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Spatial Differentiation Assessment of the Vulnerability of Marine Protected Areas to Oil Spill Stress in the Bohai Sea

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Abstract: Marine protected areas (MPAs) are pivotal in safeguarding and preserving global ocean ecosystems. However, oil spills exert both discernible and evident impacts on marine ecosystems and the biodiversity of MPAs. In this research, an environmental model for assessing vulnerability to oil spills was constructed, which amalgamates diverse indicators pertaining to pressure, state, and response capabilities into a unified index. This integration was achieved through the utilization of a geographic information system (GIS) and the analytic hierarchy process (AHP). For clarity, the Bohai Sea was segmented into seven distinct response zones. The study's results underscore the substantial spatial disparities in vulnerability when these zones are exposed to oil spills. Notably, zone 6 displayed markedly heightened vulnerability compared to the other zones, while MPAs exhibiting relatively low to extremely low vulnerabilities were primarily situated in the northern sector of zone 7 and across zone 5. This study employed a quantitative vulnerability analysis to offer valuable perspectives on the repercussions of oil spill incidents on MPAs. This emphasizes the necessity of enhancing adaptability to minimize vulnerability, benefiting MPA stakeholders susceptible to the risks associated with oil spills.

Keywords: marine protected areas; oil spills; vulnerability assessment; geographic information system; analytic hierarchy process method

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1. Introduction

Marine protected areas (MPAs) refer to defined geographical regions within the marine environment that are primarily administered in ways that aim to conserve biodiversity. MPAs play a crucial role in preserving the health and biodiversity of marine ecosystems and human well-being worldwide [1]. The global number of officially designated MPAs is growing rapidly and exponentially; currently, up to 8.16% of the global oceans are MPAs (https://www.protectedplanet.net/en, accessed on 6 July 2023).

Marine oil spill incidents are often referred to as marine killers due to their prolonged duration, extensive geographic coverage, and significant adverse effects on the environment [2], in addition to posing a serious threat to the ecological integrity and functionality of MPAs [3]. Marine oil spills generally come from ships, oil production platforms, oil pipelines, and coastal oil storage tanks [4]. For ship oil spills, according to International Tanker Owners Pollution Federation Limited (ITOPF), from 2010 to 2019, the world experienced an average of 1.8 large oil spills (>700 tons) from tanker incidents annually. In 2022 alone, there were three recorded large spills (>700 tons) and four medium spills (7–700 tons). The amount of oil spilled has decreased significantly compared to the last century [5]. If oil spills from platforms and pipelines are also included, the damage would be even more severe.

China has about 18,000 km of continental coastline, and the damage caused by marine oil spills to China's MPAs should not be overlooked. Since 2010, oil spill accidents in China have included the Dalian pipeline spill (16 July 2010), the Penglai 19-3 platform spill (2011), and the Sanchi tanker spill (6 January 2018). As an example, the Penglai 19-3 oil spill occurred at the Penglai 19-3 production platform in the Bohai Sea on 4 June 2011, and leaked pollution into the sea area surrounding the oil field and the region to the northwest. This area spanned approximately 6200 km^2, of which 870 km^2 were severely affected by the pollution. The spill caused significant damage to the marine ecosystem, and the detrimental effects persist to this day [6,7]. Such oil spill threats can have profound impacts on the ecological environment, biodiversity, and MPAs in the region. Hence, in recent years, efforts have been made to enhance the establishment and management of marine protected areas in China, aiming to safeguard its unique marine ecosystems and abundant biodiversity. Nevertheless, with increasing energy demands and human activities, the potential risk of oil spill incidents in the Bohai Sea still threatens the safety of MPAs.

Vulnerability assessment is a crucial preparatory step in reducing the negative consequences and associated risks of disasters [8]. It serves as a foundation for allocating management resources toward preparation, response, and recovery endeavors [9]. Therefore, it is crucial to assess the vulnerability of MPAs to the impacts of oil spill incidents. Such an assessment will help identify and understand the potential risks posed by oil spill incidents to these MPAs, providing a scientific basis for effective protection and management strategies.

In this study, a model for vulnerability assessment of MPAs was developed, which integrated the pressure, state, and response. The aim was to identify and analyze the spatial differentiation of the vulnerability in different MPAs in the Bohai Sea. Through assessment of the vulnerability, the results of this study provide essential insights for governments, environmental agencies, and relevant stakeholders to promote effective marine protection and risk management strategies, ensuring sustainable development and ecological security. The results of this assessment aim to provide objective and scientific decision-making recommendations for preventing and mitigating the impacts of oil spills on MPAs.

2. Materials and Methods

2.1. Research Location

The area examined in this study encompasses the Bohai Sea (117.5–122.5° E, 37–41° N) and is characterized as a semi-enclosed shallow sea, boasting a diverse range of marine life and exhibits abundant biodiversity. The sea area is densely populated with pipelines for oil transportation, tanks for oil storage, platforms for oil exploitation, and shipping routes. As of 2012, the Bohai Sea housed 27 offshore oil and gas fields, including 1669 oil production wells and 217 offshore oil production platforms [2]. These spill risks resulted in an increased frequency of oil spill incidents, such as the Dalian oil pipeline explosion in 2010 and the Penglai 19-3 platform spill in 2011, which has been mentioned above. Due to its shallow water and enclosed C-shaped structure, oil spill accidents can inflict significant damage on the coastal environment. Consequently, the Bohai Sea is highly sensitive to oil spill stress.

