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ORIGINAL ARTICLE

Coastal Flood Induced Salinity Intrusion Risk Assessment Using a Spatial Multi-criteria Approach in the South-Western Bangladesh

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Abstract

Bangladesh is extremely vulnerable to sea-level rise and other climate-induced extreme events, such as flooding, storm surge, and salinity intrusion. The south-western coastal region of Bangladesh is particularly vulnerable to salinity intrusion caused by cyclone induced storm surges and coastal floods. Salinity intrusion endanger land productivity by increasing both soil and surface water salinity. Detailed risk assessment using spatial mapping approach can contribute to mitigating the effects of salinity intrusion on natural capital and the environment. In this study, we established and evaluated a spatial multi-criteria approach for mapping the risk levels of areas to salinity intrusion impacts using field data and geospatial techniques at the local scale. We evaluated the viability of the proposed approach using Khulna District, a major coastal city and saline prone area in the south-western Bangladesh. We considered three risk components (i.e. vulnerability, exposure and hazard) with 16 relevant criteria for the study. For each criterion, an Analytical Hierarchy Process (AHP) was used to build and weight spatial raster map layers. Individual maps for each risk component were generated using a weighted sum technique, and lastly, a risk map was created by combining those. Our generated maps correctly identified relevant spatial dimensions as well as risk levels (i.e. very-high to very-low). The outcomes of our study suggest that the southern (east and west) parts of the study area are mostly susceptible to salinity intrusion due to higher storm surge impacts, lower elevation, and land use patterns than other parts. We validate our findings using a qualitative and quantitative approach. We believe that this novel approach would be useful to create risk maps that policymakers and relevant stakeholders could potentially use to evaluate risks posed by flood induced salinity intrusion in coastal regions of Bangladesh and elsewhere with similar geo-climatic context.

Keywords Salinity intrusion · Risk analysis · Geospatial Techniques · Analytical Hierarchy Process (AHP) · Bangladesh

1 Introduction

Every year millions of people around the world are affected by various natural hazards (Haque et al. 2020). Coastal regions are highly vulnerable to catastrophic natural hazards globally. The impacts of natural hazards such as cyclones, floods, salinity intrusions are common in the low-lying coastal region due to recurrent climate change impact (Hoque et al. 2019a, b). Globally, over 1.5 billion people have already been displaced by natural disasters between

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2005 and 2015 from susceptible groups (Faisal et al. 2021). Salinity intrusion is a severe issue in coastal regions around the world, particularly in low-lying developing countries, and Bangladesh is not an exception (Rabbani et al. 2018; Shaibur et al. 2021). Bangladesh is ranked 7th amongst the most impacted countries between 1998 and 2017 on the Climate Risk Index (ADPC-UNDRR 2020). The overall salinity-affected land area in Bangladesh was 83.3 million hectares in 1973; which climbed to 102 million hectares in 2000; 105.6 million hectares in 2009; and is still increasing (SRDI 2019).

More than half of the total population of Bangladesh is directly or indirectly dependent on agriculture, which contributes to 20% of the country's total GDP. Agriculture is the dominant land use in coastal Bangladesh (Baten et al. 2015) and around 53% of the coastal areas are affected by salinity intrusion (Habiba et al. 2013). Salinity intrusion decreases soil productivity and crop yield which results in severe deterioration of bio-environment and ecology (Hoque et al. 2013). Furthermore, cumulative salt intake has considerable harmful effects on human health and well-being as well. A major risk factor for increased blood pressure among the locals in the region is just because of the high intake of salt in the coastal area. Around 20 million people in Bangladesh are at high risk of hypertension due to the intrusion of saline water triggered by climate change (Shammi et al. 2019). In the middle of 2012 and 2017, the International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDRB) scientists found that women in the coastal plains, living within 20 km of the coastline and 7 m above sea level were 1.3 times more likely to miscarry than women who live inland just because of consuming salt water (UNB, D 2019; Hossain 2019). Further, it is obstructing the growth of Bangladesh, which is estimated to intensify as a result of climate change and sea level rise (Hoque et al. 2013). The reduction of freshwater flow from upstream and fluctuation of soil salinity is a major concern for the coastal area of Bangladesh (Haider and Hossain 2013). Cyclones and tidal surges also trigger this problem by bringing saline water inside the coastal area through flooding, drainage congestion and waterlogging (Hoque et al. 2013). Therefore, assessing the risk of salinity intrusion in the coastal area of Bangladesh would be useful to develop an effective salinity intrusion mitigation plan and strategies for a better future and agricultural land-use planning.

Prevention and reduction are among the effective disaster management approaches to minimize the effects of salinity intrusion on humans, property and the environment (Hoque et al. 2019a, b). Besides finding a suitable mitigation capacity option, key facts like area in terms of geographical setting that are at risk, risk factors and level of risk etc. manners of information are requisite and these kinds of information is generally derived from risk assessment (Hoque et al. 2018). However, for conducting risk assessments to maintain and understand disaster risk, gathering and analyzing related data like vulnerabilities, exposure and hazard are essential for prioritizing investment and improving the capacity to issue timely and appropriate early warnings (Perwaiz et al. 2020). Hazards are events that endanger people, property, or the other settings (Dewan 2013). Vulnerability is related to the degree to which an element is exposed and the intensity to which a hazard is expected to have an impact on a community and the environment (UNDRR 2017). The degree to which the elements at risk are subjected to a specific hazard is referred to as exposure (Cardona et al. 2012). Moreover, vulnerability, exposure, and hazard all contribute to natural disaster risk and risk is reduced by mitigation capacity measures (UNDRR 2017). Policymakers and administrators can use risk assessment maps to develop effective management plans, including targeted prevention and reduction measures. As a result, the outcomes of risk assessment can help to minimize the loss of lives and properties and possibly can offer protection from catastrophic occurrences.

Remote sensing is an important tool for tracking local, regional, and global environmental issues. Spatial analysis has recently received much of attention due to the merging of geographic information system (GIS) and satellite images for environmental research and applications (Jabbar and Zhou 2012). The information needed for risk assessment can be acquired using geospatial techniques, as these are efficient and precise methods. Remote sensing data enables the availability of time-lapse scenarios of different ecological structures by spatial scales ranging from a small area to the whole world. With the use of such dynamic spatial data, we can assess the spatial risk of hazard events. Geospatial techniques facilitate gathering and analyzing spatial data and help us link spatial and non-spatial data for strategic decision making.

The Analytical Hierarchy Process (AHP) is a widely used multi-criteria weighting approach and an effective means of combining a variety of independent factors in an MCDM (multi-criteria decision-making) process in order to get a detailed risk assessment outcome (Malczewski 1999). Studies on salinity risk mapping using geospatial techniques are very scarce in Bangladesh, although salinity causes high impacts and damages to the environment and coastal population. AHP enables the evaluation of multi-criteria layers by generating hierarchical structure that provides weights as well as categorization to allow a spatial decision-making process incorporating expert and user input (Dewan 2013). In this study, the weighted sum technique was adopted to combine weighted and ranked spatial criteria layers. AHP has already been used successfully to map hazards, vulnerabilities as well as risks of various natural hazard events such as tropical cyclones (Hoque et al. 2021), floods (Ghosh and Kar 2018), landslides (Pourghasemi et al. 2012) and earthquakes (Jena et al. 2020). Therefore, this weighting approach is found appropriate for salinity intrusion risk assessment.

Many studies have been reported on salinity intrusion, though most of them possess limited criteria and components of risk valuation (Hoque et al. 2013; Das et al. 2020; Suvra et al. 2020). Furthermore, some of them are based on different method including hydrodynamic model or Delft3D model (Akter et al. 2000), GIS-based DRASTIC model (Nahin et al. 2020), GALDIT method (Klassen and Allen 2017). However, no studies to date have used multi criteria decision making approach individually for salinity intrusion risk assessment in Bangladesh. The selection of adequate and sufficient criteria, scale, and risk components determines accurate and detailed risk information (Dewan 2013). Appropriate criteria selection and processing for each risk component (i.e., hazard, vulnerability and exposure) serve as a foundation for more reliable risk assessment (Hoque et al. 2018). Similarly, the scale of the study area is critical in obtaining detailed risk information. In order to effectively figure out the type of risk and choose the most efficient mitigation strategies in formulating appropriate management plans, precise local level risk information is essential (Wisner et al. 2014).

The main goal of this study was to develop a coastal flood induced salinity intrusion risk assessment approach and apply this approach for assessing the salinity intrusion risk in the Khulna, a major coastal district in south-western Bangladesh. The specific objectives were: (1) to develop a coastal flood induced salinity intrusion risk assessment approach integrating all risk components with their relevant criteria using the AHP approach; (2) to apply the developed approach for quantifying the degree of salinity intrusion risk in the Khulna District of coastal Bangladesh and (3) to evaluate the produced risk assessment result.

