Journal of *Marine Science and Engineering*

MDPI

Article

Oil Spill Occurrence and Pollution Risk Assessment Based on Sea State, Oil Platform Location, and Shipping Route Density in the Bohai Sea

Tao Liu [1], Ruichen Cao [2,3,*], Minxia Zhang [1], Xing Chen [1,*], Fan Bi [2,3] and Jiangling Xu [2,3]

[1] CNOOC Research Institute Limited, Beijing 100029, China; liutao1@cnooc.com.cn (T.L.); zhangmx9@cnooc.com.cn (M.Z.)
[2] North China Sea Marine Forecasting and Hazard Mitigation Center, Ministry of Natural Resources, Qingdao 266061, China; bifan@ncs.mnr.gov.cn (F.B.); xujiangling@ncs.mnr.gov.cn (J.X.)
[3] Shandong Key Laboratory of Marine Ecological Environment and Disaster Prevention and Mitigation, Qingdao 266061, China
* Correspondence: caoruichen@ncs.mnr.gov.cn (R.C.); chenxing8@cnooc.com.cn (X.C.)

Abstract: The Bohai Sea is the only semi-enclosed inland sea in China. With active marine economic activities, it faces a persistently high risk of oil spill accidents. This study assesses the occurrence risk and pollution risk of oil spills by considering factors such as sea state, the location of oil platform, and shipping route density in the Bohai Sea. The results show that the central part of the Bohai Sea, the southern Liaodong Peninsula, and the Bohai Strait area have a relatively high occurrence risk of oil spills due to busy maritime traffic and harsh sea conditions. In contrast, some areas in the northern, western, and southern parts of the Bohai Sea have a relatively low occurrence risk of oil spills because of weak maritime activity intensity and relatively calm sea state. In terms of the oil pollution risk, its distribution in the Bohai Sea shows significant seasonal characteristics, which are mainly comprehensively affected by multiple dynamic factors such as circulation, monsoon, and seawater exchange. Based on the oil pollution risk distribution, seasonally targeted strategies are proposed, which can provide a scientific basis for oil spill prevention and emergency management in the Bohai Sea, and help relevant departments formulate targeted prevention and control strategies.

Keywords: Bohai Sea; oil spill; oil pollution; risk assessment; numerical simulation

check for updates

Academic Editor: Merv Fingas

Received: 17 March 2025
Revised: 30 March 2025
Accepted: 3 April 2025
Published: 5 April 2025

Citation: Liu, T.; Cao, R.; Zhang, M.; Chen, X.; Bi, F.; Xu, J. Oil Spill Occurrence and Pollution Risk Assessment Based on Sea State, Oil Platform Location, and Shipping Route Density in the Bohai Sea. *J. Mar. Sci. Eng.* **2025**, *13*, 729. https://doi.org/10.3390/jmse13040729

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The Bohai Sea is the only semi-enclosed inland sea in China and holds a pivotal position in the pattern of the marine economy, with an average water depth of 18 m [1]. This special geographical condition is very convenient for marine economic activities, making the surrounding areas of the Bohai Sea a gathering place for many important ports and densely distributed offshore oil extraction facilities, with highly active marine economic activities. While these economic activities have promoted regional development, they have also led to a persistently high risk of oil spill accidents. Taking the oil spill accident at the Penglai 19-3 Oilfield in 2011 as an example, this accident caused about 6200 square kilometers of seawater to be polluted. The direct economic loss of fishery resources reached CNY 1.683 billion, and the loss of natural fishery resources was about CNY 3.641 billion [2,3]. These data serve as a warning that we must attribute great importance to the pollution risks posed by marine oil spills to China's marine environment, and strengthen the research, prevention, and control of marine oil spills.

In the field of oil spill risk assessment, oil spill models are essential for supervision and emergency planning. They not only need to estimate the occurrence risk of oil spills (referred to as occurrence risk) but also evaluate the oil pollution risk after an oil spill occurs (referred to as oil pollution risk) [4,5]. The occurrence risk is the starting point of the entire oil spill risk assessment. Understanding the likelihood of oil spills helps to identify areas where oil spill accidents may occur in advance. For example, if we can determine which areas in the Bohai Sea are prone to oil spills due to frequent ship navigation, dense oil platforms, or harsh sea state, we can strengthen the supervision of ship navigation and oil platform operations in these high occurrence risk areas, establish stricter safety standards, and deploy special monitoring equipment. This can reduce the probability of oil spill accidents and control occurrence risk at an early stage. This not only mitigates potential pollution to the marine environment but also avoids a series of economic losses caused by oil spill accidents, such as damage to fisheries, interruption of maritime transportation, and impact on tourism.

An assessment of the oil pollution risk is also crucial. Once an oil spill accident occurs, accurately grasping the distribution of the oil pollution risk can help us quickly judge the possible pollution range and degree of the accident. By studying the differences in oil pollution risk in different seasons and regions, such as which regions are more likely to be polluted by oil spills in a specific season and the degree of impact of pollution on the coastline and marine biological habitats, relevant departments can reasonably allocate emergency resources and develop more targeted emergency response plans. For example, sufficient oil-cleaning equipment and materials can be pre-stored in high oil pollution risk (referred to as high-risk) areas, and professional emergency response teams can be trained. In this way, when an accident occurs, a rapid response can be made to minimize the harm caused by oil spill pollution.