Geographically, the Bohai Sea is encircled by four province-level administrative regions: Shandong Province, Tianjin Municipality, Hebei Province, and Liaoning Province. It encompasses three major bays, namely, Laizhou Bay, Liaodong Bay, and Bohai Bay. According to previous studies, there are MPAs with an area of up to 9210.7 km^2 in the Bohai Sea [10,11]. To facilitate rapid response to spill accidents, the Maritime Safety Administration (MSA) divided the Bohai Sea into seven response zones. To simplify the description, these zones are denoted as zones 1–7. The details of this area are presented in Figure 1.

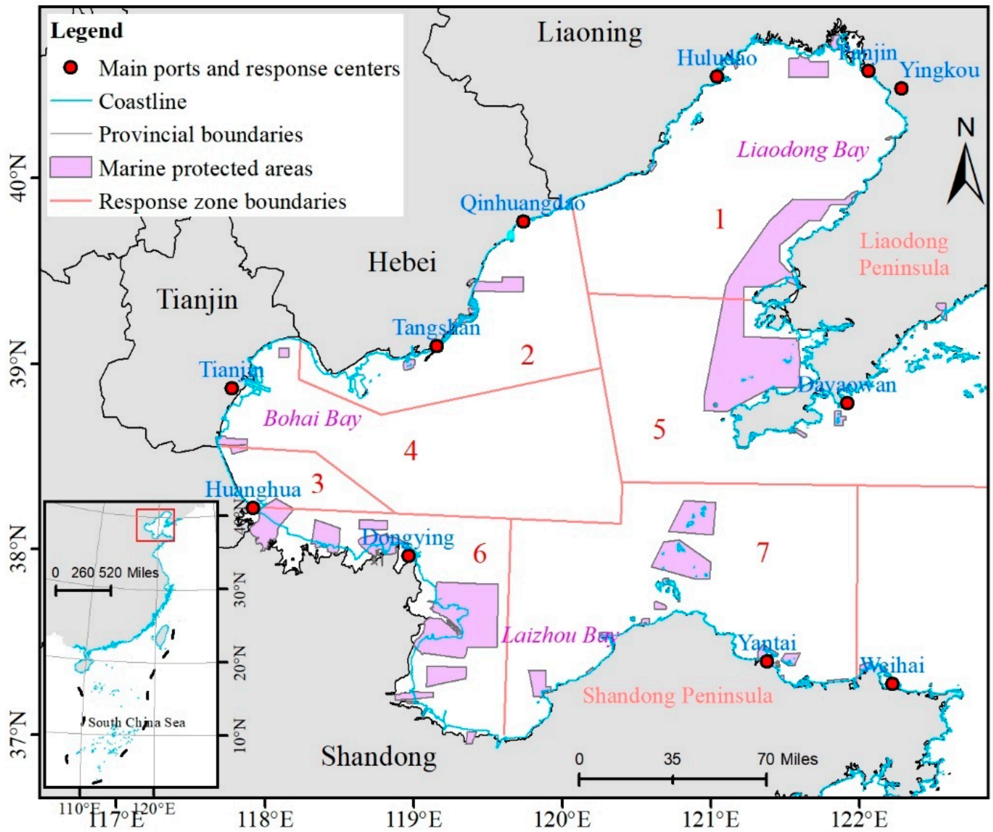

Figure 1. Location of the Bohai Sea.

2.2. Assessment Framework

The pressure-state-response (PSR) framework was initially proposed by the Organization for Economic Co-operation in the 1980s as a means to analyze environmental issues [12,13], serving as a tool to elucidate the interactions among various factors. This framework encompasses three key aspects that illustrate the ongoing feedback loop between humans and the environment: pressure (P), state (S), and response (R). By adopting this framework, a systematic approach is established to select appropriate indicators within each dimension, thereby facilitating the development of a comprehensive index system for evaluating the vulnerability of MPAs.

2.3. Assessment Indicators

Utilizing the PSR vulnerability assessment framework, in this study, we systematically decomposed the vulnerability assessment indicators for MPAs under the stress of oil spills into the pressure, state, and response. Specifically, (1) the pressure on the MPAs was manifested through various sources of oil spill risk, which are concentrated in the Bohai Sea, significantly amplifying the pressure on MPAs. To represent the sources of the oil spill risk, the following elements were chosen: oil storage tanks situated in ports, oil pipelines, offshore platforms for oil production, ships, and shipping channels. (2) The state of the MPAs was reflected by the environment in which these MPAs are situated. (3) The oil spill response capability of the MPAs was illustrated by evaluating the quantity of the corresponding oil spill response equipment stored in harbors. The details of the indices are described in Tables 1–3.

Table 1. Pressure indices (modified from [4]).

Label	Indicators	Explanation
P_1	Storage tanks	The spatial locations were derived through vectorization techniques applied to Gaofen-2 satellite images.
P_2	Pipelines	The spatial locations were digitized and derived from open-source, interactive maps that display China's energy infrastructure (https://www.bakerinstitute.org/chinas-energy-infrastructure, accessed on 19 October 2022).
P_3	Platforms	The geographic coordinates indicating the locations of oil production platforms, obtained from a published literature [14].
P_4	Ships	The spatial distribution of ship tonnage at different time intervals, obtained through digitization of data from the automatic identification system. The data were derived from a published literature [10].
P_5	Channels	Derived from electronic navigational charts issued by MSA through digitization.

Table 2. State indices.

