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Simulation of Storm Surge and Coastal Flooding from Tropical Cyclones in Bangladesh Using Delft3D

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ABSTRACT: The coastal region of Bangladesh is highly vulnerable to the adverse effects of tropical cyclones, and the changing climate has exacerbated the impacts of these cyclones and the subsequent storm surges. Moreover, characteristics of the coastal region can amplify the impact of tropical cyclones. Over the years, many cyclones have made landfall in Bangladesh's western and central coastal regions. Recently, two cyclones that have impacted the western and central coastal regions are Bulbul in 2019 and Sitrang in 2022. To evaluate the impact of these cyclones, the Delft3D modeling suite has been used. The model was validated by comparing the simulated data with tidal records collected from BIWTA, demonstrating its ability to replicate real-life scenarios accurately. For cyclone Bulbul, the coefficient of determination, RMSE, and MAE were 0.69, 0.34, and 0.24, respectively. For cyclone Sitrang, these values were 0.838, 0.32, and 0.28 for Hiron Point and 0.84, 0.53, and 0.4 for Chattogram. The inundation area for tropical cyclone Bulbul was 2255 square kilometers, while cyclone Sitrang resulted in the flooding of 1908 square kilometers.

Keywords: Tropical Cyclone; Storm Surge; Delft3D; Bay of Bengal; Bangladesh

INTRODUCTION

Among the various hydrometeorological natural hazards that impact coastal areas, tropical cyclones (TC) are considered the most perilous and destructive (Asik and Hussain, 2022). Over the last 50 years, TCs have been associated with an average of $78 million (USD) in damages and 50 fatalities each day (WMO, 2022). The influence of climate change on the intensity and frequency of tropical cyclones (TCs) has been a critical area of scientific investigation (Wu et al., 2022). In Bangladesh, this increasing trend is particularly concerning, with historical records revealing that more than a million fatalities over the course of the last five centuries due to TCs (Hadi et al., 2021). Beyond the high human toll, TCs and associated storm surges inflict significant socioeconomic, infrastructural, and environmental damage. For instance, the 1970 Bhola cyclone claimed between 300,000 and 500,000 lives, while Cyclone Gorky (1991) wrecked approximately 470 kilometers of coastal embankments and 1.75 million households (MoEFCC, 2009). More recently, Cyclone Sidr (2007) affected the livelihoods of around 7 million people, with economic losses estimated at $70.3 million for infrastructure and $19.3 million for agricultural assets (Dasgupta et al., 2010). Cyclone Aila in 2009 caused damages amounting to $270 million (Tajrin and Hossain, 2017). Severe cyclones impact Bangladesh on average once every three years, and the national adaptation finance deficit for TCs may reach as high as $25 billion (MoEFCC, 2009, 2018).

The Bay of Bengal (BoB) region generates a high incidence of TCs, largely due to favorable meteorological conditions during the pre- and post-monsoon seasons. Approximately one-sixth of TCs in the BoB make landfall along Bangladesh's coast, where unique geographical and hydrographic factors render even relatively weak cyclones highly destructive. Several cyclones have led to extensive loss of life and property in recent years, underscoring the urgency to understand storm surge mechanisms and develop predictive flooding models. A recent World Meteorological Organization (WMO) report emphasizes the necessity of early warning systems to mitigate these impacts (Cullmann et al., 2020).

In recent years, several models have been developed to simulate cyclone-driven storm surge dynamics and forecast peak surge levels in Bangladesh's coastal regions. Early models, developed from 1970 to 1990,

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primarily focused on predicting peak surge heights along coastlines (Das, 1972; Johns and Ali, 1980; Murty, Flather and Henry, 1986; Dube et al., 1997). Subsequent models advanced these predictions by incorporating surge-induced inundation estimates (Murty and Flather, 1994; Rao et al., 1997; Madsen and Jakobsen, 2004; Karim and Mimura, 2008). More recently, comprehensive modeling software like Advanced Circulation (ADCIRC), Weather Research and Forecasting Model (WRF), and Delft3D has been employed to simulate storm surges for the coastal zone of Bangladesh (Mashriqui et al., 2006; Deb and Ferreira, 2018; Jisan, Bao and Pietrafesa, 2018; Tanim and Akter, 2019; Mamnun, Bricheno and Rashed-Un-Nabi, 2020; Tanim and Goharian, 2021). These studies have largely focused on modeling surge heights for individual cyclone events or specific sections of the coastline. Despite significant advancements, numerical models face challenges in accurately reproducing coastal flooding patterns across space and time. Understanding these inundation patterns is crucial for accurately assessing the spatial extent and severity of storm surge flooding, particularly in low-lying and densely populated coastal regions. By highlighting flood-prone areas and vulnerable communities, inundation maps offer crucial information for disaster risk reduction, infrastructure design, and emergency response. The specific challenges of storm surge modeling in the Ganges-Brahmaputra-Meghna Delta (GBMD) are further detailed by Krien et al., (2017).

