Tropical cyclone risk assessment using geospatial techniques for the eastern coastal region of Bangladesh

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Abstract

Tropical cyclones frequently affect millions of people, damaging properties, livelihoods and environments in the coastal region of Bangladesh. The intensity and extent of tropical cyclones and their impacts are likely to increase in the future due to climate change. The eastern coastal region of Bangladesh is one of the most cyclone-affected coastal regions. A comprehensive spatial assessment is therefore essential to produce a risk map by identifying the areas under high cyclone risks to support mitigation strategies. This study aims to develop a comprehensive tropical cyclone risk map using geospatial techniques and to quantify the degree of risk in the eastern coastal region of Bangladesh. In total, 14 spatial criteria under three risk components, namely, vulnerability and exposure, hazard, and mitigation capacity, were assessed. A spatial layer was created for each criterion, and weighting was conducted following the Analytical Hierarchy Process. The individual risk component maps were generated from their indices, and subsequently, the overall risk map was produced by integrating the indices through a weighted overlay approach. Results demonstrate that the very-high risk zone covered 9% of the study area, whereas the high-risk zone covered 27%. Specifically, the south-western (Sandwip and Sonagazi), western (Patiya, Kutubdia, Maheshkhali, Chakaria, Cox's Bazar and Chittagong Sadar) and south-western (Teknaf) regions of the study site are likely to be under a high risk of tropical cyclone impacts. Low and very-low hazard zones constitute 11% and 28% of the study area, respectively, and most of these areas are located inland. The results of this study can be used by the concerned authorities to develop and apply effective cyclone impact mitigation plans and strategies.

Keywords: Tropical Cyclone; Vulnerability; Risk assessment; GIS; Remote sensing; Analytical hierarchy process

1. Introduction

Tropical cyclones are regarded as amongst the deadliest climatic disasters worldwide (Bakkensen and Mendelsohn, 2019). Loss of lives, widespread damages to properties and environments as well as disruptions in communication networks are the notable impacts of tropical cyclones (Dube et al., 2009; Krapivin et al., 2012; Sahoo and Bhaskaran, 2018). On average, approximately 90 tropical cyclones are formed annually around the world, and many of them turn into major catastrophic disasters (Murakami et al., 2013). Approximately 637 major tropical cyclones were documented worldwide between 1970 and 2010 (Hoque et al., 2018b; Weinkle et al., 2012). Global tropical cyclones cause approximately 1.9 million lost lives over the past two centuries (Hoque et al., 2018a; Shultz et al., 2005). On average, approximately $26 billion US dollars worth of worldwide damage occur each year due to cyclones (Bakkensen and Mendelsohn, 2019; Mendelsohn et al., 2012). In the future, climate change and anthropogenic impacts are acknowledged to highly influence tropical cyclones (Bakkensen and Mendelsohn, 2019; Rey et al., 2019). Although whether the number of cyclones will increase or not is up for debate (Varotsos and Efstathiou, 2013), the degree of tropical cyclone impacts is expected to escalate enormously in the next few years (Alam and Dominey-Howes, 2015; Mendelsohn et al., 2012; Moon et al., 2019; Ranson et al., 2014; Varotsos et al., 2015; Walsh et al., 2016). Consequently, considerable coastal people, properties and environments would be highly affected.

Given the geographic location of Bangladesh, it is ranked as the fifth most natural disaster-prone country in the world (Ahmed et al., 2016; Islam et al., 2016). Tropical cyclones with different intensities are the most common climatic hazards that affect the coastal areas of the country almost every year (Alam and Collins, 2010; Mallick et al., 2017). The physiography of the country helps in increasing the landfall intensity and cyclone impact (Islam and Peterson, 2009; Paul et al., 2010). According to historical records of the past 100 years, amongst the 508 cyclones formed in the Bay of Bengal, 17% have made landfall in the coastal areas of Bangladesh (Hoque et al., 2018b). These cyclones caused extreme casualties and damages due to the lack of appropriate warning systems and emergency infrastructure (Quader et al., 2017). Records since 1877 have shown that more than one million people have died to date due to cyclonic disasters in the country (Paul and Dutt, 2010). In the future, Bangladesh will experience severe climate change effects (Abedin et al., 2019; Karim and Mimura, 2008). Sea level rising in a warming climate will intensify the impact of tropical cyclones across the coastal districts, creating adverse impacts on the local economy and the environments (Sarwar, 2013).

