

Research Article

Quantitative Assessment of Ship Oil Spill Risk in Arctic Ice Area Based on MCDM Assessment Model

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Abstract

Given the intensifying effects of climate change and the escalating human activities in the Arctic, such as shipping and resource extraction, the likelihood of oil spills in the region has increased substantially. The assessment of oil spill risks in Arctic ice-covered regions requires careful consideration of multiple interacting factors, including environmental parameters, socioeconomic vulnerabilities, and emergency response capabilities. There is an urgent need for a systematic assessment approach to support informed risk management decisions. This research aims to develop a multi-criteria decision-making framework to quantify the key drivers of Arctic oil spill risk and classify risk levels, thereby providing a basis for targeted intervention strategies. The intricate nature of Arctic ecosystems, combined with extreme weather conditions and sparse infrastructure, renders conventional risk models insufficient. In response to this challenge, our study employs sophisticated, integrative methodologies to more effectively capture the interrelationships between various risk factors. By integrating the DEMATEL-ANP method, this paper analyzes the causal relationships and relative weights among 14 indicators across four interrelated network layers. These methods not only clarify the causal chains between factors but also account for the intricate interrelations and dependencies within the system, offering a more comprehensive and adaptable decision-making framework. This integration leverages the strengths of both methods, enhancing the depth and accuracy of the analysis. A fuzzy comprehensive evaluation (FCE) approach is applied to convert expert judgments and derived weights into 5 categorical risk levels. The fuzzy logic component handles uncertainties inherent in expert elicitation, ensuring robustness despite data scarcity. The results indicate that ecological and socioeconomic vulnerability contribute most significantly to overall risk, while environmental factors such as sea ice coverage severely constrain emergency response effectiveness. The weighted FCE score identifies the Arctic oil spill scenario as high risk. The integrated DEMATEL-ANP-FCE framework effectively addresses the challenges of limited data availability in complex risk environments and provides a scientific foundation for Arctic oil spill monitoring, emergency planning, and policy formulation.

Keywords

Arctic Oil Spill, Risk Assessment, Multi-criteria Decision-making, DEMATEL-ANP-FCE, Quantitative Risk Analysis, DANP Model, Fuzzy Comprehensive Evaluation

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1. Introduction

With the deepening of economic globalization and the accelerating retreat of Arctic sea ice due to global climate change, the Arctic region is increasingly emerging as a strategic maritime corridor of global significance. The opening of Arctic shipping routes-particularly the Northern Sea Route (NSR)-has the potential to reduce transit distances between Asia and Europe by up to 40%, thereby significantly lowering transportation costs, fuel consumption, and carbon emissions [1, 2]. These advantages have attracted growing interest from the international shipping industry, prompting a notable increase in vessel traffic through Arctic waters.

However, this surge in navigational activity has concurrently heightened the risk of marine accidents such as collisions, groundings, and mechanical failures, many of which can lead to oil spills. In the ecologically fragile Arctic environment, oil spills pose severe and often irreversible threats to marine ecosystems, particularly the habitats of marine mammals and the livelihoods of Indigenous communities that depend on them. The region's limited self-purification capacity and the complex pathways of pollutant dispersion under ice-covered conditions further exacerbate the environmental consequences of such incidents [3].

Furthermore, oil discharged from vessels due to operational errors or maritime accidents may enter the Arctic food chain if not promptly contained, ultimately contributing to regional and even global ecological disruptions [4, 5]. As a result, the development of a scientifically robust, multi-dimensional risk assessment framework-one that accounts for spill characteristics, environmental conditions, and socio-ecological vulnerability-is urgently needed. Such a framework is essential for quantifying the risks of oil spills in Arctic ice-covered waters, identifying priority risk areas, and supporting proactive environmental governance and emergency response planning in the face of increasing Arctic maritime activity.

2. Literature Review

Due to the unique geographical and climatic conditions of the Arctic region-such as sea ice drift, extreme weather, and limited accessibility-oil spill emergency response and ecological restoration remain particularly challenging. Scholars at home and abroad have conducted relevant studies, primarily focusing on constructing multi-dimensional quantitative models to assess the environmental, economic, and social impacts of oil spill incidents [6]. Methods such as Analytic Network Process (ANP) and Bayesian Networks have been employed to conduct multi-factor integrated evaluations [7, 8]. However, these models often lack a detailed characterization of ice conditions, especially in terms of the coupling mechanisms between sea ice coverage, ice concentration, ice thickness, and emergency response deployment capacity.

In the field of risk assessment modeling, Bagheri *et al* applied the Delphi method to evaluate the impact of oil spills in

the Arctic [9], while Lin *et al* employed fuzzy mathematics to analyze oil spill risks in the region [10]. Tabesh *et al* utilized Monte Carlo simulations [11], and Cai *et al* adopted the Analytic Hierarchy Process (AHP) [12] to perform risk assessments for Arctic oil spill scenarios. The Battelle Memorial Institute, through its Geneva Research Center, adopted the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method in project research. This efficient approach integrates expert consensus (via brainstorming) to precisely identify causal relationships among multiple indicators [13]. Wang *et al* proposed an innovative model combining satisfaction-importance analysis and DEMATEL to identify factors potentially hindering project performance [14]. Ou Yang *et al* developed an information security risk control model that integrates VIKOR, DEMATEL, and ANP to resolve feedback conflicts and dependencies among evaluation indicators in organizational environments [15]. In efforts to improve marine insurance regulation concerning Arctic oil spill incidents, Afenyo *et al* developed a socioeconomic impact model to assess the implications of oil spills on equitable compensation from a global governance perspective [16].

