Environmental Vulnerability Assessment in Coastal Areas with Intensive Tourism Activities: A Case Study in Ba Ria-Vung Tau Province, Vietnam

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***Abstract*—Given their geographic advantages and abundant resources, coastal tourism areas contribute significantly to socioeconomic development. However, the environment in these areas is highly vulnerable due to rapid socioeconomic development and climate change. The development of an environmental vulnerability index under intensive tourism pressure is therefore vital for sustainable coastal management. This study applied the multicriteria decision-making method to establish an environmental vulnerability assessment index based on two component indices, namely, sensitivity and adaptability, for the coastal tourism area of Ba Ria-Vung Tau province, Vietnam. The data were collected through secondary sources, surveys, in-depth interviews, remote sensing, and geographic information systems to estimate the indices and assess vulnerability. The vulnerability maps of 23 subregions in the study area were then constructed. They revealed four levels of vulnerability: low, moderate, high, and very high, which accounted for 21.74%, 34.78%, 30.43%, and 13.04% of the study area, respectively. Subsequently, three solutions were proposed to mitigate the vulnerability in the subregions with high and very high vulnerability. This study will assist decision-makers in planning and facilitating the sustainable development of coastal areas.**

***Keywords*—vulnerability, sensitivity, adaptability, multiple-criteria decision-making, coastal areas, remote sensing, geographic information systems**

I. Introduction

Coastal areas, the dynamic interface between land and sea [1], are significant ecologically and socioeconomically due to their geographical advantages and abundant resources [2]. According to Liu *et al.*, although these areas cover only 4% of Earth's land and 11% of the ocean, they are home to about 40% of the global population and contribute nearly 60% to the world economy [3]. Economic activities in these areas are diverse and involve tourism, ports, marinas, aquaculture, and various other industries [4], which makes them critical compared to inland regions [5]. Vietnam's coastal area spans over 3,260 km of coastline and includes 28 coastal provinces/cities [6]. It houses about 50% of the nation's population, contributes roughly 50% to the Gross Domestic Product (GDP), and plays a pivotal role in national economic and tourism development [7, 8]. Along this coastal region, Ba Ria-Vung Tau province stands out for its robust socioeconomic development, particularly in the tourism sector. With a 156km coastline and recognized beaches, such as Vung Tau, Long Hai, and Ho Tram, this area attracts over seven million tourists annually [9] and contributes around 4.5% to the province's gross regional domestic product [10]. Tourism in Ba Ria-Vung Tau province is one of the four crucial economic pillars of the locality, alongside industry, seaports, and high-tech agriculture [10]. However, rapid coastal development is posing challenges to sustainable development, as evidenced by escalating pollution and an increased risk of natural disasters exacerbated by climate change. This vulnerability is evident in Bangladesh's coastal regions, which are highly susceptible to tropical cyclones such as Cyclones Gorky (1991) and Sidr (2007), causing 147,000 and 4500 deaths, respectively [11]. Likewise, Typhoon Mangkhut in 2018 caused direct economic losses amounting to 5.2 billion Chinese yuan in Southeast China [12]. Regarding the study area, between 2011 and 2020, Ba Ria-Vung Tau experienced over 40 storms, tropical depressions, and natural disasters, which caused about 25 million USD in damage [10]. Coastal erosion due to rising sea levels has had a notable impact on tourism infrastructure from the city of Vung Tau to Xuyen Moc District [13]. Moreover, the 2016 environmental incident caused by Formosa Corporation's discharge degraded water quality and severely harmed coastal resources, fishermen's livelihoods, and tourism [14]. Assessing the environmental vulnerability to climate change and its socioeconomic development risks is therefore crucial for effective and sustainable coastal management.

Various approaches have been implemented to assess vulnerability in the current context. According to Schneiderbauer and Ehrlich, vulnerability is the capacity of a person or group of people to anticipate, cope with, resist, and recover from the impact of a natural or manmade disaster [15]. Additionally, Kaly *et al.* defined vulnerability as the potential for the attributes of any system, human or natural, to respond adversely to hazardous events [16]. Notably, the Intergovernmental Panel on Climate Change (IPCC) describes vulnerability as the tendency of a coastal environmental system to be adversely affected by hazards and as a function of two component indices: sensitivity and adaptability [17]. The IPCC approach, which is favored for its practicality, reliability, and ability to facilitate vulnerability reductions before and after a disaster [18], has gained significant attention from researchers [19–21]. However, IPCC-based vulnerability assessments have commonly focused on sectors such as agriculture, fisheries, forestry, biodiversity, energy, and water resources [22]. In terms of the components of vulnerability, the IPCC defines sensitivity as the degree to which a system is adversely or beneficially affected by climate change or hazards and adaptability as the capacity of a system to adjust to possible damage by taking advantage of opportunities to mitigate or respond to such consequences [17]. In some studies, sensitivity has been explained by the presence of natural, geomorphological, and ecological factors that increase the vulnerability of environmental systems [23], while adaptability is considered a system's ability to withstand or recover from changes [24], thereby reducing vulnerability when hazards occur [25].

