Coastal erosion vulnerability assessment along the eastern coast of Bangladesh using geospatial techniques

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Assessment of coastal erosion vulnerability along the eastern coast of Bangladesh using geospatial techniques.

Abstract

Coastal zones are physically, socially, and economically important. However, many coastal zones are highly vulnerable to coastal erosion due to high population density, tourist attractions, developed economy, and lowland. Erosion vulnerability assessment with limited criteria and components cannot provide detailed and accurate results. Therefore, an integrated vulnerability assessment of coastal erosion is essential to produce detailed and accurate erosion vulnerability information to support mitigation strategies. This study aims to prepare an integrated coastal erosion vulnerability approach using geospatial techniques and examine the pattern of vulnerability to coastal erosion effects in the eastern coastal region of Bangladesh. Thirteen spatial criteria under two components of vulnerability, namely, physical and socio-economic vulnerability, were assessed. These criteria were weighted on the basis of the analytical hierarchy process (AHP) and then combined to generate individual vulnerability indices. Finally, the overall vulnerability map was produced by integrating physical and social vulnerability indices. Results showed that the area of very high vulnerability includes 11% of the region, and the area of high vulnerability was 24%. Parts of Chittagong Port, Cox's Bazar, Kutubdia, Teknaf, Ukhia, Anowara, and some portions of Moheshkhali regions close to the coastline of the study site are likely to experience high vulnerability of coastal erosion impacts. The area was classified as a low- and very-low-vulnerability zone, representing 27% and 8%, respectively. For evaluating the efficiency of the outcome, the receiver operating characteristics (ROC) technique was used to validate the physical erosion vulnerability results, which stated an 85.2% success rate and 80.1% prediction rate of the produced results. The findings can be used by concerned authorities to protect coastal erosion and minimise its effects on properties and coastal environments.

Keywords: Coastal erosion; Coastal vulnerability; GIS; Remote sensing; Analytical hierarchy process

1. Introduction

Coastal erosion is a severe problem for coastal communities worldwide (Rangel-Buitrago et al., 2018). The rise in sea level will accelerate this process in many coastal areas under climate change scenarios (Li et al., 2015; Awange et al., 2018). Coastal erosion has become considered a critical issue because population concentration is high in coastal areas with many development activities, such as industrial activities and increased transportation and tourism activities (Barragán and de Andrés, 2015; Rumson et al., 2017; Thomas et al., 2018). Approximately 20% (1409 million) of the world's population live within 25 km, and 40% (2818) reside within the 100 km from the coastline (Rangel-Buitrago et al., 2018). Rapid developments are observed in coastal areas across the world. From 1950 to 2015, the number of coastal cities has increased from 472 to 2,129 (Stronkhorst et al., 2018). Globally, approximately 30% of residences in 200 m-long low coasts have been estimated to be highly affected by erosion, resulting in losses to properties in the next 50 years (Rangel-Buitrago et al., 2018). Erosion along the coast can affect human life, cultivation, biodiversity, natural resources, and other economic sectors on a large scale (Boruff et al., 2005; Kaliraj et al., 2015).

Bangladesh has become one of the most disaster-prone countries in the world due to its geographical location and various climate issues (Ahmed et al., 2016; Hoque et al., 2018a). The coastal areas of Bangladesh experience several types of hazards each year, such as coastal erosion, tropical cyclones and floods, which simultaneously result in loss of lives and damages to properties and environments (Nicholls et al., 2007; Karim and Mimura, 2008; Warrick and Ahmad, 2012; Hoque et al., 2018b). Sandwip and Kutubdia islands are located in the eastern coastal region of Bangladesh. Sandwip island's 40% of the land has been eroded in the last few decades, and Kutubdia Island has lost approximately 10% of its area (Brammer, 2014). The eastern coast of Bangladesh consists of 145 km-long beach, which is under constant threat of beach erosion (Sarwar, 2005). The coast near Chittagong has experienced an erosion rate of 36 m/year, and the Cox Bazar coast has encountered 51 m/year erosion rate (Sarwar and Woodroffe, 2013). In the future, Bangladesh will suffer from the severe effects of climate change, such as rising sea levels, which will intensify the impact of coastal erosion across coastal districts, thereby creating adverse effects on the local economy and the environment (Karim and Mimura, 2008; Sarwar, 2013; Abedin et al., 2019).