Many previous studies have also been conducted regarding the occurrence and pollution risk in the Bohai Sea. For example, based on the distribution of ships and oil platforms in the Bohai Sea, the historical oil spill accident data in the Bohai Sea from 1973 to 2002, and the relevant literature, Liu et al. (2015) established a probability model to evaluate the oil spill risk in the Bohai Sea and identified seven high occurrence risk areas [6]. However, their study mainly focused on constructing a probability model for an oil spill occurrence risk assessment, and it did not involve a numerical simulation of the oil spill pollution risk based on its occurrence risk. Subsequently, Guo et al. (2019) developed a statistical oil spill response model in the Bohai Sea [7]. According to the distribution of offshore oil platforms in the Bohai Sea, 20 potential oil spill locations were selected. Over an 18-year time span, 200 oil spill moments were randomly selected and in each oil spill simulation, the volume of the oil spill was randomly assigned. Then, based on the simulation results of all scenarios, the probability distribution of oil spill pollution was statistically calculated, achieving a quantitative assessment of the oil pollution risks to the surrounding sea areas and coastlines caused by potential oil spill accidents at offshore oil platforms in the Bohai Sea. Although their study focused on the assessment of the oil spill occurrence and pollution risk, it did not thoroughly explore the characteristics of pollution risk in relation to the factors considered, and it ignored pollution risk in relation to the densities of shipping lines. Ke et al. (2022) adopted multi-source high-resolution satellite remote sensing data to extract the distribution of two main types of oil spill risk sources, namely ships and oil platforms, in the Bohai Sea. Combined with the satellite remote sensing monitoring results of oil spills in the Bohai Sea from 2015 to 2020, their study analyzed the imaging characteristics of different types of oil under various sensors. Through the nuclear density analysis method of oil spill sources, their study obtained the spatial–temporal distribution of oil spill events, and achieved a comprehensive evaluation of the degree of pollution risk in the Bohai Sea [8].

Similarly, Tang and Su (2024) simulated the drifting and diffusion process of oil slicks in seawater under different working conditions in the sea area of Jingtang Port in the Bohai Sea, and discussed the impacts of oil spill pollution on nearby ecological protection zones, tourism and recreational areas, and fishery breeding and fishing areas [9]. However, both of these studies were limited to short-term impacts in specific regions and conditions within the Bohai Sea, ignoring the overall oil pollution risk characteristics associated with the oil platform location and shipping route density across the entire Bohai Sea.

According to previous studies, there are still some limitations in the research on oil spill risk assessment in the Bohai Sea. On the one hand, the historical oil spill data in the Bohai Sea region are relatively sparse, specifically, detailed records of small-scale oil spill accidents. This data deficiency is particularly crucial when attempting to link occurrence risks to the oil platform location and shipping route density. In the region of highly concentrated oil platforms or busy shipping lines, even small-scale spills can accumulate over time and lead to significant pollution. Without sufficient data on these minor incidents, the risk assessment process lacks the necessary data support. As a result, accurately quantifying the occurrence risk needs to consider comprehensive factors including sea state, oil platform location, and shipping route density. On the other hand, studies regarding the distribution characteristics of oil pollution risk in the Bohai Sea remain scarce. In fact, the marine environment of the Bohai Sea exhibits substantial spatial–temporal variations. Factors such as circulation and wind significantly affect the diffusion and pollution extent of oil spills.

Therefore, this study intends to (1) construct an oil spill occurrence risk assessment model by considering multiple factors such as sea state, oil platform location, and shipping route density, and depict an occurrence risk map of potential oil spills to illustrate the spatial distribution characteristics of occurrence risk in the Bohai Sea, providing a more intuitive and effective decision-making foundation for relevant departments; (2) depict and analyze the pollution risk in the Bohai Sea, taking into account multiple dynamic factors such as circulation and monsoon, so as to present the pollution impact of various regions, and furnish a scientific basis for formulating targeted prevention and control strategies.

2. Materials and Methods

As mentioned above, this study explores two types of risks, namely the occurrence risk of oil spills (referred to as occurrence risk) and the pollution risk after an oil spill occurs (referred to as pollution risk). These two types of risks are crucial for comprehensively understanding the threat of oil spills in the Bohai Sea, ensuring the safety of the marine environment in the Bohai Sea, and the stable development of related industries.

This study begins with identifying the environmental characteristics of the Bohai Sea and the current situation of oil spill accidents, then constructs a systematic assessment system, and conducts detailed index calculations and analyses for these two types of risks. The specific content is shown in the following.

2.1. Occurrence Risk

The occurrence of oil spills may be caused by various factors, including harsh sea conditions, ship collisions, and offshore oil platform leaks. This paper assumes that the occurrence risk of oil spills is mainly related to these three factors. According to the research of Guo et al. (2019), the weights of these three factors are set to 0.2, 0.4, and 0.4, respectively [7]. That is, the calculation of the occurrence risk index (R_{occur}) of oil spills in the Bohai Sea is as follows:

$$R_{occur} = 0.2R_{ocean} + 0.4R_{route} + 0.4R_{platform}, \quad (1)$$

where R_{ocean}, R_{route}, and $R_{platform}$ are the risk indexes of sea state, shipping route density, and oil platform location, respectively.

2.1.1. Marine Environments

Harsh marine environments are closely related to large waves, strong currents, and strong winds. Generally, in the Bohai Sea, we define harsh sea conditions as when the wind speed exceeds a certain threshold (such as Beaufort scale 7, with a wind speed of 13.9–17.1 m/s), the current velocity is greater than a specific value (such as 1 m/s), and the wave height reaches a certain height (such as an effective wave height exceeding 2 m). In such sea conditions, the stability of ship navigation decreases, and the external forces acting on oil platform equipment increase, thus significantly increasing the occurrence risk.

