



Assessment of coastal vulnerability using integrated fuzzy analytical hierarchy process and geospatial technology for effective coastal management

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Abstract

The vulnerability of coastal regions to climate change is a growing global concern, particularly in Bangladesh, which is vulnerable to flooding and storm surges due to its low-lying coastal areas. In this study, we used the fuzzy analytical hierarchy process (FAHP) method to assess the physical and social vulnerability of the entire coastal areas of Bangladesh, using 10 critical factors to evaluate the coastal vulnerability model (CVM). Our analysis indicates that a significant portion of the coastal regions of Bangladesh is vulnerable to the impacts of climate change. We found that one-third of the study area, encompassing around 13,000 km², was classified as having high or very high coastal vulnerability. Districts in the central delta region, such as Barguna, Bhola, Noakhali, Patuakhali, and Pirojpur, were found to have high to very high physical vulnerability. Meanwhile, the southern parts of the study area were identified as highly socially vulnerable. Our findings also showed that the coastal areas of Patuakhali, Bhola, Barguna, Satkhira, and Bagerhat were particularly vulnerable to the impacts of climate change. The coastal vulnerability map we developed using the FAHP method showed satisfactory modeling, with an AUC of 0.875. By addressing the physical and social vulnerability factors identified in our study, policymakers can take proactive steps to ensure the safety and wellbeing of coastal residents in the face of climate change.

Keywords Coastal vulnerability · Social and physical vulnerability · FAHP · ROC · Remote sensing · Bangladesh coast

Introduction

Coastal regions are of great importance for global economic, geopolitical, and social reasons. However, the frequent occurrence of coastal hazards threatens their ability to serve these purposes. Recent years have seen several coastal cities suffer

greatly due to such hazards. For example, in 2017 alone, three hurricanes in the USA caused over \$50 billion in damage, while tsunamis have resulted in hundreds of thousands of deaths and billions of dollars in damage (e.g., the 2004 Indian Ocean tsunami, and the 2011 Tohoku tsunami). While the immediate

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impacts of such disasters are evident, the longer-term consequences and the possibility of full recovery remain unknown, with some studies suggesting that it may take over 20 years of economic growth to return to pre-disaster levels (Hsiang and Jina 2014). On the other hand, some research indicates that certain industries, such as construction, recover relatively quickly after natural disasters (Groen et al. 2015). Coastal disasters are becoming more frequent due to climate change, and improving resilience to these hazards has become a global concern for scientists (Ghosh and Mistri 2021). Approximately 10 million people are affected by coastal flooding worldwide each year, and this number is expected to rise to 50 million by 2080 as a result of climate change and growing pressure from coastal populations (Ghosh and Mistri 2021). Tropical cyclones are widely considered the deadliest of natural disasters due to the significant damage they can cause from strong winds, heavy rains, and storm surges (Lau et al. 2022). Coastal regions provide both significant and insignificant benefits, but increasing human and environmental pressures are negatively affecting many coastal regions. As such, it is crucial to pay attention to the dynamic features of ecological, topographical, and socio-cultural systems in coastal regions (Baig et al. 2021). Examining the vulnerability of the coast to natural disasters is thus important to plan and reduce the death toll and suffering (Hejazi et al. 2022).

Bangladesh is highly vulnerable to coastal disasters, with the Bay of Bengal being home to many tropical cyclones during the early and late rainy seasons (Hoque et al. 2021, b). Historical sources indicate that cyclones in Bangladesh have claimed 500,000 lives in 1970 and 140,000 in 1991 (Hoque et al. 2021, b). The Meghna Estuary in Bangladesh has been among the top 10 most devastating cyclones in the country from 1876 to 2014, with a storm surge of 8.8–13.7 m (Mullick et al. 2019). Coastal flooding is frequent along Bangladesh's 800 population per square kilometer coastline, where 30% of districts are on the coast and over 50 million people live in this area (Ghosh and Mistri 2021). Coastal flooding is often caused by cyclonic storm surges triggered by strong winds and riverine flooding from high tides, resulting in massive levee breaches and salt-water intrusion into agricultural land (Ghosh and Mistri 2021). Understanding the vulnerability of the coast to natural disasters is critical for reducing the risk to life and property in Bangladesh. Furthermore, the likelihood of coastal disasters varies significantly from one location to another due to differences in climate and topography, resulting in some areas being more vulnerable to coastal hazards than others (Baig et al. 2021). Therefore, it is crucial to assess the vulnerability of coastal areas before making informed decisions regarding their management and protection (Baig et al. 2021).

Vulnerability refers to the extent to which geophysical, biological, and socio-economic systems are susceptible to and unable to deal with climate change (Füssel & Klein 2006). In simpler terms, vulnerability refers to a group's susceptibility

and ability to bounce back from hazards (Mullick et al. 2019). The coastal vulnerability index (CVI) is a well-known tool used to assess the vulnerability of coastal areas to natural disasters (Mullick et al. 2019; Rahman et al. 2022a, b; Koroglu et al. 2019; Al Mamun et al. 2022). Gornitz developed the CVI in 1991 to emphasize the potential for damage near coastlines. The CVI considers environmental and socio-economic hazards that can impact coastal regions (Ghosh and Mistri 2021).

As discussed previously, Bangladesh is a high-risk country due to its location and susceptibility to tropical cyclones and storm surges. However, limited research has been conducted on the assessment of the coastal vulnerability in Bangladesh (Hoque et al. 2021, b). In Bangladesh assessing coastal vulnerability is challenging due to the difficulties in obtaining and accessing data from various sources (Ghosh and Mistri 2021). Nonetheless, coastal vulnerability assessments in Bangladesh has been done utilizing a range of methodologies, including remote sensing, geographic information systems (GIS), statistical analysis, and field surveys. These approaches integrate multiple data sources, such as satellite imagery, topographic data, climate models, and socio-economic indicators, to provide a comprehensive understanding of the vulnerability hotspots (Ahmed et al. 2021; Hoque et al. 2021, b; Mahmood et al. 2020; Islam et al. 2020; Didar-UI Islam et al. 2015). However, studies combining social and physical vulnerability of Bangladesh have not been done so far. This study addresses this research gap and is aimed to achieve threefold objectives. The first objective is to model the spatial variation of coastal physical and social vulnerability incorporating mitigation capacity in Bangladesh. The second objective is to create a coastal vulnerability model for the study area using the FAHP model. The third objective is to validate the coastal vulnerability model using ROC-AUC (receiver operating characteristic –area under the curve) analysis. The novelty of this study lies in its use of the FAHP model, which has not been employed in previous studies on coastal vulnerability in Bangladesh. The FAHP model allows for a comprehensive assessment of vulnerability that takes into account multiple factors and produces a map of the coastal vulnerability of Bangladesh. Ten relevant factors were used to determine the spatial variation of vulnerability, including elevation, slope, land use, population density, literacy rate, poverty rate, and others.

Methods and materials

Study area

The coastal region of Bangladesh lies within the tropical zone, spanning between 21–23° north latitude and 89–93° east longitude, and experiences humid weather conditions (Fig. 1). The coastline stretches about 700 km and can be divided into three