The spatial assessment of vulnerability to coastal erosion can assist in formulating and implementing mitigation measures (Kantamaneni et al., 2018). Vulnerability is defined as the dimension of damage that can be reckoned considering certain exposure, susceptibility, and resilience factors (Balica et al., 2012). Geospatial techniques via remote sensing and spatial analysis can efficiently map and assess vulnerability to coastal erosion (Jana and Bhattacharya, 2013; Kaliraj et al., 2015; Li et al., 2015). Remote sensing can provide temporal images to map environmental characteristics from spatial scales of a few metres to whole continents (Jana and Bhattacharya, 2013). Spatial analysis helps in the collection, analysis and integration of spatial and non-spatial data for spatial decision-making (Merlotto et al., 2016; Bevacqua et al., 2018; Fitton et al., 2018). Weighting and ranking are essential to incorporate and assess multiple criteria in the erosion vulnerability assessment (Li et al., 2015). Analytical hierarchy process (AHP) is an efficient tool for integrating multiple criteria in a spatial decision-making process (Malczewski, 2010). AHP uses a hierarchical structure to assign weighting and ranking incorporating the opinions of experts and users (Malczewski, 1999; Malczewski, 2006). AHP has been employed successfully to map hazards, vulnerability and risk of other natural types of disasters, such as floods, landslides, tropical cyclones and earthquakes, making it suitable for the vulnerability assessment of coastal erosion (Roy and Blaschke, 2013; Panahi et al., 2014; Ahmed, 2015; Hoque et al., 2018a).

Many studies focus on multi-hazard coastal vulnerability assessment (Kumar and Kunte, 2012; Kunte et al., 2014; Bagdanavičiūtė et al., 2015; Denner et al., 2015; Mahapatra et al., 2015; Islam et al., 2016; Kantamaneni et al., 2018; Sahoo and Bhaskaran, 2018; Ahammed and Pandey, 2019). However, studies related to the direct assessment of coastal erosion vulnerability are limited, although coastal erosion causes significantly high occurrences, calamities and economic harm to properties and environments. Studies mostly focus on erosion vulnerability assessment based on physical criteria (Anfuso and Del Pozo, 2009; Jana and Bhattacharya, 2013). Anfuso and Del Pozo (2009) assessed vulnerability to coastal erosion by considering few physical criteria, such as land use, wave height and coastal evolution; thus far, no approach has been established to assign weight and rank in multi-criteria evaluation. Jana and Bhattacharya (2013) calculated vulnerability to coastal erosion by using only three criteria, namely, shoreline change rate, land use and population density, and coastal vulnerability was evaluated only at 1 km inland from the shoreline. Several studies have assessed coastal erosion risk by incorporating vulnerability, exposure and hazard (Li et al., 2015; Merlotto et al., 2016; Narra et al., 2017). Socio-economic criteria were not considered on a broad scale because they are equally important for assessing the risk or vulnerability of coastal erosion (Bouaziz et al., 2011; Li et al., 2015; Merlotto et al., 2016; Narra et al., 2017; Fitton et al., 2018; Serafim et al., 2019). Li et al. (2015) assessed coastal erosion risk along the coastline of Yang Muddy Coast by considering 10 vulnerability indicators and three impact indicators. Their study was conducted on a broad scale, and AHP technique was used to produce a risk map, but socio-economic criteria were not considered.

Numerous studies are reported on Bangladesh coastal vulnerability (Sarwar and Woodroffe, 2013; Islam et al., 2016; Ahmed et al., 2018a; Hoque et al., 2019a; Mullick et al., 2019; Mahmood et al., 2020). Ahmed et al. (2018a) developed a model of land susceptible to coastal erosion to explore coastal physical susceptibility to erosion and applied it in coastal Bangladesh. This model was developed by only considering physical criteria at the regional scale. Mullick et al. (2019) and Hoque et al. (2019a) developed a coastal vulnerability index to multi-hazard events by focusing on the Bangladesh coast by using a geospatial approach but did not directly focus on coastal erosion assessment. In contrast, Sarwar and Woodroffe (2013) calculated only the rate of shoreline changes for coastal Bangladesh. Recently, Mahmood et al. (2020) assessed the coastal vulnerability of Meghna estuary covering mostly the central coastal region of Bangladesh. The coastal areas of Bangladesh are classified into three coastal regions, namely, western, central and eastern, according to geomorphic characteristics (Karim and Mimura, 2008). Although the eastern coastal region is highly vulnerable to coastal erosion, its assessment of coastal erosion vulnerability incorporating socio-economic criteria has not been studied using the AHP-based multi-criteria decision-making approach.