Through reviewing the current body of domestic research, it is observed that most studies have focused on ecological impact evaluations and post-incident management recommendations. However, limited attention has been given to the proactive regulatory role of emergency response capacity during the initial phase of oil spill events. Furthermore, factors such as human settlement density, which is crucial to understanding the long-term social and economic consequences, have not been systematically analyzed. The sensitivity of ecological systems and the degree of regional economic development also play a critical role in amplifying or mitigating spill-related damage over time. In addition, the physicochemical properties of different oil types directly influence their diffusion pathways and removal efficiency in ice-covered marine environments [17], yet these key interdependencies are often underrepresented in mainstream risk assessment frameworks.

In response, this study proposes an integrated risk assessment framework that combines the DEMATEL-ANP method with the Fuzzy Comprehensive Evaluation (FCE) model. The framework is structured around four interrelated network layers: oil spill characteristics, environmental conditions, emergency response capacity, and ecological-socioeconomic vulnerability, encompassing 14 key influencing factors. The DEMATEL approach is first employed to identify the causal relationships among factors and construct a directed influence graph. Subsequently, ANP is used to compute the global weights of each factor, revealing systemic interaction mechanisms-such as the suppressive effect of emergency response capacity on spill characteristics and the delaying impact of ice conditions on response time.

Furthermore, the FCE method incorporates triangular fuzzy

numbers to account for the subjectivity and uncertainty of expert judgment, transforming qualitative assessments into five-tiered quantitative risk indicators. This integrated framework offers theoretical and practical support for Arctic

maritime environmental governance, early warning system development, and the enhancement of liability and compensation mechanisms for oil spill incidents.

3. Materials and Methods

3.1. Index System for Arctic Oil Spill Risk Assessment



Figure 1. Arctic study area.

The Scott Inlet cold seep, located off the coast of Baffin Island in the Nunavut region, is recognized as one of the most prominent subsea petroleum seepage sites, continuously releasing hydrocarbons into the Arctic marine environment. With the increase in maritime traffic, the surrounding area has emerged as a critical shipping hub. Owing to its unique geographical location, this region has been identified in multiple studies as a representative case area for oil spill response under extreme environmental conditions [18], as shown in the region highlighted in Figure 1.

In risk assessment modeling, the development of a scientifically sound and well-structured index system is the first and most critical step, as its quality directly affects the effectiveness and applicability of the entire evaluation process. In the case of Arctic oil spills, an event characterized by high complexity and uncertainty, it is essential to identify key impact factors sys-

tematically across multiple dimensions, including environmental conditions, operational constraints, and socioeconomic sensitivity. Based on the typical structure of the Analytic Network Process, this research constructs a multi-layered network model to represent the risk assessment mechanism of Arctic oil spills. Through a comprehensive review of relevant literature, Arctic oil spill risk was defined as the primary control layer, under which four interrelated network levels were established and further refined into 14 specific evaluation indicators, as shown in Figure 2. The network layer representing oil spill characteristics (S_1) includes oil type (S_{11}), spill volume (S_{12}), and sea ice coverage rate (S_{13}), which collectively reflect the scale and potential hazard of the spill. The environmental conditions of ice-covered regions (S_2) capture the specific Arctic context that contributes to oil spill events; indicators such as ice concentration (S_{21}), ice thickness (S_{22}), and wind

speed (S_{23}) describe the physical and meteorological characteristics of the region. The emergency response capacity (S_3) layer encompasses response time (S_{31}), availability of equipment (S_{32}), personnel deployment (S_{33}), and oil recovery efficiency (S_{34}), providing a measure of the operational effectiveness in mitigating spill impacts. Additionally, the ecological

and socio-economic vulnerability (S_4) layer incorporates indicators such as ecological sensitivity (S_{41}), population density (S_{42}), degree of economic development (S_{43}), and navigational priority (S_{44}), reflecting the region's potential exposure and resilience to oil spill incidents.

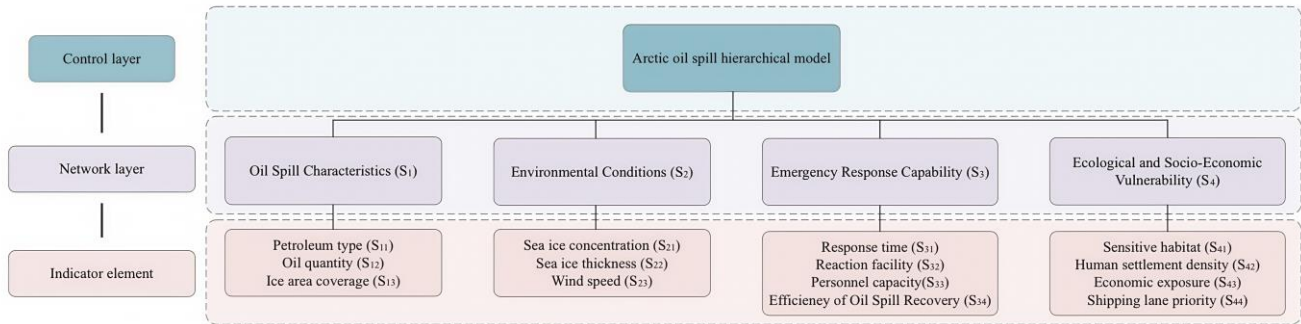


Figure 2. Structure of the indicator system.