The applications of management approaches, such as prevention and reduction, are the best means to reduce the loss caused by tropical cyclones (Ahmed et al., 2016; Joyce et al., 2009). Information regarding the spatial distribution of exposure, vulnerability, hazard, mitigation capacity and the resultant risk of tropical cyclone impacts are required to develop appropriate mitigation strategies (Khan, 2008; Rana et al., 2010). This spatial information can be derived from tropical cyclone risk mapping. Theoretically, risk is explained as the consequence of the interaction of particular hazards and the characteristics that make people, elements and environments vulnerable and exposed (Dewan, 2013a; Rashid, 2013). Hazards affecting life, elements and environments are considered events, whereas vulnerability is the degree of loss to be caused by hazards to belongings, livelihoods and elements under threat (Hoque et al., 2017). The availability of structural and non-structural measures, such as cyclone shelters and warning systems, is considered under mitigation capacity, which reduces the likely impacts of particular hazards (Cutter et al., 2008; Hoque et al., 2018a). The derived spatial information by risk mapping could be utilised by emergency management officials, developers and administrators in preparing effective cyclone mitigation plans.

Satellite remote sensing and spatial analysis can be used very efficiently for mapping tropical cyclone risks (Poompavai and Ramalingam, 2013; Yin et al., 2010). Remote sensing, other spatial and non-spatial data are used to map the influencing criteria of tropical cyclones. In the process of mapping risk (Hoque et al., 2017; Mori and Takemi, 2016), spatial analysis techniques are used under the risk components of vulnerability and exposure (Dewan, 2013b; Kunte et al., 2014), hazard (Rashid, 2013) and mitigation capacity (Hoque et al., 2018a). Several mapping approaches are reported in the literature to map the components of tropical cyclone risks (Gao et al., 2014; Hoque et al., 2018a; Quader et al., 2017; Yin et al., 2013). A few such approaches are based on a single criterion (Li and Li, 2013) whilst others follow multi-criteria (Hoque et al., 2018a; Poompavai and Ramalingam, 2013). Multi-criteria evaluation for each of the risk component is strongly required to produce detailed spatial risk information. The analytical hierarchy process (AHP) is the most efficient method to incorporate the multi-criteria evaluation of each risk component and combine them in a spatial decision-making process for mapping tropical cyclone risks (Hoque et al., 2018a; Malczewski, 2010). AHP uses a hierarchical structure to assign weight and ranking in the multi-criteria layers supported by experts and users (Roy and Blaschke, 2013). Few studies have successfully employed the AHP for mapping tropical cyclone risks (Hoque et al., 2018a; Mansour, 2019; Poompavai and Ramalingam, 2013; Yin et al., 2013).

Studies related to tropical cyclone risk mapping in Bangladesh are very limited even though tropical cyclones cause considerably high occurrences, calamities and damages to properties and environments compared with those of other affected countries of the world. Few relevant studies are found in the literature, and most of them follow single criteria with limited components of risks in their assessment (Dasgupta et al., 2011; Hoque et al., 2018b; Karim and Mimura, 2008; Kumar et al., 2011; Rana et al., 2010; Roy and Blaschke, 2013). Only two studies considered multi-criteria in mapping tropical cyclone risk assessment. Hoque et al. (2018a) assessed tropical cyclone risks by using a multi-criteria approach with all of the risk components. However, this study was conducted in a small area (approximately 151.24 sq. km) at the local scale in Sarankhola Upazila, western coastal region of Bangladesh. The second study was conducted by Quader et al. (2017) to map tropical cyclone risks using limited criteria for the entire coastal region of Bangladesh. The storm surge height, a key criterion to consider in tropical cyclone risk assessment, was underestimated in this study. Most of the selected criteria focused on social aspects rather than physical. Moreover, no established approach was used in this study to assign weighting and ranking in the multi-criteria evaluation. Following geomorphic characteristics, the coastal areas of Bangladesh are classified into three coastal regions, namely, western, central and eastern. Although the eastern coastal region is highly vulnerable to tropical cyclones, no study to date has been conducted in this region to map detailed and accurate tropical cyclone risks using the AHP based multi-criteria decision-making approach.

