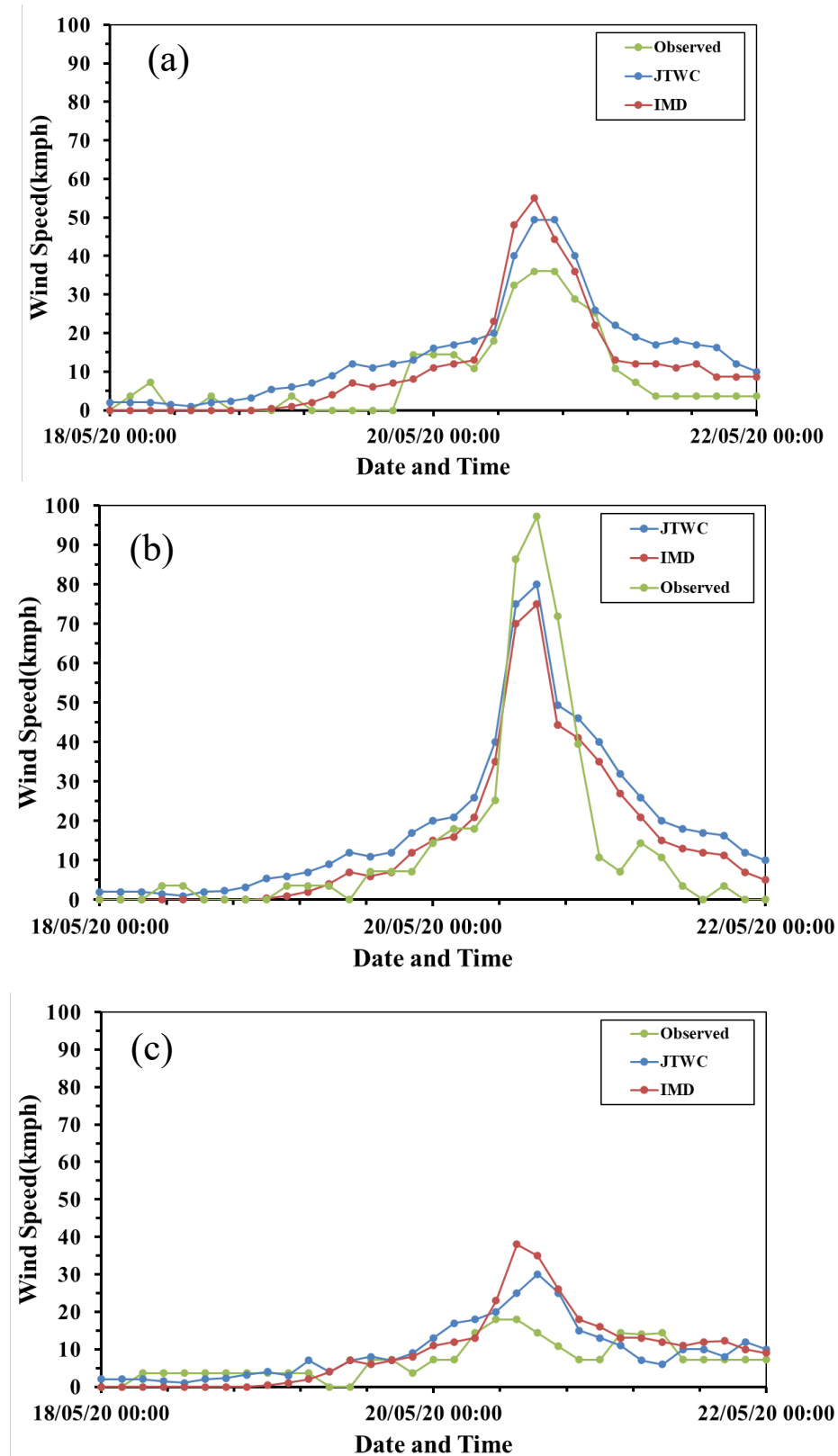


Fig. 4.12 Observed wind speed and simulated wind speed in kmph for JTWC and IMD best track for Amphan shown in time series at station (a) Khulna (b) Patuakhali (c) M. Court

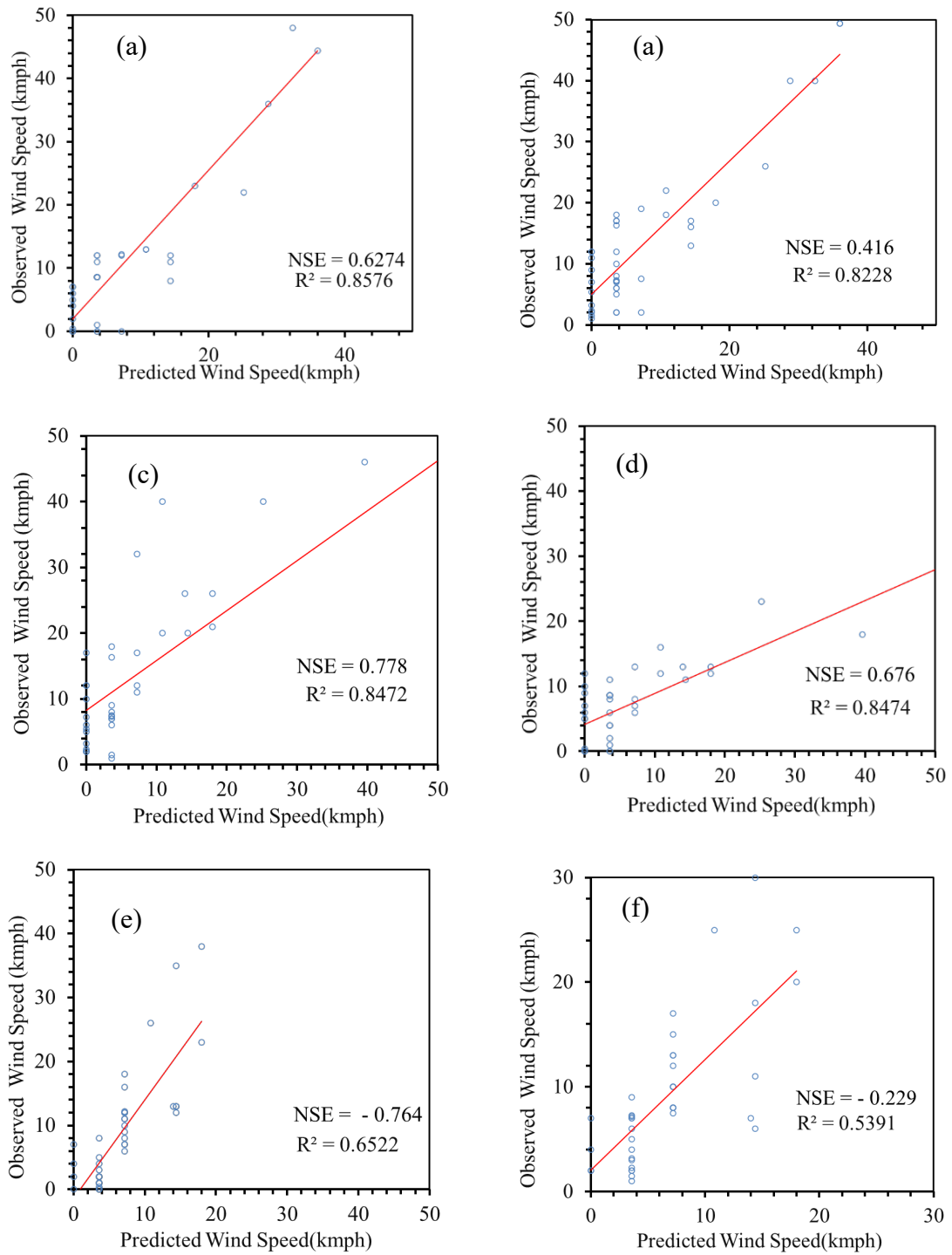


Fig. 4.13 Relationship between the simulated and observed wind speed are shown at station (a) Khulna (c) Patuakhali (e) M Court with their goodness of fit indices in the left. , Relationship between the simulated and observed wind speed are shown at station (b) Khulna (d) Patuakhali (f) M. Court with their goodness of fit indices in the right

Table 4.4 Model Goodness-of-fit indices for the calibration and validation of the wind model at three BMD station

	Station	JTCW		IMD	
		R ²	NSE	R ²	NSE
Pressure (18/05/2020 to 22/05/2020)	Khulna	0.964	0.841	0.865	0.755
	Patuakhali	0.655	0.646	0.620	0.40
	M. Court	0.818	0.719	0.854	0.50
	Mean	0.809	0.735	0.779	0.552
Wind Velocity (18/05/2020 to 22/05/2020)	Khulna	0.857	0.627	0.822	0.416
	Patuakhali	0.847	0.778	0.847	0.676
	M. Court	0.652	-0.764*	0.539	-0.229*
	Mean	0.786	0.703	0.736	0.546

* Not Considered in Mean Calculation

Comparison of the pressure filed and wind field data with the observed BMD data shows that wind speed and pressure values of the JTCW tracks are more close to the observed value as compared to the IMD track. It is clearly evident from the model goodness of fit indices shown in Table.4.4. Mean value of air pressure at three BMD station for JTCW best track were 0.809 and 0.735 for R2 and NSE respectively. And for IMD best track data the mean values were 0.779 and 0.552 for R2 and NSE respectively. JTCW tack gives more accurate wind speed and pressure values. . Mean value of wind speed at three BMD station for JTCW best track were 0.786 and 0.703 for R2 and NSE respectively. And for IMD best track data the mean values were 0.736 and 0.546 for R2 and NSE respectively. For both the case of air pressure and wind speed JTCW tack gives more accurate values than the IMD track. Due to this reason wind field and pressure filed generated by the JTCW from the cyclone model is used for the storm surge inundation model. In this way cyclone model is validated to apply the wind speed and air pressure data of the cyclone Amphan as atmospheric forcing into the storm surge inundation model.