According to the research of Guo et al. (2019) [7], this study uses three indicators, namely the effective wave height, current velocity, and wind speed, to establish the degree of harsh sea conditions, which is expressed as follows:

$$S_{ocean}(i,j) = 0.5\frac{H_{wave}(i,j)}{H_{wave\max}} + 0.25\frac{|\mathbf{U}_c(i,j)|}{|\mathbf{U}_c|_{\max}} + 0.25\frac{|\mathbf{W}(i,j)|}{|\mathbf{W}|_{\max}}, \quad (2)$$

where S_{ocean} represents the sea state severity; i and j represent the grid points corresponding to longitude and latitude; H_{wave}, $U_{current}$, and W_{Wind} represent the effective wave height, current velocity, and wind speed, respectively; the subscript max represents the maximum value of this indicator in the Bohai Sea region during the research period. Figure 1 shows the spatial distribution of sea state severity in the Bohai Sea. It can be observed that areas with relatively severe sea states are concentrated near Liaodong Bay and the Bohai Strait.

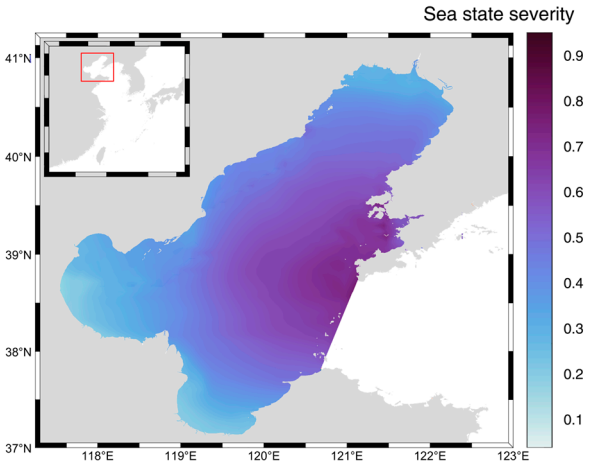


Figure 1. Sea state severity of the Bohai Sea, the red frame represents the geographical location of the Bohai Sea.

2.1.2. Shipping Route Density

Ship collisions are also an important cause of offshore oil spill accidents. This study assumes that the ship collision risk is related to the density of shipping routes. The Bohai Sea is divided into $0.1' \times 0.1'$ grid areas. The number of shipping routes passing through the grid in 2024 is counted using Marine Traffic®, and then the shipping line density (D_{route}) distribution in the Bohai Sea region is obtained. The calculation method is as follows:

$$D_{route} = \frac{\text{Routes Numbers in Cell}}{\text{Cell Area } (0.1' \times 0.1')} \text{ per year.} \quad (3)$$

Subsequently, the shipping route density in the research area is normalized to obtain a standardized shipping route density index, which can more intuitively reflect the relative shipping route density (R_{route}) of different grid areas within the entire Bohai Sea.

$$R_{route}(i,j) = \frac{D_{route}(i,j) - \min(D_{route})}{\max(D_{route}) - \min(D_{route})}. \quad (4)$$

The calculated R_{route} is shown in Figure 2. The route density is relatively high in the Bohai Bay, Laizhou Bay, and Bohai Strait.

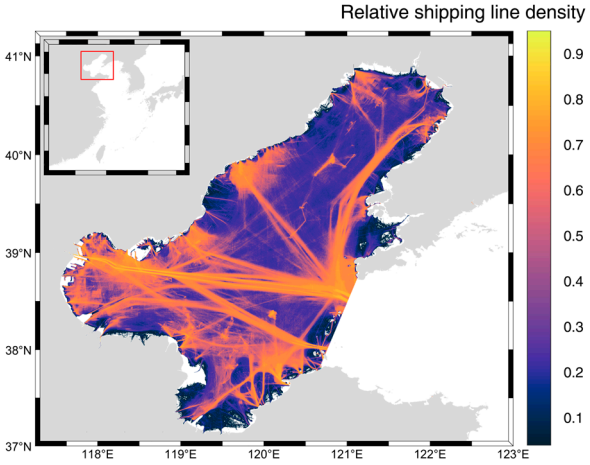


Figure 2. Relative shipping route density of the Bohai Sea, the red frame represents the geographical location of the Bohai Sea.

2.1.3. Oil Platforms

Offshore oil platforms are potential sources of oil spill risks. Considering that the number of platforms is limited and their impact on risks has a spatial distribution characteristic (Figure 3), a unified influence radius of 10 km is assigned to each platform, representing the range within which it has a significant impact on the surrounding area. The setting of this influence radius is based on multiple considerations. On the one hand, from the perspective of the impact range of historical oil spill events, under certain sea conditions and environmental conditions, after an oil spill occurs on a platform, the diffusion of oil on the sea surface is more significant within a range of 10 km. On the other hand, combined with the actual situation of the Bohai Sea, a range of 10 km can better cover the potentially affected area around the platform without overly expanding the influence range and reducing the accuracy of the risk assessment. For each grid cell, the distance to the nearest platform is calculated, and the platform influence ($I_{platform}$) in the grid cell is defined using the distance-weighted method, as follows:

$$I_{platform}(i,j) = \sum_{k=1}^{N_{platform}} \frac{1}{1 + \lambda d(i,j)}, \quad (5)$$

where i and j represent the row and column coordinates of the grid cell, $N_{platform}$ is the total number of offshore oil platforms in the research area, d is the distance from the grid cell to the k-th platform, and λ is a scale parameter used to adjust the attenuation rate of the distance on the platform influence. In this study, λ is taken as 2.

