

Risk Assessment of Storm Surges in Polder 48, Bangladesh

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Manuscript received July 18, 2025; accepted August 22, 2025; published September 23, 2025

Abstract—Bangladesh is one of the most cyclone-prone nations in the world due to its geographical location. The coastal areas, particularly low-lying polders, are highly vulnerable to storm surges, leading to immense loss of life and property. This study focuses on storm surge risk analysis in Polder 48, located in Kalapara Upazila of Patuakhali District, Bangladesh, to support risk-informed planning and disaster preparedness. A compound risk framework is established by integrating inundation and vulnerability analysis. Inundation maps are developed for three storm surge scenarios corresponding to 6 m, 8 m, and 10 m surge heights in terms of volume–elevation relationships. Meanwhile, vulnerability maps are constructed based on Land Use and Land Cover (LULC) conditions of the study area. These maps are superimposed to obtain a composite risk map on the basis of the Risk Index as a product of inundation and vulnerability values. Results indicate that under a scenario of minor breaching, the majority of the area is exposed to moderate and low levels of risk. Under scenarios that include both breaching and overtopping, however, a considerable portion of the area is exposed to high and severe risk. The findings provide crucial data for policymakers and emergency planners to devise adequate storm surge mitigation strategies in coastal Bangladesh.

Keywords—storm surge risk assessment, polder system, coastal vulnerability, inundation mapping, Bangladesh coastal zone, climate change adaptation, GIS hazard modeling

I. INTRODUCTION

Bangladesh, in the deltaic region of South Asia [1], is one of the world's most disaster-prone countries, extremely vulnerable to tropical cyclones and associated storm surges [2]. Its unique geographical position at the confluence of the Ganges-Brahmaputra-Meghna river system and its extensive 711 km long Bay of Bengal shoreline offer a mix of conditions most suitable for intensified natural disaster threats [3]. The funnel-like topography of the Bay of Bengal, which tapers towards Bangladesh's southern coast, directs and concentrates incoming cyclones, creating a geographical "death trap" for coastal people [4]. Cyclonic data reveal the devastating impact of cyclonic activity on Bangladesh, as the nation has been affected by over 250 cyclones from 1877 to 2020, comprising about 75 intense tropical storms [5]. The most devastating disasters are the 1970 Bhola Cyclone with over 300,000 fatalities, the 1991 cyclone with 138,882 fatalities, and recent disasters such as Cyclone Sidr (2007), Cyclone Aila (2009), Cyclone Amphan (2020), and Cyclone Mocha (2023) [6, 7]. The disasters highlight the very high vulnerability of the coastal region of Bangladesh to the effects of storm surges. The strength of storm surge impacts in Bangladesh results from a combination of various interrelated causes [8]. The low topography of the country [9], where coastal regions are often less than 3 meters above mean sea level, and the relatively shallow continental shelf of the Bay of Bengal, substantially heightens surge levels as they

advance onto land [10]. The funnel-like configuration of the coastline creates a channeling influence amplifying cyclonic action, while the dense coastal population of approximately 800 people per square kilometer exacerbates the danger of catastrophic losses [11]. Unexpectedly, under a 2 °C Sea Surface Temperature (SST) rise and 0.3 m sea-level rise, storm surge flooding in western Bangladesh could expand by 15.3%, with flood depth increasing up to 22.7% within 20 km of the coast [12]. According to the 2019 Inform Risk Index, Bangladesh ranks 22nd in overall disaster risk, with 1st in flooding exposure, 19th for tropical cyclones, 47th for drought, and 37th in vulnerability due to socioeconomic factors [13]. Climate change has also further intensified these problems, with sheer global warming modifying the climate picture of Bangladesh to a great extent and contributing to widespread suffering among millions [14]. Future cyclonic activity is expected to become more intense due to rising sea levels, higher sea surface temperatures, and changing precipitation patterns, making climate change adaptation and disaster risk reduction increasingly essential [14, 15]. Bangladesh's coastal region is made up of 19 districts, namely Khulna, Bagerhat, Barguna, Barisal, Bhola, Chandpur, Chittagong, Cox's Bazar, Feni, Gopalganj, Jessore, Jhalkathi, Lakshmipur, Narail, Noakhali, Patuakhali, Pirojpur, Satkhira, and Shariatpur—and is made up of 147 Upazilas, 48 of which are in 12 districts that form the exposed coast [16]. The vast coastal region is populated by high-density people whose means of livelihood is primarily agricultural and fishing-based, and they are therefore extremely vulnerable to storm surge impacts [8]. To address these issues, the Bangladesh Water Development Board (BWDB) has been running the Coastal Embankment Project (CEP) since 1961 and has constructed some 139 polders to protect coastal areas from storm surges, saline water intrusion, and river flooding [17]. However, recurring issues such as erosion, failure of embankment breaches, and the impacts of climate change require continuous maintenance and upgrading to ensure the effectiveness of these protective works [18]. Recent research has assisted in the identification of storm surge threats in coastal areas of Bangladesh. Studies have been focused on flood hazard assessment, cyclone flooding, and impacts of climate change, such as sea level increase and an increase in sea surface temperature [3, 19]. Various approaches have been used, including hydrodynamic modeling using HEC-RAS, GIS-based hazard mapping, and demographic-topographic integrated vulnerability studies [20]. Such works have set good baselines for building resilience and improving risk management action for coastal communities.

Current research in the coastal areas of Bangladesh has also been addressing storm surge hazards, flood modeling, and

climate change impacts. The cyclone-induced dike breaching flood risk in Polder 48, located in Kalapara Upazila of Patuakhali District (Kuakata Polder), was examined using a HEC-RAS 1D–2D hydrodynamic model for the simulation of the inundation scenarios [3]. Storm surge hazards related to Sea Surface Temperature (SST) rise and Sea Level Rise (SLR) were also assessed in the coastal zone [19]. Risk-based decision-making was applied with a view to determining the best polder levels for storm surge resistance in Polder No. 33, Dacope Upazila, Khulna [21]. Data collection and database studies for risk zone mapping were also carried out, and a conceptual framework for coastal risk assessment was proposed [20]. IWM (Institute of Water Modeling) submitted a report designing inundation risk maps for tsunamis and storm surges for the entire coastal zone based on the available data [22]. A cyclone risk analysis was conducted in Anowara Upazila of Chittagong by integrating hazard modeling and vulnerability mapping using historical cyclone, demographic, and topographic data to create hazard maps and estimate population risk [3]. Additionally, a study examined the forces that form severe storm surges in the Bay of Bengal, their seasonal frequency, and how tropical cyclone recurvature affects Bangladesh [23].

