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Multi-pressure based environmental vulnerability assessment in a coastal area of Bangladesh: A case study on Cox's Bazar

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A R T I C L E I N F O

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A B S T R A C T

Bangladesh ranks among the top 10 countries globally in terms of climate change impacts and faces numerous anthropogenic and natural pressures. Cox's Bazar, its primary tourist district, is experiencing severe degradation of its physical and ecological environments due to anthropogenic disturbances and climate change. To improve its environmental quality and preserve its ecological resources effectively, it is essential to develop a spatial decision support instrument addressing multi-pressures and cumulative environmental vulnerability (EV). This study presents an expert opinion-independent, scalable, and customizable spatial methodological framework, integrating multi-sourced geospatial data with GIS-based Fuzzy Logic to assess spatial distributions of five pressure groups and their resulting EV in Cox's Bazar. 18 criteria were chosen based on a structured literature review to evaluate the five pressure groups. Results revealed that 17 % to 27 % of the study area is exposed to high to very high hydro-meteorological, topographic, land resource, anthropogenic, and natural hazard pressures. The EV results indicated that one-third of the study area, majorly covering Kutubdia, Pekua, Cox's Bazar Sadar, Teknaf, and Ukhia upazilas, is highly environmentally vulnerable. For enhanced environmental protection, this study improved the existing method of environmental protection zoning by introducing a novel zoning approach that integrates in-situ biodiversity data with EV data. This new zoning method delineated 24 % (555 sq. km.) as strict, 45 % (1047 sq. km.) as medium, and 31 % (725 sq. km.) as soft protection zones in the study area. The sensitivity analysis identified land resource pressure as the most influential component of EV. With a correlation coefficient of 0.91, the accuracy assessment confirms a high level of reliability in the EV results. This study provides valuable insights into environmental pressures and vulnerability in Cox's Bazar, which are crucial for informing policies at various levels, including international and national frameworks, emphasizing terrestrial ecosystem protection, coastal vulnerability mitigation, climate change impact reduction, biodiversity preservation, and sustainable land resource management.

1. Introduction

Over the years, significant changes have occurred in the physical and biological systems on the earth's surface and in the ocean due to pressures from climate change, pollution, rapid urbanization, exponential population growth, over-exploitation of natural resources, and inappropriate use of technologies [43,66]. Pressures can be expressed as the effects of natural phenomena and anthropogenic activities that bring

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about changes in the state of the environment and affect the quality and quantity of its natural resources [50]. To enhance sustainable management and promote adaptive planning of environmental systems in coastal areas, it is crucial to identify existing pressures and assess the cumulative environmental vulnerability (EV) to those collective pressure groups [22]. The Intergovernmental Panel on Climate Change (IPCC) defined EV as the degree of susceptibility of the environment to adverse effects or pressures caused by environmental conditions or hazards [14]. It is a fundamental concept in various assessments within international organizations: The United Nations (UN) developed a Multidimensional Vulnerability Index in the context of Sustainable Development Goals [67] as well as an Economic-Environmental Vulnerability Index within the South Pacific Geoscience Commission [61]. The European Environmental Agency (2016) developed an indicator-based climate change vulnerability assessment [20] for European ecosystems and society.

The assessment of EV is extensively used in the thorough evaluation of resource systems affected by natural and human-induced pressures [21]. Results of EV assist in environmental disaster mitigation, ecological restoration, environmental protection, adaptive capacity development, and resilience building [60,72]. Therefore, addressing EV from spatial and temporal perspectives is essential to inform Target 15 of the Sustainable Development Goals (SDGs), which focuses on the protection, restoration and promotion of sustainable use of terrestrial ecosystems, sustainable forest management, and halting and reversing land degradation, and stopping biodiversity loss [68].

The Global Climate Risk Index (2019) ranked Bangladesh among the top 10 countries most vulnerable to climate change [19]. Its coastal zone is susceptible to rising sea level, erosion-accretion, salinity intrusion, tidal flooding, storm surges, and tropical cyclones, all of which are predicted to increase under future climate change [12,56]. According to Goosen et al. [26], climate change in Bangladesh is heightening the community's vulnerability to different natural hazards and exerting tremendous stress on freshwater availability, agricultural production, coastal ecosystems, and biodiversity. Additionally, anthropogenic disturbances such as urban expansion, infrastructure development, deforestation, random hill cutting, unplanned waste disposal, and incompatible land use changes are escalating the vulnerability of the coastal environment. In this context, assessing the level of cumulative EV in coastal Bangladesh is crucial for implementing effective environmental protection and vulnerability mitigation measures.

While some studies related to environmental vulnerability in coastal Bangladesh have been published [3,31,55], most have focused on specific hazards. Other studies have assessed coastal vulnerability using limited pressure indicators [18,35,42,45]. These studies lack a comprehensive evaluation of EV that includes all pressures present in coastal Bangladesh. Despite their importance for environmental management and ecological protection, previous studies did not categorize different pressures or analyze their individual impacts on the environment. Several international EV-related studies also exhibit these common gaps in their assessment frameworks [17,38,46,63]. Furthermore, the aforementioned national and global research have inadequately considered socio-economic and hydro-meteorological pressures, despite their relevance in influencing EV in a particular area. Regarding methods used, the majority of these studies have applied weight-based multi-criteria decision analysis (MCDA) techniques such as Analytical Hierarchy Process (AHP), Spatial Overlay, and Spatial Principal Component Analysis (SPCA). However, the weight-based MCDA method (i.e., AHP) is sometimes criticized for its inability to address inherent uncertainties associated with expert judgments while providing crisp numbers [16]. According to Pourghasemi et al. [51], AHP is susceptible to imprecision in assigning weights to the criteria during pairwise comparison because opinions among experts may vary. Therefore, applying an MCDA approach that relies less on expert judgments is more realistic for handling uncertainties and improving accuracy in EV assessment. Another limitation of current EV studies is that they delineate environmental protection zones based on the partitioning of EV output [49,48,30]. Although the main objective of protection zoning is to enhance ecological protection, previous studies did not consider the ecological components of the study area in the zoning process.

Considering the above-mentioned research gaps in EV analysis, this study aims to introduce and apply an expert judgment-independent, scalable, and customizable approach for a comprehensive assessment of EV in Cox's Bazar district, the southeasternmost coastal district of Bangladesh. We emphasized a multi-pressure approach, categorizing all possible threats in the study area into different pressure groups and assessing their individual impacts on the environment. We also aimed to improve the traditional method of environmental protection zoning by applying a novel zoning approach to enhance the protection of environmental and ecological resources in the study area. Due to greater methodological flexibility, the analytical framework introduced in this study can be replicated in other locations.

2. Materials and methods

2.1. Study area

Cox's Bazar, the tourism capital of Bangladesh [11], is subdivided into eight administrative units (*upazila*): Kutubdia, Pekua, Chakaria, Maheshkhali, Cox's Bazar Sadar, Ramu, Ukhia, and Teknaf (Fig. 1) With a total population of around 2.82 million (1133 per sq. km.) [8]. Climatologically, it lies in the hot and humid conditions where the average summer and winter temperatures are 33.77 °C and 18 °C, respectively. The district receives an average annual rainfall of around 3660 mm [9]. This favorable climate allows as many as 234 wildlife species (61 species are on the IUCN red list) to thrive in the area, including threatened species such as Asian elephants, sea turtles, corals, etc. ADB [1,28]. Considering the ecological diversity in the area, eight biodiversity protection sites have been nationally designated (Fig. 1b).

Different tourist spots of Cox's Bazar (Fig. 1c), including safari park, sea beaches, and archaeological sites, are annually visited by around 3.7 million people [69], making its annual tourism market worth USD 1.3 billion [34]. Its sea salt harvesting sites produce around 95 % of the country's total crude salt annually, worth USD 150–180 million [34]. Shrimp farming is another important socio-economic activity in which thousands of people are involved. However, these activities have brought a significant negative impact on the natural environment in the region by increasing pollution, decreasing groundwater levels, disturbing natural habitats, and raising salinity in the surface soil and groundwater [11,23,32,57,73,78]. Rohingya refugee exodus led deforestation and hill cutting at several locations of Ukhia and Teknaf upazilas have escalated the likelihood of landslides and flash flood occurrences [2]. Shoreline shifting with considerable erosion has been another potential threat to human settlements, agricultural land, and coastal biodiversity in this region [31,41]. Additionally, this district is exposed to tropical cyclones due to its proximity to the Bay of Bengal. Between 1904 and 2016, 22 catastrophic cyclones made landfall in the area [6], causing significant damage to its terrestrial and aquatic ecosystems [4]. Some studies identified trace and heavy metals contamination in the coastal waters of the district [53,59], which are harmful to human health and aquatic biodiversity. Considering the ecological and socio-economic significance of Cox's Bazar, and its increased vulnerability to various human-induced and natural hazards, this district was chosen as the study area for implementing the proposed research framework.