Based on the understanding of the components of vulnerability, researchers worldwide have focused on identifying specific criteria to estimate coastal vulnerability. In their study, Turriza *et al.* utilized eight natural criteria to establish an environmental vulnerability index for the coastal area of Campeche, Mexico, based on sensitivity factors. These criteria included geomorphology, elevation, coastal slope, shoreline change rate, dune, wave height, mangrove, and coral reef [26]. Using a similar multicriteria approach, Arda *et al.* evaluated coastal sensitivity by adding the criteria of land use and coastal type [27]. Beyond natural aspects, some researchers have incorporated socioeconomic criteria to assess coastal vulnerability. For example, Wang *et al.* combined natural criteria with socioeconomic criteria (i.e., population density, GDP, and level of coastal tourist attractions) to evaluate vulnerability at tourist sites in the Bohai Sea, China [28]. In another study, Zha *et al.* developed an environmental vulnerability index for tourism based on socioeconomic and environmental criteria, which included tourism labor and revenue [29]. Similarly, Cuong *et al.* used eight criteria spanning natural, socioeconomic, and environmental aspects to construct a sensitivity index for the coastal region of Southeast Vietnam [30]. These criteria included coastal type, coastal slope, species, nature reserves, population density, vulnerable population, tourism, and aquaculture. Additionally, in their study in Sri Lanka, Chandrajith *et al.* effectively utilized reliable coastal water quality data to analyze sensitivity and emphasized the importance of high-quality environmental data in coastal vulnerability assessments [31]. Some researchers have also assessed vulnerability based on adaptability. For instance, Sweet and Rejaur Rahman developed an environmental vulnerability index to support adaptation solutions for coastal areas in Bangladesh by focusing on socioeconomic criteria, such as population density, dependent population, and literacy rate [32]. In other studies, Mabrouk and Haoying integrated environmental and institutional aspects to determine the vulnerability of coastal cities by estimating their adaptability. These criteria included medical capacity, employment status, homeownership, built environment conditions, river length, and the distance from shore [33]. Deng employed socioeconomic and institutional criteria to assess adaptability in the Guangdong–Hong Kong–Macao Bay area and included tourism revenue, investment in environmental pollution control, and environmental protection personnel [34]. Additionally, to address socioeconomic, environmental, and institutional aspects, Scott *et al.* used criteria such as coastal/beach tourism impacts, tourism competitiveness, and governance quality [35].

A commonly employed approach in vulnerability assessment research is the index/indicators-based method (MCDM), which is often used alongside dynamic computer models, Geographic Information System (GIS)-based decision support tools, and visualization tools [36]. Multiple-Criteria Decision-Making (MCDM) effectively addresses the complex, multidimensional issues of selection, arrangement, and ranking by accommodating criteria with different quantitative or qualitative dimensions [37]. Researchers typically focus on criteria with varying importance (weights) to emphasize critical aspects and support effective decision-making. In most studies, the Analytic Hierarchy Process (AHP) has been utilized for weighting due to its simplicity, popularity, and ability to facilitate multidisciplinary approaches [20, 27, 28, 30, 36]. Other studies have employed Principal Component Analysis (PCA) to overcome the subjective and qualitative limitations of AHP [38–40]. Notably, some researchers have combined AHP and PCA to address criteria weighting [41–43] and ensure a balance between qualitative and quantitative factors while leveraging available real-world data. Additionally, GIS technology has been widely used to rank and map vulnerability [27, 28, 30, 33].

Research on environmental vulnerability in coastal areas often emphasizes the sensitivity of these environments to climate change and socioeconomic development. However, adaptability is rarely mentioned despite its importance as one of the two factors constituting vulnerability. In addition, in the MCDM process, researchers have yet to fully utilize available real-world data, which presents challenges in comprehensively addressing the research problem. Therefore, this study approached the development of an environmental vulnerability assessment of coastal areas experiencing intensive tourism activities based on sensitivity and adaptability indices, which were estimated using optimally weighted criteria. The weights were determined through a multidisciplinary approach that combined expert judgment and tangible real-world data. This approach ensured that the criteria and weights were established objectively and realistically and thereby increased the reliability of the assessment results.

This study makes two main contributions. (1) A composite index was developed to assess environmental vulnerability of coastal areas under tourism pressure based on two component indices: sensitivity and adaptability. These component indices were estimated using sets of criteria and corresponding weights through the MCDM tool and incorporated AHP and PCA methods combined with expert judgment. (2) A composite index and GIS technology were applied to evaluate and map the environmental vulnerability of coastal areas in Ba Ria-Vung Tau province, Vietnam.

II. Materials and Methods

A. Study Area

The study area was Ba Ria-Vung Tau province, which is located in the southeast coastal region of Vietnam with geographical coordinates ranging from 10°18′13″ to 10°39′14″ North latitude and 106°59′67″ to 107°34′73″ East longitude (Fig. 1). This area is highly dynamic, with a high population density of approximately 589 people per km^2 and diverse socioeconomic sectors, including 17 industrial parks, 51 seaports, service, and tourism, which contribute significantly to the local Gross Domestic Product (GDP) [10]. Remarkably, tourism is a key economic driver in the region, with about 48 historical relics [10], 1000 establishments offering more than 15,500 rooms for tourist accommodation along the coastline, and numerous top-tier resorts in the southeast. The coastal area selected for the vulnerability assessment is divided into 23 subregions and has notable tourism potential as well as diverse natural, socioeconomic, and environmental features.

In addition to these positives, the rapid development of this region has had several negative consequences, such as environmental pollution and resource overexploitation. Coastal waters suffer from nutrient pollution exceeding regulatory standards, though improvements are being made. Mangrove areas have declined by over 50% since 2003 due to the expansion of industrial parks, seaports, and service facilities [10]. These threaten sustainability and increase the environmental vulnerability to multiple climate change hazards. These subregions were selected for their locations, dynamic socioeconomic conditions, environmental resources exposed to multiple hazards, and the limitations of existing studies and timely assessment tools.

