A Comprehensive Risk Assessment Framework for Inland Waterway Transportation of Dangerous Goods

Xi Huang 1, Yuanqiao Wen 1,2, Fan Zhang 3,4,*, Zhongyi Sui 3,4 and Xiaodong Cheng 1

Abstract: A framework for risk assessment due to inland waterway transportation of dangerous goods is designed based on all possible event types that may be caused by the inland transportation of dangerous goods. The objective of this study is to design a framework for calculating the risks associated with changes in the transportation of dangerous goods along inland waterways. The framework is based on the traditional definition of risk and is designed for sensitive riverside environmental conditions in inland waterways. From the perspective of transportation management, this paper introduced the concept of transportability of dangerous goods and constructed a transportability assessment framework, which consists of a multi-index evaluation system and a single metric model. The result of the assessment is as an auxiliary basis to determine the transportation permit and control intensity of dangerous goods in an inland waterway specific voyage. The methodology is illustrated using a case study of transporting fireworks in the Yangtze River.

Keywords: dangerous goods; inland waterway transport; transportability; transportability risk; assessment framework

1. Introduction

Shipping plays an important role in global trade, with total ocean trade reaching 11.08 billion tons in 2019 alone [1]. As an indispensable raw material for industrial production, the annual transportation volume of dangerous goods has reached approximately 2 billion tons per year in China [2]. Meanwhile, due to the characteristics of dangerous goods and the large volume and low cost of water transportation, ship transportation accidents involving dangerous goods have high risks in terms of personal injury and death, environmental pollution, and property loss. For example, on 6 January 2018, the “Sanchi” carrying more than 110 thousand tons of condensate crashed about 160 nautical miles east of the Yangtze River estuary and caught fire until exploded. The accident led to the sinking of the ship, 3 fatalities and 29 crew missing, the condensate leaking and the exhaust gas produced by incomplete combustion caused a certain degree of air pollution, and the economic losses were up to $100 million. Therefore, a great deal of research has been conducted to improve the safety of dangerous goods transportation, including risk analysis [3,4], route planning [5,6], emergency response, and evacuation [7,8].

Since 1971, the safety management of dangerous goods transportation has undergone about 50 years of development. Beginning with the research on dangerous goods transportation risks from nuclear fuel transportation, thanks to the efforts of IMO, governments, and transportation management departments, large-scale dangerous goods transportation accidents such as Torrey Canyon and ABT Summer have not repeated; however, with the development of larger and faster ships, the threat of dangerous goods ship transportation accidents still exists [9,10].
Risks are latent and uncertain. In the field of dangerous goods transportation, risk can be understood as the estimation of adverse consequences that may result from transportation accidents of dangerous goods [11], which mainly arise from the hazardous nature of the dangerous goods themselves and the operation of the transportation process and the sensitivity of the transportation environment. Existing risk research follows the process of risk analysis–risk evaluation–risk control, in which risk analysis is the most fundamental link, including risk factor identification and risk estimation, in which risk estimation is mainly divided into frequency and consequence estimation.

According to the focus of risk analysis, existing research can be divided into two categories. One is the accident frequency estimation driven by historical data [12–14]. This type of risk is based on a large amount of historical data and can reflect the probability of accidents more clearly and intuitively by transforming the prediction of risk into a probability distribution problem, which relies on data and lacks dynamic distinction when assessing the impact of risk factors. Under specific circumstances, it may not be able to closely adapt to actual transportation. The other one is risk analysis based on the impact of accident consequences [15–17], such as accident scene simulation combined with GIS, GPS, etc., which has made a qualitative leap on the data side of the risk assessment model. It realizes the specific analysis of accident consequences by simulating transportation scenarios and can discriminately identify the high and low risks under different environmental parameters as the basis for risk control decisions, but the application of this type of research is limited by the nature of the specific cargo and the conditions of the scenario.

The route accessibility of water transportation of dangerous goods is far less than other transportation methods, so the transport cycle is relatively longer, and the uncertainty is higher. It is a typical small probability and large consequence event. Every waterborne transport accident of dangerous goods can be abstracted into a chain of accidents with a domino effect caused by an initial event formed by the action of one or more factors [16]. Existing research focuses on analyzing the frequency of accidents and the severity of consequences from the perspective of risk estimation, following the “posterior” analytical thinking based on the experience of accidents that have occurred, and the analysis of the causative chain in the formation process of the accident-causing factors is neglected [18]. From the perspective of risk control, it is more effective to reduce the probability of dangerous cargo transportation accidents [19]. However, due to the dynamic and complex changes in transport conditions, the field of transport management still lacks methods for judging whether dangerous goods are suitable for transportation.

Therefore, this paper considers the influence of transport system elements on transport risk, defines the ability of dangerous goods to adapt to waterway transport conditions (including infrastructure, means of transport and transport environment, etc.) as “transportability”, and proposes a comprehensive risk assessment framework for the inland waterway transport of dangerous goods based on traditional risk evaluation methods. The purpose of this framework is to judge the risk levels of transporting dangerous goods through different regions under dynamic transportation conditions and provide a reference for risk control and emergency response of dangerous goods waterway transportation.

2. Literature Review

Although the transport of dangerous goods has been a popular area of research (for a comprehensive review, see [20,21]), there is relatively little literature on the risks associated with the water transport of dangerous goods. This paper tracks three related research areas: risk causation analysis of dangerous goods transportation; transportation risk evaluation methods; and transportation risk evaluation framework design. The concept of transportability and evaluation ideas are proposed based on the existing risk evaluation studies.

2.1. Risk-Related Research

(a) Risk cause
The purpose of risk cause research is to dig out risk factors and identify risk sources. Uğurlu [22] analyzed the causes of fire and explosion accidents on tankers carrying liquid dangerous goods and identified thermal work, static electricity, electric arcs, and the accumulation of combustible gas as the most fundamental causes of accidents. Baalisampang et al. [23] conducted a causation analysis of fire and explosion accidents on cruise ships carrying liquid dangerous goods from 1990–2015. A study of fire and explosion accidents in maritime transport found that 31% of fire and explosion accidents at sea were caused by fuel or lubricating oil leaks in the cabin, and looked forward to the prospect of using alternative fuels to mitigate the risk of accidents. In terms of container operation risk, Chang et al. [24] quantified the ranking of risk factors using the mean and stochastic dominance methods and developed a risk map to distinguish between high- and low-risk sources, while Ellis [21] identified inadvertent ignition of dangerous goods and spontaneous combustion as the main factors leading to fatal accidents in packaged and containerized dangerous goods. Zhao et al. [25] used D-S evidence theory and expert knowledge to construct a Bayesian network structure of dangerous goods transportation accidents and calculated the posterior probability of each risk factor, and concluded that human factors, the means of transportation, and the packing and loading of dangerous goods were the three most influential causative factors. Hong et al. [26] used the Apriori algorithm to conduct association rule mining on the causes of dangerous goods vehicle accidents and found that the dangerous goods vehicle collision accidents are related to factors such as weather conditions and the height of the mainline section. Liu et al. [27] considered the influence of train length, derailment speed, and tank car location on railroad dangerous goods transportation spills and built a corresponding management framework.

In summary, the identification methods of risk cause research are mainly based on a statistical analysis of accident history data or the application of data mining algorithms to dig out hidden cause factors. Cause research mostly focuses on specific types of accidents and identifies risk sources from the perspective of transportation system components. The causes of dangerous goods transportation accidents are mostly concentrated on the state of cargo, means of transportation, transportation facilities, and human factors.

(b) Risk estimation method

To meet the needs of risk decision-making in different fields, it is often necessary to adopt an evaluation method suitable for the research object when evaluating risks. Celik et al. [28] applied fuzzy fault tree analysis to improve the execution process of transportation accident investigation, using linguistic variables to deal with ambiguities that may be involved in expressing the probability of the occurrence of basic events, and by using the concept of fuzzy sets, the state of each basic event can be described flexibly. Reniers et al. [29] developed a semi-quantitative assessment tool based on a multi-criteria analysis method to assess the relative risk level of dangerous goods transportation, which is used as a theoretical basis for transportation risk control. Verma et al. [30] developed a risk evaluation model based on the memetic algorithm for the dual goals of risk and cost based on the actual problems in the Midwestern United States, which is used to solve the problem of differential characteristics in railroad transportation and realize the safe route selection decision. John et al. [31] integrated the advantages of fuzzy set theory, hierarchical analysis, and evidence theory, and proposed a model that can solve the problem of systematic risk control. The new fuzzy risk evaluation method for uncertainty and sensitivity issues is used to increase the flexibility of the risk evaluation system and to conduct more accurate and flexible risk evaluation for seaport operations. Stavrou and Ventikos [32] have modified the traditional PFMEA method based on the characteristics of oil transfer from ship to ship, and fully exploited the advantages of this method to evaluate the incidence and severity of accidents during the transfer process. Akyildiz and Mentes [33] applied fuzzy set theory to the improvement of AHP and TOPSIS, expressed the uncertainty model parameters qualitatively, and proposed a two-dimensional scoring system, the case results show that integrated risk management by improving the method is effective and feasible. Inanloo and Tansel [34] used ALOHA to simulate the leakage and diffusion process of ammonia
in the air, combined it with ArcGIS to map the partitioning of the accident impact under different scenarios, and conducted a sensitivity analysis on the impact of wind speed on ammonia leakage. The transportation risk was visually evaluated. Ma et al. [18] used D-S evidence theory and Bayesian networks to explore possible combinations that led to accidents and combined them with EM algorithms for model parameter learning to assess accident risks.