4.5.3 Calibration and Validation of the Storm Surge Model

For the validation of the storm surge model, meteorological forcing (e.g. wind and pressure field) are applied with wave model to the previously developed tide model. Wind and pressure field data used from validation are derived from the cyclone model with IMD best track data since IMD data showed better result as compared to the JTWC best track. Now for storm surge model simulation a 5-day simulation period is selected from May 18,2020 to May 22,2020 based on the location of the cyclone, landfall and its lifetime. Simulated and observed water levels at the observation stations are plotted in time series with respect to MSL.

In Figure 4.16(a), simulated and observed water levels at Kutubdia station are plotted in time series. It shows that cyclone Amphan made landfall during high tide. Maximum water level during the storm surge also observed during the maximum high tide in all the stations. There is an overestimation of the highest water level is observed in kutubdia station . Figure 4.16(a) shows simulated and observed water levels in time series in Kutubdia station. During the time of landfall of Amphan the maximum water level observed in kutubdia station was 2.257 m during the high tide. But the model overestimated it as 2.6m. And there is an overestimation of 0.343m water level height in the predicted water level in kutubdia station. A phase difference also observed between the predicted and observed water level. And it is around 1.5-2.5 hours. Which results in the maximum water level during the high tide to be 2.4 hour after the actual occurrence of the maximum water level in this station.

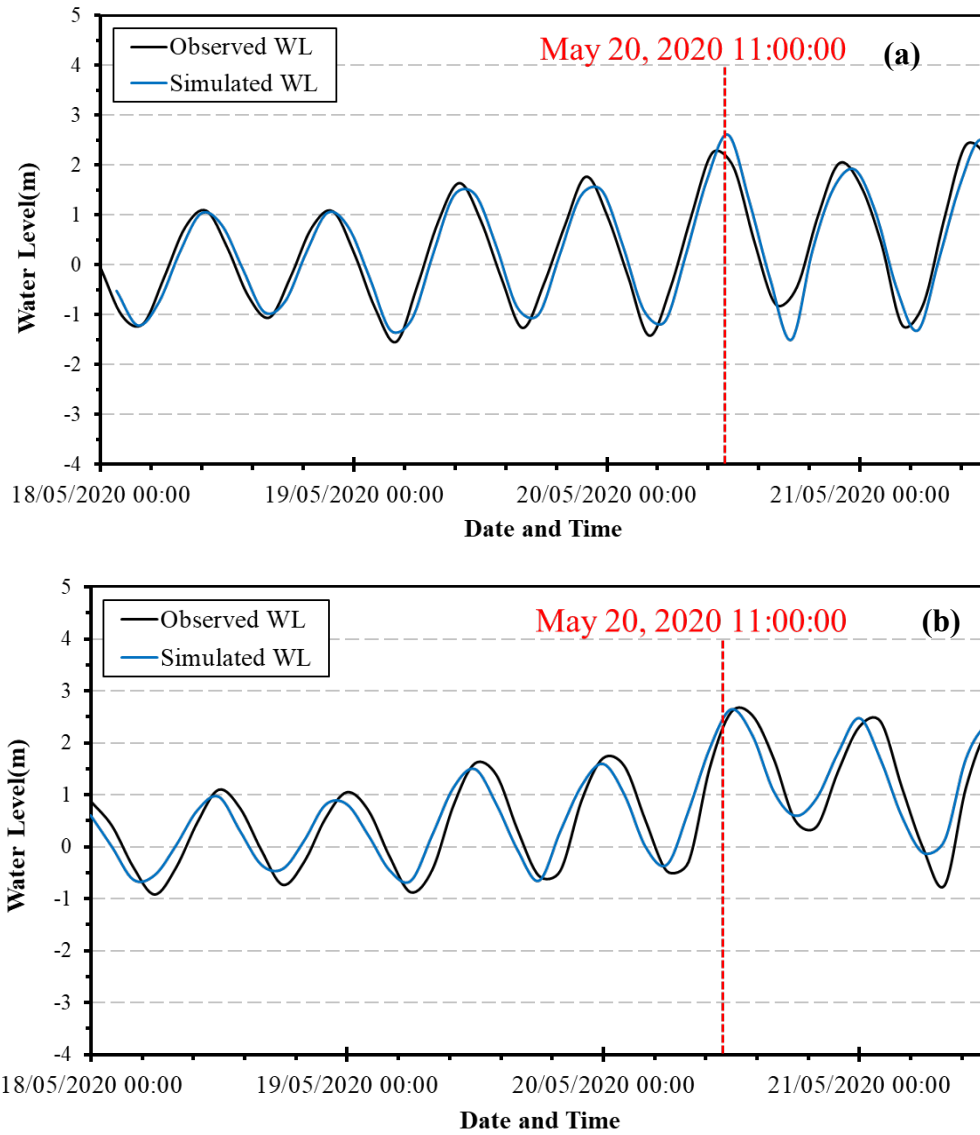


Fig. 4.14 Water level validation of the storm surge model at (a) Kutubdia, (b) Tojumuddin

But the model has successfully predicted the maximum water level in Tojumuddin station. And it was 2.584m. and the model predicted it as 2.6 m. So there very little to negligible amount of overestimation is observed in this station. Phase difference in this station is around 1-2.5 hours. And here in Tojumuddin predicted maximum water level occurred 1 hour before the actual observed maximum water level. Figure 4.16(b) shows simulated and observed water levels in time series in Tojumuddin station.

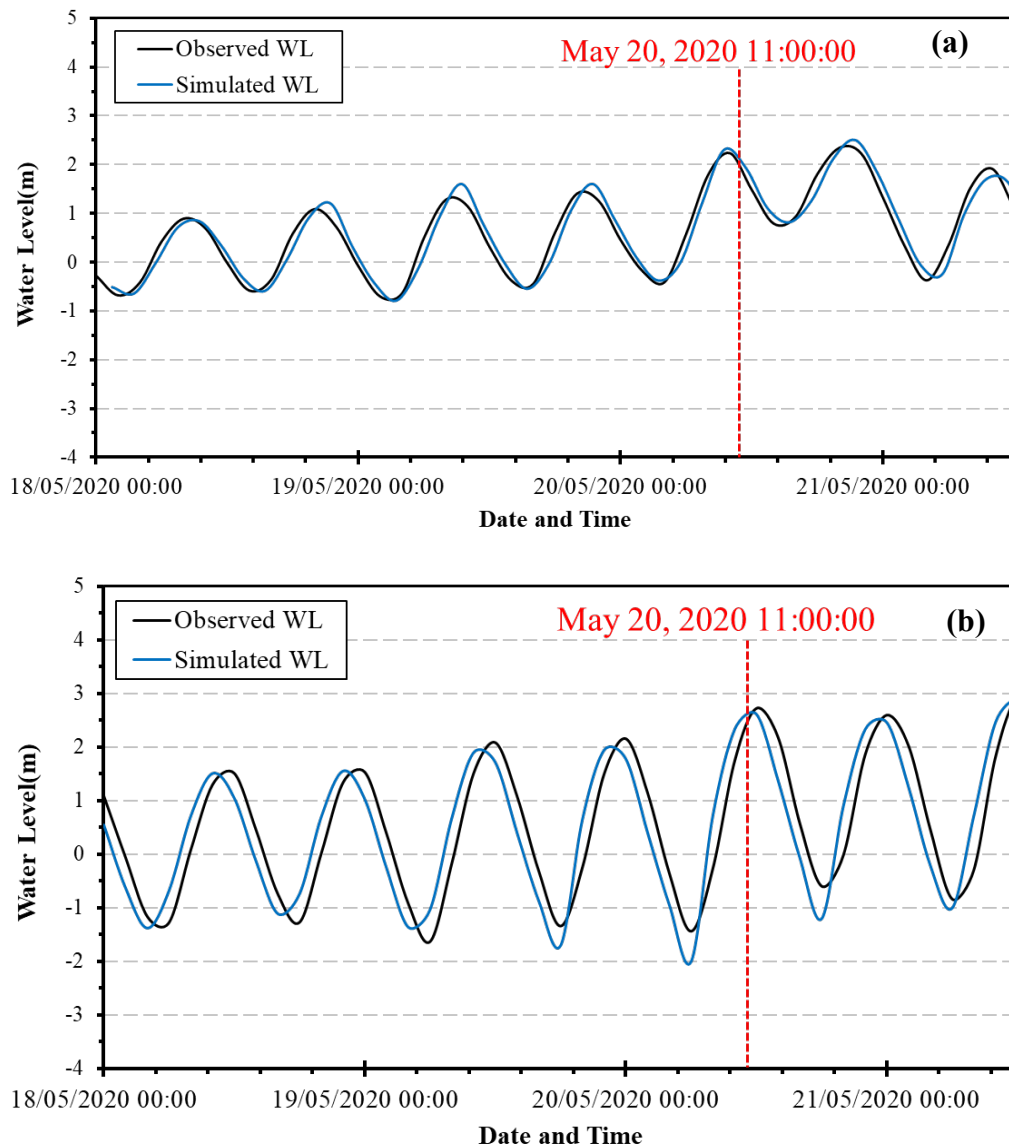


Fig. 4.15 Water level validation of the storm surge model at (a) Kuakata (b) Sadarghat(ctg)

Figure 4.17(a) shows simulated and observed water levels in time series in Kuakata station. During the time of landfall of Amphan the maximum water level observed in kuakata station was 2.33 m during the high tide. But the model overestimated it as 2.45m. And there is an overestimation of 0.12m water level height in the predicted water level in kutubdia station. A phase difference

also observed between the predicted and observed water level. And it is around 0.5-2 hours.