This study aims to prepare a coastal erosion vulnerability approach that integrates physical and socio-economic criteria by using geospatial techniques and to examine the spatial pattern of vulnerability of the impacts of coastal erosion on the eastern coastal region of Bangladesh to support mitigation measures. The specific objectives of this study include the following: (1) to develop a physical and socio-economic vulnerability indices of coastal erosion impacts by using the AHP-based multi-criteria decision-making approach; (2) to produce a vulnerability index that integrates physical and socio-economic criteria to examine the spatial pattern of the vulnerability of coastal erosion impacts, and (3) to evaluate the results of the spatial vulnerability assessment.

2. Study area

This study focused on the eastern coastal region of Bangladesh, covering the 54 coastal unions (smallest administrative unit) of Chittagong and Cox's Bazar coastal districts (Fig. 1). This region is extended from the Mirsarai Upazila along the Meghna Estuary of Feni river to Teknaf Upazila of the southern part of Bangladesh. The geographical extension of this area is 20°46′–22°29′ N latitude and 91°26′–92°20′ E longitude. The total area of the studied coastal region is 1,503 km^2 with a population of 9.2 million, who mostly depend on the resources of the Bay of Bengal (BBS, 2012). The coast is approximately 377 km-long, and the soil is composed of tidal muds, estuarine deposits, submerged beach and dune sands (Islam, 2001). Submerged sand stretches on the 145 km-long beach and extends from Cox's Bazar to Teknaf, thereby attracting millions of tourists every year. This longest sea beach has experienced extensive coastal erosion, which will likely to increase in the future (Sarwar, 2005). The tropical monsoon climate prevails over this coastal region, with a daily mean average temperature of 25.9 ℃ (Peel et al., 2007). The mean annual rainfall has been observed >3000 mm in this region (Brammer, 2014). Fish farming, fishing in the sea, salt cultivation and tourism are the main sources of economic activities that are observed in this coastal region. The rate of sea level rise is 7.8 mm per year in this coastal region, which is higher compared to the two other coastal regions of Bangladesh (Sarwar and Woodroffe, 2013). Erosion is very common in this coastal region. Rapid climate change and rising sea level may expedite the coastal erosion of this region. Consequently, increasing coastal erosion can severely damage coastal environments, hamper agricultural activities and may interrupt tourism sectors (Wright et al., 2019).

[Fig. 1 near here]

3. Materials and methods

To assess coastal erosion vulnerability, the current study adopted multi-criteria assessment methods through AHP and geospatial techniques. The AHP approach incorporates and aggregates multi-criteria decision-making process efficiently (Malczewski, 2010; Stefanidis and Stathis, 2013). The methodological aspect of the study is interpreted in Fig 2.

[Fig. 2 near here]

3.1 Data set and sources

Several criteria under two vulnerability indices were considered to assess coastal erosion vulnerability. The data used in the study were aggregated from multiple data sources comprising both national as well as international organizations considering existing literature, data availability, and several field visits Field visits were conducted primarily to evaluate the findings of the study and investigate erosion affected areas. Table 1 explains the data type, sources, and other relevant information of each criterion in a concise format.

[Table 1 near here]

3.2 Vulnerability evaluation criteria, alternatives and mapping

Thirteen criteria were selected, comprising seven physical and six socio-economic criteria. The criteria were selected on the basis of the accessibility of data and relevance to coastal erosion. GIS and remote sensing techniques were used to generate the spatial layers of the selected criteria by using ENVI 5.4 and ArcGIS 10.4 software. The cell size of each raster spatial layer was 10 m × 10 m. This study used natural break statistical techniques to classify the produced maps for its consistency in presenting the spatial pattern of erosion vulnerability (Baeza et al., 2016; Hoque et al., 2019b). The characteristics and mapping approaches of each criterion are explained in the following paragraphs. Table 2 briefly provides details about the statement of each criterion, methodology and relationship with coastal erosion vulnerability.

[Table 2 near here]

3.2.1 Criteria for physical vulnerability mapping

Seven criteria, which are related to coastal erosion of physical vulnerability, were selected. The selected criteria were elevation, slope, geomorphology, soil texture, proximity to coastline, coastal vegetation and shoreline change.

Elevation and slope play an important role in assessing vulnerability to coastal erosion (Li et al., 2015; Narra et al., 2017). Areas with low elevation and steep are highly vulnerable to coastal erosion, and areas with a gradual slope and high elevation are less vulnerable. Vulnerability increases with a decrease in elevation because wave action and tide will initially affect those areas, where ocean and sea water can reach first (Li et al., 2015). In this research, digital elevation model (DEM) was acquired from Survey of Bangladesh (SOB) with 10 m resolution to generate an elevation and slope map (Fig. 3a, 3b).