3.2. Weight Calculation Using Integrated DEMATEL-ANP Method

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) is a graph-based multi-criteria decision-making (MCDM) method that explores interdependencies and effective influence values among evaluation factors by constructing causal relationship diagrams [19]. Given the non-independence of evaluation indicators in Arctic ice-region oil spill risk assessment, the DEMATEL method is employed to identify and visualize the causal interactions among indicators. The resulting influence structure is then used as the foundation for calculating indicator weights using the Analytic Network Process (ANP), thereby forming a combined DEMATEL-ANP approach. Unlike the Analytic Hierarchy Process (AHP), which assumes mutual independence among indicators when calculating weights, the ANP method allows for interdependencies and feedback among elements [20].

In this study, a 0-4 scale was adopted to capture the degree of influence a single indicator exerts on another. A panel of four polar safety experts was invited to complete the pairwise influence assessments. The internal consistency of the expert questionnaire was tested using Cronbach's alpha, yielding a reliability coefficient of 0.97, indicating excellent consistency and reliability of the evaluation scale.

3.2.1. Procedure for Applying the DEMATEL Approach

This method effectively integrates graph theory and matrix tools, providing robust support for analyzing complex relationships among factors within a system. The specific com-

putational steps are as follows:

(1) Construct the Direct Influence Matrix

A pairwise scoring system (0-4) is used to assign values to the indicators, where 0 to 4 represent No Influence, Weak Influence, Moderate Influence, Strong Influence, and Very Strong Influence, respectively. The direct influence matrix X is obtained:

$$X_{n \times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{bmatrix} \quad (1)$$

(2) Compute the Normalized Matrix

The direct influence matrix is normalized by dividing each element by the maximum row sum, yielding the normalized matrix N :

$$N = \frac{X}{\max_{1 \leq i \leq n} \sum_{j=1}^n x_{ij}} \quad (2)$$

(3) Compute the Total Influence Matrix

The total influence matrix T is derived from the normalized matrix N , where I is the identity matrix:

$$T = N(I - N)^{-1} \quad (3)$$

(4) Calculate Influence Measures

Influence Degree (R): Sum of the row elements in T , indicating the total influence exerted by a factor on others.

$$R_i = \sum_{j=1}^n t_{ij}, \quad (i=1, 2, \dots, n) \quad (4)$$

Dependence Degree (D): Sum of the column elements in T , indicating the total influence received by a factor from others.

$$D_j = \sum_{i=1}^n t_{ji}, (j=1,2,\dots,n) \quad (5)$$

Cause Degree (R - D): If positive, the factor is a cause (net influencer); if negative, it is an effect (net receiver).

Centrality (R + D): Reflects the factor's overall importance in the system.

(5) Plot the Cause-Effect Diagram

A causal diagram is drawn with Centrality (R + D) as the x-axis and Cause Degree (R - D) as the y-axis. Centrality quantifies a factor's relative prominence within the network structure, with elevated values signifying greater systemic importance. Cause Degree evaluates a factor's function as a causal driver within the system, where higher values reflect stronger influence over other interconnected elements.

3.2.2. Weight Derivation via the Integrated DEMATEL-ANP Method

(1) Computation of the Unweighted Supermatrix

Following pairwise comparisons of element importance, normalized eigenvectors w_i are derived for each element group. These eigenvectors represent local priorities within their respective clusters. The unweighted supermatrix W_{ij} is constructed by assembling these normalized vectors, where each column sums to unity, reflecting the relative importance of element e_i in cluster j as a secondary criterion. The mathematical formulation is:

$$W_{ij} = \begin{bmatrix} w_{i1}^{j1} & w_{i1}^{j2} & \dots & w_{i1}^{jn} \\ w_{i2}^{j1} & w_{i2}^{j2} & \dots & w_{i2}^{jn} \\ \vdots & \vdots & \ddots & \vdots \\ w_{in}^{j1} & w_{in}^{j2} & \dots & w_{in}^{jn} \end{bmatrix} \quad (6)$$

(2) Derivation of the Weighted Supermatrix

The unweighted supermatrix W_{ij} captures intra-cluster priorities but lacks inter-cluster comparability. To address this, a cluster-weighted matrix H_{ij} is constructed from normalized eigenvectors of inter-cluster pairwise comparisons. The weighted supermatrix W^a is obtained by:

$$W^a = H_{ij} \times W_{ij} \quad (i,j=1,2,\dots,n) \quad (7)$$

(3) Calculation of the Limit Supermatrix

To derive stable weights, the weighted supermatrix W^a is raised to a sufficiently large power k until convergence (Markov chain principle), yielding the limit supermatrix W^∞ :

$$W^\infty = \lim_{k \rightarrow \infty} (W^a)^k \quad (8)$$

(4) Computation of Integrated Weights

The final weights ω are obtained by multiplying the limit supermatrix-derived element weights w^∞ with the criterion-layer weights γ :

$$\omega = w^\infty \cdot \gamma \quad (9)$$

3.3. Development of the Fuzzy Risk Evaluation Model

In view of the inherent fuzziness and uncertainty in oil spill risk assessment within the Arctic region, this research adopts the Fuzzy Comprehensive Evaluation (FCE) method to enhance the scientific rigor and rationality of risk identification and classification [21].