Label	Indicators	Sources of Data	Explanation
S_1	Distance from coast	Google Earth	When MPAs are situated in close proximity to the coastline, it facilitates prompt emergency response actions as MPAs are less vulnerable to oil-related incidents.
S_2	Wind speed	HY-2A satellite radar altimeter product (https://osdds.nsoas.org.cn/, accessed on 10 January 2022)	The average annual wind speed measured at the surface of the sea
S_3	Wave height	HY-2A satellite radar altimeter product (https://osdds.nsoas.org.cn/, accessed on 10 January 2022)	The annual average height of waves observed on the surface of the sea
S_4	Ocean current velocity	Simulated from general estuarine transport model (GETM) (https://getm.eu/, accessed on 1 October 2022)	The highest velocity recorded for ocean currents on the surface of the sea
S_5	Slope degree	Modeled as a derivative of the bathymetry data. (https://www.gebco.net/data_and_products/, accessed on 8 July 2022)	Revealed by the gradient or inclination of the seabed
S_6	Bathymetry	https://www.gebco.net/data_and_products/, accessed on 8 July 2022	As the water depth increases, there is typically a greater capacity for resilience and exchange, resulting in a lower sensitivity to external factors.
S_7	Seabed material	China Offshore Ocean Atlas	Based on the specified assumptions, clay was given a score of 100, silt was given a score of 70, fine sand was given a score of 50, coarse sand was given a score of 20, and sand with gravel was assigned a score of 10.
S_8	Sea Surface Temperature (SST)	Hybrid coordinate ocean model (HYCOM) (https://www.hycom.org/, accessed on 12 July 2022)	The average SST observed annually.

Table 3. Response indices (modified from [15]).

Label	Indicators	Explanation
R_1	Rescue capability	Indicated by the number of vessels deployed for rescue operations
R_2	Towing capacity	Indicated by the number of tugboats available
R_3	Firefighting capability	Indicated by the number of firefighting vessels in service
R_4	Protective suits	Indicated by the number of protective suits designed to resist chemical splashes
R_5	Capacity for containing oil	Indicated by the number of oil containment booms used for handling and containing contaminated oil spills
R_6	Capacity for trans-shipping oil	Indicated by the number of pumps used for unloading operations
R_7	Capacity for cleanup of spilled oil	Indicated by the number of oil skimming devices used for removing oil from the surfaces of water bodies

2.4. Weight Determination

In this research, the analytic hierarchy process (AHP) was employed to establish the relative importance of each indicator. The AHP is commonly used to assist decision-makers in balancing and selecting among complex decision problems. This method was initially proposed by Thomas Saaty and has been extensively utilized in vulnerability assessment [16–18]. The core idea of the AHP is to decompose a complex decision problem into multiple levels of criteria and sub-criteria. By quantifying the importance and priorities through pairwise comparisons of these criteria, the final decision can be derived. The basic steps of the AHP are as follows.

(1) Constructing the hierarchy structure: Based on the PSR framework, the target is categorized into the objective layer (vulnerability assessment), the criterion layer (pressure, state, and response), and the index layer, comprised of the 20 indicators mentioned earlier.

(2) Constructing the judgment matrix: The judgment matrix is constructed by comparing the indicators to each other based on expert suggestions within the same layer. Subsequently, the pairwise judgment matrix is created. In each case, two factors (x_i and x_j) are taken, with a_{ij} representing the relative importance of x_i and x_j to the vulnerability assessment result. The relative importance intensity scale for each indicator ranges from 1 to 9, where 1 indicates that the two factors are equally important, 3 indicates that one factor is moderately more important than another, 5 indicates that one factor is much more important than another, 7 indicates that one factor is greatly more important than another, and 9 indicates that one factor is extremely more important than another; 2, 4, 6, 8 are intermediate values between 1, 3, 5, and 7 [19]. The determination of the relative importance, as described above, is based on expert opinions. The comparison results for all pairs are represented by $A = \left(a_{ij}\right)_{n\times n}$, which is the judgment matrix.

(3) Calculating the weights: The weights are calculated using the square root method as follows:

$$\overline{w_i} = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \tag{1}$$

The calculation results are then normalized by the following equation, where w_i indicates the needed weights:

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_i}} \tag{2}$$

(4) After obtaining the weight results, a consistency check is conducted on the results. The maximum eigenvalue is calculated using the following method:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} (Aw)_i / w_i, \tag{3}$$

where w is the eigenvector (weights), A is the judgment matrix, n is the dimension of the matrix, and λ_{max} is the maximum eigenvalue.

The consistency ratio is calculated to assess the consistency of the judgment matrix. If the consistency ratio exceeds a pre-defined threshold [20], re-evaluation of the comparisons is needed. The consistency ratio (CR) is defined as the ratio of the consistency index (CI) to the random consistency index (RI):

$$CR = \frac{CI}{RI}. \tag{4}$$

The CI can be derived from the preference matrix using equation (3); CI = 0 represents complete consistency, and a larger CI value indicates greater inconsistency in the judgment matrix:

$$CI = (\lambda_{max} - n)/(n - 1), \tag{5}$$

where RI is the random consistency index (Table 4), and CR is the consistency ratio.

Table 4. RI values.

