# Environmental Sensitivity of Coastal Areas to the Water Environmental Incidents: A Case Study in the Southeastern Coastal Region of Vietnam

Cuong Tan Le*, Phuoc Van Nguyen, Quan Hong Nguyen, Huyen Thi Thu Do, and Minh Thanh Tran

***Abstract*—The environmental sensitivity of coastal areas is attracting significant attention from researchers because it can predict the consequences of water environmental incidents. Environmental sensitivity is usually estimated based on various criteria that are related to specific aspects of the physical or environmental conditions in an area combined with its socioeconomic conditions. The main objective of this study was to develop a suitable set of criteria that covers all three aspects, namely, physical, socioeconomic, and environmental conditions, to support sensitivity assessments and zoning in the southeast coastal region of Vietnam, which is the most dynamic developing coastal region in the country. In the study, multiple-criteria decision-making was used to develop the coastal environmental sensitivity criteria and calculate the criteria weights. Remote sensing was used for data collection and geographical information system for the assessment and zoning of the study areas. A set of eight suitable criteria were proposed: coastal type, coast slope, species, nature reserve, population density, vulnerable population, tourism, and aquaculture, with optimal weighting for each criterion was proposed. A thorough site survey with data collection was then conducted in 27 sub-regions of the study area. The proposed criteria were applied to evaluate and zone the areas into four sensitivity levels: low, moderate, high, and extreme, which accounted for 7.41%, 29.63%, 37.04%, and 25.93% of the study area, respectively. Practical and effective solutions were proposed for 17 sub-regions with high and extreme environmental sensitivity. The research results are expected to enhance knowledge of coastal environmental hazards and provide a reference for sustainability decision-making and planning.**

***Index Terms*—Coastal sensitivity, multiple-criteria decision-making, geographical information system, remote sensing**

## I. INTRODUCTION

Coastal areas have important geography in terms of resources [1] and advantageous conditions for socioeconomic development [2] as well as trade, services, and industry [3]. They therefore have a faster rate of urbanisation and industrialisation than other regions on a country's mainland [4]. Besides the potential development advantages, water environmental incidents identify the coastal area as vulnerable [5]. According to Zhai *et al.* [6], over-exploitation of resources and a lack of control over wastewater discharge constantly threaten the coastal environment. In addition, recent studies show extensive coastal development has degraded considerable nearshore habitats [7] and rising sea levels are a significant concern for coastal communities [8]. Vietnam's coastal areas have a population density 1.9 times higher than national average and are under tremendous pressure for development [9]. The wastewater of 90.7% of industrial parks but only 12.5% of coastal urban areas is collected and treated. Most wastewaters from ships (e.g. chemical oxygen demand, biological oxygen demand over five days, and oil parameters) and aquaculture operations (e.g. total suspended solids and ammonium parameters) exceed environmental standards. Sea level rise and environmental incidents from the mainland are tending to increase simultaneously; one notable event was the water environmental incident caused by the discharge process of Formosa Corporation in 2016 [9]. This incident degraded the quality of the water environment, seriously damaged marine life resources, and affected the livelihoods of coastal fishermen. The southeastern coastal region of Vietnam, which is located in the critical southern economic region of the country, has a very high growth rate compared to the other key economic regions. This was particularly evident from 2010 to 2020 when it contributed up to 45% of the country's annual GDP. The above evidence supports the argument that environmental sensitivity needs to be comprehensively assessed and scientifically zoned, and suitable solutions to minimise and limit the consequences of water environmental incidents need to be found.

Environmental sensitivity covers multiple definitions. According to Hatcher and Manson [10], sensitivity depends on physical characteristics, while [11] is more related to physical and human characteristics. According to Rizzo *et al.* [12], sensitivity is defined as certain physical, geomorphological, and ecological conditions that render a coastal environmental system vulnerable to negative impacts such as flooding. According to Jara *et al.* [13], sensitivity can be estimated based on the characteristic indicators related to ecological and socioeconomic factors, while for [14], a sensitivity assessment depends on the research objective, and appropriate evaluation criteria need to be selected for analysis. The concepts of "sensitivity" and "vulnerability" are distinguished. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt [15]. In other words, vulnerability includes sensitivity and adaptability, so some relevant criteria can be used to evaluate either aspect. Based on IPCC [16], environmental sensitivity in this study is

Manuscript received September 27, 2022; revised November 18, 2022; accepted December 29, 2022.

Cuong Tan Le, Huyen Thi Thu Do, and Minh Thanh Tran are with the Institute for Environment and Resources, National University of Ho Chi Minh City, Vietnam.

Phuoc Van Nguyen is with the Ho Chi Minh City Union of Science and Technology Associations, Vietnam.

Quan Hong Nguyen is with the Institute for Circular Economy Development, National University of Ho Chi Minh City, Vietnam.

*Correspondence: letancuongmttn@gmail.com (C.T.L.)

doi: 10.18178/ijesd.2023.14.3.1430

the degree to which a system, asset, or species may be adversely affected when exposed to water environmental incidents (i.e. flooding, hazardous material spills).

A comprehensive literature review showed that most studies used physical factors and focused on criteria related to geomorphology, morphology, and hydrographic regimes to analyse and evaluate sensitivity. According to *Denner* et al. [17] and Kantamaneni *et al.* [18], sensitivity is evaluated based on the criteria of geomorphology and morphology of the study area (i.e. coastal slope, beach width, dune width, and distance of vegetation behind the back beach), combined with other criteria (i.e. percentage of rock outcrop or distance of built structures. In their study, aside from the criteria beach width, dune width, and distance of vegetation behind the back beach, Palmer *et al.* [19] used the criteria percentage rock outcrop and distance to 20 m isobath. In other studies, the hydrographic regime was used to evaluate sensitivity. For example, Bagdanavičiūtė *et al.* [20] used the following criteria: wave height, shoreline change rate, and coastal slope. In addition to the criteria used by Bagdanavičiūtė *et al.* [20], Mavromatidi *et al.* [21] included the criteria relative sea-level rise and tidal range to assess sensitivity. As well as physical factors, some researchers have integrated socioeconomic factors into their sensitivity analyses: population density [22]; vulnerable population, cultural heritage, and kilometres of drainage (i.e. infrastructure) [23]; land use/land cover [24]; and education [25]. Moreover, others have approached sensitivity assessments based only on socioeconomic and environmental factors. In their study, Cai *et al.* [26] used breeding industry, port transportation, tourism, protected species, nature reserve, and water resources to assess sensitivity to chemical spills. In the study of Kankara *et al.* [27], the sensitivity analysis was based only on sociocultural, economic, and scientific criteria, sensitivity to oil pollution, and environmental importance. In some studies, evaluations have been conducted in accordance with the National Oceanic and Atmospheric Administration guidelines and based only on factors related to, or the environmental sensitivity of, the shoreline, nearshore, and onshore [28, 29]. Accordingly, biological criteria, namely, species richness, the presence of species of conservation concern, the diversity of the natural habitats, and the cover of habitat of conservation value, were selected for sensitivity assessment [30]. In the study of Sardi *et al.* [31], the sensitivity analysis was based on three criteria: shoreline type (i.e. solid man-made structure, rocky shore, sand/beach, muddy shore, and marsh/mangrove); socioeconomic factors (i.e. airports, hotels, educational sites, commercial areas, hospitals, waste discharge, parks, industrial areas, municipalities, seaport facilities, beaches, water supplies, oil and gas facilities, and fish landing); and biological resources (i.e. submerged plant/seagrass, coral/hard bottom reefs, salt marshes, and mangroves).

