Applied Environmental Research
- RESEARCH FOR SUSTAINABLE PLANET -

Research Article

A Framework for Assessing Environmental Incidents in Coastal Areas: A Case Study in the Southeastern Coastal Area of Vietnam

Cuong Le Tan[1,*], Phuoc Nguyen Van[2], Quan Nguyen Hong[1,3], Loan Tran Thi Diem[1], Minh Tran Thanh[1]

[1] *Institute for Environment and Resources, Vietnam National University of Ho Chi Minh City, Vietnam*
[2] *Ho Chi Mink City Union of Science and Technology Associations, Vietnam*
[3] *Institute for Circular Economy Development, Vietnam National University of Ho Chi Minh City, Vietnam*

[*]Corresponding author: letancuongmttn@gmail.com, tancuong@hcmier.edu.vn

Abstract

As developing dynamic regions, coastal areas have a high potential for environmental incidents, especially chemical spills, which may permanently threaten livelihoods and coastal ecosystems. Establishing an appropriate methodological framework for assessing environmental incidents in coastal areas, ensuring increased predictability and minimising potential consequences is a trend of interest to scientists. In this study, the environmental risk assessment model was applied to develop a framework for assessing environmental incidents in coastal areas due to chemical spills from the mainland based on hazard, exposure and vulnerability factors (i.e., sensitivity and adaptability). Using the multiple criteria decision-making (MCDM) method approach, suitable criteria, their optimal weights and the risk factors were determined. Modelling, remote sensing, and geographic information system (GIS) methods were used simultaneously for data collection, evaluation, and mapping. A case study was conducted in the coastal area of southeastern Vietnam, which comprises 27 subregions. These were classified into four environmental incident levels: low, medium, high, and extreme. Their prevalence was 70.37%, 3.70%, 7.41%, and 18.52% in the rainy season, and 74.07%, 7.41%, 7.41%, and 11.11% in the dry season, respectively. Based on analysis results and consultation with managers and experts, pertinent and practical solutions were proposed to reduce the risk of environmental incidents in subregions with high and extreme incident levels. Our results are expected to support policymakers in decision-making related to the sustainable development of the study area and complete the methodology framework for assessing environmental incidents in coastal areas due to multiple hazards.

ARTICLE HISTORY

Received: 31 Oct. 2022
Accepted: 3 Jan. 2023
Published: 16 Mar. 2023

KEYWORDS

Environmental incident assessment; Hazard; Vulnerability; Multiple-criteria decision-making; Coastal areas

Introduction

Given their biodiversity characteristics, their ability to provide many valuable services for livelihoods via their ecosystems [1] as well as opportune transportation modes, most coastal areas develop very dynamically [2]. Industrial, maritime [3], and tourism activities [4] have always been potential advantages in the development of coastal areas. The attractiveness of these regions is the reason for their rapid population growth in recent decades [5–6]. However, coastal areas have a higher potential for environmental incidents than other areas from the mainland due to their low terrain and fast development rates [7]. Vietnam's coastal area is located in southeastern Asia and, according to the Ministry of Natural Resources and Environment [8], has a coastline of 3,260 km and a

https://doi.org/10.35762/AER.2023002

population density of 354 people per km^2. With an average growth rate of 7.5% per year, this region is developing quickly and is expected to contribute 65%–70% to the country's GDP by 2030. Nevertheless, Vietnam's coastal areas are suffering from numerous negative impacts from the mainland. A typical example of an environmental incident is that of the wastewater discharge process of the Formosa Corporation in 2016 [8], which caused severe consequences and affected the livelihoods of coastal communities. In the southeastern coastal research area of this study, which is the most dynamic development region in Vietnam, other notable incidents include the monosodium glutamate production process of Vedan Corporation in 2008 [9] and the seafood processing of Tan Hai Industrial Park in 2017 [10], which caused serious pollution and the destruction of biological resources. The sustainable development of coastal areas is therefore not only a formality, but is also becoming a critical concern worldwide [11]. It is therefore important to eliminate hazards, reduce their potential consequences and maintain the stability of coastal ecosystems [12].

An environmental incident is an accidental event or situation that occurs with no purpose or intention [13]. Nevertheless, it has the potential to happen suddenly and carries the risk of severe impacts on the environment and society [14]. An environmental incident is distinct from the general phenomenon of environmental pollution; it takes place in the process of human activities or natural change, poses a high risk and can cause severe negative impacts on humans and the environment on a large scale [14]. Environmental incidents can therefore be considered environmental risks, so the approach to environmental incident assessments in coastal areas due to chemical spills from the mainland is similar to that of environmental risk assessments.

When conducting environmental risk assessments in coastal areas, researchers are often interested in the hazards that occur due to natural variability, but mainly focus on the consequences resulting from 'vulnerability'. According to reference [15], vulnerability is dependent on sensitivity and adaptability. Sensitivity describes how people, infrastructure and the environment are affected by hazards due to a lack of resilience when exposed to these hazards [16], while adaptability describes a system's ability to resist hazards or recover from changes [16]. Most studies estimate environmental risk based on vulnerability [17–18] or sensitivity [19–20] depending on the research conditions. However, environmental risk is also estimated based on sensitivity and exposure [21–22] or sensitivity, exposure, and adaptability [21, 23].

Our comprehensive review showed that minimal studies have been published on environmental risks in coastal areas due to human activities, especially chemical spills. Levels of environmental risk are usually estimated by integrating the hazard of the incident with the potential consequential factors [24–25]. When analysing potential consequential factors, studies have tended to focus on exposure [26–27]. Some researchers have integrated exposure with the sensitivity factor, which they determined based on criteria related to physical and social conditions [28–29] or social and environmental conditions [30]. Others have assessed potential consequential factors based on criteria related to sensitivity and adaptability [31] or simply sensitivity [32]. To determine potential consequential factors, some researchers have used risk source, safety, and risk control criteria in their hazard factor analysis [33–34]. For example, according to reference [35], the five criteria selected, and reference [36], 15 criteria selected related to the source of the risk, risk control, and incident response procedures to estimate the hazard factor. Aside from these criteria, the hazard factor has been determined based on a matrix composition of the total quotient of toxic chemicals compared to the specified threshold, production processes and risk control [34, 37].

Environmental risk assessment methods were widely used according to the multiple-criteria decision-making (MCDM) approach [38] because they can apply different dimensional or quantitative and qualitative criteria for analysis, selection, ranking, and mapping [38–39]. Most studies have used the MCDM approach to assess sensitivity [29–30] and adaptability [21, 31]. For example, reference [28] integrated MCDM and GIS to analyse the coastal area's risks, sensitivity mapping, and resource priority indexing. Thereby, the risk assessment and sensitivity mapping results have helped organisations take measures to combat oil spills in a timely manner. As well as sensitivity, reference [21] used MCDM to assess the adaptability of coastal areas from multiple natural hazards. The results were then combined with the sensitivity to create a vulnerability map and provide strategies to reduce risks and enhance adaptability. In terms of the hazard factor, studies have focused on three methods, namely, modelling [40–41], statistics [42–43], and the MCDM approach [37, 44]. However, researchers often use the statistical method for the hazard factor. Exposure factor studies often use the modelling approach [26, 37].

Our literature review showed that coastal environmental risk assessment studies have paid scant attention to mainland hazards. While they tend to develop potential consequential factors, with an emphasis on exposure, no studies have integrated hazard, exposure and vulnerability factors to assess environmental risk in coastal areas due to potential chemical spills from mainland areas.