2.2. Methodological framework

Fig. 2 provides an overview of the framework applied for analyzing EV through seven methodological steps: 1) selection of pressure groups and influencing criteria, 2) development of geospatial dataset, 3) application of fuzzy logic for calculating fuzzy membership values of

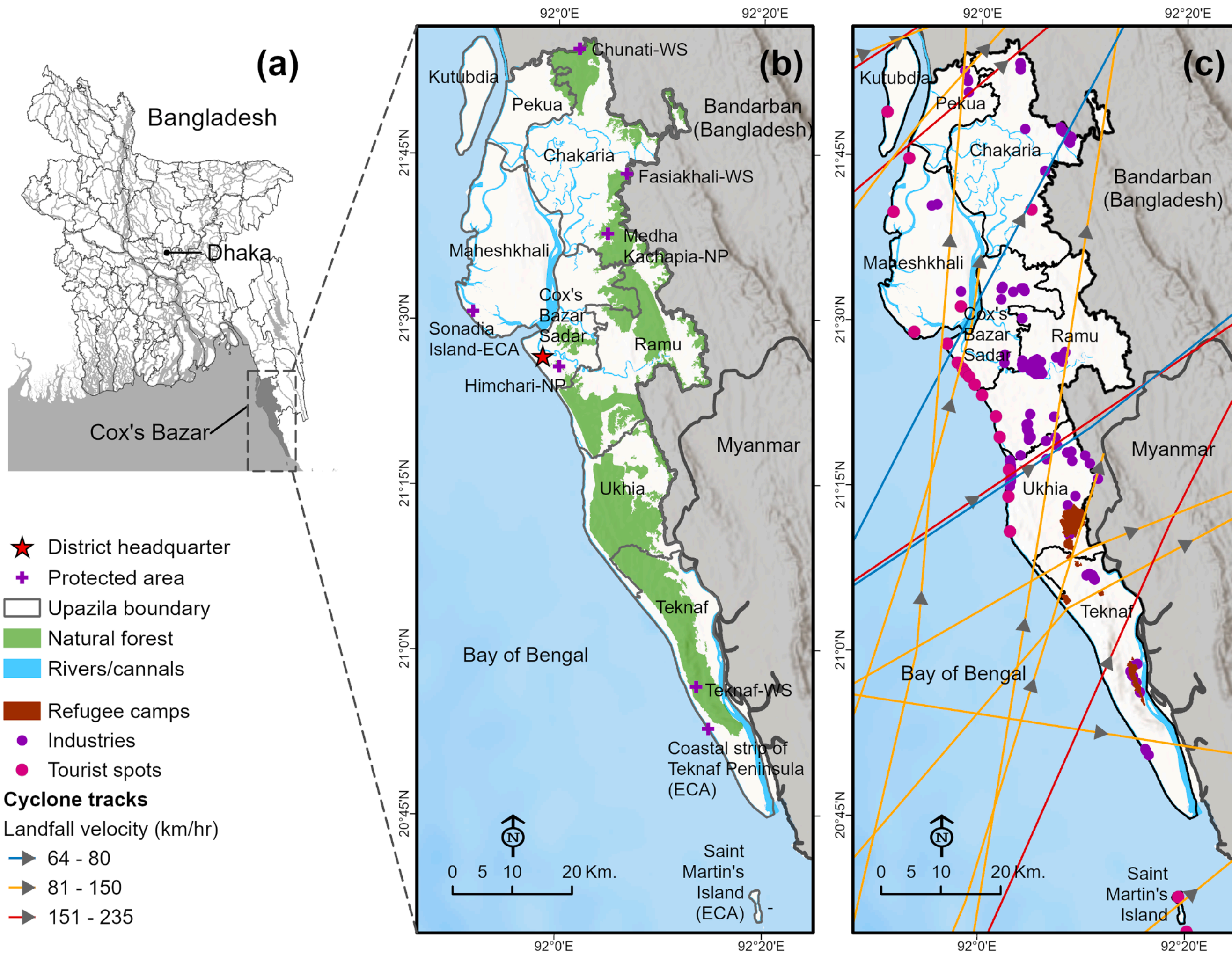

Fig. 1. Location of the study area in Bangladesh (a) and it's ecological features (b). Figure (c) shows tropical cyclone tracks making landfall in the area between 1960 and 2022, tourist spots, and location of industries. Note: ECA- Ecologically Critical Area, WS-Wildlife Sanctuary, and NP-National Park.
This figure was adapted from Roy and Depellegrin [54].

each criterion, 4) calculating pressure groups and EV, 5) sensitivity and accuracy assessments, 6) analyzing spatial patterns of EV, and 7) delineating environmental protection zones. Each of these steps is explained in the subsections from 2.2.1 to 2.2.7.

2.2.1. *Selection of pressure groups and corresponding criteria*

To identify pressure groups and their representative criteria for assessing EV, a systematic review of recently published scientific literature was performed following the widely used SALSA framework. The SALSA framework consists of four chronological steps: Search (identifying search database/s and establishing search string), Appraisal (exclusion, inclusion, and quality check), Synthesis (extracting desired data), and Analysis (analyzing results and drawing conclusions) [27,44]. To implement the SALSA protocol, this research used the Google Scholar database as the literature search engine due to its flexible navigation process, extensive journal coverage, robust collection, and more citing references compared to Web of Science or Scopus [10]. Moreover, it is the most frequently used academic search engine. Before searching for the intended literature, Google Scholar settings needed to be customized. In the *Settings* option, *Article* was selected in *Collections*, and *English* was set as the *Written Language*. In the *Advanced Search* option, searching of the *Search Strings* were set in the *Title* of the articles, and the date range was restricted between 2015 and 2020. Finally, the Search String ["environmental vulnerability" OR "environmental vulnerability assessment" OR "eco environmental vulnerability" OR "ecological vulnerability"] was used in the *Advanced Search*, which returned 634 articles. In the Appraisal stage, initially, 472 articles were yielded after excluding articles containing socio, socio-economic, economic, or social EV in the titles, and from which 87 articles were retained where MCDA, GIS, or GIS-based MCDA approaches were used as the EV assessment methods. In the Synthesis stage, all 87 articles were reviewed carefully and retained those studies that particularly focused on the South and Southeast Asian region, promoted scalable methodologies, and considered similar pressures prevailing in our study area in Bangladesh. Eventually, Hou et al. [33], Kan et al. [38], Liu et al. [40], Nguyen et al. [49], Nguyen and Liou [48], Wu et al. [74], and Xu et al. [75] were selected as the most relevant literature that enabled the identification of 18 criteria under five pressure groups summarized in Table 1: hydro-meteorological, topographic, land resource, anthropogenic, and natural hazard.

2.2.2. *Development of geospatial dataset*

Geospatial data for the selected criteria were obtained from different national and international sources chosen based on their wide application in similar research domains, higher spatial and temporal resolution, and open-source accessibility (Table 1). All geospatial data were projected to the WGS84/ UTM 46N projection system. Raster data having coarser resolution (i.e., rainfall, population, and landslide) were