The methods commonly used to assess sensitivity can be categorised into four main groups: 1) index/indicator-based (i.e. multiple-criteria decision-making (MCDM)), 2) dynamic computer models, 3) geographical information system (GIS)-based decision support tools, and 4) visualisation tools [32]. MCDM methods in particular are often given more attention because they allow researchers to quickly compare the sensitivity of different areas, which makes decisions compatible with research objectives [33]. Additionally, MCDM is usually used in combination with GIS to analyse risks, sensitivity mapping, and the priority indexing of resources [27]. Alternatively, both GIS and remote sensing (RS) are used to analyse and predict environmental changes quickly, efficiently, and reliably [34, 35].

The main contributions of this study are 1) the assessment of environmental sensitivity in coastal areas based on selected optimal criteria that integrate physical, socioeconomic, and environmental aspects; 2) the use of the MCDM approach to build a set of criteria and determine their weightings in combination with the GIS and RS methods for data collection, assessment, and zoning; and 3) the assessment of environmental sensitivity in the southeastern coastal area of Vietnam.

## II. Study Area and Methodology

### A. Study Area

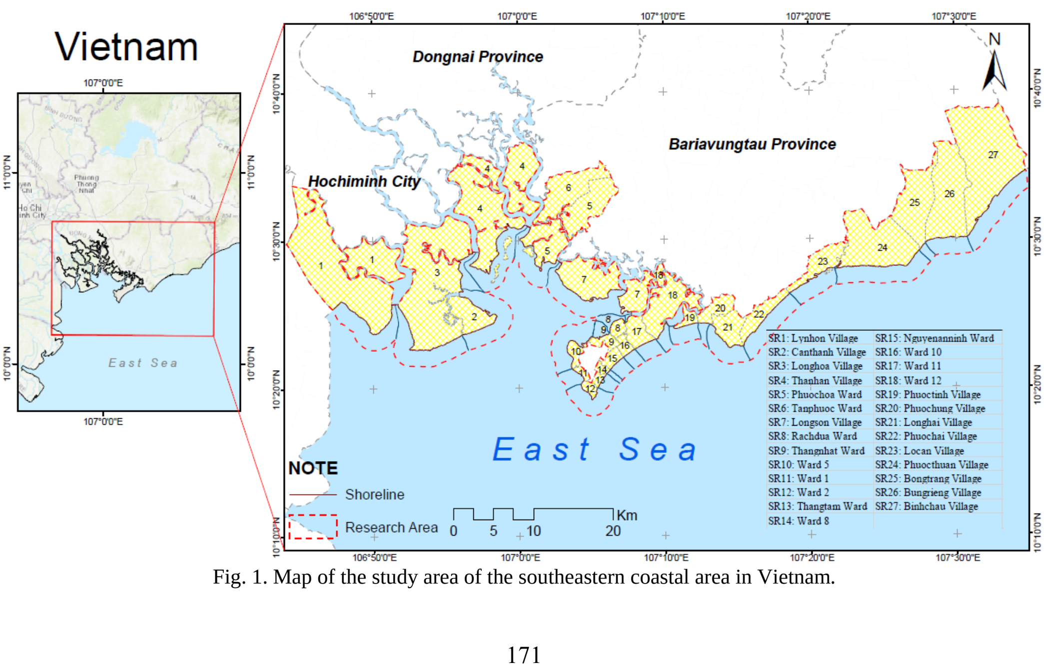

Fig. 1. Map of the study area of the southeastern coastal area in Vietnam.

The southeastern coastal region is part of Hochiminh City and Bariavungtau Province and located in the critical economic region of southern Vietnam. The region spans an area of 323 km$^2$ and a shoreline of 90 km. The region has rich resources and is advantageous for tourism development, aquaculture, seaports, and industry. This area is considered the most developed economic region in Vietnam, with 21 industrial parks, aquaculture areas, seaports, and tourist areas. Its population density has also witnessed dramatic growth, with 505 people/km$^2$. However, the awareness of environmental risks and adaptability to hazards is lower than that of the North and Central communities because the number of hazards that approach the coasts of the southeastern part is relatively small, about one-half to one-third of those that approach northern and central parts [36]. To increase the reliability of the calculation results and evaluate the sensitivity of the study area, it was discretised into 27 sub-regions (Fig. 1) that are characterised by different physical, socioeconomic, and environmental conditions according to the zoning approach of [31].

### B. Methodology

In this study, a new approach was developed based on a combination of MCDM, GIS, and RS to analyse and assess sensitivity to environmental incident risk from the water environmental incidents. The overall methodology followed in this study is represented in Fig. 2. The sub-sections that follow depict the methods and the case study in detail.

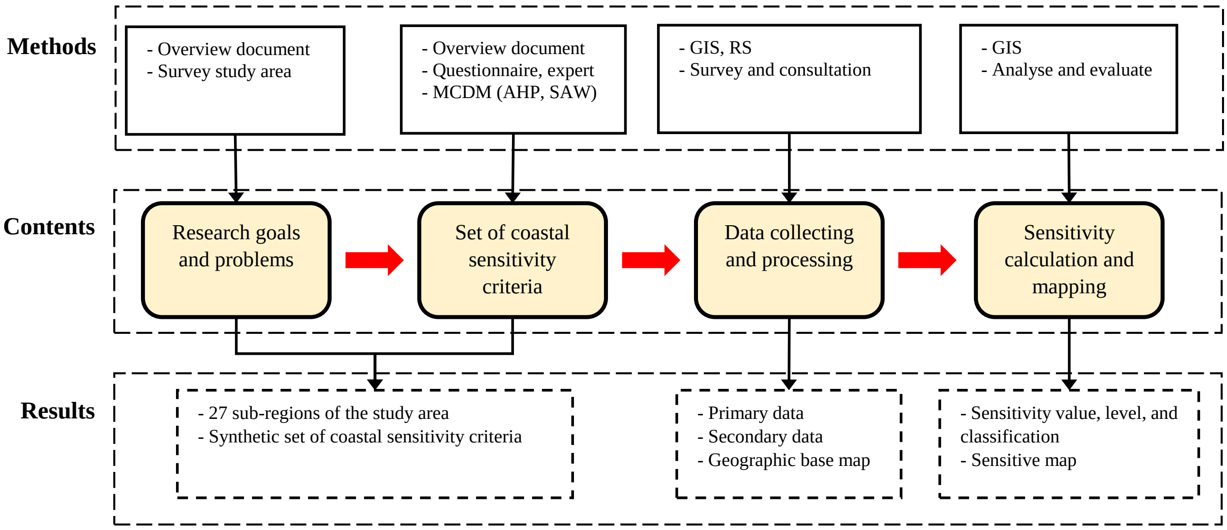


Fig. 2. Methodology framework.