Figure 4.17(b) shows simulated and observed water levels in time series in Sadarghat station in Chattogram. Following the similar trend there is a phase difference observed between the simulated and observed water level. All the high tide and low tides in the predicted data occurred 2.5 to 3.5 hours before the actual time of occurrence. It is clear from the time series water level comparison that the model slightly underpredicted the maximum water level. And it is around 0.140m. Which results in the maximum water level during the high tide to be 2.4 hours before the actual occurrence of the maximum water level in this station.

Figure 4.18 and Table 4.3 the goodness-of-fit indices of the storm surge model at the four observation stations used for model calibration and validation. Mean R^2 and NSE value found at these four observation stations are 0.815 and 0.848 respectively. These indices are indication of models good predicting skill. It is evident that the storm surge model has higher skill for observation stations near the landfall location. Tojumuddin and Kuakata are the closest station where the Amphan made landfall. R^2 and NSE are higher in these stations as compared to the other two stations which are at Kutubdia in Cox's Bazar and Sadarghat in Chattogram.

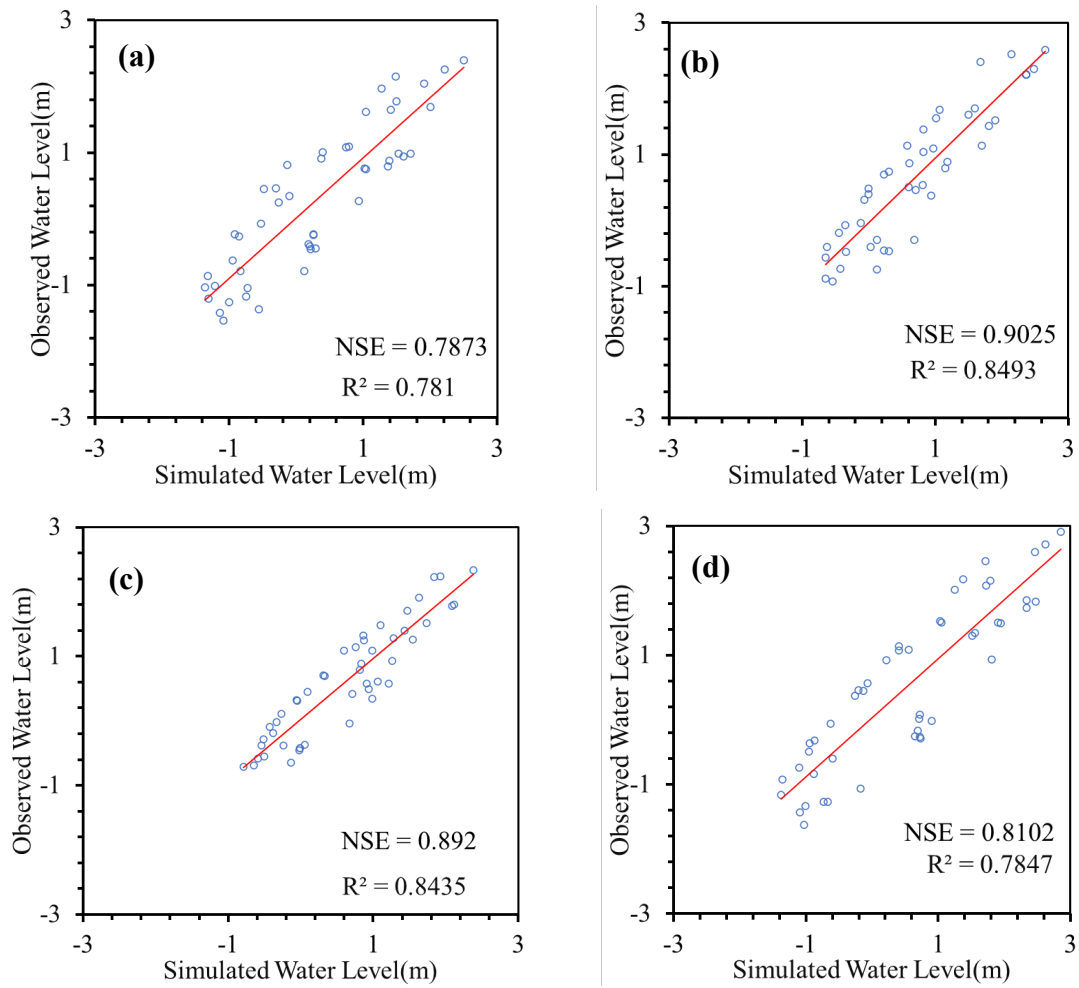


Fig. 4.16 Relationship between the simulated and observed water level at station (a) Kutubdia (b) Tojumuddin (c) Kuakata (d) Sadarghat(ctg)

Table 4.5 Evaluation of Goodness-of-fit indices for storm surge model at different station

		Station	R^2	NSE
Storm Surge Model Validation (18/05/2020 to 21/05/2020)		Kutubdia	0.781	0.787
		Tojumuddin	0.849	0.902
		Kuakata	0.843	0.89
		Sadarghat(Ctg)	0.784	0.810
		Mean	0.815	0.848

4.5.4 Validation of the Inundation Area

For the validation of the inundation area produced by the storm surge model during Amphan, inundation map is produced based on the flooding generated in the model during the simulation of May 18,2020 to May 22,2020 for the validation of the storm surge model. Figure 4.19 shows the inundation map of the flooding caused during Amphan generated from simulation of the storm surge model.

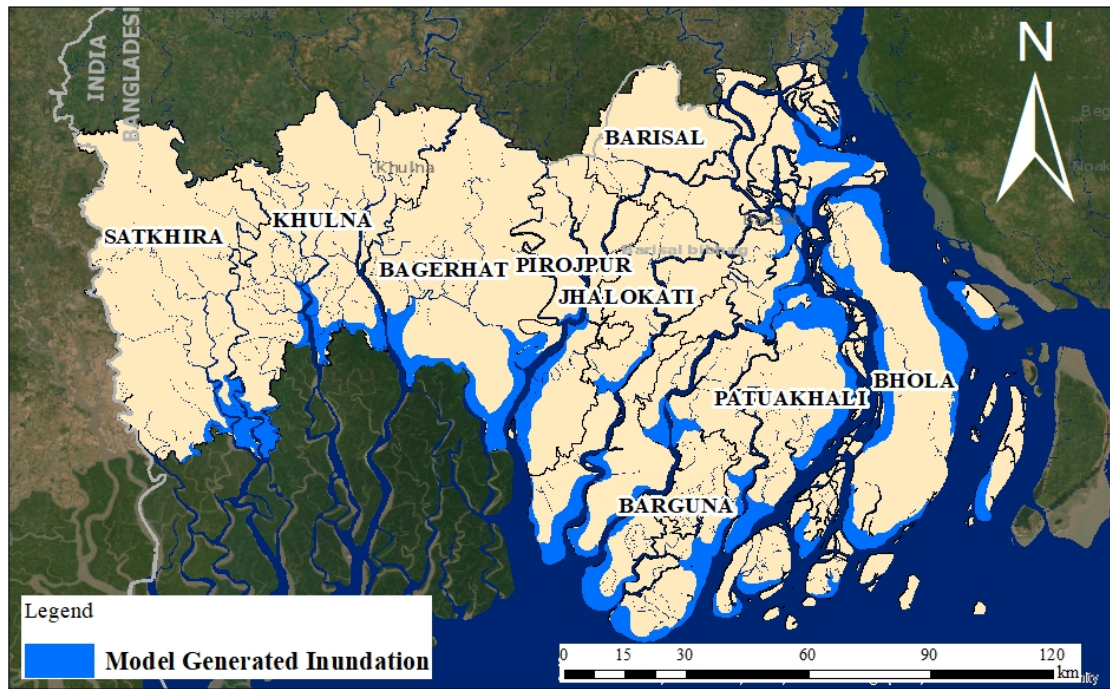


Fig. 4.17 Inundation map of the flooding caused by cyclone Amphan generated from simulation of the storm surge model

For the validation of the model derived inundation map two inundation map is used. One is, inundation map produced from the SAR images acquired by sentinel-1 satellite during the time of Amphan using Change Detection and Thresholding(CDAT) method, particularly in areas where it is challenging to directly evaluate the extent of inundation, such as the northern Bay of Bengal, owing to advancements in satellite imaging and post-processing techniques. Since SAR images do not get affected by clouds, rains, fog and all the other weather conditions, SAR images are best option for mapping flood during a cyclone. This inundation map is shown in Fig. 4.19 Inundation map of the flooding caused by cyclone Amphan in the coastal region of Bangladesh generated from the Sentinel-1 SAR image taken on May 22, 2022. Another one is an inundation map produced based on the survey conducted by an organization called Needs Assessment

Working Group (NAWG) during Amphan for assessing damage and relief activity. This inundation map is shown in Fig. 4.18. Online media and newspapers during Amphan also assessed for the validation of the inundation area.