In summary, risk evaluation objects often have the characteristics of uncertainty, sensitivity, and ambiguity. Therefore, fuzzy theory and gray theory are commonly used in research combined with traditional evaluation methods. With the development of artificial intelligence in recent years, there has been a trend to combine various algorithms with traditional risk evaluation methods to enhance the practicability and flexibility of evaluation methods.

(c) Risk assessment framework
Risk is the basis for decision-making in safety management. The risk assessment framework usually combines qualitative and quantitative models. Montewka et al. [35] established the risk assessment framework of the maritime transportation system through five steps of the defining model–defining variables–qualitative analysis–quantitative analysis–verification framework. The qualitative part used expert knowledge to create the graphical structure of the Bayesian network, and the parameter probability distribution of variables in the quantitative part is used to reduce the number of probabilities required to evaluate the framework and to perform sensitivity and uncertainty analysis of the framework. Goerlandt and Montewka [36] proposed a two-stage assessment framework based on expert opinions and decision-makers. In the first stage, the Bayesian network is used to quantify the probabilistic risk, and the second stage uses evidence to evaluate the uncertainty in the first stage, which enriched the levels of the two-stage evaluation framework. Yang et al. [37] proposed a three-part framework based on a fuzzy environment. In the first stage, the importance level of each factor of H (human)–M (substance)–E (environment)–M (management) was calculated and the triangle fuzzy numbers are used as an evaluation tool to deal with the uncertainty and ambiguity of the evaluation process. The second phase determines the correlation between control measures and corresponding factors for the first phase, and the third phase ranks the priority of each improvement measure. This framework can be used to explain the risk management and loss prevention process of a dangerous goods transportation company.

Based on the types of accidents that may be triggered by the transportation of dangerous goods, Das et al. [38] have designed a risk assessment framework for the off-site transportation of dangerous goods. The framework process includes three steps: (i) determine the accident composite index instead of the probability of occurrence, (ii) accident impact assessment, and (iii) population vulnerability assessment.

The design of the risk assessment framework usually covers both risk analysis and risk assessment, starting from the perspective of system elements or accident historical process, and reducing the uncertainty of the assessment process through appropriate methods.

2.2. How to Evaluate Transportability?
2.2.1. Definition of Transportability
Many factors affect the probability of transportation accidents and the severity of their consequences, and transportation risk evaluation often cannot include all of them. To describe and judge the transportation safety of important military equipment under different transportation conditions, the concept of “transportability” was first introduced in the aviation field to describe the inherent ability of military materials, such as high-risk munitions, to adapt to transportation, including the ability to adapt to infrastructure, means of transport, and the transportation environment. The International Maritime Dangerous Goods (IMDG) Code also clearly describes the “safety and serviceability” of dangerous goods before transport.
Currently, the transport permit for dangerous goods is determined by “the List of Prohibited Dangerous Chemicals on Inland Waterways” issued by the Ministry of Transport. However, the transport environment is a necessary vehicle for the transport process, and as dynamically changing transport conditions are often an important factor leading to risk, it is necessary to consider the impact of environmental conditions on the transport permit for dangerous goods. To reduce transport risks, many measures have been implemented in practical transport management. The Yangtze River Main Line was completely banned in 2016 for single-hulled chemical vessels and single-hulled oil tankers of 600 gross tons or more, and the Catalogue of Embargoed Dangerous Chemicals on Inland Rivers (2019 Edition) has modified 85 kinds of dangerous goods, such as acrylonitrile (stabilized) and n-butyronitrile, from a total embargo to a ban on bulk transport. Fireworks and explosives on inland rivers are mainly transported in autumn and winter, and these measures take into account the hull factor, packaging form and the possible influence of temperature on the risk of cargo transportation. The above is the same as the concept of “transportability”, reflecting the impact of different transport conditions on the safety of transport of dangerous goods.

Based on the perspective of dangerous goods waterway transport safety management, dangerous goods and waterway transport environments (including the carrying vessel) constitute the dangerous goods waterway transport system, and transport accidents can be regarded as the system integrated effect caused by the mismatch of elements within the system. Therefore, this paper proposes the concept of transportability of dangerous goods, defines the waterway transport capacity of dangerous goods as the ability of dangerous goods to adapt to waterway transport conditions, including the ability to adapt to infrastructure, means of transport, and transport environment, and uses the risk of transportability of dangerous goods as a metric to identify the risk of adaptation of transport conditions and dangerous goods in the system and the important influencing factors.

2.2.2. Overview of Transportability Evaluation

According to the development history of dangerous goods waterway transport accidents, dangerous goods transport accidents are often triggered by ordinary traffic events; if no leakage of dangerous goods occurs, the nature of the event can be treated as ordinary traffic accidents. If leakage occurs, the nature of the dangerous goods themselves will become the most important risk factors that distinguish dangerous goods transportation accidents from ordinary transportation accidents, when dangerous goods will cause different secondary accidents (fire, explosion, poisoning, etc.) due to their dangerous nature. When measuring the risk of dangerous goods transportation, the risk evaluation of transportability includes only the evaluation of the risk level of dangerous goods leakage and secondary accidents, according to the accident development trend and the classification of the accident time and impact range; see Figure 1.

FRT: normal freight transport
COSTS: costs of assets
SQM: number of impacted square meters
DGNR: dangerous goods event without release (No Release)
DGR: dangerous goods release
FAT: number of fatalities
SA: secondary accident

Transportability is a qualitative concept and is measured by the Transportability Risk Value. Cargo factors, vessel factors, infrastructure factors, and environmental factors are selected as indicators for evaluating transportability and are subdivided as shown in Figure 2.
Transportability is a qualitative concept and is measured by the Transportability Risk Value. Cargo factors, vessel factors, infrastructure factors, and environmental factors are selected as indicators for evaluating transportability and are subdivided as shown in Figure 2.

Figure 1. Conceptual diagram of waterway transportability evaluation of dangerous goods.

Figure 2. Overview of the Principles of Transportability Evaluation.
3. Framework for the Transportability Assessment: Model and Structure

Conventional risk assessment models identify factors that have a significant impact on transportation risk based on accidents that have occurred, and systems engineering theory is widely used to avoid significant risk factors. In fact, due to changes in conditions such as packaging, means of delivery, and route settings, the transportation risk of dangerous goods is also dynamically changing. The evaluation of the transportability of dangerous goods is carried out in the preparation phase of the transportation of dangerous goods, and the purpose is to evaluate the compatibility of the batch of dangerous goods with the intended transportation environment. Unlike systems engineering that considers the elements of the human–ship–environment–cargo–management, human factors and management factors are not considered in the process of the transportability evaluation process.

Clarifying the influence mechanism of various factors in the system on the transportability of dangerous goods is the basis of the assessment, as shown in Figure 3. Goods factors such as burning point and material form, ship age, and hull strength as ship factors, and waterway and hydrology as environmental factors, together constitute the inland waterway dangerous cargo transportation system targeted by this research. It should be noted that water intake and green belts are classified into environmental factors as environmental vulnerability factors. When the internal contradictory movement of the dangerous goods transportation system, that is, the interaction between various factors develops to a certain degree, it will trigger the cause, which will lead to the unsafe state of the dangerous goods transportation system, and even the hazardous scenarios.

The scope of transportability evaluation is the entire dangerous goods water transportation system, and the starting point is the goods carried on each specific voyage. The framework is based on the actual transportation process of ships, taking into account the changes in the transportability caused by the dynamic changes of the environment as the ship travels, and measuring the transportability risk value to reflect the transportability of the dangerous goods. Specifically, it is equivalent to that we have assumed a transport (with a stable cargo and carrying vessel) before the actual transport and predicted the probability and consequences of dangerous goods accidents of different magnitudes on different areas of the transport route, respectively. As the ship sails, the environmental conditions in different waters, the time period of passing through, and other factors would change, which was reflected by the input of different parameters in the model.

The framework is mainly divided into two stages, as shown in Figure 4. The main idea of the framework is to divide the passage area of dangerous goods transporting vessels into n grids, and each grid is used as an evaluation unit. In the first stage, the transportable risk value of each cell is quantified through the index system and index metric model. In the second stage, the transportability of dangerous goods is judged by combining the transportability risk values of all cells in the route area.

3.1. Hierarchical Structure of Evaluation Index System

The object of this stage 1 is a single grid as an evaluation unit. The transportability risk value of the unit segment is quantified by designing an evaluation index system. According to the risk identification analysis in Section 3 above, the risks of the inland waterway dangerous goods transportation system can be divided into internal risks and external risks. The internal risks mainly refer to the risks of goods and ship factors, which can be objectively based on information sources such as statistics from the MSA, relevant accident reports, and literature. External risks mainly refer to the risks of infrastructure and environmental vulnerability factors. Among them, the former mainly affect the probability of accidents, and the latter mainly affect the severity of accident consequences, which can be combined with the results of field investigations, expert experience, etc. The specific analysis process is determined by Preliminary Hazard Analysis (PHA), as shown in Figure 5.
To gain a deeper understanding of practitioners’ pain points regarding the water transportation of dangerous goods, this paper asked 50 related practitioners from the Yangtze River Shipping Administration, the Yangtze River Maritime Safety Administration, and dangerous goods manufacturers and shipping company personnel to collect their feedback on the selected indicator factors and screen them. Then, we removed the general and above factors with a degree of importance less than 25 times until their opinions converge. Finally, the structure and content of the evaluation index system were determined in Table 1. The specific weight distribution method is explained in Section 4.4.
The framework is mainly divided into two stages, as shown in Figure 4. The main idea of the framework is to divide the passage area of dangerous goods transporting vessels into n grids, and each grid is used as an evaluation unit. In the first stage, the transportability of dangerous goods is judged by combining the risk value of each cell into the index system and index metric. In the second stage, the transportability of dangerous goods is judged by combining the transportability risk values of all cells in the route area.