This study aims to develop a comprehensive tropical cyclone risk map that integrates vulnerability, exposure, hazard, and mitigation capacity using geospatial techniques and to quantify the degree of risk of tropical cyclone impacts for the eastern coastal region of Bangladesh. Three specific objectives in this study include the following: (1) to develop a map of vulnerability and exposure, hazard and mitigation capacity of tropical cyclone impacts using the AHP based multi-criteria decision making approach; (2) to produce a risk map integrating a vulnerability and exposure, hazard and mitigation capacity to quantify the degree of risk of tropical cyclone risk impacts and (3) to evaluate the produced risk map results.

2. Materials and methods

This study uses the AHP-based geospatial multi-criteria evaluation approach for tropical cyclone risk assessment. The AHP has a strong capability to efficiently incorporate and aggregate multi-criteria and present findings effectively (Malczewski, 1999; Mani Murali et al., 2013). Few risk assessment equations are found in the literature for mapping the risk of natural hazards (Dewan, 2013a; Eckert et al., 2012; Hoque et al., 2017; Masood and Takeuchi, 2012). Selecting an advanced and complete risk equation with essential components is essential for good and accurate risk mapping. In this study, Equation 1 was adopted to map tropical cyclone risks following an extensive review of the current literature (Dewan, 2013a; Hoque et al., 2018a; Rashid, 2013).

$$\mathbf{Risk} = \mathbf{Hazard} \times \mathbf{Vulnerability} \times \mathbf{exposure/mitigation\ \ capacity} \qquad (1)$$

Fig. 1 presents the methodological flowchart followed in this study.

[Fig. 1 near here]

2.1 Study area

The present study was conducted in the eastern coastal region of Bangladesh, which covers Chittagong and Cox's Bazar coastal districts (Fig. 2). The geographical extent of this region lies between 20°45′–20°45′ N latitude and 91°26′–92°20′ E longitude. This coastal region has an area of 7664 sq. km and a population of 9.2 million (BBS, 2012). Most of the people live under the poverty line with a population density of 1739 per sq. km (Khanam, 2017). The area is characterised by a tropical monsoon climate, and the daily mean average temperature is 25.9 °C (Peel et al., 2007). Tropical cyclone frequency, intensity and impacts are particularly high in this coastal region due to its geographical location and topographical characteristics.

Approximately 30 major tropical cyclones have made landfall on this coast during 1960–2017 and caused massive fatalities, damages to properties and environments (Quader et al., 2017). The most catastrophic tropical cyclone in this region occurred in 1991 with a loss of 138,866 lives (Alam and Dominey-Howes, 2015). This region is open to the sea by the coastal rivers, canals and creeks, which make this area more vulnerable to storm surges. This region is open to the sea by the coastal rivers, canals and creeks that increase its vulnerability to storm surges. As such, the intensity of storm surges is likely to be enhanced in this region under the rapid climate change and rising sea level (Sarwar and Woodroffe, 2013).

[Fig. 2 near here]

2.2 Data set and sources

In this study, various dynamic criteria under three risk components were selected for assessing tropical cyclone risks. The selected criteria were mapped from a wide variety of data sources, including local to international governmental and private organisations as well as multiple field investigations, using geospatial techniques. Cyclone shelter data with their spatial location obtained from the Ministry of Disaster and Relief were verified in the field. Health facilities and cyclone warning system data were collected from the local administrative offices and likewise verified in the field. Field visits were conducted between March and August in 2018 to verify the datasets as well as the findings of the study. Table 1 presents the list of datasets along with their characteristics.