Coastal geomorphology demonstrates the evolution of the landscape and reveals the relative erosion of various kinds of landforms (Hegde and Akshaya, 2015; Mahapatra et al., 2015). The geomorphological characteristics of the study area were categorised from bedrock to beach and dune sand to assess landform vulnerability to coastal erosion (Fig. 3c) (Islam et al., 2016). The coastal geomorphology layer was prepared using data obtained from the Geological Survey of Bangladesh (GOB). Soil texture is an important criterion for assessing coastal erosion vulnerability. Clay soil shows more resistance to coastal erosion, whereas sandy soil is mostly erodible (Botero-Acosta et al., 2017). Soil texture layer was then prepared using data acquired from the Bangladesh Agriculture Research Council (BARC) (Fig. 3d).

Proximity to coastline plays a vital role in the assessment of coastal erosion vulnerability. The vulnerability of shoreline, island and areas near the coast are higher than that of inland areas (Narra et al., 2017). 'Euclidean distance' tool in ArcGIS was used to generate proximity to the coastline spatial layer. On-screen manual digitisation of 2018 mosaic Sentinel 2 imagery was used to draw shoreline by using the Euclidean distance tool (Fig. 3e). Coastal vegetation protects coastal erosion by intercepting its actions to minimise the effects on coastal infrastructure and properties (Williams et al., 2018). The spatial layer of coastal vegetation was created using Sentinel-2 imagery. We used Normalised Difference Vegetation Index (NDVI) to calculate the density of coastal vegetation to categorise it into five classes in the ArcGIS platform. Mangrove vegetation was considered as coastal vegetation (Fig. 3f).

[Fig. 3 near here]

Twenty-four geometrically corrected freely available Landsat images were used to calculate shoreline change rate. These cloud-free images were collected between January to March during high tide. The two specific methods adopted for identifying coastline boundaries and calculating shoreline change rates are as follows: (1) water index algorithm for evaluating coastline boundaries between land and water and (2) digitising shoreline to run DSAS (Digital Shoreline Analysis System) tools. A modeller function of IDRISI SELVA was applied to prepare the Modified Normalised Difference Water Index (MNDWI) algorithm by using the combination of two bands of Landsat (green and mid-infrared) (Xu, 2006). An on-screen manual digitisation technique was then used to digitise the shoreline from the classified Landsat images (Kumar and Kamra, 2012). For further calculation, a baseline was made by digitising manually approximately 1 km onshore away from the nearest shoreline and then using both shorelines (1974, 1980, 1990, 1995, 2000, 2005, 2010 and 2016) and baseline. Final erosion/accretion rates were calculated using the DSAS tool. Linear regression was used for the final assessment of erosion and accretion rates at intervals of 100 m with 3,388 transects (Natesan et al., 2015). The study area was classified into five categories following the findings of shoreline change rate (Fig. 4).

[Fig. 4 near here]

3.2.2 Criteria for socio-economic vulnerability mapping

We selected six criteria to assess socio-economic vulnerability to coastal erosion. The selected criteria were population density, land use/land cover (LULC), dependent population, tourist spots, road network, and literacy rate.

Coastal population concentration and densities have a significant influence on coastal erosion (Adger et al., 2005). The age range of dependent people is between 0–14 and more than 65 years. Dependent populations are more vulnerable because they are unemployed or unable to earn. The area with less percentage of literate people is more vulnerable because people with a higher education level may seek better job options and can adapt by migrating to other places. The spatial layers of population density, dependent population and literacy rate were prepared using the Bangladesh population and housing census data of 2011 (Fig. 5a, b, c). The 2011 population and housing census was the last census, and the next one is scheduled in 2021.

LULC is a dynamic criterion for assessing vulnerability to coastal erosion. Five 10 m spatial resolution Sentinel-2 imageries were used to produce the LULC map (Fig. 5d). Pre-processing of sentinel-2 images was conducted using the Sen-2Cor tool of Sentinel Application Platform (SNAP) software. Eight LULC classes were selected to classify from satellite images by using a hybrid classification technique (Kumar et al., 2013). The selected classes were identified by implementing an unsupervised clustering algorithm. Sample data were then chosen using the maximum likelihood algorithm to conduct supervised classification by using ENVI 5.4 software. In brief, 505 samples were collected randomly during the same period from Google Earth to assess the accuracy of the classified images following the method explained in the studies of Hoque et al. (2016) and Jensen (2005). The overall accuracy and Kappa coefficient values were 92.1% and 91%, respectively.