(1) Establishment of Fuzzy Evaluation Factor Sets and Weight Sets

Based on the hierarchical structure of indicators and their respective weights, the evaluation factor sets and weight sets are constructed as shown in Table 1.

Table 1. Factor sets and weight sets.

Factor sets	Weight sets
$S = [S_1, S_2, S_3, S_4]$	$W_S = [w_{S_1}, w_{S_2}, w_{S_3}, w_{S_4}]$
$S_1 = [S_{11}, S_{12}, S_{13}]$	$W_{S_1} = [w_{S_{11}}, w_{S_{12}}, w_{S_{13}}]$
$S_2 = [S_{21}, S_{22}, S_{23}]$	$W_{S_2} = [w_{S_{21}}, w_{S_{22}}, w_{S_{23}}]$
$S_3 = [S_{31}, S_{32}, S_{33}, S_{34}]$	$W_{S_3} = [w_{S_{31}}, w_{S_{32}}, w_{S_{33}}, w_{S_{34}}]$
$S_4 = [S_{41}, S_{42}, S_{43}, S_{44}]$	$W_{S_4} = [w_{S_{41}}, w_{S_{42}}, w_{S_{43}}, w_{S_{44}}]$

(2) Construction of the oil Spill Risk Evaluation Set

Table 2. Risk scale distributions.

Risk level	Extremely high	High	Medium	Low	Ultra-low
Score	5	4	3	2	1
Score range	[4.5, 5]	[4, 4.5]	[3, 4]	[2, 3]	[0, 2]

The risk level refers to the set of all potential risk outcomes associated with the indicators of Arctic oil spill impacts. Depending on the characteristics of the indicators and practical circumstances, the risk criteria can be classified into different levels. In this research, the risk levels are defined as $V = \{\text{Extremely High, High, Medium, Low, Ultra-low}\}$, with each grade corresponding to a specific score, as detailed in Table 2.

(3) Formation of the Fuzzy Evaluation Matrix

Multiple evaluators are invited to assess the indicator layer based on the evaluation grade set. After quantifying the indicators, the membership degree F_i^j for the i -th factor with respect to the j -th evaluation grade is calculated as the proportion of evaluators who assign the j -th grade to the i -th factor relative to the total number of evaluators. The fuzzy relation matrix is then constructed as follows:

$$F_i^j = \begin{bmatrix} F_1^1 & F_1^2 & F_1^3 & \dots & F_1^j \\ F_2^1 & F_2^2 & F_2^3 & \dots & F_2^j \\ \dots & \dots & \dots & \dots & \dots \\ F_i^1 & F_i^2 & F_i^3 & \dots & F_i^j \end{bmatrix} \quad (10)$$

(4) Calculation of Membership Degrees

The weighted average operator model $M(\cdot, \oplus)$ is employed to multiply the weight set W with the fuzzy matrix F , yielding the membership degree matrix for the higher-level indicators. This process is repeated iteratively by multiplying the higher-level weight sets with their corresponding membership degree matrices until the membership degree matrix Z for the target layer is obtained.