[Table 1 near here]

2.3 Risk evaluation criteria, alternatives and mapping

In this study, criteria were selected following an intensive literature review as well as by considering data accessibility and their relevance to tropical cyclone risks. The development of spatial layers for each criterion was performed using GIS and remote sensing techniques. We generated 14 spatial criteria layers for the risk components of vulnerability, hazard and mitigation capacity. A 10 m × 10 m cell size was determined as a spatial resolution of each raster layer. Remote sensing and spatial analysis software ENVI (version 5.4) and ArcGIS (version 10.4) were used to process and prepare all the criteria layers. The natural break statistical methods were used to classify the produced maps. This statistical method was found more consistent and effective to exhibit the spatial pattern of risk in the study area (Baeza et al., 2016; Tehrany et al., 2014). The characteristics and mapping approaches for the selected criteria are detailed in the succeeding subsections.

2.3.1 Criteria for vulnerability and exposure mapping

Several criteria influence the vulnerability and exposure of any area to tropical cyclone impacts (Hoque et al., 2018a). In the present study, six criteria related to tropical cyclone vulnerability and exposure were chosen. Mainly focused on the physical aspect, the vulnerability criteria included elevation, slope, proximity to coast and cyclone track. Exposure criteria comprised land use and land cover as well as population density.

Elevation and slope play a crucial role in tropical cyclone vulnerability assessment (Dewan, 2013b; Li and Li, 2013). Areas with the characteristics of low elevation and slope are considered highly vulnerable to tropical cyclones, whereas areas with high slope and elevation are considered less vulnerable (Rao et al., 2013). In this study, a 10-m spatial resolution digital elevation model (DEM) was produced from the topographic sheets (scale 1:25000) to generate the elevation and slope map (Fig. 3a, b). This DEM was obtained from the Survey of Bangladesh (SOB).

Proximity to coastline and cyclone track are important criteria in the cyclone vulnerability assessment. Life and properties near coasts and cyclone tracks are highly vulnerable to tropical cyclone impacts than those far from such areas. Google Earth Pro ruler was used to measure the distance of different sections of the study area from the coastline to produce the coastline proximity data. These data were then used to produce the proximity to coastline spatial layers (Fig. 3c). By comparison, the International Best Track Archive for Climate Stewardship (IBTrACS) data (www.ncdc.noaa.gov/ibtracs/) from 1968 to 2018 were used to prepare the proximity to the cyclone track spatial layer (Fig. 3d) (Knapp et al., 2010). In this process, about 30 spatial cyclone tracks were identified in the study area. Next, we performed the proximity analysis developing multi-ring buffers around the cyclone tracks using ArcGIS buffer tools to produce proximity to cyclone track spatial layer.

[Fig. 3 near here]

Land use and land cover (LULC) is a valuable exposure and indicator for tropical cyclone vulnerability assessment. In this study, seven Sentinel-2 imageries with a 10 m spatial resolution were used to generate the LULC map (Fig. 3e). The pre-processing of geometric, radiometric and atmospheric corrections of sentinel-2 images were performed using the Sen-2 Cor toolbox of Sentinel Application (SNAP) software. A hybrid classification scheme was adopted to classify six LULC categories, which include mixed vegetation, settlement, salt cultivation, open water bodies, mangrove vegetation, cropland, closed water bodies and bare land. Initially, the probable classes were identified by applying an unsupervised clustering algorithm. Sample data were then selected for conducting supervised classification using a maximum likelihood algorithm (Kumar et al., 2013). All of these processes were performed using the ENVI 5.4 remote sensing software. The classification accuracy of the LULC map was determined using the random points acquired from the Google Earth imagery of the same periods. Having at least 50 points in each class, 505 total random points were generated using a stratified random sampling technique. Stratified random sampling is a probability sampling technique where the entire population is divided into different subgroups or strata, and then samples are collected randomly and proportionally from the different strata (A Ramezan et al., 2019). We followed the accuracy assessment explained in (Hoque et al., 2016; Jensen, 2005). The overall accuracy and kappa coefficient values were 92.08% and 90.94%, respectively.

The coastal population is rapidly increasing throughout the world, intensifying their exposure to tropical cyclones (Neumann et al., 2015). The spatial variation of population concentration and densities has a considerable influence on vulnerability levels (Poompavai and Ramalingam, 2013). In this study, the population density layer was prepared on the basis of the population and housing census data of 2011 (Fig. 3f), which was the last census in Bangladesh conducted by the Bangladesh Bureau of Statistics (BBS). The next one will be performed in 2021.