Tourist spots and road networks are severely affected by coastal erosion (Kim et al., 2011). Tourist spots and road network data were obtained from Bangladesh Tourism Board (BTB) and the Local Government Engineering Department (LGED), respectively. The collected data were overlaid on the study area boundary to prepare tourist spots' spatial layer (Fig. 5e). Spatial road network layer was prepared using a 1 km buffer zone as a distance from the road, which was determined following the occurrence of coastal erosion to the closeness of the road (Fig. 5f).

Qualitative data such as population density, dependent population, literacy rate, and tourist spots were obtained based on the smallest administrative boundary (Union). Primarily, all the data were collected in vector format. The vector layers were classified into five alternatives and converted to raster format with 10m spatial resolution and rest of the processes are discussed in the following section.

[Fig. 5 near here]

3.3 Alternative ranking and standardisation of criterion layers

Vulnerability ratings in the scale of five-points were assigned and ranked for each alternative of spatial criterion layers, where very low vulnerability is indicated by one and very high vulnerability is represented by 5 (Table 3). The alternatives were ranked considering the contribution to erosion vulnerability and procedures of AHP.

[Table 3 near here]

For each criterion, a 10 m-pixel raster layer was generated by converting from vector to raster model for applying the weighted overlay technique. A standardisation method was applied using the linear scale transformation Equation 1 to prepare the entire alternative ranking values into a common range from 0 to 1.

$$\boldsymbol{p} = \frac{\boldsymbol{x - min}}{\boldsymbol{- min}} \qquad (1)$$

where *p* is the standardised score, min and max refer to the minimum and maximum values, and *x* indicates the value of the single cell in the dataset.

3.4 Weighting the criteria using AHP

We employed the AHP decision-making algorithm to weigh the criteria of the two vulnerability indices and develop an overall vulnerability map (Malczewski, 1999). For each vulnerability component, the pair-wise comparison matrix was created with the help of three experts and one user, who have considerable expertise in coastal erosion related studies and applied the scale of relative established by Saaty (2008). The composite score for each vulnerability component was 1.

Consistency ratio (CR) was calculated using Eq. 2 to check the consistency in the comparison assigned by the experts and a user and ensure that CR value does not exceed 0.1.

$$\boldsymbol{CR = Consistency\ Index/Random\ Index} \quad (2)$$

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

$$\boldsymbol{CI = (\lambda_{max} - n)/(n - 1)} \quad (3)$$

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

Table 4 outlines the criterion weights and consistency ratios calculated from the pairwise comparison.

[Table 4 near here]

3.5 Overall vulnerability assessment

Erosion vulnerability assessment was performed using a weighted overlay technique in ArcGIS software with physical and socio-economic criterion layers and their assigned weights. This process produced physical and socio-economic erosion vulnerability indices. The generated indices were grouped into five vulnerability classes (very low, low, moderate, high and very high) to generate physical and socio-economic erosion vulnerability maps. Finally, the overall erosion vulnerability was assessed by combining physical and socio-economic erosion vulnerability indices. These two indices were integrated with the generated weight (Table 4) by applying a weighted overlay technique. The overall erosion vulnerability index was then categorised into five vulnerability classes (very low to very high).

3.6 Efficiency assessment of physical erosion vulnerability results

To validate the physical erosion vulnerability map, we applied the receiver operating characteristic curve (ROC) and the area under the curve (AUC). Between April 2018 and May 2020, the study area was visited multiple times by the authors and inspected erosion affected areas to collect GPS (Global Positioning System) values of the specific erosion occurrence zones for verifying the accuracy of coastal erosion vulnerability results (Fig. 6). Altogether, 172 highly erosion affected locations were identified, and then the collected points were mapped using ArcGIS 10.4 (Fig.6). Field investigations at these particular places were conducted identifying particularly vulnerable regions from the erosion vulnerability map, taking photographs, and verifying the actual vulnerability to coastal erosion. Among the total 172 locations, training datasets resemble 70% of the erosion points, while validation datasets present just 30%.

[Fig. 6 near here]

4. Results

4.1 Physical vulnerability mapping

Fig. 7 demonstrates the degree of physical vulnerability to erosion in the study area. The high and very high physical vulnerability levels in the study area cover approximately 291 and 130 km^2, respectively, which comprise 28% of the total study area. High and very high physical vulnerability was observed in the southern, western and northwestern regions. Specifically, the Bairag, Barasat, Roypur union of Anowara upazila, Khurushkul of Cox's Bazar Sadar, Dhalghat and Matarbari of Maheshkhali Upazila and Kutubdia Island and some sections of Sandwip Island are mostly near the shoreline. Areas of moderate physical vulnerability account 513 km^2 of the study area. The moderate physical vulnerability area mainly lies in Teknaf, Kutubdia, Ramu, Cox's Bazar Sadar and interior parts of Sandwip. Most portions of the Maheshkhali and Sitakunda and the eastern parts of the Sandwip Islands belong to low or very-low physical vulnerability levels. .