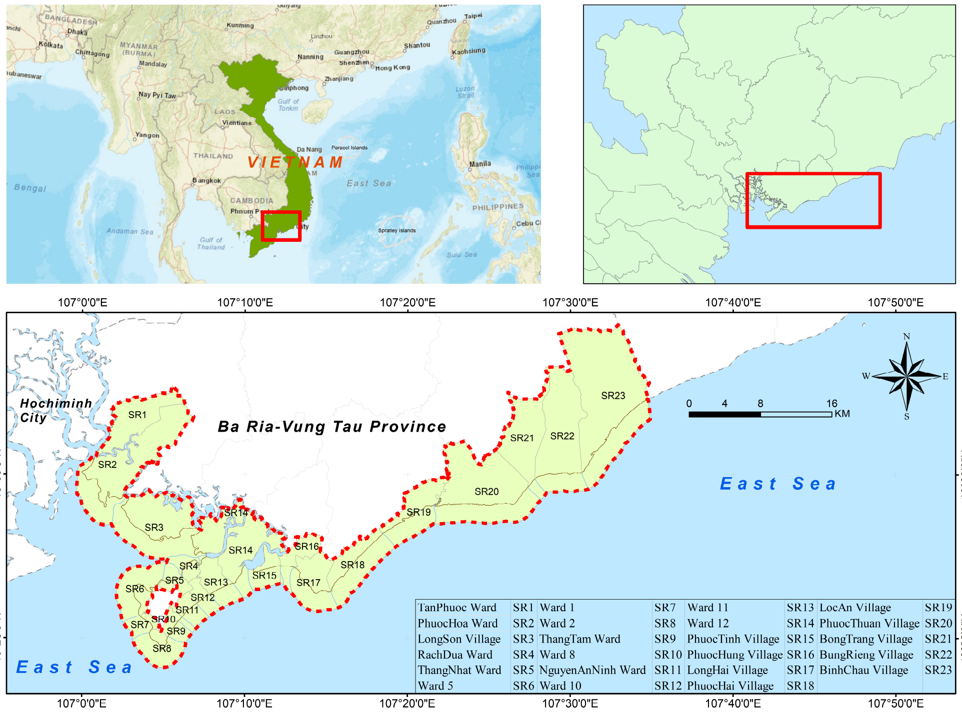

Fig. 1. The research area.

B. Methodology

In this study, an integrated approach that combined MCDM, multivariate analysis, and GIS was developed to establish a composite index for assessing the environmental vulnerability of coastal areas. The overall methodology is presented in Fig. 2.

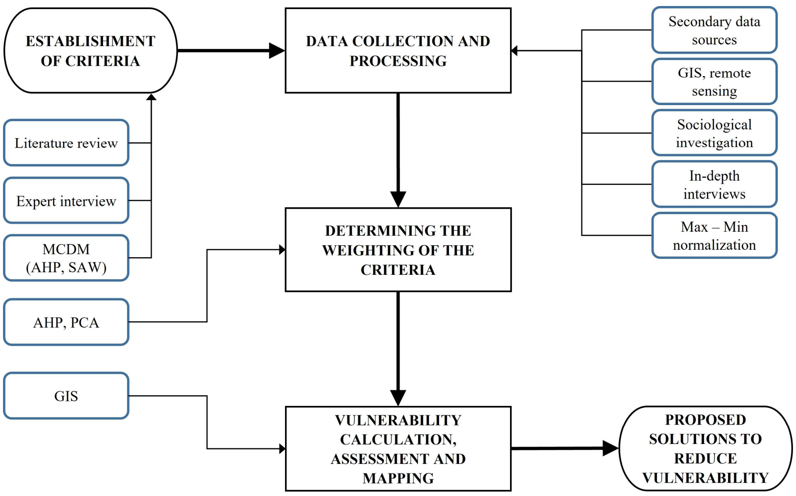

Fig. 2. Methodology framework.

1) Establishment of criteria sets

The MCDM method was employed to develop criteria sets that corresponded with the two component indices of sensitivity and adaptability. The process was as follows:

- Establishment of preliminary criteria: Based on a review of the literature and the characteristics of the study area, the preliminary criteria were selected (Table 1). These criteria are considered highly effective and are used widely by scientists to assess coastal vulnerability. Additionally, they are closely related to the natural, socioeconomic, environmental, and institutional aspects that are characteristic of the coastal tourism area of Ba Ria-Vung Tau province. The criteria were illustrated based on the actual conditions and linked to the spatial resolution of the study area. The criteria were then screened using five subcriteria with different weights: ease of understanding, alignment with the goal, accuracy and transparency, data availability, and sensitivity [44].

Table 1. Preliminary criteria

	No.	Criteria	Unit	Description	Ref.
Sensitivity index	1	Inundation	%	Ratio of the inundated area: the larger the area affected by sea level rise, the higher the sensitivity. This is the primary hazard for the study's coastal area	[45]
	2	Tide range	m	The more extensive the tidal range, the higher the sensitivity	[46]
	3	Coastal type	-	Coastal construction materials: decreasing sensitivity from the rocky shores and artificial embankments to the construction lands, sandy beaches, and wetlands	[28]
	4	Population density	people per km^2	Number of people per unit area: the higher the population density, the greater the sensitivity	[32]
	5	Tourist attractions	Tourist attractions	Number of relics, landscapes, and tourist sites: the more tourist attractions, the higher the sensitivity	[47]
	6	Tourism types	-	Diversity of tourism types, including historical sites, landmarks, and tourist spots: the greater the diversity in tourism types, the higher the sensitivity	[48]
	7	Coastal water quality	Mg/l	Average dissolved oxygen (DO) concentration in coastal seawater: the lower the DO concentration, the higher the sensitivity. This parameter is monitored regularly over several years according to the national technical regulation on marine water quality	[31]
	8	Nature reserves	-	Nature reserves, protected species and habitat areas, landscape protection areas, geographical areas designated for biodiversity, forestry, and fisheries conservation: the more diverse the types of nature reserves, the higher the sensitivity	[33]
Adaptability index	1	Tourism revenue	US$ per year	Revenue from accommodation and catering services in tourism: the higher the tourism revenue, the greater the adaptability	[49]
	2	Health and environmental workforce	People	Number of health and environmental personnel: the more health and environmental personnel in the area, the greater the adaptability	[20]
	3	Mangrove	%	Ratio of mangrove area to total natural area: the larger the mangrove area, the greater the adaptability. Mangroves are a major local concern, which must be preserved and developed	[50]
	4	Biodiversity	-	Richness of natural resources supporting adaptation: the greater the biodiversity and natural resources, the higher the adaptability	[51]
	5	Environmental incident/disaster response	-	Plans and implementation of disaster response and environmental emergency drills: the more frequently drills and response plans are conducted, the greater the adaptability	[50]
	6	Environmental awareness	-	Dissemination of environmental protection regulations and warnings about tourism risks: the more extensive environmental awareness activities are, the greater the adaptability	[52]