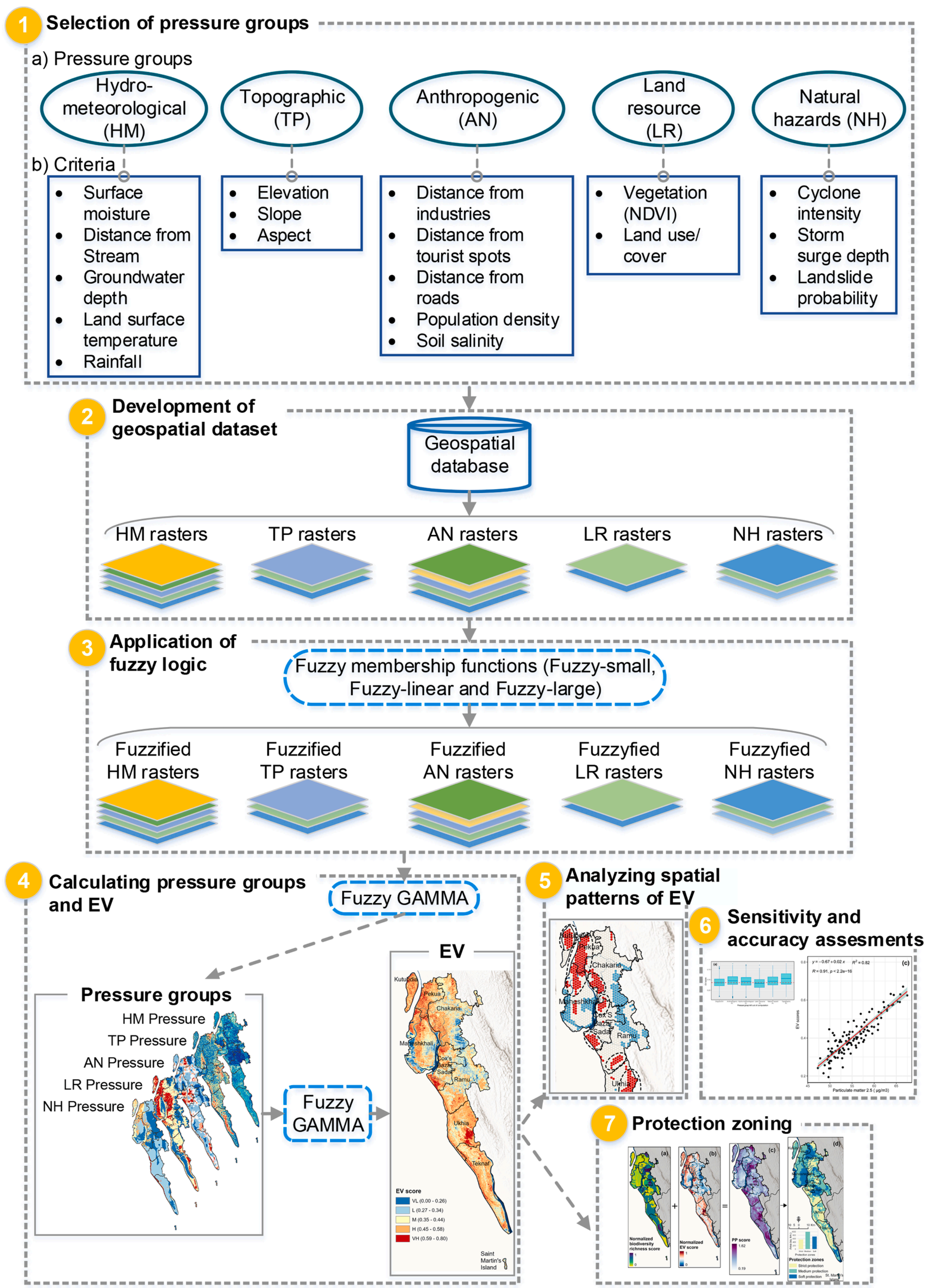

Fig. 2. Stepwise methodological framework used in this study to calculate pressure groups and EV, as well as delineate environmental protection zones. Note: EV- Environmental Vulnerability, HM- Hydro-meteorological pressure, TP- Topographic pressure, AN- Anthropogenic pressure, LR- Land Resource pressure, NH- Natural Hazard pressure, and NDVI- Normalized Difference Vegetation Index.

Table 1
Attributes of geospatial dataset used in this study.

Pressure groups	Criteria/geospatial data and unit of measurement	Description	Spatial data type and original resolution	Period covered	Data sources	References used similar criteria
Hydro-meteorological	Surface moisture (index)	Available moisture content in the surface elements.	Raster (30 m)	2014 –2022	Landsat–8 OLI (https://earthengine.google.com/)	Nguyen et al.[49]
	Distance from stream (km)	Streight-line distance of every point in the study area from the network of existing river/stream.	Vector (Polyline)	2022	OpenstreetMap (https://www.openstreetmap.org/)	Nguyen and Liou [48]
	Mean groundwater depth (m)	Average depth of the groundwater table from the surface.	Vector (Point)	1990 –2022	Bangladesh Water Development Board (BWDB)	Wu et al.[74]
	Land surface temperature (LST) anomaly (°C)	Anomaly of surface temperature of 2022 over a 9-year average surface temperature.	Raster (30 m)	2014 –2022	Landsat–8 OLI (https://earthengine.google.com/)	Nguyen et al.[49]
	Rainfall anomaly (mm)	Anomaly of rainfall of 2022 over a 22-year average rainfall.	Raster (5.54 km)	2001 –2022	CHIRPS daily precipitation (https://earthengine.google.com/)	Hou et al.[33]; Liu et al.[40]; Wu et al.[74]
Topographic	Elevation (m)	Land surface elevation.	Raster (30 m)	2014	SRTM DEM (https://earthexplorer.usgs.gov/)	Kan et al.[38]; Liu et al.[40]; Wu et al.[74]
	Surface slope (degree)	Steepness of the surface.	Raster (30 m)	2014		Kan et al.[38]; Liu et al.[40]
	Aspect	Direction of the surface slope faces.	Raster (30 m)	2014		Nguyen and Liou [48]
Land resource	Mean NDVI (index)	Average vegetation greenness.	Raster (30 m)	2014 –2022	Landsat–8 OLI (https://earthengine.google.com/)	Kan et al.[38]; Wu et al.[74]; Xu et al.[75]
	Land use/cover (LULC)	Observed uses or physical covers of the land surface.	Raster (30 m)	2022	Roy and Depellegrin[54]	Kan et al.[38]; Liu et al.[40]; Xu et al.[75]
Anthropogenic	Distance from industries (km)	Streight-line distance of every point in the study area from the location of industries.	Vector (Point)	2022	Google Maps (https://maps.google.com/); Google Earth Pro	Hou et al.[33]
	Distance from tourist spots (km)	Streight-line distance of every point in the study area from the location of beaches and other tourist spots.	Vector (Point)	2022	Bangladesh Tourism Board (http://www.tourismboard.gov.bd/); Google Maps (https://maps.google.com/)	Kan et al.[38]
	Distance from roads (km)	Streight-line distance of every point in the study area from the network of roads.	Vector (Polyline)	2022	Local Government and Engineering Department (LGED), Bangladesh; OpenstreetMap (https://www.openstreetmap.org/)	Kan et al.[38]; Wu et al.[74]
	Population density (/30 m pixel)	Number of populations per 30 m grid cell.	Raster (1 km)	2022	LandScan Global 2022 (https://landscan.ornl.gov/)	Hou et al.[33]; Liu et al.[40]; Xu et al.[75]
	Soil salinity (mmhos/cm)	Salinity concentration in surface soil.	Vector (Polygon)	2010	SRDI[62]	Wu et al.[74]
Natural hazards	Cyclone intensity (per 20 km radius)	Severity of a cyclone around its trajectory.	Vector (Polyline)	1960 –2022	International Best Track Archive for Climate Stewardship (IBTrACS_v04r00) (https://www.ncdc.noaa.gov/ibtracs/); National newspaper archive (The Daily Ittefaq, Prothom Alo, The Sangbad, and The Daily Star); Alam and Dominey-Howes[5];	Nguyen and Liou [48]
	Storm surge depth (m)	Increased water level during cyclone above the normal astronomical tide level.	Raster (30 m)	Modelled 50 years maximum surge depth based on a storm surge records from 1960 to 2022	National newspaper archive (The Daily Ittefaq, Prothom Alo, The Sangbad, and The Daily Star); Alam and Dominey-Howes[5]; SRTM DEM (https://earthexplorer.usgs.gov/)	Xu et al.[75]
	Landslide (probability)	The likelihood of landslide occurrences in each grid cell of the study area.	Raster (1 km)	2018	Global landslide hazard map (https://datacatalog.worldbank.org/dataset/global-landslide-hazard-map)	Nguyen and Liou [48]

resampled to 30 m spatial resolution using the nearest neighbor resampling method. To evaluate multicollinearity among the selected criteria, the Pearson correlation test and estimation of the variance inflation factor (VIF) were conducted. The Pearson correlation coefficient measures the degree of collinearity between two criteria or variables, where the absolute value of a correlation coefficient close to $\pm$ 0.8 indicates the presence of linear dependence between the variables; therefore, they are to be removed from consideration to avoid overestimation or exaggeration [58]. The Pearson correlation test was performed on the normalized dataset, where each criterion was normalized using the widely applied min-max normalization method [29]. The VIF, on the other hand, is a measure of multicollinearity in regression analysis. A VIF > 5 indicates moderate multicollinearity, while a VIF > 10 indicates serious multicollinearity [47]. To calculate the VIF, we fitted a multiple linear regression model, which achieved a multiple R^2 of 0.77. The multiple R^2 value and calculated McFadden pseudo R^2 of 0.24 ensured a strong linear fit of the model. Apart from the criteria dataset, a gridded biodiversity richness data for the study area was also developed using the occurrence data of threatened wildlife species collected from the Red List of Bangladesh project [36]. All geospatial and statistical analyses were performed using Google Earth Engine (GEE), ArcGIS. v10.6, and R.v.4.1.3. Detailed processing and development of the criteria dataset under selected pressure groups are elaborated in Annex I.

2.2.3. Application of Fuzzy logic

Fuzzy Logic, with its implementation of fuzzy set theory, can effectively deal with uncertainties and imprecisions that arise in expert judgment-based MCDA approaches [77]. Other benefits include its straightforwardness, ease of implementation, improved accuracy, and independence from expert perception [24]. Through membership functions, fuzzy set theory assigns a degree of non-membership or membership to each object of each criterion during the standardization process, with membership grades ranging from 0 to 1 [37]. Values of a criterion within the fuzzy set are provided with full membership (1), while values outside the fuzzy set are assigned with non-membership (0) [64]. During the fuzzification process, a suitable fuzzy membership function (i.e., Fuzzy-small, Fuzzy-large, and Fuzzy-linear) was applied to each criterion within a pressure group (Annex II). Among 18 criteria, Fuzzy-small was used for five criteria that are inversely related to their respective pressure groups (Annex II). On the other hand, Fuzzy-linear was assigned to the population density, which has a linear relationship with anthropogenic pressure, meaning that increasing population density increases the magnitude of pressure. The other 11 criteria, which have positive relationships with their corresponding pressure groups, were standardized using the Fuzzy-large membership function (Annex II). These three sigmoidal fuzzy operators followed the following mathematical expressions.