**Figure 4.** Brief stage process of transportability assessment framework.

**Figure 5.** Thoughts on determining the transportability assessment index.

| Main Indicator Layer | Secondary Indicator Layer | Weights |
|----------------------|---------------------------|---------|
| Cargo category (T11) | Package (T12) | 0.0736 |
| Carrying volume (T13) | Flammability (T14) | 0.0376 |
| Reactivity (T15) | Health hazard (T16) | 0.0599 |
| Health hazard (T16) | 0.0642 |
| Ship’s seaworthiness (T21) | Hull Structure Strength (T22) | 0.0376 |
| Sailing time period (T23) | 0.0603 |
| Channel dimension (T31) | Terminal capacity (T32) | 0.0614 |
| Supporting facilities (T33) | 0.0647 |
| Crew/Personnel casualties (T41) | Economic/Property damage (T42) | 0.1128 |
| Sensitive Area (T43) | Emergency Response Capability (T44) | 0.0614 |
|  | 0.0848 |
|  | 0.0449 |

**3.2. Multi-Unit Combined Assessment Model**

The object of this stage 2 is a single grid as an evaluation unit. The transportability of dangerous goods is judged by combining the transportability risk values of all cells in the route area. The occurrence of transportation accidents of dangerous goods onboard are usually
unpredictable. For the evaluation of the transportability, the environmental conditions of the route area need to be known, and the ship and cargo information is based on the declaration information received by the Maritime Safety Administration (MSA) before the ship enters the port. The multi-unit combination mode solves the problem of long-term transportation risk dynamic visualization.

The evaluation model of the transportability is to be carried out once for one ship, one transportation, and one evaluation for the transportation of dangerous goods. The scope of the impact of an accident during the navigation of a dangerous goods ship can be regarded as the impact area of a line of risk sources connected by several point risk sources. By comparing the model of the affected area of the dangerous goods accident, the rectangular area model is selected for the non-straight inland waterway route [38].

The location of the rectangular grid is divided according to the inland waterway mileage scale, and the size is determined according to the representative ship type and waterway scale.

The transportability risk level of each smallest unit segment is determined by the evaluation value, and different colors represent different levels. The color areas are connected to form the entire route.

According to the evaluation results of the transportability of all unit segments on the entire transportation route, the changes in the transportability risk level of the route can be obtained after connecting them. To reflect the transportability of this batch of goods on this route, the paper proposes a qualitative classification scheme based on the opinions of the competent unit and experts to achieve a more intuitive distinction.

If \( n_i \) \((i = 1, 2, 3, 4)\) represents the number of unit segments in the class \( i \) of transportable risk value, based on the above, the formula can be summarized as Equation (1):

\[
\sum_{i=1}^{4} n_i = n
\]  

(1)

According to \( n_i \) as the basis for qualitative judgment of fitness, the specific classifications are shown in Table 2. The schematic diagram of transportability assessment is shown in Figure 6. The specific process is shown in Figure 7.

Table 2. Transportability classification table.

| Basis for Judgment | Transportability Category |
|--------------------|--------------------------|
| \( n_1 \geq 1 \)   | Area prohibited          |
| \( n_1 = 0 \)      | Conditionally restricted  |
| \( n_2 < n/3 \)    | Unlimited                |
| \( n_2 \geq n/3 \) |                          |

Figure 6. The schematic diagram of transportability assessment.
Figure 7. Process of transportability assessment framework.
4. Framework for the Transportability Evaluation: Methodological Aspects

4.1. Formulation of the Mathematical Form

4.1.1. Calculation Formula of Transportability Risk Value of a Single-Unit Segment

Goods factor unit, ship factor unit, infrastructure factor unit, and environmental factor unit are evaluated according to the following Equation (2):

\[ R_k = \frac{\alpha_k}{\beta_k} \cdot \sum_{i=1}^{n} r_i \]  

(2)

where \( R_k \) is the transport risk value of factor unit \( k \); \( \alpha_k \) is the risk correction coefficient of the exposed personnel during the operation involved in the factor unit \( k \) (refer to the Appendix A.1 for the specific values, the same below); \( \beta_k \) is the risk correction factor corresponding to the comprehensive attributes of the factor unit \( k \) (refer to the Appendix A.2 for the specific values, the same below); \( r_i \) is the evaluation value of a single indicator of the factor unit \( k \); and \( n \) is the number of indicators corresponding to the factor unit.

In the design of the evaluation system, the indicators are relatively independent and integrated. The indicators cannot be completely independent of each other, but in the calculation, we assume that they are independent. To eliminate the errors caused by the assumptions, we introduced correction factors into the calculation model. According to the following Equation (3), the evaluation values of each factor unit are combined, and the total evaluation value is used as the basis for grading transportability.

\[ R_{\text{total}} = \delta \cdot \sum_{k=1}^{4} R_k \]  

(3)

where \( R_{\text{total}} \) is the evaluated value of the transportability risk, and \( \delta \) is the magnification constant, which is taken as 100 in this paper; \( R_k \) is the evaluated value of the transportability risk for each factor unit.

Risk classification can directly reflect the degree of risk and has important reference significance for management agencies and shipping companies. According to shipping conditions and the classification standards of major hazards in “GB 18218-2018 Identification of Major Hazards of Hazardous Chemicals”, the transportable risk levels are classified as shown in Table 3.

| Transportability Risk Level | \( R_{\text{total}} \) |
|-----------------------------|---------------------|
| Level 1 (red)               | \( R_{\text{total}} \geq 100 \) |
| Level 2 (orange)            | \( 100 > R_{\text{total}} \geq 50 \) |
| Level 3 (yellow)            | \( 50 > R_{\text{total}} \geq 10 \) |
| Level 4 (green)             | \( R_{\text{total}} < 10 \) |

4.1.2. Calculation Formula of Qualitative Index

Due to the characteristics of the long water transportation cycle and complex transportation environment, the evaluation index is easily affected by other factors. Therefore, a correction factor is introduced to ensure the objectivity of the evaluation. In addition to the risk attribute of the indicator itself, the correction factor considers other uncertain factors that will affect the risk. For example, the hazard of the goods category is affected by factors such as material form and temperature changes in addition to its risk category.

The evaluation model of a single qualitative index refers to Equation (4):

\[ r_i = w_i \cdot \frac{f_i}{F_i} \]  

(4)
where \( r_i \) is the transportability risk value of the qualitative indicator; \( w_i \) is the corresponding weight of the indicator; \( f_i \) is the evaluation value of the indicator; and \( F_i \) is the corresponding value of the index correction factor.

### 4.1.3. Calculation Method of Quantitative Index

The evaluation model for risk assessment indicators is the same as for the qualitative indicators described above. The purpose of risk management is to control the risk at an acceptable or negligible level. Therefore, the evaluation model of indicators introduces the upper limit of risk acceptability of the ALARP Risk Acceptability Criteria as Equation (5).

\[
r_i = w_i \cdot \frac{e_i}{E_i}
\]

where \( r_i \) is the transportation evaluation value of the quantitative index; \( w_i \) is the corresponding weight of the index; \( e_i \) is the calculated value of the evaluation model of the index; and \( E_i \) is the upper limit of the risk acceptance standard corresponding to the index.

### 4.2. Index Evaluation: Hazard Degree Evaluation Method

After determining the indicators and weight distribution of the evaluation system, based on the systematic combing of the Yangtze River dangerous goods ship transportation accidents and the actual in-depth analysis of the causative factors, the classification was sorted and categorized through consulting experts. Finally, the grading basis of the qualitative indicators and the assigned values are shown in Table 4. The evaluation set for grading each index is \( \{C_1, C_2, C_3, C_4, C_5\} \), which respectively represent a high risk, relatively high risk, general risk, relatively low risk, and low risk, as shown in Table 5.