(5) Computation of Final Scores

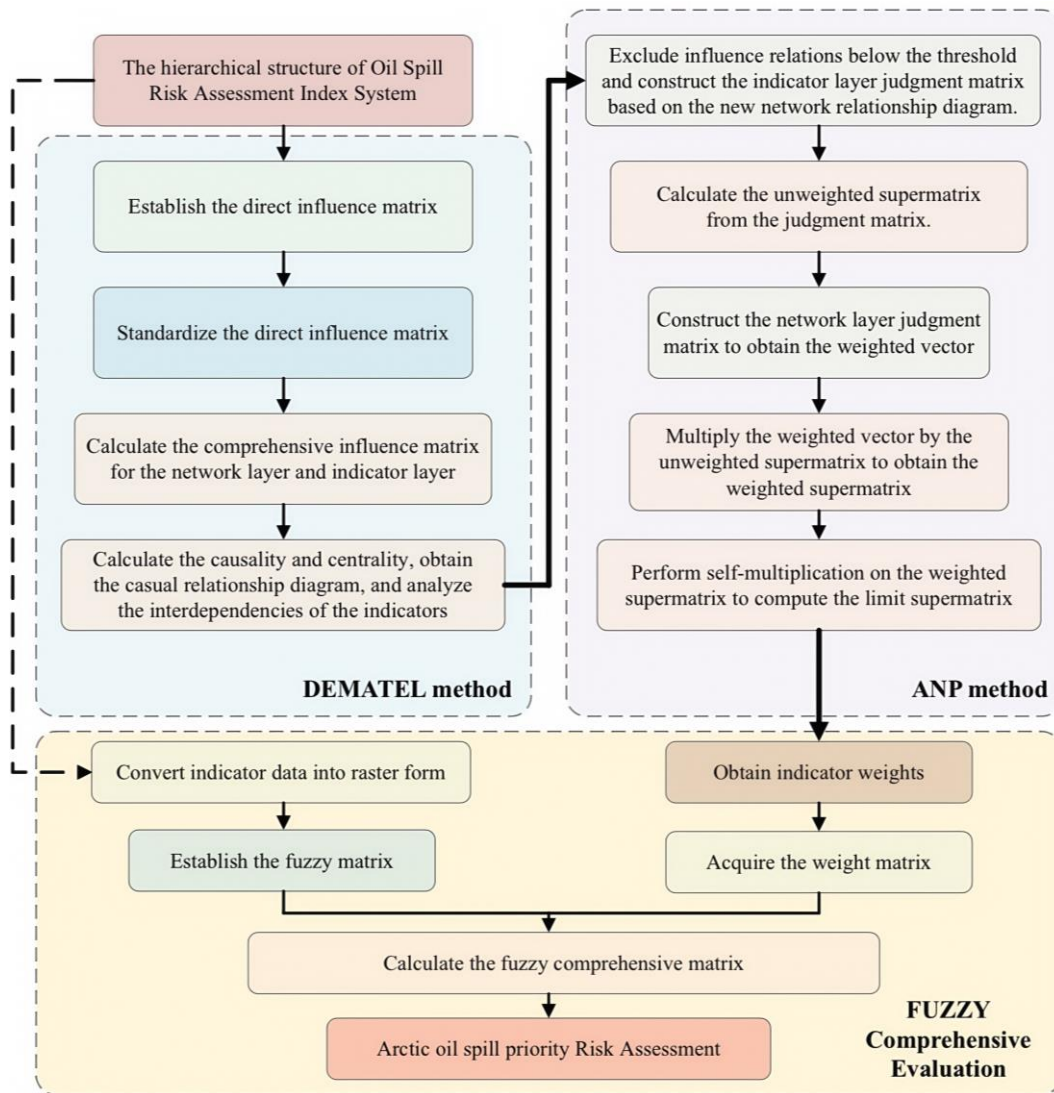


Figure 3. Flowchart of the Arctic oil spill risk assessment model.

The comprehensive evaluation score E is derived by multiplying the target-layer membership degree matrix Z with

the predefined score vector V :

$$\text{Score} = \sum_{k=1}^n Z_k \cdot V_k \quad (11)$$

The specific methodological steps are illustrated in Figure 3.

4. Results

4.1. Interdependencies Among Risk Factors

The integrated influence matrix for the selected indicator layer is presented in Table 3. Each cell in the matrix reflects the degree of influence exerted by the row indicator on the

corresponding column indicator.

Based on the matrix in Table 3, both the centrality-causality chart and the causal relationship diagram of the indicators are derived, as shown in Figure 4. In Figure 4(b), arrows indicate the direction of influence, pointing from the influencing factor to the influenced one. In Figure 4(a), The indicators within the environmental conditions group exhibit positive causality values, indicating that they act as causal factors affecting other groups. In contrast, the indicators in the emergency response capacity group have negative causality values, suggesting they belong to the result group and are predominantly influenced by other factor groups.

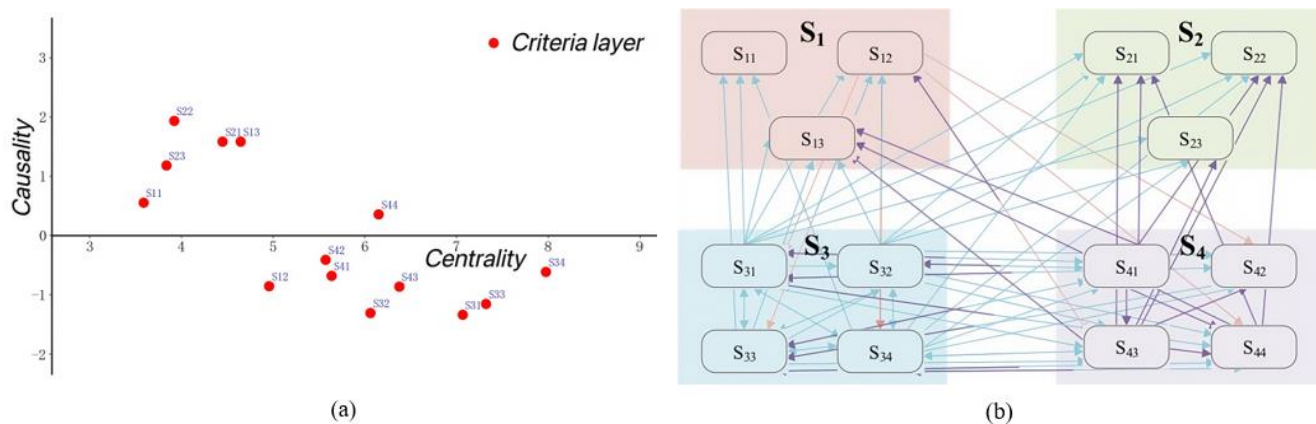


Figure 4. DEMATEL results. (a) Centrality-causality diagram. (b) Causal relationship network.

Indicators with higher centrality values, such as oil recovery efficiency, demonstrate greater overall importance within the evaluation system. Centrality analysis allows for the

identification of relatively significant indicators in Arctic oil spill risk assessment, while causality analysis helps determine those indicators with broader influence across the system.

Table 3. Total influence matrix of the indicator layer.