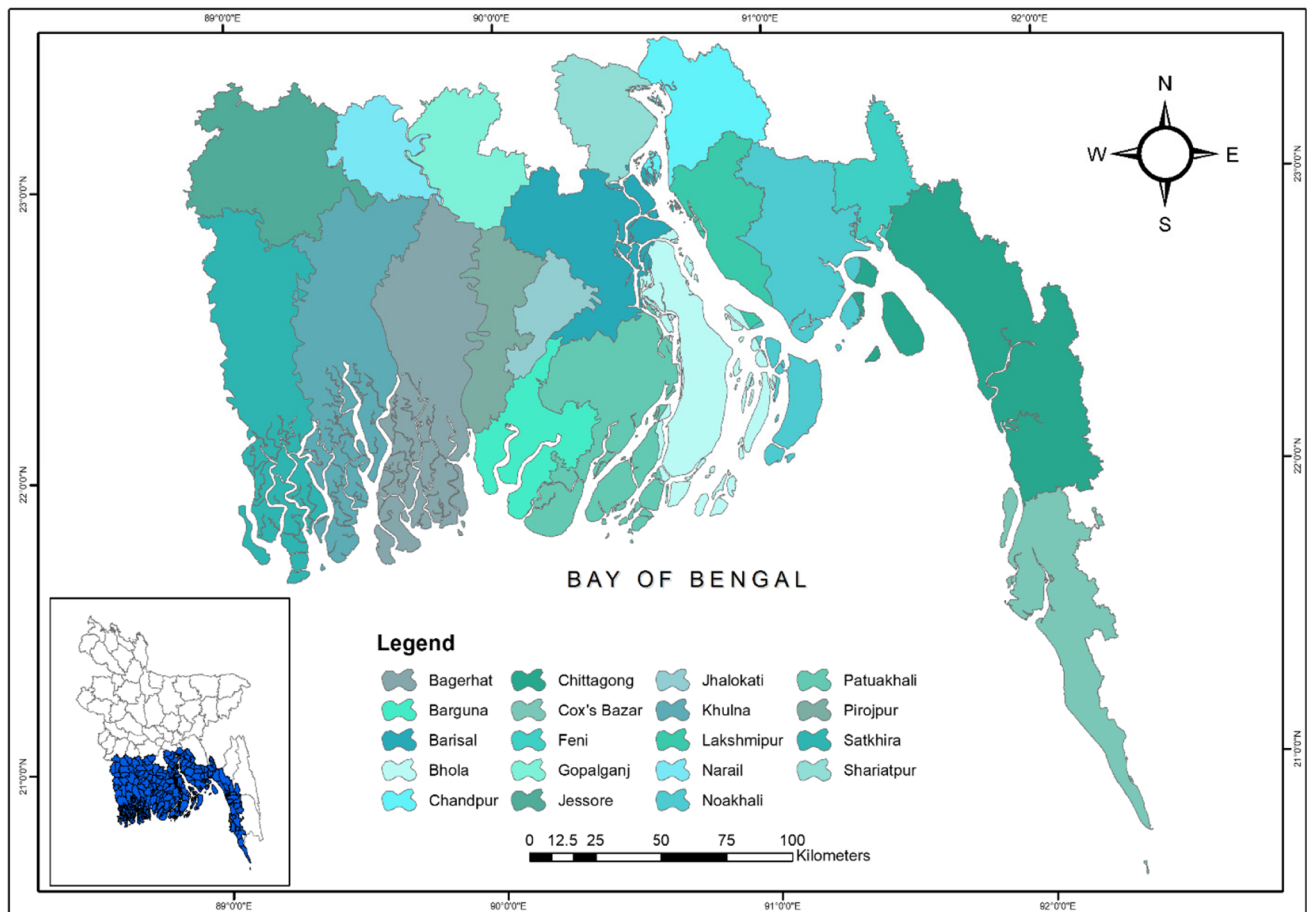


Fig. 1 location of the study area

regions, namely the eastern delta region (Pacific type), the central delta region, and the stable western delta region (Atlantic type). The tidal plain in the region is characterized by several tidal streams and creeks that form swamps and depressions. The Meghna estuary, located in central Bangladesh and draining the entire GBM basin, is subject to high river discharge, as well as complex oceanographic and hydrological conditions, including tidal and wind currents (Mullick et al. 2019). The western coastal zone is comprised of the low-lying deltaic plain, major rivers, and waterways. The Sundarban mangrove swamp forest, situated in the southwestern part of the region, serves as a natural barrier and buffer against coastal erosion. The average annual temperature in the coastal region is 24 °C, and it receives more than 2000 mm of rainfall. These climatic conditions are severely impacted by storms and cyclones (Mullick et al. 2019).

For this study, we selected 19 administrative districts in the coastal region, covering a total area of 38,061.54 km². The region has a total population of 3,843,218, with a density of 1,010 people per square kilometer (BBS 2011). Economic development in the coastal areas is hindered by the unfavorable natural environment, remoteness, inaccessibility,

and widespread poverty (Ghosh and Mistri 2021). Those residing in the coastal regions are at a higher risk of being affected by natural disasters than those living inland due to socio-economic disadvantages and physical location. Recent super cyclones, such as Sidr (Year 2007) and Aila (Year 2009), wreaked havoc on the west and central coasts, causing significant damage to property and the environment, claiming 3500 lives and injuring 191 others (Hoque et al. 2021, b).

Data sources

Various parameters were used to measure tropical cyclone vulnerability. Using geospatial approaches, we produced spatial data to analyze the criteria from diverse sources. Table 1 shows the study's datasets.

Criteria for vulnerability assessment

In this study, our criteria and sub-factors for measuring vulnerability to tropical cyclones were selected based on a thorough literature review. The importance and impact of these

Table 1 Details of the datasets used in the present study

Data type	Source	Time period	Purpose of use
Digital elevation model (DEM)	United States Geological Survey (USGS), Google Earth Engine	2014	Elevation, slope
Sentinel 2	Earth Explorer	2021	Land cover
Cyclone track	Bangladesh Institute of Development Studies	1960–2009	Proximity to cyclone track, Cyclone frequency
Population	Bangladesh Bureau of Statistics (BBS)	Population Census, 2011	Population density, ratio of female/children/older population, literacy rate
Coastline	Author	2011	Proximity to coastline

factors were taken into consideration to ensure a comprehensive evaluation. We created 10 spatial criterion levels in the geospatial environment to measure vulnerability, which were divided into two categories: physical and social indicators. The selection of parameters for vulnerability assessment to tropical cyclones was based on a careful rationale and selection criteria process. Each parameter was chosen to capture specific aspects that are known to influence vulnerability and contribute to the understanding of the potential impacts of cyclones on coastal communities. For following reasons, we selected the mentioned parameters:

Altitude was considered as a parameter because it plays a crucial role in determining the vulnerability of an area to cyclones. Low-lying areas are more susceptible to storm surges and flooding, which can lead to severe damage and loss of life. High-altitude areas, on the other hand, are generally safer from these risks. Slope is an important factor in vulnerability assessment as it affects the susceptibility of an area to landslides and erosion during cyclonic events. Areas with steep slopes are more prone to these hazards, while areas with gentle slopes are relatively less vulnerable. The proximity of an area to cyclone tracks is a critical factor in vulnerability assessment. Areas located closer to the typical paths of cyclones are at higher risk of experiencing the direct impacts, such as strong winds, heavy rainfall, and storm surges. Coastal proximity is a significant determinant of vulnerability to tropical cyclones. Areas near coastlines are more exposed to storm surges, coastal erosion, and other hazards associated with cyclonic events. These areas often have a higher population density and infrastructure, making them more vulnerable to cyclone-induced damage.

The choice of land cover as a parameter is based on the recognition that certain types of land cover are more vulnerable to cyclonic events. For example, coastal areas with extensive mangrove forests tend to provide natural protection against storm surges, while urbanized areas with dense infrastructure and limited green spaces may experience more severe impacts. Population density is a key social parameter in vulnerability assessment. Higher population density implies a greater number of people and assets exposed to cyclonic hazards, making evacuation,

emergency response, and recovery efforts more challenging. Densely populated areas often face resource constraints and have limited access to essential services during and after cyclonic events. The inclusion of the proportion of children and older people is based on the vulnerability of these demographic groups to the effects of cyclones. Children and older individuals may have limited mobility, reduced resilience, and higher susceptibility to health risks during cyclonic events. Addressing their specific needs and vulnerabilities is crucial in disaster risk reduction and management. Education and literacy rates are indicative of the knowledge and awareness levels within a community. Higher education levels enable better understanding of cyclonic risks, preparedness measures, and access to information on recovery and rebuilding efforts. Communities with higher education and literacy rates are generally more resilient and better prepared to mitigate cyclone impacts. The inclusion of the proportion of female population recognizes the specific vulnerabilities faced by women during cyclonic events. Factors such as limited mobility, financial constraints, and social dynamics can influence the ability of women to cope with and recover from cyclones. Addressing gender-specific vulnerabilities is essential for ensuring effective disaster risk reduction and promoting gender equity in disaster management.

The selection of these parameters was based on scientific evidence, previous studies on vulnerability assessment to tropical cyclones, and the understanding of the specific characteristics and dynamics of cyclonic events. By considering these parameters collectively, a more comprehensive assessment of vulnerability to tropical cyclones can be achieved, leading to the development of targeted interventions and strategies for reducing the impacts on coastal communities.

To prepare the criterion layers, we used ArcGIS and ENVI to process and prepare the data. The classification of the resulting maps was carried out using the natural breaks method, which was chosen because it better illustrates the geographical distribution of risk (Mullick et al. 2019). The next sections describe the data preparation procedures:

Preparation of physical indicators

The preparation of physical indicators was a significant focus of this study. We considered several physical factors that contribute to vulnerability to natural disasters, such as altitude, slope, proximity to cyclone tracks and coastlines, and land cover. Elevation and slope were identified as critical factors in assessing vulnerability to tropical cyclones, with low-lying, sloping areas being more vulnerable and high altitude and steep areas being safer.

To produce the elevation and slope maps, we used a DEM with a spatial resolution of 30 m. The topographic sheet (scale 1: 25,000) used to create the DEM was provided by the United States Geological Survey (USGS), which has an accuracy of 1/30 cm. The Bangladesh Institute of Development Studies provided the information used to create the storm surge buffers and cyclone trajectories. We identified 21 different cyclone tracks between 1960 and 2009, ranging in intensity from 1 to 4. In contrast, distances from the coast of the study region were calculated using Google Earth imagery.