This study aims to examine inundation patterns for two cyclones, Cyclone Bulbul on the western coast and Cyclone Sitrang on the central coast, that made landfall along different coastal zones of Bangladesh. Cyclone Bulbul, one of the longest-lasting transnational cyclones to affect the country, has distinctive characteristics in terms of landfall location, intensity, and associated casualties, highlighting the need for a detailed assessment of its effect (Sonet et al., 2024). Cyclone Sitrang, on the other hand, was selected due to its recent occurrence and substantial geomorphological impact on the islands along the central coast of Bangladesh (Tamim and Islam, 2023). Furthermore, Sitrang demonstrated unique meteorological features, including a recurving path influenced by upper atmospheric conditions, a high translational speed, and a relatively short lifespan of 69 hours (Wahiduzzaman and Paul, 2024). This analysis uses Delft3D and Delft Dashboard, combined with global meteorological and oceanographic datasets, to develop a model which can be applicable across the entire coastal region of Bangladesh.

STUDY AREA

Bangladesh, located in South Asia, is a floodplain delta within the Ganges–Brahmaputra–Meghna (GBM) basin. With a coastline stretching 710 kilometers, the country's coastal zone spans 19 districts and 147 upazilas, comprising about 32% of Bangladesh's land area (Islam, 2004; WARPO, 2004). Moreover, approximately 38.5 million people (25% of the population) live in this coastal zone (BBS, 2011). This zone is divided into inner and exposed coastal regions, with significant variation in population density: 482 people per km² in the inner coast and 1,012 people per km² in the exposed coast, compared to a national average of 839 per km². About 6.8 million households are located here, many of which face significant economic challenges (Islam, 2004).

The coastal zone itself is divided into three sections: the eastern zone, predominantly the Chittagong coastal plain; the central zone, an active region influenced by continuous land subsidence and accretion (Brammer, 2014; Rezaie et al., 2019); and the western part features a flat topography, with numerous small rivers, narrow channels, and distributaries, including the Sundarbans, the world's largest mangrove forest (Fig. 1). Nearly 90% of the total upstream discharge originates from the Ganges, Brahmaputra, and Meghna rivers and flows through the central zone via the Meghna River (Rezaie et al., 2014). The entire coastal region faces numerous natural hazards, e.g., storm surges, sea level rise, and salinity intrusion, which are exacerbated by unique geographic features such as the Bay of Bengal's triangular entrance, a shallow continental shelf, and strong tide–surge interactions (Ali, 1999; Debsarma, 2009; Chowdhury, 2013). These dynamic characteristics make modeling storm surges and other physical processes in this region particularly challenging.

MATERIALS AND METHODS

Storm Surge Inundation Modeling using Delft3D

In order to investigate the inundation of the coastal region, the flow module of the Delft3D software was utilized. Following the Boussinesq approximation, the flow module, largely used for multi-dimensional hydrodynamic simulations, solves the Navier-Stokes equations for an incompressible fluid. Additionally, the tropical cyclone toolbox of the Delft dashboard was used to prepare the cyclone wind file for the simulations. To run the model, 1 second time step was defined, and horizontal eddy diffusivity and viscosity were set as 1 m^2/s. Finally, according to the study of Bastidas et al. (2016), threshold depth, nonlinear triad interaction parameters, and depth-induced breaking alpha parameters do not have any notable impact on the result of such simulations.