#### 1) Set of coastal sensitivity criteria

The simple additive weighting (SAW) method, also known as a scoring method, is a simple and most often used multi-attribute decision technique. The method is used to select and consider suitable criteria, with the processing of SAW consisting of main steps (i.e. calculate the evaluation scores for each criterion, determine the weightings for each criterion, and evaluate each alternative) [37]. The analytic hierarchy process (AHP) method is used to calculate the weighted criteria, with the processing of AHP consisting of main steps (i.e., construct a pair-wise comparison matrix, calculate the weight of the criteria, and analyse consistency [38]. Those methods were combined with the secondary data collection and expert consultation methods were combined to establish a set of sensitivity criteria and determine the weights. The process was as follows:

1) Establish an initial set of criteria: Relevant published research papers and specific conditions of relating to the study area were reviewed to determine the preliminary criteria by focusing on the physical, socioeconomic, and environmental aspects. Each selected preliminary criterion had a different level of importance and was selected based on sub-criteria (i.e. simplicity/ease, alignment with the goal, data availability, accuracy/transparency, and sensitivity) [37].
2) Conduct survey by questionnaire: Initially, 20 experts from distinct fields, of which 50% had scientific backgrounds related to the environment and 50% had an acquaintance with the research area, participated in the survey. Seventeen experts provided their feedback, which was then used to determine the weightings of the sub-criteria via the AHP method as well as the evaluation scores of each criterion corresponding to the sub-criteria.
3) Select suitable criteria: Multi-criteria analysis was conducted using the SAW method to calculate the evaluation scores for each preliminary criterion, which then served as the basis for screening and selecting suitable criteria. The evaluation score formula is as follows [37].

$$V\left(a_j\right)=\sum_{i=1}^{m} w_i v_{ij} \tag{1}$$

where: $V(a_j)$ is the result of the evaluation score of the $j^{th}$ criteria, $w_i$ is the weight of the $i^{th}$ sub-criteria, and $v_{ij}$ is the score rated by sub-criteria ith for the $j^{th}$ criteria.

The weightings of the sub-criteria, the evaluation scores of each criterion, and the selected appropriate criteria are described in detail in Tables I and II.

TABLE I: SELECTED CRITERIA

| Criteria | Description | Reference |
|---|---|---|
| C1 | Coastal construction materials. Coastal sub-regions with many cliffs and rocky beaches have lower environmental sensitivity than those with sandy beaches and wetlands | [39] |
| C2 | The average slope of the coastal sub-region. The lower the slope of the coastal sub-region, the greater the sensitivity | [18] |
| C3 | A group of aquatic organisms with similar biological characteristics. Sub-regions with rare and precious species (i.e. priority protection) have higher sensitivity than those without priority species | [26] |
| C4 | Inclusion of nature reserves, demarcated geographical areas, and functional zones for biodiversity conservation. The higher the priority level of nature protection and conservation of the coastal sub-region, the greater the sensitivity | [40] |
| C5 | Measurement of the population per unit area. The higher the population density of the coastal sub-region, the greater the sensitivity | [41] |
| C6 | The ratio of the population under 12 and over 65 years of age to the sub-region population. The higher the vulnerable population in the coastal sub-region, the greater the sensitivity | [41] |
| C7 | Current status of tourism and entertainment activities in the sub-region. Coastal sub-regions with developed tourism activities and diversified tourism services have higher sensitivity than those without tourism activities | [42] |
| C8 | The ratio of aquaculture area to total natural area. The larger the sub-region with a planned aquaculture area, the higher the sensitivity | [42] |

TABLE II: EVALUATION SCORES OF EACH CRITERION

| Criteria (Notation) | Score for each sub-criterion | | | | | Total score |
|---|---|---|---|---|---|---|
| | Simplicity and ease (0.17) | Alignment with the goal (0.28) | Data availability (0.18) | Accuracy and transparency (0.16) | Sensitivity (0.21) | |
| Coastal type (C1) | 0.57 | 1.19 | 0.65 | 0.61 | 0.67 | 3.65 |
| Coastal slope (C2) | 0.58 | 1.10 | 0.72 | 0.66 | 0.66 | 3.69 |
| Species (C3) | 0.51 | 1.19 | 0.48 | 0.44 | 0.92 | 3.50 |
| Nature reserve (C4) | 0.61 | 1.17 | 0.75 | 0.63 | 1.06 | 4.18 |
| Population density (C5) | 0.75 | 1.09 | 0.87 | 0.72 | 0.82 | 4.20 |
| Vulnerable population (C6) | 0.58 | 1.27 | 0.69 | 0.56 | 0.80 | 3.86 |
| Tourism (C7) | 0.60 | 1.10 | 0.69 | 0.60 | 0.80 | 3.76 |
| Aquaculture (C8) | 0.58 | 1.29 | 0.67 | 0.58 | 0.97 | 4.05 |

4) Determine the weighting of the selection criteria: The experts participating in the first survey were consulted a second time, which guaranteed the research objective of satisfaction with the criteria's importance. The results of the second consultation were used to calculate the weights of the selection criteria using the AHP method, as shown in Table III.

TABLE III: THE WEIGHTING OF EACH CRITERION

| Criteria | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|---|---|---|---|---|---|---|---|---|
| Weighting | 0.09 | 0.09 | 0.06 | 0.17 | 0.24 | 0.15 | 0.09 | 0.11 |

### 2) *Data collecting and processing*

The data for the calculation were collected from various sources, as shown in Table IV.

TABLE IV: SOURCE OF SENSITIVITY CRITERIA

| Criteria | Data source |
|---|---|
| C1 | Satellite imagery PlanetScope (https://www.planet.com/explorer) |
| C2 | Department of Natural Resources and Environment; Department of Science and Technology |
| C3 | Survey and consultation (Department of Natural Resources and Environment; Department of Agriculture and Rural Development) |
| C4 | Survey and consultation (Department of Natural Resources and Environment; Department of Agriculture and Rural Development) |
| C5 | Statistical yearbook 2021 |
| C6 | Statistical yearbook 2021 |
| C7 | Survey and consultation (Department of Tourism) |
| C8 | Statistical yearbook 2021 |

1) Coastal type: PlanetScope satellite images (see Table V and Table VI for details) were processed using ENVI 5.2 software together with GIS to help identify and analyse five coastal types, namely, cliffs, rocky shores, artificial embankments, sandbanks, and wetlands, corresponding to five levels, as shown in the evaluation scale in Table VII. These satellite images have been used in many studies that have required high accuracy, such as those involving coastline vulnerability assessments [43], coastline changes [44], oil spill detection [45], and artificial reef monitoring [46]. The coastal type was determined as follows:

- Data collection: In addition to the satellite images in Table V, the field data of the study area were collected to facilitate interpretation and classification. The geographical map data of the study area (i.e. water systems, terrain, technical infrastructure, and boundaries) were also used to support the classification process.