The main contributions of this study are (i) the development of a framework that integrates hazard, exposure and vulnerability factors (i.e., sensitivity and adaptability) to assess environmental incidents in coastal areas due to chemical spills from the mainland; (ii) the use of the MCDM approach to determine the appropriate criteria, optimal weight of each criterion and the weight of the factors constituting environmental incident levels; and (iii) the assessment of environmental incidents in the southeastern coastal area of Vietnam.

Material and methods

1) Study area

The study area was located in the southeastern coastal area of Vietnam, which is adjacent to the East Sea. It has a coastline of 90 km with the geographic coordinates 10°18'05"–10°48'12" North latitude and 106°44'04"–107°34'49" East longitude. The area used for the calculation included 780 km^2 of landmass (27 coastal communes) and a water surface of 596 km^2 (4 km offshore area) (Figure 1). The study area has 21 industrial parks covering an area of 8,510 hectares, and the 476 investment projects account for a total capital investment of US$19.98 billion. There are 65 subjects involved in hazardous chemicals (i.e., factories, chemical warehouses, and petrochemical zones), most of which are located in industrial parks. These subjects that use hazardous chemicals are primarily where chemical products are manufactured, traded, or stored. In addition, the chemical types of these hazards are miscellaneous, with large volumes or inadequate response capacity, so there are potential risks of chemical spills in coastal areas. The study area is also home to 481,765 citizens, with a population density of 505 people per km^2. The potential risk of chemical spills that can seriously threaten ecosystems and the livelihoods of the community is therefore always present.

2) Methodology

In this study, we developed a new approach based on an environmental risk and vulnerability assessment model with the aim of establishing a framework for assessing environmental incidents in coastal areas due to chemical spills from the mainland (Figure 2).

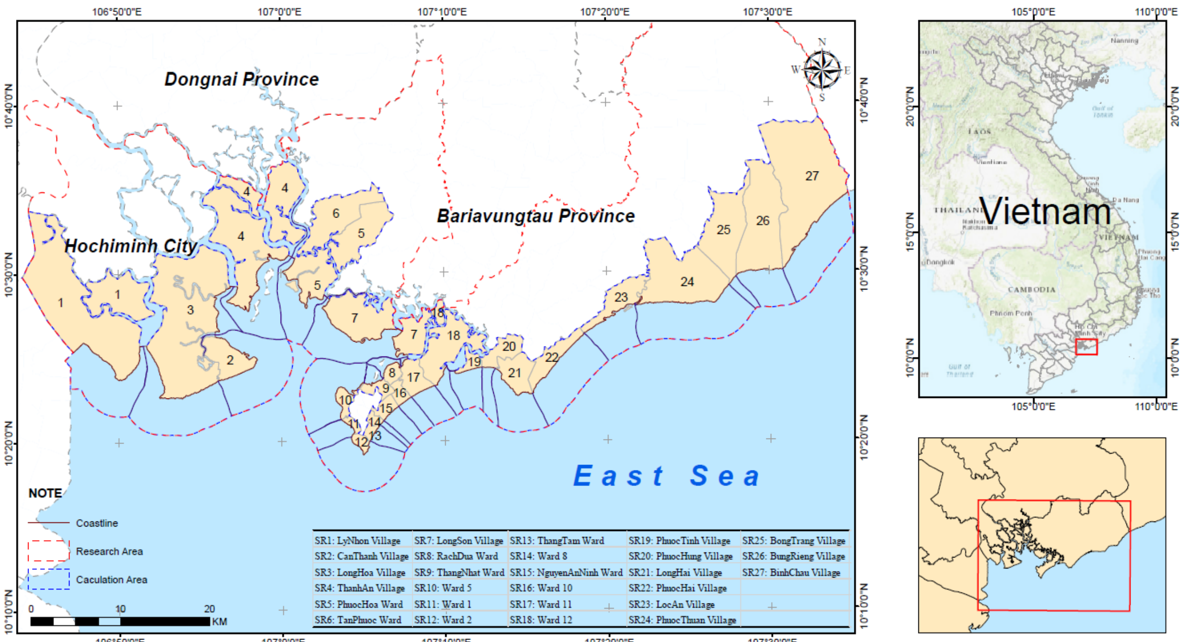

Figure 1 Location of the study.

https://doi.org/10.35762/AER.2023002

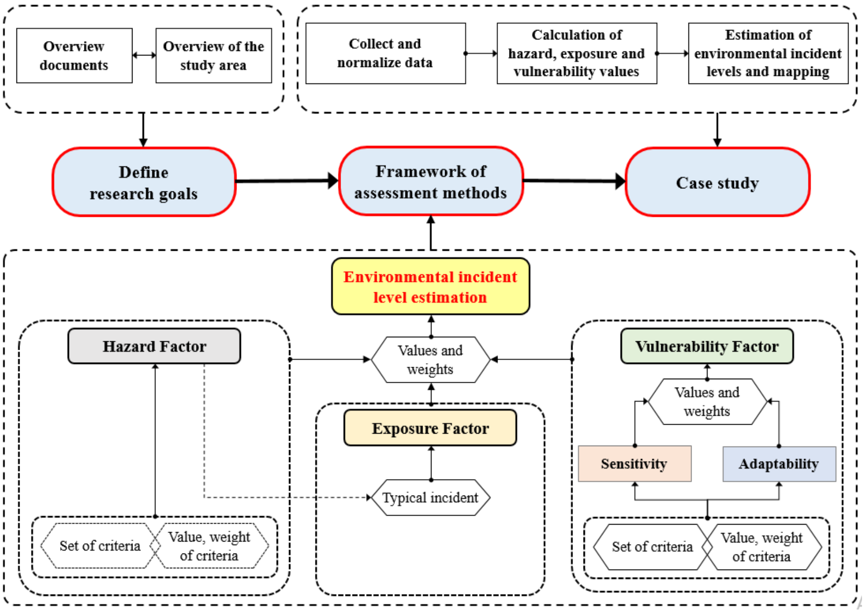

Figure 2 Methodology framework.

2.1) Establish sets of criteria

2.1.1) Select suitable criteria

Based on our review of the literature, we established preliminary criteria comprising three sets of criteria, namely, hazard, sensitivity, and adaptability. Next, a questionnaire was developed, and we consulted with 20 experts (scientists and managers) via email on the importance of the sub-criteria and evaluation values of each preliminary criterion against the sub-criteria. From the collected data and the weights of the sub-criteria determined by the analytic hierarchy process (AHP) method [45], the evaluation value was calculated using Eq. 1 [46], which was also used to screen and select the appropriate criteria.

$$V(a_j) = \sum_{i=1}^{m} w_i \, v_{ij} \qquad \text{(Eq. 1)}$$

where $V(aj)$ is the result of the evaluation value of the j^{th} criteria, w_i is the weight of the i^{th} sub-criteria, and $\boldsymbol{v_{ij}}$ is the value rated by sub-criteria i for the j^{th} criteria.

