

Article

Dynamic Social Risk Assessment for Inland Waterway Lock Reservation Scheduling: A Stakeholder-Informed Dynamic Weighting and Two-Dimensional Cloud Model

Rong Li ^{1,2}, Qing Liu ^{1,3} , Xifei He ^{1,*} and Lei Wang ¹

¹ School of Transportation and Logistics Engineering, Wuhan University of Technology, Wuhan 430063, China; 335147@whut.edu.cn (R.L.); lqwhutjt@whut.edu.cn (Q.L.); wl175345973@whut.edu.cn (L.W.)

² Office of Scientific Research, Zhejiang Institute of Communications, Hangzhou 311100, China

³ State Key Laboratory of Maritime Technology and Safety, Wuhan University of Technology, Wuhan 430062, China

* Correspondence: 358726@whut.edu.cn

Abstract

Inland waterway locks are critical navigation infrastructures in waterborne transport systems, and their operational reliability is closely associated with the resilience and service capacity of regional inland waterway networks. As lockage demand continues to increase, reservation scheduling has emerged as an important institutional and operational instrument for improving traffic organization, alleviating congestion, and enhancing the adaptive capacity of lock operations. However, the implementation of reservation-based rules may reshape lockage resource allocation, priority mechanisms, vessel arrival patterns, and stakeholder benefit structures, thereby generating social risks that cannot be adequately captured by conventional engineering safety assessment methods. To address this issue, this study develops a stakeholder-informed dynamic social risk assessment framework for inland waterway lock reservation scheduling. First, a hybrid scheduling mode combining priority reservation and declaration-based queuing is conceptualized, and its operational process is characterized through lockage resource allocation, vessel reservation/declaration, coordinated water-area control, anchorage and safety inspection, and sequenced vessel lockage. Second, drawing on the social amplification of risk framework, a social risk assessment indicator system is constructed from four dimensions: legality, rationality, feasibility, and controllability. Third, a Dynamic Weighting Model is introduced to adaptively update indicator weights according to changes in scheduling rules and operational states, while a Two-Dimensional Cloud Model is developed to jointly represent risk probability and risk consequence under uncertainty. The proposed approach is validated using the reservation scheduling scenario of the Three Gorges locks. The results indicate that the overall social risk is classified as level 2, corresponding to a moderately low risk level, suggesting that the reservation scheduling mode is generally compatible with lock operation and navigation management requirements. Among the four dimensions, controllability exhibits the highest relative risk, indicating that greater attention should be paid to safety management, reservation compliance, public opinion guidance, and emergency response. The proposed framework provides a systematic and visual decision-support tool for risk identification, risk grading, and scheme optimization in inland waterway lock reservation scheduling.



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Keywords: inland waterway locks; reservation mode; social risks; dynamic weights; two-dimensional cloud model; waterway transportation resilience

1. Introduction

Inland navigation occupies an important position in the comprehensive transportation system, and compared with common modes of transportation such as roads and railroads, inland navigation possesses significant advantages such as large capacity and low tariffs. It can provide an effective guarantee for the transportation of bulk materials in the basin. As an important navigational building in the waterway, inland waterway locks are comprehensive control hubs of the waterway, but they also restrict transportation efficiency to a certain extent. Therefore, it is especially necessary to set corresponding scheduling rules according to the actual situation of the waterway conditions and lock operation and management. The traditional scheduling organization of inland river locks usually adopts a queuing mode based on first come first service (FCFS), and the vessel waiting time is an important index under the queuing rule used to measure the efficiency of lock navigation [1]. However, along with the increasing demand for ship crossing, optimization rules such as the reservation system are also applied to the dynamic regulation of the time sequence of ships waiting for locks, and the safety and fairness of lock scheduling are also considered to be evaluated dimensions that are on an equal footing with efficiency [2–5].

Against the backdrop of the gradual promotion of reservation scheduling rules, ship lock operation and management have evolved from a conventional operational dispatching problem into an institutional arrangement involving the participation and strategic interaction of multiple stakeholders. The allocation of appointment resources, the design of time-window rules, and the adjustment of priority mechanisms may all reshape the opportunity structure and interest distribution among different vessel types and transport operators. Such institutional redistribution not only affects vessel operating efficiency, but may also evolve into social risks through cognitive bias, information diffusion, and collective behavioral responses.

Unlike conventional engineering safety risks, risks under reservation scheduling scenarios are more prominently manifested as institutional operation risks and social response risks. Their sources do not stem from a single accident or event, but from the combined effects of legitimacy perception, rationality judgment, implementation feasibility, and risk controllability during the process of rule adjustment. When scheduling rules deviate from stakeholder expectations, individual dissatisfaction may be amplified through media communication and group interaction, potentially triggering public opinion fluctuations or even collective incidents. Such risks are characterized by pronounced amplification, coupling, and context dependence, making them difficult to represent using traditional accident probability models.

Existing studies on ship lock safety evaluation have mostly focused on physical risk identification and risk grading associated with equipment failures, environmental disturbances, or human operational errors, with an emphasis on the quantitative analysis of accident occurrence probability and consequence severity. Although such methods are highly applicable to engineering safety management, they exhibit several limitations when applied to social risks arising from institutional change. First, they insufficiently incorporate subjective factors such as institutional trust and perceived procedural fairness. Second, they are unable to capture the dynamic evolution of risks during the process of information diffusion and social amplification. Third, indicator weights are usually specified in a static manner, making it difficult to reflect risk-sensitivity adjustments induced by changes in operational states. Social risk assessment is necessary for major decisions such as the optimization of the lock scheduling mode [6,7].