- Expert consultations: Ten experts closely related to the research issue were selected for interviews. They included five scientists specializing in the environment and five managers in the environment, resources, and tourism sectors within the study area. These experts were interviewed about the importance of the subcriteria, the scoring of the preliminary criteria corresponding to the subcriteria, and the threshold scores for criteria selection. Subsequently, the weights of the subcriteria were calculated using the AHP method and the expert interview results [53] (Table 2). In AHP, the Consistency Ratio (*CR*) was computed to validate the experts' evaluations of the pairwise comparison matrix. The weighting results were accepted if the *CR* value was <0.1, as calculated using Eq. (1) [53]:

$$CR = CI/RI \quad (1)$$

where *RI* is a random index, and *CI* is the consistency index calculated in Eq. (2):

$$CI = (\lambda - n)/(n - 1) \quad (2)$$

where λ is the largest Eigenvalue of the matrix, and *n* represents the order of the matrix.

Table 2. Weights of the subcriteria

Subcriterion	Notation	Weight	
		Sensitivity index	Adaptability index
Simplicity and ease	SC1	0.206	0.151
Alignment with the goal	SC2	0.297	0.244
Accuracy and transparency	SC3	0.161	0.228
Data availability	SC4	0.149	0.169
Sensitivity	SC5	0.187	0.208

- Criteria screening: The Simple Additive Weighting (SAW) method was used to calculate the score for each criterion according to Eq. (3) [44] based on the weighted values of the subcriteria (Table 2) and the results of the expert consultation on the evaluation scores of the preliminary criteria. Finally, the official criteria were selected (i.e., those with a score ≥3).

$$V(a_j) = \sum_{i=1}^{m} w_i \, v_{ij} \quad (3)$$

where $V(a_j)$ is the result of the evaluation value of the j^{th}

criteria, w_i is the weight of the i^{th} subcriteria, and v_{ij} is the value rated by subcriteria i for the j^{th} criteria.

2) Data collection and normalization

a) Data collection and processing

Collected data must have a scientific basis and statistical significance to meet the requirements of quantitative research [54]. This study gathered the data for each criterion from various sources, that is, remote sensing image processing, GIS spatial data processing, field surveys, in-depth interviews, surveys, and secondary data collection (Table 3).

Table 3. Data sources

	No.	Criteria	Data source
Sensitivity index	1	Inundation	GIS data on inundation due to sea level rise simulated from Representative Concentration Pathway (RCP) 4.5 scenario in 2025 [13]
	2	Coastal type	Landsat imagery United States Geological Survey, Landsat 8 2022 (30m resolution, cloud cover <5%) (https://earthexplorer.usgs.gov/)
	3	Tourist attractions	Field investigation, in-depth interviews
	4	Tourism types	Field investigation, in-depth interviews
	5	Coastal water quality	Monitoring data for the years 2019, 2020, 2021, and 2022 from the Department of Agriculture and Environment of Ba Ria-Vung Tau province [55]
	6	Nature reserves	Inheriting research data [30]
Adaptability index	1	Tourism revenue	Statistical Yearbook 2022 [56]
	2	Health and environmental workforce	Statistical Yearbook 2022 [56]
	3	Mangrove	Field investigation, in-depth interviews
	4	Environmental incident/disaster response	Sociological investigation
	5	Environmental awareness	Sociological investigation

In addition to the criterion data collected and processed from secondary sources (Table 3), other criterion data were collected and processed as follows:

- Inundation: Using Arc Geographic Information System (ArcGIS) 10.8 software, the study overlaid the data layers of each subregion's administrative boundaries and inundation data due to sea level rise in 2025 based on the RCP 4.5 scenario [13]. The inundation rate for each subregion was then extracted, calculated, and statistically analyzed;
- Coastal type: The study first collected data for the research area, which included Landsat 8 satellite image data in 2022 from EarthExplorer, spatial data on administrative boundaries, and average tidal levels (highest and lowest). Field survey data were also collected for validation. Then, using Environment for Visualizing Images (ENVI) 5.2 and ArcGIS 10.8 software, five coastal material types (i.e., rocky shores, artificial embankments, construction lands, sandy beaches, and wetlands) were classified. The classification method applied was the maximum likelihood classifier, which is widely used and effective in classifying coastal materials [57]. Additionally, the Kappa coefficient, which was used to evaluate the classification results, was calculated to be 0.90, thereby indicating reliable results [58]. Finally, the coastal type values were identified for each subregion;
- Mangroves, tourist attractions, and tourism types: The data gained from field surveys were integrated with that obtained from in-depth interviews with administrators involved in managing environmental resources and tourism in the study area;
- Environmental incident/disaster response and environmental awareness: The study conducted a sociological investigation involving two groups: (1) multisectoral administrators from the Department of Agriculture and Environment; the Department of Culture, Sports and Tourism; district-level Economic and Department of Agriculture and Environment offices, and commune-level People's Committees; (2) tourism business establishments along the coastline within the study area. Based on the procedure recommended by Sudman [59], to ensure representativeness and statistical significance, 124 subjects, including 66 from the multisectoral administration group and 58 from the tourism business group, were identified to participate in the sociological survey. Each participant was required to complete a questionnaire, the answers to which were then processed to obtain the criterion data for each subregion.