Fuzzy-small:

$$\mu_x = \frac{1}{1 + \left(\frac{x}{f_2}\right)^{f_1}} \tag{1}$$

Fuzzy-linear:

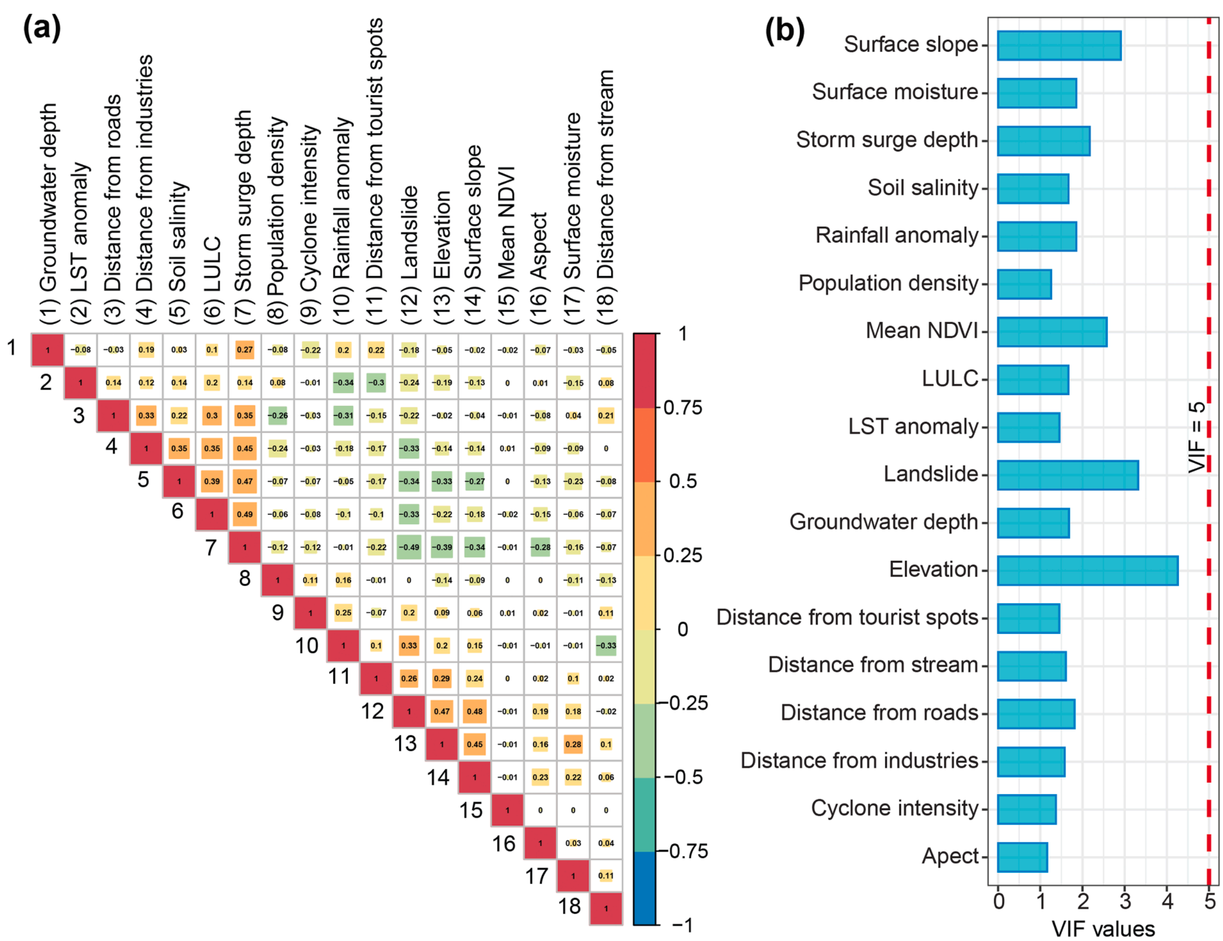

Fig. 3. Multicollinearity analysis of the selected criteria used for calculating EV. Pairwise correlation coefficients (a) and VIF values for individual criteria (b). The dashed line on (b) shows the VIF 5 limit below which multicollinearity is considered negligible. The correlogram was developed using the *corrplot* package in R v.4.1.3.

$$\mu_x = 0 \text{ if } x < \min;\ \mu_x = 1 \text{ if } x > \max;\ \text{else } \mu_x = \frac{(x - \min)}{(\max - \min)} \tag{2}$$

Fuzzy-large:

$$\mu_x = \frac{1}{1 + \left(\frac{x}{f_2}\right)^{-f_1}} \tag{3}$$

Where min and max are user input values from Annex II, x is the cell value of the criterion dataset, and f_1 and f_2 are input data spread and midpoint, respectively.

2.2.4. Calculating pressure groups and EV

Fuzzy GAMMA was used to aggregate the fuzzified criteria and calculate pressure scores for each of the five pressure groups Fig. 3 and Fig. 4). The five calculated pressures were further integrated using the same fuzzy overlay operation to calculate the EV in the study area (Fig. 5a). Fuzzy GAMMA is an algebraic product of the Fuzzy PRODUCT and the Fuzzy SUM raised to the power of Gamma. The Fuzzy Product for each cell is calculated by multiplying all the fuzzy membership values for all the input fuzzified criteria at that cell. Fuzzy SUM is an increasing linear combination function that adds the membership values of each set to which the cell location belongs. Gamma ranges from 0 to 1. When Gamma is 0, the resulting Fuzzy Gamma is equal to the Fuzzy Product. When Gamma is 1, the Fuzzy Gamma output is the same as the Fuzzy Sum. The advantage of using Fuzzy GAMMA is that it reduces extreme values by compromising the increasing and decreasing tendencies of SUM and PRODUCT operators, respectively, and thus optimizes membership combinations in estimation. The Fuzzy GAMMA follows the equation below.

$$\mu_\gamma = \left(\Pi_{i=1}^{n}\mu_i\right)^{1-\gamma} \times \left(1 - \Pi_{i=1}^{n}(1-\mu_i)\right)^{\gamma} \tag{4}$$

Where γ is the variable between 0 and 1, n is the number of fuzzified criteria layers, and μ_i denotes the membership value of i^{th} criterion layer.

2.2.5. Analyzing spatial patterns of EV

The spatial patterns of EV in the study area were analyzed using Local Indicators of Spatial Association (LISA) statistics. Among several LISA statistics, the Getis–Ord Gi* was used to distinguish statistically significant spatial clusters of high (hot spots) and low EV values (cold spots) in the study area [25] (Fig. 5b). It calculates local statistics (p-value and z-scores) for each feature in relation to its neighbors where p-values indicate the probability of randomness and z-scores represent standard deviations. Hot spots and cold spots are defined by the

