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# Environmental Risk Modeling and Management of Dredging and Dredged-Material Disposal Operations with a Sustainable Coastal and Marine Environment Approach

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**ABSTRACT**

Purpose: This study develops an integrated fuzzy multi-criteria framework for modeling and prioritizing environmental risks associated with dredging and dredged-material disposal operations at Khorramshahr Port, with emphasis on sustainable coastal and marine management.

Design/methodology/approach: Environmental risks were identified through a review of scientific and technical sources and consultation with specialists in port management, dredging, and marine environmental protection. Twenty-seven risks were classified into physicochemical and ecological categories for dredging and disposal operations. The relative importance of severity, occurrence probability, and detectability was determined using the Fuzzy Analytic Hierarchy Process. Expert ratings expressed as triangular fuzzy numbers were then analyzed using Fuzzy TOPSIS, and each risk was ranked according to its closeness to the positive ideal solution.

Findings: Severity received the greatest fuzzy weight, followed by occurrence probability and detectability. Changes in seabed morphology ranked first among physicochemical dredging risks, while destruction of benthic habitats was the highest-priority ecological dredging risk. For dredged-material disposal, increased water turbidity was the leading physicochemical risk and destruction of benthic habitats was the most critical ecological risk.

Research limitations/implications: The assessment was based on expert judgment in a single port and should be validated using monitoring data and applications in other coastal settings.

Originality/value: The proposed framework integrates fuzzy criteria weighting and ideal-solution ranking in a structured environmental risk-management model. It provides port authorities with a transparent basis for identifying critical hazards, prioritizing mitigation measures, allocating monitoring resources, and supporting environmentally responsible dredging and disposal decisions. It can also be updated when new monitoring evidence becomes available.

## 1. Introduction

Ports are critical nodes in international supply chains, and more than four-fifths of world merchandise trade by volume is transported by sea [1, 2]. Maintaining navigation channels and port access therefore requires regular dredging and the management of dredged material. At the same time, international maritime and environmental policies increasingly require ports to improve ecological performance, reduce emissions and pollution, and integrate environmental protection into infrastructure planning [3, 4].

Dredging supports navigational safety, terminal accessibility, and infrastructure development, but it can also modify seabed morphology, resuspend contaminated sediment, increase turbidity and suspended solids, and disturb coastal habitats [5–7]. Dredged-material disposal may transfer these impacts to disposal sites through sediment accumulation, pollutant redistribution, burial of benthic communities, and changes in water and sediment quality. Inadequate control can increase environmental and maintenance costs and undermine the long-term sustainability of port operations.

Green-port research treats environmental performance as a strategic component of competitiveness rather than a separate compliance issue [8–10]. Effective management requires the identification and prioritization of risks that differ in likelihood, severity, and detectability. Conventional scoring methods are often limited when evidence is incomplete and expert judgments are imprecise, particularly in estuarine systems where hydrodynamic, sedimentary, ecological, and operational conditions interact [11].

Fuzzy multi-criteria decision-making methods provide a practical means of representing linguistic assessments and combining several risk dimensions. Fuzzy AHP supports criteria weighting through pairwise comparisons, whereas Fuzzy TOPSIS ranks alternatives according to their distances from positive and negative ideal solutions [12–16]. However, their integrated application to both dredging and dredged-material disposal risks in Iranian ports remains limited.

Accordingly, this study develops and applies an integrated Fuzzy AHP–Fuzzy TOPSIS framework at Khorramshahr Port. The objectives were to identify and classify environmental risks, determine the relative importance of severity, occurrence probability, and detectability, prioritize the risks within each operational category, and derive management priorities for sustainable coastal and marine operations.

## 2. Theoretical Background

### 2.1. Environmental Risks of Dredging and Disposal

Dredging-induced impacts depend on sediment properties, dredging technology, hydrodynamic conditions, contaminant levels, and the sensitivity of receiving ecosystems. Physicochemical effects include seabed alteration, turbidity, suspended-solids release, erosion, contaminant mobilization, and changes in sediment quality. Ecological effects include habitat destruction, loss or displacement of benthic species, food-chain disturbance, and physiological stress in aquatic organisms [5–7]. Because these effects may be temporary, cumulative, or spatially transferred, monitoring and management must address both the dredging site and the disposal area.