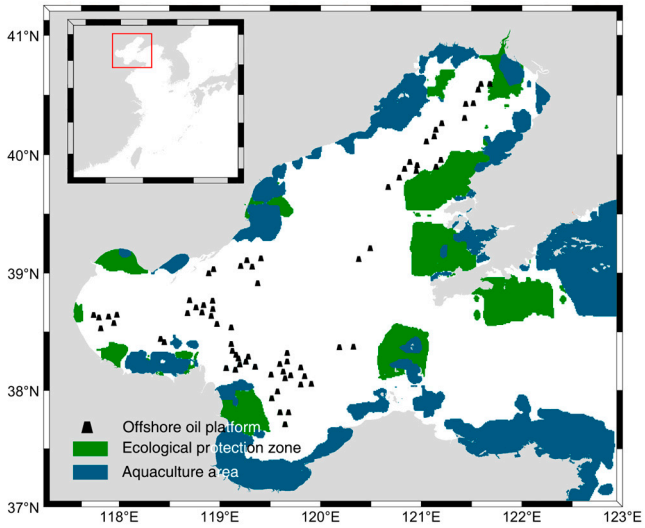


Figure 3. Spatial distribution of offshore oil platforms, ecological protection zones, and aquaculture areas in the Bohai Sea, the red frame represents the geographical location of the Bohai Sea.

2.2. Oil Pollution Risk

Uniformly distributed oil spill sources are set in the Bohai Sea. The pollution impact of each oil spill source is associated with the occurrence risk of oil spills in that area, and finally, the results of all oil spill pollutions are superimposed to obtain the overall pollution risk distribution in the Bohai Sea, which is calculated through the oil spill model, as follows.

According to the study of Cao et al. (2021) [4], the oil spill model uses the Lagrange particle tracking method to simulate the convective-diffusion process of oil spills. Specifically, the motion of oil particles in three-dimensional space satisfies the following relationship:

$$\frac{d\mathbf{S}}{dt} = \begin{cases} \mathbf{U}_c + \mathbf{U}_d + \alpha D\mathbf{W} & z = 0 \\ \mathbf{U}_c + \left(w_b + \frac{\partial K_z}{\partial z}\right)\vec{k} & -H \le z < 0 \end{cases}, \quad (6)$$

where $\mathbf{S} = (x, y, z)$ is the displacement vector of the oil particle; x, y, and z are the three-dimensional coordinates of the particle; $\mathbf{U}_c$ is the current velocity; $\mathbf{U}_d$ is the diffusion velocity, representing the turbulent diffusion effect; w_b is the buoyancy velocity of the oil droplet, representing the wind stress effect, where $\alpha = 0.03$ is the wind stress drag coefficient; $\mathbf{W}$ is the wind speed at a height of 10 m above the sea surface; D is a transformation matrix used to calculate the wind deflection angle. For the specific model introduction, please refer to Cao et al. (2021) [10]. This particle tracking framework has been validated across multiple scenarios in previous studies. For example, Li et al. (2018) and Cao et al. (2021) showed an agreement between model outputs and field observations from the Penglai 19-3 oil spill, particularly in simulating pollution extents and coastline impacts [10,11]. Cao et al. (2023) further validated the model using observation data from drones and a ship radar related to the *A Symphony* oil spill incident, confirming its capability to predict oil transport under complex hydrodynamic conditions. Cao et al. (2022) and Li et al. (2022) also verified the model's parameterization of wave-induced mixing and oil weathering processes based on laboratory experiment data [12,13]. These independent validations across different spatial scales, environmental conditions, and spill magnitudes, establish the model's reliability in simulating oil spill transport.

Simulations are carried out in four seasons, respectively (i.e., spring: March–May; summer: June–August; autumn: September-November; winter: December–February). The time span is 20 years, from 2001 to 2020, and the simulation duration is from the beginning to the end of each season, that is, 3 months.

The oil pollution risk (OPR) is calculated as the ratio of the cumulative number of times a grid cell is polluted to the number of runs (Equation (7)):

$$\mathrm{OPR} = \frac{1}{N \cdot M} \sum_{i=1}^{N} \sum_{m=1}^{M} W_m F_m, \tag{7}$$

where N is the time span of 20 years; M is the number of oil spill sources; W_m is the influence weight of the m-th oil spill source, which is determined by the occurrence risk index of oil spills; $\mathrm{F_m}$ is a logical matrix used to determine whether the grid points in the area are polluted by the m-th oil spill source (i.e., polluted grids are marked as 1). The coastline of the Bohai Sea is discretized into several segments through grids with a resolution of $0.01^\circ \times 0.01^\circ$. The length of the polluted coastline L_P is calculated by adding up the lengths of all polluted coastline segments, as follows:

$$L_P = \sum_{k=1}^{K} L_k \tag{8}$$

where K is the total number of polluted coastline segments and L_k is the length of the k-th polluted coastline segment.

2.3. Experiments Procedure

The hydrodynamic background field input of the model is generated by the Regional Ocean Modeling System (ROMS) with the Simulating Waves Nearshore (SWAN) wind-wave generation and propagation model with a spatial resolution of 2 km, a temporal resolution of 1 h, and 20 vertical layers [14,15]. The hydrodynamic field is validated based on in situ observations in previous studies [4,10], and shows a good consistency with the observational data, indicating that the hydrodynamic background field is reliable. The wind field was derived from the NCEP Climate Forecast System Version 2, with a spatial resolution of 0.5° and temporal resolution of 6 h.

In this study, the crude oil mainly produced in the Bohai Oilfield is selected as the object of the oil spill simulation, and the results of its property analysis are shown in Table 1.

Table 1. Model settings.