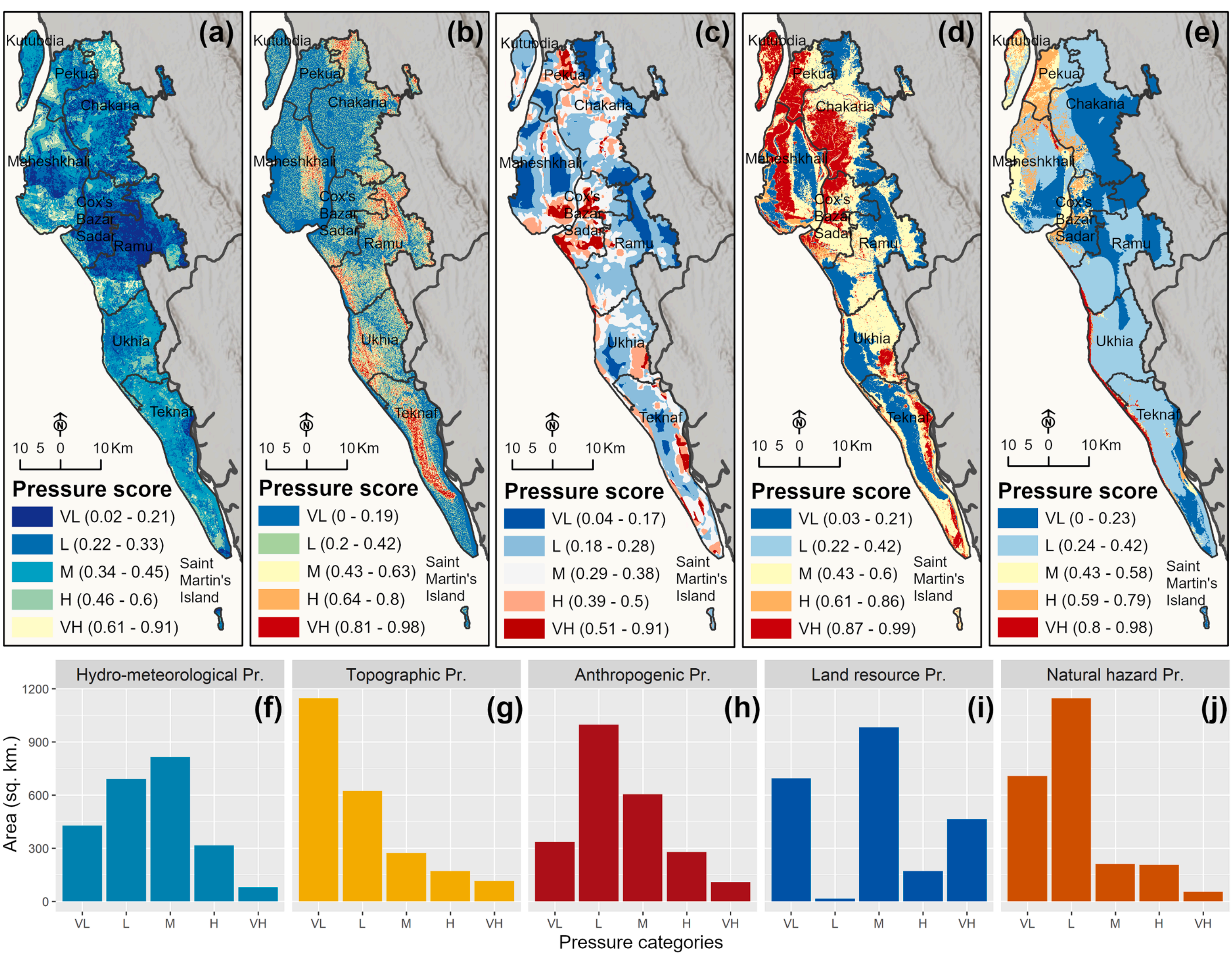

Fig. 4. Spatial distribution of environmental pressures in the study area : hydro-meteorological pressure (a), topographic pressure (b), anthropogenic pressure (c), land resource pressure (d), and natural hazard pressure (e). The areas covered by different pressure levels of the respective pressure categories are shown in Figures f, g, h, I, and j. Note: VL- Very low, L- Low, M- Moderate, H- High, and VH- Very high. The above statistics were obtained using the natural breaks classification; however, a different classification approach would provide slightly different area measurement (Annex V).

statistically significant positive values with higher z-scores and statistically significant negative values with lower z-scores, respectively. In both cases, p-values are smaller enough. Additionally, Local Moran's I was applied to measure the spatial distribution of EV values in terms of local clusters and outliers [7] (Fig. 5c). Locations with high positive Moran's I indicate that they have similar high or low-value neighbors and are part of a cluster. On the other hand, locations with high negative Moran's I represent outliers, as they have dissimilar value neighbors. Moran's I typically detects four possible clusters and outliers in the data: High-High (high values with high-value neighbors), High-Low (high values with low-value neighbors), Low-Low (low values with low-value neighbors), and Low-High (low values with high-value neighbors).

2.2.6. *Sensitivity and accuracy assessments*

A leave-one-out sensitivity analysis was conducted to determine the significance of individual pressure groups on the estimated EV. In this analysis, the EV was recalculated by excluding one pressure group at a time. The resulting EVs were compared to the original EV (Fig. 6a). To evaluate the accuracy of the EV map and ensure its reliability, annual global Particulate Matter 2.5 µm in diameter ($PM_{2.5}$) data for 2022 was used as a proxy of anthropogenic disturbance, and the data was obtained from the NASA Socioeconomic Data and Applications Center (SEDAC)

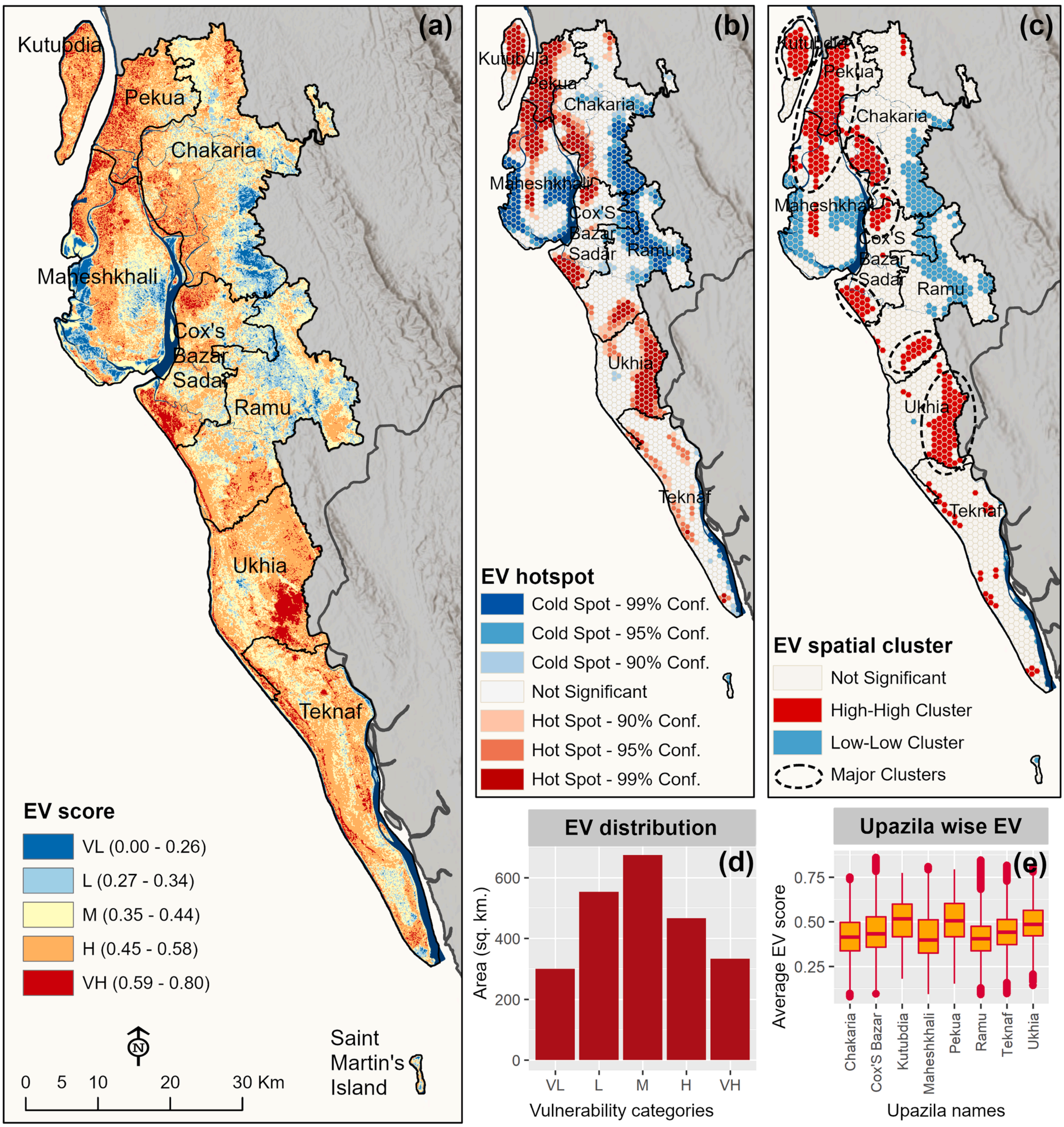

Fig. 5. Geospatial distribution of EV scores in the study area (a), statistically significant hotspots and cold spots (b), major clusters of the high EV (c), areas under different EV categories (d), and the spread of EV scores per administrative units (e). Note: VL- Very-Low, L- Low, M- Moderate, H- High, and VH- Very-High.

(Fig. 6b). The $PM_{2.5}$ concentration (μg/m^3) was estimated from MODIS, MISR, SeaWiFS, and VIIRS aerosol optical depth (AOD) in version 5.04 of the dataset. For more technical details about the data, readers refer to Van Donkelaar et al., [70]. The $PM_{2.5}$ concentration and EV values were extracted to 120 sample points randomly generated in the study area (Fig. 6b), and the correlation between $PM_{2.5}$ and EV was calculated (Fig. 6c).