### 2.2. Sustainable Port Environmental Management

Environmental governance, monitoring systems, and green innovation are increasingly associated with port sustainability and resilience [8–10, 17]. Smart-port technologies and digital transformation can strengthen monitoring, traceability, early warning, and adaptive management [18, 19]. Long-term environmental performance also depends on governance capacity, stakeholder coordination, and the integration of ecological indicators into operational decisions [20–22].

### 2.3. Fuzzy Risk Assessment

Fuzzy set theory represents vague judgments by membership functions rather than crisp values [23]. In Fuzzy AHP, triangular fuzzy numbers are used to compare criteria and estimate their relative importance [14, 15, 24]. Fuzzy TOPSIS constructs weighted normalized evaluations, identifies fuzzy positive and negative ideal solutions, and calculates a closeness coefficient for ranking alternatives [16, 25]. The combined approach is suitable for environmental risk assessment because it preserves uncertainty while producing an explicit priority order [13, 26].

### 2.4. Research Gap

Previous port studies have examined environmental performance, sustainability policies, monitoring, smart-port development, and fuzzy risk analysis, but few provide an integrated framework covering the full chain from risk identification to prioritization for dredging and dredged-material disposal. Table 1 summarizes representative contributions and the methodological position of the present study.

**Table 1. Selected studies on environmental risk management and fuzzy decision-making in ports**

| Author(s) | Year | Approach | Key contribution |
|---|---|---|---|
| Acciaro et al. [9] | 2014 | Port sustainability framework | Environmental innovation is influenced by managerial, institutional, and operational conditions. |
| Lam and Notteboom [8] | 2014 | Green-port management | Leading ports use different regulatory, economic, and operational tools to reduce environmental impacts. |
| Aregall et al. [10] | 2018 | Green-port governance | Port environmental strategies require coordination across port and hinterland systems. |
| PIANC [5] | 2019 | Dredging guidance | Structured selection and monitoring improve the environmental management of dredging activities. |
| Molavi et al. [18] | 2020 | Smart-port framework | Digital technologies support efficiency, safety, and sustainability-oriented port management. |
| Lu et al. [20] | 2022 | Port sustainability | Environmental governance and green innovation strengthen sustainability performance. |
| Yousefi et al. [26] | 2014 | Fuzzy maritime risk analysis | Fuzzy MCDM enables systematic prioritization of environmental risks under uncertainty. |
| Dymova et al. [13] | 2013 | Fuzzy TOPSIS | Generalized fuzzy TOPSIS improves ranking robustness when evaluations are imprecise. |

*Source: Compiled by the authors from the reviewed literature.*

The present study extends this literature by integrating risk identification, fuzzy criteria weighting, and fuzzy ideal-solution ranking in one case-based framework that distinguishes dredging from disposal and physicochemical from ecological impacts.

## 3. Materials and Methods

### 3.1. Study Area and Research Design

Khorramshahr Port is located in Khuzestan Province along the Arvand waterway. Its riverine–estuarine setting, sediment dynamics, navigation requirements, and environmental sensitivity make it an appropriate case for evaluating dredging and disposal risks. The study was applied and descriptive–analytical and employed a fuzzy multi-criteria decision-making design.

### 3.2. Risk Identification and Data Collection

The research was implemented in three phases. First, environmental risks were identified from scientific literature, technical guidance, and expert brainstorming. A purposive panel of specialists in port management, marine environmental protection, dredging engineering, and maritime operations reviewed the risk list and data-collection instruments. The final set contained 27 risks classified into dredging physicochemical risks, dredging ecological risks, disposal physicochemical risks, and disposal ecological risks.

Second, experts completed pairwise-comparison questionnaires for severity, occurrence probability, and detectability. Third, each risk was evaluated on the three criteria using linguistic ratings represented by triangular fuzzy numbers. Expert judgments were aggregated and used to construct the fuzzy decision matrices.

### 3.3. Analytical Framework

The framework begins with risk identification and classification, continues with Fuzzy AHP weighting of the assessment criteria, and concludes with Fuzzy TOPSIS prioritization. The managerial outputs include identification of critical risks, design of mitigation measures, allocation of monitoring resources, and support for sustainable port governance. Figure 1 presents the complete workflow.