2.1.2) Determine the criteria weight

The set of weighted criteria is represented by C = {C1, C2, ..., Cn}. The best-worst group method was used to determine the optimal weights and weight variability [47]:

- Criterion B (best criterion) and W (worst criterion) selected in set C were determined based on the screening results, and the appropriate criteria were selected.
- A second round of consultations with the experts was conducted via a questionnaire. A rating scale from 1 to 9 was used to indicate the importance of the criteria. The set of criteria $A_B = (a_{B1}, a_{B2},..a_{Bn})$ and $A_W = (a_{1W}, a_{2W},..a_{nW})$ represent the best and worst set of criteria, respectively, where a_{Bi} denotes the preference of criterion B over criterion i, a_{Wi} denotes the preference of criterion i over criterion W, and $a_{BB} = a_{WW} = 1$.
- The optimal weights of the criteria were determined based on the model M2 [47]:

$$Min\ Max_k w'_k \mu_k = Min(\mu)$$

in which: $\mu \geq w'_k \mu_k \ \forall k \epsilon D$

$$\left|\frac{w_B}{w_i} - a_{Bi}\right| \leq \mu_k \ \forall i \epsilon C, \forall k \epsilon D$$

and $\left|\frac{w_i}{w_W} - a_{Wi}\right| \leq \mu_k \ \forall i \epsilon C, \forall k \epsilon D$ (Eq. 2)

in which: $\sum_{i \epsilon C} w_i = 1$ and $w_i \geq 0\ \forall i \epsilon C$

where: w'_k is the importance of k^{th} expert in the set of experts D, with w'_k (0,1) and $\sum_{k \epsilon D} w'_k = 1$; w_B and w_w are the weights of B and W, respectively; w_i is the weight of criteria i; and μ_k is the consistency ratio (CR) for the k^{th} expert, with $\mu_k = Max_i\left\{\left|\frac{W_B}{W_i} - a^k_{Bi}\right|, \left|\frac{W_i}{W_W} - a^k_{iW}\right|\right\}$.

Based on the results calculated using Eq. 2, the range of weighted variations w_i according to the lower limit w_{min} and upper limit w_{max} was determined [48].

- The consistency ratio of the k^{th} expert CR_k and group CR^G was determined according to Eq. 3:

https://doi.org/10.35762/AER.2023002

$$CR_k = w'_k \left(\frac{\mu_k}{CI^{\theta}}\right) \quad \text{(Eq. 3)}$$

$$CR^G = Max_k(CR_k)$$

where θ shows the sensitivity of the model ($\theta \geq 0$), $\forall k \in D$

Each criterion's optimal weight and weighted variation range was determined when the consistency index <0.1.

2.2) Determine the component factors

2.2.1) Hazard factor

Based on the set of hazard criteria and the weights of the criteria, the hazard value of the subjects that use hazardous chemicals was then estimated using Eq. 4 [46]:

$$HI_j = \sum_{i=1}^{m} w_i \, v_{ij} \quad \text{(Eq. 4)}$$

where: HI_j is the hazard value of the j^{th} subject that uses hazardous chemicals; w_i is the weight of the i^{th} criteria; and v_{ij} is the value of the j^{th} subject that uses hazardous chemicals with respect to the i^{th} criteria.

2.2.2) Exposure factor

Flows in near-shore areas that are wide and shallow in extent are considerably affected by tides, wind, and wave forces. MIKE 21, which is a two-way software system based on the cell-centred finite volume method implemented on unstructured flexible mesh, has therefore frequently been used to simulate sudden releases of hazardous substances into coastal waters [37, 49–50]. We used the Hydrodynamic and Oil Spill modules to simulate contaminant transmission due to hydrocarbon substance spills. The simulation scenario was selected for the subject that uses hazardous chemicals at very high hazard values, with a large volume of typical chemicals on the list of regulated hazardous chemicals [51]. The final simulation results were combined with the GIS results to determine the exposure level of each subregion.

2.2.3) Vulnerability factor

Vulnerability is directly proportional to sensitivity but inversely proportional to adaptability and was estimated according to Eq. 5 [15]:

$$CVI = \frac{SI + (H_{ES} - AI)}{2} \quad \text{(Eq. 5)}$$

where CVI is the vulnerability index; SI and AI are the indices of sensitivity and adaptability, respectively; and H_{ES} is the highest value of the evaluation scale (in this study, H_{ES} was 5).

From the set of criteria and their weights, the sensitivity and adaptability values of the coastal area were determined using Eq. 6 [41]:

$$SI_j = \sum_{i=1}^{n} w_i \, v_{ij} \quad \text{(Eq. 6)}$$

$$AI_j = \sum_{k=1}^{m} w_k \, v_{kj}$$

where SI_j and AI_j are the sensitivity and adaptability values of the j^{th} subregion; w_i and w_k are the weights of the i and k^{th} criteria, respectively; and v_{ij} and v_{kj} are the values of the j^{th} subregion according to the i and k^{th} criteria, respectively.

2.3) Environmental incident assessment and mapping

Environmental incidents in coastal areas due to chemical spills from the mainland were estimated based on Eq. 7 in accordance with the environmental risk assessment approach [52]:

$$EI = CVIW_{CVI} + EIW_{EI} + HIW_{HI} \quad \text{(Eq. 7)}$$

where EI is the value representing the environmental incident level; CVI, EI, and HI are the vulnerability, exposure, and hazard values, respectively; and W_{CVI}, W_{EI}, and W_{HI} are the respective weights.

For the GIS methodological approach [53], GIS software was used to calculate the value representing the environmental incident level. Each assessment value data file and the weight of each corresponding criterion were assigned on an attribute layer, which was then combined with the layer map data to create an environmental incident map of the 27 subregions categorised into four levels: low, moderate, high, and extreme. The model used to estimate the environmental incident level of each subregion is presented in Figure 3.

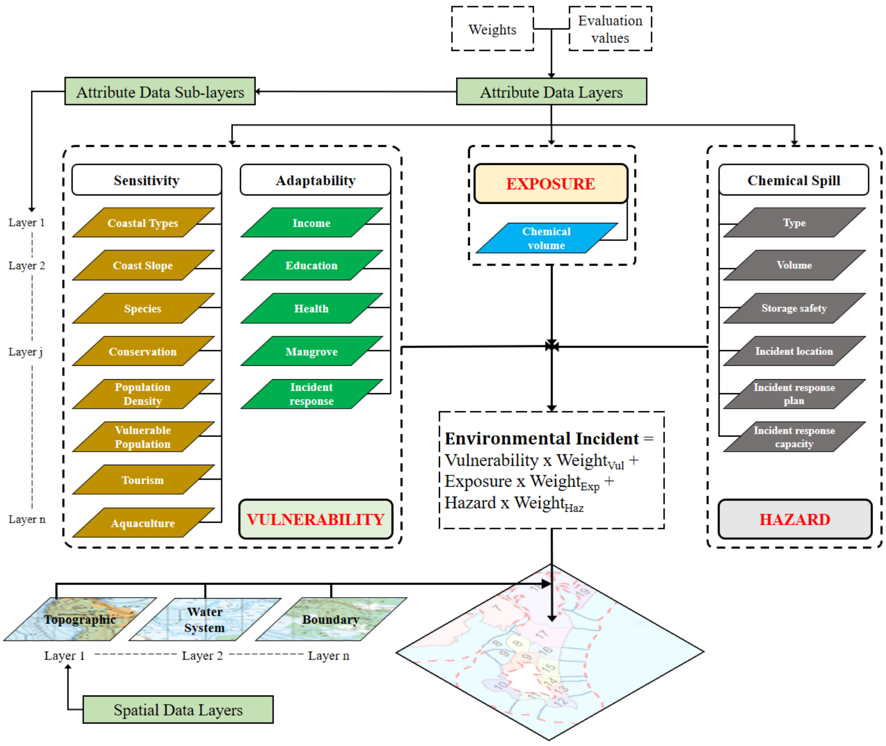

Figure 1 Environmental incident calculation model based on the GIS approach.

3) Data collecting and processing

3.1) Data collecting

3.1.1) Secondary data collection

The secondary data were collected from various sources, including coastal slope, environmental incident response, population density, vulnerable populations, income, education, health, aquaculture, and tourism data from the Department of Natural Resources and Environment. Species, nature reserve, and mangrove data were collected from the Department of Natural Resources and Environment and the Department of Agriculture and Rural Development. Topographic and hydrological data were collected from the Department of Natural Resources and Environment and the Southern Regional Hydrometeorological Centre. Satellite imagery was collected from https://www.planet.com/explorer.