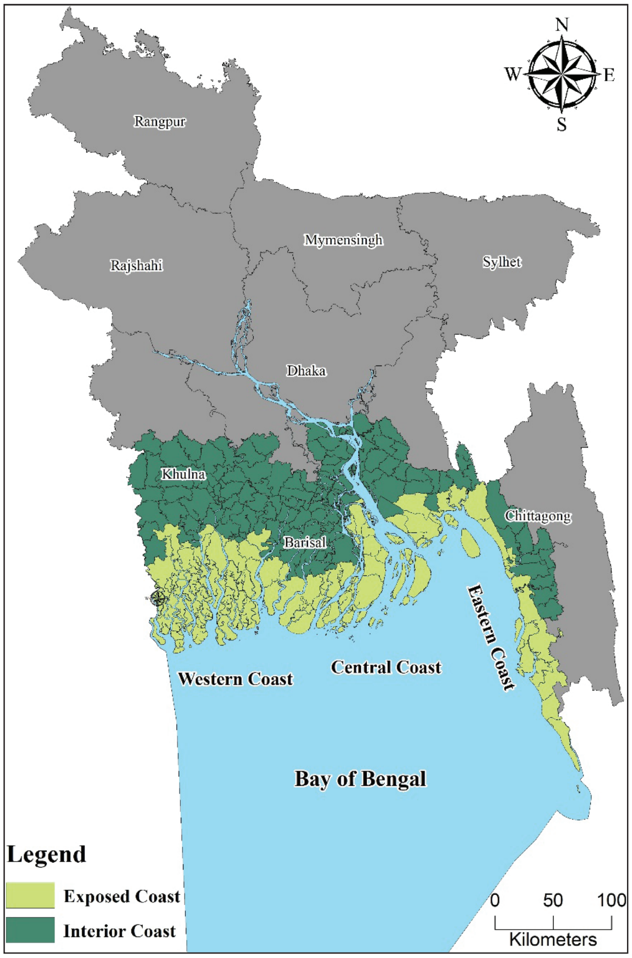


Figure 1: Coastal Zone of Bangladesh

Grid and Bathymetry

For this study, global datasets were exclusively utilized to ensure comprehensive coverage and reproducibility. The bathymetry used in this study was collected from the General Bathymetric Chart of the Ocean (GEBCO), which even though has a lower resolution in the nearshore region but is a widely accepted global bathymetry dataset around the world (Marks and Smith, 2006; Vrdoljak, 2021). The land topography data from the Shuttle Radar Topography Mission (SRTM), along with GEBCO's bathymetry data, was utilized for the model. The data used was in WGS84 coordinate system and referenced to the Mean Sea Level (MSL) datum.

The structured grid used for the simulations was created in the Delft dashboard. A resolution of 0.01 degrees was selected as a compromise between computational limitations and achieving sufficient detail to observe coastal region inundation accurately.

The manning coefficient was set based on different land use and land cover of the area (ocean 0.02; river 0.01; mangrove 0.08; land 0.03; and grassland 0.05). These values were derived from validated models in the Northern Bay of Bengal, enhancing the simulation's accuracy in predicting storm surge behavior.

Boundaries and Wind Forcing

Both upstream boundary and open boundary conditions have been used in this study. Along the open boundary in the BoB, the water level was derived from the TPXO 8.0 global inverse tidal model, which provided tidal components information. For the upstream boundary, three locations were set: Hardinge Bridge, Bahadurabad Transit, and Bhairab Bazar, which correspond to the Ganges, Brahmaputra, and Meghna rivers, respectively. Discharge data for these locations, obtained from the Bangladesh Water Development Board (BWDB), were used to simulate the influence of freshwater inflow from upstream.

The wind data in a spiderweb grid was generated using the tropical cyclone toolbox in the Delft dashboard for the cyclones Bulbul and Sitrang.

Validation of the Model

Water level data from the Delft dashboard was used to evaluate the performance of the model. The model output was compared to the water level data for two stations: Hiron Point and Cox's Bazar. In order to assess the model performance, the coefficient of determination (R-squared), root mean square error (RMSE), and mean absolute error (MAE). In equations 1 & 2, $X_{obs,\,i}$ represents the observed value at the i-th data point, $X_{model,\,i}$ is the model's predicted value at the same point, and i is the index of the data points from 1 to n.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i}-X_{model,i})^2}{n}} \quad (1)$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n} | X_{obs,i} - X_{model,i}| \quad (2)$$

The stations Hiron Point and Cox's Bazar were chosen because they are near the coastline. The model cannot distinguish stations situated further inland due to their lower resolution.

RESULTS AND DISCUSSION

Selected Cyclones

Cyclone Bulbul

Cyclone Bulbul made landfall in India on November 10th, 2019, at midnight, crossing the western coastal region of Bangladesh early in the morning (Fig. 2). During the cyclone period, the maximum sustained wind speed (*Vmax*) increased from 20 knots to a peak of 100 knots on November 9, while the central pressure (*Pc*) decreased to a minimum of 959 hPa (Knapp et al., 2010). One of the most incessant cyclones to hit Bangladesh in the past 52 years, the storm remained there for around 36 hours. Because of the severe precipitation and tidal surge, the affected coastal sea line had an average flooding of more than three meters. The Khulna Met Office reports that the storm struck the Sundarbans with winds between 120 and 130 km/h. The Sundarbans performed as a buffer, significantly reducing the destruction that might have occurred due to the TC. This resulted in extensive damage to the forest and various economic sectors, e.g., fisheries, livestock, as well as the death of 9 people due to various causes.