2.3.2 Criteria for hazard mapping

The probability of tropical cyclone hazard occurrence is calculated by analysing its previous location, time, intensity, frequency and several environmental factors (Hoque et al., 2018a). We selected four criteria such as storm surge height, cyclone wind speed, cyclone frequency and precipitation intensity for hazard assessment.

One of the catastrophic features of tropical cyclones is the storm surge, which can cause sudden flooding and significant damage to coastal communities. We produced a storm surge height spatial layer by employing past storm surge data and a 10-m spatial resolution bare earth DEM (Fig. 4a). This DEM was created from the topographic sheets (scale 1:25000). A 20-year return period maximum surge height of 8.77 m was considered in the storm surge model. The Gumbel distribution for frequency analysis was used to estimate maximum surge heights using historical cyclone data from 1960 to 2018. We calculated the surge decay coefficient of chosen surge height. Thereafter, following numerous raster calculator equations within the ArcGIS platform, the storm surge height map was prepared using the estimated surge decay-coefficient and DEM. The processing techniques used to generate storm surge height map are explained in (Hoque et al., 2018b).

Cyclone wind speed is largely responsible for the destruction of infrastructures on the affected areas (Cardona et al., 2014). We prepared a cyclone wind speed spatial layer and considered the relevant data constraint following only the Cyclone Mora (2017) wind speed spatial distribution data (Fig. 4b). A devastating tropical cyclone, Cyclone Mora made landfall on 31**st** May 2017 in the eastern coastal region of Bangladesh. With maximum sustained winds of 110 km/h, this cyclone caused considerable fatalities and damages.

Cyclone frequency influences the hazard intensity for a particular area because compared with occasional or rarely occurring hazards, frequent cyclone hazards present the great likelihood to affect an area (Poompavai and Ramalingam, 2013). In this study, we prepared the cyclone frequency spatial layer using the previous historical cyclone track data from 1960 to 2018 (Fig. 4c). From our field verifications, approximately 24 tropical cyclones have affected the study area over the last 68 years. The spatial analyst tool of ArcGIS (version 10.4) was used to convert the cyclone frequency data into a spatial layer.

[Fig. 4 near here]

Tropical cyclones cause extreme rainfall that ultimately intensifies flooding in the affected area. We were unable to collect spatial rainfall data linked to the landfall of tropical cyclones in the study area. Consequently, the daily precipitation data between 1950 and 2018 acquired from the Bangladesh Meteorological Department (BMD) were used to prepare the precipitation intensity map (Fig. 4d). Initially, we generated an annual precipitation intensity map by interpolating data from 35 rainfall stations covering Bangladesh on to a regular grid, and then the study area was extracted from this map. For interpolation, a kriging interpolation technique was applied using ArcGIS (Oliver and Webster, 1990).

2.3.3 Criteria for mitigation capacity mapping

Mitigation capacity indicates that key initiatives are planned and implemented to minimise the hazard impacts. We selected four mitigation capacity criteria (i.e., cyclone shelters, health facilities, coastal vegetation and cyclone warning systems) to assess the mitigation capacity in the study area.

As an effective mitigation initiative, cyclone shelters provide emergency shelter to affected communities and protect them from the risk of storm surges during the cyclone event (Mallick and Rahman, 2013). Emergency health cares are likewise supported by the local health facilities prior to cyclone landfall. Cyclone shelter data were acquired from the Ministry of Disaster Management and Relief, whereas health facilities data were obtained from the local administrative office and verified in the field. We utilised the 'Euclidian distance' technique to prepare spatial layers of distance to cyclone shelter and health facilities (Fig. 5a, b).

Coastal vegetation is considered protection during cyclone events to minimise the effects of wind and storm surges on coastal infrastructure and properties (Das and Vincent, 2009). In this study, the coastal vegetation map was prepared using the vegetation data acquired from the Bangladesh Forest Department (Fig. 5c). These vegetation data were prepared using the RapidEye 5-meter spatial resolution satellite imagery for 2016 under the 'Climate Resilient Participatory Afforestation and Reforestation' project of the Government of Bangladesh. In addition, an effective warning system plays a vital role to evacuate the people and belongings to reduce the impacts during cyclone events (Akhand, 2003). The warning system data including the information of equipment and processes were collected from the local administrative office and analyzed according to different parameters of the local warning system. The processed data were then verified in the field through discussions with local people and experts. Subsequently, the verified warning system information was categorized into three classes (i.e., effective, moderate and ineffective) based on local administrative units (Fig. 5d).