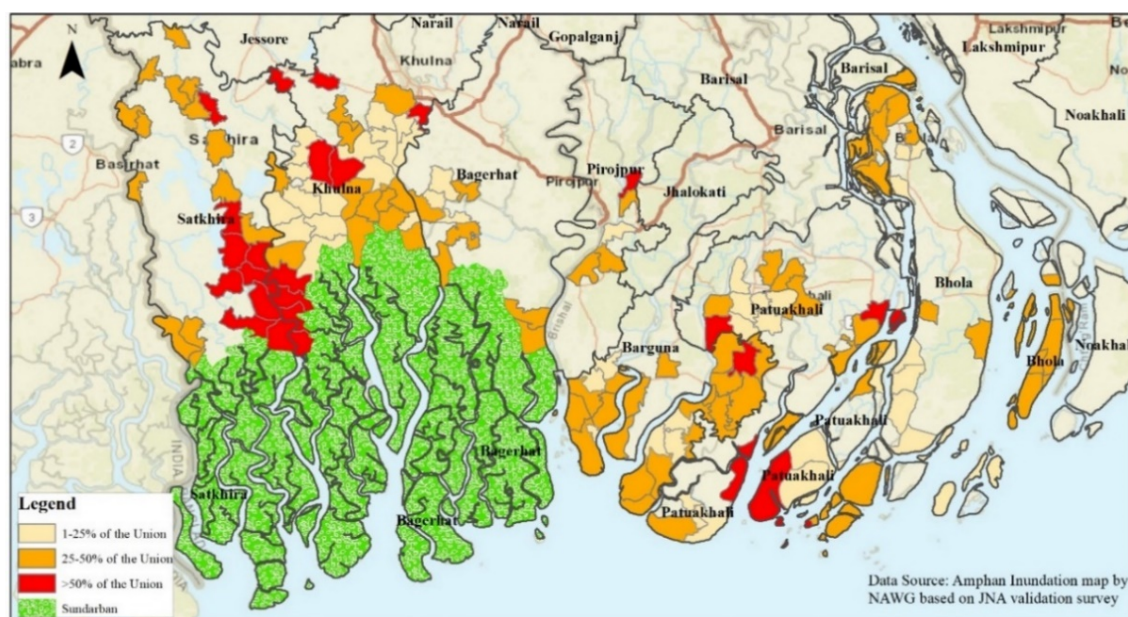


Fig. 4.18 Inundation map based on the validation survey by NAWG, Bangladesh.

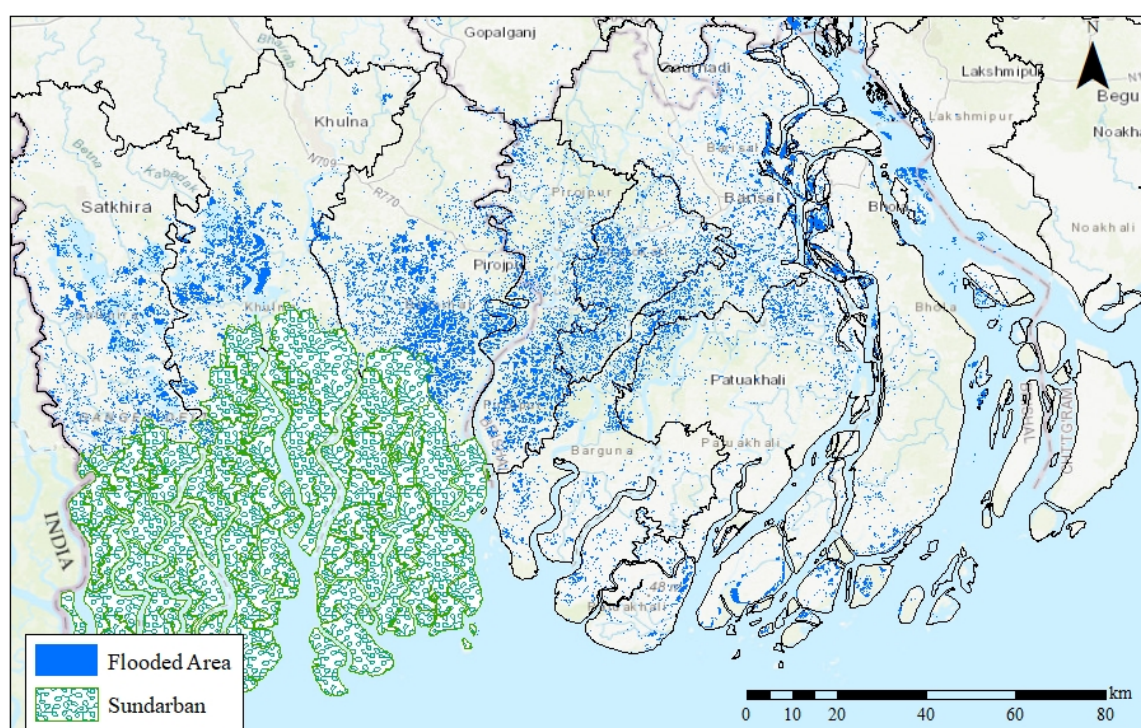


Fig. 4.19 Inundation map of the flooding caused by cyclone Amphan in the coastal region of Bangladesh generated from the Sentinel-1 SAR image taken on May 22, 2022

At first two inundation maps which are selected for the validation of the inundation area are compared. The comparison shows that inundation area found in the inundation map produced from SAR images are also marked as flooded area in the inundation map based on the field survey. Also, there are some regions appeared to be flooded in the satellite derived flood map which are not considered as flood in survey derived inundation map. In such case, online media and newspaper during this time are searched for any reporting of flood in that region.

In Fig. 4.18, the inundation map published by NAWG, there is no flood reported in Jhalokati. Media and newspaper reports during the time of Amphan confirms flooding in Jhalokati district's low land areas (Bangladesh, 2020). So, the field survey did not cover all the flooded areas. It missed some areas where the area flooded during Amphan. Satellite derived inundation map in Figure 4.20 shows that Jhalokati district is cover with many blue patches. Which is a clear indication of flooding in this region. There are also a few cases that are checked using online media and newspaper reports.

Moreover, the inundation map generated using Sentinel-1 SAR images shows specific locations where flooding took place during Amphan, whereas inundation map produced by NAWG field survey doesn't shows the flooded areas. Its only gives an idea about the unions which are inundated and what percentage of the union is inundated during the flooding caused by Amphan. But now the actual location of the flood itself. Also, the inundation map derived by NAWG field survey missed few areas which are actually flooded during Amphan as stated earlier. So, to validate the inundation map produced by the storm surge model in this study, inundation map generated using Sentinel-1 SAR images is selected. Since this validation is done by comparing flooded areas.