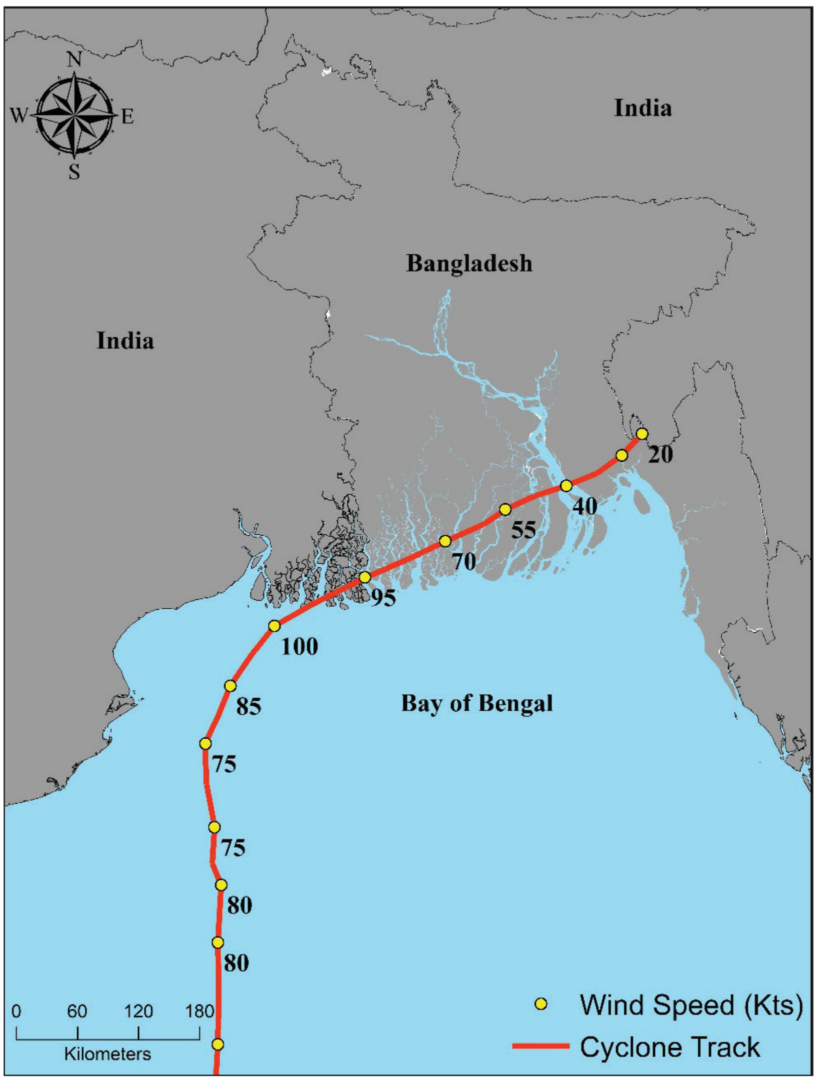


Figure 2: Cyclone Bulbul Track and Wind Speed

Cyclone Sitrang

On October 22, 2022, Cyclonic Storm Sitrang emerged in the Bay of Bengal, making landfall late at night on October 24^{th}. The formation of this cyclone stemmed from a low-pressure system that developed near the Bay of Bengal, specifically off the Andaman and Nicobar Islands, within the latitudinal range of 10°N to 15°N and longitudinal range of 90°E to 95°E. The cyclone crossed over the central coastal region of Bangladesh (Naveed Anzum et al., 2025) (Fig. 3). The cyclone gradually intensified, with *Vmax* increasing from 35 to 45 knots and *Pc* decreasing slightly from 999 hPa to 994 hPa over a 30-hour period (Knapp et al., 2010). The impact of Cyclone Sitrang was significant, leading to the evacuation of approximately one million people and resulting in at least 35 fatalities. In Bangladesh, the cyclone destroyed over 20,000 homes, and Dhaka, the capital, experienced severe flooding and intense rainfall as a direct consequence. Additionally, more than eight million individuals faced disruptions due to widespread power outages. Economic losses in the agricultural sector were estimated at approximately $34.4 million.