b) Data normalization

The data were measured using different scales, so the study normalized them using Eqs. (4–5). Specifically, Eq. (4) was used when the criteria had a positive relationship with vulnerability, whereas Eq. (5) was used for the criteria with a negative relationship [60, 61]. The normalized criterion data had values ranging from 0 to 1.

$$X_j = \frac{X_h - X_{min}}{X_{max} - X_{min}} \quad (4)$$

$$X_j = \frac{X_{max} - X_h}{X_{max} - X_{min}} \quad (5)$$

where X_j is the normalized value of the criteria, X_h is the collected value of the criteria, and X_{max} and X_{min} are the minimum and maximum collected values of the criteria, respectively.

3) Determining the weighting of the criteria

The AHP and PCA methods were synthesized to calculate the weights for the criteria corresponding to the two component indices of sensitivity and adaptability:

- AHP weights: Ten experts were consulted a second time regarding the importance of the official criteria. The AHP method was then used to calculate the criterion weights [53];
- PCA weights: To effectively utilize the quantitative data that was collected and normalized, we employed the PCA method, which is a widely used multivariate statistical technique for determining weights [62, 63]. Here, the principal components were retained (Eq. (6)) if they had an Eigenvalue >1 [64] or if the total

cumulative variance explanation of the principal components was ≥70% [62]. The first principal component corresponded to the largest Eigenvalue and explained the greatest variance of the criteria [65].

$$Z_i = \sum_{i=1}^{p} \sum_{j=1}^{m} a_{ij} X_j, p \square m \quad (6)$$

where Z_i are the principal components, which are linear combinations of the criteria, a_{ij} are the loading values, X_j are the criteria, p is the number of principal components, and m is the number of criteria.

Each principal component always has a set of loading values a_{ij}, which reflect the importance of the criteria influencing that principal component. Understandably, W_{PCAj} is a linear combination of k loading values weighted by their variability and thus reflects the contribution of the j^{th} criterion to form k principal components. The PCA weights corresponding to each criterion were calculated according to Eq. (7) [65] and normalized to a range of 0 to 1 using Eqs. (4–5).

$$W_{PCA_j} = \sum_{i=1}^{k} |a_{ij}| \, \omega_i \quad (7)$$

where W_{PCAj} is the PCA weight for each criterion, a_{ij} are the loading values of the j^{th} criterion corresponding to the i^{th} principal component, w_i is the variance contribution ratio of the i^{th} principal component, and k is the number of principal components selected.

- Synthetic weights from AHP and PCA: The synthetic weights of the criteria were calculated using Eq. (8) [65]:

$$W_{SYN_j} = \frac{W_{AHP_j} \times W_{PCA_j}}{\sum_{j=1}^{m} W_{AHP_j} \times W_{PCA_j}} \quad (8)$$

where W_{SYNj} is the synthesized weight of the j^{th} criterion, W_{AHPj} is the AHP weight of the j^{th} criterion, and W_{PCAj} is the PCA weight of the j^{th} criterion.

4) Vulnerability calculation, assessment, and mapping

Based on the established criteria and weights, an algorithm was developed to calculate the environmental vulnerability index for coastal area. Using GIS technology, the calculation and mapping of vulnerability were performed as follows:

- The sensitivity and adaptability indices were estimated using Eqs. (9–10) [35, 66]:

$$CSI_j = \sum_{i}^{n} S_{ij} \times WS_i \quad (9)$$

$$CAI_j = \sum_{i}^{m} A_{ij} \times WA_i \quad (10)$$

where CSI_j and CAI_j are the sensitivity and adaptability indices for the j^{th} subregion, S_{ij} and A_{ij} are the normalized data of the criteria for the j^{th} subregion, and WS_i and WA_i are the synthetic weights of the i^{th} criteria.

- The environmental vulnerability index for coastal areas, which correlates positively with sensitivity and negatively with adaptability, was calculated using Eq. (11) [34]:

$$CTVI_j = \frac{CSI_j}{CAI_j} \quad (11)$$

- Vulnerability assessment and mapping: ArcGIS 10.8 was used to calculate and map the environmental vulnerability of the coastal tourism area. Following the approach of Dhiman *et al.* [66], normalized criterion data and weights were inputted into an attribute layer embedded with spatial data. The GIS overlay function was then used to calculate and create environmental vulnerability maps, which were grouped into four levels (i.e., low, moderate, high, and very high) according to the 23 research subregions. Eventually, based on the results and expert opinions, environmental vulnerability reduction solutions were proposed for the subregions with high and very high vulnerability.

III. RESULT AND DISCUSSION

A. Establishment of Criteria Sets, Criterion Weights, and Vulnerability Assessment Index

Based on the preliminary criteria (Table 1), expert consultations, and the application of the MCDM method, the evaluation scores for each preliminary criterion were calculated. Criteria with evaluation scores ≥3 were selected as the official criteria (Table 4 and Table 5).