	S11	S12	S13	S21	S22	S23	S31	S32	S33	S34	S41	S42	S43	S44
S11	0.0706	0.1301	0.0593	0.0562	0.0391	0.0553	0.2398	0.1981	0.2426	0.268	0.2032	0.1738	0.1969	0.1378
S12	0.0664	0.1279	0.0818	0.0543	0.0382	0.0517	0.2376	0.1982	0.2411	0.2181	0.177	0.1742	0.2215	0.1635
S13	0.0969	0.1817	0.0972	0.1659	0.114	0.1354	0.3507	0.2967	0.351	0.357	0.2418	0.2072	0.2697	0.2505
S21	0.0934	0.1761	0.1669	0.0894	0.1119	0.1322	0.3428	0.2895	0.3204	0.3485	0.2354	0.2016	0.2627	0.2451
S22	0.0926	0.1736	0.1398	0.1356	0.0599	0.1054	0.3352	0.2837	0.3361	0.3413	0.2309	0.1972	0.2575	0.239
S23	0.0789	0.1504	0.126	0.1223	0.0518	0.0676	0.2764	0.2303	0.2781	0.2813	0.2038	0.1972	0.2281	0.215
S31	0.1416	0.2518	0.0804	0.0742	0.0527	0.072	0.2295	0.2781	0.3074	0.3295	0.2729	0.2464	0.3008	0.228
S32	0.0808	0.1778	0.0677	0.0634	0.0446	0.0616	0.2873	0.1722	0.2684	0.2914	0.2213	0.2178	0.2455	0.1806
S33	0.1439	0.2288	0.1401	0.1345	0.0844	0.1299	0.3233	0.2929	0.2525	0.3512	0.2626	0.2306	0.2895	0.2215
S34	0.1816	0.3028	0.1814	0.174	0.1186	0.167	0.3943	0.3345	0.3964	0.3056	0.2766	0.2635	0.3314	0.2568
S41	0.1261	0.2158	0.0979	0.0927	0.0708	0.1132	0.273	0.2248	0.2749	0.2775	0.1531	0.1939	0.2013	0.163

	S ₁₁	S ₁₂	S ₁₃	S ₂₁	S ₂₂	S ₂₃	S ₃₁	S ₃₂	S ₃₃	S ₃₄	S ₄₁	S ₄₂	S ₄₃	S ₄₄
S42	0.1074	0.2336	0.0713	0.0656	0.0459	0.0632	0.2805	0.2824	0.3072	0.2849	0.2106	0.1576	0.2832	0.1914
S43	0.1119	0.2674	0.0767	0.0701	0.0494	0.0669	0.2942	0.2945	0.3211	0.2982	0.2207	0.2634	0.201	0.2235
S44	0.1222	0.2879	0.1432	0.1362	0.1103	0.1065	0.3365	0.3069	0.3401	0.3407	0.2486	0.2649	0.3275	0.1823

4.2. Weighting Results of the Index System Based on DANP

The weight results derived from expert scoring and subsequent ANP calculations are presented in Table 4. To ensure the reliability and domain relevance of the results, four experts were invited to participate in the evaluation process. These experts possess extensive experience in the fields of Arctic environmental science, maritime safety, oil spill emergency response, and ecological risk assessment. Their judgments provide a comprehensive and interdisciplinary foundation for the weighting process.

As shown in Table 4, the weighting results derived from the DANP methodology reveal a clear hierarchy of importance among the Arctic oil spill risk assessment indicators. Ecological and Socioeconomic Vulnerability emerges as the most critical dimension, accounting for 44.83% of the total weight, with Economic Exposure (S₄₃) representing the single most influential factor at 16.21% of the comprehensive weight. This dominance reflects the profound long-term consequences oil spills can have on Arctic communities and ecosystems, where economic activities are particularly vulnerable to marine envi-

ronmental disruptions. The Emergency Response Capability category follows in significance with 29.17% of the total weight, where Response Time (S₃₁) and Personnel Capacity (S₃₃) stand out as crucial operational factors. Environmental Conditions, particularly Sea Ice Thickness (S₂₂) and Concentration (S₂₁), collectively contribute 19.99% to the overall risk assessment, underscoring the unique challenges posed by Arctic marine conditions. Interestingly, while Oil Spill Characteristics represent the smallest category at just 6.00%, the Ice Area Coverage indicator (S₁₃) within this group carries substantial relative importance (76.07%), highlighting how Arctic-specific conditions fundamentally alter the risk profile of spills compared to temperate regions. The comprehensive weighting structure demonstrates how traditional oil spill risk factors are recontextualized in the Arctic environment, with greater emphasis placed on ecological fragility, response limitations, and socioeconomic consequences rather than just the physical characteristics of the spill itself. This weighting scheme provides a nuanced framework for prioritizing risk mitigation strategies that account for both the unique environmental conditions and the heightened vulnerability of Arctic social-ecological systems.

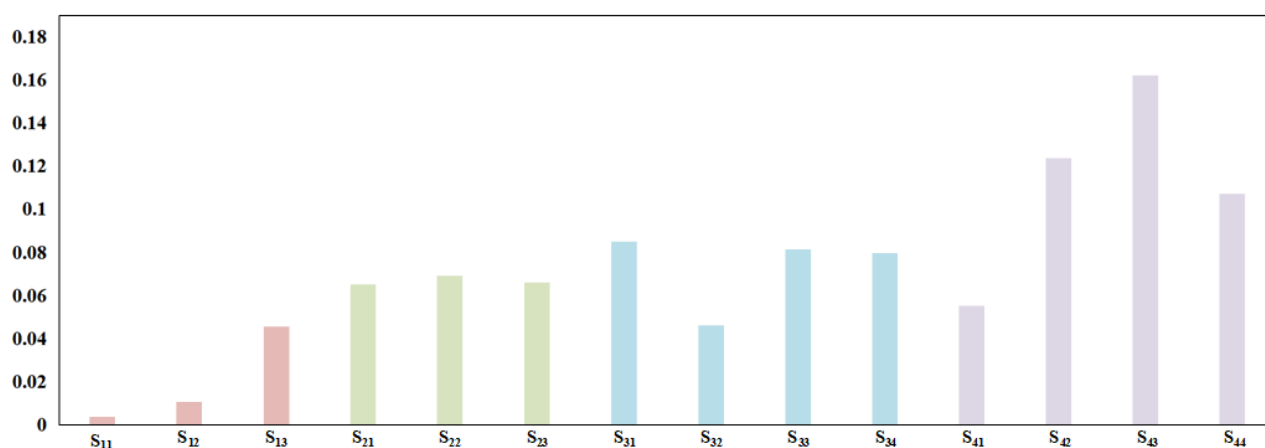


Figure 5. Weight histograms for the indicator impact factors.