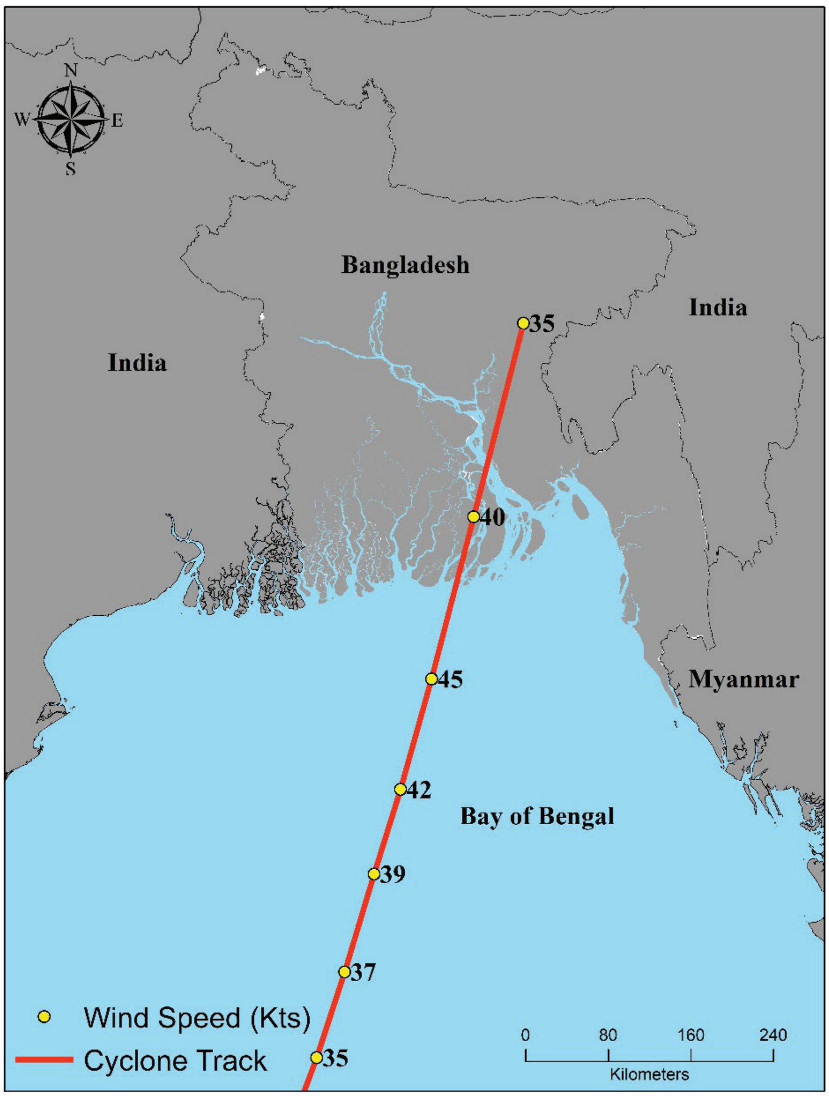


Figure 3: Cyclone Sitrang Track and Wind Speed

Validation of Delft3D Model

The model is adjusted using different roughness and drag coefficient values. The values of the wind drag coefficient were calculated using Hwang (2011). This method incorporates a provision for saturation when wind speeds exceed 30 ms^{-1} and even exhibits a decrease at exceptionally strong speeds. The water level output of the model showed similarities with data collected from BIWTA.

From Figure 4A, it can be observed that there is strong agreement between the measured and modeled water level at Hiron Point for cyclone Bulbul. The coefficient of determination, RMSE and MAE for the cyclone Bulbul are 0.69, 0.34 and 0.24 (Table 3). The result indicates that the model can accurately capture tidal oscillation and storm surge dynamics during the model run period (4th November – 11th November 2019). The water level and phase timings during this time period align closely. However, the peak water level calculated by the model is 3.9m, which is higher than the water level measured in situ (3.43m).

Table 3: Calculated Coefficient of Determination (R-squared), RMSE and MAE value for Tropical Cyclone Bulbul and Sitrang

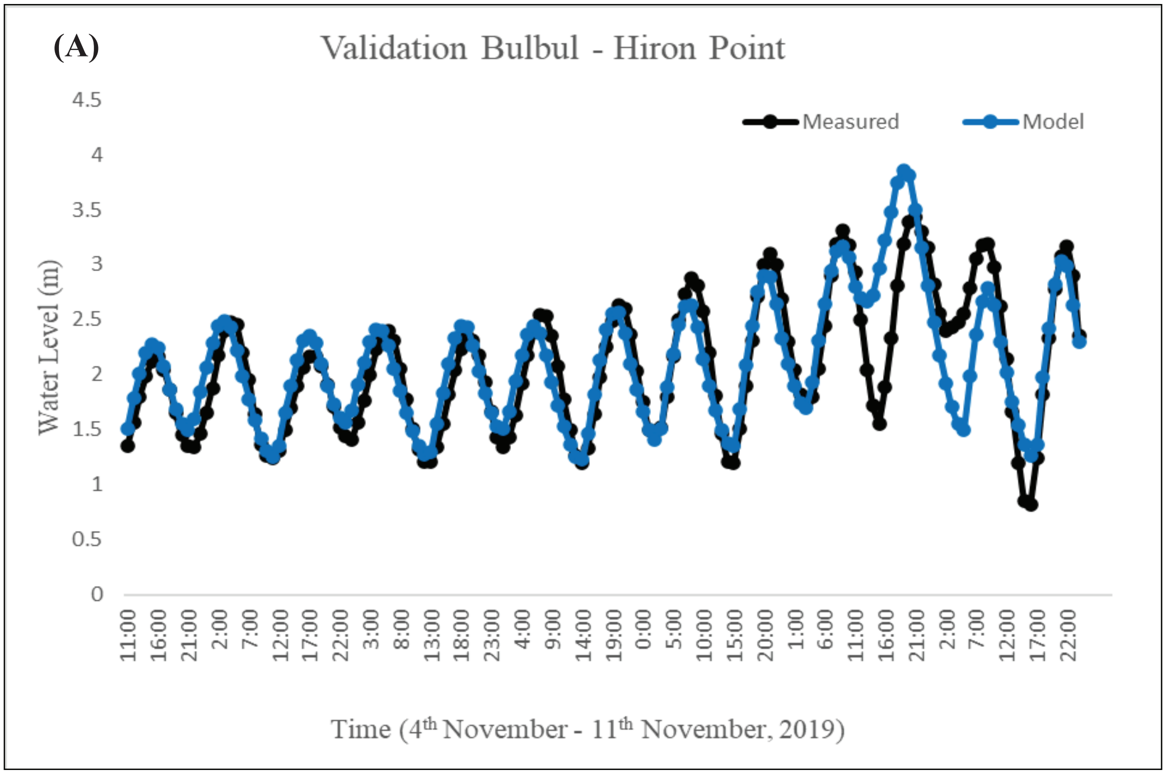
Cyclone	Hiron Point			Chattogram		
	R^2	RMSE	MAE	R^2	RMSE	MAE
Bulbul	0.69	0.34	0.24	-	-	-
Sitrang	0.83	0.32	0.28	0.84	0.53	0.40