2 Materials and method

2.1 The approach

For this study, a spatial multi-criteria assessment techniques in the form of AHP is used as a method of analysis which was first introduced by Saaty (1977). It is a most appropriate technique for supporting priority setting and better decision making when the phenomenon that is being studied involves both the quantitative and qualitative aspects of a decision (Dewan 2013).

Numerous risk equations exist for understanding risk for any type of hazard. However, choosing an appropriate risk assessment formula is mandatory for accurate results (Hoque et al. 2019a, b). After examining available literature (Saulnier et al. 2020; Tostevin 2017), the following equation has been implemented in this study to evaluate the risk:

$$\text{Risk} = \text{Vulnerability} \times \text{Exposure} \times \text{Hazard} \tag{1}$$

The flow of the processes used in this study is presented in Fig. 1.

2.2 The study area

We examine our novel approach on Khulna District, a south-western coastal saline-prone region in Bangladesh. The geographical extent of this region lies between 21°41′ and 23°00′ north latitudes and in between 89°14′ and 89°45′ east longitudes. To ensure consistency, we did not include the Sundarbans area in our study (Fig. 2). The main rivers that run through the district are the Koputaksha, Rupsha, Pasur, Kazibacha, Sibsha, Bhadra, and Sutarkali, all the rivers flow into the Bay of Bengal via streams and canals. They are tidal and navigable year round (Saran et al 2018; BBS 2013). The rivers cover an area of approximately 607.80 km^2, accounting for approximately 13.84% of the district's total area (BBS 2013). However, in 1973, the total amount of salinity-affected land in the Khulna district was 120.04 hectares, which increased to 147.96 hectares within four decades, in total the amount has climbed by 23.3% and is still rising (SRDI 2010). The southwestern coast of Bangladesh is prone to tropical cyclones and storm surges that floods areas with saline water (Dasgupta et al. 2010). According to the results of the various storm surge flooding extents with current sea levels, even a small cyclone with a 1-m surge has the potential to affect 1% of Bangladesh's area, and might reach the city of Khulna (Ashrafuzzaman et al. 2022). Moreover, the district has a hot summer and a mild winter. Summer lasts from the middle of April to the middle of June. Winter begins in November and continues through February. Rainfall is typically heavy between June and September. The annual rainfall in Khulna district totaled 162.3 mm in 2011 (BBS 2013).

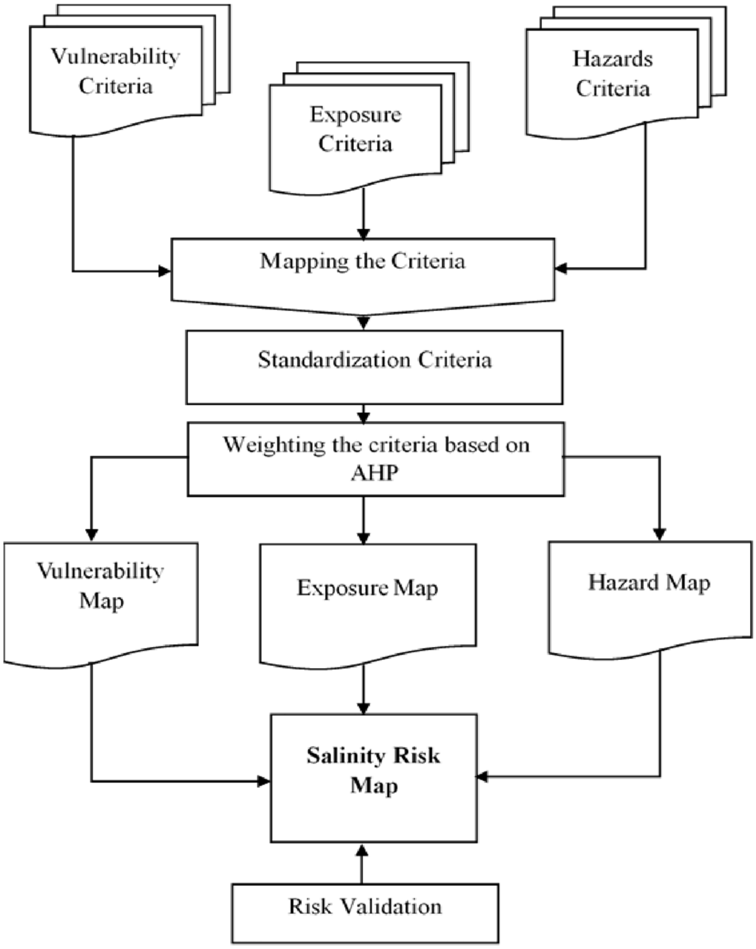
2.3 Dataset and data sources

For this study, various dynamic criteria were selected for risk assessment under three risk components. We used a wide range of data from a number of sources for preparing spatial criterion layers using GIS and remote sensing techniques. Hence, we collected those data from national to international government and private organizations along with fieldwork. More details are given in Table 1.

2.4 Risk evaluation criteria

Based on a literature study, we have identified several relevant factors as criteria for this study, prioritizing their

Fig. 1 Flowchart for salinity risk assessment used in this work



influence in the context of salinity intrusion risk assessment. Afterwards, we mapped all the selected criteria to convert those into thematic raster layers using GIS and RS techniques. A total of 16 distinct criteria layers were prepared under three risk components including hazard, vulnerability and exposure. We considered 15 m × 15 m cell size for individual raster layers with the Universal Transverse Mercator (UTM) zone 45 north and World Geodetic System (WGS)-1984 datum. We used ArcGIS 10.8 software with natural break and defined interval (e.g. rate of sea level change) statistical methods to create all the raster layers. The relevance of chosen criteria with details are provided in below.

2.4.1 Criteria for hazard mapping

The threat of salinity has emerged as a serious issue along Bangladesh's coast. It has a several adverse effects on the ecology, agricultural practice, and people's livelihoods (Akter 2018). There are several causes of salinity intrusion in Bangladesh's coastal region (Mahmuduzzaman et al. 2014). Based on the relevance of the study, five criteria were chosen to evaluate the possible hazard condition of the study area. These are salinity level, rate of sea-level change, mean tide range, storm surges height, distance to the river channel. The criteria were selected based on location, time, intensity, frequency and some environmental factors.

i. *Salinity level* The amount of salt dissolved in a body of water is called saline water. It is usually measured in g/L or dS/cm. For this study, surface water salinity data was collected from the Bangladesh Water Development Board (BWDB). We, then processed raw salinity data to create thematic salinity level raster criteria layer through IDW (Inverse Distance Weighting) interpolation technique using ArcMap version 10.8 software (Fig. 3a). IDW is more suitable method to interpolate surface water salinity (Borovskaya et al. 2022).
ii. *Rate of sea-level change* Sea level rise has a direct impact on salinity intrusion in inland (Baten et al 2015).When sea level, or mean tidal elevation is high, salinities are greater than when sea level is low. More specifically sea level rise causes salinity intrusion (Akhi et al. 2019). However, climate change impacts