Despite previous research, general risk assessment remains crucial in coming up with effective disaster management and preparedness plans. Merging Geographic Information System (GIS) software and storm surge modeling provides robust features in risk mapping and assessing vulnerability, enabling planners and decision-makers to optimize development priorities and safeguard existing assets. This study aims to assess storm surge risk in Polder 48, located in Bangladesh's southern coastal zone, a region frequently affected by cyclones and storm surges. The unique objectives are: (1) to prepare risk maps to define risk levels in various zones in the study area, (2) to identify vulnerable features and their respective vulnerability levels, and (3) to develop a decision-making benchmark so that a risk-based storm surge contingency plan for the selected area may be prepared. Based on this extensive risk analysis, the study hopes to contribute towards enhanced disaster preparedness and resilience in one of the world's most cyclone-prone coastal areas.

II. MATERIALS AND METHODS

A. Study Area

This study focuses on Polder 48, located at Kalapara Upazila of the Patuakhali district, in Bangladesh's southwest coastal delta [24]. It is located in the Kalapara Upazila of Patuakhali District in the southwest coastal zone of Bangladesh, also known as Kuakata, and spans an area of 50.75 square kilometers. The polder's coordinates are 21°05'28" N 90°05'17" E to 21°05'6" N 90°14'14" E. It is encircled by dikes, including a 20-kilometer sea-facing dike on its southern side. The Andharmanik, Galachipa, and Khaprabhanga rivers lie to the east, west, and north, respectively. Polders, such as Polder 48, were constructed in the 1960s as embankments in Bangladesh's coastal areas. It is part of the Coastal Embankment Improvement Project (CEIP-1). Additionally, Polder 48 features four different heights: 5.18 m, 5.8 m, 6.1 m, and 7.5 m, with an average

height of around 6 m. The region is very vulnerable to a combination of natural hazards like tidal surges, intrusion of saline water, and seasonal flooding of the Ganges River. Though the region abounds with rich natural resources like arable land, fresh and brackish water, forestland, and fisheries, livelihoods are always at risk because of rising salinity, freshwater shortage, and recurrent cyclonic storms that can produce storm surges of as much as 6 meters [25]. The polderization process in Bangladesh began in the early 1960s, initially prompted by local initiatives in the pre-polderization phase and later by state action through the Bangladesh Water Development Board (BWDB) [26]. To date, 139 polders have been constructed along the coastal stretch for the protection of agricultural lands and human settlements from tidal floods [27]. A polder is a low-lying area enclosed by earth embankments (dykes), hydrologically isolated except by water management structures that are controlled [28]. Polder 48 was formed approximately 35 years ago after repeated flooding in the area took place. Local residents actively participated in constructing the polder system on a voluntary basis. Bangladesh Water Development Board (BWDB) purchased the land only for areas where permanent structures such as sluice gates and regulators were established. The polder covers an area that had a population of 24,240 based on the 2011 census [29]. The polder is bounded by a dike 20 km long facing the sea on the southern edge, which keeps out the direct effects of storm surges. Climate and topography in Polder 48 support the cultivation of an assortment of crops, including paddy, pulses, vegetables, spices, and other cash crops. Fruit farming is also common in the area, with orchards of banana, guava, coconut, date, and palm trees. Timber trees are also grown on the slope of embankments, and the flora of the region includes a myriad of medicinal plants, shrubs, and herbs with herbal medicine prospects. The study area is illustrated in Fig. 1.

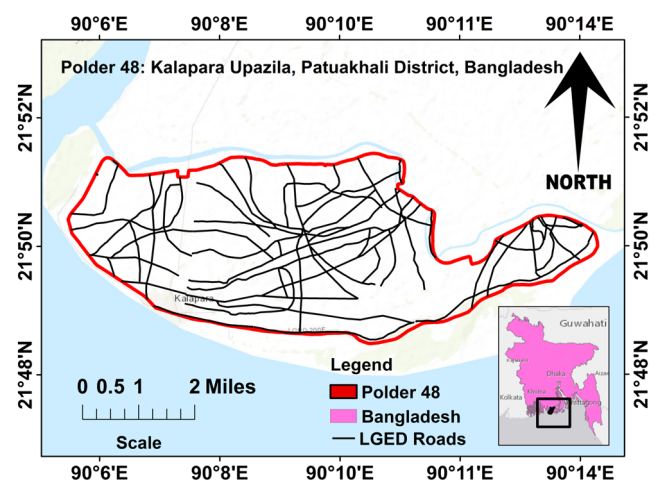


Fig. 1. Location of the study area, Polder 48 [3].

B. Historical Major Cyclones in Bangladesh

Storm surges, often described as coastal floods or tsunami-like events of rising water, are typically linked to low-pressure weather systems like tropical and strong extratropical cyclones [30]. Their severity is influenced by factors such as the depth and shape of the water body, the storm's trajectory, and tidal conditions [31]. Most fatalities during tropical cyclones are caused by storm surges [32]. In

Bangladesh, coastal areas experience cyclonic destruction nearly every 2–3 years, particularly in early summer (April–May) or late monsoon (October–November), as these storms often originate from low-pressure systems over the Bay of Bengal. Key meteorological factors behind storm surges include strong, inward-spiraling winds over a wide area and the low-pressure-induced water dome beneath the cyclone's center [33]. Tropical cyclones in the Bay of Bengal often last for a week or more and can generate the highest storm surges reaching up to 13.7 meters [34]. These surges lose height as they move inland into shallower coastal areas [35]. Combined water levels (from storm surge and tide) of around 10 meters occur roughly once every 20 years, while 7-meter surges happen more frequently—about once every five years. The coastal region of Bangladesh also faces wind-driven waves, which can reach up to 3 meters under severe conditions, influenced by factors like wind speed, direction, and water depth. Cyclones in this region typically follow a northwestward path before curving eastward [35], though their trajectories can vary. When high rainfall and sea level rise accompany a cyclone, storm surges become more dangerous, especially if they coincide with high tide, potentially raising water levels up to 12 meters. Such events can cause catastrophic damage to life and property. Table 1 provides a summary of major cyclones in Bangladesh, focusing on critical factors such as wind speed, surge height, and the resulting loss of life.