TABLE V: SPECTRAL CHANNEL CHARACTERISTICS IN PLANETSCOPE SATELLITE IMAGES

| Channel | Wavelength (μm) | Resolution (m) |
|---|---|---|
| B1-Blue | 0.450–0.515 | 3 |
| B2-Green | 0.525–0.600 | 3 |
| B3-Red | 0.630–0.680 | 3 |
| B4-Near-infrared spectroscopy | 0.845–0.885 | 3 |

- Image preprocessing: The accuracy of the satellite images was increased during classification (i.e. removing clouds and image stripes). The images were then combined and cropped as appropriate for the study area.
- Classification and interpretation system: The calculation of measures accuracy requires the presence of independence [47] (i.e. the more objects to interpret, the higher the accuracy). Five target objects were digitised via a visual interpretation of the satellite images.
- Classification: The maximum likelihood classification method was used to classify the interpretation objectives [48, 49]. Accordingly, each pixel was assigned to a class of interpretation objects if the probability of that pixel belonging to a particular class was greatest [50].
- Testing and evaluation: The Yamane Eq. (2) [51] was used to test for the average sample size, and the number of test samples was approximately 400. The Kappa coefficient [52, 53] was then used to evaluate the concordance between the different data sources. The Kappa value of 0.87 indicated the compatibility of the classification results.

$$n = \frac{Z^2 pq}{e^2} \tag{2}$$

where: $n$ is the sample size, $Z^2$ is the abscissa of the normal curve that cuts off an area $\alpha$ at the tails ($1-\alpha$ equals the desired confidence level, e.g. 95%), $e$ is the desired level of precision (95% confidence level equivalent to $e$ = 5%), $p$ is the estimated proportion of an attribute that is present in the population, and $q$ is $1-p$.

- Post-classification processing: The data information were generalised by creating maps based on classes so that the five target objects corresponded to five categorical data classes. Eventually, the coastal types for each sub-region were determined.

TABLE VI: LIST OF SATELLITE IMAGES USED IN THIS STUDY

| Imagery code | Time |
|---|---|
| 20210306_032155_70_2426_3B_AnalyticMS_SR | 2021-03-06T03:21:55 |
| 20210306_032157_96_2426_3B_ AnalyticMS_SR | 2021-03-06T03:21:57 |
| 20210305_023940_31_2264_3B_ AnalyticMS_SR | 2021-03-05T02:39:40 |
| 20210305_023942_57_2264_3B_ AnalyticMS_SR | 2021-03-05T02:39:42 |
| 20210305_024025_12_2251_3B_AnalyticMS_SR | 2021-03-05T02:40:25 |
| 20210305_024027_56_2251_3B_AnalyticMS_SR | 2021-03-05T02:40:27 |
| 20210305_024030_01_2251_3B_AnalyticMS_SR | 2021-03-05T02:40:30 |
| 20210308_024019_31_2262_3B_AnalyticMS_SR | 2021-03-08T02:40:19 |
| 20210305_004911_0f32_3B_AnalyticMS_SR | 2021-03-05T00:49:09 |
| 20210305_004910_0f32_3B_AnalyticMS_SR | 2021-03-05T00:49:10 |
| 20210305_004911_0f32_3B_AnalyticMS_SR | 2021-03-05T00:49:11 |

2) Coastal slope: The ratio of the altitude change to the horizontal distance between any two points landwards and seawards of the shoreline (i.e. coastal slope) [54]. Two data sources of seabed topographic data at scale 1: 50000 [55] and 1: 25000 [56] were then collected and calculated coastal slope according to Eq. (3) [57].

$$tan(a) = \frac{D}{H} 100\% \tag{3}$$

where: $tan(a)$ is the coastal slope (%), $D$ is the difference in seafloor elevation between the position of the shoreline and any position seawards (m), and $H$ is the horizontal distance between the position of the shoreline and any position seawards (m).

3) The rest of the data types: The balance of the data types (Table IV) were synthesised from the results of the secondary data collection and direct interviews with the experts in state management related to the research area.

Finally, all the collected data were normalised based on the rating scale in Table VII to facilitate the assessment sensitivity.

TABLE VII: EVALUATION SCALE

| Criteria | Unit | Evaluation scores | | | | | Reference |
|---|---|---|---|---|---|---|---|
| | | Very low | Low | Moderate | High | Very high | |
| | | 1 | 2 | 3 | 4 | 5 | |
| C1 | - | Cliffs | Rocky shores | Artificial embankments | Sandbanks | Wetlands | [39] |
| C2 | % | >1.14 | >0.87–1.14 | >0.49–0.87 | >0.26–0.49 | ≤0.26 | This study |
| C3 | - | No rare species | Rare species | Rare and near-endangered species | Rare and endangered species | Rare and critically endangered species | [26, 40] |
| C4 | - | - | Landscape protection area | Biodiversity conservation | Nature reserve | World biosphere reserves | [40] |
| C5 | Persons/km$^2$ | <450 | 450–<800 | 800–<1150 | 1150–<1400 | ≥1400 | [41] |
| C6 | % | <20 | 20–<40 | 40–<60 | 60–<80 | ≥80 | [41] |
| C7 | - | - | Scenic spots, cultural heritage | Beaches for tourists | Public beaches | Public beaches, beach sports | [42] |
| C8 | % | <10 | 10–<20 | 20–<35 | 35–<50 | ≥50 | [42] |

### *3) Sensitivity calculation and mapping*

The linear weighted sum method [58, 59], where sensitivity is a linear combination of criteria with different weightings, was determined by the Eq. (4) [37]:

$$SI(a_j) = \sum_{i=1}^{m} w_i v_{ij} \qquad (4)$$

where: $SI(a_j)$ is the sensitivity score of the $j^{th}$ sub-region, $w_i$ is the weight of the $i^{th}$ criteria, and $v_{ij}$ is the evaluation score of the $i^{th}$ criteria with respect to the $j^{th}$ sub-region.

Using Eq. (4) and based on the coastal computational GIS model of [58], GIS was used to calculate the environmental sensitivity value in which each criterion evaluation data would correspond to an attribute layer, similar to the criterion weighting (see also Fig. 3). The attribute and spatial data were combined to construct an environmental sensitivity map of the 27 sub-regions with four levels of environmental sensitivity (i.e. low, moderate, high, and extreme).