3.1.2) Investigation and interviews

We collected information on the subjects that use hazardous chemicals from the Department of Natural Resources and Environment. Chemical spill hazards were determined using Eq. 8 [44]:

$$GNR = \sum_{i=1}^{n} \frac{q_i}{Q_i} \qquad \text{(Eq. 8)}$$

where *GNR* is the value of the the identified hazard source, *n* is the amount of the hazardous chemicals, *qi* (ton) is the maximum storage quantity of the chemical, and *Qi* (ton) is the threshold value [51].

Questionnaires were then developed, and the subjects with *GNR* values >1 were interviewed to collect data and identify environmental incident hazards.

3.2) Data processing

3.2.1) Coastal type

The satellite images were processed using ENVI 5.2 software and GIS to identify the research objects. PlanetScope satellite imagery of 2021 was used with a resolution of approximately 3 m per pixel. The process of determining the type of coastline was carried out in five main stages: image preprocessing, image interpretation, classification, testing and evaluation. As a result, five coastal objects were identified, namely, cliffs, rocky shores, artificial embankments, sandbanks, and wetlands.

3.2.2) Coastal slope

A coastal slope is the change in altitude relative to the horizontal distance between any two points landwards and seawards of the coastline [54]. The coastal slope was calculated using E.q 9 [55]:

$$tan(a) = \frac{D}{H}.100\% \qquad \text{(Eq. 9)}$$

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).

3.2.3) The rest of the data types

The remaining data were synthesised from the secondary data collection, investigation and interviews with the subjects who were using hazardous chemicals.

Finally, all the data were aggregated and processed to form a preliminary dataset. The dataset was then converted to values ranging from 1 to 5 (Table 1) based on an evaluation scale to facilitate the environmental incident estimation.

Table 1 Evaluation scale

Criteria/symbol		**Evaluation values**					**References**
		Very low	**Low**	**Moderate**	**High**	**Very high**	
		1	**2**	**3**	**4**	**5**	
Hazard							
Chemical types	H1	Only one	–	2–3	–	>3	[51]
Chemical volumes	H2	Does not exceed	More than two times the chemical volume relative to the threshold	More than two to three times the chemical volume relative to the threshold	-	More than three times the chemical volume relative to the threshold	[51]
Chemical storage safety	H3	The dam contains enough	-	The dam contains nearly enough	-	No dam	[56]
Chemical incident location	H4	1 km to the river system and coastal waters	<1 km to the level 2 sub-river systems	<1 km to the level 1 sub-river systems	<1 km to the main river	<1 km to the coastal waters	This study
Chemical incident response plan	H5	Fully compliant	Except for incident response equipment	Only approved plans	Unapproved plans	No plan	[56]
Chemical incident response capacity	H6	Annual exercises or assumptions	-	Random exercises or assumptions	-	No exercises or assumptions	[56]
Sensitivity							
Coastal type	S1	Cliffs	Rocky shores	Artificial embankments	Sandbanks	Wetlands	[52]
Coastal slope (%)	S2	>1.14	>0.87–1.14	>0.49–0.87	>0.26– 0.49	0.26	
Population density (people per km^2)	S3	<450	450–<800	800–<1,150	1,150–<1,400	1,400	[21]
Vulnerable population (%)	S4	<20	20–<40	40–<60	60–<80	80	[21]
Tourism	S5	-	Scenic spots, cultural heritage	Beaches for tourists	Public beaches	Public beaches, beach sports	[57]
Aquaculture (%)	S6	<10	10–<20	20–<35	35–<50	50	[57]
Species	S7	No rare species	Rare species	Rare and near-endangered species	Rare and endangered species	Rare and critically endangered species	[58–59]
Nature reserve	S8	–	Landscape protection area	Biodiversity conservation	Nature reserve	World biosphere reserves	[58]
Exposure							
Exposure level (%)		< 20	20–<40	40–<60	60–<80	80	[60]
Adaptability							
Income (US$ per month)	A1	<195.65	195.65–<217.39	217.39–<230.43	230.43–<246.83	246.83	This study
Education (%)	A2	<20	20–<40	40–<60	60–<80	80	[21]
Health (%)	A3	<20	20–<40	40–<60	60–<80	80	This study
Mangrove (%)	A4	<7.67	7.67–15.35	>15.35–23.02	>23.02–30.70	>30.70	This study
Environmental incident response	A5	No plan	Have a plan but no exercises or assumptions	Infrequent exercises or assumptions	Exercises or assumptions >1 time/year	Organising	[56]

https://doi.org/10.35762/AER.2023002

Results and discussion

1) Establish criteria set, criterion weights, and component factor weights

Based on the collected data and Eq. 1, Eq. 2, and Eq. 3, the sub-criteria weights; assessment values of the preliminary criteria for each sub-criterion; selected suitable criteria; optimal weighting of each criterion of the set of criteria, namely, hazard, sensitivity, and adaptability; and the weights of each factor constituting the assessment of environmental incidents were calculated and are shown in Tables 2–4.

Table 2 Evaluation values of each criteria

Sets of criteria	Values for each sub-criterion					Total values
	Ease of understanding	Alignment with the goal	Accuracy and transparency	Sensitivity	Data availability	
Hazard [61]	0.15*	0.26*	0.25*	0.22*	0.12*	
H1	0.54	1.06	1.03	0.80	0.48	3.91
H2	0.63	1.12	1.03	0.88	0.42	4.08
H3	0.58	0.98	1.05	0.70	0.49	3.79
H4	0.54	1.19	0.94	0.93	0.41	4.01
H5	0.54	1.15	1.03	0.70	0.45	3.87
H6	0.47	1.09	0.82	0.78	0.39	3.55
Sensitivity [62]	0.17*	0.28*	0.16*	0.21*	0.18*	
S1	0.57	1.19	0.61	0.67	0.65	3.65
S2	0.58	1.10	0.66	0.66	0.72	3.69
S3	0.75	1.09	0.72	0.82	0.87	4.20
S4	0.58	1.27	0.56	0.80	0.69	3.86
S5	0.60	1.10	0.60	0.80	0.69	3.76
S6	0.58	1.29	0.58	0.97	0.67	4.05
S7	0.51	1.19	0.44	0.92	0.48	3.50
S8	0.61	1.17	0.63	1.06	0.75	4.18
Adaptability	0.13*	0.24*	0.19*	0.14*	0.30*	
A1	0.47	0.99	0.66	0.49	0.92	3.53
A2	0.54	0.92	0.76	0.45	1.18	3.84
A3	0.54	0.88	0.77	0.50	1.27	3.97
A4	0.50	1.00	0.74	0.62	1.32	4.19
A5	0.47	0.93	0.70	0.60	1.22	3.92

Note: * are the weights of the five sub-criteria that were determined from expert consultation and the AHP method (i.e., ease of understanding; alignment with the goal; accuracy and transparency; sensitivity; and data availability) used to screen the preliminary criteria of each factor (i.e., hazard; sensitivity; and adaptability).