[Fig. 5 near here]

2.4 Alternative ranking and standardisation of criteria layers

Risk ratings were assigned and ranked for each alternative of spatial criteria in the scale of 5-points, where 1 indicates very-low risk and 5 indicates very-high risk (Table 2). The alternatives were ranked considering the contribution to risk and AHP guidelines.

[Table 2 near here]

A 10-m pixel raster layer was created for each criterion, converting them from vector to raster to apply the weighted overlay technique. A standardisation process was performed using a linear scale transformation in Equation 2 to bring the entire alternative ranking values into a common range from 0 to 1.

$$\mathbf{p} = \frac{\mathbf{x - min}}{\mathbf{max - min}} \tag{2}$$

where p refers to standardised score; min and max indicate the minimum and maximum values of each dataset, respectively; and x means a value of the single cell in the dataset.

2.5 Weighting the criteria using AHP

In the present study, the AHP decision-making algorithm was adopted to weigh the criteria of the three risk components for developing a risk map. The pairwise comparison matrix was developed for each of the risk components with the help of four experts and a user, who followed the "scale of relative importance" developed by Saaty (2008) (Table S1). All of them had considerable experience in coastal research, cyclone factors and their influence on the study site. The total score of each risk component was 1.

We calculated the consistency ratio (CR) to justify the consistency of comparison assigned by the experts and user. The comparisons are considered at the acceptable level if the CR value is equal or less than 0.1. The CR was calculated using Equation 3:

$$\text{CR} = \text{Consistency Index/Random Index}, \quad (3)$$

where random index (RI) presents the randomly generated average consistency index, and the consistency index (CI) can be calculated as follows:

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

where λ_{max} is the largest eigenvalue of the matrix and *n* denotes the matrix order (Malczewski, 2010).

Table 3 outlines the criteria weights and consistency ratios calculated from the pairwise comparison.

[Table 3 near here]

2.6 Risk assessment

On the basis of the weighted overlay technique, we developed the vulnerability and exposure, hazard and mitigation capacity indices incorporating their related criteria weights. Afterward, we produced the vulnerability and exposure, hazard and mitigation capacity maps grouping the specific index values into five levels (i.e., very-low, low, moderate, high and very-high). Finally, an integrated risk index was generated using Equation 1 following the raster calculator within the ArcGIS platform. A standardisation process was then executed using Equation 2 to bring the risk index values in the scale from 0 to 1. Thereafter, a risk map was produced to classify the risk index values into five categories of risk (i.e., very-low, low, moderate, high and very-high).

2.7 Risk mapping validation

The validation of spatial risk assessment results is challenging, no specific validation approaches are available in the literature. We employed a qualitative validation approach to evaluate the risk assessment results (Roy and Blaschke, 2013). The study area was visited between March and August 2018 to obtain feedback from the local people, experts and policymakers regarding our software-generated risk assessment results. Feedback was obtained from approximately 70 people across the study area. In addition, in-depth personal observation was conducted by identifying the specific risk levels to particular areas from the map and verifying the actual risk to tropical cyclones. Historical tropical cyclone occurrences and their impacts were likewise discovered from the visited sites through informal discussion with local people.

3. Results and discussion

3.1 Vulnerability and exposure mapping

The produced vulnerability and exposure map (Fig. 6a) shows that 40% (3056 km^2) of the study area was exposed to high to very-high vulnerability to tropical cyclone impacts. These areas are located in the western and north-western region of the study area, particularly Sandwip, Kutubdia, Chakaria, Anowara, Chittagong Sadar, Maheshkhali, Cox's Bazar and part of Mirsharai as well as Banskhali. Several important factors, such as closeness to cyclone track and coastline, lower elevation, gentle slopes, high population densities and land cover types, are accountable for this high vulnerability and exposure to tropical cyclone risks. In addition, approximately 25% (1935 km^2) of the study area was classified under moderate vulnerability. Meanwhile, 35% (2568 km^2) was classified with very-low to low vulnerability and exposure to tropical cyclones. Very-low to low vulnerable and exposure areas covered the eastern and north-eastern parts of the study area. The lesser vulnerability of these areas to tropical cyclones is specifically due to their higher elevation, steep slope, low population and distance from coastlines.