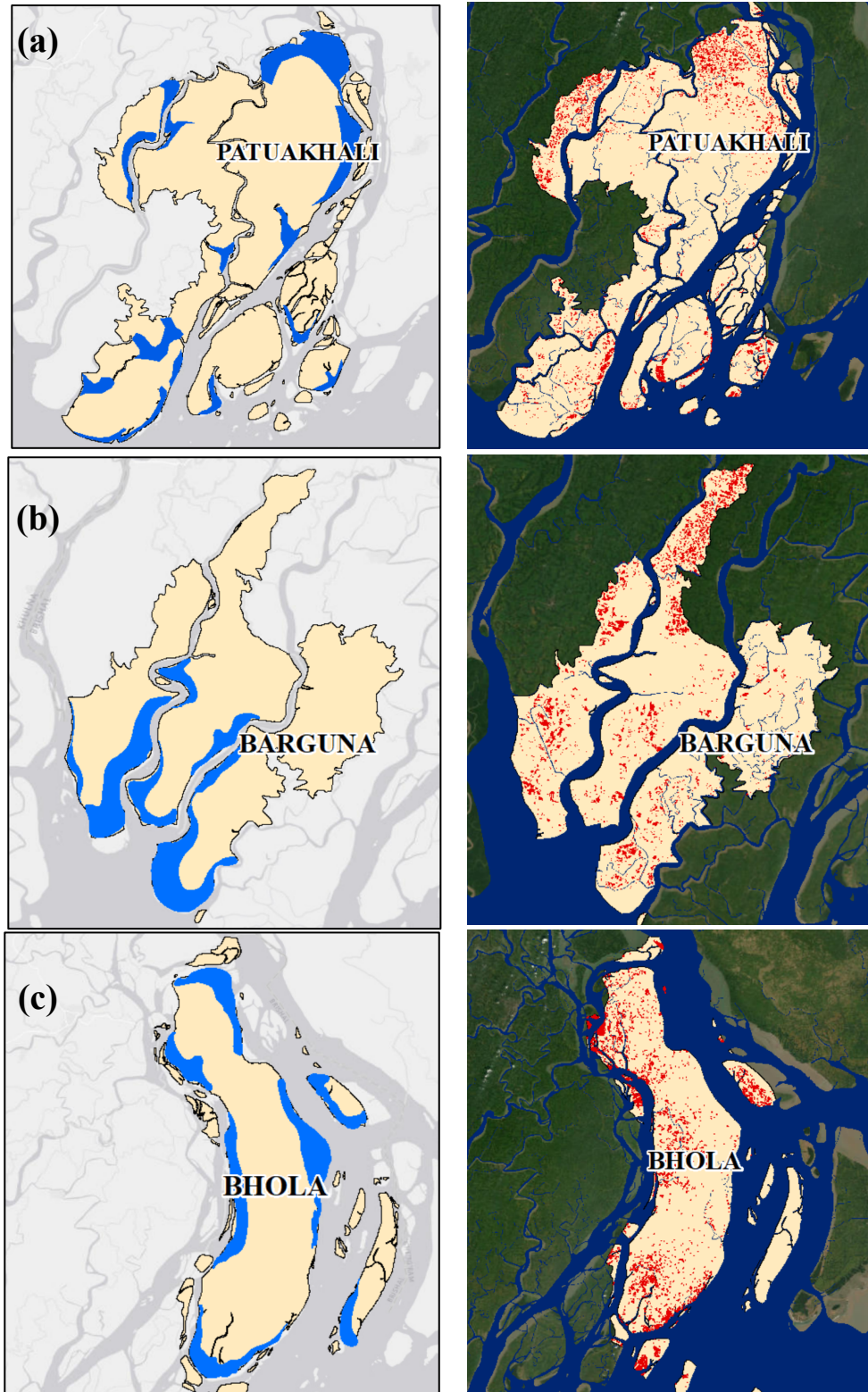


Fig. 4.20 Comparison between model generated inundation area and satellite derived inundation area in (a) Patuakhali (b) Barguna (c) Bhola during cyclone Amphan

Fig. 4.20, Fig. 4.21, Fig. 4.22 shows side by side comparison between the model simulated inundation area and satellite derived inundation area for 9 coastal districts which are affected by flood during Amphan. On the left of these images model simulated inundation area is shown in blue patches. And on the right side of these images Sentinel-1 satellite derived inundation areas during the cyclone Amphan is shown with red patches. In Fig. 4.20, Inundated area predicted by the model during Amphan in Patuakhali, Barguna and Bhola district are compared with the inundated area generated from the satellite images. The model has managed to predict most of the inundated areas with few false estimates of areas to be inundated in Patuakhali district. But the model missed few areas as well which are shown as inundated in the satellite image on the right. These areas are located far away from the coast. The model managed to predict most of the inundated areas near the coast and river. But more inland flooded areas are not marked as flooded by the model. In Fig. 4.20(b) Overestimation of the flooded area is observed in Barguna district. But similar result is observed as in the case of Patuakhali. The model has failed to predict flood in more inland areas. In Figure Fig. 4.20(c) side by side comparison shows that model has successfully predicted the flooded areas in most of the areas in Bhola with few overestimation of flood in the east and north of the island.

In Fig. 4.21 side by side comparison of the flooded areas in Barisal, Jhalokati and Pirojpur district predicted and generated by the model and the satellite imagery are shown. These three district are distant away from the sea as compared to Barguna, Patuakhali and Bhola. In Barisal district flood in the areas near Meghna River is successfully predicted by the model. But the model missed flooded areas that are not adjacent to Meghna. In Fig. 4.21(b) flooded areas in Jhalokati district is compared. In this district the model performance is very poor, and it is very clear from the side-by-side comparison of the images. In the left-hand side flood image by the model shows that flood only occurred

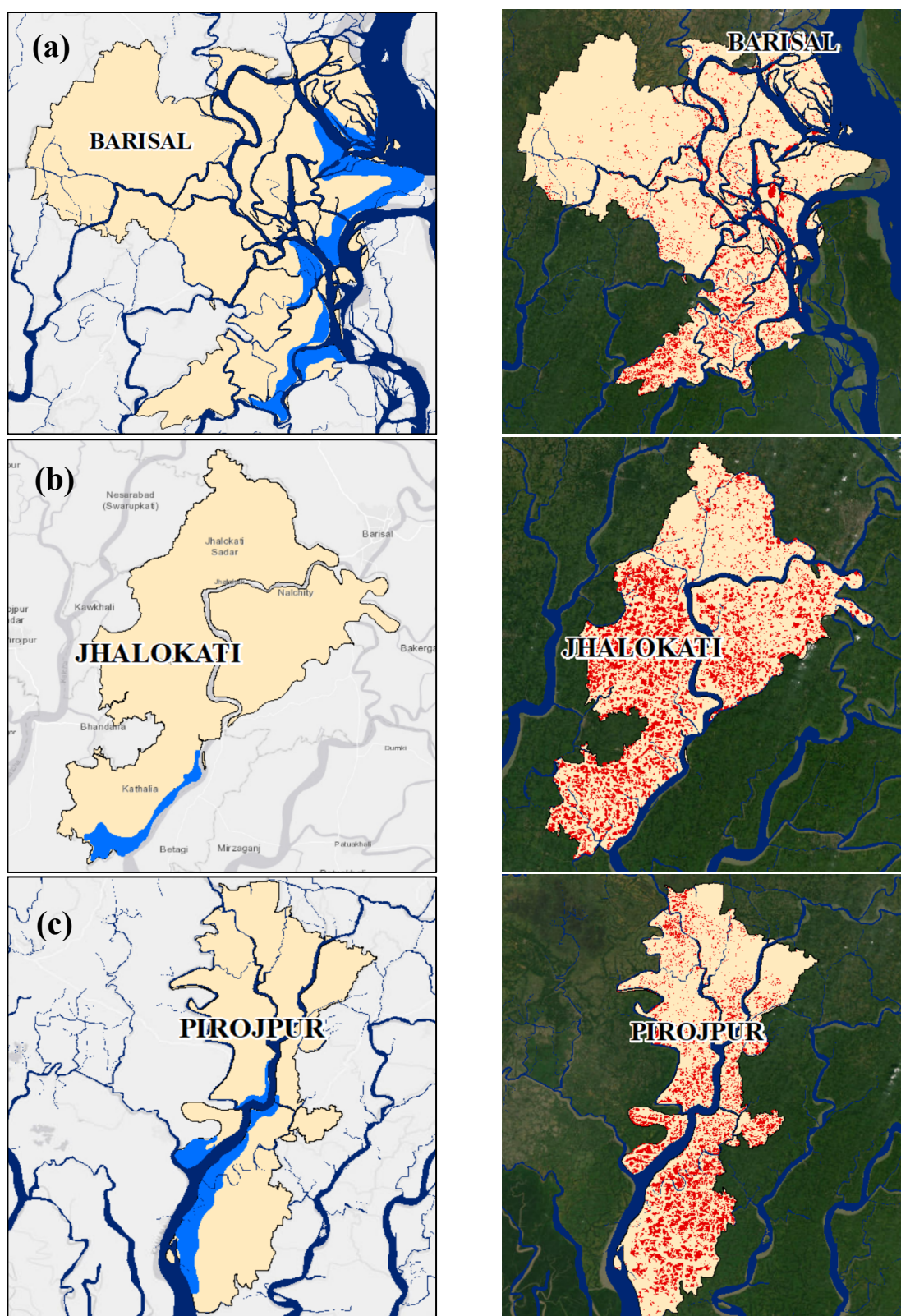


Fig. 4.21 Comparison between model generated inundation area and satellite derived inundation area in (a) Barisal (b) Jhalokati (c) Pirojpur during cyclone Amphan