#### Table 4. Qualitative index grading basis.

| Index                               | Grading Basis                                                                 |
|-------------------------------------|--------------------------------------------------------------------------------|
| Cargo category (T_{11})             | Possibility of accidents caused by substance category attributes               |
| Package (T_{12})                    | Consistency with “IMDG” packaging requirements                                |
| Reactivity (T_{15})                 | How easy it is to achieve the conditions required for the reaction            |
| Health hazard (T_{16})              | Degree of harm to organisms                                                  |
| Transportability (T_{21})           | The overall quality of the ship, including age, crew, equipment, etc.         |
| Hull Structure Strength (T_{22})    | Bending and tensile strength of hull materials and structures                 |
| Sailing time period (T_{23})        | Visibility, severe weather conditions                                         |
| Supporting facilities (T_{33})      | Hazardous chemicals anchorage, berthing area, navigation aid facilities       |
| Emergency Response Capability (T_{44}) | Emergency response time, distance from emergency storage, completeness of emergency equipment |

#### Table 5. Qualitative index grading assignment criteria.

| Grading | Value |
|---------|-------|
| C_1     | 1     |
| C_2     | 0.8   |
| C_3     | 0.6   |
| C_4     | 0.4   |
| C_5     | 0.2   |

For quantitative indicators that can be directly represented by numerical values, the risk evaluation method is adopted, and the risk is classified according to the numerical interval, as shown in Tables 6 and 7.
Table 6. Quantitative index grading basis.

| Index Characterization | Characterization |
|------------------------|------------------|
| Carrying volume (T₁₃)  | The ratio of actual capacity to deadweight |
| Flammability (T₁₄)     | Ignition point (°C) |
| Channel dimension (T₃₁)| Channel class     |
| Terminal capacity (T₃₂)| Dock unloading capacity (t) |

Table 7. Quantitative index grading assignment criteria.

| Grading | Value | The Ratio of Actual Capacity to Deadweight | Ignition Point (°C) | Channel Class | Dock Unloading Capacity (t) |
|---------|-------|-------------------------------------------|--------------------|---------------|-----------------------------|
| C₁      | 1     | >1                                        | \                 | Class 3       | <5000                       |
| C₂      | 0.8   | (0.75, 1)                                 | >93.3 °C           | \             | \                           |
| C₃      | 0.6   | (0.5, 0.75)                               | ≤93.3 °C           | Class 2       | [5000, 10,000)              |
| C₄      | 0.4   | (0.25, 0.5)                               | ≤37.8 °C           | \             | \                           |
| C₅      | 0.2   | <0.25                                     | ≤22.8 °C           | Class 1       | ≥10,000                     |

4.3. Mathematical Model

In risk-related research, there are many expressions of risk measurement models. Dangerous cargo transportation accidents are typical small-probability and large-impact events, so this paper selects the accident probability and the severity of the accident consequences to measure the risk value as Equation (6).

\[
Risk = \text{Probability} \times \text{Consequence}
\]  

(6)

Based on the above, this paper proposes a human risk measurement model, an economic risk measurement model, and a sensitive area risk measurement model for the transportation of dangerous goods. Among them, the personnel risk mainly refers to the risk of life or injury of the crew and those who may be affected by the accident within the scope of the accident, the economic risk mainly refers to the severity of the loss that other ships may suffer from the accident within the scope of the accident, and the area sensitivity risk mainly considers the major environmental damage that may be caused by the water transportation accident of dangerous goods. When the dangerous goods are carried along the route, it passes through special environmental areas on both sides of the strait, such as water intakes, quayside gathering areas, anchorages, etc.

4.3.1. Human Risk Measurement Model

With the movement of the dangerous goods carrying ship, the personnel risk at a certain point in the unit segment is equal to the sum of all the accident consequences along the segment at that point \[39\]. Using this principle for reference, the personnel risk quantification model of dangerous cargo ship transportation can be expressed as Equation (7):

\[
R_s(l, i, t) = \sum_{i=1}^{4} \sum_{l=1}^{5} \int_0^1 p(h, l, i, t) \times p_{ik} \times L_h(x, y) \times dx
\]  

(7)

where \(R_s(l, i, t)\) is the human risk on the corresponding unit segment \(l\); \(p(h, l, i, t)\) represents the probability of accident size \(h\) occurring in time period \(t\) for dangerous goods of class \(i\) on the segment \(l\) of the voyage; \(p_{ik}\) indicates the probability of the secondary accident \(k\) after a leak; and \(L_h(x, y)\) indicates the probability of an accident causing an individual death at point \((x, y)\).

In this paper, the secondary accidents of dangerous goods are divided into three categories: explosion, fire, and leakage, represented by different \(k\) values. The accident
scale is divided into five categories: small, average, large, major, and very large according to the division basis in the “Water Traffic Accident Statistics Approach” [40].

4.3.2. Economic Risk Measurement Model

The economic risk mainly quantifies the degree of risk that other vessels around the transport vessel may be affected by the transport vessel accident in the unit area. The calculation model is shown as Equation (8):

$$R_v(l, i, t) = \sum_{k=1}^{3} \sum_{h=1}^{4} \sum_{p=1}^{5} \int p(h, l, i, t) \times p_{hk} \times L_{ss} \times Q \times \lambda_{sh}(x, y) \times dx$$  \hspace{1cm} (8)

where $R_v(l, i, t)$ indicates the risk of ship property on the voyage; $L_{ss}$ represents the possibility of multiple ships in the unit area if an accident occurs; $Q$ represents the average flow of ships in the accident area; and $\lambda_{sh}(x, y)$ represents the ship’s damage rate at the point $(x, y)$ caused by the consequences of the accident.

4.3.3. Sensitive Area Risk Measurement Model

In this paper, the environmentally sensitive areas are divided into three categories, which are denoted by $Z_1, Z_2, and Z_3$. They are water resource areas such as water intake, ecologically relatively fragile areas such as riverbank parks and nature reserves, and areas susceptible to economic losses such as terminals and anchorages, in order. If an accident occurs, the severity of the environmental exposure consequences of the section $l$ of dangerous goods of category $i$ should be equal to the sum of the number of each sensitive area and the corresponding risk weight coefficient of the environmentally sensitive area [39], as shown in Equation (9).

$$S_Z(i) = \sum_{i=1}^{3} \sum_{j=1}^{5} S_{Z_j}(l, i) \delta_{Z_j}(i)$$  \hspace{1cm} (9)

where $S_Z(i)$ denotes the relative total number of environmentally sensitive areas exposed in the event of a transport accident of class $i$ dangerous goods; $S_{Z_j}(l, i)$ denotes the number of environmentally sensitive areas of class $j$ in the area affected in the event of a transport accident of class $i$ dangerous goods on section $l$; and $\delta_{Z_j}(i)$ denotes the risk weight coefficient of class $i$ dangerous goods to environmentally sensitive areas of class $j$.

Based on the above, the risk quantification model for environmentally sensitive areas is shown in Equation (10)

$$R_Z(l, i) = \sum_{i=1}^{3} p(l, i) \times p_{ik} \times S_{Z_j}(l, i) \delta_{Z_j}(i)$$  \hspace{1cm} (10)

where $R_Z(l, i)$ denotes the risk of exposure to sensitive areas for class $i$ dangerous goods on the section $l$; $p(l, i)$ denotes the probability of a ship accident for class $i$ dangerous goods on the section $l$; and $p_{ik}$ is the probability of a class $k$ accident following a spill of class $i$ dangerous goods.

4.4. Weight Distribution Method: Structural Entropy Method

The Structural Entropy Method is a combination of subjective and objective weighting methods. Its principle is to combine the Delphi method and the fuzzy decision analysis method [41]. The subjective evaluation method is adopted by relevant experts to evaluate the importance of indicators based on subjective experience and quantitatively assess the uncertainty of the value, then calculate the entropy value and perform “blindness” analysis to obtain the weight value of each indicator; the main steps are as follows:

Step 1: Form a typical ranking by consulting and collecting expert opinions.

Set $n$ indicators as an indicator set $T = \{T_1, T_2, \ldots, T_n\}$, collect the ranking of experts on their importance (the smaller the number, the higher the importance), the indicator
set corresponds to the sorted positive integer set written as \((a_{i1}, a_{i2}, \ldots, a_{in})\), then we can obtain the indicator weight sort matrix \(A = (a_{ij})_{k \times n}\), where \(i = 1, 2, \ldots, k; j = 1, 2, \ldots, n\); \(a_{ij}\) indicates the importance ranking of the indicator \(T_j\) by the expert \(i\), as Table 8 shown.

**Table 8.** Expert ranking list of index importance.

| Expert Serial Number/Index Serial Number | \(T_1\) | \(T_2\) | \(\ldots\) | \(T_j\) | \(\ldots\) | \(T_n\) |
|-----------------------------------------|--------|--------|---------|--------|---------|--------|
| Expert 1                               | \(a_{11}\) | \(a_{12}\) | \(\ldots\) | \(a_{1j}\) | \(\ldots\) | \(a_{1n}\) |
| Expert \(i\)                           | \(a_{i1}\) | \(a_{i2}\) | \(\ldots\) | \(a_{ij}\) | \(\ldots\) | \(a_{in}\) |
| Expert \(k\)                           | \(a_{k1}\) | \(a_{k2}\) | \(\ldots\) | \(a_{kj}\) | \(\ldots\) | \(a_{kn}\) |

**Step 2:** Calculate the index membership degree according to the entropy function and construct the membership degree matrix.

According to the information of the entropy function, qualitatively transform the opinions of the importance of experts; that is, calculate the membership degree of each expert index. Perform mathematical transformation on the information entropy function to obtain the membership function as Equation (11):

\[
B(x) = -\ln(m - x)/\ln(m - 1)
\]  

(11)

where \(x(x = 1, 2, \ldots, n)\) is the number of qualitative rankings evaluated by experts for each index, \(m\) is the number of conversion parameters, \(m = n + 2\), and \(B(x)\) is the corresponding membership function value of \(x\). Construct membership matrix \(B\) as Equation (12):

\[
B = \begin{bmatrix}
    b_{11} & \ldots & b_{1j} & \ldots & b_{1n} \\
    \vdots & \vdots & \vdots & \vdots & \vdots \\
    b_{i1} & \ldots & b_{ij} & \ldots & b_{in} \\
    \vdots & \vdots & \vdots & \vdots & \vdots \\
    b_{k1} & \ldots & b_{kj} & \ldots & b_{kn}
\end{bmatrix}
\]

(12)

where \(b_{ij}\) is the membership value of expert \(i\)’s evaluation and ranking of the index \(j\).