Table 1. Some major cyclones that hit the Bangladesh coast [36–38]

Date	Maximum Wind Speed (km/h)	Storm Surge Height (meters)	Death Toll
30 October 1960	210	4.6–6.1	5149
28 May 1963	203	4.2–5.2	11,520
11 May 1965	161	3.7–7.6	19,279
15 December 1965	217	2.4–3.6	873
01 October 1966	139	6.0–6.7	850
12 November 1970	224	6.0–10.0	300,000
25 May 1985	154	3.0–4.6	11,069
29 April 1991	225	6.0–7.6	138,882
19 May 1997	232	3.1–4.6	155
15 November 2007 (Sidr)	223	6.1–7.6	3363
27 October 2008 (Rashmi)	85	1.5–2.5	15
April 2009 (Bijli)	95	2.1–3	7
25 May 2009 (Aila)	92	4.0–4.6	190
16 May 2013 (Mahasen)	95	1	17
29 July 2015 (Komen)	100	1–2	45
21 May 2016 (Roanu)	85	0.9–1.2	21
30 May 2017 (Mora)	130	1.2–1.5	6
4 May 2019 (Fani)	215	1.5–3	17
Amphan: May 15–21, 2020	204	up to 4.5	128
Yaas: May 23–27, 2021	139	1.8–2.2	20
Sitrang: October 21–25, 2022	83	3	35
Mocha: May 11–14, 2023	256	3–3.5	41
Remal: May 25–27, 2024	100	3–4	54

In recent years, the cyclonic activity in the Bay of Bengal has become more frequent due to climate change [39]. Cyclone-induced storm surge is considered the key factor for cyclonic disasters in the coastal region of Bangladesh. Bangladesh is considered to experience 40% of the global storm surges [11]. Table 2 presents the approximate percentage of storm surge impact in various regions.

Storm surge impacts in Bangladesh are severe due to its low-lying terrain, the funnel-shaped Bay of Bengal, high tides, a shallow continental shelf, dense population, seasonal

worker migration during cyclone seasons (April–May and October–November), and climate change effects such as sea level rise and increasing temperatures, which influence cyclone intensity and frequency. Fig. 2 shows the tracks of major cyclones that crossed Bangladesh.

Table 2. Approximate percentage of storm surge impact in various regions [11]

Region	Percentage
Bangladesh	40
Asia (excluding Bangladesh)	20
North America	20
Europe	10
Africa and South America	5
Australia and New Zealand	5

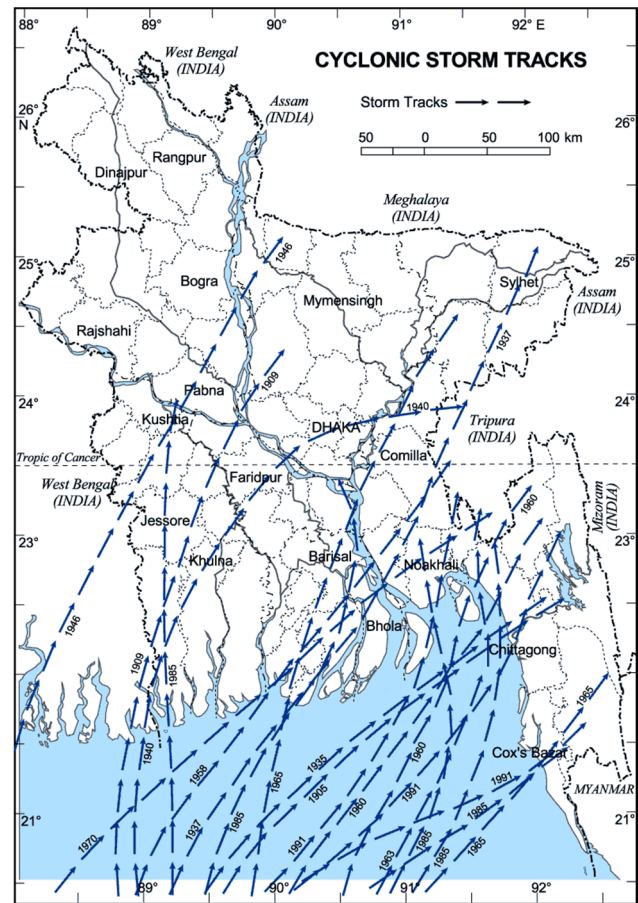


Fig. 2. Tracks of major cyclones that have crossed Bangladesh [40, 41].

C. Data Collection

Both primary and secondary data were essential for completing this study. Primary data collection involved direct engagement with local communities, focusing on participants aged 40 years and above to capture historical perspectives on cyclonic events and storm surge impacts in the study area. Polder 48's height and breaching width measurements were collected from the Bangladesh Water Development Board (BWDB). Informal discussions with local residents supplemented these formal interviews, offering valuable insights into current area conditions and community experiences during past storm surges. Secondary data collection complemented the primary research through the acquisition of Digital Elevation Model (DEM) data at 30 m×30 m resolution from the United States Geological Survey

(USGS), as shown in Fig. 3. Additionally, essential shapefiles were obtained for Local Government Engineering Department (LGED) roads, social institutions, cyclone shelters, and land use patterns sourced from Water Resources Planning Organization (WARPO). The land use land cover map illustrated in Fig. 4 provides a comprehensive spatial representation of the study area's diverse land cover patterns, illustrating the distribution of agricultural lands, water bodies, settlements, and other landscape features that are critical for understanding storm surge vulnerability and impact assessment across different land use categories within the coastal zone.