Additionally, we identified different forms of land cover that are particularly vulnerable to the destructive forces of natural disasters. To create the spatial layers of land cover, we relied on Sentinel-2 imagery. We verified the accuracy of the land cover map by randomly creating locations in Google Earth imagery and using the Kappa coefficient to assess accuracy based on previous research.

The maximum likelihood classification (MLC) method was used to map land use and land cover using Sentinel-2 imagery in this study. The MLC algorithm assigns each pixel in the image to the class with the highest likelihood of occurrence based on its spectral signature. The resulting map was validated using the Kappa coefficient, which compares the agreement between the classified map and a reference map to assess the accuracy of the classification. A value of 0 indicates no agreement beyond chance, while a value of 1 indicates perfect agreement. The study found a Kappa coefficient of 0.85, indicating strong agreement between the classified map and the reference map. The use of MLC and Sentinel-2 imagery proved effective for accurate land use and land cover mapping, with the resulting map providing valuable information for land management and monitoring purposes.

Preparation of indicators for social vulnerability including mitigation capacity

Social vulnerability is an important aspect to consider in disaster risk reduction, as it can significantly influence the impact of natural hazards on communities. To measure social vulnerability including mitigation capacity in this study, data from the 2011 Population and Housing Census were used. Several scientific arguments support the inclusion of these indicators in the study.

Firstly, population density is a key factor in determining vulnerability to natural hazards. Higher population density in an area increases the likelihood of disaster occurrence and also makes it more challenging for affected populations to recover from disasters. Studies have shown that densely populated areas are more vulnerable to natural hazards, including tropical storms, due to factors such as limited resources, poor infrastructure, and reduced access to emergency services.

Secondly, the proportion of children and older people in a community can influence vulnerability to natural hazards. These groups are more vulnerable to the effects of disasters due to their reduced ability to implement emergency measures, including evacuation. In the case of tropical storms, children and older people may be more susceptible to injury, illness, and death due to exposure to floodwaters, high winds, and storm surges.

Thirdly, education and literacy rates play an important role in determining social vulnerability. Research has shown that communities with higher levels of education tend to be better prepared for disasters, as they are more likely to have knowledge of potential hazards, participate in evacuation and other preparedness measures, and have access to information on recovery and rebuilding efforts.

Finally, recent studies suggest that women in Bangladesh face greater challenges during disasters due to factors such as mobility, financial situation, and lack of knowledge. By including the proportion of female population as an indicator in the study, it is possible to better understand the specific vulnerabilities faced by women during disasters and develop targeted interventions to address these issues.

Therefore, the inclusion of social vulnerability indicators in this study provides a more comprehensive understanding of the factors that influence the exposure and vulnerability of coastal communities to tropical storms. By considering both physical and social indicators of vulnerability, it is possible to develop more effective disaster risk reduction strategies that address the specific needs of different groups within the population.

Vulnerability assessment

In this study, a vulnerability assessment was conducted to determine how vulnerable a community is to tropical cyclone damage, integrating both physical and social variables into a FAHP-based multi-criteria assessment approach. Several vulnerability equations have been published in scientific works to assess vulnerability to natural hazards, including tropical cyclones (Ahmed et al. 2021). The vulnerability equation used in this study is based on previous research, as shown in Eq. (1) (Dewan 2013; Rashid 2013, Hoque et al. 2021, b):

$$\text{Vulnerability} = \text{physical vulnerability} \times \text{social vulnerability} \tag{1}$$

To achieve the vulnerability model, several following steps have been done.

Ranking of indicator

First, each criterion was ranked using natural breaks (e.g., elevation, slope) and manual categorization to classify each indicator, such as proximity to cyclone track, and coastline. Subsequently, the sub-factors were ranked for each criterion to indicate the degree of vulnerability (ranks 1–5), with the lowest rank representing the lowest degree of vulnerability. To ensure homogeneity between the physical and social criteria, the latter were transformed into a grid format with a comparable cell value using block units.

Each of the spatial criteria was transformed into a grid level, and the raster criterion levels were used to standardize the rank values of the spatial criterion levels. The normalization was completed using Eq. (2):

$$\rho = (x - \text{min})/\text{max} \tag{2}$$

Here, ρ refers to the standardized score, min and max represent the lowest and maximum values of each dataset, respectively, and x indicates the cell value in each spatial raster layer.

FAHP and criteria weighting

Fuzzy set theory, introduced by Zadeh in 1965, is a modeling strategy used to recreate complicated systems that are difficult to understand in terms of precise numbers. Fuzzy logic, which enables the processing of unclear, imprecise, and vague information, is commonly used in decision making to implement spatial objects on a map as a fuzzy membership function (Mullick et al. 2019). Unlike classical set theory, which states that the unique number of an object either belongs to a particular set or not, in fuzzy set theory, objects can have a membership value that varies between 0 and 1, indicating the degree of membership. In this study, the FAHP method was used to weight the criteria. While other researchers have used a variety of FAHP strategies, we used the integrated FAHP methods proposed by Chang (1996) and employed a triangular fuzzy number (TFN) to simplify the pairwise comparison and avoid the tedious procedure of comparing. The FAHP technique used in this study to calculate the criterion weights consists of five phases, and the FAHP model is described in detail in the supplements.

Implementation process

Phase 1 consisted of choosing the pertinent standards for categorizing tropical cyclone vulnerability assessments.

In phase 2, using a geometric mean method to combine the opinions of the five experts, pair-wise comparison matrices were built depending on the relative relevance of the chosen criteria following Eq. 3 (Hoque et al. 2021, b). The major source used to rank the criteria about the spatial issue is the opinions of experts and decision-makers. A few linguistic variables qualitatively express these assessments. The judgments must be quantified at this point using a fuzzy set and the appropriate membership function. Fuzzy set theory and fuzzy membership functions (FMF) play a significant role in the representation of ambiguous data. It also enables the application of mathematical operations and programming in the fuzzy domain. A fuzzy set is a class of objects defined by a function that gives each item a membership grade ranging from 0 to 1 and vice versa. In this research, the verbal factors were translated into quantitative values using a triangular fuzzy set. Table 3 illustrates the connection between quantitative values and language variables.

$$F = (a, b, c), N = 1, 2 \dots \dots \dots, N \tag{3}$$

(F = triangular fuzzy member & N = number of DMs)

where $a = (a_1 \times a_2 \times a_3 \dots \times a_N)^{1/N}$, $b = (b_1 \times b_2 \times b_3 \dots \times b_N)^{1/N}$, $c = (c_1 \times c_2 \times c_3 \dots \times c_N)^{1/N}$

Phase 3 involved averaging and synthesizing pair-wise comparison matrices to create a set of overall priorities for the hierarchy.

In phase 4, calculating the maximal eigenvector or relative weights and λ_{max} ensures that the order of the items is consistent; then, using Eq. 4, calculate the consistency index (CI) for each matrix order n . The consistency ratio (CR) was computed to support the expert ratings in the pair-wise matrices (Wu et al. 2009). If the consistency ratio is 0.1 or below, the judgment is deemed to be accurate. The following equation was used to calculate the CR (Saaty 1980).

$$\text{CI} = (\lambda_{\text{max}} - n)/(n - 1) \tag{4}$$

$$\text{CR} = (\text{CI}/\text{RI}) \tag{5}$$

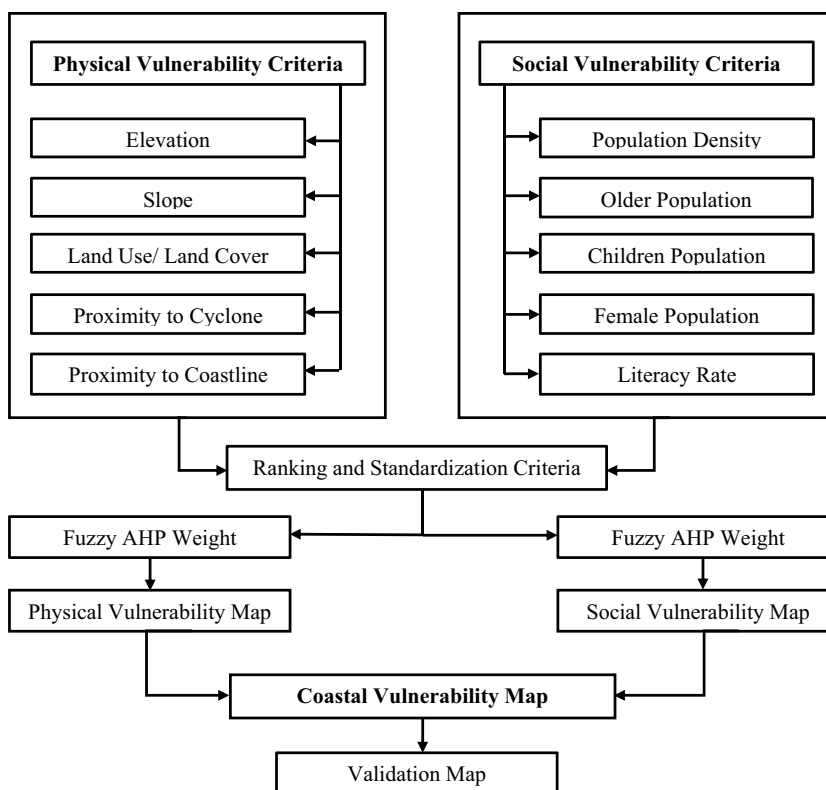
where n indicates the number of items in the matrix being compared, the largest eigenvalue is represented by λ_{max} , and RI is a random index derived from a large number of simulation runs, and it depends on the following matrix’s order.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Model validation