Model Parameter	Value
Oil density (20 °C)	957 $\mathrm{kg \cdot m^{-3}}$
Oil dynamic viscosity (50 °C)	376 mPa·s
Particle number for each run	100,000
Leakage duration for each run	2 h
Leakage amount for each run	500 $\mathrm{m^3}$
Simulation duration for each run	90 days

In this study, 113 potential oil spill locations are evenly distributed in the Bohai Sea at intervals of 0.25° (orange dots in Figure 4). The uniform distribution of potential oil spill points ensures that each area has an equal probability of encountering oil spill pollution. Randomly selecting oil spill locations may lead to uneven distribution of these locations, resulting in a possible denser distribution in higher-risk areas. Then, in the four seasons (i.e., spring: March–May; summer: June–August; autumn: September–November; winter: December–February), with a time span of 21 years from 2001 to 2021, the simulation duration is from the beginning to the end of each season, that is, 3 months. This study assumes that the oil spill occurs on the sea surface and does not consider human intervention.

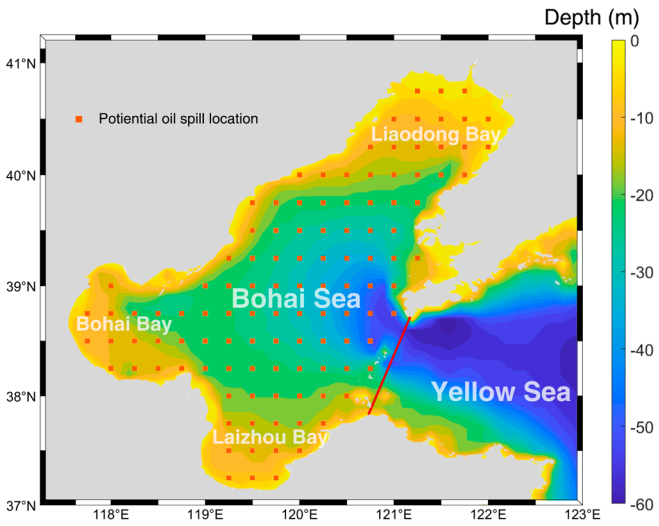


Figure 4. Potential oil spill locations in the Bohai Sea (orange square), the background color represents the water depth, the red solid line is the boundary line between the Bohai Sea and the Yellow Sea.

The simulation duration is set to 3 months, which allows the oil spill to have sufficient time to spread and fully takes into account the characteristics of seasonal ocean currents and wind fields. Moreover, when the oil spill has spread for 3 months, emergency responders also have enough time to respond to oil spills threatening the coastline. For oil spills far from the coastline, on the one hand, human intervention may not bring meaningful social and economic benefits and may even exacerbate ecological damage [16]. On the other hand, the oil spill can also be consumed through the natural weathering process after 3 months [17].

3. Results and Discussion

3.1. Occurrence Risk of Oil Spills

Figure 5 shows the distribution of the occurrence risk of oil spills in the Bohai Sea. It can be seen from the figure that the central part of the Bohai Sea, the southern tip of Liaodong Peninsula, and the Bohai Strait area show a relatively high occurrence risk of oil spills. This area connects the maritime traffic between the Bohai Sea and the Yellow Sea, and the maritime traffic is extremely busy. At the same time, the Laotieshan Channel in the Bohai Strait, as an important water exchange channel between the Bohai Sea and the Yellow Sea, has large-scale wind speeds and current velocities all year round, and the sea conditions are harsh, which also leads to a relatively high probability of oil spills in this area.

Relatively speaking, the occurrence risk of oil spills in some areas in the northern, western, and southern parts of the Bohai Sea is relatively low. This may be attributed to the weak intensity of maritime activities in these areas and the weak internal circulation of the Bohai Sea throughout the year, which has an annual average current velocity of less than 5 cm/s [18].

It should be noted that due to the limitation of only having the annual shipping route density distribution data, this study did not explore the seasonal variation in the occurrence risk of oil spills. Therefore, the distribution of the occurrence risk of oil spills in the Bohai Sea presented in this section is evaluated based on annual shipping route density, annual average current velocity, wave height, and wind speed. The subsequent research on the distribution of oil spill pollution risks will evaluate the distribution of oil spill pollution based on environmental dynamic factors in different seasons. Future research can introduce seasonal shipping route density information to obtain a more accurate distribution of the occurrence risk of oil spills and, based on this, obtain a more accurate distribution of oil spill pollution.

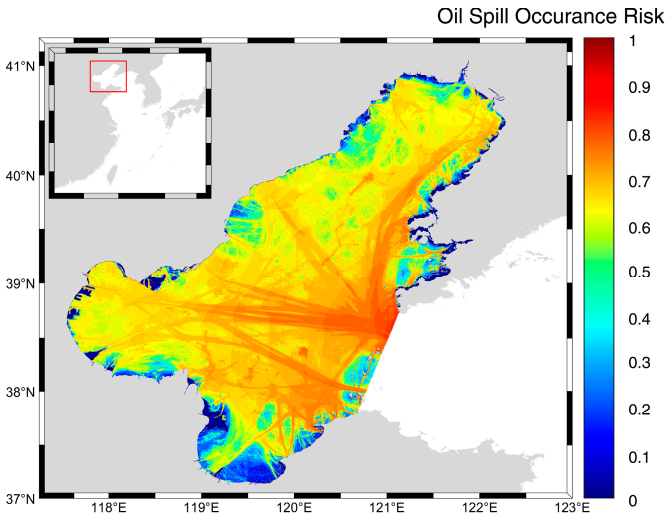


Figure 5. Occurrence risk of oil spills in the Bohai Sea, the red frame represents the geographical location of the Bohai Sea.