[Fig. 7 near here]

4.2 Socio-economic vulnerability mapping

Fig. 8 displays the spatial distribution of socio-economic vulnerability to erosion in the study region. It introduces a pattern of coincidence with social and economic growth. High and very-high degree of socio-economic vulnerability was observed in the middle and southern portions of the study site, which covers approximately 824 km^2. The southern part of Ukhia and Teknaf, Northern part of Moheshkhali, almost every union of Kutubdia, Chittagong Port, Cox's Bazar, Sitakunda and Hathazari; and Sandwip, Mirsharai and Teknaf have low and very-low socio-economic vulnerability levels. More than half (54%) of the total study area has a high or very-high socio-economic vulnerability level, and low or very-low vulnerability levels occur in 24% of the study region (Fig. 8).

[Fig. 8 near here]

4.3 Overall vulnerability mapping

Fig. 9 spatially depicts the overall vulnerability to the coastal erosion of the study area. The overall vulnerability mapping shows that 523 km^2, which is approximately one-third (34.50%) of the total study area, represents a high and very high degree of vulnerability; this area is mainly located near to the coastlines or undergone continuous high erosional activities and may have inadequate mitigation measures. In the exposed parts of Chittagong city, Cox's Bazar, Kutubdia, Teknaf, Ukhia, Anowara and some portions of Moheshkhali, high and very high vulnerability to coastal erosion were explicitly observed (Table 5). Approximately 35.50% (533 km^2) of the area was covered by low and very low vulnerability zone, mostly toward inland from the coastline and at the interior part of the study site. Most of these areas experienced accretion activities and included the north-eastern (Mirsharai, Sandwip) and southern parts (Moheshkhali, Ramu) of the study site (Table 5). In addition, approximately 30% of the region was regarded as a moderately vulnerable region. Strong mitigation measures may modify vulnerability results in certain areas, although consistency was found among physical, socio-economic, and overall vulnerability results..

[Fig. 9 near here]

[Table 5 near here]

4.4 Efficiency assessment of physical erosion vulnerability approach

Fig.10 illustrates the success and prediction rate curves of the model performance employed for the study, which reveals, 0.852 of success rate that interprets 85.2% AUC success accuracy for the applied AHP model. On the contrary, the AUC of the prediction rate resembles 0.801, interpreting 80.1% of prediction accuracy for the physical erosion vulnerability results. The values of AUC range between 0.5 to 0.1, values higher than 0.8, and close to 1 represents a higher accuracy (Chen et al., 2018). Therefore, AUC values of prediction rate (80.1%) and success rate (85.2%) of this analysis resemble a successful outcome of our developed physical erosion vulnerability assessment approach.

[Fig. 10 near here]

5. Discussion

In the recent past, the importance of the coastal region has increased significantly. Consequently, the rate of coastal erosion around the world also has been increased dramatically, which is threatening the livings and economy of coastal people. The intensity of coastal erosion is likely to be enhanced in the future due to sea-level rise, which is related to climate change. Therefore, a coastal erosion vulnerability assessment integrating physical and social components is necessary to restrict coastal erosion and promote sustainable development.

Numerous methods around the world have been performed to assess coastal erosion vulnerability and risk. Most of the studies were conducted considering physical components or social components, either grid-based or performed on a regional scale (Jana and Bhattacharya, 2013; Ahmed et al., 2018a; Awange et al., 2018; Fitton et al., 2018). Thus, the motivation of the research was to propose an integrated vulnerability assessment technique taking into account physical and socio-economic components. This is because we believe in vulnerability assessment, both physical and social factors are equally important. Moreover, to our knowledge, this study is the first integrated approach for the eastern coast of Bangladesh focussing on coastal erosion vulnerability. In total, 13 vulnerability criteria (7 physical and 6 socio-economic) were selected to assess coastal erosion vulnerability through the AHP model. The findings demonstrated, for overall vulnerability, the high and very-high vulnerability class cover around 34% of the study area. Similarly, for physical vulnerability high and very-high vulnerability class represents around 28% of the study area. Conversely, more than half (55%)