**Step 3:** “Blindness” analysis of expert ranking to optimize uncertainty deviation.

Substituting \(x = a_{ij}\) into Equation (11), the quantitative transformation value of \(a_{ij}\) can be obtained, and the corresponding matrix \(B = (b_{ij})_{k \times n}\) is the membership matrix of the ranking number. Calculate the consensus of \(k\) experts on the indicator \(T_j\), which is called the average importance, denoted as \(b_j\), \(b_j = (b_{1j} + b_{2j} + \ldots + b_{nj})/k\).

Define the uncertainty arising from expert \(i\)’s cognition as cognitive blindness about the indicator \(T_j\), recorded as \(Q_j (j \geq 0)\), then

\[
Q_j = \left\lfloor \left( \max(b_{1j}, b_{2j}, \ldots, b_{kj}) - b_j\right) + \left[ b_j - \min(b_{1j}, b_{2j}, \ldots, b_{kj}) \right] \right\rfloor / 2
\]

(13)

Define \(\mu_j\) as the overall knowledge of \(k\) experts on indicator \(T_j\) (>0), with

\[
\mu_j = b_j(1 - Q_j)
\]

(14)

**Step 4:** Normalize the overall awareness to obtain the index weight.

According to Equation (14), the weight of the indicator \(j\) is obtained as follows.

\[
w_j = \frac{\mu_j}{\sum_{i=1}^{n} \mu_i}
\]

(15)
where \( \mu_j > 0 \) (j = 1, 2, \ldots, n), \( \sum_{i=1}^{n} \mu_i = 1 \).

\((w_1, w_2, \ldots, w_n)\) is the unanimous judgment of the k experts on the importance of each indicator in the indicator set \( T = \{T_1, T_2, \ldots, T_n\} \). \( w = (w_1, w_2, \ldots, w_n) \) is the weight vector corresponding to the indicators set \( T \).

Based on the above method steps, we designed a ranking questionnaire for the importance of indicators and distributed them to 50 field experts and practitioners. After removing some repetitive rankings, we finally obtained 10 effective ranking results of the importance of indicators. The feedback results are organized as follows:

(i) The feedback results of main indicator layer

After sorting, the feedback results for importance ranking of main indicator layer are shown in the Table 9.

Table 9. The Importance ranking table of main indicator layer.

| Indicators/Expert Serial Number | \( T_1 \) | \( T_2 \) | \( T_3 \) | \( T_4 \) |
|---------------------------------|----------|----------|----------|----------|
| expert1                         | 2        | 3        | 4        | 1        |
| expert2                         | 1        | 4        | 3        | 2        |
| expert3                         | 1        | 2        | 4        | 3        |
| expert4                         | 1        | 3        | 4        | 2        |
| expert5                         | 2        | 3        | 4        | 1        |
| expert6                         | 1        | 4        | 2        | 3        |
| expert7                         | 1        | 3        | 4        | 2        |
| expert8                         | 3        | 4        | 2        | 1        |
| expert9                         | 2        | 3        | 4        | 1        |
| expert10                        | 1        | 4        | 3        | 2        |

The ranking matrix of the main indicators was collated as:

\[
A_1 = \begin{bmatrix}
2 & 3 & 4 & 1 \\
1 & 4 & 3 & 2 \\
1 & 2 & 4 & 3 \\
1 & 3 & 4 & 2 \\
2 & 3 & 4 & 1 \\
1 & 4 & 2 & 3 \\
1 & 3 & 4 & 2 \\
3 & 4 & 2 & 1 \\
2 & 3 & 4 & 1 \\
1 & 4 & 3 & 2 \\
\end{bmatrix}
\]

According to the above calculation steps, the weight vector of the main indicators can be obtained as:

\( w = (0.3200, 0.2010, 0.1750, 0.3040) \)

(ii) The feedback results of the secondary indicator layer

After sorting, the feedback results for importance ranking of secondary indicator layer are shown in the Table 10.

Similarly, according to the above steps, the weights of secondary indicators can be assigned, respectively, as follows:

\( w_1 = (0.2300, 0.1258, 0.1175, 0.3513, 0.1513, 0.1747, 0.2007) \)

\( w_2 = (0.3782, 0.3000, 0.3218) \)

\( w_3 = (0.3564, 0.3346, 0.3091) \)

\( w_4 = (0.3712, 0.2019, 0.2791, 0.1479) \)

According to the weight of the corresponding main indicator layer, the actual weight of each indicator can be obtained as shown in Table 1.
### Table 10. The Importance ranking table of secondary indicator layer.

| Indicators/Expert Serial Number | T11 | T12 | T13 | T14 | T15 | T16 | T21 | T22 |
|--------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| expert1                        | 1   | 5   | 6   | 2   | 4   | 3   | 1   | 2   |
| expert2                        | 1   | 6   | 3   | 4   | 5   | 1   | 2   | 1   |
| expert3                        | 2   | 6   | 4   | 1   | 5   | 3   | 1   | 3   |
| expert4                        | 4   | 6   | 5   | 1   | 3   | 2   | 1   | 2   |
| expert5                        | 1   | 4   | 6   | 5   | 3   | 2   | 2   | 3   |
| expert6                        | 2   | 5   | 6   | 1   | 4   | 3   | 1   | 2   |
| expert7                        | 2   | 4   | 3   | 6   | 1   | 5   | 1   | 3   |
| expert8                        | 1   | 6   | 5   | 4   | 3   | 2   | 2   | 3   |
| expert9                        | 3   | 4   | 6   | 5   | 2   | 1   | 3   | 1   |
| expert10                       | 2   | 5   | 6   | 3   | 4   | 1   | 2   | 3   |

| Indicators/Expert serial number | T23 | T31 | T32 | T33 | T41 | T42 | T43 | T44 |
|--------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| expert1                        | 3   | 3   | 2   | 1   | 1   | 2   | 3   | 4   |
| expert2                        | 3   | 2   | 1   | 3   | 1   | 3   | 2   | 4   |
| expert3                        | 2   | 1   | 2   | 3   | 1   | 3   | 2   | 4   |
| expert4                        | 3   | 1   | 3   | 2   | 1   | 3   | 2   | 4   |
| expert5                        | 1   | 1   | 2   | 3   | 1   | 4   | 2   | 3   |
| expert6                        | 3   | 2   | 3   | 1   | 1   | 2   | 3   | 4   |
| expert7                        | 2   | 2   | 1   | 3   | 1   | 3   | 2   | 4   |
| expert8                        | 1   | 2   | 1   | 3   | 1   | 3   | 2   | 4   |
| expert9                        | 2   | 3   | 2   | 1   | 1   | 3   | 2   | 4   |
| expert10                       | 1   | 1   | 3   | 2   | 1   | 3   | 2   | 4   |

### 5. Case Study

#### 5.1. Case Scenario

Ship X is a container ship owned by a shipping company. It plans to carry 1200 tons of fireworks one day from Chongqing Port to Wuhan Port for unloading. The container volume is 200, and the number of packages is 100,000. The goods have been packaged and sealed in moisture-proof before packing and marked as dangerous goods following the International Maritime Dangerous Goods Regulations. Information on passing ports and related infrastructure can be obtained by consulting. The accident frequency and other data are calculated from the actual transportation data of the Yangtze River.

Limited by the degree of informatization of inland river traffic, it is impossible to use the actual measurement data of the environmental conditions of all the unit areas of the route for calculation at this stage. Therefore, the environmental conditions of the unit segment of the quantitative indicators of the mathematical model only select the representative water area to participate in the calculation. In the example, a 2 km rectangular water area with Wuhan Tianxingzhou Bridge as the centerline is selected. According to the above-mentioned evaluation method of transportability, the transportability of the goods to be transported this time is evaluated and analyzed.

#### 5.2. Data Preparation and Parameter Calculation

Numerous parameters are involved in the above computational model; mainly probabilistic parameters and consequence metric models. Among them, the ignition probability is related to the leakage volume of dangerous goods, the physical and chemical properties, and the environment in which they are located. Existing studies usually take empirical values with accumulated accident data, and some scholars construct ignition probability prediction models according to specific scenario classifications [42]. In this paper, we synthesize empirical values from related studies such as the Yangtze River mainline ship accident reports and Purple Book to determine the reference values of ignition probability for spill events [43], as shown in Table 11.
Table 11. Reference values for the probability of immediate and delayed ignition of a spill of dangerous goods from a ship.

| Value Category                      | Probability of Immediate Ignition | Remarks                                                                 |
|-------------------------------------|-----------------------------------|-------------------------------------------------------------------------|
| According to leakage rate (liquid)  | >1 kg/s                           | 0.005~0.01                                                              |
|                                    | 1–50 kg/s                         | 0.01–0.05                                                               |
|                                    | >50 kg/s                          | 0.05–0.3                                                                |
| According to leakage rate (gas)     | <1 kg/s                           | 0.01–0.05                                                               |
|                                    | 1–50 kg/s                         | 0.05–0.2                                                                |
|                                    | >50 kg/s                          | 0.2–0.5                                                                 |
| Solid/packaged goods               |                                   | 0.05–0.1                                                                |

| Ignition source                     | Probability of Delayed Ignition   | Remarks                                                                 |
|-------------------------------------|----------------------------------|-------------------------------------------------------------------------|
| No ignition source                  | 0.01–0.05                        | The values are based on the flash point and flammability of the substance. |
| Minimal ignition sources            | 0.05–0.2                         |                                                                         |
| Few ignition sources                | 0.2–0.3                          |                                                                         |
| Many ignition sources               | 0.3–0.8                          |                                                                         |

The consequence models of dangerous goods accidents are mainly divided into three categories: fire, explosion, and leakage. The appropriate consequence metric model is selected according to the material and environmental characteristics. For details, see Figure 8.