Using ROC and AUC, we assessed the cyclone vulnerability map in this study. Deterministic and probabilistic reasoning

Fig. 2 Flowchart for the methodology adopted



can both be evaluated using the ROC AUC method (Youssef et al. 2016). Many different natural disaster forecasts, such as floods, landslides, and droughts, have used this method to test their sensitivity, vulnerability, and risk models (Talukdar et al. 2021; Mullick et al. 2019). We therefore used the ROC AUC method. First, we created an inventory map of 140 validation locations based on existing studies (Hoque et al. 2017; Bhowmik and Cabral 2013), published reports and fieldwork. This prediction curve was calculated using the inventory map prepared. A prediction curve was created using a validation dataset consisting of all cyclone affected areas.

The outline of the methodology employed for assessing the coastal vulnerability of Bangladesh has been given in Fig. 2.

Results

Spatial variation of the physical indicators and their relevance

This study focuses on several physical factors that impact the vulnerability of the coastal region, including elevation, slope, proximity to cyclone tracks, proximity to coastline, and land cover.

Elevation and slope

The elevation and slope of the ground surface are crucial topographic features for assessing coastal vulnerability. The

elevation map, created with a spatial resolution of 30 m from a digital elevation model (DEM), indicates the height or slope of the ground surface. The higher the elevation and slope, the less vulnerable the area. Conversely, areas with low elevation and shallow slope are more vulnerable, which corresponds to the coastal area. The elevation and slope maps were classified into four classes: less than 3.5, 3.5–6.5, 6.5–9.5, and more than 9.5 m (Fig. 3). Higher altitude places were given higher weights, while the lower altitude places were given lower weights. The slope of the entire region was classified into shallow, gentle, moderate, and steep categories, with shallow and gentle slopes being weighted higher, while moderate and steep slopes were weighted lower.

Proximity to the coastline and proximity to the cyclone track

In addition to elevation and slope, factors such as distance from cyclone tracks and coastline were considered in determining a location’s vulnerability to coastal disasters. Tropical cyclones pose the greatest risk to the coastal region, and areas that have experienced recent cyclones and are located along the coastline are at the highest risk for damage to people and property. The datasets of cyclone tracks were used for buffer analysis in ArcGIS, and the distances from the coastline of the study area were calculated using the software. Places close to the coast and cyclone tracks are more vulnerable than those far from them. The distances from the

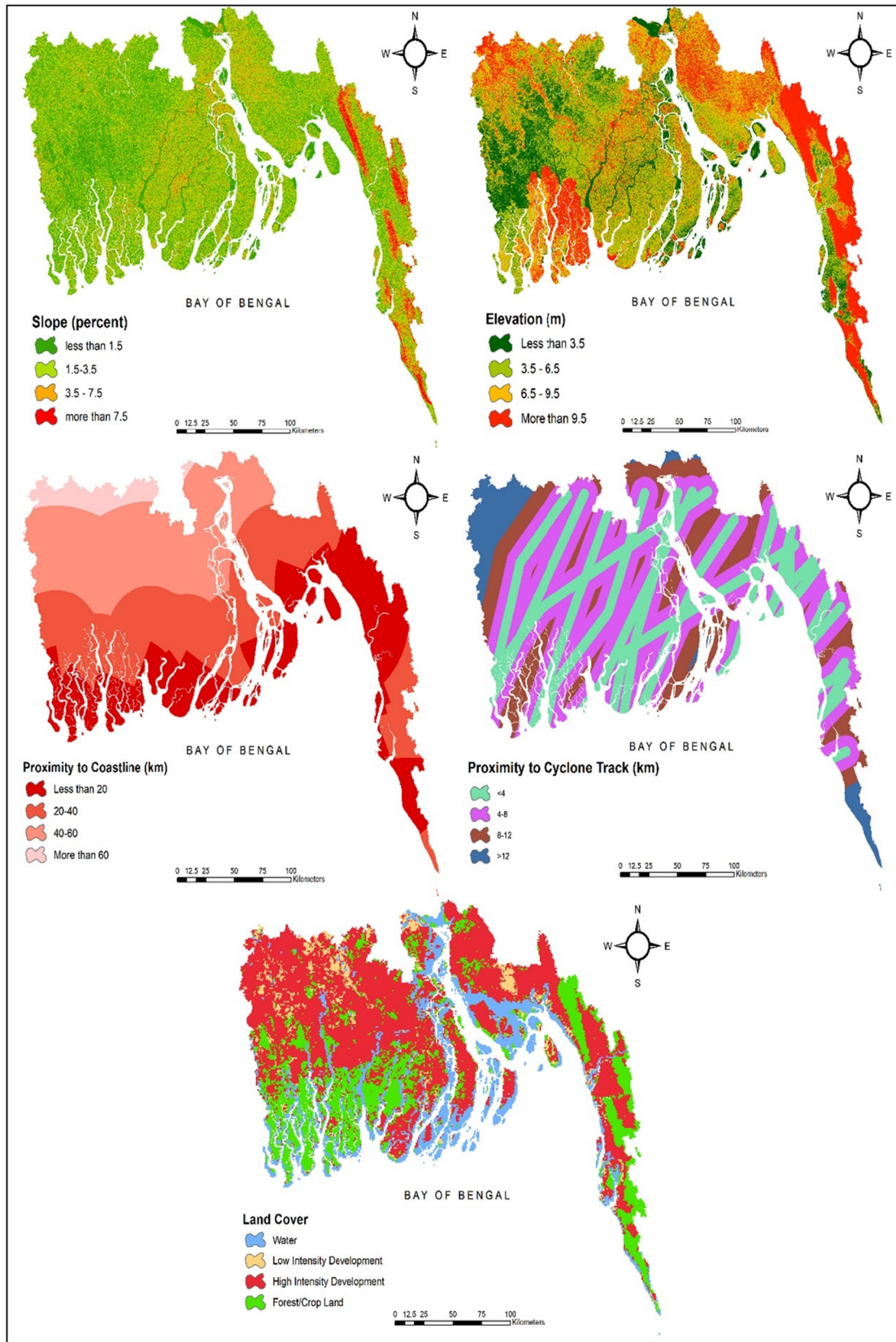


Fig. 3 Description of the physical indicators

cyclone tracks were divided into four classes: less than 4 km, 4–8 km, 8–12 km, and more than 12 km, while the distances from the coastline were divided into four classes: less than 20 km, 20–40 km, 40–60 km, and more than 60 km. Classes more than 40 km from the coast were given high weight.

Land use/land cover

The impact of land use and land cover (LULC) on coastal vulnerability can be significant. By analyzing LULC patterns in a given location, we can gain insights into the level of vulnerability of coastal areas. In this study region, with the exception of Chittagong and Sundarban in the eastern and western parts of the region, over 65 percent of the territory is heavily developed, as shown in Fig. 3. The vegetation belt surrounding the largest mangrove forest in the world has traditionally provided a protective barrier for the inhabitants of this region. However, the continuous destruction of this forest ecosystem is making the people in this region increasingly vulnerable to coastal hazards and disasters. The less developed areas where the socio-economic conditions of the people are poor are particularly susceptible to natural disasters.

To assess LULC, the land cover was classified into four categories: water bodies, forest land, arable land, and areas with high and low intensity of cultivation. For this study, more weight was given to forest land and areas with high building intensity, as they can be considered as strengths against coastal disasters. It is therefore important to manage and monitor land use and land cover patterns in coastal areas to mitigate vulnerability and reduce the risk of coastal disasters.

Spatial variation of the social indicators including mitigation capacity and their relevance

This study aimed to investigate social factors that could potentially impact coastal vulnerability. The factors examined included population density, literacy rate, proportion of female population, proportion of children in the population, and proportion of elderly population. The most recent data from the Population and Housing Census (2011) was used to create spatial levels associated with social factors. It is worth noting that Bangladesh conducts a population and housing census every 10 years, and the next census will be in 2021 (Hoque et al. 2021, b).