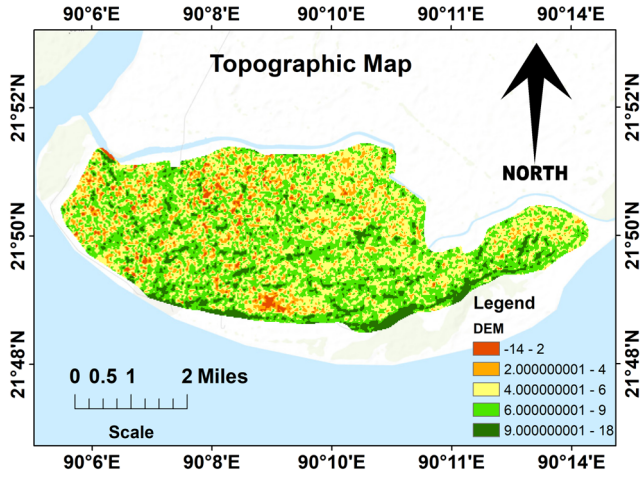


Fig. 3. Topographic map of Polder 48.

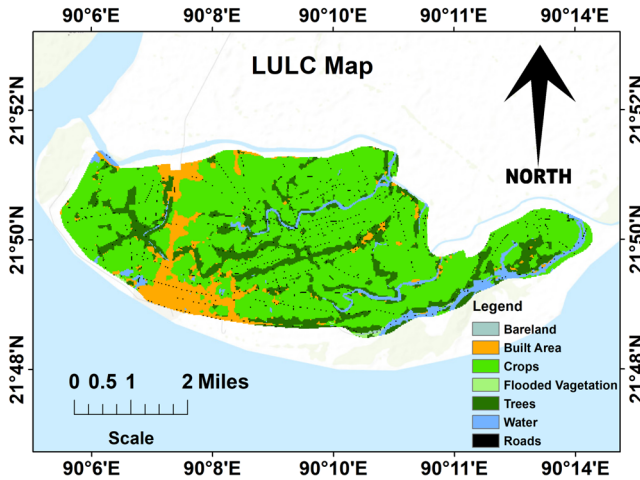


Fig. 4. Land use and land cover map of Polder 48.

D. Methodology

The theoretical framework for assessing storm surge risk begins with predicting flood depth and spatial extent under different probabilities of occurrence [42]. These predictions are quantified and represented using a Hazard Index, which reflects the severity of the potential hazard in specific areas. Additionally, an Importance Index is incorporated into the analysis. This index takes into account critical factors such as social infrastructure (e.g., schools, hospitals, community centers) and the road network, which are essential for emergency response and recovery. The final Risk Index for each area is determined by combining the Hazard Index and the Importance Index [43]. This integration provides a more comprehensive understanding of the overall risk to each

region. Based on the calculated Risk Index, the entire polder region is classified into four distinct risk categories: low-risk, moderate-risk, high-risk, and severe-risk areas, enabling targeted interventions and prioritization of resources. The risk of storm surges in a given area is influenced by key factors, including the depth of inundation, population density, and patterns of land use [21]. These elements play a critical role in determining the level of vulnerability and the potential impacts on both human lives and livelihoods. By systematically analyzing these parameters, a robust framework for risk evaluation and mitigation can be developed. Areas with higher inundation levels, greater population concentrations, and extensive land use modifications are generally at greater risk. To evaluate the potential danger posed by such natural disasters, a systematic approach is used to calculate a Risk Index. This index helps in assessing the severity of the threat and aids in planning appropriate mitigation measures. The Risk Index (RI) is calculated using the formula:

$$RI = HF \times VF \quad (1)$$

where, HF = Hazard Factor, and VF = Vulnerability Factor. The Hazard Factor (HF) and Vulnerability Factor (VF) are calculated as:

$$HF = \left(\frac{10 \times \text{Hazard Index of an Area}}{\text{Highest Hazard Index}} \right) \quad (2)$$

$$VF = \left(\frac{10 \times \text{Vulnerability Index of an Area}}{\text{Highest Vulnerability Index}} \right) \quad (3)$$

The entire process followed in this thesis is illustrated through a flow chart provided in Fig. 5.

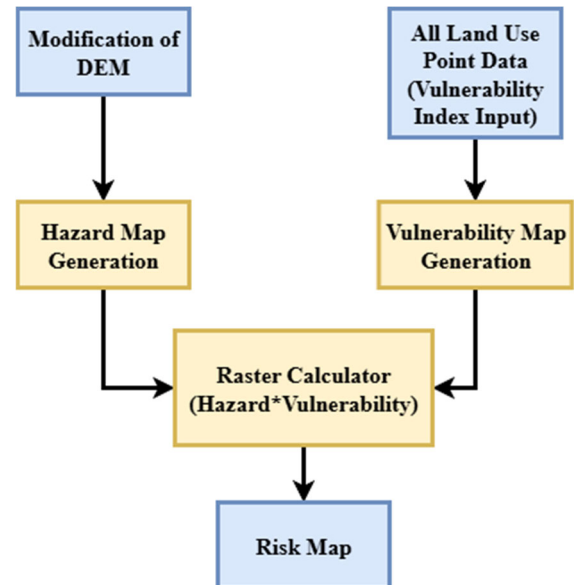


Fig. 5. The risk assessment procedure.