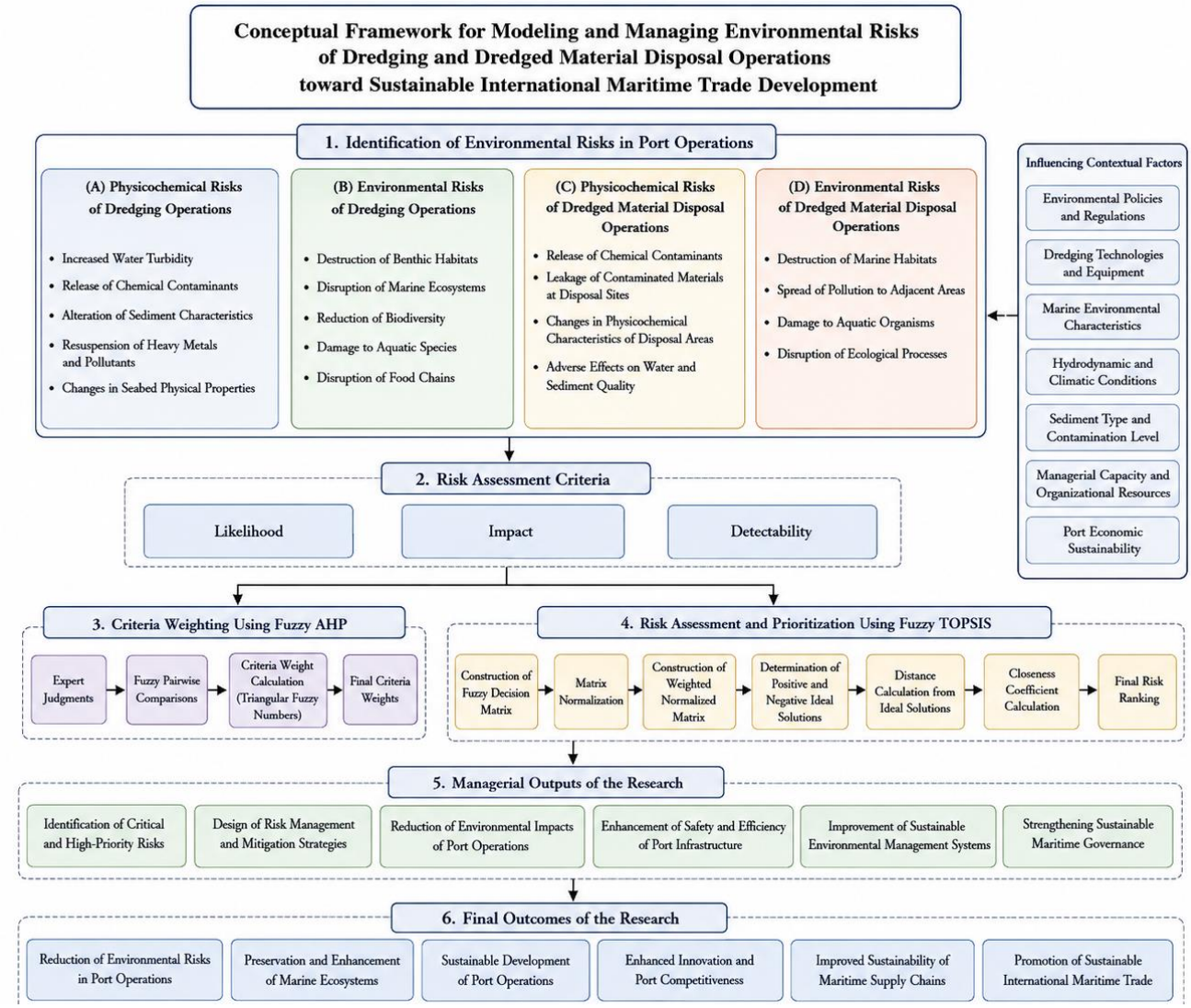



**Figure 1. Conceptual framework for modeling and managing the environmental risks of dredging and dredged-material disposal operations**

### 3.4. Fuzzy AHP and Fuzzy TOPSIS Procedures

Triangular fuzzy numbers were used to represent the lower, most probable, and upper values of expert judgments. The relative weights of severity, occurrence probability, and detectability were obtained by Fuzzy AHP. The Fuzzy TOPSIS procedure then comprised construction of the fuzzy decision matrix, aggregation of group judgments, normalization, formation of the weighted normalized matrix, identification of the positive and negative ideal solutions, calculation of separation measures, and computation of the closeness coefficient.