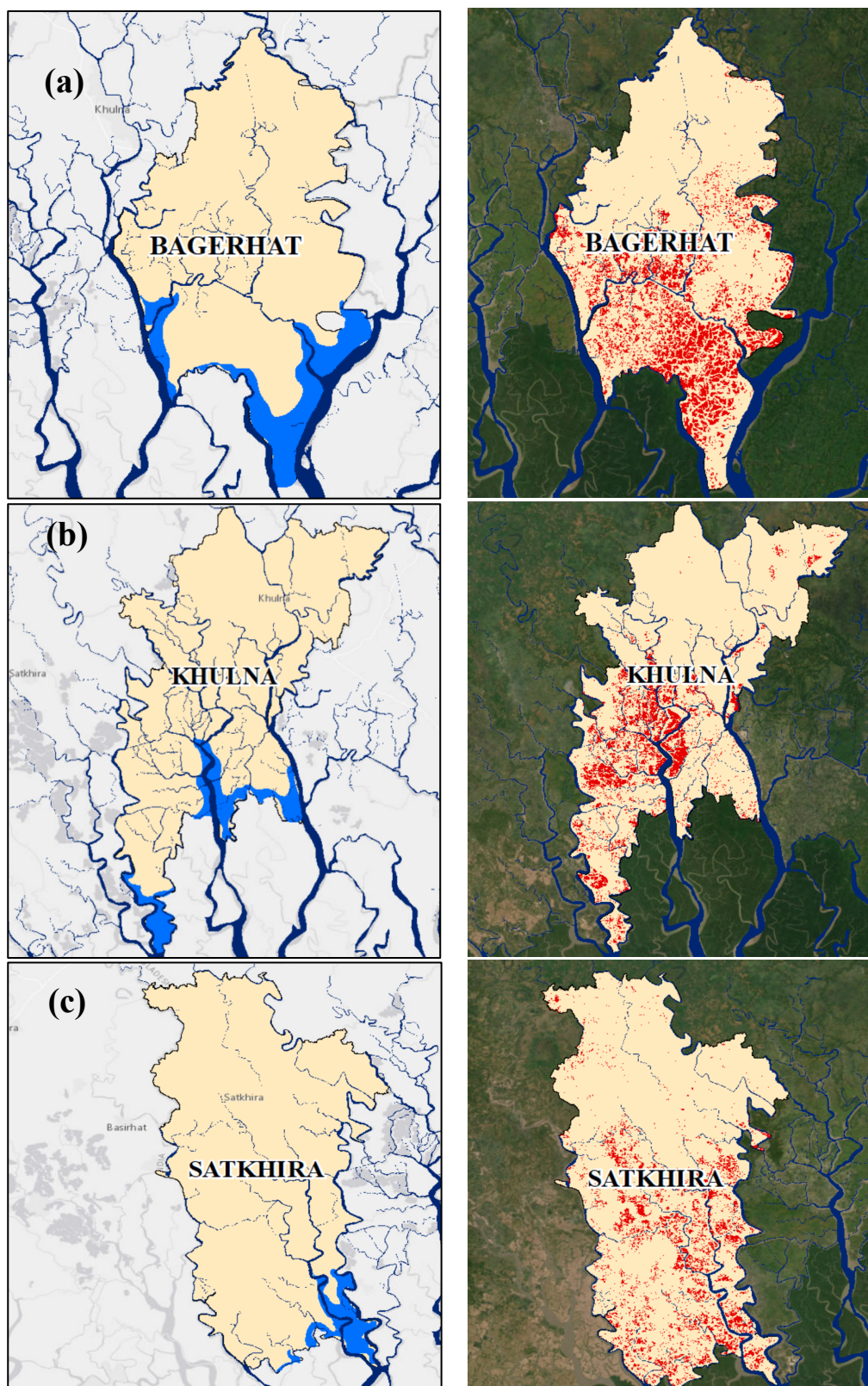


Fig. 4.22 Comparison between model generated inundation area and satellite derived inundation area in (a) Bagerhat (b) Khulna (c) Satkhira during cyclone Amphan

in a small area near Biskhali river. But satellite derived image shows that flood occurred in most of the southern part of the district. Same result is found in Pirojpur, which is clear in Fig. 4.21(c). In the flood image generated by the model flood occurred only areas near the Baleshwar River. But it missed areas distant away from the river where flood took place during cyclone Amphan.

In Fig. 4.22 predicted flooded areas are compared with the satellite derived flood areas during Amphan in Bagerhat, Khulna and Satkhira districts. Being guarded by Sundarbans from the sea similar results are found in these three districts. Bagerhat is the most adjacent district near sea. Side by side comparison of flooded area of Bagerhat in Fig. 4.22(a) shows that the lowland areas in southern of the Bagerhat district are flooded whereas only certain areas adjacent to the Baleshwar River is predicted as flooded by the model. Being more distant away from the sea same result is found in Khulna and Satkhira. In these two districts the model predicted flood in few areas near the major rivers. The model does not depict flooding in areas that are not close to a river, as seen in satellite images.

Also there is a possibility that the inland flooded areas which are not close to any river or coast in the satellite derived inundation map are caused due to the pluvial flooding caused by heavy rainfall. Due to cyclone heavy rainfall took place in the coastal zone. This leads to waterlogging and flooding in the coastal zones area. Coastal region of Bangladesh are enclosed by polders, it reported that these coastal polders faces severe drainage congestion during heavy rainfall. Since the storm surge inundation model does not cover the simulation of pluvial flooding, flooding related to heavy rainfall is not found in the inundation map produced by the model. This could be another reason for inland flooding that is not represented in the inundation map generated by the model.

Chapter 5: DISCUSSION

In this chapter results derived from the in different stages of the storm surge model development are discussed. This chapter is divided into three sections tide model, wind model and storm surge model.

5.1 TIDE MODEL

As mentioned earlier the accuracy of storm surge models heavily relies on the accuracy of the tide model or tide only storm surge model. Any error or inaccuracy in the tide model can impact the accuracy of the storm surge predictions. A validated tide model provides a baseline for the expected water level variations due to tides, and storm surge models can then simulate the additional water level increase during a storm event.

Goodness of fit parameters shows that the tide model has successfully simulated the tidal patterns and tidal ranges at different tidal observation station with slight phase difference and slight variation in tidal range. A mean value of 0.812 and 0.821 is found for R^2 and NSE respectively. During the validation of the tide model maximum phase difference of 2 hours was observed in Kuakata observation station. In Kutubdia and Tojumuddin stations this variation was between 1.5 to 2 hours. And in Sadarghat(CTG) no significant phase different was observed. Water level differences in most of the stations was below 0.5 m during high and low tide. Maximum difference in water level was also observed in Kuakata during high tide. Since tide surge interaction plays an important role in predicting the surge height and the occurrence time of the peak surge height during a cyclone, so variation in tidal phase and water level must be acknowledged. Even though the goodness of fit parameters found from the water level comparison indicates a high level of accuracy, these

variations or deviations must be considered. Because these variations will the final outcome of the storm surge model.

There are few factors that might be associated with these discrepancies in tidal characteristics between the observed and the simulated water level. One is nearshore and estuarine bathymetry. In this study GEBCO-19 ocean bathymetry data and estuarine and river bathymetry data is used. Since coastal zone is a constantly changing and highly dynamic in nature. There is a possibility of discrepancy in bathymetry. Since GEBCO bathymetry data is created from deep sea survey and some nearshore bathymetry data provided from third party agencies, there is a possibility of outdated bathymetry data specially in the nearshore zone. There is also possibility of BWDB bathymetry data to be outdated. Despite these limitations in these datasets, we have to use these datasets, since these are the only sources to get ocean bathymetry data. On the other hand, GEBCO dataset is a widely used dataset in tide and storm surge modelling related studies.

There is another possibility of error that might come from the atmospheric influences. In the development of the tide model no atmospheric forcing is introduced as a forcing, only astronomical forcing is considered. Since there is constant wind in constant zone specially in the month of April, May, wind drag force might play an important role in the tide level prediction and other tidal characteristics. This tide only run doesn't consider these wind forces. A possible solution could be selection of a period of the year when the weather is calm and so that there is no possibility of significant effect of wind on the tide model. Since time period selected from both calibration and validation is in the month of May, so these could be a reason for these variations in tidal characteristics.

So, this can be concluded that discrepancies in tide level and tidal range must be acknowledged in the water level predictions derived from tide model

and storm surge model. Consideration need to be taken to acknowledge these issues.

5.2 CYCLONE MODEL

Comparison of the wind speed and air pressure values at three BMD weather stations shows that cyclone model outputs varies significantly due to the best track data variability to the different organization. In this study JTWC and IMD best track data is compared and used for the validation of the cyclone model. In this study JTWC track data showed much more similarity with observed data as compared to the IMD data. Mean value of wind speed at three BMD station for JTWC best track were 0.786 and 0.703 for R^2 and NSE respectively. And for IMD best track data the mean values were 0.736 and 0.546 for R^2 and NSE respectively. For both the case of air pressure and wind speed JTWC track gives more accurate values than the IMD track. It is found from the comparison that JTWC. Both JTWC and IMD best track overestimate the wind speed data in all the stations. Except in predicting the peak wind speed at Patuakhali both the track underestimates the peak wind speed value. There is a difference of 10 to 15 kmph in peak wind speed is observed at three BMD stations when JTWC best track data is used. And this difference increased to 20 to 25 kmph in case of IMD data. In case of air pressure data, there is both overestimation and underestimation in observed during the lifetime of the cyclone. This deviation varies during the lifetime of the cyclone in the range between 1 to 6 milibar. These deviations in wind speed and air pressure data are caused by the discrepancy in the best track data than the actual cyclone data and the limitations of the parametric model. Since parametric models use few information of the cyclone to produce the cyclone pressure field and wind field, there are many assumptions and simplification in developing the wind field and pressure field data.

JTWC best track data showed significantly better goodness of fit values than IMD data. Thus in this study JTWC data generated wind field and pressure field values are used to model the storm surge produced by the cyclone Amphan. Some previous storm surge studies in this region are based on IMD and IBTrACS (Krien *et al.*, 2017) best track data. Although BMD officials suggested IMD best track data. According to them IMD best track data provides better storm surge predictions as compared to others. But it is evident from this study that cyclone models using JTWC best track data can produce much more realistic representations of wind field and pressure field during a cyclone. So the more rational approach would be to generate the wind field and pressure field from the cyclone model using the available best track data provided by different organizations. Then based on the similarities of the generated wind speed and air pressure data with the observed wind speed and air pressure data most appropriate wind field and pressure field data representing the cyclone can be selected and used as model forcing in the storm surge model.