Order	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

2.5. Vulnerability Assessment Model

This study involved buffer analysis to assess pressure indicators, including oil tanks, oil pipelines, oil platforms, and shipping lanes. The buffer distances were determined based on empirical evidence from historical accidents, with values set at 35 km for oil pipelines and storage tanks, 29 km for platforms, and 27 km for shipping lanes. This approach has been demonstrated to be feasible and efficient in prior research conducted by Wang et al. [4]. The ship tonnage was determined by converting data from the automatic identification system (AIS), with samples collected every 3 days. The data chosen to represent the ship tonnage were extracted from the first minute of each hour, every day. For more comprehensive details, please refer to Liu et al. [11]. To facilitate comprehensive analysis, all of the indicators were standardized. The state indicators (S1–S7), including the distance from the coast, sea surface wind speed, wave height, sea surface ocean current velocity, slope degree, bathymetry, and sea surface temperature (SST), were recorded as point shapefiles. These shapefiles were then imported into a geographic information system (GIS) and converted directly into raster data. Regarding the state indicator (S8), specific numerical values were assigned to different compositions. Significantly, clay, silt, fine sand, coarse sand, and sand with gravel were assigned weights of 100, 70, 50, 20, and 10 based on the findings of Wang et al. [15]. To analyze the response indicators, emergency equipment has been strategically placed at key ports surrounding the sea area. The locations and quantity of such equipment have been recorded in point shapefiles. The inverse distance weighting (IDW) interpolation method was adopted to convert discrete spatial data into continuous data. This interpolation technique allows the estimation of values at unmeasured locations based on surrounding data points.

To address the potential interactions among different indicators, the preprocessed indicator data mentioned above were transformed into raster data and processed in a GIS environment using 1000 m × 1000 m grid cells. Using the following formula, these indicators were subsequently normalized individually as follows:

$$N = (x_k - Min)/(Max - Min) \tag{6}$$

In Equation (4), the normalized value (N) for each indicator is calculated based on the actual value of the grid cell (x), the grid cell identifier (k), the minimum value (Min) of each indicator, and the maximum value (Max) of each indicator.

Following the data processing using a GIS tool, an assessment model was created to evaluate the vulnerability of MPAs to oil spill incidents.

$$\mathrm{P, S, R} = \sum_{i=1}^{h} (N_k \times w_i), \tag{7}$$

where P, S, and R are the values of the pressure, state, and response indicators, respectively. h is the number of indices for the pressure, state, or response. N_k is the normalized value of index k. The assessment of the vulnerability was conducted utilizing the following formula:

$$\text{Vulnerability} = (\text{Pressure} + \text{State} + (1 - \text{Response})). \tag{8}$$

3. Results

3.1. Obstacle Degree Analysis

The weights assigned to each indicator offered valuable insights into the primary factors influencing the vulnerability (Table 5). Out of the 20 indicators employed, five indicators had weights of less than 0.03, which were calculated using the product of the weight of the criterion layer and the weight of the index layer. Among these five indicators, three pertained to the response ability (protective suits, firefighting capability, and rescue capability), and two were related to the pressure (channels and pipelines). The indicators associated with the pressure and the response had the highest weights.

Table 5. Weight distribution for each indicator.

Criterion Layer	Weight of Criterion Layer	Label	Index Layer	Weight of Index Layer
Pressure	0.2599	P_1	Storage tanks	0.1764
		P_2	Pipelines	0.0934
		P_3	Platforms	0.2899
		P_4	Ships	0.333
		P_5	Channels	0.1073
State	0.4126	S_1	Distance from coast	0.1133
		S_2	Wind speed	0.0906
		S_3	Wave height	0.0906
		S_4	Ocean current velocity	0.1236
		S_5	Slope degree	0.1747
		S_6	Bathymetry	0.1347
		S_7	Seabed material	0.1686
		S_8	SST	0.1039
Response	0.3275	R_1	Rescue capability	0.0881
		R_2	Towing capacity	0.1331
		R_3	Firefighting capability	0.0372
		R_4	Protective suits	0.0292
		R_5	Capacity for containing oil	0.2768
		R_6	Capacity for trans-shipping oil	0.2003
		R_7	Capacity for cleanup of spilled oil	0.2353

3.2. Variability in Vulnerability across Spatial Zones

In this study, the vulnerability of the MPAs exhibited differences across different locations. To provide a precise and quantitative representation of these differences, the results are presented based on seven response zones. The normalized values of the integrated pressure, state, response, and vulnerability were categorized into five levels using the quantile distribution method: extremely low, relatively low, medium, relatively high, and extremely high. The areas (the unit of measurement is square kilometers) of each level within each response zone were identified, as shown in Figure 2, which clearly presents the areas occupied by the five levels of MPAs in the different zones under oil spill stress.

3.3. Pressure

By employing GIS spatial analysis and visualization techniques, the distinct pressures arising from spill resources were identified. Subsequently, the integrated pressure was calculated by combining these pressure metrics and was represented visually in a GIS using weighted calculations, as described in Section 2.4 (Figure 3). The MPAs were distributed in all of the response zones, but the areas in zones 2, 3, and 4 were smaller, and the areas in zones 1, 5, 6, and 7 were larger. Therefore, the analysis of the MPAs mainly focused on the zones with larger areas. It can be seen from Figure 4 that the high pressure MPAs were mainly located in zones 1 and 7, and the low pressure MPAs were mainly located in zones 5 and 6.