3.2 Hazard mapping

Fig. 6b shows the spatial variation and degree of hazard in the study area. Hazard mapping illustrates that 22% (1652 km^2) of the study site was considered a very-high hazard zone, followed by 21% (1661 km^2) as a high hazard zone. Most of these areas were located in the north-western, western and south-western portions of the study site, specifically, the southern part of Teknaf, Cox's Bazar, Maheshkhali, Kutubdia, Chakaria, Banskhali, Sandwip and coastline areas extending from Chittagong Sadar to Sonagzi. The main reasons for high hazard intensity in these locations are high storm surge impacts due to proximity to coastlines, low elevation, high precipitation intensity and frequency of cyclones. The area classified as a moderate hazard zone covered 19% (1399 km^2) of the study site and was mostly located in the central portion of the study site. A considerable area along the coastline of Ramu, Ukhia and Teknaf were classified as a moderate hazard zone due to the lesser impact of storm surge as a hilly area. Conversely, 18% (1403 km^2) and 20% (1444 km^2) of the area were categorised as low and very-low hazard zones, respectively. These two categories covered most of the hilly regions, located in the eastern and north-eastern portion of the study site. The hazard levels were notably low in these areas due to few influences of high wind speed, storm surge and precipitation.

3.3 Mitigation capacity mapping

Fig. 6c shows the overall mitigation capacity of the study site against the tropical cyclone impacts. High mitigation capacity areas refer to appropriate actions that are already planned and implemented to minimise the levels of risk to hazards. From mitigation mapping, the north-western and westerns portion of the study site showed high to very-high mitigation capacity. These areas accounted for 25% (1906 km^2) of the study site, with most of them close to basic facilities and infrastructure such as a cyclone shelter, hospital and effective warning system. However, a considerable area (24% ~ 1803 km^2) along and a little farther from the coast covering Sandwip, Chakaria, Kutubdia, Maheshkhali Cox Bazar and parts of Teknaf were classified under moderate mitigation capacity. In this area, many coastal people living and tourists frequently visit. Moreover, low and very low mitigation capacity was observed in the eastern and south-eastern sides of the study site, comprising 51% (3850 km^2) of the area. Proper mitigation processes are absent in these locations, and at present, many refugees (fled from Myanmar) live there.

[Fig. 6 near here]

3.4 Risk mapping

The overall risk of the study site to tropical cyclones is depicted spatially in Fig. 6d. Risk mapping illustrates that a very-high-risk zone covered 9% (650 km^2) of the study site, whereas high-risk zone constituted 27% (2046 km^2). Both of these category risk zones were located in the north-western, western, south-western and southern parts of the study site. High risks to tropical cyclone impacts were explicitly observed in Sandwip, Sonagazi, Patiya, Kutubdia, Maheshkhali, Chakaria, Teknaf, and parts of Hathazari, Chittagong and Cox's Bazar Sadar (Table S2). Most of these areas are located close to the coastlines and have inadequate mitigation measures. Furthermore, 25% (1827 km^2) of the area was considered a moderate risk zone. By contrast, 39% (3036 km^2) of the area was at the low and very low risk zone, mostly toward inland from the coastlines and located at the interior part of the study site. Most of these areas are located in the highland, north-eastern (Parshuram, part of Fatikchhari, Rangunia) and eastern parts (Satkania, Lohagara, Ramu) of the study site, bordering India (Table S2). Consistency was found in the spatial distribution of risk assessment results with the degree of vulnerability and hazard outputs, specifically; areas near the coast or with low elevation, steep slope, dense population, strong wind and high rainfall. However, the risk levels of several areas changed due to their mitigation capacity status.