The fuzzy decision matrix is expressed in Eq. (1), and a triangular fuzzy number is defined in Eq. (2).

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad (1)$$

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}) \quad (2)$$

When evaluations are provided by k decision-makers, the aggregated fuzzy value is calculated using the group aggregation relationship shown below. The fuzzy criteria-weight vector and its triangular components are then defined by Eqs. (3) and (4) [27].

$$\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk})$$

$$W_j(w_1, w_2, \dots, w_n) \quad (3)$$

$$W_{ij}(w_{j1}, w_{j2}, w_{j3}) \quad (4)$$

Benefit and cost criteria are normalized using Eqs. (5) and (6), after which the weighted normalized fuzzy matrix is formed using Eqs. (7) and (8).

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \qquad c_j^* = \max_i c_{ij} \quad (5)$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \qquad a_j^- = \min_i a_{ij} \quad (6)$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j \quad (7)$$

$$\widetilde{D} = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix} \quad (8)$$

The fuzzy positive and negative ideal solutions are determined by Eqs. (9) and (10). The separation of each risk from these solutions is calculated through Eqs. (11) and (12), and the final closeness coefficient is obtained from Eq. (13). A higher closeness coefficient indicates a higher risk priority.

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*) \quad (9)$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-) \quad (10)$$

$$S_i^* = \sum_{i=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^*\right) \quad (11)$$

$$S_i^- = \sum_{i=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \quad (12)$$

$$CC_i = \frac{S_i^-}{S_i^* + S_i^-}, \qquad i = 1,2, \dots, m \quad (13)$$

## 4. Results and Discussion

### 4.1. Identified Environmental Risks

The review and expert consultation process identified 27 risks. Nine were related to dredging operations and 18 to dredged-material disposal. Table 2 presents the complete classification and coding used in the subsequent analysis.

**Table 2. Environmental risks associated with dredging and dredged-material disposal operations**

| Operation | Category | Code | Identified risk |
|---|---|---|---|
| Dredging | Physicochemical | A1 | Changes in seabed morphology |
| Dredging | Physicochemical | A2 | Disturbance of the seabed structure |
| Dredging | Physicochemical | A3 | Turbidity and increased water cloudiness |
| Dredging | Physicochemical | A4 | Increased concentration of suspended solids |
| Dredging | Physicochemical | A5 | Acceleration of coastal erosion |
| Dredging | Ecological | B1 | Destruction of benthic habitats |
| Dredging | Ecological | B2 | Loss of benthic species |
| Dredging | Ecological | B3 | Disruption of food chains |
| Dredging | Ecological | B4 | Displacement of species from their natural habitats |
| Dredged material disposal | Physicochemical | C1 | Changes in seabed morphology |
| Dredged material disposal | Physicochemical | C2 | Increase in water level at the sediment disposal site |
| Dredged material disposal | Physicochemical | C3 | Increased sediment accumulation at the disposal site |
| Dredged material disposal | Physicochemical | C4 | Increased water turbidity |
| Dredged material disposal | Physicochemical | C5 | Increased concentration of heavy metals, including mercury and lead |
| Dredged material disposal | Physicochemical | C6 | Increased concentration of suspended solids |

| Operation | Category | Code | Identified risk |
|---|---|---|---|
| Dredged material disposal | Physicochemical | C7 | Increased concentration of dissolved solids |
| Dredged material disposal | Physicochemical | C8 | Increased concentration of petroleum hydrocarbons |
| Dredged material disposal | Ecological | D1 | Destruction of benthic habitats |
| Dredged material disposal | Ecological | D2 | Loss of benthic species |
| Dredged material disposal | Ecological | D3 | Stress induction in aquatic organisms at the disposal site |
| Dredged material disposal | Ecological | D4 | Impacts of suspended sediments on fish, including suffocation |
| Dredged material disposal | Ecological | D5 | Introduction of invasive species into sediment disposal habitats |
| Dredged material disposal | Ecological | D6 | Increased competition among species for food resources and habitats |
| Dredged material disposal | Ecological | D7 | Disruption of food chains |
| Dredged material disposal | Ecological | D8 | Accumulation of heavy metals, including mercury and lead, in aquatic organisms |
| Dredged material disposal | Ecological | D9 | Contamination of seafood intended for human consumption |
| Dredged material disposal | Ecological | D10 | Burial of coral reefs due to marine disposal of dredged materials |