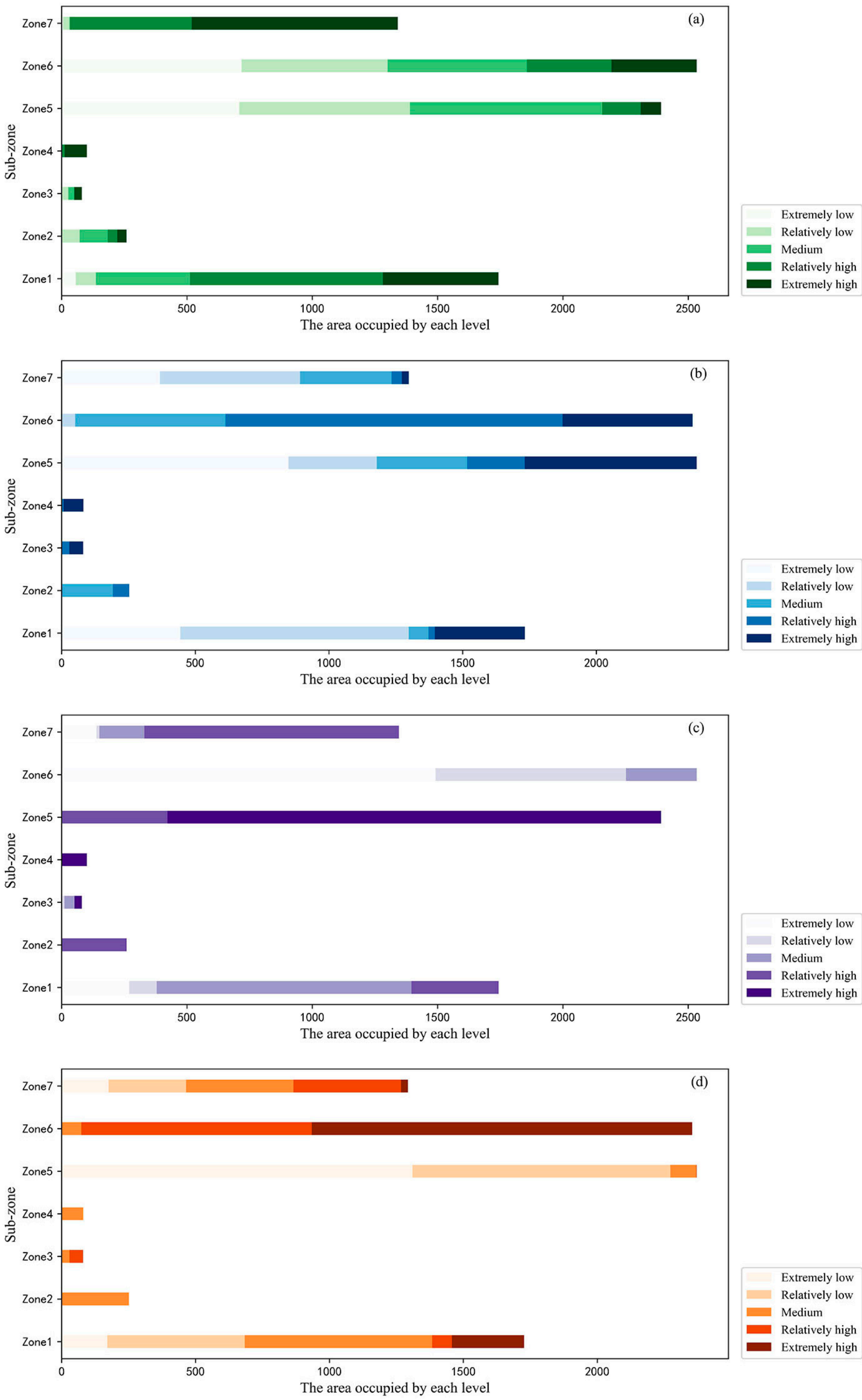

Figure 2. Areas occupied by each level in Zones 1–7: (**a**) pressure, (**b**) state, (**c**) response, and (**d**) vulnerability.

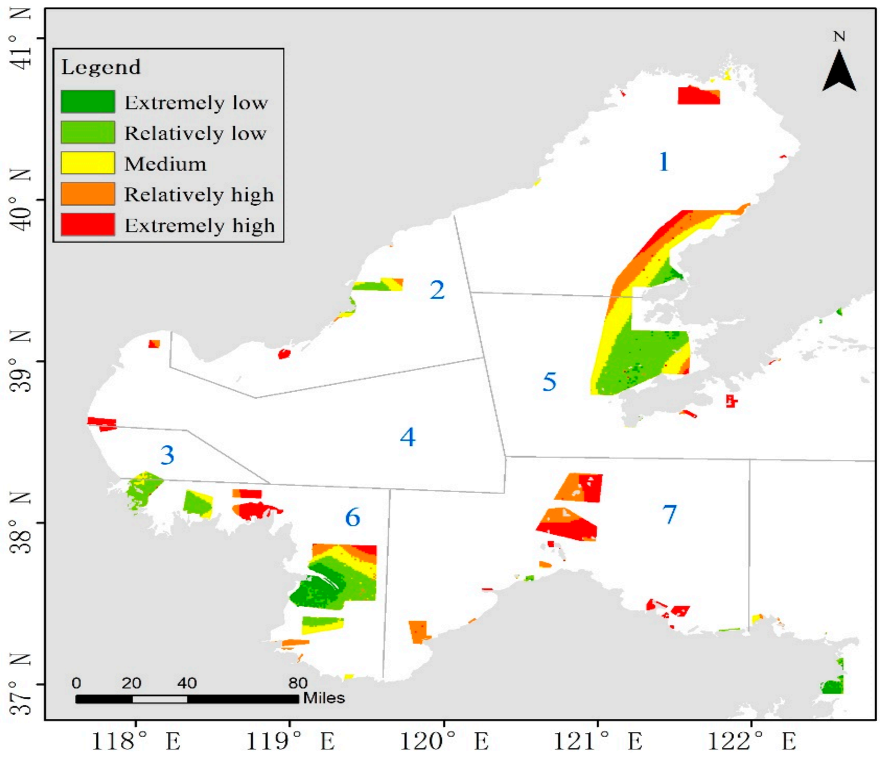

Figure 3. Variability in the integrated pressure of oil-spill stress across MPAs.