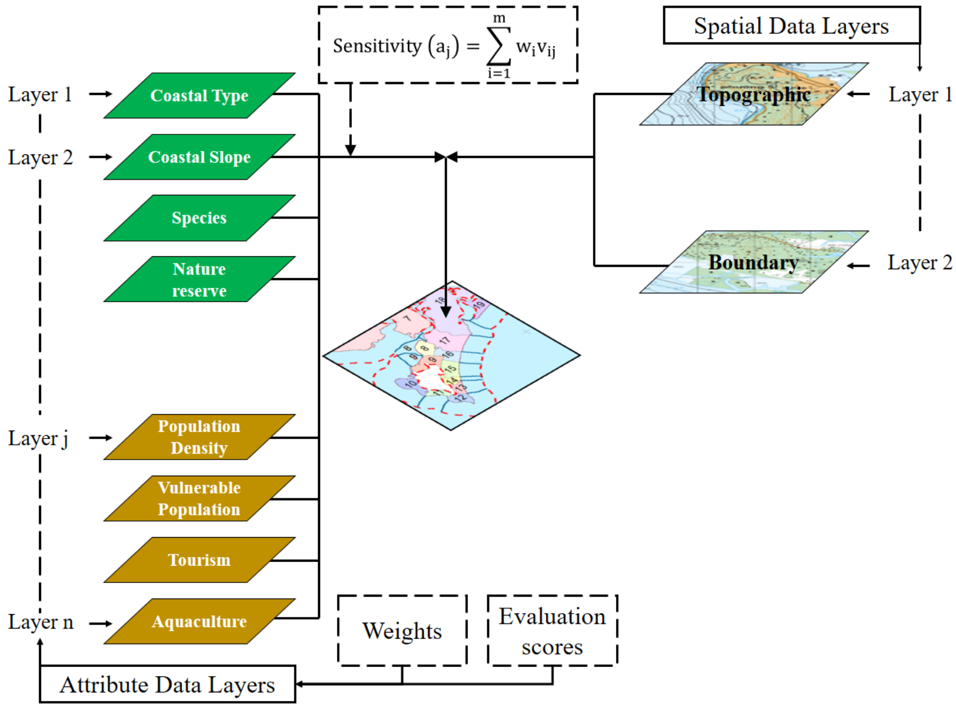


Fig. 3. Sensitivity calculation model based on GIS.

## III. RESULTS AND DISCUSSION

### *A. Assessment and Classification of Environmental Sensitivity*

Based on the set of sensitivity criteria, the weighted results of each criterion, and the collected evaluation data, the sensitivity value of each sub-region was calculated, as shown in Table VIII. The sensitivity values ranged from 1.78 to 3.33 and were classified into four ranks from 1 to 4 that corresponded to the sensitivity levels low, moderate, high, and extreme. The classification results of each sub-region were used for zoning (Fig. 4). Following the calculation and zoning, the results showed:

1) Most (17/27; 62.96%) sub-regions had high and extreme sensitivity and were primarily concentrated in Bariavungtau Province. The remaining 37.04% of the sub-regions had low and moderate sensitivity. Specifically:

- The sub-regions of extreme sensitivity (SR11, SR12, SR16, SR17, SR18, SR21, and SR22), with the highest sensitivity at SR17, are sub-regions with the potential to suffer very high consequences when water environmental incidents occur. In particular, these regions have elevated population densities. Notably, children and the elderly account for a much higher proportion of the population than in the coastal sub-regions with lower sensitivity. In addition, these sub-regions have great potential for tourism development and aquaculture and have several rare and endangered species that need to be prioritised for protection.
- The sub-regions of high sensitivity (SR1, SR2, SR3, SR9, SR10, SR13, SR15, SR19, SR20, and SR25) have the potential for high consequences when environmental incidents occur. These regions are characterised by a relatively high population density but limited tourism and aquaculture activities. A few sub-regions have sandy beaches interspersed with wetlands with reasonably small slopes (SR1, SR2, and SR3), while others (SR1, SR2, SR3, and SR25) include endangered species as well as biosphere reserves that need to be protected.
- The sub-regions of moderate sensitivity (SR4, SR7, SR8, SR14, SR23, SR24, SR26, and SR27) are sparsely populated areas with underdeveloped tourism and aquaculture. These sub-regions also have relatively high coastal slopes, some of which have coastal rocks, and almost no rare species.
- Among the sub-regions of low sensitivity (SR5 and SR6), SR5 has the lowest sensitivity. These sub-regions have low population densities and vulnerable populations. Tourism and aquaculture activities have not been developed or do not exist. Moreover, the coastline is mainly characterised by rocky beaches and man-made embankments, the coastal slope is relatively high, rare and precious species are almost non-existent, and there are no coastal nature reserves.