## 4.2. Criteria Weights and Linguistic Ratings

Fuzzy AHP assigned the greatest importance to severity, followed by occurrence probability and detectability. The triangular weights are reported in Table 3. This ordering indicates that experts emphasized the magnitude of environmental consequences while also accounting for the likelihood and detectability of each event.

**Table 3. Fuzzy AHP weights of the environmental risk criteria**

| Criterion | Detectability | Occurrence | Severity |
|---|---|---|---|
| Weight | (0.421, 0.538, 0.663) | (0.654, 0.781, 0.892) | (0.712, 0.820, 0.914) |

The linguistic scale used to translate expert assessments into triangular fuzzy numbers is shown in Table 4.

**Table 4. Fuzzy linguistic scale for detectability, occurrence probability, and severity**

| Detectability | Occurrence probability | Severity | Fuzzy number |
|---|---|---|---|
| Extremely Unlikely | Greater than 36% | Hazardous / Catastrophic | (9, 10, 10) |
| Very Low Probability | 30–36% | Critical | (8, 9, 10) |
| Extremely Low Probability | 24–30% | Very High | (7, 8, 9) |
| Low Probability | 18–24% | High | (6, 7, 8) |
| Below Average Probability | 12–18% | Significant | (5, 6, 7) |
| Moderate Probability | 6–12% | Moderate | (4, 5, 6) |
| Above Average Probability | 3–6% | Low | (3, 4, 5) |
| High Probability | 1.5–3% | Relatively Low | (2, 3, 4) |
| Very High Probability | Less than 1.5% | Negligible | (1, 2, 3) |
| Almost Certain Detectability | Risks are effectively controlled through preventive measures | None | (1, 1, 2) |

## 4.3. Fuzzy Decision Matrices

The 27 risks were evaluated against severity, occurrence, and detectability. Table 5 combines the four category-specific Fuzzy TOPSIS decision matrices. Higher triangular ratings represent greater severity, occurrence, or difficulty of detection according to the adopted scale.

**Table 5. Combined Fuzzy TOPSIS decision matrix for dredging and dredged-material disposal risks**

| Operation | Category | Code | Severity | Occurrence | Detectability |
|---|---|---|---|---|---|
| Dredging | Physicochemical | A1 | (8, 9, 10) | (7, 8, 9) | (4, 5, 6) |
| Dredging | Physicochemical | A2 | (5, 6, 7) | (4, 5, 6) | (3, 4, 5) |
| Dredging | Physicochemical | A3 | (4, 5, 6) | (5, 6, 7) | (3, 4, 5) |