Table 4. Evaluation values of each preliminary criterion

Preliminary criteria	Values for each subcriterion					Total value
	SC1	SC2	SC3	SC4	SC5	
Sensitivity index	0.206*	0.297*	0.161*	0.147*	0.187*	
Inundation	0.865	1.455	0.708	0.626	0.842	4.496
Tide range	0.515	0.832	0.499	0.492	0.598	2.936
Coastal type	0.865	1.129	0.628	0.551	0.617	3.790
Population density	0.453	0.861	0.451	0.462	0.598	2.826
Tourist attractions	0.906	1.366	0.805	0.671	0.804	4.552
Tourism types	0.803	1.426	0.741	0.641	0.804	4.414
Coastal water quality	0.845	1.010	0.660	0.611	0.729	3.855
Nature reserves	0.721	1.099	0.483	0.522	0.692	3.516
Adaptability index	0.151*	0.244*	0.228*	0.169*	0.208*	
Tourism revenue	0.755	1.196	1.049	0.777	0.811	4.588
Health and environmental workforce	0.634	1.074	1.049	0.794	0.686	4.237
Mangroves	0.634	1.000	0.844	0.625	0.894	3.998
Biodiversity	0.393	0.683	0.570	0.389	0.707	2.742
Environmental incident/disaster response	0.544	1.122	0.707	0.592	0.936	3.900
Environmental awareness	0.513	1.025	0.752	0.592	0.832	3.714

Note: (*) are the weights of the subcriteria were calculated using the AHP method and the expert interview results.

Table 5. Selected criteria

	Criteria	Notation
Sensitivity index	Inundation	S1
	Coastal type	S2
	Tourist attractions	S3
	Tourism types	S4
	Coastal water quality	S5
	Nature reserves	S6
Adaptability index	Tourism revenue	A1
	Health and environmental workforce	A2
	Mangroves	A3
	Environmental incident/disaster response	A4
	Environmental awareness	A5

Table 6. Eigenvalues, variances, and loadings from PCA extraction

Index	Title	PC1	PC2	PC3
Sensitivity	**Eigenvalues**	2.512	1.322	1.019
	Variance contribution	41.86%	22.03%	16.99%
	S1	0.102	0.904	– 0.233
	S2	– 0.777	– 0.050	– 0.031
	S3	0.874	0.078	– 0.057
	S4	0.836	– 0.336	0.214
	S5	– 0.527	0.603	0.423
	S6	0.107	– 0.141	0.939
Adaptability	**Eigenvalues**	1.836	1.335	1.097
	Variance contribution	36.72%	26.69%	21.95%
	A1	0.376	0.780	– 0.266
	A2	0.720	0.021	0.558
	A3	– 0.914	– 0.104	0.101
	A4	– 0.098	0.905	0.223
	A5	– 0.004	0.029	0.939

Table 7. The weighting of each criterion

Criteria		AHP weights	PCA weights	Synthetic weights
Sensitivity index	S1	0.145	0.132	0.114
	S2	0.156	0.160	0.149
	S3	0.110	0.184	0.121
	S4	0.185	0.215	0.238
	S5	0.206	0.199	0.245
	S6	0.200	0.110	0.132
Adaptability index	A1	0.182	0.235	0.220
	A2	0.138	0.228	0.162
	A3	0.197	0.224	0.227
	A4	0.243	0.189	0.237
	A5	0.240	0.125	0.154

Based on the results of the second expert consultation and the application of the AHP method, the criterion weights according to the AHP method were determined. Simultaneously, since the study had collected the normalized data and applied the PCA method, the study established the criterion weights according to PCA. The PCA weight calculations indicated that only three Principal Components (PC1, PC2, and PC3) were adequate to explain over 80% of the variance of the criteria for the two indices (80.88% for sensitivity and 85.36% for adaptability) (Table 6). Finally, using Eq. (8), the synthetic weights for each criterion were determined, as shown in Table 7.

The study applied the IPCC (2014) approach [17] to assess coastal environmental vulnerability by incorporating sensitivity and adaptability components. The criteria for assigning corresponding weights were selected using MCDM with both qualitative and quantitative data. For the sensitivity index, the criteria coastal water quality and tourism types play an important role in increasing vulnerability to hazards. In contrast, for the adaptability index, the criteria tourism revenue, mangroves, and environmental incident/disaster response contribute significantly to reducing vulnerability. Policymakers can adjust and employ this index to evaluate the vulnerability of coastal areas, particularly those with significant tourism activities and hazard-typically sea level rise. Based on criterion weights, vulnerability mitigation strategies can then be considered, such as improving coastal water quality, promoting sustainable tourism, and enhancing mangrove conservation.

However, there are several challenges in implementing the coastal vulnerability index in real-world settings. The criteria are often complex and require continuous alignment with real-world conditions, as the context is constantly changing and unpredictable. Therefore, the index may vary from area to area and must be regularly updated, especially in regions exposed to multiple hazards. Furthermore, although PCA analysis addressed the subjectivity of the criteria weights (AHP's expert judgment), collecting quantitative data for the criteria remains challenging, particularly in areas lacking comprehensive data systems. These shortcomings complicate the index establishment process, leading to the exclusion of criteria or factors that effectively reflect the vulnerability. These limitations negatively affect the accuracy and certainty of policymakers' decision-making processes.

B. Assessment and Mapping of Coastal Environmental Vulnerability

Based on the collected and normalized data, the synthetic weights for each criterion were determined (Table 7). Using the algorithms in Eqs. (9–10) and the functionalities of ArcGIS 10.8, the values and maps of the environmental vulnerability index for coastal areas with active tourism activities were established, as shown in Table 8 and Figs. 3–5.