of the study area of socio-economic index covered by very-high and high vulnerability class combined. Consistency was found among physical, socio-economic, and overall vulnerability results. The spatial distribution suggests Chittagong city, Cox's Bazar city, Teknaf, Kutubdia, and Ukhia Upazila are most vulnerable to coastal erosion, such finding is consistent with the outcome of Ahmed et al. (2018b), Hoque et al. (2019a), Mullick et al. (2019) and Ahmed et al. (2020). The majority portion of those Upazilas consists of mostly low elevation, steep slope, non-existence of mangrove, high population density, vulnerable land cover class, presence of roads, and other factors that made those regions more vulnerable. However, amongst all physical vulnerability criteria, the shoreline change rate was considered as the most crucial factor for assessing physical erosion vulnerability. The 42 years of analysis between 1974 and 2016 reveals the shoreline change rate ranges from -100m/yr to 83.96m/yr, and this finding corroborated by Hoque et al. (2019a), Sarwar and Woodroffe (2013) and (Roy and Mahmood, 2016). Apart from this, among social vulnerability, population density, and LULC acted as critical indicators in measuring the socio-economic vulnerability of the result. For instance, regions with high population density and other highly vulnerable socio-economic factors have demonstrated the actual picture of coastal erosion vulnerability. The integration of socio-economic index has strengthened the performance of erosion vulnerability models of previous works conducted considering only physical components or socio-economic components (Jana and Bhattacharya, 2013; Ahmed et al., 2018a; Awange et al., 2018; Fitton et al., 2018). Furthermore, the current study consolidates the other similar works of Hoque et al. (2019a), Martins et al. (2017), Li et al. (2015), Merlotto et al. (2016) and Narra et al. (2017). Thus, the proposed integrated model can be applied by planners and coastal engineers to restrict coastal erosion and maintain sustainable development.

However, this study has been confined by the availability of information and data for several criteria. For example, some essential criteria could be considered to evaluate the impacts of climate change on coastal erosion, such as sea-level rise, tide range, and significant wave height. Besides, the authors also had to overcome several challenges in managing the data-quality and provide up-to-date data because the study site belongs to a third-world country. The population census used was out-dated for the socio-economic criteria because it was performed in 2011, no alternatives are available because the next population census will be conducted in 2021. In addition, managing high-resolution LULC data was very difficult and challenging due to budgetary constraints. Therefore, freely available Sentinel-2 imagery was used for developing the LULC layer. DEM was used to quantify the elevation and slope criteria with a resolution of 10m. Future research may consider high-resolution satellite imagery, higher-resolution DEM, such as light detection and ranging (LiDAR), better-scale criteria, and other variables for improved erosion vulnerability assessment performance. Moreover, the current study was performed using a single model (AHP). However, the application of different multi-criteria decision analysis (MCDM) models (Fuzzy-AHP, Fuzzy Logic), Statistical models (Bivariate and multi-bivariate), artificial neural network (ANN), and Machine learning models may provide better output. Therefore, future studies can consider multiple models to compare between them as many other studies considering several models to assess other natural hazards such as floods, landslides, drought, etc. The best model can be attributed by the policymakers to inhibit future consequences of coastal erosion.

6. Recommendations for future coastal management

In order to protect the eastern coast from future coastal erosion, we have proposed some management strategies by considering current coastal erosion vulnerability results. The recommendations are summarized and outlined in Table 6. The specific degree of vulnerability results of this study was used to recommend the management strategies. Recommendations for future coastal management has been exhibited in details below:

- Due to the rapid shoreline changes, some portions of the study area belong to a very high degree of vulnerability. Establishing set back zones by establishing sea walls likely to be very useful to minimise the erosion rate. Moreover, shoreline stabilisation techniques such as mangrove plantation also recommended minimising slow coastal erosion (Sharma et al., 2016; Hoque et al., 2019a; Mullick et al., 2019). The coastlines of Sandwip Island, Kutubdia, Hathazari, and Bashkhali experienced rapid erosion (Figure 4). In some of these areas, three cross-dams have already been placed, and more cross-dams can be designed and built. Furthermore, developing additional polders along the coastlines with necessary observance can be a cost-efficient technique measure to conserve the agricultural lands and physical infrastructures located adjacent to the coastline.

Table 6. Suggested strategies for future coastal management.

Degree of vulnerability	Recommendation for future coastal management
Very high	a) Setback zones by establishing sea walls b) Shoreline stabilisation techniques and mangrove plantation. c) Cross-dams and polders, set back zones
High	a) Placement of additional geo-textile bags and replacing damaged ones. b) Developing set back zone and polders.
Moderate	a) Mangrove plantation b) A policy for future development.
Low and very low	a) Conservation of existing mangrove plantation and restrict human intervene.