Table 4. Weights of oil spill risk assessment indicators.

Control layer	Network layer	Relative weight	Indicator element	Relative weight	Comprehensive weight
Arctic oil spill hierarchical model	Oil spill characteristics (S ₁)	0.0600	Petroleum type (S ₁₁)	0.0631	0.0038
			Oil quantity (S ₁₂)	0.1763	0.0106
			Ice area coverage (S ₁₃)	0.7607	0.0457
	Environmental conditions (S ₂)	0.1999	Sea ice concentration (S ₂₁)	0.3255	0.0651
			Sea ice thickness (S ₂₂)	0.3451	0.0690
			Wind speed (S ₂₃)	0.3294	0.0659
	Emergency response capability (S ₃)	0.2917	Response time (S ₃₁)	0.2902	0.0847
			Reaction facility (S ₃₂)	0.1578	0.0460
			Personnel capacity (S ₃₃)	0.2786	0.0813
			Efficiency of oil spill recovery (S ₃₄)	0.2734	0.0798
	Ecological and socio-economic vulnerability (S ₄)	0.4483	Sensitive habitat (S ₄₁)	0.1233	0.0553
			Human settlement density (S ₄₂)	0.2758	0.1236
			Economic exposure (S ₄₃)	0.3615	0.1621
			Shipping lane priority (S ₄₄)	0.2394	0.1073

For enhanced visualization of the weighting distribution among different evaluation indicators, the quantified weight values are graphically illustrated in Figure 5.

4.3. Fuzzy Evaluation Matrix and Risk Analysis

To further enhance the reliability and comprehensiveness of the risk evaluation, 30 evaluators were invited to assess each indicator based on predefined evaluation criteria. The panel of evaluators was composed of a diverse and interdisciplinary group, including academic researchers in Arctic environmental science, government officials from maritime regula-

tory agencies, emergency response practitioners, and industry experts in oil spill prevention and control. This ensured that the evaluations incorporated both theoretical insights and practical field experience. Risk factors related to an oil spill were evaluated, and their score distributions are detailed in Table 5. As a multi-level index system, the hierarchical structure of this paper requires multi-level fuzzy comprehensive evaluation to obtain the final evaluation results. According to the statistical results, the fuzzy evaluation of Network layer S is carried out, and its weight set and fuzzy matrix are WS and FS respectively.

Table 5. Questionnaire data statistics table.

Risk level	Extremely high risk	High risk	Medium risk	Low risk	Ultra-low risk
S ₁₁	5	15	6	2	2
S ₁₂	21	5	3	1	0
S ₁₃	15	6	6	2	1
S ₂₁	3	12	6	4	5
S ₂₂	19	7	4	0	0
S ₂₃	0	6	17	3	4
S ₃₁	13	11	3	2	1
S ₃₂	4	21	2	2	1

Risk level	Extremely high risk	High risk	Medium risk	Low risk	Ultra-low risk
S ₃₃	11	15	1	1	2
S ₃₄	17	4	4	3	2
S ₄₁	13	8	7	2	0
S ₄₂	17	8	4	1	0
S ₄₃	20	4	3	2	1
S ₄₄	12	10	4	2	2

$$W_S = [0.06 \quad 0.1999 \quad 0.2917 \quad 0.4483] \quad (12)$$

$$F_S = \begin{bmatrix} 0.5143 & 0.2131 & 0.1824 & 0.0608 & 0.0295 \\ 0.2511 & 0.2766 & 0.2978 & 0.0763 & 0.0982 \\ 0.4039 & 0.3926 & 0.0853 & 0.0665 & 0.0517 \\ 0.5465 & 0.2344 & 0.1336 & 0.0575 & 0.028 \end{bmatrix} \quad (13)$$

$$Z_S = W_S \times F_S = [0.4439 \quad 0.2877 \quad 0.1552 \quad 0.0641 \quad 0.049] \quad (14)$$

$$score = [0.4439 \quad 0.2877 \quad 0.1552 \quad 0.0641 \quad 0.049] \times \begin{bmatrix} 5 \\ 4 \\ 3 \\ 2 \\ 1 \end{bmatrix} = 4.01 \quad (15)$$

Upon synthesizing the four sub-layers, the system-level assessment (S layer) indicates a high-risk classification. This suggests that even though certain components exhibit only moderate risk, oil spill incidents in the Arctic's ice-covered context still present substantial potential hazards. The result underscores the cumulative and interactive effects of multiple factors in amplifying the overall risk level.