The environmental vulnerability index values for the coastal subregions ranged from 0.401 to 2.038. Among these, 10 of the 23 subregions (43.48%), which were predominantly in the Long Dat and Xuyen Moc districts, had high and very high vulnerability values. The remaining 13 of the 23 subregions (56.52%) had low and moderate vulnerability values.

- The subregions with high (SR1, SR6, SR12, SR16, SR17, SR21, SR23) or very high vulnerability (SR15, SR18, SR22) accounted for 43.48% of the subregions, with the highest vulnerability observed in SR15 (Phuoc Tinh Village, Long Dat District). These subregions also had high (SR6, SR12, SR16, SR22) or very high sensitivity (SR15, SR17, SR18, SR21, SR23), while adaptability was low (SR1, SR12, SR15, SR18, SR22) or moderate (SR6, SR16, SR17, SR21, SR23). The high and very high sensitivity in these subregions was due to the development of tourism, diverse tourism types and numerous attractions with high tourist numbers. Some also faced high inundation risks, poor coastal water quality, and had nature reserves that were vulnerable to negative impacts from climate change. Conversely, the subregions with low or moderate adaptability had low tourism revenue and underdeveloped infrastructure, with few disaster response drills or environmental awareness activities and numerous environmental protection violations;
- The study found that 56.52% of the subregions (SR2–

SR5, SR7–SR11, SR13, SR14, SR19, SR20) had low or moderate vulnerability levels. Some of these subregions, although characterized by low (SR4, SR5) or moderate sensitivity (SR9, SR11, SR13, SR14, SR19), had very high (SR9, SR19, SR20), high (SR8, SR14) or moderate adaptability (SR2, SR3, SR7, SR10, SR11, SR16).

Table 8. Calculated values of the environmental vulnerability index for coastal areas

Subregion	Notation	Sensitivity	Adaptability	Vulnerability
Tan Phuoc Ward	SR1	0.192	0.284	1.477
Phuoc Hoa Ward	SR2	0.374	0.421	1.125
Long Son Village	SR3	0.363	0.417	1.148
Rach Dua Ward	SR4	0.213	0.184	0.860
Thang Nhat Ward	SR5	0.182	0.095	0.521
Ward 5	SR6	0.305	0.410	1.344
Ward 1	SR7	0.373	0.362	0.973
Ward 2	SR8	0.429	0.464	1.080
Thang Tam Ward	SR9	0.575	0.268	0.466
Ward 8	SR10	0.304	0.338	1.115
Nguyen An Ninh Ward	SR11	0.357	0.249	0.699
Ward 10	SR12	0.278	0.373	1.342
Ward 11	SR13	0.293	0.308	1.049
Ward 12	SR14	0.497	0.254	0.511
Phuoc Tinh Village	SR15	0.217	0.443	2.038
Phuoc Hung Village	SR16	0.318	0.397	1.249
Long Hai Village	SR17	0.320	0.444	1.388
Phuoc Hai Village	SR18	0.294	0.482	1.638
Loc An Village	SR19	0.637	0.256	0.401
Phuoc Thuan Village	SR20	0.580	0.528	0.911
Bong Trang Village	SR21	0.314	0.451	1.436
Bung Rieng Village	SR22	0.229	0.427	1.868
Binh Chau Village	SR23	0.392	0.548	1.396

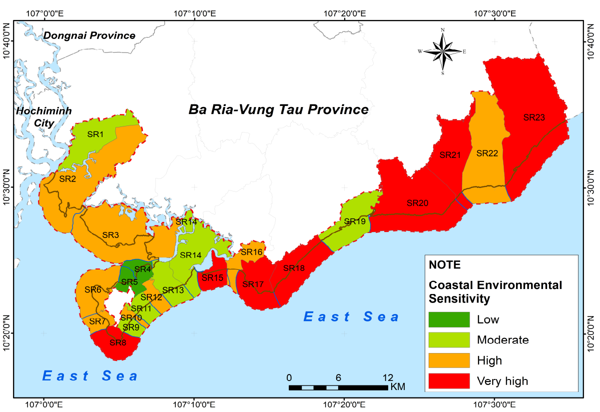

Fig. 3. Maps of coastal sensitivity.

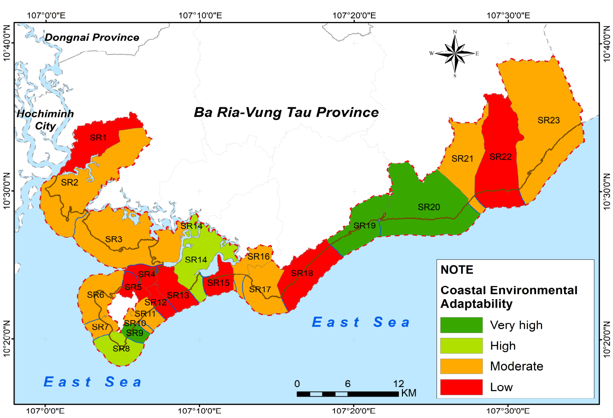

Fig. 4. Maps of coastal adaptability.

Hazards from climate change significantly affect the coastal areas of Ba Ria-Vung Tau province. Natural hazards (i.e., flooding, salinity intrusion, erosion, and storms) and anthropogenic hazards (water environmental incidents) have severely damaged tourism infrastructure and disrupted local economic growth. The results indicated that over 40% of the subregions had high and very high vulnerability values, while the figure increased to 65% if only sensitivity was considered. The low-lying topography and the downstream location of river systems, with many sandy beaches and wetlands, have facilitated the robust tourism development in these areas. However, the downside of prominent tourism is that these subregions have experienced significant impacts from inundation and saltwater intrusion, especially during heavy rainfall. Therefore, these areas should be prioritized for vulnerability reduction strategies and tourism infrastructure protection.