2.2.7. Delineating environmental protection zones

Defining environmental protection zones based on the existing environmental condition of an area is essential for decision-making in environmental protection and conservation efforts [71,30]. It helps decision-makers understand which areas should be prioritized for implementing management measures to mitigate existing threats, reduce environmental degradation, improve ecological health, and

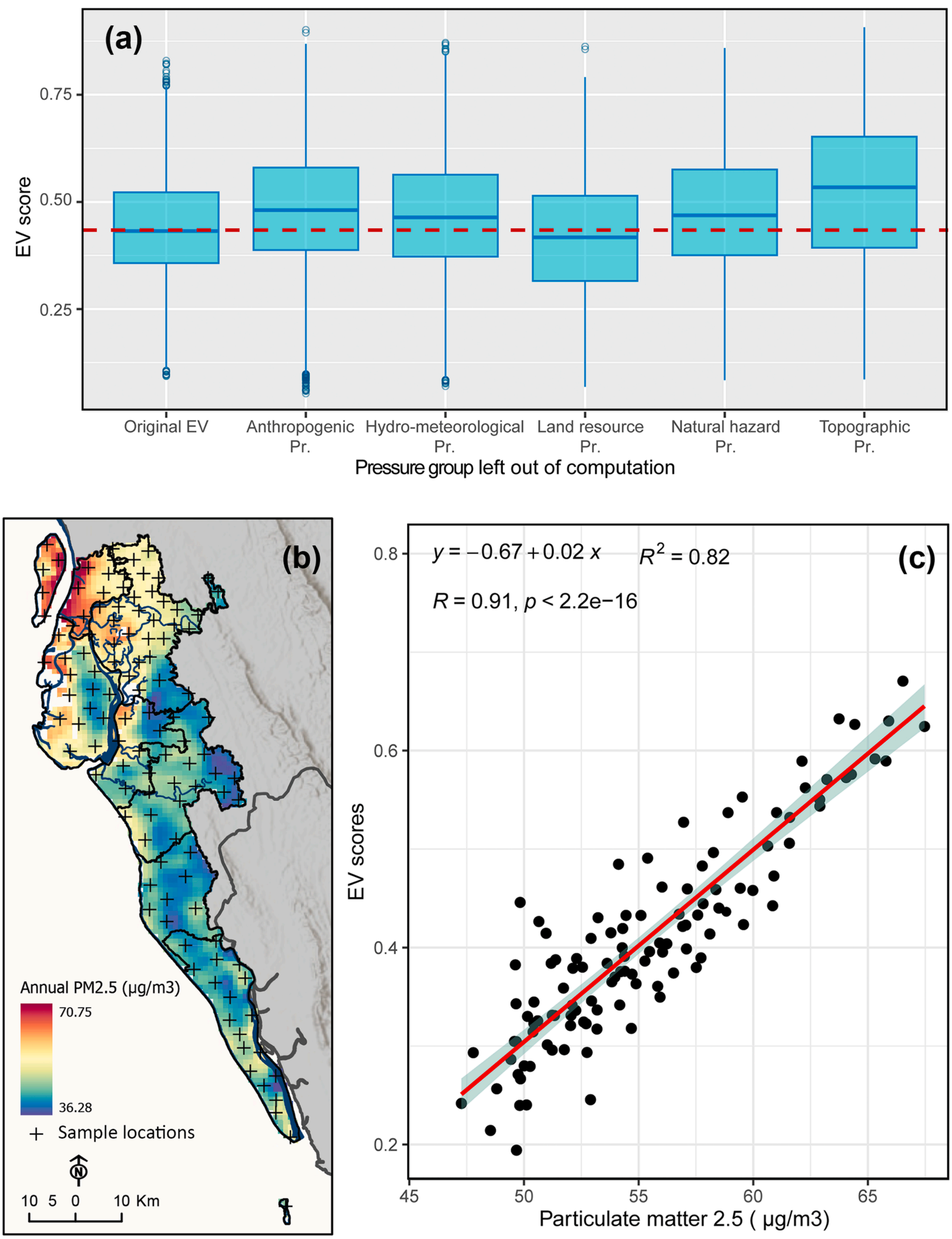

Fig. 6. Sensitivity and accuracy analyses. Comparison between the original EV and the EVs computed by leaving out one of the pressure groups at a time (as mentioned on the horizontal axis) where the dashed line represents the median value of the original EV (a); distribution of annual $PM_{2.5}$ concentration for 2022 and 120 sample points randomly distributed in the study area at which $PM_{2.5}$ and EV values were extracted (b); and correlation between $PM_{2.5}$ and EV (c).

protect biodiversity. Traditional practice of delineating protection zones is based on the partitioning of EV output [49,48,30]. However, existing literature did not consider ecological components of the study area in the zoning process, even though the main objective of zoning is to enhance ecological protection. This study improves the zoning process by incorporating in-situ threatened biodiversity richness data. The gridded biodiversity richness was calculated using the spatial *Extent of Occurrences* (EOO) of 168 threatened species from seven wildlife groups: Amphibians, Birds, Butterflies, Crustaceans, Freshwater Fishes, Mammals, and Reptiles (Annex IV). The EOOs of threatened species were collected from the IUCN Bangladesh, [36]. The total number of species was counted for each cell in a 30 m regular grid using Eq. (5), and the grid was then converted into raster format.

$$BR_k = \sum_{i=1}^{\varnothing} P\{S_p(WG_{i,k})\} \tag{5}$$

Where BR_k is the biodiversity richness value for cell k, P is the presence (1) or absence (0) of individual species (S_p) in i^{th} wildlife group (WG) in cell k, and $\varnothing$ is the number of species in the corresponding wildlife group.

The normalized biodiversity richness data (Fig. 7a) was integrated with the normalized EV data (Fig. 7b) using Eq. (6) for calculating protection priority (PP) score (Fig. 7c).

$$PP_k = nEV_k + nBR_k \tag{6}$$

Where PP_k is the protection priority score for cell k, nEV_k is the normalized EV score in cell k, and nBR_k is the normalized biodiversity richness score in cell k. The normalization of both EV and biodiversity richness scores was performed using the min-max normalization technique, which scaled both data between 0 and 1.

The PP scores obtained from Eq. (6) were classified into three categories using natural breaks, where areas with high, moderate, and low PP scores were delineated as strict, medium, and soft protection zones, respectively (Fig. 7d).

3. Results

3.1. Results of multicollinearity assessment

Fig. 3a shows pairwise correlation coefficients of the selected criteria as a measure of multicollinearity. According to the Person's test results, all correlation coefficient values fell within the range of 0.49 to −0.49, much lower than the threshold of 0.8 or −0.8, indicating that most criteria are independent. Among the 18 criteria, storm surge depth, LULC, soil salinity, distance from industries, elevation, landslide probability, and surface slope exhibited moderate collinearity among some of them, as evident from their correlation coefficients being close to ± 0.5; however, these correlations were not deemed significant enough to warrant their removal from consideration. As shown in Fig. 3b, the VIF values ranged between 1.16 and 4.2, demonstrating insignificant collinearity among the criteria used in the EV computation.

3.2. Spatial distribution of environmental pressures

The spatial distributions of five environmental pressures in the study area are shown in Fig. 4. The pressure scores obtained for each pressure group were classified into five relative categories, from very low to very high, based on the data distribution. Results show that except

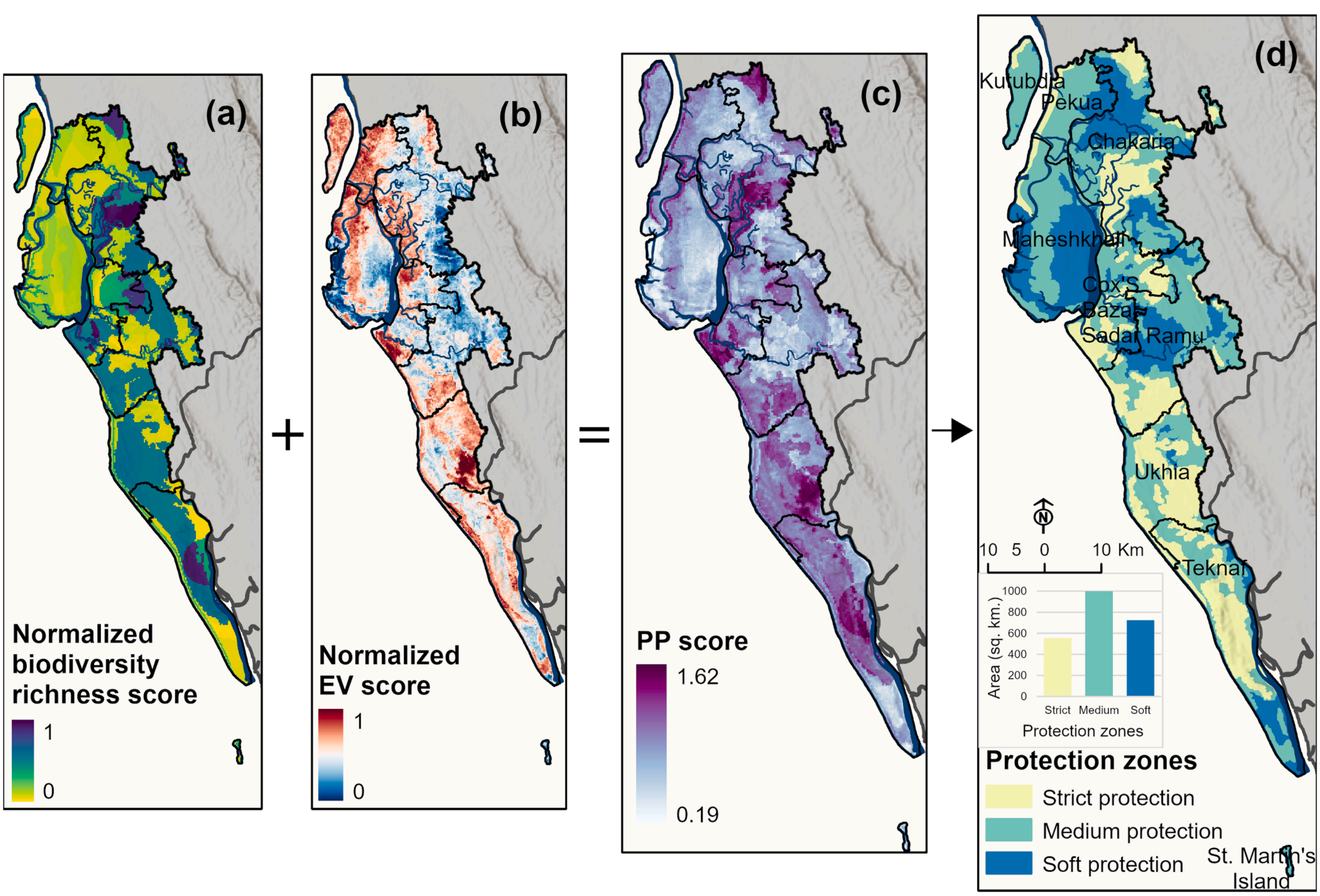

Fig. 7. Environmental protection zones (d) in the study area delineated from protection priority (PP) scores (c). PP scores were calculated from threatened biodiversity richness (a) and EV distribution (b).