Table 3 Selected criteria

Criteria	Description	References
Hazard		
H1	The greater the number of hazardous chemicals stored, the higher the probability of an environmental incident.	[51]
H2	The larger the volume of chemicals stored at a time compared to the threshold, the higher the probability of an environmental incident.	[44]
H3	The more secure the hazardous chemical storage facility (i.e., dam), the lower the probability of an environmental incident.	[34]
H4	The location of potentially hazardous chemical spills affecting coastal areas.	[37]
H5	The higher the responsibility of the subject that uses hazardous chemicals to prevent environmental incidents, the lower the risk of an environmental incident.	[51]
H6	The higher the capacity of the subject that uses hazardous chemicals to respond to chemical spills, the lower the risk of an environmental incident.	[51]
Sensitivity		
S1	Areas with many cliffs are less sensitive than those with wetlands and sandy beaches.	[63]
S2	The larger the slope, the lower the sensitivity.	[63]
S3	The lower the population density, the lower the sensitivity.	[64]
S4	The lower the proportion of the population over 65 and under 12 years of age compared to the total population of the region, the lower the sensitivity.	[21]
S5	The more types of tourism, the higher the sensitivity.	[57]
S6	The smaller the aquaculture area, the lower the sensitivity.	[57]
S7	Areas without rare and endangered species are less sensitive than areas with priority species that require protection.	[59]
S8	The lower the priority level of protection and conservation of coastal areas, the lower the sensitivity.	[58]

Table 3 Selected criteria (*continued*)

Criteria	Description	References
Exposure	Potential environmental incident exposures are classified based on the subregion with the highest exposure.	[60]
Adaptability		
A1	The higher the per capita income, the greater the adaptability.	[65]
A2	The higher the proportion of people with universal education, the greater the adaptability.	[65]
A3	The larger the proportion of the healthcare workers in the workforce, the higher the adaptability, based on the subregion with the highest health number of healthcare workers.	[66]
A4	The larger the mangrove area, the higher the adaptability.	[66]
A5	The greater the resources for responding to environmental incidents, the higher the adaptability.	[66]

Table 4 The optimal weights of the criteria, factors, and their range

Criteria	Optimal weights of the criteria and their range		
	W_{min}	W_i	W_{max}
Hazard [61]			
H1	0.13	0.14	0.14
H2	0.45	0.46	0.47
H3	0.14	0.14	0.14
H4	0.14	0.14	0.14
H5	0.08	0.08	0.09
H6	0.04	0.04	0.04
Sensitivity			
S1	0.05	0.05	0.06
S2	0.05	0.07	0.07
S3	0.25	0.25	0.27
S4	0.14	0.19	0.18
S5	0.05	0.05	0.06
S6	0.14	0.14	0.14
S7	0.04	0.04	0.05
S8	0.22	0.22	0.23
Adaptability			
A1	0.14	0.15	0.15
A2	0.06	0.07	0.07
A3	0.18	0.19	0.19
A4	0.32	0.34	0.34
A5	0.25	0.25	0.27
Factors			
Hazard	-	0.22	-
Exposure	-	0.33	-
Vulnerability	-	0.45	-

2) Evaluation and mapping

The hazard values of the 15 subjects (15/65 chemical spill hazards were selected with GNR >1, based on Eq.8), which were using hazardous chemicals in the study area, were determined as being from 1.96 to 4.02 [61]. The subjects with 'high' and 'very high' values (i.e., stored large volumes of many hazardous chemicals at a time and were operating in locations near the sea) accounted for 46.67% of all the subjects.

The vulnerability level was calculated as 2.08–2.67, in which the sensitivity value was 1.98–3.25 and adaptability 2.28–3.49, and was classified into four levels (Figure 4). The subregions with 'high' and 'extreme' vulnerability accounted for 62.96% of all the subregions. These were identified as the most sensitive subregions due to the high population density, developed tourism and presence of species that need priority protection. The subregions with low adaptability due to low-income communities and mangroves have largely been transformed for development projects.

The simulation scenario assumes the spill of 50% volume of the chemical stored (17.8 tons of isopentane C_5H_{12}) in 72 hours for subjects that use hazardous chemicals belonging to the group with very high hazard values, operating in the production and consumption of basic chemicals and petrochemical products. The results of the simulations showed that the exposure levels for the subregions were significantly changed due to the seasonal hydrological regime (Figure 4). In the dry season, the exposure was mainly localised with a slight spread to the sea. Exposure levels of 18.52% in the subregions were considered 'high' and 'extreme' levels, and 55.56% in the subregions were not indicated. In the rainy season, the exposure range was more expansive: the 'high' and 'extreme' exposure subregions accounted for 25.93%, and only 40.74% of the subregions showed no signs of exposure.

https://doi.org/10.35762/AER.2023002

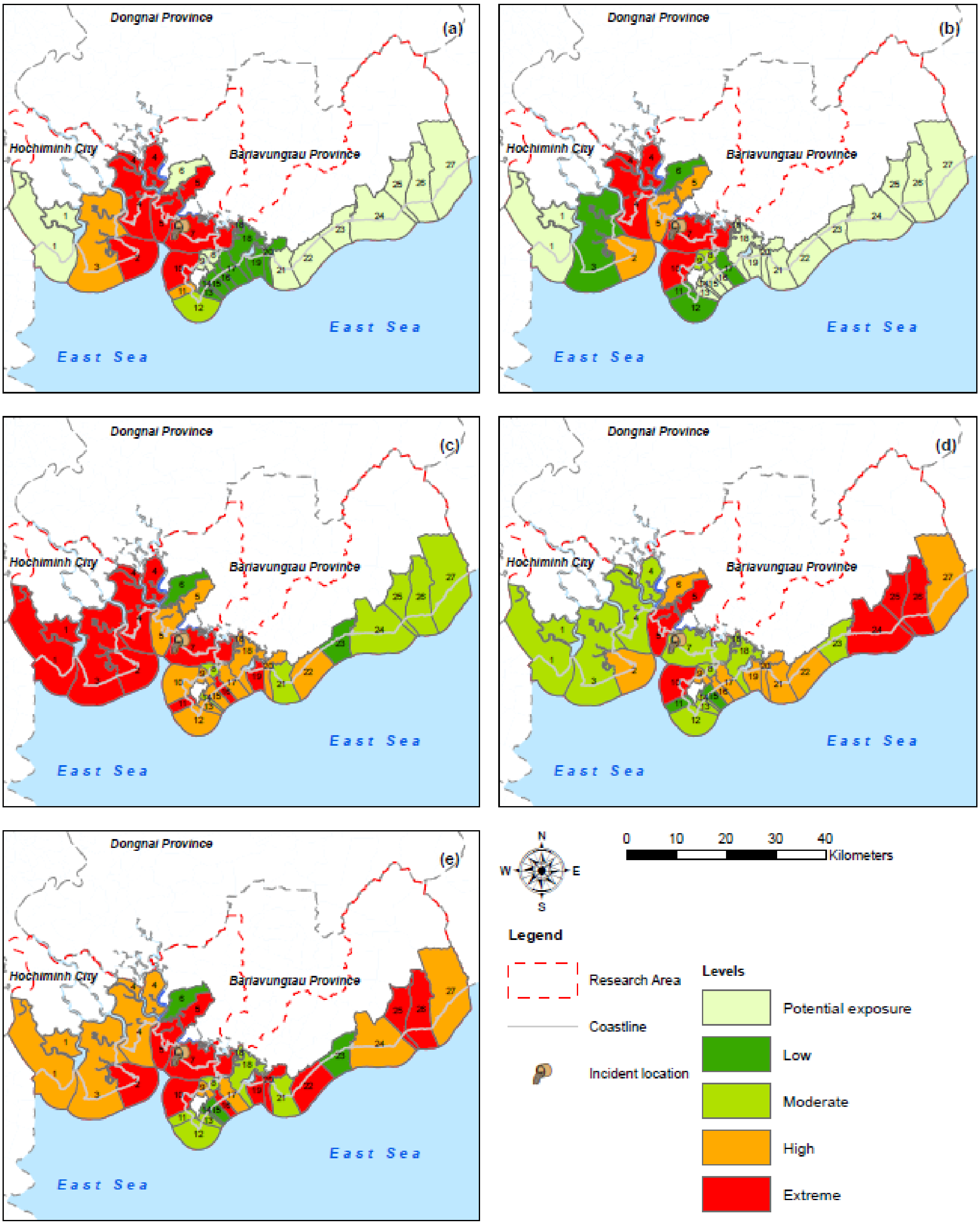

Figure 4 Map in the southeastern coastal area of (a) exposure in the rainy season, (b) exposure in the dry season, (c) sensitivity, (d) adaptability, and (e) vulnerability.