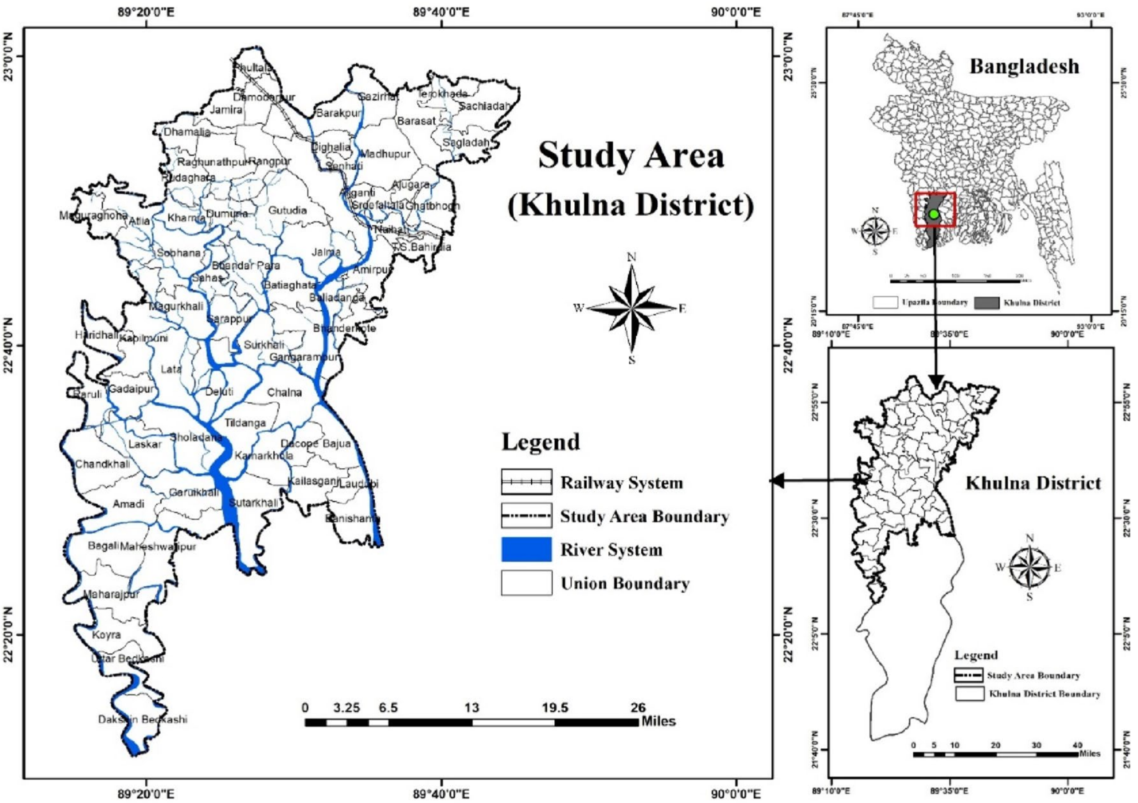


Fig. 2 Location of Khulna District in the southwestern coastal Bangladesh

Table 1 Data types and sources used in the present study

Data type	Data source	Time period	Output layer
Sentinel 2a (10 m resolution)	USGS	16.01.2022	Land use and land cover, Proximity to settlement, Distance to coastal vegetation
ASTER-(DEM) 30 m spatial resolution	Earth data	2013	Elevation, slope, storm surge height, distance to river channel
Cyclone track	International Best Track Archive for Climate Stewardship (IBTrACS)	1968–2020	Cyclone track density
Population Density	Bangladesh Bureau of Statistics (BBS)	2011	Population Density
Surface water salinity Data	Bangladesh Water Development Board (BWDB)	2017–2019	Salinity level
Soil Salinity	SRDI	2018–2022	Soil salinity
Water level	BWDB	2018–2020	Mean tide range, Rate of sea level change
Geology	https://pubs.er.usgs.gov/publication/ofr97470H	–	Geology
Embankment	LGED	–	Embankment density

accelerate the sea level rise that will continue to affect Bangladesh's coast through increased salinity intrusion in low-lying areas (Akter et al. 2016)**.** Sea level rise is considered a severe threat to coastal inhabitants and the impacts of sea level rise are projected to become more severe in later future (Hoque et al. 2019a, b). For this study, the annual tide gauge data from the Bangladesh Water Development Board (BWDB) were collected to evaluate the rate of sea-level change. Then we conducted a quality check for acquired data before entering in a spreadsheet to get the high and low tide values. After that, we used

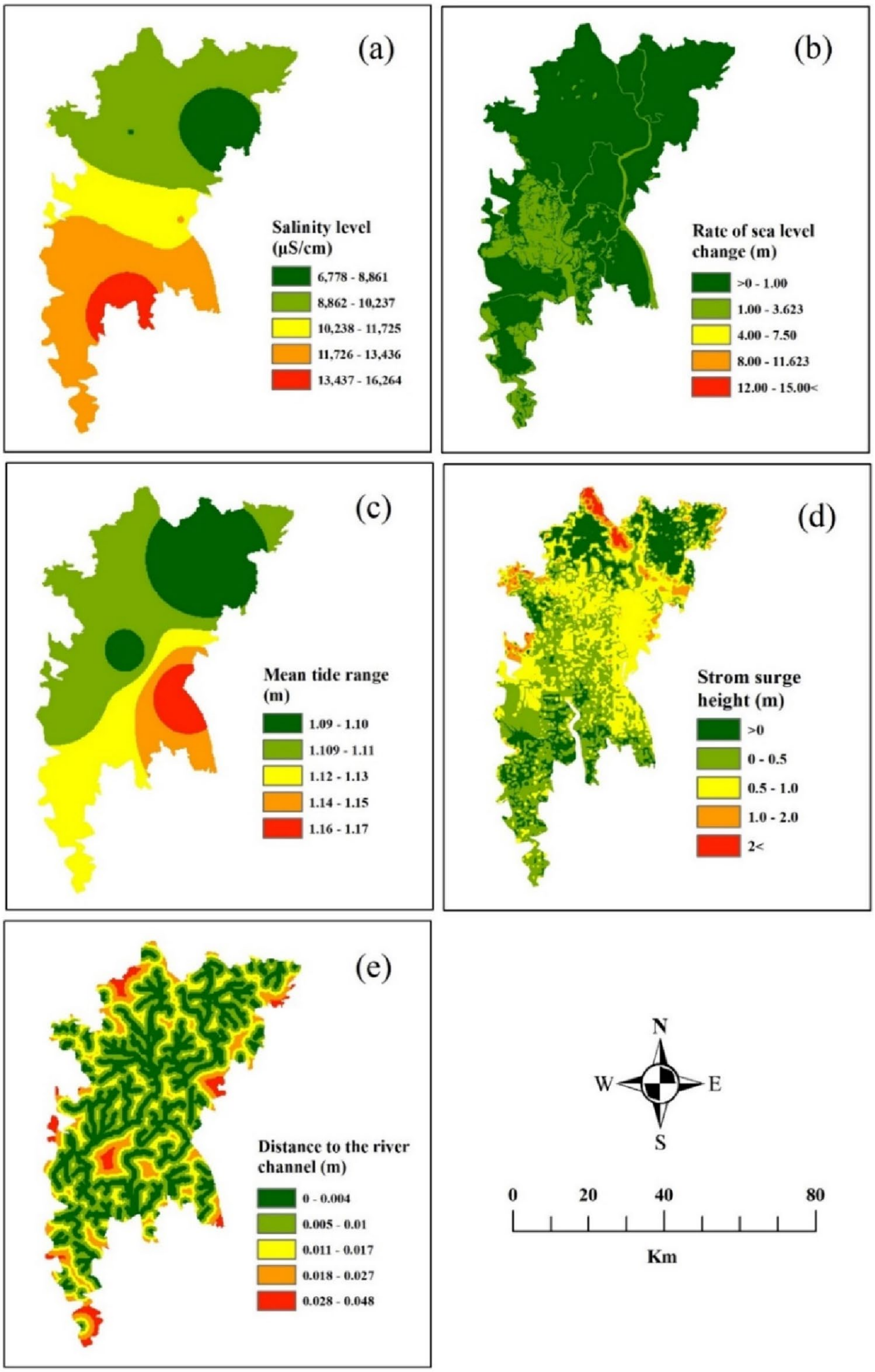


Fig. 3 Hazard mapping criteria used in the study: **a** salinity level, **b** rate of sea-level change, **c** mean tide range, **d** storm surge height, and **e** distance to the river channel

ASTER DEM 30 m data with the Raster Calculator tool from ArcGIS 10.8 software to get the final rate of sea level change criteria (Fig. 3b) mapping output.

iii. *Mean tide range* The vertical fluctuation between low and high tides is known as the tidal range (Stembridge 2014).Salinity varies with both tidal stage and tidal elevation. Therefore, a small tidal range results in less inland inundation and saline intrusion. On the other hand, high tide range provides a wide range of inundation with salinity. In this study, we calculated the mean tide range based on the annual tide gauge data. Then we joined those data with study area using Arc-

GIS 10.8. Next, we used IDW interpolation technique to get the mean tide range final thematic map (Fig. 3c).

iv. *Storm surges height* Storm surge heights regulate extensive inundation and flooding in the coastal zones (Hoque et al. 2018). However, storm surge induced flood cause salinity intrusion in the coastal belt of Bangladesh (Mahmuduzzaman et al. 2014). We adopted Gumbel distribution to conduct the frequency analysis in the present study. Using the calculated surge decay coefficient of surge height and a bare-earth DEM, we used different raster calculator equations using ArcGIS 10.8 to prepare a storm surge height map (Fig. 3d). The techniques adopted to produce the storm surge height map are detailed in Hoque et al. (2018).

v. *Distance to the river channel* The amount of salt intrusion into any place is significantly influenced by the distance to the river. River mouth and tidal freshwater of the river upstream comprises a pathway for exchanging water and materials between a drainage basin and coastal sea (Liu et al. 2007). Additionally, the land near the coastal belt and next to the active stream is more susceptible to coastal flood than the area farther away (Murshed et al. 2022). In this work, we extracted stream network information from ASTER DEM Earth data to create a distance to the river channel map (Fig. 3e). Then we used the Euclidian distance tool from ArcMap 10.3 to get the final thematic layer.