- The study area under high coastal erosion vulnerability consists of the longest natural beach, which is 145 km long. Unfortunately, slow and continuous beach erosion puts the sandy beaches at risk. Geo-textile bags filled with sand were already installed in various erosion affected areas. Even though powerful wave activities commonly damaged a few of the established geo-textile bags still this is a more suitable and cost-effective measure for these coastlines. However, various illegitimate and harmful for ecosystem developments were noticed during field-work, mostly near the tourist spot. These unplanned infrastructures are serious threats to coastal areas and biodiversity. Governments must take a more active policy and strategy to stop them.
- The moderate vulnerability zones mainly situated in the interior portions of the study area, and some portions of Ramu Upazila also under moderate erosion vulnerability.

However, those areas can be in danger in the future under rapid climate change scenarios. Plantation of mangrove and robust policy for future development may be applicable for those vulnerable zones.

- Low and very-low vulnerability zones also covered a considerable portion of study areas coastlines, specifically, the coastlines of Sandwip, Mirsharai and Maheshkhli Upazilas. High accretion rate and presence of mangroves minimized the degree of vulnerability in those areas. However, conservation of existing mangrove plantations and restrict human intervention can be good mitigation measures for those low to very-vulnerable regions.

7. Conclusion

We prepared an integrated coastal erosion vulnerability approach combining physical and socio-economic criteria for examining the spatial pattern of vulnerability of the eastern coastal region (1,503 km^2) of Bangladesh to the coastal erosion. Several field visits were conducted to acquire erosion locations and the ROC technique was used to validate the physical erosion vulnerability results. The vulnerability map exhibited high vulnerability to coastal erosion impacts for Bairag, Barasat, Roypur union of Anowara Upazila, Khurushkul of Cox'sBazar Sadar, Dhalghat and Matarbari of Maheshkhali Upazila and almost all the unions of Kutubdia Island and part of Sandwip Island, which are quite close to the coastline. Communities, tourist attractions, and protected environments situatedwithin these high-vulnerability areas are directly affected by coastal erosion, as evidenced by damages to infrastructures, households, agricultural lands, and tourist attractions. Despite the few limitations listed above in the discussion section, the findings and recommendations of this current study are still very helpful in developing mitigation policies and practices to restrict coastal erosion consequences in Bangladesh's coastal region.

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Figure captions:

Fig. 1 Study area, eastern coastal region of Bangladesh. (a) Union (administrative unit) boundary of Eastern Coast mapped on Landsat 8 OLI (Operational Land Imager) images and (b) overall study area in the context of the coastal region of Bangladesh.

Fig. 2 Flowchart used for assessing coastal erosion vulnerability in this study.

Fig. 3 Physical vulnerability criteria layers: (a) elevation, (b) slope, (c) geomorphology, (d) soil texture, (e) proximity to coastline and (f) coastal vegetation.

Fig. 4 Zoomed-in view of selected localities: (a) Transect orientation of the zone includes Sandwip Island, Mirsharai, Sitakunda and Hathazari. (b) Transect orientation of the zone includes Chittagong city, Anowara and Bashkhali. (c) Transect orientation of the zone includes Kutubdia Island, Chakaria and Maheshkhali. (d) Transect orientation of the zone includes Cox's Bazar City, Ramu and Teknaf. (e) Zone-wise distribution of entire shoreline, illustrating shoreline change vulnerability.

Fig. 5 Socio-economic vulnerability criteria layers: (a) population density, (b) dependent population, (c) literacy rate, (d) LULC, (e) tourist spots and (f) road network.

Fig. 6 Field visit locations for validating the erosion vulnerability results in the study area.

Fig. 7 Physical vulnerability map showing spatial pattern and degree of vulnerability to coastal erosion.

Fig. 8 Socio-economic vulnerability map showing spatial pattern and degree of vulnerability to coastal erosion.

Fig. 9 Overall vulnerability map showing spatial pattern and degree of vulnerability to coastal erosion resulting from spatial physical vulnerability and socio-economic vulnerability indices.

Fig. 10. Area under the curve for success rate (85.2%) and prediction rate (80.1%).

Table captions:

Table 1. Data type and sources used for coastal erosion assessment.

Table 2. Description of the selected criteria, methods of calculation and rationale for coastal erosion vulnerability assessment.

Table 3. Ranking of alternative criteria following the contribution to coastal erosion vulnerability.

Table 4. Criterion weights and consistency ratios calculated from the pairwise comparison matrices.

Table 5. Distribution of districts, upazilas and unions in different vulnerability classes.