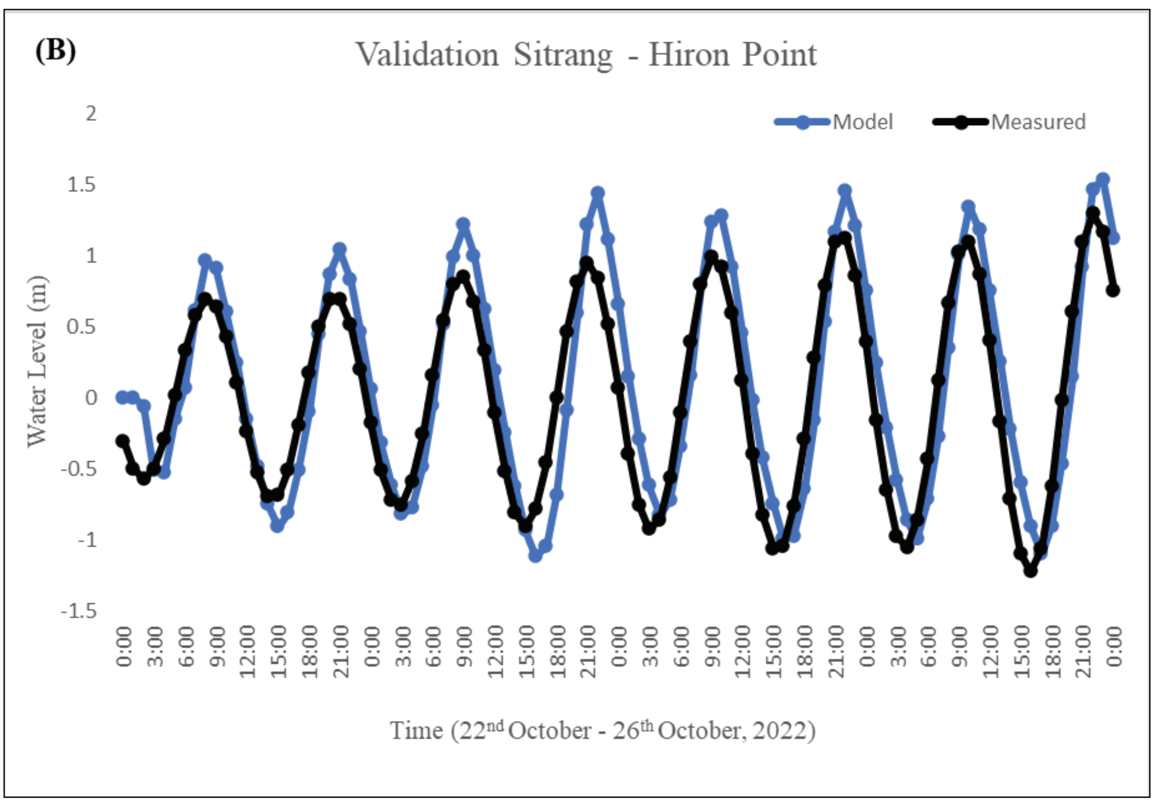
The model validation for Cyclone Sitrang at Hiron Point (Fig. 4B) and Chattogram (Fig. 4C) highlights the model's capacity to simulate tidal fluctuations and storm-induced water levels during the cyclone period (22nd October – 26th October 2022) accurately. At both locations, the modeled water levels align well with the measured data, accurately capturing tidal phases and amplitudes. Cyclone Sitrang's coefficient of determination (R^2), RMSE, and MAE values were 0.838, 0.32, and 0.28 at Hiron Point and 0.84, 0.53, and 0.4 at Chattogram, respectively (Table 1). It can be observed from Fig. 3B that the model slightly overestimates water levels at Hiron Point compared to the measured data. In contrast, at Chattogram, the model underestimates water levels, likely due to the tide gauge's inland location in an upstream river channel, where the model's spatial resolution may not fully resolve local hydrodynamic processes. Additionally, due to environmental constraints, there are no tide gauges in the central coastal zone, and the available gauges are either inland or located in smaller river channels. This absence of tide gauges in the central zone necessitated the use of the two tide gauges located in the western (Hiron Point) and eastern (Chattogram) coastal regions. Despite these limitations, the results validate the model's capability to analyze cyclone-induced hydrodynamic changes in the region.