2.4.2 Selected criteria for vulnerability mapping

Some factors that influence saline intrusion sensitivity have been chosen as vulnerability criteria for this study. We have selected six distinct criteria in total for vulnerability mapping in this study (e.g. elevation, slope, geology, soil salinity, proximity to coastline and proximity to cyclone track).

i. *Proximity to the coastline* It is one of the vital factors for coastal salinity intrusion vulnerability mapping. Generally, areas close to the coast are considered more vulnerable to salinity intrusion than areas further inland. (Hoque et al. 2018). Therefore, for this study, we utilized the Google Earth Pro ruler tool to create the proximity to the coastline criteria layer (Fig. 4a). The proximity between the study area and the coastline were measured in this process. After that, we used the buffer tool from ArcTool box to get the final proximity to the coastline criteria layer.

ii. *Cyclone track density* Cyclone track density is another important criterion for salinity intrusion vulnerability assessment as it also causes inundation to coastal region. For this, the IBTrACS (International Best Track Archive for Climate Stewardship) data were used to prepare the cyclone tack density spatial layer (Fig. 4b). Around 31 cyclone track lines were found in the study area between 1968–2020-time period. ArcGIS line density tool was used to get the output map.

iii. *Elevation* While evaluating vulnerability, coastal elevation is very crucial. Flood-induced salinity intrusion is more likely to occur in places with gentle slopes than with steep slopes at higher elevations (Hoque et al. 2018). In the current study, an elevation criteria layer was produced (Fig. 4c) employing ASTER Digital Elevation Model (DEM) data with a 30 m spatial resolution.

iv. *Slope* Because of rising sea-level, coastal regions' slope patterns have a significant impact on coastal flooding (Hoque et al. 2019a, b). For this factor (Fig. 4d), we used an ASTER Digital Elevation Model (DEM) data with a resolution of 30 m to generate a thematic slope layer. Afterwards, the slope percentages were calculated using the ArcGIS spatial analyst extension tool.

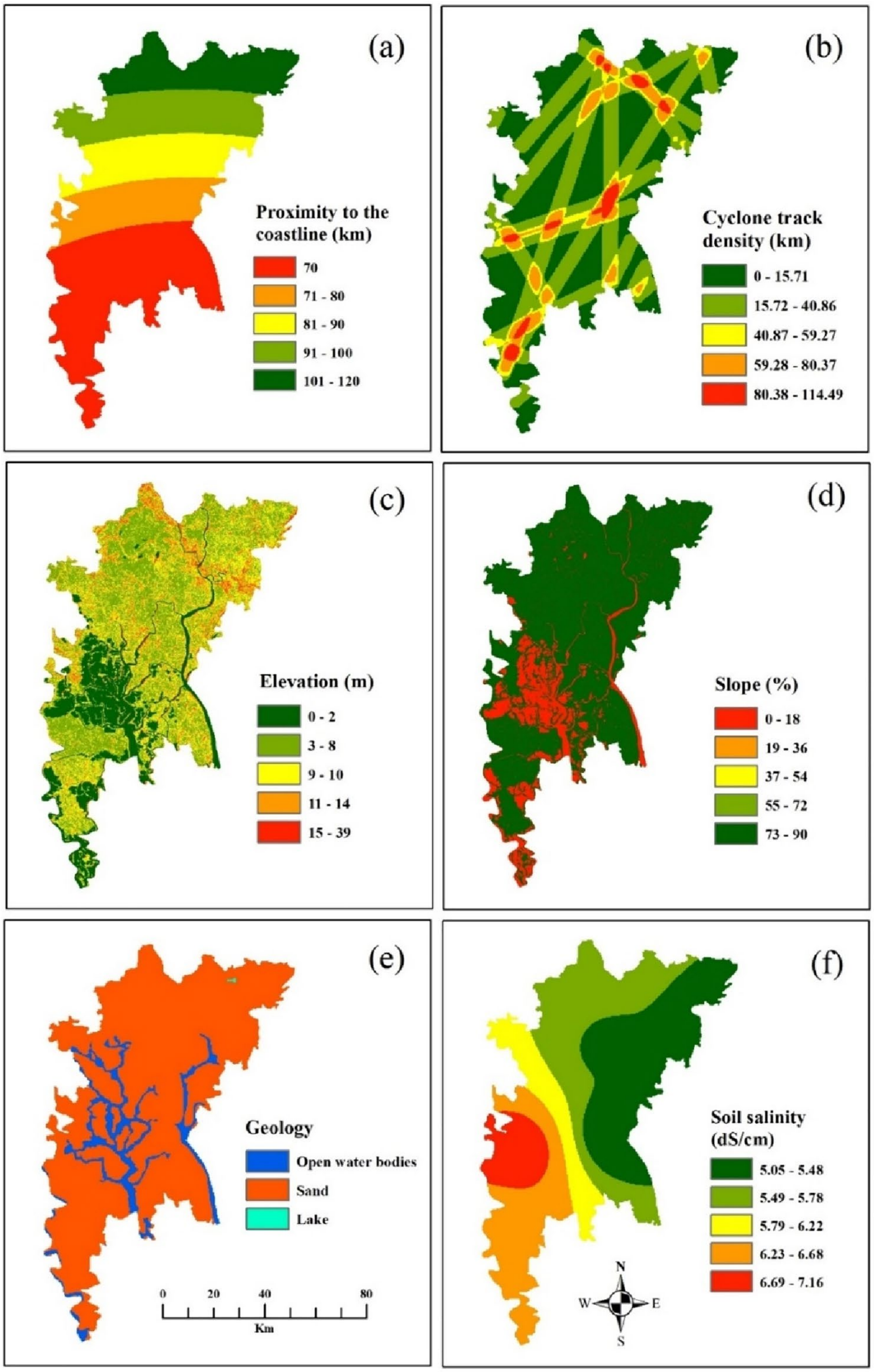
v. *Geology* A detailed picture of the coastal geology is essential to understand the landward salinity intrusion threat clearly (Meyer et al. 2019). In this study, data were collected from the USGS website ("Digital Geologic and Geophysical Data of Bangladesh," 1997) and then converted into a spatial layer using ArcMap 10.3 (Fig. 4e).

vi. *Soil salinity* Soil salinity is a leading threat to land productivity, water resources and agriculture in coastal Bangladesh (Gopalakrishnan and Kumar 2020).Therefore, there are numerous interacting drivers that influence soil salinity in Bangladesh, including climate variability, saline river water inundation, storm surge inundation, depth to groundwater table, groundwater salinity, and shrimp farming (Nicholls et al. 2018). In this study, soil sample were collected from the Soil Resource Development Institute (SRDI). After that, we processed those raw data using the Microsoft excel program and combined it with the study area shape file using ArcMap 10.8. We, then used IDW interpolation tool from the Arc Toolbox to generate the thematic layer (Fig. 4f).

2.4.3 Criteria for exposure mapping

In total, five criteria were selected linked to exposure for this study including LULC, population density, proximity to the settlement, embankment density, and distance from coastal vegetation.

Fig. 4 Criteria layers for vulnerability mapping: **a** proximity to the coastline, **b** cyclone track density, **c** elevation, **d** slope, **e** geology, and **f** soil salinity



i. *LULC (Land Use and Land Cover)* Land use and land cover is an essential indicator which plays a vital role in salinity intrusion. However, coastal regions of Bangladesh are diverse and dynamic in terms of land use patterns. Shrimp cultivation became one of the obvious land use techniques in the coastal area due to rising salinity (Hasan et al. 2020). To create the LULC criteria map (Fig. 5a), we used a Sentinel-2a image with a 10 m spatial resolution. All of these processes were performed using the ArcGIS 10.3 software. The Maximum Likelihood Classification (MLC) approach was adopted to get the LULC map. Then some random points obtained from the Google Earth imagery of the same time frames were used to assess the classification accuracy of the LULC map. A simple random sampling was used to produce 300 points, with at least 50 points in each class. Correspondingly, the kappa coefficient and total accuracy were 87% and 82% in accuracy assessment, respectively (see Table 2).

ii. *Population density* Coastal population density has a considerable influence on salinity intrusion risk assessment. Furthermore, saltwater intrusion has a great impact on people who are living in coastal areas of Bangladesh. In this study, we prepared the population density criteria layer (Fig. 5b) utilizing the population and housing census data.