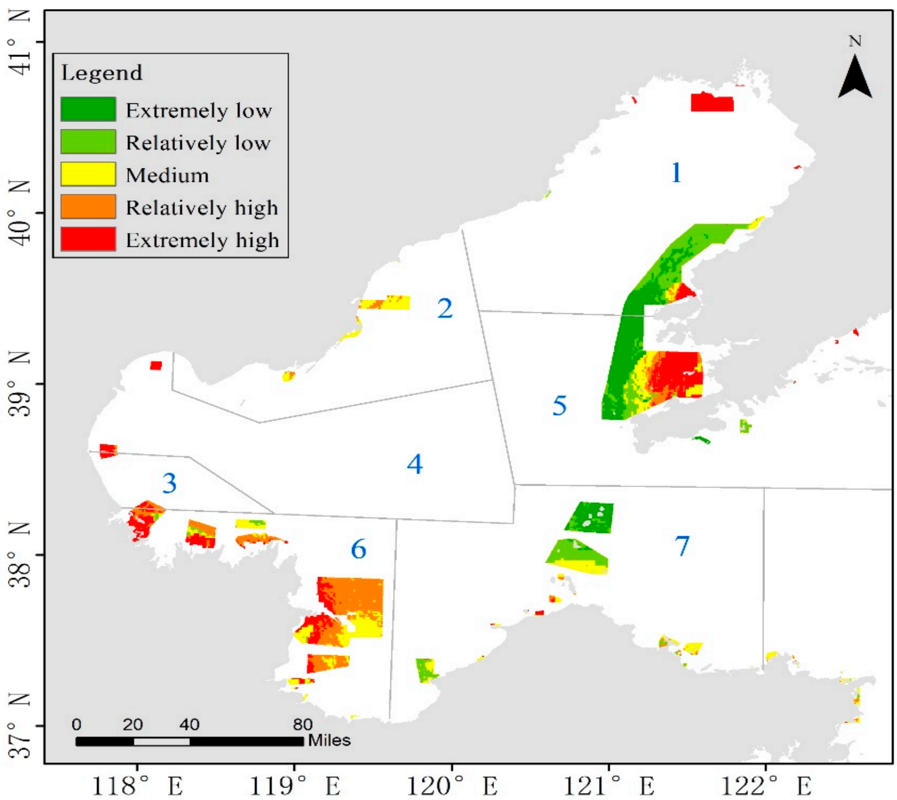

Figure 4. Variability in the integrated state of MPAs regarding oil-spill stress.

3.4. State

By integrating the weighted calculations with the results of the spatial analysis, the overall state of the MPAs was determined. (Figure 4). The results indicate the state variations of the MPAs to oil spill pressures. Based on the spatial distribution of the integrated state, it was observed that most of the MPAs in zone 6 exhibited extremely high and relatively high sensitivities, and most of the MPAs in zone 7 exhibited extremely low and relatively low sensitivities. The large MPAs located in the western part of the Liaodong Peninsula were located in zones 1 and 5, and most of them had a low sensitivity.

3.5. Response

The response for each index was identified. Afterward, the integrated response capacity was calculated utilizing the weighted results and spatial overlay analysis. The spatial distribution of the integrated response indicators (Figure 5) revealed that nearly all of the MPAs in response to zone 6 exhibited a response capability below the medium level. Additionally, the MPAs in the northern part of zone 7 exhibited a relatively high response capability, while those in response zones 5 exhibited an extremely high response capability.