E. Storm Surge Flood Risk Mapping

In this study, storm surge-induced flood risk assessment is conducted through Geographic Information System (GIS) based mapping and scenario analysis using storm surge heights of 6 m, 8 m, and 10 m. Required data include

maximum water depth, structural features, land-use patterns, and population distribution within the study area. Water depth is calculated by determining discharge and volume based on two scenarios—overtopping and breaching. For overtopping, the formula proposed by Hughes and Nadal (2009) [44] is used:

$$q_o = \sqrt{gH_{m0}^3} \left(0.034 + 0.53 \left(\frac{-R_c}{H_{m0}} \right)^{1.58} \right) \quad (4)$$

where, g = gravitational acceleration (m^2/s), H_{m0} = energy-based significant wave height (m), R_c = freeboard (m), and q_o = overtopping discharge per unit length ($\text{m}^3/\text{s}/\text{m}$). For breaching, the discharge (m^3/s) formula used follows the US Army Corps of Engineers (USACE) methodology:

$$Q = C \cdot A \cdot \sqrt{2gH} \quad (5)$$

Here, Area, $A = W \times H_b$, and $H = H_s - E_p$. The coefficient C is the discharge coefficient, typically ranging between 0.6 and 0.8 for breached embankments. In this context, A represents the cross-sectional area (in m^2), W is the breach width (in meters), and H_b is the breach height (in meters). The head difference H is calculated by subtracting the ground elevation inside the polder (in meters), E_p , from the storm surge height (in meters, on the sea side), H_s . Subsequently, the volume of water (V in m^3) is calculated using:

$$V = Q \cdot T \quad (6)$$

In this case, Q is the discharge (in m^3/s) and T is the duration of the storm surge (in seconds). The areas corresponding to different elevations are obtained using ArcMap 10.8 Desktop Software. Subsequently, the corresponding volumes at each elevation are determined in Table 3. Finally, a Volume vs. Elevation graph is plotted, as illustrated in Fig. 6. Using the graph, water depth is calculated for the preparation of the hazard, vulnerability, and risk map.

Table 3. Volume and area corresponding to elevation

Elevation (m)	Cumulative Area (m^2)	Area (km^2)	Volume (m^3)
0	134,757	0.1347574	943,301.8
1	348,418.4	0.2136614	1,050,133
2	915,817.9	0.5673995	1,333,832
3	2,383,077.9	1.46726	2,067,462
4	6,397,429.9	4.014352	4,074,638
6	26,474,509.9	20.07708	24,151,718
8	43,229,639.9	16.75513	40,906,848
10	48,939,096.9	5.709457	46,616,305
18	50,738,816.9	1.79972	53,815,185
Sum		50.7388173	

1) Preparation of hazard map

The Hazard Index represents the key factor contributing to risk, which, in this case, is the depth of the storm surge. For the purpose of calculating the Hazard Factor (HF), the depth of inundation is considered the Hazard Index. This index is categorized on a scale ranging from 1 to 5, reflecting varying levels of risk. To derive the Inundation Map, the elevation values from the DEM are subtracted from the water depth

values. It is then reclassified at different elevations. Table 4 depicts the classification of Hazard Index based on depth of inundation.

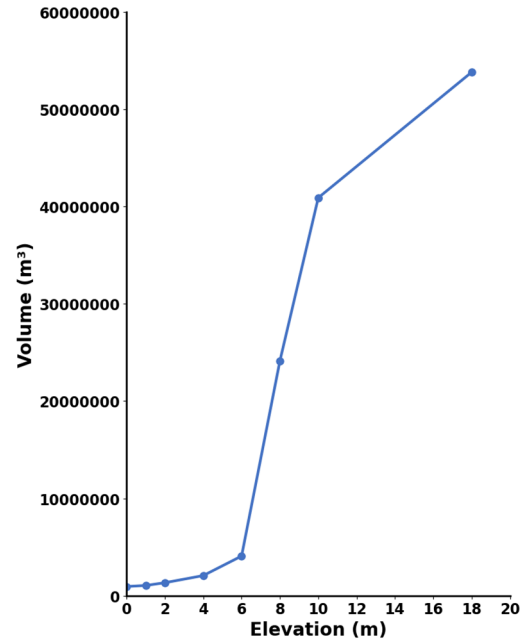


Fig. 6. Volume vs. elevation curve.

Table 4. Depth of inundation and corresponding Hazard Index [45]

Depth of Inundation (m)	Hazard Index
0–1	1
1–2	2
2–3	3
3–4	4
4 or above	5

2) Preparation of vulnerability map

The graph presented in Fig. 7 illustrates the Vulnerability Index across four different land use classes [46]. Firstly, five separate flood danger maps were created for five different classes based on flood depth (Table 4). Afterwards, every hazard map was classified into 8 groups in accordance with the graph's Vulnerability Index. Thus, five different vulnerability maps were generated for five different classes (water body, commercial area, residential area, cultivable land, and transportation). The vulnerability maps were then transformed into point-shaped files. Each point shape file was merged to form a single point shape file. A single raster was created, and finally, the raster file was reclassified, and a vulnerability map with four separate classifications (low, moderate, high, and very high vulnerability) was created.

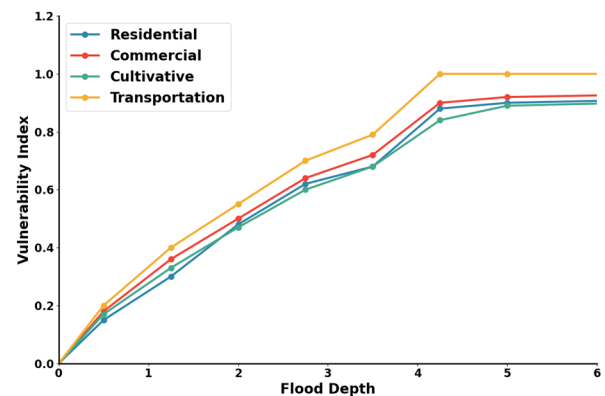


Fig. 7. Vulnerability index based on flood depth.

3) Risk classification and risk mapping

Finally, the raster values of the hazard map and vulnerability map are multiplied to obtain the risk map. On the basis of findings, the areas are classified into the following categories:

- *Low risk area with risk index value: $0 < RI \leq 19$*
- *Moderate risk area with risk index value: $20 < RI \leq 39$*
- *Higher risk area with risk index value: $40 < RI \leq 60$*
- *Severe risk index value: $RI > 60$.*

III. RESULTS AND DISCUSSIONS

Polder 48, located in the coastal region of Kuakata in Kalapara, Patuakhali District, Bangladesh, is a 50.75 square kilometer area bordered by rivers and protected by embankments, including a 20-kilometre sea-facing dike with varying crest elevations, with heights of 5.18 m, 5.8 m, 6.1 m, and 7.5 m, averaging around 6 m. The area, home to a vulnerable population primarily engaged in agriculture and fishing, faces significant risks from natural disasters such as cyclones and storm surges. The housing infrastructure, consisting of low-cost materials like thatched huts and bamboo-framed homes, offers minimal resistance against extreme weather events. To assess and mitigate these risks, three storm surge scenarios (6 m, 8 m, and 10 m water depths) are analyzed to determine the water depth at various points within the region. These assessments aim to strengthen the region's resilience by developing effective risk mitigation strategies and ensuring that early warning systems enable residents to evacuate or seek refuge in cyclone shelters.