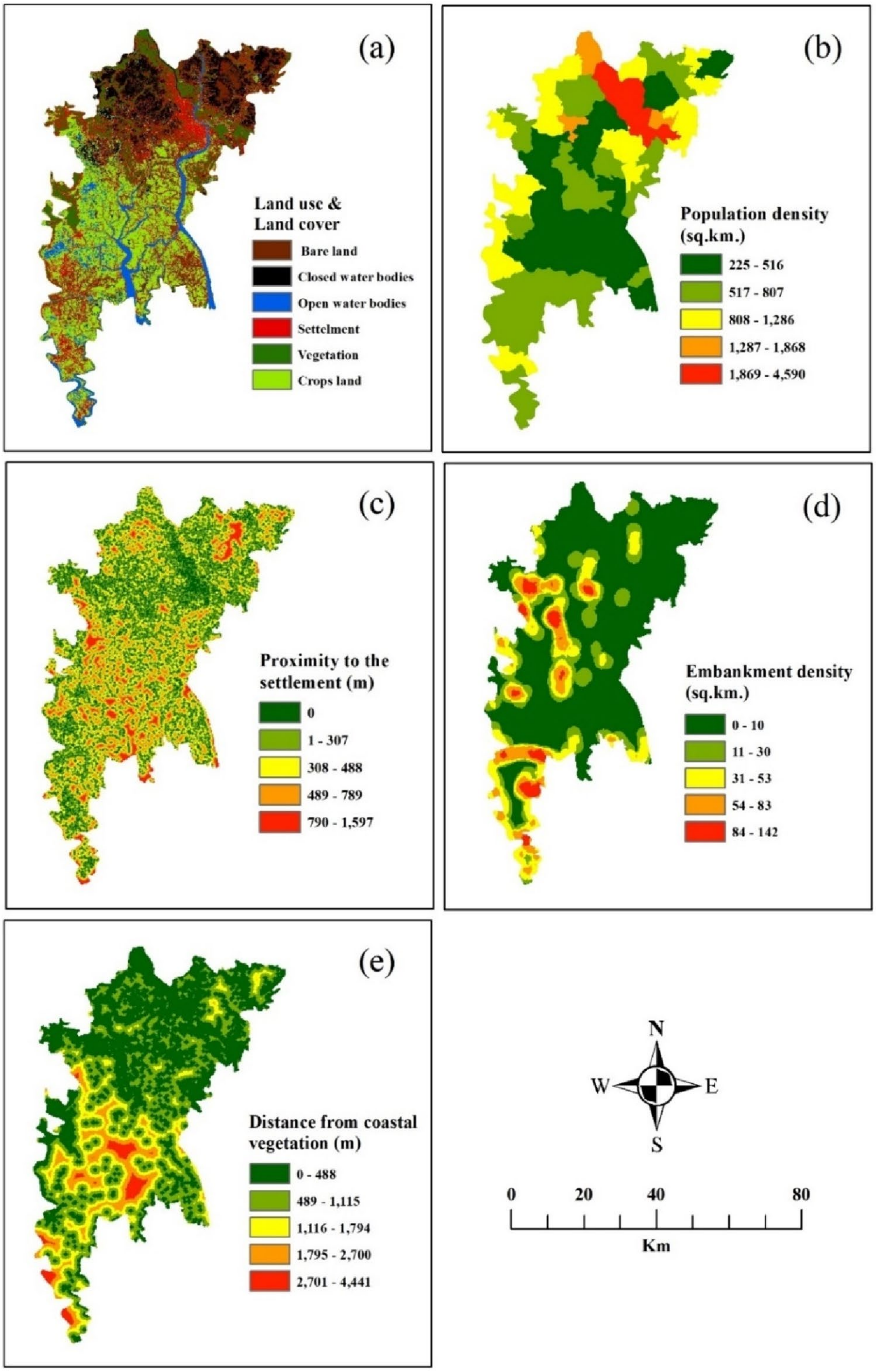


Fig. 5 Criteria layers for exposure mapping: **a** land use and land cover, **b** population density, **c** proximity to the settlement, **d** embankment density, and **e** distance from the coastal vegetation

Table 2 Land use and land cover classification schemes used in the study

Land use and land cover class	Explanation
Settlement	Rural and urban settlements, infrastructures
Closed water bodies	Wetlands, ponds, lakes, reservoirs, and low-lying areas
Open water bodies	Active river, inland waterway, and permanent open water bodies
Crops land	Agricultural crop lands, and vegetation fields
Vegetation	Homestead forest, mangrove forest, deciduous forest, and others
Bare Land	Sand fills, barren land, undeveloped space, and bare soil

The census was conducted in 2011 by BBS (Bangladesh Bureau of Statistics).

iii. *Proximity to the settlement* That is another vital factor. In this study, we used the Sentinel-2a image to produce the land cover map. Afterwards, we extracted the settlement portion and then used ArcMap Euclidian distance tool to map the proximity to the settlement (Fig. 5c).

iv. *Embankment density* Coastal embankment aids in defending coastal land from inundation by tidal waves and storm surges (Habiba and Shaw 2018). There is no doubt that embankment is a vital factor for coastal salinity intrusion risk assessment. For this study, we collected coastal embankment data from the Local Government Engineering Department (LGED). We, then used the line density tool of ArcGIS to generate embankment density layer (Fig. 5d).

v. *Distance from coastal vegetation* By reducing the effects of various threats, coastal vegetation serves as a powerful form of protection for individuals, property, and the ecosystem. We used Sentinel 2a satellite imagery for this study to identify the vegetation along the coast. Using ArcMap, we extracted the vegetation cover portion from the land cover classified map then used the Euclidean distance tool same as the settlement criteria making process (Fig. 5e).

2.5 Alternative ranking and standardization criteria layer

We performed the ranking on all selected criteria layers considering risk levels one to five. Rank one indicates very-low, whereas rank five indicates very-high risk conditions (Table 3). Consequently, in order to simplify the multi-criteria decision approach adopting the AHP techniques, standardization was done on every criteria layer to transform their rank value into a linear scale (e.g. 0 to 1). Standardization was done by using the following Eq. (2). That process aided in bringing each raster criteria layer into an equivalent scale (0–1) to support the AHP based multi-criteria decision

Table 3 Alternative ranking pattern based on the involvement to the salinity intrusion risk

Components	Risk criteria layers	Ranking (based on risk level)				
		Very Low(1)	Low(2)	Moderate(3)	High(4)	Very High(5)
Hazard	Salinity level (µS/cm)	6778–8861	8862–10,237	10,238–11725	11,726–13,436	13,437–16,264
	Rate of sea-level change (m)	0	–	–	0–3.632	–
	Mean tide range (m)	1.09–1.10	1.11–1.109	1.12–1.13	1.14–1.15	1.16–1.17
	Storm surges height (cm)	> 0	0–0.5	0.5–1	1–2	2 <
	Distance to the river channel (m)	0-0.004	0.005-0.01	0.011-0.017	0.018-0.027	0.028-0.048
Vulnerability	Proximity to the coast line (km)	101–120	91–100	81–90	71–80	0–70
	Cyclone track density (sq.km.)	0–15.71	15.72–40.86	40.87–59.27	59.28–80.37	80.38–114.49
	Elevation (m)	15–39	11–14	9–10	3–8	0–2
	Slope (%)	71.1–89	53.1–71	35.1–53	17.1–35	0–17
	Geology			Lake	Water	Sand
	Soil salinity (dS/cm)	5.05–5.48	5.49–5.78	5.79–6.22	6.23–6.69	6.7–7.16
Exposure	LULC (Land use & land cover)	Open water bodies, bare land	Closed water bodies	Settlement	Vegetation	Crop land
	Population density (per sq. km.)	225–580	581–898	899–1285	1286–1876	1877–4590
	Proximity to the settlement (m)	> 1	1—307	308—488	489—789	790—1,597
	Embankment density (sq.km)	84–142	54–83	31–53	11–30	0–10
	Distance from coastal vegetation (m)	2701–4441	1795–2700	1116–1794	489–1115	0–488

making approach. Besides, we transformed every single map layer into 15 m spatial resolution so that we could run the weighted sum techniques in this study.

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

Here, the cell value is represented by x, the minimum and maximum values for each dataset are represented by min and max, and p denotes the standardized score (Hoque et al. 2018).

2.6 Use of AHP to weight the criteria

This study used the analytical hierarchy process to assign the weight for salinity intrusion risk assessment criteria. The relative scale of importance (9 points scale) between criteria established by Saaty (1977) was used to weigh the criteria (see Table 4). The individual pairwise matrix for qualitative judgment were received from four experts chosen at the national level and a user. The experts were selected based on their experience and research in the relevant field, familiarity with the study site and impact of salinity there. They represent both academic, governmental and research organizations.

The total score was 1 for all the components. We used the following Eq. (3) for consistency ratio (CR) to calculate or justify the accuracy of the user judgment in the comparison matrix. Therefore, we considered the judgment reliable if the CR remains equivalent or below 0.1 (Hoque et al. 2018).

$$CR = \frac{Consistency\ Index}{Random\ Index} \tag{3}$$

here, Random Index (RI) represents the randomly generated average consistency index, and Consistency Index (CI) which is defined as follows.

$$CI = \frac{(\lambda max - \mathrm{n})}{(\mathrm{n} - 1)} \tag{4}$$

where, λ_{max} refers to the leading eigenvalue of the matrix plus n represents the matrix of order (Hoque et al. 2018).