Regarding population density, the number of people living on the coast is growing faster in this region than anywhere else in the world, and densely inhabited places are more vulnerable to the impacts of tropical cyclones than places with lower population density (Hoque et al. 2021, b). Thus, population density was determined using information from the census conducted by the Bangladesh Bureau of Statistics in 2011, and the data was divided into four classes:

less than 485, 486–675, 676–1055, and more than 1055 people per square kilometer. The weighting was based on the criterion that densely populated areas are more prone to disasters than less densely populated areas.

Additionally, literacy rate was found to be an important factor in determining a community's vulnerability to cyclones. People with higher levels of education have a better understanding of the threat of hurricanes and are more likely to evacuate their homes and take other precautions to reduce the impact of potential damage. The spatial layer was created using information from the 2011 census conducted by the Bangladesh Bureau of Statistics, and the area was classified into four categories based on the proportion of educated people living there: less than 40%, 40–51%, 52–65%, and more than 65% (Fig. 4).

The factors discussed in the study, including population density, literacy rate, proportion of female population, proportion of children in the population, and proportion of elderly population, all have the potential to influence coastal vulnerability. For example, areas with high population density are more likely to be affected by tropical disasters than less densely populated areas. Similarly, areas with low literacy rates may be less likely to understand the risks associated with hurricanes and other natural hazards, and may not take appropriate precautions to protect themselves and their property. By analyzing these social factors, the study provides important information that can be used to develop effective policies and strategies to reduce the vulnerability of coastal communities to natural disasters.

The factors of age and gender can greatly impact vulnerability to coastal hazards. Older and younger individuals may have difficulty with evacuation measures, and may not have access to early warning systems or other forms of assistance during disasters. Similarly, women in Bangladesh are often more affected by natural disasters due to obstacles and problems related to freedom of movement, awareness, resource availability, and safety. The study used data from the 2011 census of the Bangladesh Bureau of Statistics to create spatial layers based on the proportion of female population, population with children, and elderly population, with a higher weight given to areas with a higher proportion of these vulnerable groups. Understanding the social factors that contribute to vulnerability can help communities and policymakers develop effective strategies to mitigate the impacts of coastal hazards.

Coastal vulnerability modeling

Weight estimation using FAHP model

The overlay analysis was used to produce the vulnerability map by combining physical and social indices according to relevant spatial levels and their respective weights. To determine the weights, the FAHP model was used to create a

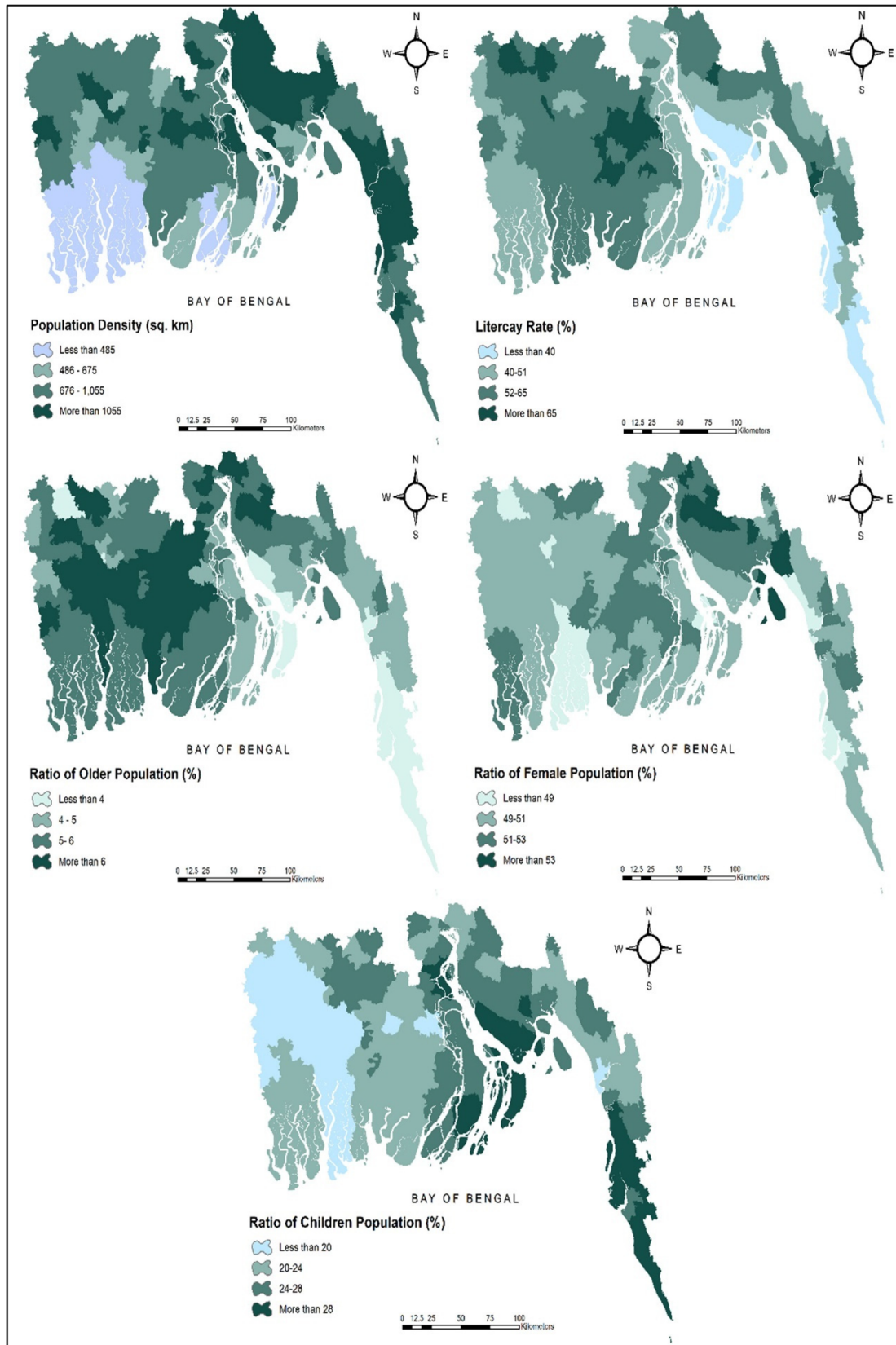


Fig. 4 Description of the social indicators

pairwise comparison matrix between the 10 factors. Among the physical indicators, distance to cyclone track was considered the most influential factor for vulnerability and was assigned the highest weight. Land use, land cover, slope, and elevation were weighted in descending order of importance. In contrast, distance from the coast had the lowest influence on coastal vulnerability, so it was assigned the lowest weight among the physical indicators.

Population density had the greatest influence on social and coastal vulnerability and was assigned the highest weight among the social indicators. The other social indicators had relatively less influence, so they were given lower weights. Distance to coastline, population density, and land cover had relatively higher weights of 0.25, 0.23, and 0.16, respectively. Together, these three factors had an influence of about 64%. In comparison, literacy rate and the proportion of the female population had lower eigenvalues among all 10 factors Table 2.

Physical vulnerability modeling

The physical vulnerability map was created by integrating all physical indicators into the ArcGIS software raster calculator based on the assigned weights, allowing for a comprehensive analysis of the region's vulnerability to natural disasters. This map displays a value that can range from 0 to 1, indicating low to high vulnerability. The physical vulnerability map was subsequently classified into the following five vulnerability classes using the natural break method: very low, low, moderate, high, and very high.

The resulting data revealed that more than two-thirds of the study region, i.e., 60.32%, was classified as high to extremely high vulnerability. In comparison, very high and high hazard classifications accounted for 21.73% and 38.59% of the total, respectively (Table 3).

Further analysis showed that Satkhira, Khulna, Bagerhat, Barguna, Bhola, Noakhali, Patuakhali, and Pirojpur districts were classified as having high or very high vulnerability to the impact of coastal natural disasters (Fig. 5). This highlights the urgent need for measures to be taken to reduce the region's vulnerability to natural disasters, particularly in these districts.

The low altitude, shallow slope, proximity to the coast, presence of cyclone tracks, and vulnerable land cover classes are some of the key factors contributing to the high physical vulnerability of the region. Proximity to the coast is especially important, as this not only increases exposure to hazards but also limits options for evacuation and other protective measures.

To mitigate the impact of coastal hazards, it is essential to prioritize measures that address the identified vulnerabilities. These could include improving infrastructure, promoting early warning systems, increasing access to information, and developing effective evacuation plans. By taking these steps, we can work toward reducing the

vulnerability of the region and protecting the lives and livelihoods of its inhabitants.