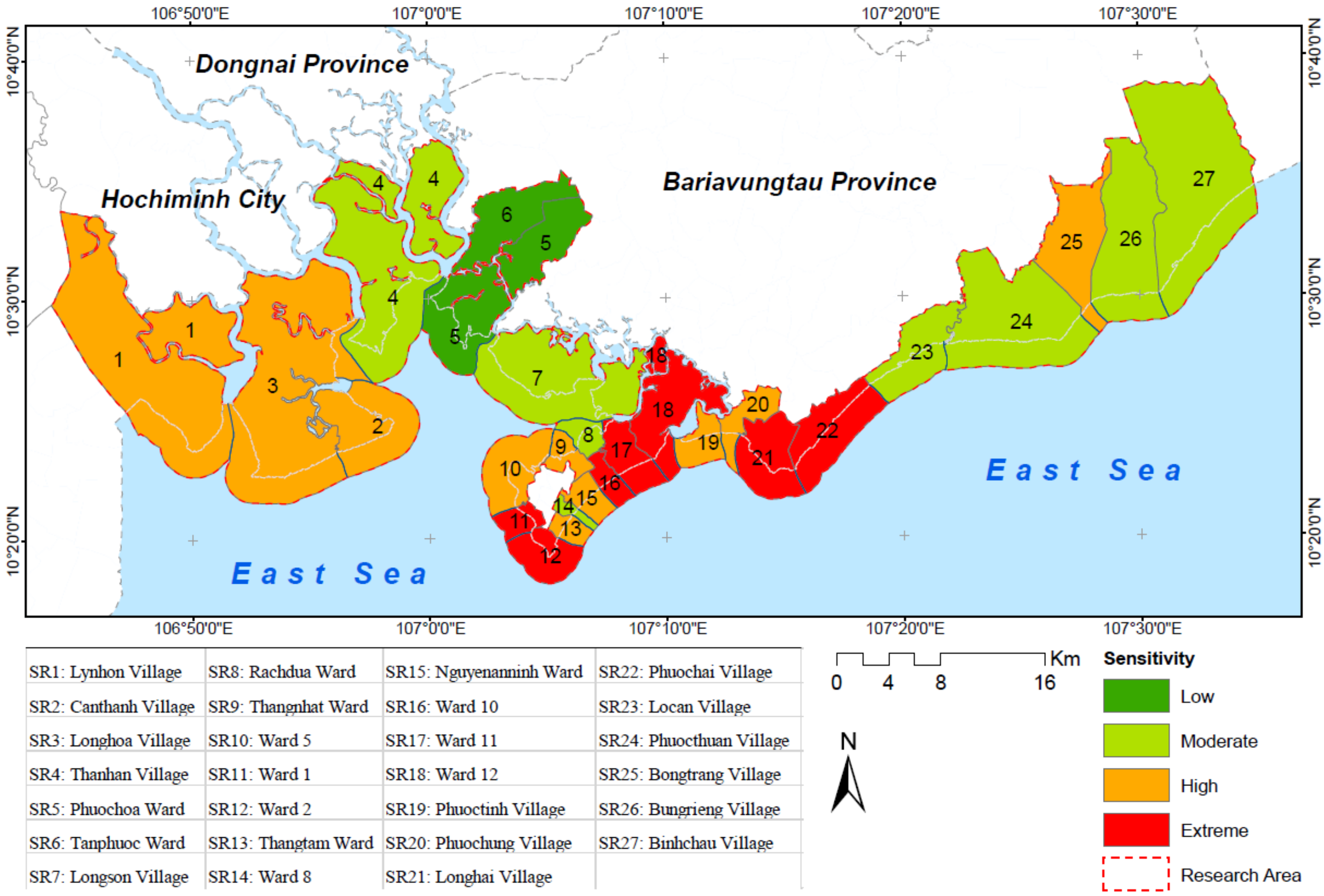


Fig. 4. Map of environmental sensitivity in the southeastern coastal region of Vietnam.

2) The evaluation criteria have different levels of importance, which is shown in detail through the calculation results. The sensitivity reduction strategy should therefore focus on the importance of the following criteria:

- The socioeconomic criteria (59%) influenced the analysis and sensitivity assessment results. The criterion of population density had the highest contribution rate (24%), which is the most important factor in assessing coastal sensitivity because the coastal sub-regions in the study area have not been suitably spatially planned for urban development and livelihoods, followed by vulnerable populations (15%), aquaculture (11%), and tourism (9%). Specifically, the calculation results showed that the population density criterion scores contributed significantly compared to the values of the remaining criteria. It is clear that because the study area has very dynamic economic development, it has a very high population density. Additionally, although important, the remaining criteria are primarily of low or medium value. Accordingly, strategies aimed at reducing sensitivity in sub-regions where socioeconomic aspects are important need to take into account the criteria of population density and vulnerable populations, followed by those related to aquaculture and tourism.

- The physical and environmental criteria had a lower influence on the analysis and sensitivity assessment results, except for the nature reserve criterion, which plays an important role and accounted for 17% of the sensitivity value. The remaining criteria had low contributions at 9%, 9%, and 6% for coastal type, coastal slope, and species, respectively. The results of the sensitivity calculation showed that the value scores of the physical and environmental criteria accounted for a tiny percentage of the results. Strategies to reduce sensitivity in sub-regions where physical and environmental aspects are important need to consider the nature reserve criteria first, followed by the coastal type, coastal slope, and species.

TABLE VIII: SENSITIVITY CALCULATION RESULTS FOR EACH SUB-REGION

| Sub-region | Sensitivity | Sub-region | Sensitivity |
|---|---|---|---|
| Lynhon Village | 2.80 | Nguyenanninh Ward | 2.83 |
| Canthanh Village | 2.73 | Ward 10 | 3.18 |
| Longhoa Village | 2.76 | Ward 11 | 3.33 |
| Thanhan Village | 2.34 | Ward 12 | 2.97 |
| Phuochoa Ward | 1.78 | Phuoctinh Village | 2.91 |
| Tanphuoc Ward | 2.02 | Phuochung Village | 2.85 |
| Longson Village | 2.35 | Longhai Village | 3.24 |
| Rachdua Ward | 2.56 | Phuochai Village | 3.24 |
| Thangnhat Ward | 2.92 | Locan Village | 2.36 |
| Ward 5 | 2.92 | Phuocthuan Village | 2.56 |
| Ward 1 | 3.07 | Bongtrang Village | 2.65 |
| Ward 2 | 3.01 | Bungrieng Village | 2.47 |
| Thangtam Ward | 2.65 | Binhchau Village | 2.56 |
| Ward 8 | 2.56 | | |

3) The sensitivity map is merely limited to a certain spatial extent, so the species criterion between adjoining sub-regions has a slight basis for determination with high confidence. In addition, the actual process of collecting expert data has not yet recorded the participation of experts in ecology and society.

### *B. Strategies to Reduce Environmental Sensitivity*

The sub-regions with high and extreme sensitivity are high population density, vulnerable populations, and development activities that do not comply with the spatial distribution plan, such as aquaculture and tourism. Therefore, these sub-regions are easily affected and negatively impacted when water environmental incidents occur. Three groups of strategies are proposed for implementation in the above sub-regions:

1) Sustainable urban space development: It is imperative to review and adjust planning and reasonably ensure space for urban development in coastal sub-regions, thereby arranging and stabilising coastal communities' places of residence in line with the planning. Additionally, a plan should be implemented to control the rate of natural population growth by focusing on raising public awareness.
2) Exploitation and rational use of coastal resources: The need exists to strengthen control of coastal development activities and to focus on activities related to aquaculture and tourism development. Additional plans could include restoring the landscape and environment in coastal areas, especially aquaculture areas that are no longer suitable for planning, developing coastal nature reserves, and combining the protection of rare and endangered species that need to be prioritised for protection. Furthermore, it would be of value to review and adjust the tourism development strategy to ensure that coastal tourist areas are associated with the protection of landscapes, natural resources, and the environment.
3) Improve capacity to respond to water environmental incidents: This would entail increasing investment in incident response resources, focusing on enhancing their capacity to participate in community responses, widely disseminating environmental incident response plans to coastal communities, regularly organising drills to respond to environmental incidents, and periodically conducting investigations and classifying hazards (i.e. flooding, hazardous material spills) so as to develop a reasonable strategy that eliminates or reduces the risk of environmental incidents, thus helping to minimise potential damage.

## IV. CONCLUSIONS

The southeastern coastal region of Vietnam faces numerous environmental risks from water environmental incidents, especially from those stemming from human activities on the mainland. The absence of a comprehensive assessment approach for environmental sensitivity in coastal areas is causing multiple obstacles with respect to sustainability planning. A research approach that combined MCDM, GIS, and RS to build sets of criteria that included physical, environmental, and socioeconomic aspects was undertaken to analyse and assess the level of environmental sensitivity in the sub-regions in this study.

The environmental sensitivity results were categorised into four different sensitivities, namely, low, moderate, high, and extreme, at 7.41%, 29.63%, 37.04%, and 25.93%, respectively. As a result, the study produced an environmental sensitivity map to solve the research problem. Three strategies were proposed to reduce environmental sensitivity for high and extremely sensitive sub-regions. Specifically, criteria related to socioeconomic factors should be given more attention as they accounted for 59% of the results, while the criteria related to physical and environmental factors contributed 41% (nature reserves need to be considered before developing a protection strategy).