| Operation | Category | Code | Severity | Occurrence | Detectability |
|---|---|---|---|---|---|
| Dredging | Physicochemical | A4 | (3, 4, 5) | (3, 4, 5) | (1, 2, 3) |
| Dredging | Physicochemical | A5 | (3, 4, 5) | (1, 2, 3) | (2, 3, 4) |
| Dredging | Ecological | B1 | (8, 9, 10) | (7, 8, 9) | (6, 7, 8) |
| Dredging | Ecological | B2 | (6, 7, 8) | (4, 5, 6) | (3, 4, 5) |
| Dredging | Ecological | B3 | (4, 5, 6) | (3, 4, 5) | (2, 3, 4) |
| Dredging | Ecological | B4 | (6, 7, 8) | (6, 7, 8) | (5, 6, 7) |
| Disposal | Physicochemical | C1 | (6, 7, 8) | (5, 6, 7) | (4, 5, 6) |
| Disposal | Physicochemical | C2 | (4, 5, 6) | (4, 5, 6) | (3, 4, 5) |
| Disposal | Physicochemical | C3 | (7, 8, 9) | (6, 7, 8) | (6, 7, 8) |
| Disposal | Physicochemical | C4 | (8, 9, 10) | (7, 8, 9) | (7, 8, 9) |
| Disposal | Physicochemical | C5 | (6, 7, 8) | (6, 7, 8) | (6, 7, 8) |
| Disposal | Physicochemical | C6 | (5, 6, 7) | (5, 6, 7) | (5, 6, 7) |
| Disposal | Physicochemical | C7 | (4, 5, 6) | (4, 5, 6) | (4, 5, 6) |
| Disposal | Physicochemical | C8 | (6, 7, 8) | (5, 6, 7) | (5, 6, 7) |
| Disposal | Ecological | D1 | (8, 9, 10) | (7, 8, 9) | (8, 9, 10) |
| Disposal | Ecological | D2 | (7, 8, 9) | (8, 9, 10) | (8, 9, 10) |
| Disposal | Ecological | D3 | (7, 8, 9) | (6, 7, 8) | (6, 7, 8) |
| Disposal | Ecological | D4 | (5, 6, 7) | (4, 5, 6) | (4, 5, 6) |
| Disposal | Ecological | D5 | (8, 9, 10) | (7, 8, 9) | (7, 8, 9) |
| Disposal | Ecological | D6 | (7, 8, 9) | (7, 8, 9) | (7, 8, 9) |
| Disposal | Ecological | D7 | (6, 7, 8) | (6, 7, 8) | (6, 7, 8) |
| Disposal | Ecological | D8 | (7, 8, 9) | (6, 7, 8) | (6, 7, 8) |
| Disposal | Ecological | D9 | (6, 7, 8) | (5, 6, 7) | (5, 6, 7) |
| Disposal | Ecological | D10 | (5, 6, 7) | (5, 6, 7) | (5, 6, 7) |

### 4.4. Risk Prioritization

The final Fuzzy TOPSIS results are presented in Table 6. Within each operational category, a higher closeness coefficient indicates a higher-priority risk. For dredging physicochemical risks, changes in seabed morphology (A1) ranked first (CI = 0.798). For dredging ecological risks, destruction of benthic habitats (B1) ranked first (CI = 0.852), closely followed by species displacement (B4; CI = 0.844).

For dredged-material disposal, increased water turbidity (C4) was the leading physicochemical risk (CI = 0.884), followed by increased sediment accumulation at the disposal site (C3; CI = 0.865). Destruction of benthic habitats (D1) was the leading ecological disposal risk (CI = 0.876), followed by loss of benthic species (D2; CI = 0.851).

**Table 6. Final Fuzzy TOPSIS ranking of environmental risks**

| Operation | Category | Code | d+ | d− | CI | Rank |
|---|---|---|---|---|---|---|
| Dredging | Physicochemical | A1 | 0.032 | 0.126 | 0.798 | 1 |
| Dredging | Physicochemical | A2 | 0.034 | 0.125 | 0.786 | 2 |
| Dredging | Physicochemical | A3 | 0.041 | 0.116 | 0.739 | 3 |
| Dredging | Physicochemical | A4 | 0.045 | 0.114 | 0.716 | 4 |
| Dredging | Physicochemical | A5 | 0.049 | 0.108 | 0.688 | 5 |
| Dredging | Ecological | B1 | 0.022 | 0.125 | 0.852 | 1 |
| Dredging | Ecological | B2 | 0.029 | 0.114 | 0.798 | 3 |
| Dredging | Ecological | B3 | 0.032 | 0.114 | 0.779 | 4 |
| Dredging | Ecological | B4 | 0.024 | 0.127 | 0.844 | 2 |
| Dredged material disposal | Physicochemical | C1 | 0.026 | 0.110 | 0.807 | 5 |
| Dredged material disposal | Physicochemical | C2 | 0.033 | 0.100 | 0.750 | 8 |
| Dredged material disposal | Physicochemical | C3 | 0.018 | 0.117 | 0.865 | 2 |
| Dredged material disposal | Physicochemical | C4 | 0.015 | 0.118 | 0.884 | 1 |
| Dredged material disposal | Physicochemical | C5 | 0.021 | 0.121 | 0.855 | 3 |
| Dredged material disposal | Physicochemical | C6 | 0.026 | 0.108 | 0.805 | 6 |