A. Analysis of Water Depth

This study requires data on the maximum water depth caused by storm surges, the structural features vulnerable to such events within the study area. Three storm surge scenarios are considered, with heights of 6 m, 8 m, and 10 m, and durations of 10 minutes, as illustrated in Table 5, for which the corresponding water depths are determined.

Table 5. Different scenarios of flooding

Scenario	Surge Height (m)	Duration (minutes)	Way of Flooding
S1	8	10	Overtopping
S2	10	10	Overtopping & Breaching
S3	6	10	Breaching

1) Scenario 1: Overtopping only

Table 6. Scenario 1

Parameter	Value
Surge Height (H_s)	8 m
Polder Crest Height (H_c)	6 m
Freeboard (R_c)	2 m
Wave Height (H_{m0})	8 m
Wave-Affected Length (L_w)	3000 m
Duration (T)	10 minutes
Overtopping Rate (q_0)	6.03 m ³ /s/m

For Scenario 1, overtopping discharge per unit length (q_0) is calculated using Eq. (4) and the data from Table 6. Finally, overtopping volume, $V_{s1} = q_0 \times L_w \times T = 10,854,000$ m³.

2) Scenario 2: Overtopping & Breaching

a) Overtopping component

Table 7. Scenario 2 (Overtopping component)

Parameter	Value
Surge Height (H_s)	10 m
Polder Crest Height (H_c)	6 m
Freeboard (R_c)	2 m
Wave Height (H_{m0})	8 m
Wave-Affected Length (L_w)	4000 m
Duration (T)	10 minutes
Overtopping Rate (q_0)	14 m ³ /s/m

b) Breaching component

Table 8. Scenario 2 (Breaching component)

Parameter	Value
Storm Surge Height (H_s)	10 m
Discharge Coefficient (C)	0.7
Duration (T)	10 minutes
Breach Width (W)	50 m
Breach Height (H_b)	4 m
Ground Elevation (E_p)	2 m

For Scenario 2, the overtopping discharge per unit length (q_0) is calculated using Eq. (4) and the data from Table 7, which provides the necessary parameters for the overtopping component. The overtopping discharge q_0 is found to be 14 m³/s/m, and the corresponding overtopping volume, $V_1 = 33,600,000$ m³. Additionally, the breaching discharge is calculated using Eqs. (5) and (6), with the data from Table 8. The breaching volume, $V_2 = 1,051,800$ m³. So, Total Volume (V_{s2}) = $V_1 + V_2 = 33,600,000 + 1,051,800 = 34,651,800$ m³.

3) Scenario 3: Breaching only

Table 9. Scenario 3

Parameter	Value
Storm Surge Height (H_s)	6 m
Discharge Coefficient (C)	0.8
Duration (T)	10 minutes
Breach Width (W)	150 m
Breach Height (H_b)	4 m
Ground Elevation (E_p)	2 m

For Scenario 3, the breaching discharge is calculated using Eqs. (5) and (6), with the data from Table 9. The breaching volume, $V_{s3} = 2,551,500$ m³. Table 10 shows the water depth in the study area under different storm surge scenarios, using the volume (m³) vs. elevation (m) curve presented in Fig. 6.

Table 10. Water depth in the study area during different flooding scenarios

Scenario	Surge Height(m)	Duration (min.)	Way of Flooding	Volume (m ³)	Water Depth(m)
S1	8	10	Overtopping	10,854,000	4.7
S2	10	10	Overtopping & Breaching	34,651,800	7.1
S3	6	10	Breaching	2,551,500	3.5

NOTE: Around 300 mm of rainfall is considered for mapping.

B. Results of Hazard Assessment

The main objective of the hazard assessment was to

evaluate the geographical extent of the inundation pattern in Polder 48. The Hazard Index is based on storm surge inundation depth and is classified on a scale from 1 to 5 (Dry Land, Very Low, Low, Moderate, High), as presented in Table 4, to represent different hazard levels. An inundation map is generated by subtracting DEM elevation from water depth, followed by reclassification into hazard categories. Hazard maps for each scenario are shown in Figs. 8–10. Table 11 illustrates the flooded areas across different scenarios.

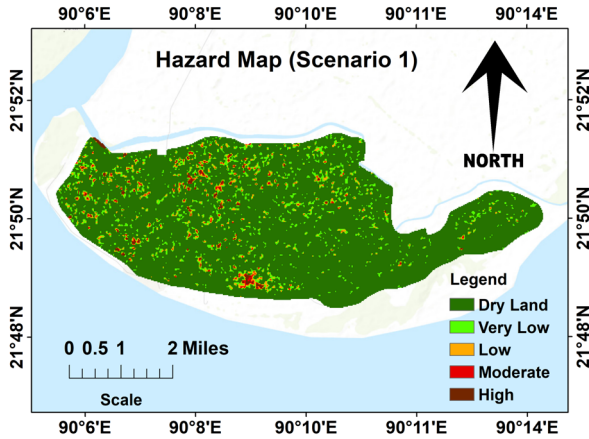


Fig. 8. Hazard map for Scenario 1.

The hazard maps under three different scenarios reveal significant spatial variability in flood hazards across the study area. In Scenario 1, the region is predominantly characterized by “Dry Land” and “Very Low” hazard levels, with only a few scattered pockets of “Moderate” and “High” hazard zones, indicating limited flood-prone areas under current or baseline conditions. However, Scenario 2 exhibits a stark contrast, with a widespread increase in hazard levels, as evidenced by the extensive distribution of “Low,” “Moderate,” and “High” hazard zones throughout the area. This suggests a substantial rise in vulnerability, possibly due to intensified hydrological events or land use changes. Scenario 3, on the other hand, displays a pattern similar to Scenario 1, with mostly “Dry Land” and “Very Low” hazard zones and minimal high-hazard areas, implying an effective mitigation or adaptation measure under this condition. Overall, the comparison highlights that Scenario 2 presents the most critical situation, necessitating urgent risk management interventions, whereas Scenarios 1 and 3 reflect more controlled hazard conditions.