Below are the criteria weights calculated from the pairwise comparison matrices and the corresponding consistency ratio of comparison (see Table 5).

2.7 Risk assessment

In this study, we applied the weighted sum technique on every spatial criteria layers of all three risk components. Besides this practice, we generated the vulnerability, exposure and hazard index by incorporating the weights of their related criteria. Then the formed indices were categorized into five distinct groups (e.g. very low, low, moderate, high, and very high) for generating hazard, vulnerability and exposure indices. Then, using the raster calculator in the ArcMap and the accepted Eq. (1) for risk assessment, a salinity risk index was generated by multiplying all the risk components (e.g. hazard, vulnerability, and exposure) indices. Then,

Table 5 Produced weights of the criteria using AHP in the study

Risk components	Criteria	Weight
Hazard	Salinity level	0.32
	Rate of sea-level change	0.11
	Mean tide range (m)	0.15
	Storm surges height (cm)	0.35
	Distance to the river channel	0.08
Consistency ratio	0.04	
Vulnerability	Proximity to the coast line(km)	0.25
	Cyclone track density	0.06
	elevation(m)	0.24
	Slope (%)	0.16
	Geology	0.07
	Soil salinity	0.21
Consistency ratio	0.06	
Exposure	LULC (Land use & land cover)	0.17
	Population density (sq.km,)	0.3
	Proximity to the settlement	0.15
	Embankment density	0.24
	Distance from coastal vegetation	0.14
Consistency ratio	0.03	

Table 4 Scale of relative importance used in the study (adapted from Saaty 2008)

Relative importance	Definition	Description
1	Equal importance	When two factors contribute equally to the target
3	Moderate importance	When experience and judgment elevate one factor significantly over another
5	Strong Importance	When judgment and experience strongly favors one factor over another
7	Very strong importance	When one factor is strongly favored over another and its supremacy is proved in practice
9	Extreme importance	When the evidence supporting one factor over another is of the highest grade of confirmation

2, 4, 6, 8 used to express the median value we normalized the risk index values to make it within 0–1, adopting the Eq. (2) and categorized this into five different groups (e.g. very-high, high, moderate, low and very-low) (Hoque et al. 2018).

2.8 Risk validation

The validation of spatial risk assessment result is difficult because no specific authentication approaches are available for validation. However, for evaluating the risk assessment results, we used firstly a qualitative validation approach (Hoque et al. 2019a, b). Between 10 and 12 November 2022, the study area was visited to gather feedback from locals, professionals (e.g., university professors, departmental specialist), and from decision makers (i.e. local government representatives and administrators) on the resulting risk assessment map. Approximately 40 people from the study area provided their feedback. Nevertheless, an extensive self-observation in several places of the study area was carried out too, to justify the authenticity of the software generated salinity intrusion risk assessment results.

The study also used the receiver operating characteristics curve (ROC) and area under the curve (AUC) based quantitative validation approach for validating the salinity intrusion risk assessment generated using AHP and geospatial techniques. This validation approach has been reported in various studies on vulnerability, susceptibility and natural hazards risk models (see Bui et al. 2019; Hoque et al. 2020, 2021; Nohani et al. 2019 for example). For this, we, first identified the areas that were affected by salinity to develop an inventory map with 106 validation points based on the salinity monitoring stations maintained by BWDB, SRDI and our own field work. The prepared inventory map was used for ROC and AUC analysis in the GIS environment using ArcSDM tool.

3 Results

3.1 Salinity intrusion hazard mapping

We developed the salinity intrusion hazard map dividing it into five zones represented by the hazard index values. The graphic reveals that 16% of the study area, largely in the vicinity of the coastal river, is in the very high hazard zone, whereas 21% is in the high hazard zone and roughly 25% is in the moderate hazard zone. Additionally, 27% and 11% of the overall area, with the majority of them being inland and distant from the ocean, are located in the low and very-low hazard zones. The salinity intrusion hazard map (Fig. 6) also showed that the south-western and south-eastern portions of the study regions are situated in higher danger susceptible zones compared to other parts of the study area. On the other hand, the northern and northeastern regions are discovered to be less hazard prone.

3.2 Salinity intrusion vulnerability mapping

Salinity intrusion vulnerability was identified and classified into five different levels. Vulnerability map (Fig. 7) indicates that the very-high and high vulnerable class combined accounted for around 14.31% and 18.68%, respectively, whereas 46% of the examined area was classified as having a low to very-low susceptibility level. On the other hand, around 35.34% of the study area consists of high to very- high exposure to the salinity intrusion. The findings indicated that approximately 5.67% and 13.21% of the study areas are characterized as having a very high to high risk of salinity intrusion.

3.3 Salinity intrusion exposure mapping

According to the salinity intrusion exposure map (Fig. 8), 35.72% of the study area is less vulnerable to salinity intrusion with a high to very-high level exposure. These areas are located in the study area's north western and north-eastern regions. This high exposure to salinity intrusion risks is linked to a number of important factors, including high