3.2. Oil Pollution Risk of Oil Spills

As shown in Figure 6, the surface circulation in the Bohai Sea is affected by the east Asian summer and winter monsoons. The southeastern wind prevails in summer, and the northwestern wind prevails in winter [19]. The circulation in the Bohai Sea changes with climatic conditions, being strong in winter and weak in summer. The circulation is mainly characterized by closed-loop currents in Liaodong Bay, Bohai Bay, and Laizhou Bay, each forming its own system [20]. In the Bohai Strait, there are branches of the Yellow Sea Warm Current (or the Western Korean Coastal Current) flowing into the Bohai Sea and the Northern Shandong Coastal Current flowing out of the Bohai Sea. Generally, underwater oil mainly diffuses along the Northern Shandong Coastal Current and in the weak circulation in the Bohai Sea. The current velocity in most areas of the Bohai Sea is less than 5 cm/s throughout the year, mainly in the central part of the Bohai Sea and the circulations in the three bays in the Bohai Sea. In addition to the circulation, the main dynamic factors affecting the transport of oil on the sea surface are tides and wind stress.

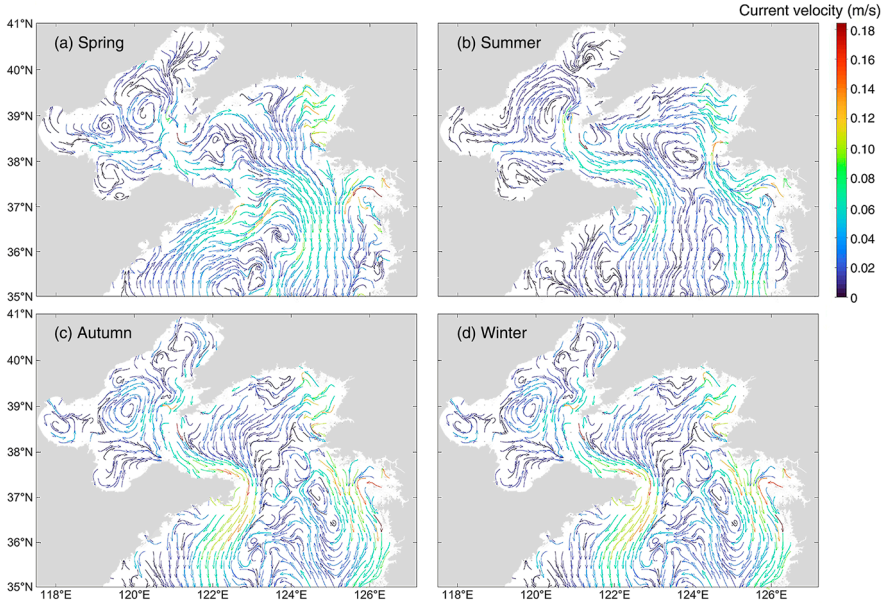


Figure 6. Surface circulation in the Bohai Sea at different seasons.

As shown in Figure 7, the OPR distribution in the Bohai Sea has significant seasonal characteristics. Specifically, in spring, the high-risk areas are concentrated in the waters around the Liaodong Peninsula. The Laotieshan Channel in this area is an important water exchange channel between the Bohai Sea and the Yellow Sea [21], and the complex hydrodynamic conditions increase the risk of oil spills occurrence. In this season, the OPR of the coastline is relatively low, and this is mainly due to the fact that the northern Shandong coastal current hardly flows out of the Bohai Sea in spring [22], which greatly limits the diffusion of oil from the Bohai Sea to the North Yellow Sea, so the OPR transmission from the Bohai Sea to the Yellow Sea remains at a relatively low level in spring. To mitigate these risks, it is essential to strengthen navigational controls in the Laotieshan Channel. Additionally, surveillance along the northern Shandong coast should be intensified.

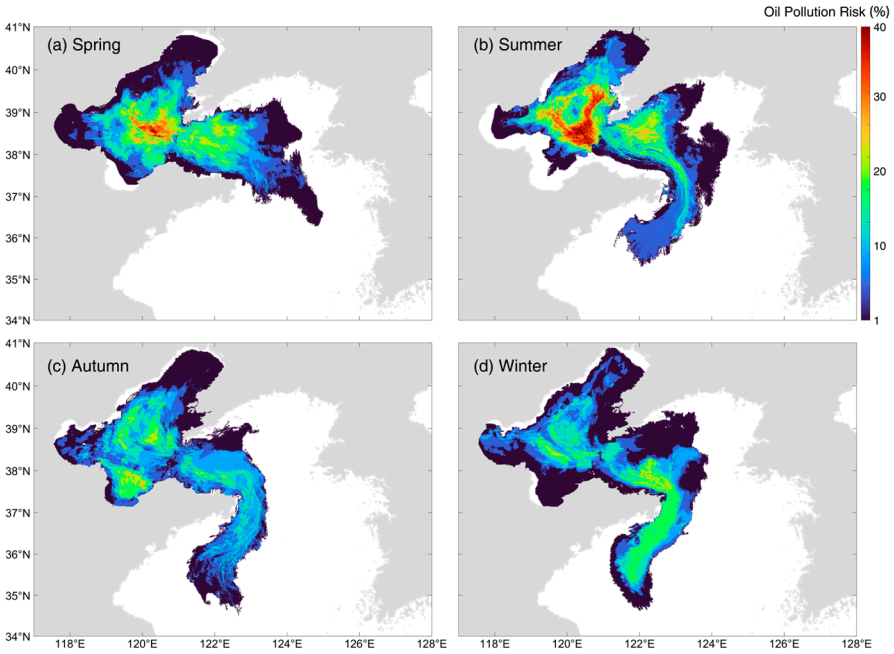


Figure 7. Oil pollution risk in the Bohai Sea at different seasons.