5.3 STORM SURGE INUNDATION MODEL

Predicted and observed Water levels at four stations are compared. Comparison results of the storm surge inundation model showed satisfactorily good model goodness of fit indices values. The mean value of R^2 and NSE is 0.815 and 0.848 respectively. Analysis of the observed water level during the cyclone Amphan in the water level stations shows that maximum water level took place in Sadarghat(ctg). And it was 2.79m. But the storm surge inundation model predicted maximum water level at Tojumuddin. It is 2.74m. At Sadarghat(ctg) station predicted water level was 2.65m. Although it is the second highest water level among the four stations. The deviation in the maximum water levels at these four stations ranges between 0.12m to 0.35m. Maximum deviation in the maximum water level is observed in Kutubdia station and then in Sadarghat(ctg). A phase difference of 1hr to 3.5 hr is

observed in the predicted water level. Model goodness-of-fit indices at the stations shows that at Kutubdia and Sadarghat(ctg) station these indices values are the lowest. So, these two stations are the stations with highest error in the predicted water level. A pattern is observed from the model goodness of fit indices that predictive skill of the storm surge inundation model at different location decreases as the distance from the landfall location increases. Kutubdia and Kuakata are the nearest station from the landfall location of Amphan. Then Sadarghat(ctg) and then Kutubdia is the farthest away from the landfall location. From Table 4.5 Tojumuddin and Kuakata has the higher indices values as compared to the other distant stations. And Kutubdia has the least indices values. In station Kuakata and Tojumuddin the storm surge inundation model showed better prediction in water level and the peak water level.

Comparison of the model generated inundation area with the reference inundation maps during Amphan shows that the storm surge inundation model has managed to predict floodings in the areas adjacent to the sea rather than the inland flooded which are not adjacent to the sea. A conclusion can be derived from the result that flooding generated by the model on land can predict flooding that occurred areas near the sea and river. The flood predicting capability of the model get reduced as the distance of the location of the flooded area increases from the sea and river. Bathymetry plays an important role in this case. In Delft3D refers to the bathymetry of the rivers, sea and the land topography. These three things are merged and used to make the bathymetry of Delft3D. But the most important parts of the bathymetry that play the role here is the land topography. And then bathymetry of the river. Land topography used here is not SRTM 30m global DEM. SRTM is a Digital Surface Model(DSM). It includes houses, buildings, vegetations etc. These things are modelled as high ground in the bathymetry. Due to this reason water is not moving across these locations. Another reason could be improper modelling of

the coastal embankments. Proper representation or modelling of the coastal polder is important to simulate the inundation scenario. Since the resolution of DEM user here is 30m, surely it fails to completely represent the coastal embankments. Also to model the inundation due to Amphan requires complete modelling of the breaching locations in embankments. It is not modelled during the preparation of the bathymetry during the model setup. So only inundations due to overtopping of the embankment is simulated. Another reason mentioned earlier is the river bathymetry. Specially simulating the inundation in inland areas it plays an important role. During the bathymetry preparation only bathymetry of the major coastal rivers is added collected from the BWDB. So water levels are not properly simulated in small rivers. It results in the incomplete representation of the inundation scenario. Also river discharges are not added in the model due to the lack of discharge data. The combined effect of river discharge and storm surge in the flooding is called compound flooding. It is found that compound flooding has an important role in the storm surge height and in the extent of flooding during a cyclone.

Chapter 6: CONCLUSIONS

6.1 Key Findings

- Calibration and validation of the tide model or the tide only hydrodynamic model simulation can be affected by the weather condition during the calibration and validation time period. A windy weather condition will have an additive effect on the observed water level. Comparing it with the result from tide only simulation will affect the calibration and the validation of the model. So, weather condition during calibration and simulation period needs to be considered during the simulation. Selection of a time period with clear weather condition based on the meteorological data can be beneficial in this case.
- Distance of the water level station used for model calibration and validation from the water way can influence the outcome of the model calibration and validation. To avoid these disturbances in the water level during observation due to the movement of the water vehicle can be avoided by selecting water level stations that are not near any water way or stations with little to negligible effect on water level due to water vehicle movement.
- Predicting skills of the storm surge model depends on the landfall location. It decreases as the distance from the landfall location increases.
- Bathymetry is important for proper flood mapping. Updated bathymetry and estuary data is required. SRTM data is not good for mapping requires deduction of artefacts such as buildings, trees etc. In a completely validated storm surge model Proper inundation extent mapping will depend on: Land topography DEM is important.. For proper inundation modelling

proper modelling of the levees and embankments are important. Proper modelling of levees require more high resolution DEM and use of more finer grid resolution in model setup. In modelling storm surge induced flooding due to previous cyclone will require proper knowledge of the levee breaching activities at different location during that time. Online media and newspapers can be great source to building a database of breaching activities. Without introducing breaching activities in the model it is not possible to get the actual flooding caused by the storm surge. Although it not a very easy task to know which the levee is breached and to incorporate them in the model. Also incorporation of bathymetry of small rivers is necessary for the simulating the actual scenario due to storm surge.

- This study points out some of the challenges of storm surge inundation modelling in a data scarce region like Bangladesh. In a summary they are: incomplete representation of bathymetry due to lack of high resolution land topography data, lack of wave data, improper modelling of embankment and breaching locations in the embankment and lack of discharge data in the coastal rivers.

6.2 Limitation of the Study

- Due to the lack of wave data validation of the wave model is not done in this study. Since wave setup has a role in the overall height of the storm surge, validation of the wave model is important to simulate the actual water level during a storm surge. In a study done on cyclone SIDR it is found that Wave setup for is about 30 cm (Krien et al., 2017) of the overall storm surge height.
- The updated bathymetry used in this study only covers the major coastal rivers. And its impacts the output of the inundation scenario of the storm

surge inundation model. It is discussed in the discussion chapter in details.

- Previous study shows that there is a variable amount of land subsidence occurs in different part of Bangladesh. And for coastal region this amount is 7.82mm per year(Meem et.al. 2016) .So Land subsidence need to be considered during predicting the accurate inundation scenario due to a storm surge.
- The effect of compound flooding is not analysed since river discharges are not included in the study due to lack of discharge data in coastal rivers. Also pluvial flooding is not considered when modelling storm surge inundation model. Since during the time of cyclone there is intense amount of rainfall occur in the coastal regions. For proper inundation scenario modelling the effect of rain can improve the result of the storm surge inundation model.

6.3 Practical Implication

- Methodology used in this study can be used for future studies in storm surge inundation modelling specially in data scarce region like Bangladesh. Since this study highlights issues associated with the common methodologies and datasets used in storm surge inundation modelling, findings from this study can be of great help for storm surge inundation modelling related studies.
- The storm surge inundation model developed in this study predicted water level during a storm surge with good accuracy. Although it failed to accurately simulate the inundation produced due to storm surge. Still this can be used as a prediction tool to predict storm surge height at different locations of the Bangladesh coast by using cyclone track forecast published during a cyclone by different organisations such as IMD, JTWC.

Since in this region storm surge related forecasts are still given by region by mentioning predicted water levels in different location of the coast.

6.4 Recommendation for Further Study

- Since wave model have a significant impact found in many studies proper validation of wave model will lead to much more accurate storm surge modelling.
- SRTM can be used for Storm surge inundation modelling, but the this data set need to be updated by removing artefacts specially trees and building from the DEM.
- This study uses GEBCO 2019 bathymetry as ocean bathymetry for both deep and near shore. Near shore bathymetry can be improved by using bathymetry charts prepared by Bangladesh NAVY. It is used in some storm surge studies in the coastal region of Bangladesh.
- Importance of the land topography for the modelling the inundation scenario due to a storm surge is discussed in Chapter: 6. Govt and other associated organizations such as Survey of Bangladesh(SOB) should come forward to generate a high resolution DEM for coastal area for more precise storm surge inundation modelling in this region.