The research results make a vital contribution to related research works and can support policymakers in making decisions regarding the direction of stable development in coastal areas with similar development conditions. This will in turn contribute to reducing the potential consequences of any water environmental incidents occurring in the coastal areas. In addition, this approach can be used to formulate an integrated methodology framework for sustainable coastal development.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

Cuong Tan Le carried out the research review, analysed the results, conducted fieldwork, supported the method framework, and wrote the paper; Phuoc Van Nguyen reviewed and revised the paper; Quan Hong Nguyen guided the research direction and the research process; Huyen Thi Thu Do and Minh Thanh Tran conducted interviews, analysed data, and presented the results on GIS. All authors had approved the final version.

## ACKNOWLEDGMENT

This research is funded by Vietnam National University HoChiMinh City (VNU-HCM) under grant number C2021-24-05 and TX2023-24-01.

## REFERENCES

[1] J. Shaji, "Coastal sensitivity assessment for Thiruvananthapuram, west coast of India," *Natural Hazards*, vol. 73, no. 3, pp. 1369-1392, 2014.

[2] T. G. Montaño and A. C. Gonzales, "Human insecurity and conflict: Effect of coastal communities' vulnerability to climate change," *International Journal of Environmental Science Development*, vol. 9, no. 7, pp. 187-191, 2018.

[3] M. A. Silhadi, W. Refes, and S. Mazouzi, "Assessment of coastal ecosystems vulnerability to pollution: Algiers coast, Algeria," *Environmental Science and Pollution Research*, vol. 27, no. 34, pp. 42670-42684, 2020.

[4] Q. He, *et al.*, "Economic development and coastal ecosystem change in China," *Scientific Reports*, vol. 4, no. 1, pp. 1-9, 2014.

[5] S. A. Mohamed, "Coastal vulnerability assessment using GIS-Based multicriteria analysis of Alexandria-northwestern Nile Delta, Egypt," *African Earth Sciences*, vol. 163, pp. 103-151, 2020.

[6] T. Zhai, *et al.*, "Assessing ecological risks caused by human activities in rapid urbanization coastal areas: Towards an integrated approach to determining key areas of terrestrial-oceanic ecosystems preservation and restoration," *Science of the Total Environment*, vol. 708, p. 135153, 2020.

[7] L. M. Chou, T. C. Toh, and C. S. L. Ng, "Effectiveness of reef restoration in Singapore's rapidly urbanizing coastal environment," *International Journal of Environmental Science Development*, vol. 8, no. 8, pp. 576-580, 2017.

[8] S. El-Shahat, A. M. El-Zafarany, T. A. El Seoud, and S. A. Ghoniem, "Vulnerability assessment of African coasts to sea level rise using GIS and remote sensing," *Environment, Development Sustainability*, vol. 23, no. 2, pp. 2827-2845, 2021.

[9] Ministry of Natural resources and Environment Vietnam, "Report on the national environmental current state of marine and island for the period 2016-2020 (Overview)," 2021.

[10] S. V. Hatcher and G. K. Manson, "A revised coastal sensitivity index for Canada's marine coasts calculated using nonparametric statistics," *Canadian Journal of Earth Sciences*, vol. 99, no. 999, pp. 1-9, 2021.

[11] A. Mooser *et al.*, "Most attractive scenic sites of the Bulgarian black sea coast: Characterization and sensitivity to natural and human factors," *Land*, vol. 11, no. 1, p. 70, 2022.

[12] A. Rizzo, P. Aucelli, F. Gracia, and G. Anfuso, "A novelty coastal susceptibility assessment method: Application to Valdelagrana area (SW Spain)," *Journal of Coastal Conservation*, vol. 22, no. 5, pp. 973-987, 2018.

[13] H. J. Jara *et al.*, "Current and future socio-ecological vulnerability and adaptation of artisanal fisheries communities in Peru, the case of the Huaura province," *Marine Policy*, vol. 119, p. 104003, 2020.

[14] A. Mencattini and L. Mari, "A conceptual framework for concept definition in measurement: The case of 'sensitivity'" *Measurement*, vol. 72 pp. 77–87, 2015.

[15] L. Olsson *et al.*, "Livelihoods and poverty: Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change," Cambridge University Press, 2014, pp. 793-832.

[16] IPCC, "Glossary annex in: Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change," Cambridge University Press, pp. 1757-1776, 2014.

[17] K. Denner, M. Phillips, R. Jenkins, and T. Thomas, "A coastal vulnerability and environmental risk assessment of Loughor Estuary, South Wales," *Ocean Coastal Management*, vol. 116, pp. 478-490, 2015.

[18] K. Kantamaneni, M. Phillips, T. Thomas, and R. Jenkins, "Assessing coastal vulnerability: Development of a combined physical and economic index," *Ocean Coastal Management*, vol. 158, pp. 164-175, 2018.

[19] B. Palmer *et al.*, "Preliminary coastal vulnerability assessment for kwazulu-natal, South Africa," *Journal of Coastal Research*, pp. 1390-1395, 2011.

[20] I. Bagdanavičiūtė, L. Kelpšaitė, and T. Soomere, "Multi-criteria evaluation approach to coastal vulnerability index development in micro-tidal low-lying areas," *Ocean Coastal Management*, vol. 104, pp. 124-135, 2015.

[21] A. Mavromatidi, E. Briche, and C. Claeys, "Mapping and analyzing socio-environmental vulnerability to coastal hazards induced by climate change: An application to coastal Mediterranean cities in France," *Cities*, vol. 72, pp. 189-200, 2018.

[22] B. Sahoo and P. Bhaskaran, "Multi-hazard risk assessment of coastal vulnerability from tropical cyclones — A GIS based approach for the Odisha coast," *Journal of Environmental Management*, vol. 206, pp. 1166-1178, 2018.

[23] C. Giannakidou, D. Diakoulaki, and C. Memos, "Implementing a flood vulnerability index in urban coastal areas with industrial activity," *Natural Hazards*, vol. 97, no. 1, pp. 99-120, 2019.

[24] T. S. Sankari, A. Chandramouli, K. Gokul, S. M. Surya, and J. Saravanavel, "Coastal vulnerability mapping using geospatial technologies in cuddalore-pichavaram coastal tract, Tamil Nadu, India," *Aquatic Procedia*, vol. 4, pp. 412-418, 2015.

[25] A. Satta, M. Snoussi, M. Puddu, L. Flayou, and R. Hout, "An index-based method to assess risks of climate-related hazards in coastal zones: The case of Tetouan," *Estuarine, Coastal and Shelf Science*, vol. 175, pp. 93-105, 2016.

[26] L. Cai, L. Yan, J. Ni, and C. Wang, "Assessment of ecological vulnerability under oil spill stress," *Sustainability*, vol. 7, no. 10, pp. 13073-13084, 2015.