Based on the simulation scenario and Eq. 7, the environmental incident level of each subregion was calculated, as shown in Table 5. The environmental incident level was 2.15–3.70 for the dry season and 2.15–3.73 for the rainy season and was classified into four ranks from 1 to 4, which corresponded with the environmental incident levels: low, moderate, high, and extreme. The classification results for each subregion were used to map the environmental incident levels (Figure 5). Following the calculations and mapping, the results showed:

(1) The 'high' and 'extreme' environmental incident subregions increased from the dry season to the rainy season from 5/27 (18.52%) to 7/27 (25.93%), respectively. This increase was mainly due to the seasonal change in the coastal hydrological regime, which led to a variable exposure range. During the rainy season, the exposure range was wider, which resulted in a more significant number of exposed subregions.

(2) The 'high' and 'extreme' environmental incident subregions had the potential for high exposure due to their proximity to environmental incident hazard sources. However, these subregions were also vulnerable due to their high sensitivity (i.e., the vulnerable population and aquaculture criteria values of these subregions were higher than the mean values of 24.42% and 38.46%, respectively) but low adaptability (i.e., the income, education, health, and environmental incident response criteria values of these subregions were lower than the mean values of 17.80%, 6.79%, 32.18%, and 8.35%, respectively).

(3) The 'low' and 'moderate' environmental incident subregions had low exposure or no signs of exposure based on the simulated scenario. These subregions had lower vulnerability than the other subregions due to their low sensitivity and high adaptability.

(4) The environmental incident map was limited to a particular spatial extent. Accordingly, some of the criteria related to sensitivity, adaptability and vulnerability (e.g., species and environmental incident response) across the adjacent subregions were not identified with high confidence. In addition, the actual process of collecting expert data did not include the participation of ecological and social experts.

3) Solutions to reduce environmental incidents in coastal areas

Based on the calculation results and consultation with managers in the study area, we propose pertinent and practical solutions to reduce the environmental incident levels in 'high' and 'extreme' subregions:

(1) Minimise the risk of incidents: It is necessary to review and adjust the maximum storage volume of hazardous chemicals permitted at a time by following the operating conditions of each chemical spill hazard. At the same time, periodic inspections should be strengthened, subjects that use hazardous chemicals should be required to comply with the restrictions outlined in an approved chemical spill response plan [51] regarding the highest volume of stored chemicals permissible at a time, and a permit should be issued by the competent authority.

(2) Reduce vulnerability: Resilience should be increased through increased investment in health facilities, the attraction of local resources combined with professional training for livelihood generation, and the creation of jobs to provide workers with stable incomes [67]. In addition, it is necessary to review and adjust spatial planning appropriately to ensure a sustainable population density, decrease the proportion of vulnerable populations, and reduce the area of unsustainable aquaculture in given areas, which will contribute to reducing sensitivity in subregions. And not only that, it is necessary to zone the environment protection [68] (i.e., strict protection zone, emission restricted zone, and others [67]) based on the results of adaptability and sensitivity analysis. Finally, strengthen control of chemical hazards, and restore and protect coastal mangrove resources for environmental protection zones.

(3) Limit potential exposure: This requires increased investment in incident response equipment [69–70] and regulatory annual incident response exercises [51], which will contribute to reducing exposure during a chemical spill. In addition, it is necessary to review chemical hazards under the development planning [67] and the environmental protection law [70], which focuses on controlling hazardous sources discharged into the coastal environment, developing in parallel with pollution prevention and control.

Table 5 Calculation results of environmental incidents

Subregion	Environmental incident value		Subregion	Environmental incident value	
	Dry season	Rainy season		Dry season	Rainy season
LyNhon Village	2.32	2.32	NguyenAnNinh Ward	2.16	2.16
CanThanh Village	3.07	3.73	Ward 10	2.39	2.39
LongHoa Village	2.34	3.00	Ward 11	2.33	2.33
ThanhAn Village	3.31	3.64	Ward 12	2.26	2.26
PhuocHoa Ward	3.07	3.40	PhuocTinh Village	2.41	2.41
TanPhuoc Ward	2.19	2.19	PhuocHung Village	2.37	2.37
LongSon Village	3.70	3.70	LongHai Village	2.28	2.28
RachDua Ward	2.58	2.25	PhuocHai Village	2.40	2.40
ThangNhat Ward	2.66	2.33	LocAn Village	2.15	2.15
Ward 5	3.69	3.69	PhuocThuan Village	2.33	2.33
Ward 1	2.27	2.93	BongTrang Village	2.39	2.39
Ward 2	2.26	2.59	BungRieng Village	2.37	2.37
ThangTam Ward	2.26	2.26	BinhChau Village	2.30	2.30
Ward 8	2.21	2.21			

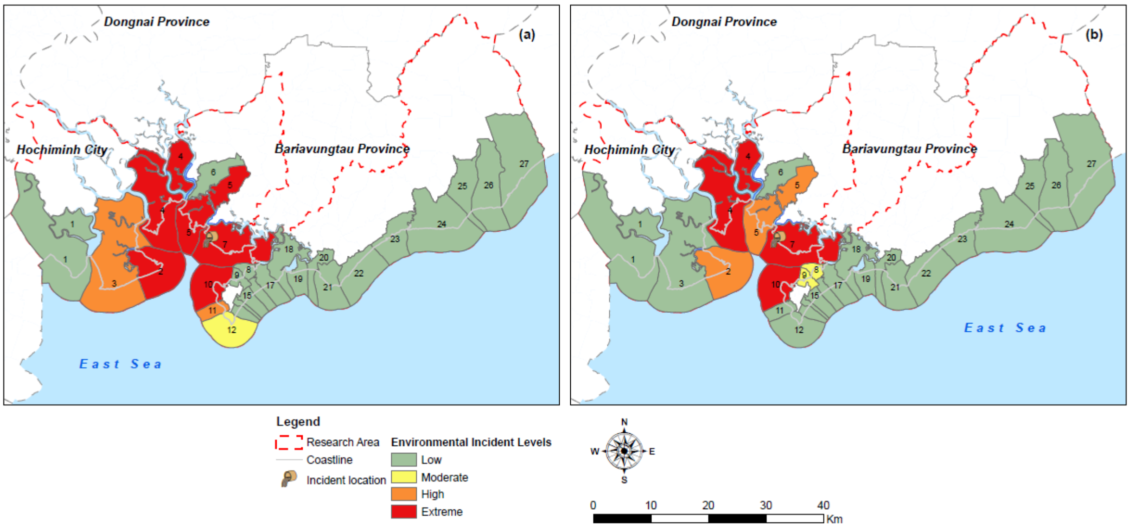

Figure 5 Environmental incident level map of (a) the rainy season and (b) the dry season.

Conclusions

In this study, a framework for assessing environmental incidents in coastal areas due to chemical spills from the mainland was developed by integrating hazard, exposure and vulnerability factors, where vulnerability was formed from sensitivity and adaptability. In addition to a comprehensive evaluation framework, appropriate assessment criteria, the optimal weighting of each criterion, as well as component factors were proposed. The southeastern coastal area in Vietnam was then used in the pilot study to analyse and evaluate environmental incidents caused by chemical spills. The environmental incident levels of 27 subregions in the study area were identified and categorised into four levels, namely, low, medium, high, and extreme, for the rainy season (prevalence: 70.37%, 3.70%, 7.41%, and 18.52%, respectively) and the dry season (prevalence: 74.07%, 7.41%, 7.41%, and 11.11%, respectively). In the subregions, the 'high' and 'extreme' environmental incident levels accounted for 18.52% and 25.93%, respectively, in the dry and rainy seasons, thus demonstrating their high sensitivity, low adaptability, and closeness to incident sources. An assessment and analysis were then carried out and strategies proposed to minimise the impact of environmental incidents. Our study makes an essential contribution to perfecting the framework of methods used to assess environmental incidents in coastal areas with a focus on hazards from the mainland, thus ultimately contributing to the sustainable development of coastal areas.