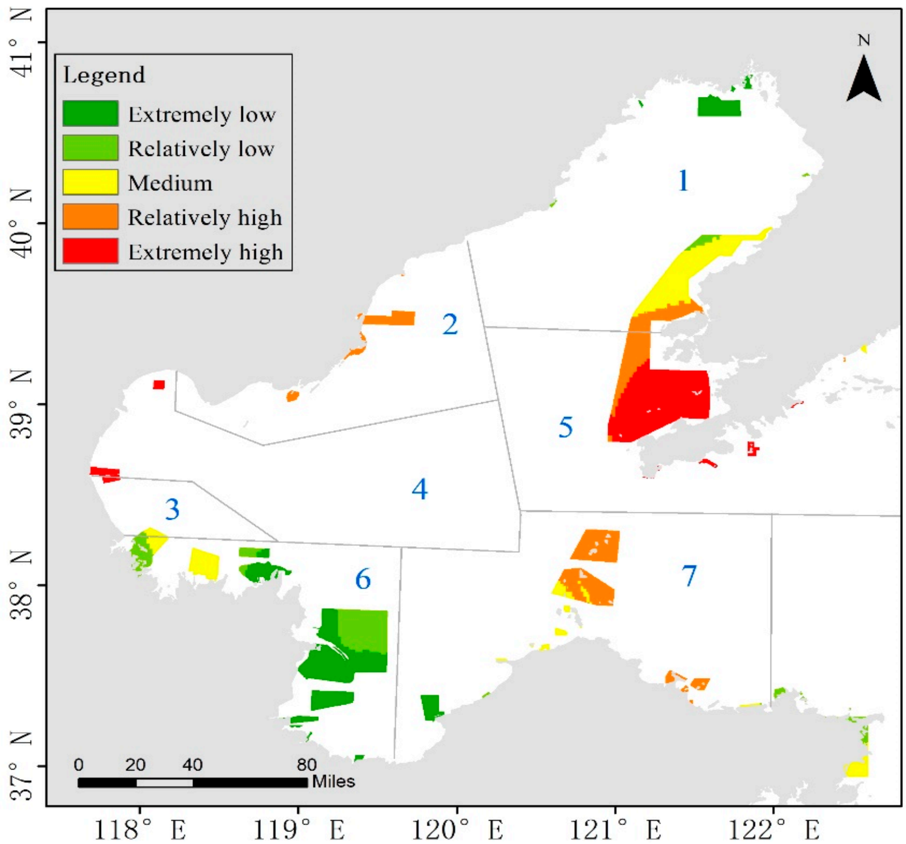

Figure 5. Variability in the integrated response of MPAs to oil-spill stress.

3.6. Vulnerability

Under the influence of oil spill stress, the vulnerability of the MPAs in the different zones exhibited distinct spatial variations. Notably, Figure 6 highlights the significance of response zone 6, and all of the MPAs in this zone surpassed the range of the relatively high and extremely high sensitivity. In response zone 5, all of the MPAs had low and extremely low vulnerabilities. Geographically, the MPAs situated in the northern part of Liaodong Bay exhibited a pronounced vulnerability.

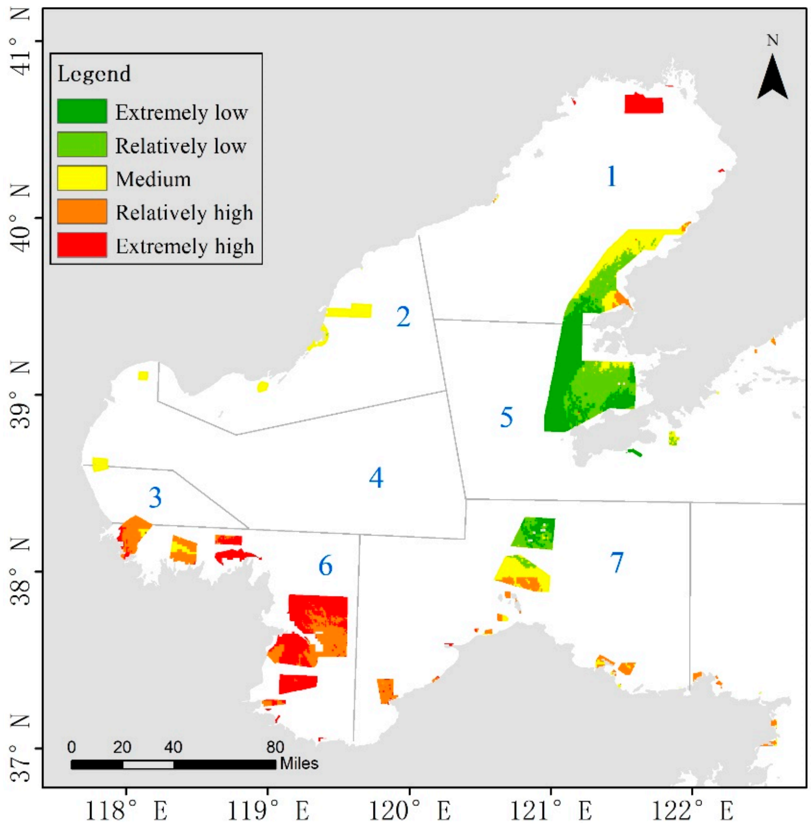

Figure 6. Variability in the integrated vulnerability of MPAs to oil-spill stress.

4. Discussion

4.1. Analysis of Indicator Selection

This section provides a detailed explanation of the rationale and justification for selecting each indicator.

Pressure: Oil spills in the Bohai Sea originate from various risk sources, including oil well blowouts, marine vessel accidents, pipeline spills, collisions in shipping lanes, and the explosion of coastal oil storage tanks [4]. Hence, this study encompasses all potential pressure sources in the Bohai Sea, including platforms, ships, tanks, channels, and pipelines. These factors cover all of the oil spill pressure sources in the Bohai Sea.

State: For S2–S4, spilled oil on the sea surface can be transported by sea surface winds, waves, and upper-ocean currents in a passive manner [21–23]. Higher wind speeds lead to the spilled oil remaining on MPAs for a shorter duration and also increase the rate of oil evaporation. Additionally, wind-induced waves play a crucial role in naturally cleaning stranded oil, as wave action effectively removes oil from shorelines. In certain cases, the currents resulting from tides and winds are also significant. Consequently, areas characterized by elevated current velocities, wave heights, and wind speeds tend to be less susceptible. The influences of the above factors were evaluated using average annual data. For S5–S6, the gradient of the seafloor influences the longevity of spilled oil, and bathymetry plays a significant role in ocean circulation by impeding water flow in shallower waters. A more pronounced seafloor slope and deeper water enhance the water exchange capacity, leading to a reduced sensitivity [24,25]. For S7, the extent of the oil penetration greatly impacts the oil residence, and it is influenced by the sediment particle size of the seabed material. Seabed materials with larger grain sizes lead to increased penetration [26]. For S8, the integration of crude oil into seawater intensifies its toxicity. Lower temperatures can decelerate weathering processes [27], whereas higher temperatures lead to an increase in the amount of dissolution. According to the weighted results, the slope degree, seabed material, and bathymetry have the most significant effects on the sensitivity.