topographic pressures, predominant in the hills of Chakaria, Maheshkhali, Ramu, Ukhia, and Teknaf, higher values of all other pressures are primarily concentrated in the northern part of the study area, covering Pekua, Chakaria, Maheshkhali, and Cox's Bazar Sadar. Around 17 % (472 sq. km.) of the study area is exposed to high to very high pressure (scores ≥ 0.46, Fig. 4f) due to varying hydro-meteorological conditions. Areas including Matarbari power plant site, Cox's Bazar urban area, refugee camps, and the northern upland of Chakaria exhibit higher hydro-meteorological pressures characterized by highly anomalous rainfall and LST, inadequate stream connectivity, and deficit surface moisture. About one-third of the area (816 sq. km.), including Kutubdia and the highlands of Ukhia and Teknaf upazilas, exhibits moderate hydro-meteorological pressure (scores = 0.34 - 0.45, Figs. 4a and 4f). On the other hand, the central regions of Cox's Bazar Sadar, Chakaria, and Ramu upazilas, dominated by homestead vegetation and agricultural lands, represent low to very low pressure scores (≤ 0.33, Figs. 4a and 4f), constituting 48 % (1117 sq. km.) of the study area.

Regarding topographic pressure, half of the area (1146 sq. km.) experience very low pressure (scores ≤ 0.19, Figs. 4b and 4g). This category includes extensive flat regions with low elevation (< 10 m) in Kutubdia, Pekua, Chakaria, Maheshkhali, Cox's Bazar Sadar, and the southern and southeastern parts of Teknaf upazila (Fig. 4b). Moderately elevated forest areas with low slope gradients, particularly in the southern part of Ramu, the eastern part of Ukhia, and the northern part of Teknaf, accounting for 623 sq. km. (27 %), demonstrate low topographic impacts (Fig. 4b and g). In contrast, moderate to very high topographic pressure scores (≥ 0.43), covering 23 % (558 sq. km.) of the area, are observed in the hills with steep slopes (> 10 degrees) of north and northeastern Chakaria, Maheshkhali, Ramu, Ukhia, and Teknaf upazilas.

Human-induced pressures are concentrated near anthropogenic developments in the area. According to Fig. 4c and h, 17 % (388 sq. km.) of the study area is exposed to high to very high anthropogenic pressures (scores ≥ 0.39) and covers the northern portion of Pekua, the southeastern Maheshkhali, sea beaches, refugee settlements in Ukhia and Teknaf, Cox's Bazar city, and the central part of Cox's Bazar Sadar upazila. Moderately affected locations (25 % of the area) can be found in industrial areas, tourist attractions, deforested surfaces, and urban settlements. However, lush agricultural fields, coastal mangroves, protected forests, and scattered rural settlements, accounting for 58 % of the study area, show low to very low anthropogenic impacts (scores $\leq$ 0.28).

High to very high land resource pressures, covering 27 % (635 sq. km.) of the study area, are mainly concentrated in aquaculture and salt production sites, tourist spots, urban areas, and refugee camps (Fig. 4d and i). Croplands and non-urbanized settlements in all upazilas, constituting 42 % of the study area, depict moderate land resource pressure (score = 0.43 - 0.6, Fig. 4d and i). Reserved forests and other dense hilly forests of Teknaf, Ukhia, Chakaria, Ramu, and Maheshkhali upazilas represent low to very low human-induced pressure scores ($\leq$ 0.42).

Due to its proximity to the Bay of Bengal, the study area is exposed to cyclones and storm surges. Additionally, deforestation and unlawful hill-cutting increase the vulnerability of hilly areas to landslides. The results reveal that 2.4 % of the study area, mostly distributed along the coastal strip of Cox's Bazar, Ramu, Ukhia, and Teknaf Upazilas, experience very high (score$\geq$ 0.8) natural hazard pressure (Fig. 4e and j). Moderate to high pressures (scores = 0.43 - 0.79) are observed in18 % of the area, including Kutubdia, western Maheshkhali coast, western Pekua, the southwestern fringe of Chakaria, and western parts of Cox's Bazar Sadar upazila. The remaining study area experiences low pressures from natural hazards.

3.3. Spatial distribution and patterns of EV scores

The spatial distribution of EV scores reveals that 34 % (799 sq. km.) of the study area experiences high to very high EVs (score = 0.45 - 0.80, Fig. 5a and d). These higher EVs are mainly observed in Kutubdia, Pekua, Cox's Bazar Sadar, and Ukhia upazilas (Fig. 5a). Moderate Evs (scores = 0.35 – 0.44) are found in extensive arable lands and human settlements located in the piedmonts and plains of Chakaria, Ramu, northeastern Cox's Bazar Sadar, eastern Maheshkhali, and the northern and southern Teknaf peninsula (Fig. 5a). This category represents 29 % (675 sq. km.) of the study area (Fig. 5d). Lower environmentally vulnerable areas, on the other hand, making up 37 % (853 sq. km.) of the study area, include southeastern hill forests of Chakaria, northeastern hill forests of Ramu, central parts of the Saint Martin's Island, and coastal strip of the Maheshkhali Island (Fig. 5a and d). Among the eight upazilas in the study area, Kutubdia, Pekua, and Ukhia represent high average EV (score > 0.49) (Fig. 5e).

Fig. 4b shows the spatial pattern of EV scores in the study area in terms of hot spots and cold spots. Kutubdia, Pekua, northern Maheshkhali, southwestern Chakaria, Cox's Bazar city, southern Ramu, and eastern portion of Ukhia exhibit statistically significant higher EV values (EV hot spots) with positive z-scores ($z > 2.6$; $p < 0.01$) (Fig. 5b). Conversely, the northeastern and northwestern regions of the study area, where different pressure intensities are considerably lower, show EV cold spots with statistically significant lower EV scores and negative z-scores ($z < -1.64$; $p < 0.01$) (Fig. 5b).

Furthermore, Local Moran's I identifies seven major High-High clusters located in northern Kutubdia, western Pekua and northern Maheshkhali, southwestern Chakaria, Cox's Bazar City, northwestern Cox's Bazar Sadar, southern Ramu, and eastern Ukhia, where EV values are higher in the high-value neighborhoods (Fig. 5c). Low-Low clusters, in contrast, representing lower EV scores in the low-value neighborhoods, are found in eastern Chakaria, eastern Ramu, and both eastern and western parts of Maheshkhali Island. Overall, EV hotspots or High-High EV clusters are typically characterized by extensive anthropogenic activities and higher hydro-meteorological, topographic, land resource, and natural hazard impacts compared to the neighboring areas.

3.4. Results of sensitivity and accuracy assessments

In Fig. 6a, the original EV is plotted, with its median value represented by a dashed line. Other boxplots represent EV values computed by discarding one pressure group at a time. The results indicate that except for 'land resource pressure,' the direction of EV change is consistent across the other pressure groups. If anthropogenic, hydro-meteorological, natural hazard, or topographic pressure is excluded from the EV computation one at a time, the resulting EV score increases in each case. In contrast, land resource pressure plays a diminishing role; neglecting this particular pressure results in lower EV. In other words, a higher land resource-based pressure at current condition leads to increase environmental vulnerability. Among the five different pressures, land resource has the most influence on EV, while topographic pressure has the least. Regarding the accuracy assessment of the EV map, the correlation between $PM_{2.5}$ (Fig. 6b) and EV yielded a correlation coefficient of 0.91 (Fig. 6c), indicating strong reliability of the calculated EV map.

3.5. Delineated environmental protection zones

The proposed environmental protection zones are regions that require different levels of protection measures to reduce threats and improve environmental quality. The EV result and biodiversity richness data contributed to identifying three distinct levels of environmental protection zones. Strict protection zones (Fig. 7d), making up 24 % (555 sq. km.) of the study area, are characterized by high PP scores (> 1) due to high threatened biodiversity richness and EV scores. This protection category mainly covers hill forests and croplands in Chakaria, Ramu, Ukhia, and Teknaf. Alongside three reserved forests (Chuntati WS, Fasiakhali WS, and Teknaf WS) and Himachari NP, Cox's Bazar urban area, aquaculture sites of Chakaria, and coastlines are included in this protection category. Zones defined for medium protection (45 % / 1047 sq. km.) can be observed in all upazilas, with prominence in the northern part of the study area, where croplands, forests, and salt pans are dominant LULCs. This protection category consists of medium PP scores (0.72 - 1) resulting from moderate biodiversity richness and moderate to high EV scores. Soft protection zones, on the other hand, comprising 31 % (725 sq. km.) of the study area, cover arable fields and rural homesteads in the eastern Maheshkhali, northern Chakaria, central Ramu, and the southern Teknaf peninsula (Fig. 7d). In these areas, both biodiversity richness and EV scores are poor (PP score < 0.72) (Fig. 7a and b).