Acknowledgment

We received financial support for this study from Vietnam National University Ho Chi Minh City under grant number C2021-24-25. The authors would like to thank the Institute for Environment and Resources for their support and for creating favourable conditions for us to complete this study.

Conflicts of interest

The authors hereby declare that they have no conflicts of interest in relation to the publication of this article.

References

[1] Chakraborty, S., Majumdar, D., Sahoo, S., Saha, S. Assessment of future coastal risk zones along the Andaman coast to strengthen sustainable development. Environmental Earth Sciences, 2021, 80(18), 1–27.

[2] Islam, M., Amir, A.A., Begum, R.A. Community awareness towards coastal hazard and adaptation strategies in Pahang Coast of Malaysia. Natural Hazards, 2021, 107(2), 1593–1620.

[3] Pourkerman, M., Marriner, N., Hamzeh, M.-A., Lahijani, H., Morhange, C., Amjadi, S., ..., Afarin, M. Socioeconomic impacts of environmental risks in the western Makran zone (Chabahar, Iran). Natural Hazards, 2022, 112(2), 1823–1849.

[4] Singh, S., Bhat, J.A., Shah, S., Pala, N.A. Coastal resource management and tourism development in Fiji Islands: a conservation challenge. Environment, Development and Sustainability, 2021, 23(3), 3009–3027.

[5] Hietala, R., Ijäs, A., Pikner, T., Kull, A., Printsmann, A., Kuusik, M., ..., Kostamo, K. Data integration and participatory process in developing integrated coastal zone management (ICZM) in the northern Baltic Sea. Journal of Coastal Conservation, 2021, 25(5), 1–15.

[6] Rustadi, Setiawan, A., Darmawan, I.G.B., Haerudin, N. Identification of saline water intrusion using integrated geoelectrical method in the coastal aquifer of Holo-Quaternary Formation, Lampung Bay. Applied Environmental Research, 2022, 44(3), 76–87.

[7] Mohd, F.A., Maulud, K.N.A., Karim, O.A., Begum, R.A., Awang, N.A., Ahmad, A., ..., Mohtar, W.H.M.W. Comprehensive coastal vulnerability assessment and adaptation for Cherating-Pekan coast, Pahang, Malaysia. Ocean Coastal Management, 2019, 182, 104948.

[8] Ministry of Natural Resources and Environment. Report on the nationnal environmental current state of marine and island for the period 2016-2020 (Overview). 2021.

[9] Nguyen, H.P., Pham, H.T. The dark side of development in Vietnam: Lessons from the killing of the Thi Vai River. Journal of Macromarketing, 2012, 32(1), 74–86.

[10] Institute for Environment and Resources. Report on assessment of causes of mass death of cage-raised fish on Cha Va River. 2015.

[11] Huang, X., Gong, J., Chen, P., Tian, Y., Hu, X. Towards the adaptability of coastal resilience: Vulnerability analysis of underground gas pipe-line system after hurricanes using LiDAR data. Ocean and Coastal Management 2021, 209, 105694.

[12] Tian, H., Lindenmayer, D.B., Wong, G.T., Mao, Z., Huang, Y., Xue, X. A methodological framework for coastal development assessment: A case study of Fujian Province, China. Science of the Total Environment, 2018, 615, 572–580.

[13] Wiens, J.A., Parker, K.R. Analyzing the effects of accidental environmental impacts: Approaches and assumptions. Ecological Applications, 1995, 5(4), 1069–1083.

[14] Xu, S., Zhai, Y., Wang, J., Teng, Y., Jia, S. Characteristics of environmental incidents and environmental risk management in China. 2012 International Conference on Biomedical Engineering and Biotechnology, Macau, 28-30 May IEEE, 2012, 1255–1259.

[15] Intergovernmental Panel on Climate Change. 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, 1–32.

[16] Intergovernmental Panel on Climate Change. Managing the risks of extreme events and disasters to advance climate change adaptation. Cambridge University Press, 2012.

[17] Lar, N.M., Pumijumnong, N., Roachanakanan, R., Arunrat, N., and Tint, S. An assessment of climate variability on farmers' livelihoods vulnerability in Ayeyarwady Delta of Myanmar. Applied Environmental Research, 2018, 40(1), 1–12.

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

[19] Wang, G., Liu, Y., Wang, H., Wang, X. A comprehensive risk analysis of coastal zones in China. Estuarine, Coastal and Shelf Science, 2014, 140, 22–31.

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

[21] Zhang, Y., Ruckelshaus, M., Arkema, K.K., Han, B., Lu, F., Zheng, H., Ouyang, Z. Synthetic vulnerability assessment to inform climate-change adaptation along an urbanized coast of Shenzhen, China. Journal of environmental management, 2020, 255, 109915.

[22] Mucerino, L., Albarella, M., Carpi, L., Besio, G., Benedetti, A., Corradi, N., ..., Ferrari, M. Coastal exposure assessment on Bonassola bay. Ocean and Coastal Management, 2019, 167, 20–31.

[23] Fu, X. and Peng, Z.-R. Assessing the sea-level rise vulnerability in coastal communities: A case study in the Tampa Bay Region, US. Cities, 2018, 88, 144–154.

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

[25] Ding, G., Xin, L., Guo, Q., Wei, Y., Li, M., Liu, X. Environmental risk assessment approaches for industry park and their applications. Resources, Conservation & Recycling, 2020, 159, 104844.

[26] Jia, P., Wang, Q., Lu, X., Zhang, B., Li, C., Li, S., ..., Wang, Y. Simulation of the effect of an oil refining project on the water environment using the MIKE 21 model. Physics Chemistry of the Earth, Parts A/B/C, 2017, 103, 91–100.

[27] Guo, G., Cheng, G. Mathematical modelling and application for simulation of water pollution accidents. Process Safety and Environmental Protection, 2019, 127, 189-196.

[28] Kankara, R., Arockiaraj, S., Prabhu, K. Environmental sensitivity mapping and risk assessment for oil spill along the Chennai Coast in India. Marine Pollution Bulletin, 2016, 106 (1–2), 95–103.

[29] Cao, G., Gao, Y., Wang, J., Zhou, X., Bi, J., Ma, Z. Spatially resolved risk assessment of environmental incidents in China. Journal of Cleaner Production, 2019, 219, 856-864.

[30] Yu, F., Xue, S., Zhao, Y., Chen, G. Risk assessment of oil spills in the Chinese Bohai Sea for prevention and readiness. Marine Pollution Bulletin, 2018, 135, 915–922.

[31] Hagenlocher, M., Renaud, F.G., Haas, S., Sebesvari, Z. Vulnerability and risk of deltaic social-ecological systems exposed to multiple hazards. Science of the Total Environment, 2018, 631, 71–80.

[32] Sardi, S.S., Qurban, M.A., Li, W., Kadinjappalli, K.P., Manikandan, P.K., Hariri, M.M., ..., El-Askary, H. 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, 2020, 150, 110588.

[33] Zhao, K., Quan, D., Yang, D., Yang, J., Lin, K. A system for identifying and analyzing environmental accident risk sources. Procedia Environmental Sciences, 2010, 2, 1413–1421.