3.5 Validation of risk map

The validation of risk mapping results by using a qualitative approach was promising. The summary of feedback obtained from local people, experts and policymakers on our results is shown in Table S3. Amongst the 70 respondents, approximately 47 (67%) respondents were highly satisfied with our results, whereas 15 (21%) were only satisfied. Conversely, approximately 8 (12%) of respondents were not satisfied with our results. Our risk map showed that areas of Sandwip, Sonagazi, Patiya, Kutubdia, Maheshkhali, Chakaria, Teknaf, parts of Hathazari, Cox's Bazar and Chittagong Sadar are under higher risk to tropical cyclones. The acquired field visit data likewise demonstrated similar levels of risk. Furthermore, good mitigation measures were observed along the coasts in the areas of Chittagong Sadar, Mirshari and Sitakunda. The levels of risks declined in the final risk map due to the reflection of mitigation measures in these areas, although the levels of hazard and vulnerability in these areas were found high.

4. Conclusion

In this study, we developed a comprehensive tropical cyclone risk map and quantified the degree of risk of the eastern coastal region (7664 sq. km) of Bangladesh to tropical cyclones. For the first time, the three components of risks are integrated, under which and the spatial layer of each criterion was created using remote sensing and GIS techniques to develop the tropical cyclone risk map. The risk map validation was successfully performed by adopting a field-based qualitative approach. The risk map illustrates high risks to tropical cyclone impacts for Sandwip, Sonagazi, Patiya, Kutubdia, Maheshkhali, Chakaria, Teknaf, as well as parts of Chittagong Sadar and Hathazari that are mostly close to coastlines. Communities, infrastructure and environments located within these high-risk areas are under primary impacts of tropical cyclones, such as storm surges, wind speed and heavy rainfall. In addition, Hathazari, Fatikchhari, Feni Sadar and Patiya located in the interior parts and away from the coastline are likewise under considerable risk of tropical cyclones. These locations are subjected to mostly secondary impacts, such as intense precipitation, wind speed, mudslide and thunderstorm. The concerned authorities could use these results to develop proactive mitigation strategies in the identified tropical cyclone risk zones to protect humans and resources from the catastrophic impacts of tropical cyclone disasters.

This study encountered several limitations, which may influence the outcomes. Multiple criteria were considered for effective risk assessment. However, managing quality and up to date data for each criteria processing was challenging as a developing country's study site. For instance, high resolution topographic data such as Light Detection and Ranging (LiDAR) was required for good risk assessment; instead, we used the 10-m resolution DEM. The LULC of the study site was classified using freely available 10-m spatial resolution sentinel imagery;

however, high resolution satellite data could have performed well. In addition, the used population data were old because the last population and housing census conducted in Bangladesh was in 2011, and the next one is scheduled in 2021. Furthermore, only one cyclone wind speed was considered due to spatial data unavailability. The sea level rise could be considered for assessing the effects of climate change on the storm surges. Another drawback is that, a qualitative validation approach was used to evaluate the risk assessment results. Quantitative judgment can effectively validate the produced results. The qualitative feedback collection was also limited to 70 respondents due to time constraint and lack of funding. These drawbacks can be addressed in future studies.

Despite the few limitations mentioned above, the generated risk assessment results in this study are still very useful to develop and apply on effective mitigation policy and measures for reducing the impacts of tropical cyclones in the coastal region of Bangladesh. The example of mitigation measures for the study site, in particular, high tropical cyclone risk areas (Sandwip, Sonagazi, Patiya, Kutubdia, Maheshkhali, Chakaria, Teknaf, Sadar and Hathazari) may include planting mangrove trees along the coast, constructing cyclone shelter and emergency management structure, developing warning systems, or creating setback zones by erecting sea walls or dykes. Indeed, the intensity and frequency of cyclones may increase in the Bay of Bengal, thereby minimizing the impacts that would largely rely on the capacity of communities to adapt planning and applying strong mitigation measures. The developed maps of risk components in this study may assist as a strong baseline to formulate coastal risk management strategies that would combat and minimise the effects of tropical cyclones in the eastern coastal region of Bangladesh. Since many coastal areas of the world are often affected by tropical cyclones. This developed and evaluated approach can be used to mapping tropical cyclone risk in other coastal environments. Although the selection of criteria, data type and scale are site-specific.

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Conflicts of interest

The authors declare no conflict of interest.

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