4. Discussion

4.1. Advantages of the EV assessment framework

The EV assessment framework applied in this study is straightforward and well structured, where all the existing threats in the study area were categorized and assessed under specific pressure groups. Unlike other methods, it doesn't rely on expert suggestions in the weighting process, ensuring the results are more realistic and less prone to uncertainties and imprecisions [15,39,77]. A key advantage of using fuzzy logic in the EV assessment is its ability to utilize data from any measurement scale [52]. This flexibility allows incorporation of a greater number of variables and thus enhances the framework's usability in diverse multi-criteria-based decision-making. Managers can tailor the criteria to address specific local pressures, whether anthropogenic, hydrometeorological, or topographic. This framework is scalable and can be applied to any study area, regardless of spatial scale, by adjusting the criteria based on available pressures and relevant spatial data. Usually, the more criteria included in the assessment framework, the better the result is. This adaptability ensures the framework's relevance and usefulness in diverse coastal regions, facilitating targeted management interventions. Additionally, the integration of in-situ threatened biodiversity distribution in the framework provides a scientific definition for delineating environmental protection zones, which was lacking in previous studies. This approach of protection zoning enhances environmental and ecological protections in both terrestrial and aquatic study areas by considering the ecological resources of the study area, not just the EV results.

4.2. EV status in the proposed environmental protection zones

EV scores in strict protection zones are comparatively higher due to elevated anthropogenic and land resource pressures, as well as high elevation and slope gradient. While overall hydrometeorological pressures are medium to high in most of the strict protection zones, extreme LST anomaly (1.41 °C −8.49 °C) and insufficient surface moisture seem to be contributing factors to higher EVs. Certain anthropogenic activities such as sea salt extraction in Chakaria and Pekua, shrimp farming in Chakaria, beach tourism along the coastlines of Cox's Bazar Sadar and Ramu, industrial operation in southern Ramu, and Rohingya refugee settlements in Ukhia and Teknaf upazilas, exacerbate environmental degradation by raising EVs in these zones. Despite four nationally designated conservation sites (Chunati WS, Fasiakhali WS, Himchari NP, and Teknaf WS) within strict protection zones, they still exhibit high EV scores due to the increased hydrometeorological and topographic pressures. In medium protection zones, EV scores range from moderate to high. However, in Pekua, Kutubdia, and northern Maheshkhali, EV scores are particularly high, especially in salt harvesting sites. The recent establishment of a coal-fired power plant (1200 MW) at Matarbari in Moheshkhali, which falls within this protection category, reflects high EV scores due to the possibility of releasing potentially toxic elements into the surrounding environment. These protection zones are also highly exposed to landslides, cyclones, and cyclone-induced storm surges. Areas delineated as soft protection zones have moderate to low EV scores due to lower hydrometeorological, land resource, and anthropogenic pressures. Additionally, due to the remoteness of the coastline, these areas have lower exposure to natural hazards, such as storm surges and tropical cyclones. The relatively flat topography, sparse settlements with abundant vegetation, and extensive arable lands significantly contribute to lower EVs. The low population density and absence of tourism activities in soft protection zones are also important reasons for their decreased EV scores.

4.3. Implications for environmental management in coastal area

The results of the study provide valuable insights for coastal management. The main research finding suggests that improved decision-making is needed with comprehensive data integration. Since the EV assessment framework incorporates diverse criteria, it allows coastal managers to make more informed and nuanced decisions based on a comprehensive understanding of environmental pressures. Environmental assessments become more robust and thus may lead to more effective management strategies. For instance, by analyzing EV scores and integrating biodiversity data, the framework enables the delineation of environmental protection zones. This helps coastal managers prioritize areas for conservation efforts based on their vulnerability and ecological significance. The identification of strict, medium, and soft protection zones allows for tailored management approaches that can mitigate specific threats and pressures, enhancing the overall effectiveness of conservation initiatives. In the case of Cox's Bazar area, new environmental protection zones were proposed, which do not fully match with the existing ones. This demonstrates that integrating comprehensive data helps make more accurate decisions, particularly in the context of marine protection zones, which are regarded as one of the most effective tools for integrated coastal management [13].

Another relevant implication for coastal management is related to the enhanced monitoring and management of human activities, which are repeatedly reported to have negative impacts on ecological services [76,79]. The detailed analysis of EV scores highlights the impact of various anthropogenic activities, such as tourism, industrial operations, and refugee settlements, on environmental degradation. Coastal managers can use this information to implement stricter regulations and monitoring protocols in high-impact areas. For instance, activities like sea salt extraction, shrimp farming, and coal-fired power plants in Cox's Bazar area can be closely monitored and managed to minimize their environmental impact.

Finally, the assessment framework considers hydrometeorological pressures and topographic factors, which are critical in understanding the vulnerability of coastal zones to natural hazards like cyclones, storm surges, and landslides. Coastal managers can use this information to develop and implement disaster risk reduction strategies, enhance early warning systems, and design climate-resilient infrastructure. This proactive approach helps reduce the risk and impact of natural disasters on coastal communities and ecosystems, especially as shifting traditional practices towards more climate-aware approaches is considered one of the key actions to address coastal management and engineering challenges [65].

4.4. Limitations and future developments

There are some limitations of this study, such as it did not include sea-level and shoreline changes of the study area in the assessment framework due to the lacking of reliable data. A coarser resolution landslide probability data was used because of the unavailability of actual locations of landslide occurrences in the study area. The evapotranspiration, an important hydro-meteorological parameter was also not included in the assessment because of insufficient spatial and temporal coverage. Though earthquake and tsunami occasionally occur in the area, they were not included in the assessment framework because of the lacking of their locational data. Future research should consider these variables as well as pressures from potentially toxic elements and persistent organic pollution in the assessment framework for obtaining better EV results. This study used the natural breaks classification method in visualizing vulnerability maps. However, a different classification approach identical across multiple maps might help the reader to compare them easily. Future research should compare the effectiveness of different data classification methods in this kind of study. This research used data with varying spatial and temporal resolutions, which usually introduce uncertainty in analysis. Such uncertainties were not analyzed in this research, which is a potential limitation and needs to be assessed in future studies.

5. Conclusions

The spatial assessment of EV lies at the cornerstone of ecological and environmental resource management. This study was conducted in the ecologically and socio-economically important area of Bangladesh: Cox's Bazar, where the environment is exposed to several anthropogenic and natural pressures. For assessing EV, a diversified geospatial dataset characterizing five pressure determinants and the consolidation of geostatistical techniques such as GIS-based fuzzy logic were used through a comprehensive methodological framework. The integration of EV with a threatened biodiversity distribution map was developed and used in this study to provide a valid ground for delineating environmental protection zones. This study identified unplanned urbanization, expansion of refugee camps and human settlements, deforestation, hill cutting, unsustainable land-use practices, and uncontrolled tourism activities as major anthropogenic pressures in the study area that have been deteriorating environmental quality. Results summarized that 34.3 % of the study area is exposed to high to very-high environmental vulnerability due to increased pressure determinants. Kubtubdia and Pekua followed by Ukhia, Teknaf, and Cox's Bazar Sadar upazilas represented higher EVs (average EV> 0.48) where pressures from five determinants are high. Such higher EVs led to the development of EV hotspots in the area, covering 513 sq. km., with seven major high-EV clusters. Considering ecological significance, this study suggests that 24 % of the area should be designed for strict environmental protection.

The findings of this study are useful for decision-makers, environmental planners, local stakeholders, and conservation practitioners to enhance the overall environmental conditions in the study area. The spatializations of multi-pressure impacts and the delineation of environmental protection zones in this study can support achieving SDG Target 15, which focuses on the protection and restoration of terrestrial habitat and biodiversity in the study area. Lastly, the overall findings of this study validate the necessity of reassessing existing policies and measures to curb environmental degradation, not only in the study area but also in other environmentally vulnerable locations of Bangladesh.

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CRediT authorship contribution statement

Nusrat Sumaiya: Project administration. **Muhammad Al-Amin Hoque:** Writing – review & editing. **Ieva Misiūnė:** Writing – review & editing, Writing – original draft. **Maurizio Ambrosino:** Writing – review & editing. **Daniel Depellegrin:** Writing – review & editing, Writing – original draft, Supervision. **Sanjoy Roy:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Monojit Saha:** Writing – review & editing, Writing – original draft, Software, Data curation. **Md Mehedi Hasan:** Writing – original draft. **Afifa Razzaque:** Writing – review & editing, Data curation.

Declaration of Competing 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.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.geomat.2024.100030.

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