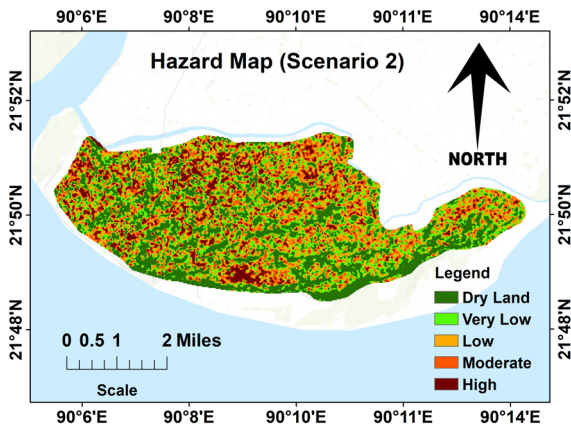


Fig. 9. Hazard map for Scenario 2.

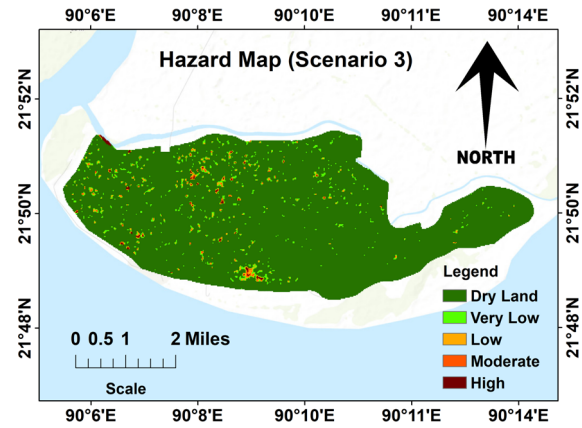


Fig. 10. Hazard map for Scenario 3.

Table 11. Inundated areas for different scenarios

Scenario	Surge Height(m)	Duration (minutes)	Way of Flooding	Flooded Areas (km ²)
S1	8	10	Overtopping	16.1
S2	10	10	Overtopping & Breaching	38
S3	6	10	Breaching	5.7

C. Results of Vulnerability Assessment

Vulnerability maps are prepared considering the vulnerability factors for different Land Use and Land Cover (LULC) in that area. These maps are reclassified into four vulnerability levels such as Low, Moderate, High, and Very High. Vulnerability maps for each scenario are also shown in Figs. 11–13.

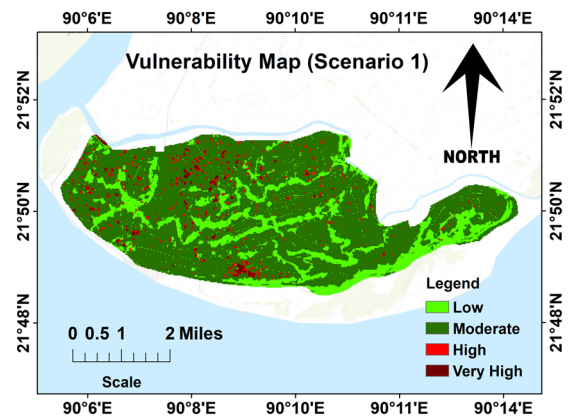


Fig. 11. Vulnerability map for Scenario 1.

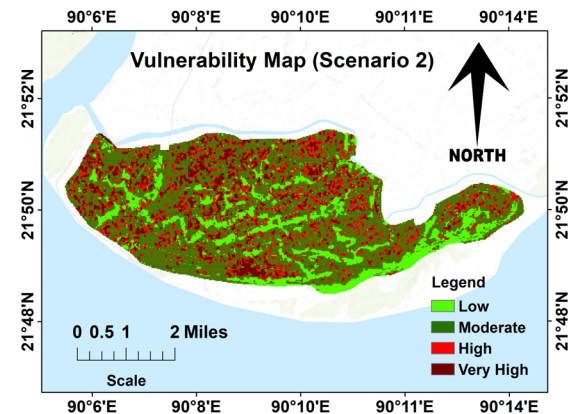


Fig. 12. Vulnerability map for Scenario 2.

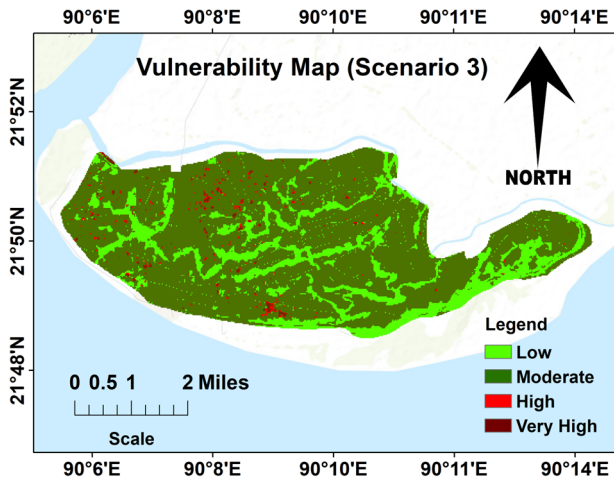


Fig. 13. Vulnerability Map for Scenario 3.

In Scenario 1, the region is predominantly characterized by low to moderate vulnerability, with very limited areas falling under high or very high categories, indicating a generally resilient condition under baseline or favorable assumptions. In contrast, Scenario 2 exhibits a significant increase in vulnerability, with a widespread distribution of high and very high-risk zones, particularly concentrated in the central and north-eastern parts of the region. This scenario likely reflects a worst-case or highly stressed condition, possibly integrating factors such as increased rainfall intensity or land-use change. Scenario 3 shows a pattern similar to Scenario 1, with most areas falling under low vulnerability, and only sparse pockets of high or very high vulnerability, suggesting that mitigation measures or improved conditions may have been applied in this scenario.