In summer, the high-risk areas in the ocean are mainly concentrated on the west coast of the Liaodong Peninsula. Some of the spilled oil will flow into the Yellow Sea along the Lubei Coastal Current, which is closely related to the circulation pattern in this season. At the same time, the coastline risk is concentrated around the Liaodong Peninsula. It is worth emphasizing that summer is the peak period of seawater exchange between the Bohai Sea and the Yellow Sea [21], and the OPR near the Bohai Strait is relatively high. To mitigate these risks, it is advisable to deploy additional floating barriers and skimming equipment near the Bohai Strait during the peak exchange season to intercept potential oil spills.

In autumn, as the summer monsoon gradually changes to the winter monsoon, the Lubei Coastal Current strengthens. At this time, the wind speed is relatively weak, resulting in more oil diffusing along the Lubei Coastal Current. The high-risk areas of the coastline are concentrated in Laizhou Bay, reflecting the coupling relationship between the dynamic conditions in this season and the distribution of oil pollution. To mitigate these risks, it is necessary to guide oil tankers away from high-risk areas when the current in Laizhou Bay is at its peak.

In winter, the high-risk areas are concentrated on the east side of the Bohai Strait. The internal circulation of the Bohai Sea plays a key role in winter. Under the influence of the winter monsoon, the majority of oil spills in the Bohai Sea are transported out of the Bohai Sea along the Lubei Coastal Current and predominantly remain on the southern side of

the Shandong Peninsula. To effectively respond to the pollution risk, cleanup equipment should be pre-positioned along the southern coast of Shandong to enable a prompt response to any oil spills that strand in the area.

In summary, the OPR in the Bohai Sea is comprehensively affected by multiple dynamic factors such as circulation, monsoon, and seawater exchange in different seasons, showing a complex and regular distribution characteristic. This is of great significance for an in-depth understanding of the oil spill pollution mechanism in the Bohai Sea and formulating targeted prevention and control strategies. Notably, high-risk areas, particularly in Laizhou Bay and the Bohai Strait, overlap significantly with the ecological protection zones and aquaculture areas shown in Figure 3. In response to the seasonal differences in oil spill pollution risk, strategies should include multi-sensor monitoring networks combining satellite and buoy data, drills in different pollution scenarios, and real-time risk mapping.

4. Conclusions

This study constructs an oil spill risk assessment model that comprehensively considers factors such as the oil platform location and shipping route density, and systematically assesses the occurrence risk and pollution risk of oil spills in the Bohai Sea. The research results clarify the distribution characteristics of oil spill risks in different areas of the Bohai Sea, providing an important scientific basis for oil spill prevention and emergency management.

In terms of the occurrence risk of oil spills, the central part of the Bohai Sea, the southern tip of the Liaodong Peninsula, and the Bohai Strait area show a relatively high occurrence risk of oil spills due to busy maritime traffic and harsh sea conditions. In contrast, in some areas in the northern, western, and southern parts of the Bohai Sea, due to weak maritime activity intensity and weak internal circulation, the occurrence risk of oil spills is relatively low. However, limited by the existing data, this study did not conduct an in-depth exploration of the seasonal variation in the occurrence risk of oil spills. Future research should introduce seasonal shipping route density information to obtain a more accurate assessment result.

In terms of the oil pollution risk, the risk distribution of the sea surface and coastline in the Bohai Sea shows significant seasonal characteristics. In spring, the waters around the Liaodong Peninsula are high-risk areas for oil spills, but the risk of the coastline being polluted is relatively low. In summer, the west coast of the Liaodong Peninsula is a high-risk area in the ocean, and some oil spills flow into the Yellow Sea, with the coastline risk concentrated around the Liaodong Peninsula. In autumn, as the wind direction changes, the Northern Shandong Coastal Current strengthens, and the high-risk areas of the coastline are concentrated in Laizhou Bay. In winter, the high-risk areas of sea-surface oil spills are concentrated on the east side of the Bohai Strait, and the pollution risk of the coastline of Bohai Bay is at its highest. These seasonal changes are mainly affected by multiple dynamic factors such as circulation, monsoon, and seawater exchange.

Based on the distribution of oil pollution risk, several policy recommendations are proposed. Seasonally targeted measures include implementing stricter navigation regulations for tankers in the high-risk area of the Bohai Strait and Laizhou Bay. Optimizing the deployment of oil spill response equipment by pre-positioning relevant tools in high-risk areas and establishing regional emergency response teams is also crucial. Systematically, strengthening cross-regional cooperation among marine management agencies and integrating risk distribution results into existing marine environmental protection policies are both necessary.

Future research should focus on data refinement by introducing monthly or seasonal shipping route data. Additionally, sensitivity analysis should be expanded to evaluate the impact of changes in dynamic factors on oil spill risk assessment results.