Social vulnerability modeling

The social vulnerability map was produced by integrating five social indicators into the ArcGIS software raster calculator using assigned weights. The resulting social vulnerability map has a range of values from 0 to 1, with higher values indicating higher vulnerability. The map was then classified into five vulnerability classes using the natural disruption algorithm: very low, low, moderate, high, and very high. The southern, central, and southern parts of the study area were found to have high levels of social vulnerability, with a high population density and a large number of dependent individuals, including women, children, and the elderly. Conversely, the low social vulnerability category covered only 4314.01 km² and 10.8% of the study area (Fig. 6).

As per Table 4, the medium social vulnerability class accounts for the highest percentage (29.2%) of the study area, which amounts to 11,695.86 km². However, the high and very high classes covered nearly 17,980 km² and 44.8% of the area. Several factors contribute to the high social vulnerability of the region, including a high population density, low literacy rate, and a higher number of dependent individuals.

The districts of Satkhira, Khulna, Bagerhat, Barguna, and Patuakhali have been classified as having high and very high social vulnerability. On the other hand, people living in some parts of the study area, such as Chandpur, Chittagong, Cox's Bazar, Lakshmipur, and Noakhali, are less socially vulnerable. These regions are mainly in the southern and northeastern parts of the country and have a better socio-economic status than other parts of the study area.

To mitigate the social vulnerability in the high-risk areas, it is crucial to implement strategies such as public awareness campaigns, early warning systems, and evacuation plans that specifically cater to the needs of the dependent populations, such as women, children, and the elderly. Additionally, increasing access to education and improving literacy rates, along with creating more economic opportunities, could also help to reduce social vulnerability.

Coastal vulnerability modeling

Upon completion of the physical and social vulnerability maps through the use of the FAHP model, the final coastal vulnerability map was effortlessly produced by multiplying the previously generated models. The resulting map has a value ranging from 0 to 1, which indicates the level of vulnerability, with 0 being the lowest and 1 being the highest. However, to better understand the vulnerability levels, the final coastal vulnerability map was classified into five

Table 2 CR values and criteria weights from pairwise comparison matrices

Component	Criteria	Weight
Physical vulnerability	Elevation (m)	0.11
	Slope	0.11
	Distance to cyclone track (km)	0.25
	Distance to coastline (km)	0.04
	LULU	0.16
Social vulnerability	Population density (km ²)	0.23
	Dependent population (%)	0.02
	Disabled population (%)	0.03
	Female population (%)	0.03
	Literacy rate (%)	0.01

Table 3 Area coverage of physical vulnerability

Class	Area (km ²)	Percentage
Very high	8445.058	21.73%
High	14,997.459	38.59%
Moderate	6832.219	17.58%
Low	6867.196	17.67%
Very low	1721.657	4.43%

classes utilizing the natural break algorithm: very low, low, moderate, high, and very high (Fig. 7).

Figure 7 suggests that the west and central coasts of Bangladesh are more susceptible to vulnerability than the east coast. This observation can be attributed to the lower altitude and slope, which heightens the risk socio-economic situations of the people residing on the western and central coasts. Table 5 provides that more than a third (34.8%) of the study area falls into a high to very high physical hazard class. Despite this, the largest percentage of the study area, covering an area of 12,675.67 km², has only moderate vulnerability.

Meanwhile, the eastern region of Bangladesh, specifically districts such as Shariatpur, Feni, Cox’s Bazar, and Chittagong, with an area of over 12,645.79 km², has a relatively low to very low vulnerability rate, comprising 32.5% of the total study area. These results suggest that the management strategies implemented should prioritize areas that are classified as having high to very high vulnerability levels to minimize potential risks and damages.

Validation of coastal vulnerability model

We used ROC-AUC to validate the coastal vulnerability model. Figure 8 illustrates the performance of the model used in this study with a prediction curve. Figure 8 shows

Fig. 5 Spatial pattern and class of physical vulnerability

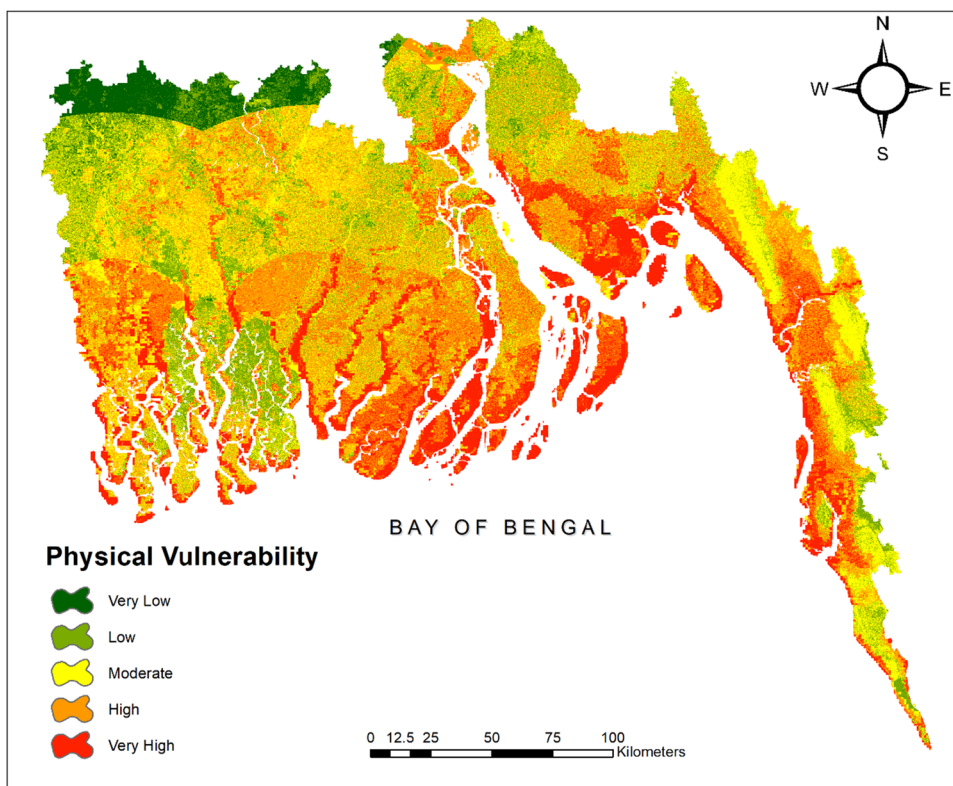


Fig. 6 Spatial pattern and class of social vulnerability

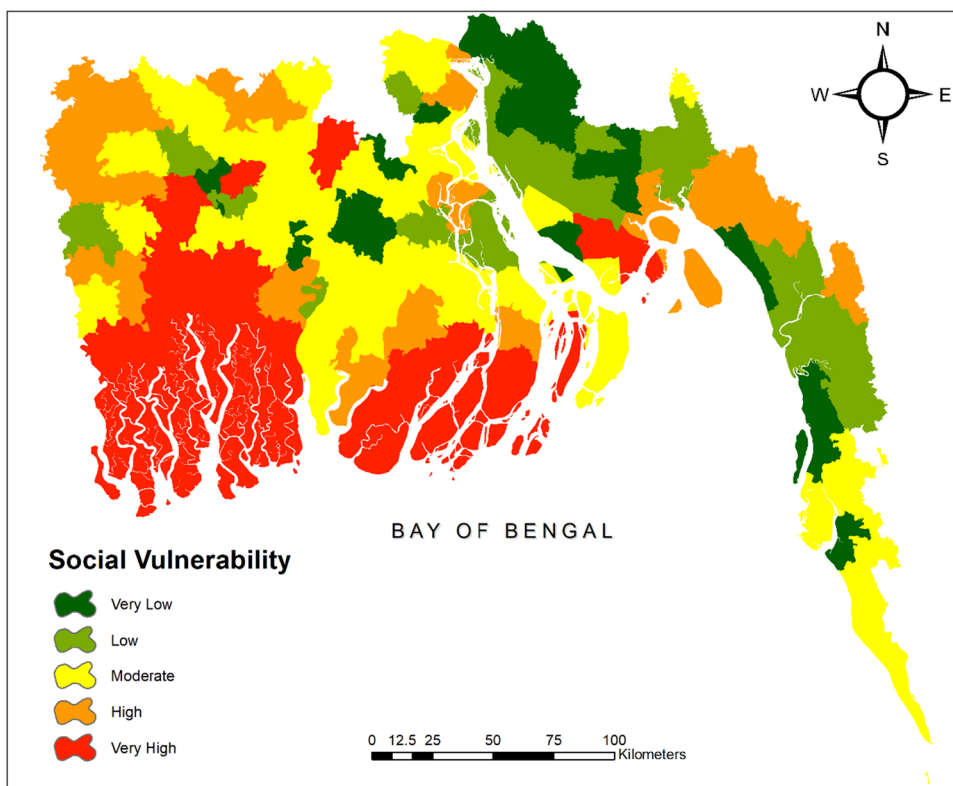


Table 4 Area coverage of social vulnerability

Class	Area (km ²)	Percentage
Very high	10,631.07	26.5
High	7339.18	18.3
Moderate	11,695.86	29.2
Low	6082.26	15.2
Very low	4314.01	10.8

that the model achieves an AUC value of 0.875 of the ROC curve, which signifies the acceptability of the model created. The range of AUC values is from 0 to 1, indicating higher accuracy toward 1 and vice versa (Das and Pal 2020). AUC values above 0.80 usually indicate the reliability of the results of a model. Apart from the ROC, we have collected information about the damages takes place in the district of high CVI values to validate the model indirectly. Here is a summary of cyclones that hit Barguna, Bhola, Noakhali, Patuakhali, and Pirojpur districts of Bangladesh from 2019 to 2021, along with the damages:

1. Cyclone Bulbul (2019)

- Date: November 9–10, 2019
- Affected Districts: Barguna, Bhola, Patuakhali, and Pirojpur (along with other coastal districts)

- Damages: Cyclone Bulbul caused significant damages to infrastructure, including houses, schools, and embankments. It also led to the disruption of power supply and caused widespread flooding and crop damage.
- Sources: News reports, government assessments, and relief agencies’ reports.