[34] Liu, R., Zhang, K., Zhang, Z., Borthwick, A.G. Watershed-scale environmental risk assessment of accidental water pollution: The case of Laoguan River, China. Journal of environmental informatics, 2018, 31, 87–96.

[35] Amendola, A., Contini, S. A Methodology for risk analysis of industrial areas: The Aripar case study. Industrial Safety Series, 1998, 6.

[36] Liu, R., Borthwick, A.G., Lan, D., Zeng, W. Environmental risk mapping of accidental pollution and its zonal prevention in a city. Process Safety and Environmental Protection, 2013, 91(5), 397–404.

[37] Dong, L., Liu, J., Du, X., Dai, C., Liu, R. Simulation-based risk analysis of water pollution accidents combining multistressors and multi-receptors in a coastal watershed. Ecological Indicators, 2018, 92, 161–170.

[38] Alvarez, P.A., Ishizaka, A., Martinez, L. Multiple-criteria decision-making sorting methods: A survey. Expert Systems With Applications, 2021, 183, 115368.

[39] Mardani, A., Jusoh, A., Nor, K., Khalifah, Z., Zakwan, N., Valipour, A. Multiple criteria decision-making techniques and their applications – A review of the literature from 2000 to 2014. Economic Research-Ekonomska Istra ivanja, 2015, 28(1), 516–571.

[40] Al Shami, A., Harik, G., Alameddine, I., Bruschi, D., Garcia, D.A., El-Fadel, M. Risk assessment of oil spills along the Mediterranean coast: A sensitivity analysis of the choice of hazard quantification. Science of the Total Environment, 2017, 574, 234–245.

[41] Monteiro, C.B., Oleinik, P.H., Leal, T.F., Marques, W.C., Nicolodi, J.L., Lopes, B.d.C.F.L. Integrated environmental vulnerability to oil spills in sensitive areas. Environmental Pollution, 2020, 267, 115238.

[42] Gymez, A.G., Ondiviela, B., Puente, A., Juanes, J.A. Environmental risk assessment of water quality in harbor areas: A new methodology applied to European ports. Journal of Environmental Management, 2015, 155, 77–88.

[43] Neuparth, T., Moreira, S., Santos, M., Reis-Henriques, M. Hazardous and noxious substances (HNS) in the marine environment: Prioritizing HNS that pose major risk in a European context. Marine Pollution Bulletin, 2011, 62(1), 21–28.

[44] Peng, J., Song, Y., Yuan, P., Xiao, S., Han, L. An novel identification method of the environmental risk sources for surface water pollution accidents in chemical industrial parks. Journal of Environmental sciences, 2013, 25(7), 1441–1449.

[45] Saaty, T.L. How to make a decision: the analytic hierarchy process. European journal of operational research, 1990, 48(1), 9–26.

[46] Afshari, A., Mojahed, M., Yusuff, R.M. Simple additive weighting approach to personnel selection problem. International journal of innovation, management technology, 2010, 1(5), 511.

[47] Safarzadeh, S., Khansefid, S., Rasti-Barzoki, M. A group multi-criteria decision-making based on best-worst method. Computers & Industrial Engineering, 2018, 126, 111–121.

[48] Rezaei, J. Best-worst multi-criteria decision-making method: Some properties and a linear model. Omega, 2015, 64, 126–130.

[49] Paliwal, R., Patra, R.R. Applicability of MIKE 21 to assess temporal and spatial variation in water

quality of an estuary under the impact of effluent from an industrial estate. Water Science & Technology, 2011, 63(9), 1932–1943.
[50] DHI. MIKE 21 flow model FM. 2014.
[51] Government. Decree No. 113/2017/ND-CP specifying and providing guidelines for implementation of certain articles of the Law on Chemicals. Hanoi-Vietnam, 2017.
[52] Chaib, W., Guerfi, M., Hemdane, Y. Evaluation of coastal vulnerability and exposure to erosion and submersion risks in Bou Ismail Bay (Algeria) using the coastal risk index (CRI). Arabian Journal of Geosciences, 2020, 13(11), 1–18.
[53] Dhiman, R., Kalbar, P., Inamdar, A.B. GIS coupled multiple criteria decision making approach for classifying urban coastal areas in India. Habitat International, 2018, 71, 125–134.
[54] Thieler, E.R., ES, H.K. National assessment of coastal vulnerability to future sea-level rise: Preliminary results for the US Atlantic Coast. US Geological Survey, Open-File Report, 1999, 99–593.
[55] Ministry of Natural resources and Environment. Circular No. 29/2016/TT-BTNMT on technical regulations for the establishment of coastal protection corridors. Hanoi-Vietnam, 2016.
[56] Government. Decision No. 26/2016/QD-TTg the Regulation on response to hazardous chemical incidents. Hanoi-Vietnam, 2016.
[57] Ministry of Natural Resources and Environment. Regulations on the process of overcoming consequences of oil spill incidents at sea. 2018, No. 33/2018/TT-BTNMT.
[58] National Assembly. Law on Biodiversity No. 20/2008/QH12. Hanoi-Vietnam, 2008.
[59] Cai, L., Yan, L., Ni, J., Wang, C. Assessment of ecological vulnerability under oil spill stress. Sustainability, 2015, 7(10), 13073–13084.
[60] Bagdanavi iūtė, I., Kelp aitė, L., Soomere, T. Multi-criteria evaluation approach to coastal vulnerability index development in micro-tidal low-lying areas. Ocean Coastal Management, 2015, 104, 124–135.
[61] Cuong, L.T., Phuoc, N.V., Quan, N.H., Huyen, D.T.T., Loan, T.T.D. Hazard analysis of environmental incidents in coastal areas: A case study in the Southeastern Coastal Region of Vietnam. [In press], 2022, Vietnam National University of Ho Chi Minh City, Vietnam.
[62] Cuong, L.T., Phuoc, N.V., Quan, N.H., Huyen, D.T.T., Minh, T.T. Environmental sensitivity of coastal areas to the water environmental incidents: A case study in the Southeastern Coastal Region of Vietnam. [Manuscript submitted for publication], 2022, Vietnam National University of Ho Chi Minh City, Vietnam.
[63] Peterson, J., Michel, J., Zengel, S., White, M., Lord, C., Plank, C. Environmental sensitivity index guidelines: Version 3.0. NOAA technical memorandum NOS-OR&R 11, 2002.
[64] Mavromatidi, A., Briche, E., Claeys, C. Mapping and analyzing socio-environmental vulnerability to coastal hazards induced by climate change: An application to coastal Mediterranean cities in France. Cities, 2018, 72, 189–200.
[65] Lins-de-Barros, F.M. Integrated coastal vulnerability assessment: A methodology for coastal cities management integrating socioeconomic, physical and environmental dimensions - Case study of Regiro dos Lagos, Rio de Janeiro, Brazil. Ocean & Coastal Management, 2017, 149, 1–11.
[66] Nguyen, K.-A., Liou, Y.-A., Terry, J.P. Vulnerability of Vietnam to typhoons: A spatial assessment based on hazards, exposure and adaptive capacity. Science of the Total Environment, 2019, 682, 31–46.
[67] People's Committee. The planning for Bariavungtau Province in the 2021–2030 period, with a vision to 2050. Bariavungtau Province-Vietnam, 2021.
[68] Government. Decree No. 08/2022/ND-CP detailing a number of articles of the Law on Environmental Protection. Hanoi-Vietnam, 2022.
[69] National Assembly. Law on Chemicals No. 6/2007/QH12. Hanoi-Vietnam, 2007.
[70] National Assembly. Law on Environmental Protection No. 72/2020/QH14. Hanoi-Vietnam, 2020.