5.2.1. Probability of Accidents in Dangerous Goods Ship Transportation

According to the dangerous goods ship data of 2016–2018 under the jurisdiction of the Yangtze River Maritime Bureau, dangerous cargo ships were declared a total of 312,551 times, with a total channel length of 2688.6 km, so the probability of dangerous cargo ship accidents on the Yangtze River mainline can be estimated as $2.249 \times 10^{-7}$ times/km. To distinguish accident-prone areas from ordinary waters, the accident occurrence rate is divided into four levels, based on the degree of risk of waters classified in the Ministry of Transport’s “National Water Traffic Safety Supervision and Rescue System Layout Plan” by combining regional navigation conditions and regional ship accident data [44], see Appendix A.3 for the specific values.
5.2.2. Probability of Secondary Leakage

To address the problem of insufficient samples of inland waterway transport data of dangerous goods, this paper uses information diffusion theory to calculate the probability of leakage accidents, with the idea of fuzzy mathematical processing of samples and diffusion of single-valued samples into set-valued samples. Table 12 separates the number of secondary accidents caused by transport accidents resulting in dangerous goods leakage and the total number of accidents on dangerous goods vessels recorded in the last three years on the Yangtze River Main Line as the basis for calculation.

| Year | Number of Leakage Pollution Accidents |
|------|--------------------------------------|
| 2016 | 0                                    |
| 2017 | 0                                    |
| 2018 | 2                                    |

The detailed steps of the information diffusion method can be found in the literature “Natural hazard risk assessment: Theory and practice” [45], and the annual probability of leakage pollution accidents on the Yangtze River mainline is 0.284794. In addition, the probability of leakage accidents for a specific type of dangerous goods transported by different categories has large variability, and since the data mechanism of waterway transport has not been completely perfected, the leakage rate of road transport based on the type of dangerous goods statistics can be referred [46]. The final probability of secondary leakage from ships transporting dangerous goods on waterways is shown in Table 13.

| Dangerous Goods Category | The Conditional Probability of Leakage |
|--------------------------|---------------------------------------|
| 1 Explosives             | 0.0054                                |
| 2 Gas                    | 0.045824                              |
| 3 Flammable liquid       | 0.15886                               |
| 4 Solids                 | 0.0035                                |
| 5 Oxides                 | 0.00558                               |
| 6 Toxic substances       | 0.00749                               |
| 7 Radioactive materials  | 0.00114                               |
| 8 Corrosives             | 0.0366822                             |
| 9 Miscellaneous hazardous materials | 0.0203062 |

5.2.3. Probability Model of Individual Death

With the point \((x, 0)\) on the fragment as the center of the circle and the maximum distance of the area of death caused by the consequences of the accident as the radius of the circle, the probability of death of an individual at the point \((x, y)\) can be expressed by the ratio of the chord length of the point to the diameter of the circle [47], as in Equation (16).

\[
L_{k,l}(x, y) = 2r\left(1 - \left(\frac{y}{r}\right)^2\right)^{\frac{1}{2}}/L
\]

where \(r\) is the maximum action distance in the death radius region; \(L\) is the segment length; \(y\) is the vertical distance from the calculated point to the \(x\)-axis, \(y < r\).

In the actual calculation, considering the open space on the water surface and the distance between ships’ travel, the main fatal area of the explosion/fire accident is in a certain range with the accident point as the radius. When the scope of the accident is small \((r \text{ less than two times the width of the ship})\), casualties mainly consider the crew of the accident ship, \(y\) takes half the ship width value, that is, the average probability of death to take half the ship’s width at the probability of death; when the explosion range is
larger \((r \text{ greater than two times the width of the ship})\), \(y\) takes \((1/2)r\), that is, the average probability of death takes \((1/2)r\) at the probability of death.

5.2.4. Risk Acceptability Criteria

(i) Acceptability Criteria for human risk

“The Acceptable Risk Criteria for Individuals and Socially Acceptable Risk Criteria for Hazardous Chemical Production and Storage Installations (for Trial Implementation)” promulgated by the State Administration of Safety Supervision in 2014 provides a detailed specification of the acceptable risk criteria for personnel, as shown in Figure 9a.

(ii) Acceptable criteria for economic risk

According to the F-L curve of the acceptable level of economic risk in the chemical industry (Figure 9b), an economic risk of \(5 \times 10^{-6}/\text{year}\) is an acceptable level when different degrees of economic loss occur. Combined with the actual Yangtze River mainline water transport, the acceptable level of economic risk for a single voyage is \(5 \times 10^{-11}\).

(iii) Acceptable risk criteria for environmentally sensitive areas

Since there is no uniform standard for environmental risk limit values in China, the critical value \(E_3\) of a risk index for environmentally sensitive areas refers to the Dutch national environmental policy planning risk standard, as shown in Figure 9c.

There are many high-density crowd focused places and many drinking water sources on both sides of the Yangtze River mainline, so according to the special characteristics of the Yangtze River mainline water environment, the environmental risk acceptable standard for the unit navigation section is \(10^{-8}\).

5.3. Framework Evaluation Results

The evaluation values of indexes are selected by experts through the evaluation criteria corresponding to the indicators, and the specific values are shown in Table 14.
Table 14. Relevant values for indicator calculation.

| Index | Weight | Evaluation Value (for Waters of Different Levels) | Correction Value/Risk Acceptance Standard | Transportation Risk Value |
|-------|--------|-------------------------------------------------|------------------------------------------|---------------------------|
|       |        |                                                 |                                          |                           |
|       |        |                                                 | 2                                        | 0.01472                   |
| T_{11} | 0.0736 | 0.4                                             | 1                                        | 0.02418                   |
| T_{12} | 0.0403 | 0.6                                             | 1.5                                      | 0.01504                   |
| T_{13} | 0.0376 | 0.6                                             | 2                                        | 0.01452                   |
| T_{14} | 0.0484 | 0.6                                             | 1.5                                      | 0.02236                   |
| T_{15} | 0.0559 | 0.6                                             | 2                                        | 0.02568                   |
| T_{16} | 0.0642 | 0.8                                             | 1                                        | 0.0304                    |
| T_{17} | 0.076  | 0.4                                             | 1                                        | 0.02412                   |
| T_{18} | 0.0603 | 0.4                                             | 1                                         | 0.01294                   |
| T_{19} | 0.0647 | 0.2                                             | 1                                         | 0.01294                   |
| T_{20} | 0.0624 | 0.6                                             | 1.5                                      | 0.02496                   |
| T_{21} | 0.0586 | 0.2                                             | 2                                         | 0.00586                   |
| T_{22} | 0.0541 | 0.2                                             | 1                                         | 0.01082                   |

The transportability risk of the environmental unit is calculated by taking the environmental conditions of the representative waters, and the values of the transportability risk of the environmental unit of the four types of waters are shown in Table 15.

Table 15. Transportability risk values for fireworks carried on Ship X.

| Different Levels of Water | Probability of Accident | R_1 | R_2 | R_3 | R_4 | R_{total} |
|---------------------------|-------------------------|-----|-----|-----|-----|-----------|
| High risk                 | 10^{-6}                 |     |     |     |     | 0.587     | 81.260    |
| Relatively high risk      | 5 \times 10^{-7}        | 0.134| 0.055| 0.375|     | 0.397     | 62.260    |
| General risk              | 10^{-7}                 |     |     |     |     | 0.245     | 47.051    |
| Other                     | 10^{-8}                 |     |     |     |     | 0.210     | 43.631    |

Substituting for the area’s class through which the Chongqing–Wuhan route passes, and assuming that all parameters except accident probability remain unchanged, the approximate trend of the fitted curve of the transportability risk value along the route is shown in Figure 10.

According to the analysis of the above-mentioned results, the risk of people in the environmental unit has exceeded the acceptable risk standard when passing through the high-risk waters and relatively high-risk waters, mainly because the chosen representative waters, i.e., Tianxingzhou waters, have a high population density on both sides of the coast, which may affect people on both sides of the coast if a major or even extra-large-scale accident occurs. In response to this situation, ship X can take the measure of splitting the load to more holds to reduce the possibility of complete explosion of the load; when passing through the area with a high population density on both sides of the shore, the...
competent authorities can be contacted to evacuate the number of people in the affected area appropriately to achieve the purpose of controlling the risk of people.

Figure 10. Change trend of transportability risk values for fireworks carried on Ship X. (Note: A1-A22 represent Changshou, Fuling, Fengdu, Wanzhou, Yunyang, Fengjie, Wushan, Badong, Three Gorges gate area, Gezhouba gate area, Yichang, Zhicheng, Zhijiang, Jingzhou, Jiangling, Shishou, Jili, Yueyang, Honghu, Jiayu, and Wuhan waters, respectively.).