D. Results of Risk Assessment

The risk map is generated by combining the hazard map and vulnerability map, reflecting the overall potential for damage in a given area. The risk maps for each scenario are depicted in Figs. 14–16, illustrating the varying levels of risk—Low Risk, Moderate Risk, High Risk, and Severe Risk—based on the combined analysis of hazard and vulnerability maps for each storm surge scenario. This classification helps prioritize areas for intervention and resource allocation.

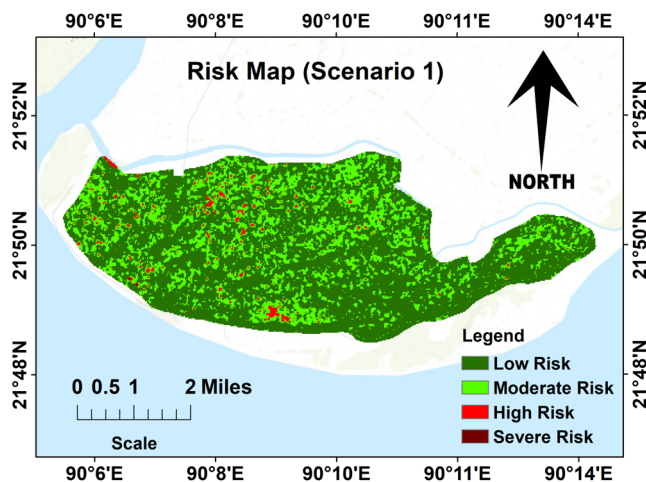


Fig. 14. Risk map for Scenario 1.

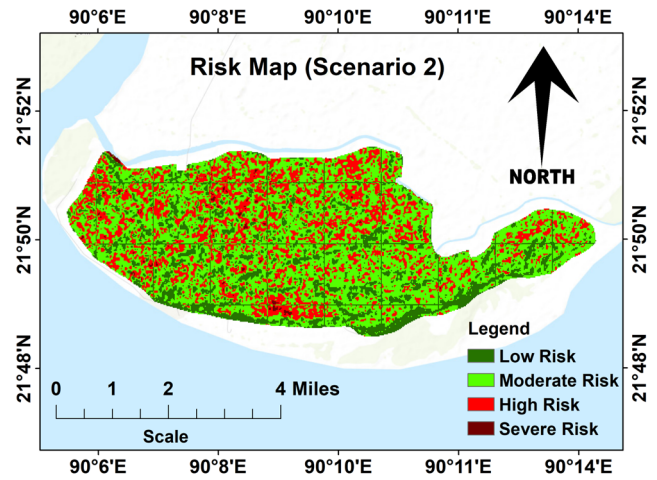


Fig. 15. Risk map for Scenario 2.

The assessment is made against moderate to extreme storm surge events, and it reveals that the Polder 48 is prone to moderate to high risk if such extreme events occur. However, for normal storm surges, which are comparatively more common, Polder 48 is identified as a low to moderate risk area compared to other coastal polders. Table 11 provides various areas flooded for every surge scenario: 5.7 km² for a 6 m surge, 16.1 km² for an 8 m surge, and 38 km² for a 10 m surge.

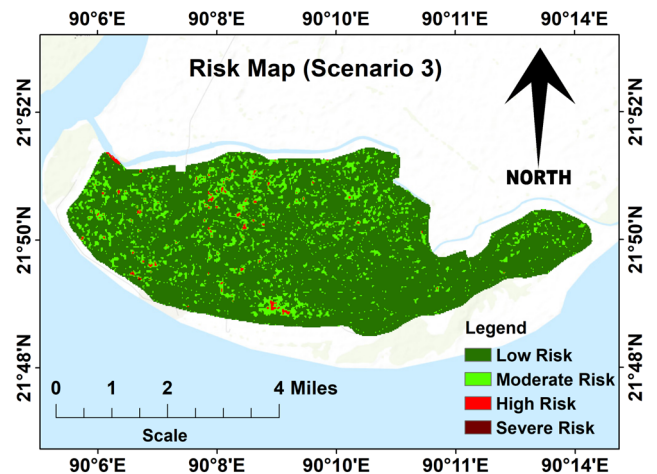


Fig. 16. Risk Map for Scenario 3.

These extremes can lead to the utmost suffering and fatalities if storm surge risk predictions are not successfully implemented. Effective storm surge prediction and control strategies, such as the establishment of cyclone centers and the strengthening of vulnerable sections of the polder embankment, can significantly reduce the impact of storm surges on the affected population.

IV. CONCLUSION

This study emphasizes the significance of risk analysis in managing storm surge disasters in highly exposed and vulnerable coastal areas like Bangladesh. The outcomes indicate that Polder 48 is extremely unlikely to be threatened by a 10 m storm surge, while the risk is predominantly low for 6 m and 8 m surges. Though the 10 m surge scenario is improbable, highland and medium-high land zones are more vulnerable to flooding, and certain areas of medium-low land are not affected due to their proximity to rivers. Nevertheless,

it was limited by secondary data shortcomings at the polder level and employed approximated values based on local views. For better subsequent studies, the utilization of advanced modeling packages like HEC-RAS or Delft 3D would be most appropriate for more realistic inundation maps, and the incorporation of technologies for precise water depth predictions must be considered. Economic valuation, population exposure, and community preparedness must also be considered to better comprehend the risks and make mitigation more effective.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Conceptualization: D.H., S.D., and M.M.A.; Methodology: D.H. and S.D.; Software: D.H. and S.D.; Validation: S.D.; Writing—Original Draft Preparation: D.H. and S.D.; Writing—Review and Editing: S.D. and D.H.; Supervision: M.M.A.; Data Collection and Feedback: M.M.A. All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGMENT

We express our sincere gratitude to Sayed Tariqur Rahman, Sub-Assistant Engineer of Bangladesh Water Development Board (BWDB), Kalapara, Patuakhali, for his valuable support in assisting with the data collection.

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