Evaluating Inundation Extent

The inundation extent for tropical cyclones Bulbul and Sitrang can be seen in Figure 5. It should be noted that due to the exclusion of polders, the extent of inundation is greater than in real-world scenarios. This was done because it is necessary to understand the scale of damage that may occur in case of embankment failure. A similar event occurred during cyclone Sidr, when polders were breached, causing massive damage.

The Tropical cyclone Bulbul led to an inundation area of 2255 square kilometers, which is 1.53% of the landmass of the country. TC Sitrang caused flooding to a total of 1908.76 square kilometers (1.3% of the total country) (Fig. 5). The color-coded data points in the figure represent water depths derived from Delft3D model simulations. It should be noted that the inundation extent shown here is larger than what typically occurs in real-world scenarios, as polders have been intentionally excluded from the model (Rahman et al., 2019). In future studies, we aim to incorporate polders into the model simulations to better reflect real-world scenarios.


(A)
Validation Bulbul - Hiron Point
Measured
Model
Water Level (m)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
11:00 16:00 21:00 2:00 7:00 12:00 17:00 22:00 3:00 8:00 13:00 18:00 23:00 4:00 9:00 14:00 19:00 0:00 5:00 10:00 15:00 20:00 1:00 6:00 11:00 16:00 21:00 2:00 7:00 12:00 17:00 22:00
Time (4th November - 11th November, 2019)


(B)
Validation Sitrang - Hiron Point
Model
Measured
Water Level (m)
2
1.5
1
0.5
0
-0.5
-1
-1.5
0:00 3:00 6:00 9:00 12:00 15:00 18:00 21:00 0:00 3:00 6:00 9:00 12:00 15:00 18:00 21:00 0:00 3:00 6:00 9:00 12:00 15:00 18:00 21:00 0:00 3:00 6:00 9:00 12:00 15:00 18:00 21:00 0:00
Time (22nd October - 26th October, 2022)

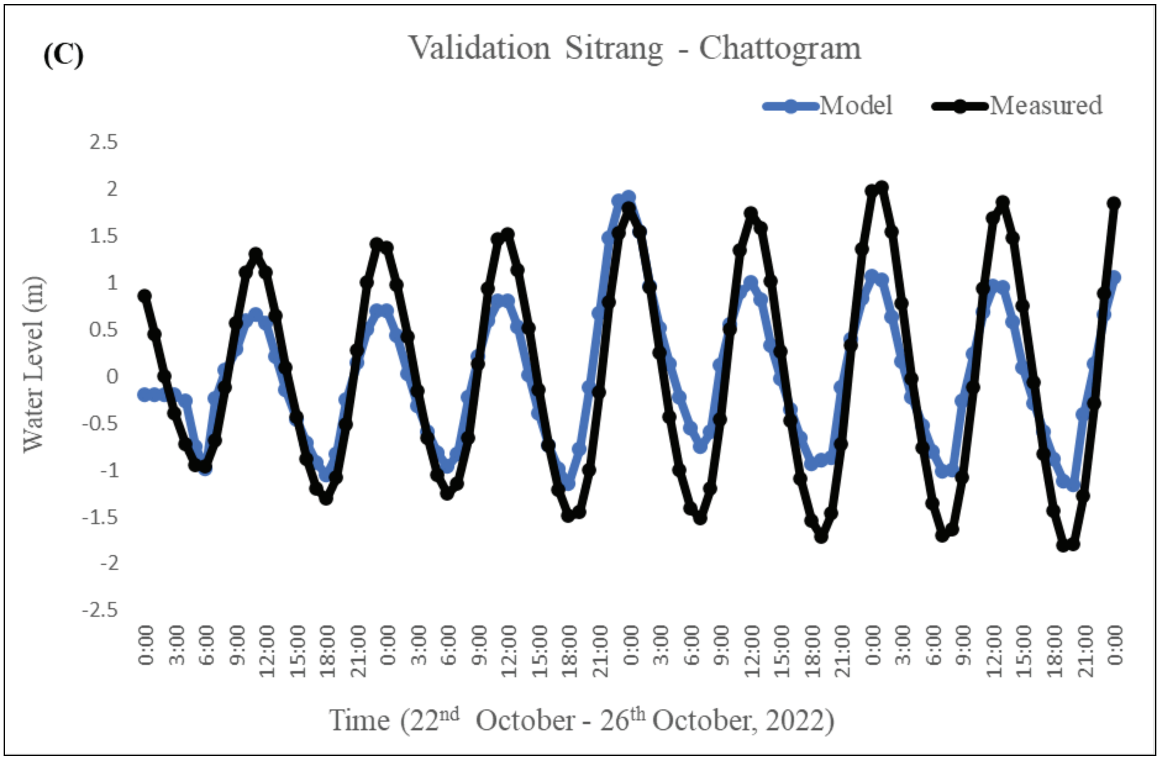


Figure 4: Validation of the Model for the Tropical Cyclones (A) Bulbul – Hiron Point and (B) Sitrang – Hiron Point and (C) Sitrang – Chattogram