Author Contributions: Conceptualization, T.L., R.C. and X.C.; data curation, X.C.; funding acquisition, X.C.; investigation, M.Z.; methodology, T.L., R.C. and F.B.; project administration, T.L., X.C. and J.X.; resources, F.B. and J.X.; software, T.L., M.Z. and X.C.; supervision, X.C. and J.X.; validation, R.C. and X.C.; visualization, F.B.; writing—original draft, R.C.; writing—review and editing, T.L. and M.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China, grant number 2023YFC3108300.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: Author Tao Liu, Minxia Zhang and Xing Chen was employed by the company CNOOC Research Institute Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Guo, J.; Liu, X.; Xie, Q. Characteristics of the Bohai Sea Oil Spill and Its Impact on the Bohai Sea Ecosystem. *Chin. Sci. Bull.* **2013**, *58*, 2276–2281. [CrossRef]
2. Pan, G.; Qiu, S.; Liu, X.; Hu, X. Estimating the Economic Damages from the Penglai 19-3 Oil Spill to the Yantai Fisheries in the Bohai Sea of Northeast China. *Mar. Policy* **2015**, *62*, 18–24. [CrossRef]
3. Han, H.; Huang, S.; Liu, S.; Sha, J.; Lv, X. An Assessment of Marine Ecosystem Damage from the Penglai 19-3 Oil Spill Accident. *J. Mar. Sci. Eng.* **2021**, *9*, 732. [CrossRef]
4. Cao, R.; Rong, Z.; Chen, H.; Liu, Y.; Mu, L.; Lv, X. Modeling the Long-Term Transport and Fate of Oil Spilled from the 2021 A Symphony Tanker Collision in the Yellow Sea, China: Reliability of the Stochastic Simulation. *Ocean Model.* **2023**, *186*, 102285. [CrossRef]
5. Cao, R.; Guo, J.; Rong, Z.; Chen, H.; Lv, X. Oil Pollution Risks on Coastlines in the Eastern China Seas. *Environ. Pollut.* **2025**, *372*, 125994. [CrossRef]
6. Liu, X.; Guo, J.; Guo, M.; Hu, X.; Tang, C.; Wang, C.; Xing, Q. Modelling of Oil Spill Trajectory for 2011 Penglai 19-3 Coastal Drilling Field, China. *Appl. Math. Model.* **2015**, *39*, 5331–5340. [CrossRef]
7. Guo, W.; Zhang, S.; Wu, G. Quantitative Oil Spill Risk from Offshore Fields in the Bohai Sea, China. *Sci. Total Environ.* **2019**, *688*, 494–504. [CrossRef]
8. Ke, L.; Li, Y.; Zhang, S.; Fan, J. Multisource remote sensing oil spill risk assessment and longsequence monitoring in the Bohai Sea. *Mar. Sci.* **2022**, *46*, 17–27. (In Chinese)
9. Tang, X.; Su, S. Simulation Analysis of Oil Spill Drift Diffusion in Jingtang Port Area. *Ship Ocean Engineer.* **2024**, *4*, 118–123. (In Chinese)
10. Cao, R.; Chen, H.; Rong, Z.; Lv, X. Impact of Ocean Waves on Transport of Underwater Spilled Oil in the Bohai Sea. *Mar. Pollut. Bull.* **2021**, *171*, 112702. [CrossRef]
11. Li, Y.; Chen, H.; Lv, X. Impact of Error in Ocean Dynamical Background, on the Transport of Underwater Spilled Oil. *Ocean Model.* **2018**, *132*, 30–45. [CrossRef]
12. Cao, R.; Chen, H.; Li, H.; Fu, H.; Wang, Y.; Bao, M.; Tuo, W.; Lv, X. A Mesoscale Assessment of Sinking Oil during Dispersant Treatment. *Ocean Eng.* **2022**, *263*, 112341. [CrossRef]
13. Li, Y.; Cao, R.; Chen, H.; Mu, L.; Lv, X. Impact of Oil−sediment Interaction on Transport of Underwater Spilled Oil in the Bohai Sea. *Ocean Eng.* **2022**, *247*, 110687. [CrossRef]
14. Haidvogel, D.B.; Arango, H.G.; Hedstrom, K.; Beckmann, A.; Malanotte-Rizzoli, P.; Shchepetkin, A.F. Model Evaluation Experiments in the North Atlantic Basin: Simulations in Nonlinear Terrain-Following Coordinates. *Dyn. Atmos. Ocean.* **2000**, *32*, 239–281. [CrossRef]
15. Shchepetkin, A.F.; McWilliams, J.C. The Regional Oceanic Modeling System (ROMS): A Split-Explicit, Free-Surface, Topography-Following-Coordinate Oceanic Model. *Ocean Model.* **2005**, *9*, 347–404. [CrossRef]
16. Alves, T.M.; Kokinou, E.; Zodiatis, G.; Radhakrishnan, H.; Panagiotakis, C.; Lardner, R. Multidisciplinary Oil Spill Modeling to Protect Coastal Communities and the Environment of the Eastern Mediterranean Sea. *Sci. Rep.* **2016**, *6*, 36882. [CrossRef]

17. Reed, M.; Leirvik, F.; Johansen, Ø.; Brørs, B. Numerical Algorithm to Compute the Effects of Breaking Waves on Surface Oil Spilled at Sea. In *Final Report Submitted to the Coastal Response Research Center*; SINTEF Institute for Materials and Chemistry: Trondheim, Norway, 2009; pp. 7–60.
18. Huang, D.; Su, J.; Backhaus, J.O. Modelling the Seasonal Thermal Stratification and Baroclinic Circulation in the Bohai Sea. *Cont. Shelf Res.* **1999**, *19*, 1485–1505. [CrossRef]
19. Lee, H.J.; Chao, S.Y. A Climatological Description of Circulation in and around the East China Sea. *Deep. Res. Part II Top. Stud. Oceanogr.* **2003**, *50*, 1065–1084. [CrossRef]
20. Wu, W.; Zhai, F.; Liu, C.; Gu, Y.; Li, P. Three-Dimensional Structure of Summer Circulation in the Bohai Sea and Its Intraseasonal Variability. *Ocean Dyn.* **2023**, *73*, 679–698. [CrossRef]
21. Xu, Y.; Zhou, F.; Meng, Q.; Zeng, D.; Yan, T.; Zhang, W. How Do Topography and Thermal Front Influence the Water Transport from the Northern Laotieshan Channel to the Bohai Sea Interior in Summer? *Deep. Res. Part II Top. Stud. Oceanogr.* **2023**, *208*, 105261. [CrossRef]
22. Zhang, Z.; Qiao, F.; Guo, J.; Guo, B. Seasonal Changes and Driving Forces of Inflow and Outflow through the Bohai Strait. *Cont. Shelf Res.* **2018**, *154*, 1–8. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.