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Appendices

Appendix A: [GEE Script]

```
var beforeStart = '2022-01-01'
var beforeEnd = '2022-01-30'
var afterStart = '2022-06-01'
var afterEnd = '2022-06-18'

var Sylhet = admin1.filter(ee.Filter.eq('ADM1_NAME', 'Sylhet'))
var geometry = Sylhet.geometry()
Map.addLayer(geometry, {color: 'grey'}, 'Sylhet Division')

var collection= ee.ImageCollection('COPERNICUS/S1_GRD')
  .filter(ee.Filter.eq('instrumentMode', 'IW'))
  .filter(ee.Filter.listContains('transmitterReceiverPolarisation', 'VH'))
  .filter(ee.Filter.eq('orbitProperties_pass', 'DESCENDING'))
  .filter(ee.Filter.eq('resolution_meters', 10))
  .filterBounds(geometry)
  .select('VH');

var beforeCollection = collection.filterDate(beforeStart, beforeEnd)
var afterCollection = collection.filterDate(afterStart, afterEnd)

var before = beforeCollection.mosaic().clip(geometry);
var after = afterCollection.mosaic().clip(geometry);

Map.addLayer(before, {min:-25,max:0}, 'Before Floods', false);
Map.addLayer(after, {min:-25,max:0}, 'After Floods', false);

var beforeFiltered = ee.Image(toDB(RefinedLee(toNatural(before))))
var afterFiltered = ee.Image(toDB(RefinedLee(toNatural(after))))

Map.addLayer(beforeFiltered, {min:-25,max:0}, 'Before Filtered', false);
Map.addLayer(afterFiltered, {min:-25,max:0}, 'After Filtered', false);

var difference = afterFiltered.divide(beforeFiltered);

// Define a threshold
var diffThreshold = 1.25;
// Initial estimate of flooded pixels
var flooded = difference.gt(diffThreshold).rename('water').selfMask();
Map.addLayer(flooded, {min:0, max:1, palette: ['orange']}, 'Initial Flood Area', false);

// Mask out area with permanent/semi-permanent water
var permanentWater = gsw.select('seasonality').gte(5).clip(geometry)
var flooded = flooded.where(permanentWater, 0).selfMask()
Map.addLayer(permanentWater.selfMask(), {min:0, max:1, palette: ['blue']}, 'Permanent Water')
```

```

// Mask out areas with more than 5 percent slope using the HydroSHEDS DEM
var slopeThreshold = 5;
var terrain = ee.Algorithms.Terrain(hydrosheds);
var slope = terrain.select('slope');
var flooded = flooded.updateMask(slope.lt(slopeThreshold));
Map.addLayer(slope.gte(slopeThreshold).selfMask(), {min:0, max:1, palette: ['cyan']}, 'Steep
Areas', false)

// Remove isolated pixels
// connectedPixelCount is Zoom dependent, so visual result will vary
var connectedPixelThreshold = 8;
var connections = flooded.connectedPixelCount(25)
var flooded = flooded.updateMask(connections.gt(connectedPixelThreshold))
Map.addLayer(connections.lte(connectedPixelThreshold).selfMask(), {min:0, max:1, palette:
['yellow']}, 'Disconnected Areas', false)

Map.addLayer(flooded, {min:0, max:1, palette: ['red']}, 'Flooded Areas');

// Calculate Affected Area
print('Total District Area (Ha)', geometry.area().divide(10000))

var stats = flooded.multiply(ee.Image.pixelArea()).reduceRegion({
  reducer: ee.Reducer.sum(),
  geometry: geometry,
  scale: 30,
  maxPixels: 1e10,
  tileScale: 16
})
print('Flooded Area (Ha)', ee.Number(stats.get('water')).divide(10000))

#####
// Speckle Filtering Functions
#####

// Function to convert from dB
function toNatural(img) {
  return ee.Image(10.0).pow(img.select(0).divide(10.0));
}

//Function to convert to dB
function toDB(img) {
  return ee.Image(img).log10().multiply(10.0);
}

//Appllying a Refined Lee Speckle filter as coded in the SNAP 3.0 S1TBX:

//https://github.com/senbox-org/s1tbx/blob/master/s1tbx-op-sar-
processing/src/main/java/org/esa/s1tbx/sar/gpf/filtering/SpeckleFilters/RefinedLee.java
//Adapted by Guido Lemoine

```

```

// by Guido Lemoine
function RefinedLee(img) {
  // img must be in natural units, i.e. not in dB!
  // Set up 3x3 kernels
  var weights3 = ee.List.repeat(ee.List.repeat(1,3),3);
  var kernel3 = ee.Kernel.fixed(3,3, weights3, 1, 1, false);

  var mean3 = img.reduceNeighborhood(ee.Reducer.mean(), kernel3);
  var variance3 = img.reduceNeighborhood(ee.Reducer.variance(), kernel3);

  // Use a sample of the 3x3 windows inside a 7x7 windows to determine gradients and
  // directions
  var sample_weights = ee.List([[0,0,0,0,0,0,0], [0,1,0,1,0,1,0],[0,0,0,0,0,0,0], [0,1,0,1,0,1,0],
  [0,0,0,0,0,0,0], [0,1,0,1,0,1,0],[0,0,0,0,0,0,0]]);

  var sample_kernel = ee.Kernel.fixed(7,7, sample_weights, 3,3, false);

  // Calculate mean and variance for the sampled windows and store as 9 bands
  var sample_mean = mean3.neighborhoodToBands(sample_kernel);
  var sample_var = variance3.neighborhoodToBands(sample_kernel);

  // Determine the 4 gradients for the sampled windows
  var gradients = sample_mean.select(1).subtract(sample_mean.select(7)).abs();
  gradients = gradients.addBands(sample_mean.select(6).subtract(sample_mean.select(2)).abs());
  gradients = gradients.addBands(sample_mean.select(3).subtract(sample_mean.select(5)).abs());
  gradients = gradients.addBands(sample_mean.select(0).subtract(sample_mean.select(8)).abs());

  // And find the maximum gradient amongst gradient bands
  var max_gradient = gradients.reduce(ee.Reducer.max());

  // Create a mask for band pixels that are the maximum gradient
  var gradmask = gradients.eq(max_gradient);

  // duplicate gradmask bands: each gradient represents 2 directions
  gradmask = gradmask.addBands(gradmask);

  // Determine the 8 directions
  var directions =
  sample_mean.select(1).subtract(sample_mean.select(4)).gt(sample_mean.select(4).subtract(sample_mean.select(7))).multiply(1);
  directions =
  directions.addBands(sample_mean.select(6).subtract(sample_mean.select(4)).gt(sample_mean.select(4).subtract(sample_mean.select(2))).multiply(2));
  directions =
  directions.addBands(sample_mean.select(3).subtract(sample_mean.select(4)).gt(sample_mean.select(4).subtract(sample_mean.select(5))).multiply(3));
  directions =
  directions.addBands(sample_mean.select(0).subtract(sample_mean.select(4)).gt(sample_mean.select(4).subtract(sample_mean.select(8))).multiply(4));
  // The next 4 are the not() of the previous 4

```

```

directions = directions.addBands(directions.select(0).not().multiply(5));
directions = directions.addBands(directions.select(1).not().multiply(6));
directions = directions.addBands(directions.select(2).not().multiply(7));
directions = directions.addBands(directions.select(3).not().multiply(8));

// Mask all values that are not 1-8
directions = directions.updateMask(gradmask);

// "collapse" the stack into a single band image (due to masking, each pixel has just one value
// (1-8) in its directional band, and is otherwise masked)
directions = directions.reduce(ee.Reducer.sum());

//var pal = ['ffffff', 'ff0000', 'ffff00', '00ff00', '00ffff', '0000ff', 'ff00ff', '000000'];
//Map.addLayer(directions.reduce(ee.Reducer.sum()), {min:1, max:8, palette: pal}, 'Directions',
false);

var sample_stats = sample_var.divide(sample_mean.multiply(sample_mean));

// Calculate localNoiseVariance
var sigmaV =
sample_stats.toArray().arraySort().arraySlice(0,0,5).arrayReduce(ee.Reducer.mean(), [0]);

// Set up the 7*7 kernels for directional statistics
var rect_weights = ee.List.repeat(ee.List.repeat(0,7),3).cat(ee.List.repeat(ee.List.repeat(1,7),4));

var diag_weights = ee.List([[1,0,0,0,0,0,0], [1,1,0,0,0,0,0], [1,1,1,0,0,0,0],
[1,1,1,1,0,0,0], [1,1,1,1,1,0,0], [1,1,1,1,1,1,0], [1,1,1,1,1,1,1]]);

var rect_kernel = ee.Kernel.fixed(7,7, rect_weights, 3, 3, false);
var diag_kernel = ee.Kernel.fixed(7,7, diag_weights, 3, 3, false);

// Create stacks for mean and variance using the original kernels. Mask with relevant direction.
var dir_mean = img.reduceNeighborhood(ee.Reducer.mean(),
rect_kernel).updateMask(directions.eq(1));
var dir_var = img.reduceNeighborhood(ee.Reducer.variance(),
rect_kernel).updateMask(directions.eq(1));

dir_mean = dir_mean.addBands(img.reduceNeighborhood(ee.Reducer.mean(),
diag_kernel).updateMask(directions.eq(2)));
dir_var = dir_var.addBands(img.reduceNeighborhood(ee.Reducer.variance(),
diag_kernel).updateMask(directions.eq(2)));

// and add the bands for rotated kernels
for (var i=1; i<4; i++) {
dir_mean = dir_mean.addBands(img.reduceNeighborhood(ee.Reducer.mean(),
rect_kernel.rotate(i)).updateMask(directions.eq(2*i+1)));
dir_var = dir_var.addBands(img.reduceNeighborhood(ee.Reducer.variance(),
rect_kernel.rotate(i)).updateMask(directions.eq(2*i+1)));
dir_mean = dir_mean.addBands(img.reduceNeighborhood(ee.Reducer.mean(),
diag_kernel.rotate(i)).updateMask(directions.eq(2*i+2)));

```

```

    dir_var = dir_var.addBands(img.reduceNeighborhood(ee.Reducer.variance(),
diag_kernel.rotate(i)).updateMask(directions.eq(2*i+2)));
  }

  // "collapse" the stack into a single band image (due to masking, each pixel has just one value
in it's directional band, and is otherwise masked)
  dir_mean = dir_mean.reduce(ee.Reducer.sum());
  dir_var = dir_var.reduce(ee.Reducer.sum());

  // A finally generate the filtered value
  var varX =
dir_var.subtract(dir_mean.multiply(dir_mean).multiply(sigmaV)).divide(sigmaV.add(1.0));

  var b = varX.divide(dir_var);

  var result = dir_mean.add(b.multiply(img.subtract(dir_mean)));
  return(result.arrayFlatten(['sum']));
}

```

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