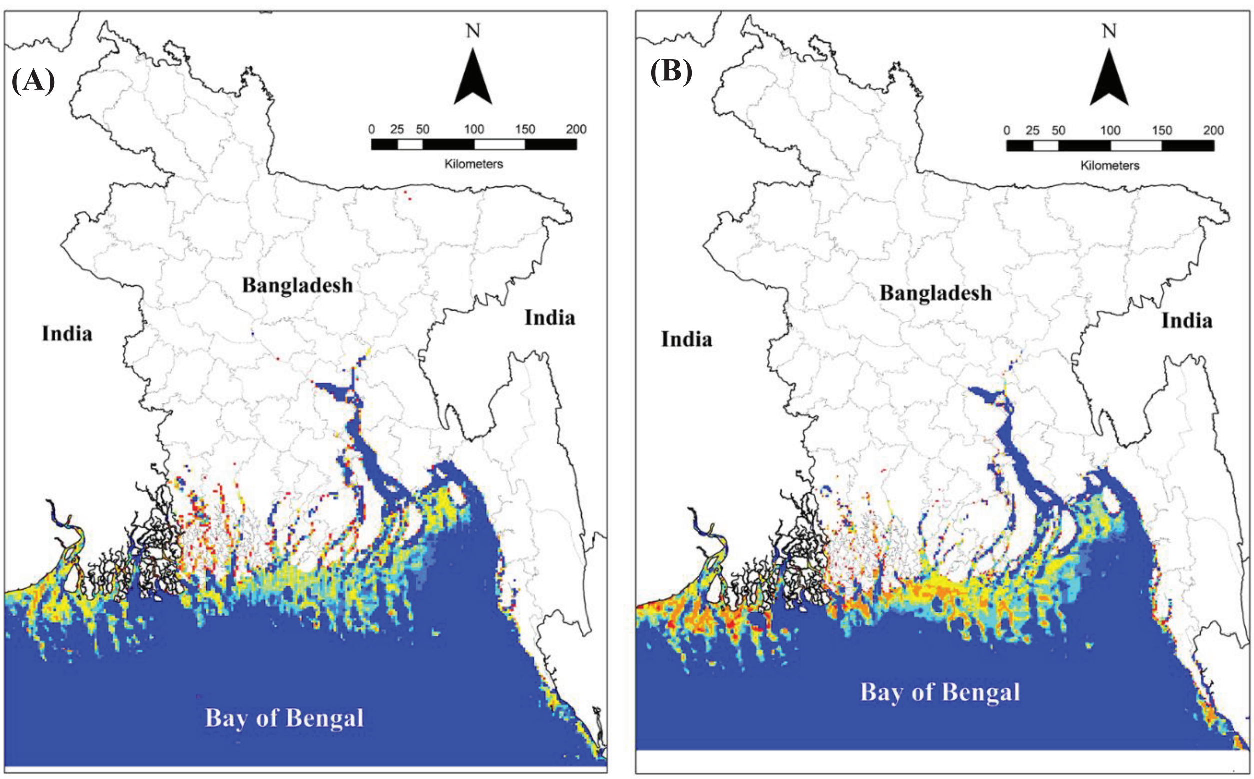


Figure 5: Inundation Map for Tropical Cyclone (A) Bulbul and (B) Sitrang

CONCLUSIONS

The study employed the open-source Delft3D modeling suite and globally available data to simulate coastal storm surge dynamics and evaluate storm surge inundation patterns. Specifically for this study, the cyclones Bulbul and Sitrang were selected. The model demonstrated reasonable accuracy when compared with in-situ water level data, as evidenced by RMSE and MAE values. The result indicated that cyclone Bulbul affected a larger area (2255 km^2) compared to cyclone Sitrang (1908 km^2), accounting for 1.53% and 1.3% of the country's total landmass, respectively. The study highlights the potential of using globally available datasets for storm surge modeling in data-scarce regions like Bangladesh. However, significant limitations remain. The reliance on global datasets resulted in lower-resolution bathymetric and topographic data in nearshore areas, contributing to errors in inundation estimates. Furthermore, the exclusion of polder dynamics, which play a critical role in real-world flooding scenarios, limits the applicability of the findings. Importantly, due to the absence of high-resolution observational data or published records documenting cyclone-induced inundation extents for Cyclones Bulbul and Sitrang, the model's inundation outputs could not be directly validated against real-world observations. Future research should focus on integrating high-resolution local datasets and validating against satellite-derived inundation data to provide more realistic assessments of coastal flooding risks, informing mitigation strategies and disaster preparedness for vulnerable coastal communities.

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