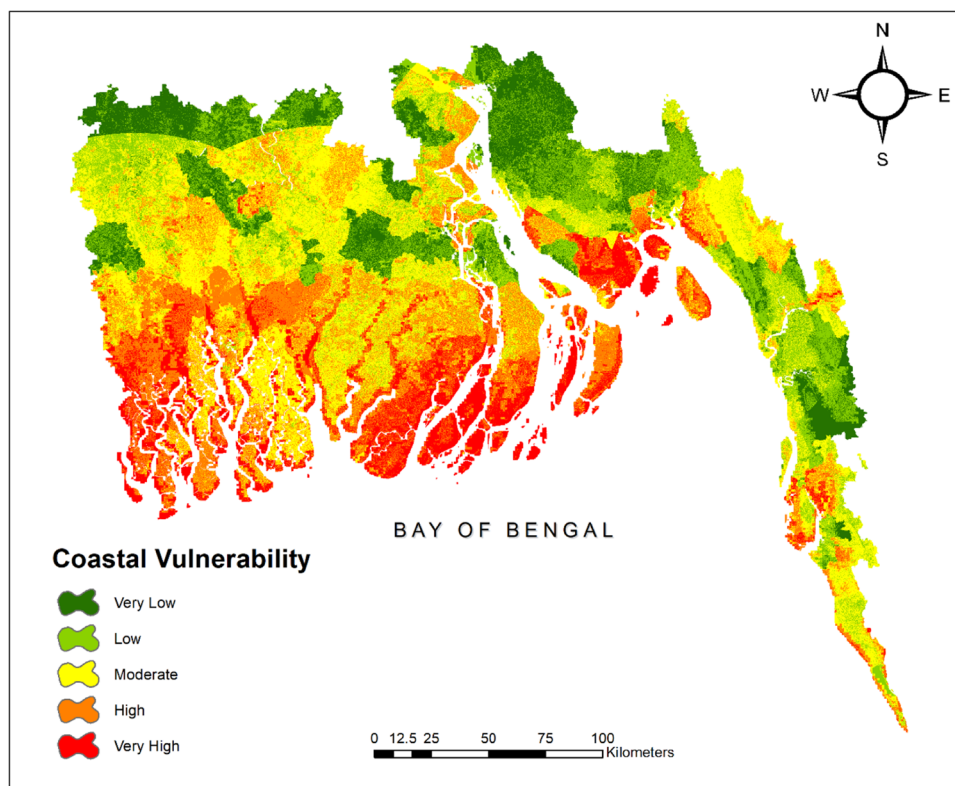
2. Cyclone Amphan (2020)

- Date: May 20, 2020
- Affected Districts: Barguna, Bhola, Noakhali, Patuakhali, Pirojpur (along with other coastal districts)
- Damages: Cyclone Amphan resulted in severe damages to infrastructure, including houses, schools, and hospitals. It caused extensive flooding, uprooted trees, and disrupted power supply. The cyclone also caused damage to agriculture and aquaculture, impacting the livelihoods of the coastal communities.
- Sources: News reports, government assessments, and relief agencies’ reports.

3. Cyclone Yaas (2021)

- Date: May 25–26, 2021
- Affected Districts: Barguna, Bhola, Noakhali, Patuakhali, and Pirojpur (along with other coastal districts)
- Damages: Cyclone Yaas resulted in damages to houses, crops, and infrastructure in the affected dis-

Fig. 7 Spatial pattern and class of coastal vulnerability



districts. It caused flooding, power outages, and disruption of transportation systems. The cyclone also led to the displacement of people and affected the fishing and agricultural sectors. (Sources: government assessments, and relief agencies' reports.¹)

Therefore, it can be stated that the results of this study are very satisfactory and reliable and can be used for further research and management plans.

Discussion and conclusion

The coastal region of Bangladesh has been most frequently hit by cyclones. Against this background, the present study thoroughly examines the vulnerability to tropical cyclones. FAHP and geospatial methods were used to determine the spatial pattern of vulnerability based on two vulnerability criteria: physical and social. A total of ten parameters were used in this study for these two criteria. The ROC and AUC were

successfully used to validate the spatial vulnerability map and it was found that the coastal vulnerability model constructed was 87.5% reliable. The densely populated coastal areas of Bangladesh also fall into the “highly vulnerable” category. People and their livelihoods in the rural areas are exposed to sea level rise, coastal flooding and extreme tidal surges. The vulnerability of coastal areas is also increasing due to the destruction of the largest mangrove forest in the world. The coastal vulnerability map shows that most of the districts in the western and central coastal regions are particularly vulnerable to the impacts of coastal disasters, including Satkhira, Barguna, Bagerhat, Bhola, Noakhali, and Patuakhali.

Understanding the novelty

Coastal vulnerability is a multifaceted phenomenon that requires the consideration of both physical and social factors to adequately quantify the extent of the vulnerability. In this study, ten parameters were assessed, including altitude, slope, distance from the cyclone track, distance from the coast, land cover, population density, literacy rate, proportion of women in the population, proportion of children in the population, and proportion of elderly population, to model coastal vulnerability. Of the physical factors, distance from the cyclone track was deemed the most critical parameter followed by land use, land cover, slope, and altitude. While some argue that elevation should be given more

¹ Please note that the information provided is a summary, and for more specific details and comprehensive reports on damages, it is recommended to refer to official government reports. Ministry of Disaster Management and Relief, Bangladesh: <http://www.modmr.gov.bd/>

Department of Disaster Management, Bangladesh: <http://www.ddm.gov.bd/>

Table 5 Coverage of vulnerable coastal area

Class	Area (km ²)	Percentage
Very high	4746.71	12.2
High	8795.21	22.6
Moderate	12,675.67	32.6
Low	7321.15	18.8
Very low	5324.64	13.7

weight, Nageswara Rao et al. (2008) considered slope to be the more appropriate variable as it better captures the area. Meanwhile, distance from the coast was the least influential parameter in determining coastal vulnerability and was thus assigned the lowest weight. The inclusion of socio-economic characteristics in coastal vulnerability modeling is crucial to accurately define vulnerable regions. However, assessing socio-economic data on an interval scale presents a challenge. Thus, it is not often included in the coastal vulnerability index (CVI). Nevertheless, socio-economic variables significantly contribute to coastal vulnerability since socio-economic changes occur more rapidly than physical changes (Szlafszien 2005). Population density was considered the most influential social parameter in this study due to its effect on both social and coastal vulnerability.

Tropical risk assessment

The present study aimed to conduct a comprehensive risk assessment of the vulnerability of Bangladesh's coasts to tropical cyclones using the FAHP model, which can serve as a basis for more comprehensive, consequential, and policy-relevant studies in the future. By doing so, we hope to enhance our understanding of the socio-economic factors that affect vulnerability and to develop appropriate management strategies to reduce the impact of natural disasters on Bangladesh's coastal regions. Bangladesh is highly susceptible to cyclones, yet there is a dearth of research on its vulnerability. Some studies have analyzed the risk, vulnerability, impact, and adaptation to tropical cyclones in Bangladesh's coastal areas (Alam et al. 2020; Mullick et al. 2019). Quader et al. (2017) mapped the hazards to human life and livelihoods posed by natural hazards in coastal areas of Bangladesh using limited criteria that primarily focused on social aspects. At a more compressed scale, Hoque et al. (2018) built a model for tropical cyclones using a multi-criteria approach. Recently, Hoque et al. (2019) and Alam et al. (2020) used geospatial methods to evaluate the probability of a tropical cyclone on the east coast of Bangladesh. We also compared with previous researches on the development of index, which shows that our work is new and novel (Table 6).