[27] R. Kankara, S. Arockiaraj, and K. Prabhu, "Environmental sensitivity mapping and risk assessment for oil spill along the Chennai Coast in India," *Mar Pollut Bull*, vol. 106, no. 1-2, pp. 95-103, 2016.

[28] J. Peterson, "Environmental sensitivity index guidelines: Version 3.0," *NOAA Technical Memorandum NOS-OR&R 11*, 2002.

[29] J. Peterson *et al.*, "Environmental sensitivity index guidelines: Version 4.0," *NOAA Technical Memorandum NOS OR&R 52*, 2019.

[30] M. Marignani *et al.*, "Identification and prioritization of areas with high environmental risk in Mediterranean coastal areas: A flexible approach," *Science of the Total Environment*, vol. 590, pp. 566-578, 2017.

[31] S. S. Sardi *et al.*, "Assessment of areas environmentally sensitive to oil spills in the western Arabian Gulf, Saudi Arabia, for planning and undertaking an effective response," *Marine Pollution Bulletin*, vol. 150, p. 110588, 2020.

[32] I. Sekovski, L. Del Río, and C. Armaroli, "Development of a coastal vulnerability index using analytical hierarchy process and application to Ravenna province (Italy)," *Ocean Coastal Management*, vol. 183, pp. 104982, 2020.

[33] N. Rangel-Buitrago and G. Anfuso, *Risk Assessment of Storms in Coastal Zones: Case Studies from Cartagena (Colombia) and Cadiz (Spain)*, Springer, 2015.

[34] R. Al-Adamat, "The use of GIS and remote sensing to investigate groundwater vulnerability to contamination and surface water susceptibility to pollution at Mafraq Dumpsite/Jordan," *International Journal of Environmental Science Development*, vol. 9, no. 12, pp. 361-367, 2018.

[35] Fazel Amiri, Vahid Rahdari, B. Pradhan, and T. Tabatabaei, "Multi-temporal landsat images based on eco-environmental change analysis in and around Chah Nimeh reservoir, Balochestan (Iran)," *Environmental Earth Sciences*, vol. 72, no. 3, pp. 801-809, 2014.
[36] H. Takagi, T. V. Ty, and N. D. Thao, "Investigation on floods in Can Tho City: influence of ocean tides and sea level rise for the Mekong Delta's largest city," *Coastal Disasters and Climate Change in Vietnam*, Elsevier, 2014, pp. 257-274.
[37] A. Afshari, M. Mojahed, and R. M. Yusuff, "Simple additive weighting approach to personnel selection problem," *International Journal of Innovation, Management Technology*, vol. 1, no. 5, pp. 511, 2010.
[38] T. L. Saaty, "How to make a decision: The analytic hierarchy process," *European Journal of Operational Research*, vol. 48, no. 1, pp. 9-26, 1990.
[39] W. Chaib, M. Guerfi, and Y. Hemdane, "Evaluation of coastal vulnerability and exposure to erosion and submersion risks in Bou Ismail Bay (Algeria) using the coastal risk index (CRI)," *Geosciences*, vol. 13, no. 11, pp. 1-18, 2020.
[40] National Assembly, "Biodiversity law," 2008.
[41] [Y. Zhang *et al.*, "Synthetic vulnerability assessment to inform climate-change adaptation along an urbanized coast of Shenzhen, China," *Journal of Environmental Management*, vol. 255, 109915, 2020.
[42] Ministry of Natural Resources and Environment, "Regulations on the process of overcoming consequences of oil spill incidents at sea," vol. No. 33/2018/TT-BTNMT, 2018.
[43] M. Nazeer, M. Waqas, M. I. Shahzad, I. Zia, and W. Wu, "Coastline vulnerability assessment through landsat and cubesats in a coastal mega city," *Remote Sensing*, vol. 12, no. 5, pp. 749, 2020.
[44] K. Darwish and S. Smith, "A comparison of landsat-8 OLI, sentinel-2 MSI and planetscope satellite imagery for assessing coastline change in El-Alamein, Egypt," *Engineering Proceedings*, vol. 10, no. 1, p. 23, 2021.
[45] S.-H. Park, H.-S. Jung, M.-J. Lee, W.-J. Lee, and M.-J. Choi, "Oil spill detection from PlanetScope satellite image: application to Oil spill Accident near Ras Al Zour area, Kuwait in august 2017," *Journal of coastal Research*, vol. 90, no. SI, pp. 251-260, 2019.
[46] S. W. Ricci and D. R. Bohnenstiehl, "Monitoring visitation at North Carolina artificial reef sites using high spatiotemporal resolution PlanetScope imagery," *Regional Studies in Marine Science*, vol. 55, 102511, 2022.
[47] M. Möller, J. Birger, A. Gidudu, and C. Gläßer, "A framework for the geometric accuracy assessment of classified objects," *International Journal of Remote Sensing*, vol. 34, no. 24, pp. 8685-8698, 2013.
[48] J. A. Richards and X. Jia, "Image classification methodologies," *Remote Sensing Digital Image Analysis: An Introduction*, pp. 295-332, 2006.
[49] J. A. Richards and J. Richards, *Remote Sensing Digital Image Analysis*, Springer, 1986.
[50] P. S. Sisodia, V. Tiwari, and A. Kumar, "Analysis of supervised maximum likelihood classification for remote sensing image," presented at International Conference on Recent Advances and Innovations in Engineering (ICRAIE-2014), 2014. IEEE.
[51] G. D. Israel, "Determining sample size," *University of Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences, EDIS, Florida*, 1992.
[52] H. C. Kraemer, "Kappa coefficient," *Wiley StatsRef: Statistics Reference Online*, pp. 1-4, 2014.
[53] J. Cohen, "A coefficient of agreement for nominal scales," *Educational Psychological Measurement*, vol. 20, no. 1, pp. 37-46, 1960.
[54] E. R. Thieler and H.-K. ES, "National assessment of coastal vulnerability to future sea-level rise: Preliminary results for the US Atlantic coast," *US Geological Survey, Open-File Report*, pp. 99-593, 1999.
[55] Ministry of Natural Resources and Environment, "Technical regulations on establishment of coastal protection corridors," vol. No. 29/2016/TT-BTNMT, 2016.
[56] Department of Natural Resources and Environment of Bariavungtau province, "Summary report on design project of coastal protection corridor Bariavungtau province," 2021.
[57] HCMC Department of Science and Technology, "Summary report on research on the effects of climate change on the flora of Can Gio mangrove and propose solutions to protect," 2021.
[58] R. Dhiman, P. Kalbar, and A. B. Inamdar, "GIS coupled multiple criteria decision making approach for classifying urban coastal areas in India," *Habitat International*, vol. 71, pp. 125-134, 2018.
[59] C. B. Monteiro *et al.*, "Integrated environmental vulnerability to oil spills in sensitive areas," *Environmental Pollution*, vol. 267, p. 115238, 2020.