Response: Given the delicate ecological environment and dense population in the Bohai Sea area and considering the advantages and disadvantages of different oil spill response methods [28], mechanical methods rather than chemical methods, natural degradation methods, bioremediation methods, and in situ burning methods are generally preferred as the primary response options. These measures require combat ships (firefighting vessels, tugboats, and vessels deployed for rescue operations) and salvage-related equipment (protective suits, oil containment booms, oil skimming devices, and pumps). The configuration of these facilities represents the adaptability of the MPAs to oil spill disasters.

4.2. Analysis of Methodology Selection

Various comprehensive evaluation models have been utilized in vulnerability assessment, for instance, the vulnerability scoping diagram (VSD) [29], the vulnerability assessment framework (VAF) [30], the driver-pressure-state-impact-response (DPSIR) model [31], and the PSR model. This study showcases the practicality of utilizing a PSR framework to assess the vulnerability of MPAs to oil spill stress. Nevertheless, certain technical aspects necessitate further elaboration and discussion.

First, to assess the pressure indicators, in this study, GIS buffer analysis was utilized to empirically determine the buffer distances based on the influence range of historical accidents. This approach introduces a certain level of subjectivity.

Second, the current, wave, and wind indicators used in this study were based on annual average data, which may overlook the impact of vulnerability during different seasons. Given that seasonal variations can cause fluctuations and changes in the indicators, relying solely on annual average data may not fully reflect the actual situation. Therefore, in future research, it is advisable to consider using more frequent data collection and analysis to obtain a more comprehensive understanding of the seasonal variations in the vulnerability trends.

Third, the allocation of weights was conducted using the AHP method. Although the AHP method is a commonly used decision analysis tool, its process involves subjective judgment and trade-offs by decision-makers. Different decision-makers may assign different weights based on their personal experiences, knowledge, and preferences, introducing a certain degree of subjectivity. To enhance the objectivity of the weight allocation, future studies could explore other multi-criteria decision-making methods and incorporate expert opinions or stakeholder engagement to ensure the rationality and credibility of the weights. In this way, the importance and impact of the vulnerability indicators in the vulnerability assessment of the MPAs can be evaluated more reliably.

4.3. Analysis of Vulnerability

In this study, the vulnerability of MPAs in the Bohai Sea in China (response zones 1–7) was analyzed, and significant spatial variations in their susceptibility under the influence of oil spills were revealed. The key findings are as follows.

(1) Pressure results: It can be concluded that the high-pressure areas were mainly located in zones 1 and 7, and these places were also areas with dense oil spill risk sources.

(2) State results: Most of the high-sensitivity MPAs were located in zone 6. In addition, the MPAs in the western part of the Liaodong Peninsula (located in zone 5) also exhibited a high sensitivity.

(3) Response results: The low adaptability MPAs were predominantly located in zone 6, and the high adaptability MPAs were predominantly located in zones 5 and 7. This phenomenon was directly related to the oil spill deployment of the emergency facilities in the different ports.

In addition, the MPAs with relatively high and extremely high vulnerabilities were predominantly located in zone 6, and a small proportion was located in the northern part of zone 1 and the southern part of zone 7. The MPAs with relatively low and extremely low vulnerabilities were predominantly located in the northern part of zone 7 and the entirety of zone 5. Overall, the comprehensive analysis indicates that quite a few of the MPAs in the

Bohai Sea experienced high pressure, high sensitivity, low emergency response capabilities, and high vulnerability under oil spill stress.

China possesses a vast marine area of over 3 million km^2. In this context, MPAs play a crucial role in safeguarding marine ecological security. However, recent oil spills have further exacerbated marine environmental issues, inflicting damage on MPAs. To address this concern, the Chinese government has put into effect a range of measures aimed at oil spill prevention and control, such as enhancing monitoring and early warning systems, developing emergency response plans, strengthening legal and regulatory measures, raising awareness and education levels, and promoting clean energy and sustainable development. The implementation of these measures requires collaboration and efforts from governments, environmental organizations, research institutions, and society at large. Through comprehensive management and protection measures, we can better safeguard the security of MPAs and reduce the damage caused by oil spill accidents to the marine ecosystem.

5. Conclusions

Marine oil spills are a widespread challenge faced by major maritime nations around the world, posing a significant threat to MPAs. Developing effective strategies to mitigate the adverse impacts of oil spills on MPAs is crucial and should be informed by vulnerability assessments. Vulnerability assessments serve as a scientific foundation for preventing and reducing the impact of oil spills. In this study, the vulnerability of MPAs in the Bohai Sea area to oil spill stress was thoroughly assessed. The assessment incorporated various indicators related to pressure, state, and response aspects. Employing a PSR framework and a GIS-based method, spatial variations in vulnerability were analyzed. Seven management zones were considered in the assessment, and notable spatial differences in MPA vulnerability were revealed. A comparison highlighted significant variations in vulnerability both between and within the zones. Overall, several MPAs in the study area exhibited high pressure, high sensitivity, low response capability, and consequently, high vulnerability. These findings offer valuable insights for future research endeavors aimed at mitigating oil spill impacts on MPAs. Further research should focus on evaluating how enhancing preparedness and response measures may impact the vulnerability of MPAs.

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