5. Discussion

This study systematically evaluated the contributions of 14 indicators to Arctic oil spill risk using a multi-criteria decision-making framework. Among the four major categories, spill characteristics, environmental conditions, emergency response capacity, and ecological and socioeconomic vulnerability, the indicators under ecological and socioeconomic vulnerability exhibited the highest weights. In particular, population density (S₄₂), economic development level (S₄₃), and navigation priority (S₄₄) were identified as dominant contributors to overall risk. Similar to findings from tropical coastal regions, where oil spill vulnerability increases with higher population density and economic reliance on marine resources [22], Arctic coastal communities may experience similar patterns of socioeconomic sensitivity, particularly in areas with clustered settlements and limited adaptive capacity. In protected coastal regions, areas with intensive human activity, such as fishing and tourism, also exhibited heightened vulnerability [23]. The proposed evaluation framework suc-

cessfully distinguishes indicators with high systemic importance, thereby facilitating evidence-based prioritization of risk management efforts.

The DEMATEL analysis revealed distinct causal structures among indicators. Ice coverage rate and oil type were identified as high-causality, upstream variables, while indicators related to emergency response (e.g., equipment availability, response time) were more often classified as downstream or result-oriented. These findings underscore how environmental constraints can diminish the operational effectiveness of human interventions. Unlike traditional AHP approaches that assume indicator independence, the integrated DEMATEL-ANP method captures feedback loops and interdependencies among variables. Similar modeling strategies have been applied in maritime logistics and energy planning, validating the utility of ANP for structurally complex, risk-driven systems [24, 25]. In this study, the global weights derived from ANP reflect both the direct influence and network-mediated effects of each indicator, leading to a more robust and context-sensitive risk quantification.

A key strength of extending the DEMATEL-ANP framework with Fuzzy Comprehensive Evaluation (FCE) lies in its ability to translate expert-elicited indicators into graded risk levels, as validated by our findings. Without FCE, the model would only produce weights, not actionable risk categories. Applying FCE enabled us to categorize regions into discrete risk levels (e.g., medium, high), revealing how small variations in key indicators can shift overall risk tiers. This outcome aligns with existing applications in high-uncertainty environments. Similarly, flood risk assessment studies combining DEMATEL-ANP with fuzzy evaluation showed that traditional threshold-based categorizations often mask intermediate risk gradations vital for dynamic response planning [26]. By enabling us to model risk as a continuum rather than a binary state, FCE enhances the interpretability and flexibility of our risk assessment. This proves especially useful in Arctic oil spill scenarios, where operational complexity and environmental variability demand nuanced, threshold-sensitive decision tools.

The integrated DEMATEL-ANP-FCE framework offers a transparent and adaptable approach to assessing oil spill risks in the Arctic, especially under conditions of limited data and

logistical constraints. While the current model operates as a static evaluation mechanism, it effectively identifies high-priority risk factors. These insights support strategic investments in early monitoring, emergency preparedness, and targeted policy interventions. Previous research has validated the feasibility of combining ANP and fuzzy evaluation for Arctic oil spill scenarios, yielding structured and interpretable indicator hierarchies.

To improve practical applicability, future research could integrate spatial and temporal elements. Coupling the model with GIS-based visualization of risk zones would help identify spatial clusters of high-risk Arctic areas and inform targeted interventions [27]. Implementing dynamic oil-spill trajectory models that incorporate ice movement, ocean currents, and wind—for example, using discrete-element simulations used in Arctic ice-condition scenarios—can significantly enhance temporal accuracy [17]. Furthermore, incorporating Indigenous knowledge and stakeholder input through community maps and traditional-use data—such as those developed by the Alaska Ocean Observing System—enriches the risk framework with local experience and boosts its credibility and inclusiveness.

6. Conclusions

This research proposes a comprehensive assessment method for oil spill risk in the Arctic ice-covered regions. By establishing an evaluation framework encompassing four dimensions, including spill characteristics, environmental conditions, emergency response capacity, and ecological-socioeconomic vulnerability, an integrated model combining DANP (Decision-Making Trial and Evaluation Laboratory with Analytic Network Process) and FCE (Fuzzy Comprehensive Evaluation) is employed to achieve quantitative risk assessment. Expert consultation with Arctic maritime safety specialists and an extensive literature review were used to inform the model development. Findings reveal that ecological and socioeconomic vulnerability contributes most significantly to the overall risk, with indicators such as population density, economic development level, and shipping priority playing decisive roles. The research also reveals that the distinctive environmental factors in the Arctic, especially ice coverage, substantially restrict the efficacy of emergency responses. The FCE method computes the comprehensive membership degrees across different risk levels by multiplying the fuzzy evaluation matrix with the weight vector, and then derives the final risk score through weighted summation based on predefined level values. The resulting Arctic oil spill risk score is 4.01, corresponding to a high-risk classification. The proposed model offers a scientific basis for Arctic maritime safety management and policymaking. However, limitations remain, such as the lack of consideration for spatiotemporal dynamics. Future research will aim to address these gaps by integrating GIS-based spatial analysis with dynamic oil spill diffusion modeling, incorporating

Indigenous ecological knowledge, and applying machine learning algorithms to enhance the model's accuracy and applicability. These advancements are expected to promote more intelligent and precise risk management for Arctic oil spill scenarios.

Abbreviations

MCDM	Multi-criteria Decision-making
ANP	Analytic Network Process
AHP	Analytic Hierarchy Process
FCE	Fuzzy Comprehensive Evaluation
DEMATEL	Decision Making Trial and Evaluation Laboratory
DANP	DEMATEL-based Analytic Network Process

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The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflicts of interest.

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