| Operation | Category | Code | d+ | d− | CI | Rank |
|---|---|---|---|---|---|---|
| Dredged material disposal | Physicochemical | C7 | 0.032 | 0.103 | 0.764 | 7 |
| Dredged material disposal | Physicochemical | C8 | 0.022 | 0.117 | 0.841 | 4 |
| Dredged material disposal | Ecological | D1 | 0.036 | 0.254 | 0.876 | 1 |
| Dredged material disposal | Ecological | D2 | 0.044 | 0.251 | 0.851 | 2 |
| Dredged material disposal | Ecological | D3 | 0.052 | 0.231 | 0.816 | 6 |
| Dredged material disposal | Ecological | D4 | 0.073 | 0.202 | 0.735 | 10 |
| Dredged material disposal | Ecological | D5 | 0.048 | 0.231 | 0.828 | 3 |
| Dredged material disposal | Ecological | D6 | 0.049 | 0.230 | 0.824 | 4 |
| Dredged material disposal | Ecological | D7 | 0.053 | 0.228 | 0.811 | 7 |
| Dredged material disposal | Ecological | D8 | 0.051 | 0.229 | 0.818 | 5 |
| Dredged material disposal | Ecological | D9 | 0.069 | 0.205 | 0.748 | 9 |
| Dredged material disposal | Ecological | D10 | 0.058 | 0.220 | 0.791 | 8 |

### 4.5. Discussion

The dominance of seabed-morphology alteration among dredging physicochemical risks reflects the direct interaction between excavation, sediment transport, hydrodynamics, and navigation-channel stability. Without bathymetric and morphodynamic monitoring, repeated dredging can modify erosion and deposition patterns, increase maintenance requirements, and reduce navigational reliability. This result supports the use of adaptive dredging plans based on pre- and post-operation surveys, sediment budgets, and threshold-based monitoring [5, 24].

The high ranking of benthic-habitat destruction in both dredging and disposal confirms the sensitivity of bottom communities to excavation, burial, resuspension, and substrate alteration [6, 7]. Mitigation should therefore include ecological baseline surveys, avoidance of sensitive seasons and habitats, selection of lower-impact technologies, and post-operation recovery monitoring. The ranking of turbidity as the principal physicochemical disposal risk also highlights the need for real-time suspended-solids monitoring, controlled placement, and operational shutdown thresholds.

The results are consistent with green-port and sustainability research emphasizing that environmental capability contributes to resilience, stakeholder legitimacy, and long-term competitiveness [8–10, 17]. Digital monitoring and decision-support platforms can improve the timeliness of environmental information and strengthen preventive management [18, 19].

Methodologically, combining Fuzzy AHP and Fuzzy TOPSIS enabled the study to distinguish the importance of risk criteria from the performance of individual risks. This separation reduces the masking effect of a single score and provides a transparent basis for allocating mitigation and monitoring resources. The framework can be updated as new monitoring data or expert judgments become available, but its current results remain context-dependent and should not be generalized without local validation.

## 5. Conclusions

This study developed an integrated Fuzzy AHP–Fuzzy TOPSIS framework for environmental risk management of dredging and dredged-material disposal at Khorramshahr Port. Twenty-seven risks were identified and classified into physicochemical and ecological categories. Severity received the highest fuzzy weight, followed by occurrence probability and detectability. Changes in seabed morphology and destruction of benthic habitats were the highest-priority dredging risks, while increased water turbidity and destruction of benthic habitats were the leading disposal risks.

The findings indicate that sustainable dredging management requires simultaneous attention to morphological stability, water quality, contaminant control, and ecological integrity. Port authorities should establish integrated monitoring programs, define operational environmental thresholds, improve sediment characterization and disposal-site selection, and incorporate risk priorities into contracting, scheduling, and emergency-response procedures.

The study is limited by its single-port case design and reliance on expert judgments. Future research should validate the rankings using field measurements, compare alternative dredging technologies and disposal scenarios, and integrate fuzzy MCDM with

geographic information systems, hydrodynamic and sediment-transport models, artificial intelligence, and dynamic risk monitoring. Such extensions can strengthen evidence-based port governance and the resilience of coastal and marine infrastructure.

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