6. Discussion and Limitations

The transportability assessment framework of dangerous goods proposed in this paper takes into account the dynamic changes of risk when dangerous goods are transported in different environments via inland waterways. Unlike most existing risk evaluation models, the framework considers the degree of matching between dangerous goods and inland waterway transport environment as the fundamental reason for determining the safety of dangerous goods transport. Although the transportability risk of different classes of waters has been distinguished in Section 5.3, and the transportability of the fireworks in this case scenario can be generally judged to be conditionally restricted when transported via Chongqing to the Wuhan port, the case is limited in accuracy because only a representative section of waters is selected to participate in the calculation of the transportability risk value of the environmental unit due to the difficulty of collecting inland river environmental data. In general, the limitations of the current study are mainly as follows.

(a) The transportability evaluation framework draws on the idea of risk evaluation, and the concept of risk itself is subjective in nature. The establishment of the indicator system of the evaluation framework relies mainly on practitioners’ perceptions, and although we have weakened the subjectivity in the allocation of indicator weights, there is still subjectivity in the selection of indicators, the determination of weights, and the evaluation process that cannot be ignored.

(b) The regional extent of the evaluation grid should be divided according to the similarity of environmental conditions because our framework assumes that cargo and vessel factors will not change abruptly when environmental conditions remain similar, and the transportability risk presents a stable state at this time. Since detailed inland river environmental data samples cannot be collected at present, the uniform segmented chain grid division approach is adopted in this paper. This problem may need to rely on real-time and intelligent inland waterway shipping monitoring in the future to find a solution.
(c) The calculation models for individual indicators of personnel risk, economic risk, and sensitive area risk follow the traditional risk quantification methods, which do not take into account the numerous uncertainties involved in dangerous goods accidents in practical applications, and the accident model parameters involved can only be taken empirically. In the subsequent study, the accuracy of the model will be greatly improved if real-time environmental data can be accessed for accident scenario simulation.

7. Conclusions

The concept of “transportability” presented in this study is different from traditional dangerous goods transport risks and is designed specifically for the transport of large volumes of dangerous goods on board which are prone to secondary accidents. The acceptance of dangerous goods accidents in the special waterway transport environment of inland waterways is considered in the form of risk acceptability criteria. The whole framework quantifies the transportability of dangerous goods based on the information of dangerous goods and the proposed voyage, calculates the risk of secondary accidents for the batch of dangerous goods on the grid cells through which the transport route passes, derives the evaluation value of each grid cell by combining the cargo, ship, and channel facilities conditions, and integrates the evaluation value of the grid cells of the whole route to derive the qualitative evaluation of the transportability of dangerous goods for the voyage. For example, the TNT equivalent model is chosen in the above-mentioned case of pyrotechnic transport, and the vulnerability of the adjacent people, ships, and sensitive areas is taken into account. The results of the framework evaluation have a certain degree of differentiation for the transportability of dangerous goods in different classes of waters and can visually identify the influencing factors and their degree of influence.

However, the accuracy of the model is limited. The subjectivity of the grid division and indicator system affects the evaluation results. The selection of indicators focuses on quantifiability and importance, which can be further optimized. The parameters in the calculation model are limited by the current level of information technology, and subsequent continuous improvement is needed through a large amount of data accumulation and cases.

The framework can provide a transportation management basis for maritime authorities to facilitate their adoption of targeted management models for different transportability and improve the safety of inland waterway transportation of dangerous goods. Dangerous goods manufacturers can also use it as a reference to judge whether newborn dangerous goods can be transported. With the improvement of inland waterway information collection systems in the future, the parameterizable dynamic transportability evaluation system can also be used as an objective function together with other objectives (transportation cost, navigation operation planning) to optimize the selection of berths and terminals in transportation, and can also help maritime management authorities to develop contingency plans for the approaching population, navigable dense areas, sensitive areas, etc.

Author Contributions: Conceptualization, Y.W.; methodology, Y.W. and X.H.; software, X.C.; validation, X.H. and Z.S.; formal analysis, X.H. and Z.S.; investigation, X.C.; resources, F.Z.; data curation, F.Z.; writing—original draft preparation, X.H.; writing—review and editing, F.Z.; visualization, Z.S.; supervision, F.Z.; project administration, F.Z.; funding acquisition, Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (NSFC) through Grant No. 52072287.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to thank the anonymous reviewers and editors for their constructive comments, which is very helpful to improve the paper.

Conflicts of Interest: The authors declare no conflict of interest.
Appendix A. Detailed Lists of Some Variables Included in the Model and Their Sources

Appendix A.1. The Range of Variable $\alpha_k$

The value range of $\alpha_k$ is quoted from “GB 18218-2018 The standard of major hazard source identification”.

Table A1. Table of Correction factor value $\alpha_k$ for exposed persons.

| Number of People Potentially Exposed | $\alpha_k$ |
|--------------------------------------|------------|
| More than 100                        | 2          |
| 50–99                                | 1.5        |
| 30–49                                | 1.2        |
| 1–29                                 | 1          |
| 0                                    | 0.5        |

Appendix A.2. The Range of Variable $\beta_k$

The value range of $\beta_k$ is determined by the domain experts based on the comprehensive conditions of the unit.

Table A2. Table of value range of $\beta_k$.

| Comprehensive Conditions of the Evaluation Unit | $\beta_k$ |
|-------------------------------------------------|-----------|
| Good                                            | 2         |
| General                                         | 1.5       |
| Lacking                                         | 1         |

Appendix A.3. Risk Level Classification of the Yangtze River Mainline Waters

In this study, the average accident rate of the Yangtze River mainline is used as a reference basis for accident probability, and when evaluating the transportability of different kinds of dangerous goods, the accident rate is divided into four levels based on the risk level of waters classified in the “Layout Plan of National Water Transportation Safety Supervision and Rescue System” of the Ministry of Transport of the People’s Republic of China (Tables 3 and 4). Considering the special characteristics of certain waters, the ship travels extremely slowly in the dam area waters compared with other waters, and its probability of traffic accidents is extremely small, so the special waters such as the lock waters are classified within other waters.

Table A3. Risk level classification of the Yangtze River mainline waters.

| Serial Number | Risk Level | Name of Water Area | Accident Probability |
|---------------|------------|--------------------|----------------------|
| 1             | High Risk  | Chongqing          |                      |
| 2             |            | Changshou          |                      |
| 3             |            | Fengdu             |                      |
| 4             |            | Yunnan             |                      |
| 5             |            | Fengjie            |                      |
| 6             |            | Badong             |                      |
| 7             |            | Wanzhou            |                      |
| 8             |            | Wushan             |                      |
| 9             |            | Three Gorges Dam area(excluding the lock area) | $10^{-6}$ |
| 10            |            | Gezhouba Dam(excluding the lock area) | $10^{-6}$ |
| 11            |            | Wuhan              |                      |
| 12            |            | Wuhan Port Area    |                      |
| 13            |            | Nanjing            |                      |
| 14            |            | Zhenjiang          |                      |
| 15            |            | Yangzhou           |                      |
| 16            |            | Taizhou            |                      |
| 17            |            | Jiangyin           |                      |
| 18            |            | Zhangjiagang       |                      |
| 19            |            | Nantong            |                      |
| 20            |            | Changshu           |                      |
Table A3. Cont.

| Serial Number | Risk Level | Name of Water Area | Accident Probability |
|---------------|------------|--------------------|----------------------|
| 21            | Relatively High Risk | Taicang | |
| 22            |             | Luzhou           | $5 \times 10^{-7}$   |
| 23            |             | Yichang          |                     |
| 24            |             | Guizhou          |                     |
| 25            |             | Zicheng          |                     |
| 26            |             | Zhijiang         |                     |
| 27            |             | Jingzhou         |                     |
| 28            |             | Yueyang          |                     |
| 29            |             | Liuli            |                     |
| 30            |             | Linxiang         |                     |
| 31            |             | Honghu           |                     |
| 32            |             | Jujiang          |                     |
| 33            |             | Wuxiang          |                     |
| 34            |             | Hukou            |                     |
| 35            |             | Huangshi         |                     |
| 36            |             | Ezhou            |                     |
| 37            |             | Herb             |                     |
| 38            |             | Anqing           |                     |
| 39            |             | Chizhou          |                     |
| 40            |             | Wuhu             |                     |
| 41            |             | Tongling         |                     |
| 42            |             | Digang           |                     |
| 43            |             | Maanshan         |                     |
| 44            | General risk | Yibin            | $10^{-7}$            |
| 45            |             | Fuling           |                     |
| 46            |             | Other            | $10^{-8}$            |