However, no research has used multi-criteria assessment to map the vulnerability of the entire Bangladesh coast to tropical cyclones. In this study, both physical and social factors are considered for modeling the vulnerability of the entire coast of Bangladesh using a sophisticated FAHP model, which overcomes several limitations of the aforementioned studies.

Through the use of the FAHP model, physical and social vulnerability maps were generated and multiplied to obtain the final coastal vulnerability index. The results show that 34.8% of the study area is classified as "high" or "extremely high" in terms of physical hazards, while most of the region (12,675.67 km²) lies in regions of moderate vulnerability. In contrast, the eastern region, including districts such as Shariatpur, Feni, Cox's Bazar, and Chittagong, covering an area of 12,645.79 km², is only 32.5% or less vulnerable. These findings can be utilized to prioritize management strategies and allocate resources in vulnerable areas to reduce the risks and damages associated with natural disasters.

Policy implication

Based on the vulnerability map created, management strategies can be developed to reduce the impact of tropical cyclones on the vulnerable coastal areas of Bangladesh. Here are some potential strategies:

- Early warning systems: Given the rapidity of tropical cyclones, early warning systems are essential to reduce the loss of life and property damage. Since the west and central

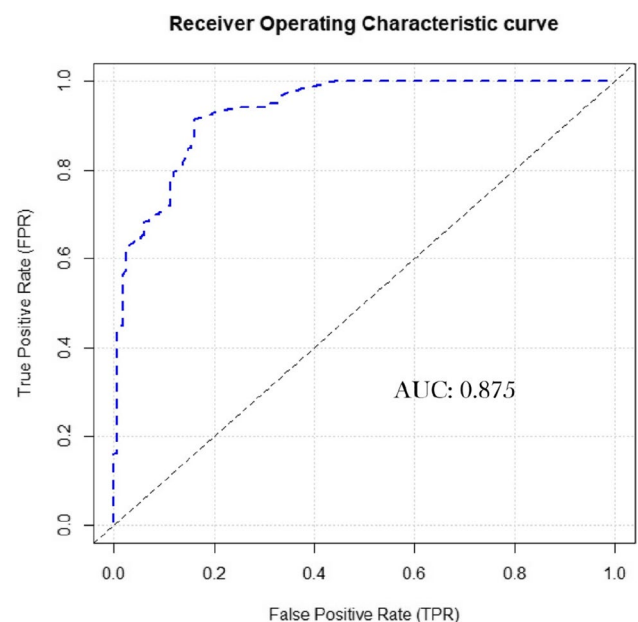


Fig. 8 Accuracy assessment of coastal vulnerability model using ROC-AUC

Table 6 Comparative assessment of tropical cyclone risk based on literature review

Study	Location	Key findings	Concluding remarks
Hamid et al. (2019)	Coastal investigation	Coastal vulnerability estimation relies on index development affected by various variables. Integration of contemporary technology enhances the assessment of vulnerability and environmental risk. Consideration of appropriate data, spatial scale, and geomorphology is crucial	Acknowledging and incorporating relevant data, spatial characteristics, and geomorphological factors are essential for accurate coastal vulnerability assessments and effective environmental risk management
Koroglu et al. (2019)	Barcelona Province	Comparative analysis of four CVI computation approaches for Barcelona coastline revealed site-specific rankings' limited applicability elsewhere. Development of region-specific ranking categories is recommended for reliable overall CVI calculation. CVI tools aid decision-making to enhance coastal zone resilience despite potential categorization bias	To provide reliable inputs for local coastal zone management, developing region-specific ranking categories is crucial. Despite potential biases, CVI tools remain valuable in decision-making processes for increasing coastal resilience
Furlan et al. (2021)	Italian coast	Introduction of Multi-dimensional Coastal Vulnerability Index (MDim-CVI) incorporating physical, environmental, and socio-economic indicators ranks Italian coastal provinces based on relative vulnerability to extreme sea level scenarios	The proposed Multi-dimensional Coastal Vulnerability Index (MDim-CVI) offers an enhanced approach for assessing coastal vulnerability, integrating various indicators. It enables ranking of coastal provinces based on their relative vulnerability to extreme sea level events, providing valuable insights for coastal management initiatives
Pantusa et al. (2022)	Calabria coastline, Italy	The proposed index assesses the relative vulnerability of different coastal transects, aiding local coastal management. The index proves particularly useful for low-lying coastlines with erosive conditions and anthropogenic pressures. Limited investment budgets highlight the importance of reliable tools for coastal management	The proposed index offers a reliable tool for assessing the relative vulnerability of different coastal transects, especially in low-lying areas with erosive conditions and anthropogenic pressures. It is particularly valuable for coastal management under limited investment budgets
Noor and Abdul Maulud (2022)	Southeast Asia	Southeast Asian coastlines are highly susceptible to climate change impacts, including ocean warming, rainfall pattern changes, storm frequency, and rising sea levels. Population expansion, urbanization, industry, and tourism in coastal areas contribute to increased pressures	Climate change impacts pose significant threats to Southeast Asian coastlines, including rising sea levels, altered rainfall patterns, and increased storm frequency. Urgent attention is required to address the underlying causes, such as population growth, urbanization, industrial activities, and tourism in coastal regions
Rahman et al. (2022a, b)	Rakhain community, Bangladesh	Vulnerability to cyclones and natural hazards encompasses social, economic, physical, and institutional aspects. An index-based approach facilitates the quantification and identification of vulnerability components	Understanding vulnerability as a multifaceted process involving social, economic, physical, and institutional factors is crucial for effective cyclone and natural hazard management. Index-based approaches provide valuable insights into the contributing elements of vulnerability, aiding targeted interventions
Hossain et al. (2022)	Purba Medinipur-Balasore coastal stretch	Comparative analysis of Gornitz's CVI model and the AHP method for assessing physical vulnerability under climate change scenarios. Remote sensing and GIS techniques prove efficient for such research. Five physical and five social indicators were used in this study	Comparative analysis of assessment methods revealed the efficiency of remote sensing and GIS techniques in evaluating physical vulnerability under climate change scenarios. Incorporating a combination of physical and social indicators provides a comprehensive understanding of coastal vulnerability

coasts are the most vulnerable areas, it is crucial to focus on strengthening early warning systems in these regions.

- **Infrastructure development:** Since the coastal areas of Bangladesh are exposed to tidal surges and floods, it is essential to construct infrastructure that can withstand natural disasters. This infrastructure could include strengthening the embankments, developing cyclone shelters, and improving drainage systems.
- **Public awareness campaigns:** Literacy rate is one of the socio-economic factors that affect coastal vulnerability. Therefore, public awareness campaigns can play a critical role in educating the people living in vulnerable areas about the risks associated with tropical cyclones and the ways to mitigate them.
- **Mangrove conservation:** Mangroves have proven to be a natural barrier against tidal surges, cyclones, and floods. Conserving and restoring mangroves in vulnerable areas can significantly reduce the risk and impact of tropical cyclones.
- **Government policy interventions:** The government can provide incentives for people to relocate from vulnerable areas, especially in the west and central coasts, to safer areas. The government can also provide subsidies for retrofitting homes and buildings to make them more cyclone-resistant.

By implementing these strategies, it is possible to reduce the impact of tropical cyclones on the vulnerable coastal areas of Bangladesh. However, it is important to note that no strategy can fully eliminate the risks associated with natural disasters, and continued research and development are necessary to address this issue.

Limitations of the study

In this paper, a multi-criteria analysis based on GIS was created and implemented to assess the cyclone vulnerability of the coastal area of Bangladesh. In particular, this has been done to determine the probability of different types of storms. We strive to obtain datasets that are both of the highest quality and as up-to-date as possible. For example, to examine the criterion of social vulnerability, we used census data from 2011. Census data for 2021 has not yet been released due to COVID-19. Therefore, we were forced to use this 10-year-old data. In this study, satellite data with a modest resolution, such as Landsat 8 photos and SRTM DEM (30 m), were used to create the slope, elevation and LULC map. Due to the use of a medium resolution dataset and an old census, these results are not particularly satisfactory. Another difficulty is that we have obtained the essential data from several departments in Bangladesh, where the data has not been regularly updated and some of the health facilities and cyclone shelters are still under development. As a result,

some of the latest data may be missing. Further studies are needed to address these limitations.

Despite its certain limitations, this study is crucial in formulating the management strategy of the government and coastal authorities for the highly vulnerable zone. The development of shelters and medical facilities, the use of natural solutions, afforestation along the coast and the construction of sealing walls or dykes are possible measures to mitigate cyclones. Research can be further improved by incorporating environmental and climate elements such as sea temperature, precipitation, and solar radiation, and by using high-resolution satellite data (Worldview, IKONOS, QuickBird). This could improve the accuracy of coastal vulnerability model.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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