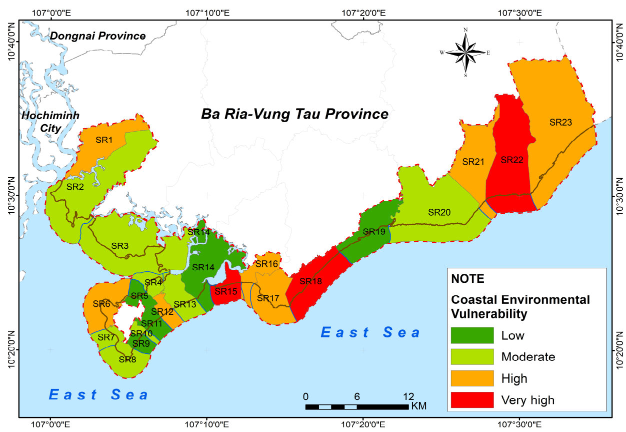

Fig. 5. Maps of coastal vulnerability.

By applying the index, the vulnerability of many regions worldwide has been assessed quickly, enabling the proposal of effective strategies. Dada *et al.* proposed a coastal vulnerability index for the West African coast, focusing on flooding and erosion, which supports adaptation strategies for policymakers [45]. Wang *et al.* successfully applied an index based on the pressure-state-response framework to evaluate vulnerability at tourist sites in the Bohai Sea, China [28]. In two major tourism-dependent beaches, Fig Tree Bay and Vrysi Beach, Cyprus, Theocharidis *et al.* applied a coastal vulnerability index to assess coastal risks from natural processes and human interventions [67]. In Vietnam, Cuong *et al.* proposed a vulnerability index based on two components, sensitivity and adaptability, which is a crucial element of the environmental incident assessment framework for the Southeastern coastal region [20].

C. Strategies to Increase Sustainability in Coastal Areas

Based on the assessment results and expert and manager opinions, three groups of solutions were proposed to reduce the coastal vulnerability in the subregions classified as having high or very high vulnerability.

1) Policy and management: Review and adjust the coastal development plans to prioritize sustainable coastal development. Such planning should include prioritizing sustainable coastal, limiting high-risk activities that could harm coastal area, coastal water quality and conserving and developing coastal environmental resources, particularly mangroves and nature reserves.
2) Scientific research and technology: Enhance research related to environmental risk assessments and coastal vulnerability due to multiple hazards to support decision-makers in planning and management. Additionally, apply scientific technology to manage tourism infrastructure and environmental resources effectively.
3) Communication and education: Strengthen communication efforts regarding sustainable coastal development by focusing on protecting natural resources and the tourism environment. Improve adaptability by disseminating plans and conducting regular environmental emergency response drills in coastal areas.

Policymakers initially focus on implementing solutions for the most vulnerable subregions and extend these efforts to the entire region. Meanwhile, scientists must continue exploring coastal vulnerability and environmental risks, as the index needs to be updated regularly to reflect real-world conditions. The study provided a comprehensive set of strategies based on the vulnerability calculations and mapped results. However, further research is needed to develop criteria-specific solutions, particularly those that significantly impact the overall vulnerability values.

IV. Conclusion

This study employed MCDM to develop a composite index to assess the environmental vulnerability of coastal areas in Ba Ria-Vung Tau province, Vietnam, with a focus on sensitivity and adaptability. The sensitivity index was quantified using six criteria related to natural, socioeconomic, and environmental factors. In contrast, the adaptability index was quantified using five criteria related to socioeconomic, environmental, and institutional implementation factors. Based on the established index, the AHP and PCA methods were combined to calculate the weights for the criteria, which leveraged both the quantitative and qualitative data. GIS technology was then applied to spatial assess and map the environmental vulnerability of 23 coastal subregions in Ba Ria-Vung Tau province into four levels of vulnerability: low, moderate, high, and very high. The study found that 10 subregions need to prioritize vulnerability reduction strategies and promote sustainable coastal development. Additionally, policymakers must focus on their significant contributions to environmental vulnerability, including coastal water quality, tourism types, tourism revenue, mangroves, and environmental incident/disaster response.

The vulnerability approach based on the two-component model (sensitivity and adaptability) has shown practical effectiveness, especially in contexts where future hazards are uncertain. The selection of criteria related to specific hazards or sectors enables hazard-specific or sector-specific vulnerability assessments, thereby supporting timely decision-making by policymakers. However, the criteria should be adapted to the real-world conditions of each region due to distinctions in socioeconomic, geographic, and data infrastructure characteristics.

In terms of future research directions, it would be beneficial to adapt and establish a similar synthetic environmental vulnerability index for areas with characteristics analogous to those of the coastal area of Ba Ria-Vung Tau province. Such an index would support timely assessments and decision-making related to sustainable coastal development, especially areas with intensive tourism development. Future studies should address the limitations in criterion selection, ensuring that criteria comprehensively reflect the environmental vulnerability of coastal areas, which is particularly vital as each region has different economic bases and hazard exposures. Coastal authorities need further investment in developing data systems to quantify the criteria effectively. Additionally, future research could explore the application of diverse statistical methods and machine learning techniques to enhance accuracy and proactiveness in assessing coastal vulnerability.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M.T.T conducted the research review, analyzed the results, performed fieldwork, supported the methodological framework, and wrote the paper. C.T.L supervised the research direction and process, reviewed, and revised the paper. L.T.D.T, D.D.S, and D.A.T conducted interviews, collected, processed, and analyzed data, and presented the results using GIS; all authors had approved the final version.

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