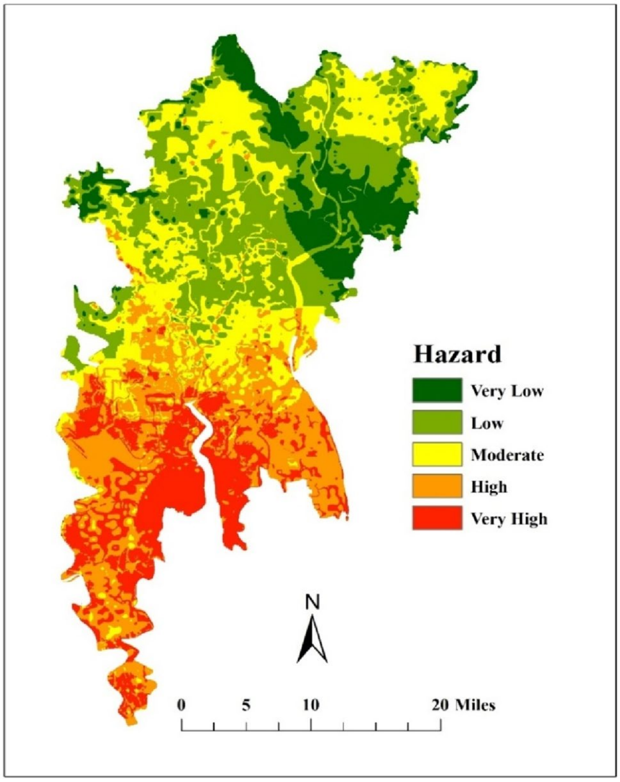


Fig. 6 Salinity intrusion hazard map of the study area

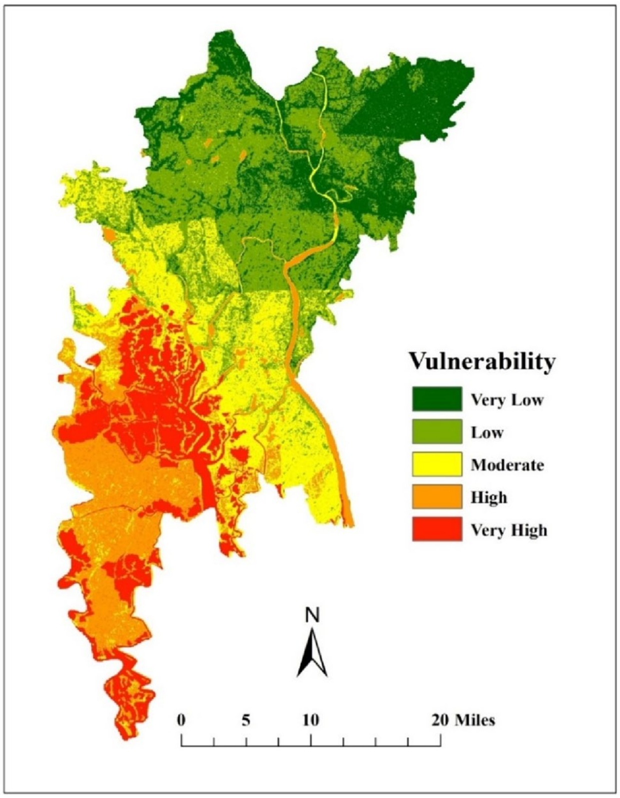


Fig. 7 Salinity intrusion vulnerability map of the area

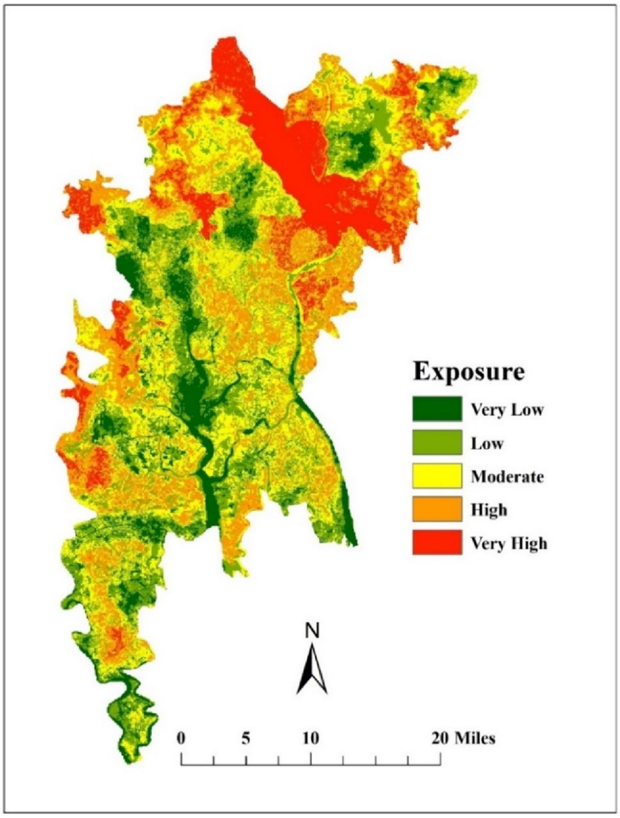


Fig. 8 Salinity intrusion exposure map of the area

population densities, embankment density, and land cover types.

Furthermore, approximately 29.32% of the study area is categorized as moderately exposed. Western parts of the study area have low to very-low exposure. Those sites are extremely susceptible to salinity intrusion because of lesser embankment densities, population density, and distance from coastal vegetation and settlement.

3.4 Salinity intrusion risk mapping

The method applied in this research developed a thorough salinity intrusion risk matrix by classifying the standardized risk indexes into five levels. Our output risk map (Fig. 9) indicates that about 13.21% of the research field is situated in the high-risk category and around 5.67% of area lies in the extremely high-risk category; most of these areas are primarily located near tidal rivers. Besides, due to some factors (e.g. distance from the shoreline, available embankments, storm surge height, and others), those two zones comprised just a small portion of the study area. On the other hand, the moderate risk zone accounted for 17.16% of the study area. The low and very low risk zones accounted for 27.40% and 36.55% of the total, mainly located in upland areas distant from the shore.

3.5 Validation of risk mapping

The qualitative method was used in this study to verify the results of salinity risk assessments. The qualitative method included in-depth personal observation and conversation with residents, professionals, and decision-makers for their thoughts on the created salinity risk map. Based on the opinions of local inhabitants, professionals, and decision-makers, the spatial salinity risk assessment results were promising (Table 6). Out of 45 respondents, approximately 30 (66.6%) were highly satisfied, 15 (33.3%) were satisfied, and none were dissatisfied with the results. Furthermore, the risk map showed that the south-western and south-eastern parts are located in high to very-high risk zone areas. Authors' ground observation generated the similar results.

Our study also used the quantitative validation technique to verify the findings using ROC and AUC method. Figure 10 exhibits the ROC and AUC for AHP model for salinity risk mapping used in the present study. We found that the observed accuracy of the AHP technique is 0.858 (85.80%). The values of AUC generally range between 0.5 and 0.1. The values close to 1 indicates higher accuracy. Therefore, the model is efficiently performed to produce the AHP based salinity risk map, and it shows good outcome.

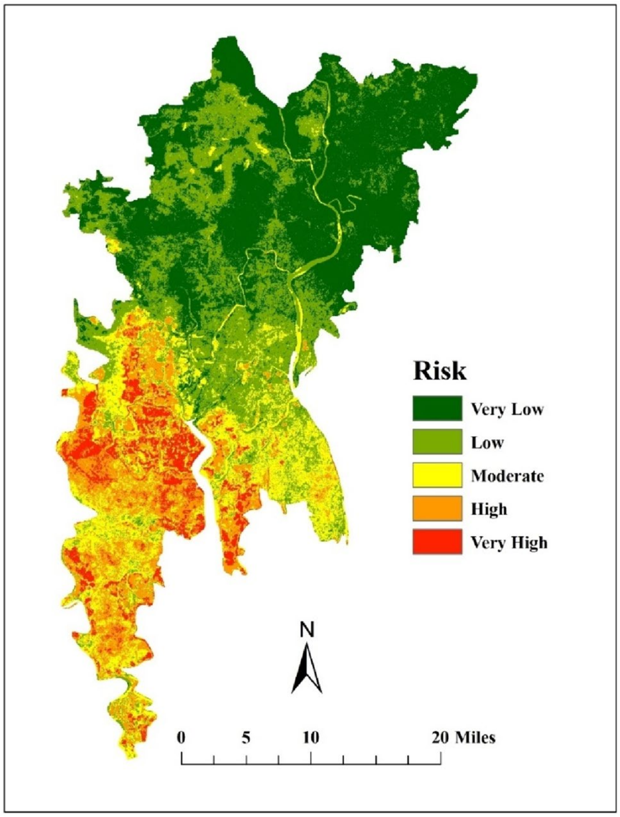


Fig. 9 Salinity intrusion risk map of the area

4 Discussion

The coastal regions have gained increased significance in recent years due to their vulnerability to a climate induced disasters including salinity intrusion. Salinity intrusion, in fact, poses a significant threat to the well-being and economies of coastal communities with a direct impact on food security (Paul and Jabed 2018). The projected sea level rise due to climate change is anticipated to further escalate salinity intrusion in many low-lying coastal areas in the coming years (Khanom 2016; Thanh et al. 2023). Multiple studies corroborate these forecasts, indicating a future scenario marked by more frequent and severe events (Ashrafuzzaman et al. 2022; Akhi et al. 2019; Dasgupta et al. 2015). Addressing these impending challenges requires implementing a thorough salinity intrusion risk mapping technique that encompasses all relevant factors. Therefore, we developed a detailed salinity intrusion risk mapping technique that incorporates all the possible risk components and applied our technique for Khulna District in coastal Bangladesh. Our study represents the first comprehensive endeavour on coastal salinity intrusion risk assessment for the western coast of Bangladesh. It also offered detailed information on salinity risk, making it valuable for policymakers and administrators.

The findings of our study indicated higher risk in the southwestern and southeastern coastal regions. The higher risk in those regions were attributed to proximity to the coastline, frequent storm surges and higher salinity level. Conversely, the northern and northeastern regions are less hazard-prone due to lower susceptibility to storm surges, salinity, and water impact which was in consistent with the findings of Mainuddin et al. (2011). The resulting salinity intrusion vulnerability map (see Fig. 7) demonstrates that, 54% of our study area is moderate to highly vulnerable to salinity intrusion. The south-western and eastern portions of the study area are more susceptible to the negative impacts of salinity intrusion. High sensitivity areas were identified by the lower elevation, proximity to the cyclone track and coastline, gentle slopes, soil salinity and geology, among other criteria. On the other hand, locations in the north and north-west were less susceptible to salinity intrusion as these regions are less steep and distant from the coastline, coastal river steams, and cyclone tracks. In terms of salinity intrusion risk map, the areas are primarily located in the south-eastern regions (e.g., Dacope) and southwestern regions (e.g., Koyra, Paikgacha). Batiaghata, Dacope, Paikgacha, and Koyra Upazilas were found to be at high risk, and they are expected to be significantly impacted by climate change. Our result aligns with the findings of Akhi et al. (2019), Faisal et al. (2021) and Shaibur et al. (2021). The impacts of salinity intrusion will be higher in the areas identified as high risk in our study. Salinity intrusion highly affects people's livelihoods in affected areas, reducing their regular income. Crop cultivators, livestock rearers and day labourers will be affected mainly by salinity. The saline water adversely affects food production and, thereby, will also affects food security. There will be a big crisis in drinking

Table 6 Summary of feedback on our findings from locals, professionals, and decision-makers

Kinds of people	Number of respondents	Feedback		
		Highly satisfied	Satisfied	Not satisfied
Professionals	5	2	3	0
Decision-makers	5	1	3	1
General people	35	23	8	4
Total	45	26 (57.8%)	14 (31.11%)	5 (11.11%)