References

1. UNCTAD. Review of Maritime Transport 2020. Available online: https://unctad.org/system/files/official-document/rmt2020_en.pdf (accessed on 8 August 2021).
2. China Report Net. China Hazardous Chemical Transportation Industry Analysis Report 2020—Market Operation Trend and Development Prospect Research. 2020. Available online: http://baogao.chinabaogao.com/wuliu/364083364083.html.2021.01.015 (accessed on 8 August 2021).
3. Saat, M.R.; Werth, C.J.; Schaeffer, D.; Yoon, H.; Barkan, C.P. Environmental risk analysis of hazardous material rail transportation. J. Hazard. Mater. 2014, 264, 560–569. [CrossRef] [PubMed]
4. Soeanu, A.; Debbabi, M.; Alhadidi, D.; Makkawi, M.; Allouche, M.; Bélanger, M.; Léchevin, N. Transportation risk analysis using probabilistic model checking. Expert Syst. Appl. 2015, 42, 4410–4421. [CrossRef]
5. Inanloo, B.; Tansel, B. A transportation network assessment tool for hazardous material cargo routing: Weighing exposure health risks, proximity to vulnerable areas, delay costs and trucking expenses. J. Loss Prev. Process. Ind. 2016, 40, 266–276. [CrossRef]
6. Pamučar, D.; Ljubojević, S.; Kostadinović, D.; Dorović, B. Cost and risk aggregation in multi-objective route planning for hazardous materials transportation—A neuro-fuzzy and artificial bee colony approach. Expert Syst. Appl. 2016, 65, 1–15. [CrossRef]
7. Gai, W.-M.; Du, Y.; Deng, Y.-F. Evacuation risk assessment of regional evacuation for major accidents and its application in emergency planning: A case study. Saf. Sci. 2018, 106, 203–218. [CrossRef]
8. Yoo, B.; Choi, S.D. Emergency Evacuation Plan for Hazardous Chemicals Leakage Accidents Using GIS-based Risk Analysis Techniques in South Korea. Int. J. Environ. Res. Public Health 2019, 16, 1948. [CrossRef]
9. Akten, N. Shipping accidents: A serious threat for marine environment. J. Black Sea/Mediterr. Environ. 2006, 12, 269–304.
10. Gasparotti, C. Risk assessment of marine oil spills. Environ. Eng. Manag. J. 2010, 9, 527–534. [CrossRef]
11. Li, S.; Meng, Q.; Qi, X. An overview of maritime waterway quantitative risk assessment models. Risk Anal. Int. J. 2012, 32, 496–512. [CrossRef]
12. Fabiano, B.; Curro, F.; Palazzi, E.; Pastorino, R. A framework for risk assessment and decision-making strategies in dangerous good transportation. J. Hazard. Mater. 2002, 93, 1–15. [CrossRef]
13. Ren, H.; Song, Y.; Wang, J.; Hu, Y.; Lei, J. A Deep Learning Approach to the Citywide Traffic Accident Risk Prediction. In Proceedings of the 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 4–7 November 2018.
14. Salminen, S.; Klen, T.; Ojansen, K. Risk taking and accident frequency among Finnish forestry workers. Saf. Sci. 1999, 33, 143–153. [CrossRef]
15. Jiang, J.; Wang, P.; Lung, W.-S.; Guo, L.; Li, M. A GIS-based generic real-time risk assessment framework and decision tools for chemical spills in the river basin. J. Hazard. Mater. 2012, 227, 280–291. [CrossRef]
16. Khakzad, N.; Khan, F.; Amyotte, P.; Cozzani, V. Risk management of domino effects considering dynamic consequence analysis. Risk Anal. 2014, 34, 1128–1138. [CrossRef]
17. Shah, S.A.; Brijs, T.; Ahmad, N.; Pirdavani, A.; Shen, Y.; Basheer, M.A. Road safety risk evaluation using gis-based data envelopment analysis—Artificial neural networks approach. *Appl. Sci.* **2017**, *7*, 886. [CrossRef]

18. Ma, X.; Xing, Y.; Lu, J. Causation Analysis of Hazardous Material Road Transportation Accidents by Bayesian Network Using Genie. *J. Adv. Transp.* **2018**, *2018*, 6248105. [CrossRef]

19. Chakrabarti, U.K.; Parikh, J.K. Applying HAZAN methodology to hazmat transportation risk assessment. *Process. Saf. Environ. Prot.* **2012**, *90*, 368–385. [CrossRef]

20. Ditta, A.; Figueroa, O.; Galindo, G.; Yie-Pinedo, R. A review on research in transportation of hazardous materials. *Socio-Econ. Plan. Sci.* **2019**, *68*, 100665. [CrossRef]

21. Ellis, J. Analysis of accidents and incidents occurring during transport of packaged dangerous goods by sea. *Saf. Sci.* **2011**, *49*, 1231–1237. [CrossRef]

22. Uğurlu, Ö. Analysis of fire and explosion accidents occurring in tankers transporting hazardous cargoes. *Int. J. Ind. Ergon.* **2016**, *55*, 1–11. [CrossRef]

23. Baalisampang, T.; Abbassi, R.; Garaniya, V.; Khan, F.; Dadashzadeh, M. Review and analysis of fire and explosion accidents in maritime transportation. *Ocean. Eng.* **2018**, *158*, 350–366. [CrossRef]

24. Chang, C.-H.; Xu, J.; Song, D.-P. An analysis of safety and security risks in container shipping operations: A case study of Taiwan. *Saf. Sci.* **2014**, *63*, 168–178. [CrossRef]

25. Zhao, L.; Wang, X.; Qian, Y. Analysis of factors that influence hazardous material transportation accidents based on Bayesian networks: A case study in China. *Saf. Sci.* **2012**, *50*, 1049–1055. [CrossRef]

26. Hong, J.; Tamakloe, R.; Park, D. Application of association rules mining algorithm for hazardous materials transportation crashes on expressway. *Accid. Anal. Prev.* **2020**, *142*, 105497. [CrossRef]

27. Liu, X.; Saat, M.R.; Barkan, C.P. Probability analysis of multiple-tank-car release incidents in railway hazardous materials transportation. *J. Hazard. Mater.* **2014**, *276*, 442–451. [CrossRef]

28. Celik, M.; Lavasani, S.M.; Wang, J. A risk-based modelling approach to enhance shipping accident investigation. *Saf. Sci.* **2010**, *48*, 18–27. [CrossRef]

29. Reniers, G.L.L.; Jongh, K.D.; Gorrens, B.; Lauwers, D.; Leest, M.V.; Witlox, F. Transportation Risk Analysis tool for hazardous materials systems—A case study for open sea collisions involving RoPax vessels. *Reliab. Eng. Syst. Saf.* **2014**, *124*, 142–157. [CrossRef]

30. Verma, M.; Verter, V.; Gendreau, M. A tactical planning model for railroad transportation of dangerous goods. *Transp. Sci.* **2011**, *45*, 163–174. [CrossRef]

31. John, A.; Paraskevadakis, D.; Bury, A.; Yang, Z.; Riahi, R.; Wang, J. An integrated fuzzy risk assessment for seaport operations. *Saf. Sci.* **2014**, *68*, 180–194. [CrossRef]

32. Stavrou, D.I.; Ventikos, N.P. A novel approach in risk evaluation for ship-to-ship (STS) transfer of cargo using process failure mode and effects analysis (PFMEA). *J. Risk Res.* **2016**, *19*, 913–933. [CrossRef]

33. Akyildiz, H.; Mentes, A. An integrated risk assessment based on uncertainty analysis for cargo vessel safety. *Saf. Sci.* **2017**, *92*, 34–43. [CrossRef]

34. Inanloo, B.; Tansel, B. Explosion impacts during transport of hazardous cargo: GIS-based characterization of overpressure impacts and delineation of flammable zones for ammonia. *J. Environ. Manag.* **2015**, *156*, 1–9. [CrossRef]

35. Montewka, J.; Ehlers, S.; Goerlant, F.; Hinz, T.; Tabri, K.; Kujala, P. A framework for risk assessment for maritime transportation systems—A case study for open sea collisions involving RoPax vessels. *Reliab. Eng. Syst. Saf.* **2014**, *124*, 142–157. [CrossRef]

36. Goerlant, F.; Montewka, J. A framework for risk analysis of maritime transportation systems: A case study for oil spill from tankers in a ship–ship collision. *Saf. Sci.* **2015**, *76*, 42–66. [CrossRef]

37. Yang, Q.; Lin, K.-S.; Li, Y.-L. A quality function deployment-based framework for the risk management of hazardous material transportation process. *J. Loss Prev. Process. Ind.* **2018**, *52*, 81–92. [CrossRef]

38. Das, A.; Gupta, A.K.; Mazumder, T.N. A comprehensive risk assessment framework for offsite transportation of inflammable hazardous waste. *J. Hazard. Mater.* **2012**, *227*, 88–96. [CrossRef] [PubMed]

39. Li, Q. *Risk Analysis of Road Transport of Liquid Dangerous Goods*; Beijing JiaoTong University: Beijing, China, 2010.

40. Ministry of Transport of the People’s Republic of China. *Water Traffic Accident Statistics Approach*; Ministry of Transport Order No. 5 of 2002; Ministry of Transport of the People’s Republic of China: Beijing, China, 2002.

41. Cheng, Q. Structural entropy weighting method for determining the weights of evaluation indexes. *Syst. Eng. Theory Pract.* **2010**, *7*, 1225–1228.

42. Yuan, X.; Zhu, C.; Ge, X.; Ren, C.; Wang, K. Study on the ignition probability of hazardous chemical spills. *Chin. J. Saf. Sci.* **2011**, *21*, 39–45.

43. Uijit de Haag, P.A.M.; Ale, B.J.M. Purple book: Guidelines for quantitative risk assessment. *RIVM Hague* **1999**, *3*, 1–47.

44. Ministry of Transport of the People’s Republic of China. *National Water Traffic Safety Supervision and Rescue System Layout Plan*; Government Planning Documents; Ministry of Transport of the People’s Republic of China: Beijing, China, 2007.

45. Huang, C. *Natural Hazard Risk Assessment: Theory and Practice*; Science Press: Beijing, China, 2005.
46. Battelle. *Comparative Risks of Hazardous Materials and Non-Hazardous Materials Truck Shipment Accidents/Incidents*; Federal Motor Carrier Safety Administration: Washington, DC, USA, 2001.

47. Ball, D.J.; Floyd, P.J. *Societal Risks. Final Report. School of Health, Biological; Environmental Sciences; Middlesex University*; London, UK, 2001.