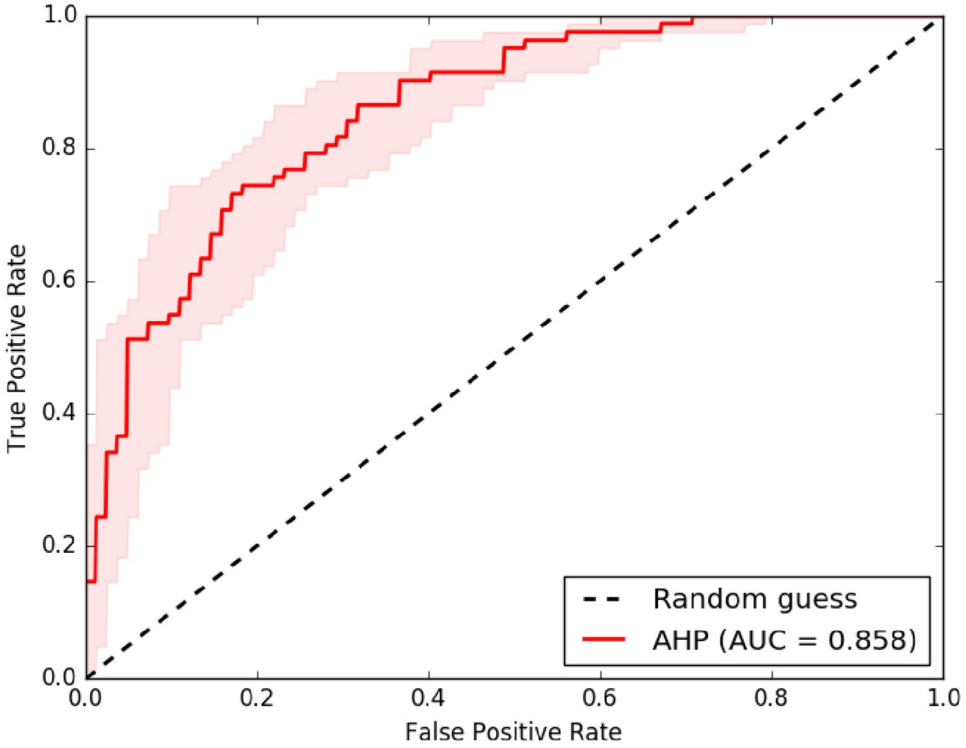


Fig. 10 ROC curve and AUC value analysis for validating the salinity risk map

water. Salinity in drinking water also caused hypertension or high blood pressure among residents in the coastal areas. Rainwater harvesting, seasonal storage of water, desalinization plant, construction of sluice gates, salt-tolerant rice, construction of embankment and polders are some potential mitigation measures to minimize the impacts of salinity intrusion in high-risk prone areas in the region.

A minor inconsistency was observed between the vulnerability maps and exposure components maps, indicating that the southwestern regions of the study area predominantly belonged to the high to very-high vulnerable class. The heightened sensitivity in these areas was attributed to several factors such as lower elevation, proximity to cyclone tracks and the coastline, gentle slopes, soil salinity, and geological characteristics. In contrast, locations in the north and northwest exhibited lower susceptibility to salinity intrusion, as these areas have less steep terrain and are farther from the coastline, coastal river streams, and cyclone tracks. This finding aligns with the results reported in (Shaibur et al. 2021). On the contrary, in the salinity intrusion exposure map study area's north western and north-eastern regions (Khulna city) are showing higher coverage. This may be due to some prominent factors like higher population densities (with infrastructure, housing, production capacities and other tangible human assets) on those areas, lesser embankment density, and land use/cover in those areas, that were considered for exposure mapping. Nevertheless, among all the exposure criteria, the population density was regarded as the most crucial factor for assessing salinity intrusion risks.

Due to its geographical location, Bangladesh is highly vulnerable to climate change and experience frequent natural disasters (Faisal et al. 2021). Tropical cyclones, floods, and rising sea levels pose significant threats (Sheet & Impacts 2015), particularly in coastal areas with critical urban centers and protected zones (Eriksson 2017), and ecologically important dynamic landscapes (Mukul et al. 2019). Various climate-related risks, including altered rainfall patterns, temperature changes, storm surges, and saline intrusion, intensify the challenges faced by the population (Warming 2013). Over the past 35 years, salinity in Bangladesh has increased by approximately 26%, extending beyond coastal areas (Dasgupta et al. 2015; Khanom 2016; Mahmuduzzaman et al. 2014; Warming 2013). Rising sea levels have expanded salt-water intrusion by up to 15 km north of the coastline, reaching 160 km inland during the dry season. This intrusion adversely affected ecological and socioeconomic systems, impacting essential facilities in coastal region (Hossain et al. 2018). Human activities also, such as converting agricultural lands into shrimp ponds, exacerbate salt-water intrusion, causing significant damage to soil, human health, and the ecosystem (Akhi et al. 2019; SRDI 2019; Roy et al. 2022).

Despite three decades of coping with salinity related challenges, local communities have implemented small-scale adaptive measures, including cultivating salt-tolerant crops, practicing rainwater harvesting, switching livestock to another profession, and elevating house foundations (Habiba et al. 2013). However, larger-scale initiatives addressing food security, biodiversity conservation, and sustainable livelihoods are yet to be initiated (Hossain et al. 2018). A comprehensive understanding of the causes and impacts of increased salinity is crucial for successful adaptation planning. Emphasizing this necessity is essential for broader benefits, including food security, biodiversity conservation, environmental protection, and sustainable livelihoods.

In the near future, the salinization of river water in coastal Bangladesh is anticipated to emerge as a significant threat, particularly in the southwest coastal region. According to predictions, Bagerhat, Barguna, Barisal, Bhola, Khulna, Jhalokati, Pirojpur, and Satkhira Districts are expected to face the most severe consequences due to the escalating river salinity in response to climate change (Ashrafuzzaman et al. 2022; Bricheno et al. 2021; Sheet & Impacts 2015). In such circumstances, the utilization of an Analytic Hierarchy Process (AHP) based multi-criteria integrated geospatial technique holds great potential for to identify salinity intruded risk areas for implementing effective adaptation and mitigation measures. Soil salinization is a significant global agricultural issue that challenges sustainable development goals relevant to food security, agriculture, resource conservation, and nutrition (Sahab et al. 2021). In coastal areas of many South and Southeast Asian countries, such as India, Myanmar and Vietnam, salinity intrusion is considered as a major obstacle to agricultural production, specifically in low-lying deltaic plains of those countries that face the ocean (Ahmad 2015; Loc et al. 2021; Oo et al. 2017; Sahab et al. 2021). The salinity problem can spread over 50% of the total global irrigated areas by 2050 if proper strategies are not implemented to tackle the problem (Singh 2021). It is, therefore, essential to manage the soil salinization problem to achieve most of the Sustainable Development Goals (SDGs) prepared by the United Nations. For instance, soil salinization management is essential to attaining ‘Zero Hunger’ (SDG2) and ‘Life on Land’ (SDG15). Further, climate change is accelerating the impact of salinity by raising the sea level. It is, therefore, imperative to act appropriately to reduce the adverse effects of climate change to achieve the UN SDG13, i.e., ‘Climate Action’.

Our study also recognizes some challenges in collecting high-quality datasets, particularly due to various requirements. To map elevation and slope, the rate of sea level change, and as a fundamental input for the storm surge height map, we employed ASTER DEM in particular. High resolution DEM data, instead can be used in this area to get better results. Due to data unavailability, data for salinity level and tide range criteria data were only collected for two to four years; if this could be extended to twenty to thirty years, the results would be more reliable. To enhance the salinity intrusion risk assessment, future research should employ high-resolution satellite images, LiDAR, and additional variables. While our study employed AHP, future investigations should explore various models, such as Fuzzy-AHP, Fuzzy Logic, statistical models, artificial neural network, and machine learning, for more robust outcomes. Integrating AHP with geospatial techniques achieved an efficiency of approximately 85.80%, as assessed by ROC and AUC methodologies on a salinity inventory map. This highlights the significance of AHP techniques in predicting salinity intrusion risks globally, offering a practical tool for planners and coastal engineers to promote sustainable development. The present study recommends to continue monitoring programs using developed approach to track the progression of salinity intrusion over time in the coastal areas of Bangladesh for tackling impact of future impacts of salinity intrusion by proposing and implicating effective mitigation and adaptation measures.

5 Conclusion

In this paper, we used geospatial techniques to develop a coastal flood induced salinity intrusion risk assessment approach utilizing the multi criteria decision making strategy. To verify the developed approach, we chose the Khulna district as our study area, which is one of the most salinity prone areas in coastal Bangladesh. We used both the qualitative and quantitative (ROC and AUC technique) approaches as well as the personal observation to verify the salinity intrusion risk mapping result. The findings revealed that using GIS and remote sensing tools integrating AHP, a comprehensive risk assessment can be done at the local level. In addition, all of the necessary criteria for each risk component were mapped using GIS and remote sensing tools. In the context of assigning relative weights, the AHP was discovered to be efficient in this study. Our current research indicates that the south-eastern and south-western parts of the research region are more susceptible to salinity intrusion risk than any other parts. Therefore, there is a lesser risk of salinity intrusion in the inland areas, which includes the central, northeastern, and western regions.

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Data availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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