Moreover, reservation scheduling rules exhibit distinct stage-specific and context-dependent characteristics. Under normal operating conditions, rule implementation may remain relatively stable. However, under peak congestion, equipment maintenance, or

emergency scenarios, the pressure of rule enforcement and the intensity of interest conflicts may increase substantially, resulting in corresponding changes in the risk structure. Therefore, developing an evaluation method that can simultaneously characterize the state of institutional operation and capture the dynamic evolution of risk constitutes a key technical challenge in the study of social risks associated with reservation scheduling.

Based on the above research gap, the purpose of this study is not merely to develop an evaluation method, but to provide a problem-oriented framework for identifying, measuring, and interpreting social risks associated with inland waterway lock reservation scheduling. This study focuses on clarifying the potential social risks induced by reservation scheduling rules, incorporating stakeholder perceptions into the construction and evaluation of risk indicators, and characterizing the state-dependent evolution and uncertainty of social risks under different scheduling rules and operational conditions. On this basis, an integrated assessment framework combining stakeholder-informed indicator construction, the Dynamic Weighting Model, and the Two-Dimensional Cloud Model is proposed and applied to the Three Gorges lock case to identify key risk dimensions and derive practical management implications. The contributions of this study are as follows:

- (1) Constructing a social risk assessment indicator system for the inland waterway lock reservation scheduling mode, considering stakeholder perspectives. Based on the stakeholder network, social-risk-influencing factors are identified and extracted in conjunction with the social amplification of risk framework. The evaluation index system is built from four dimensions: legality, rationality, feasibility, and controllability.
- (2) To capture the state-dependent nature of social risks, a state-deviation-driven dynamic weighting mechanism is introduced, through which the weights assigned to individual risk indicators can be adaptively updated as scheduling rules change and operational states evolve. The standard weights represent the basic risk information of the lock scheduling model, while weight multipliers are introduced to reflect differences in metrics caused by varying processes under different rules, effectively reducing assessment and decision-making distortions.
- (3) Proposing a new multi-attribute decision-making (MADM) method that combines dynamic empowerment with the Two-Dimensional Cloud Model. By considering both risk probability and risk consequence symmetry, two-dimensional base variables for social risk assessment are constructed. By generating the overall cloud drop distribution pattern, the method visually captures the ambiguity and stochasticity of social risk and enables dynamic estimation of the integrated risk of complex systems under uncertainty.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature on lock navigation scheduling rules, societal risk assessment, and risk assessment methods, thereby clarifying the research basis and methodological gaps. Section 3 conceptualizes the inland waterway lock reservation scheduling mode and describes the operational logic of the priority reservation and declaration-based queuing mechanism. Section 4 constructs a social risk assessment indicator system for inland waterway lock reservation scheduling from a stakeholder perspective, with the indicators organized under the dimensions of legality, rationality, feasibility, and controllability. Section 5 develops the proposed assessment methodology by integrating the Dynamic Weighting Model with the Two-Dimensional Cloud Model to characterize the state-dependent evolution and uncertainty of social risks. Section 6 presents a case study of the Three Gorges locks to validate the applicability and effectiveness of the proposed approach. Finally, Section 7 concludes the paper and discusses directions for future research.

2. Literature Review

2.1. Research on the Lock Navigation Scheduling Rules

During periods when the demand for ships crossing the lock is relatively calm, the queuing rule of FCFS is usually adopted. Scholars typically study the organization of ship transportation and the layout of locks [8–12]. Verstichel et al. [8] introduced an integrated approach to solving the generalized lock scheduling problem. Three interrelated subproblems can be discerned: ship placement, chamber assignment, and lockage operation scheduling. Based on this, Ting et al. [3] proposed two priority scheduling modes, namely the shortest processing time first (SPF) and chamber packing without tow breaking (PAC), and compared them with FCFS. Subsequently, more researchers devoted their efforts to optimizing the ship lock scheduling rules to achieve better scheduling performance. Yuan et al. [13] considered water–land trans-shipment as a new and efficient way to relieve the pressure on the lock for ships passing a dam. Zheng et al. [14] examined the coordinated dispatching of the Three Gorges ship lock and the ship lift, given a situation where the passing capacity of the Three Gorges Hub ship lock reached its limit. Deng et al. [15] proposed a congestion charging scheme and a mobile service window scheme to alleviate delays for ships in the dam area. Li et al. [5] introduced a reservation dispatching rule and applied it to the dispatching management of the Three Gorges ship lock. In summary, we see that efficiency, safety, and fairness are the most valued principles in lock scheduling, and the design and optimization of rules need to fully consider the relationships among them.

2.2. Research on the Societal Risk Assessment

The establishment of a social risk assessment mechanism for major decisions helps stakeholders to clarify the main aspects of conflicts and promotes the democratic and scientific nature of decision-making. Hassel et al. [16] proposed that systematic evaluations of the suitability and effectiveness of proactive societal safety interventions are scarce—especially for complex interventions where impacts are difficult to observe directly or where there are delays between intervention and its effects. Tsang et al. [17] introduced a simple and unambiguous procedure for developing a parametric societal risk function based on rigorous loss modeling of response-specific probabilistic scenarios. Cui et al. [18] proposed a quantitative development evaluation model based on connection values for the coordinated assessment of the WSE water resources system. Yang et al. [19] established a theoretical framework and proposed an integrated methodology to evaluate the societal impact of disrupted infrastructure during disaster events. Özdemir et al. [20] aimed to evaluate the sustainable and intelligent urban transportation systems of fifty global economies by using nine main and fifty-six sub-criteria. Wang et al. [21] proposed that societal risk acceptance criteria (SRAC) be used in the shipping industry as a benchmark to determine whether the actual ship risk is under control. Lucas et al. [22] built on a domain-overarching definition of systemic risks by highlighting crucial properties that distinguish them from conventional risks and plain disasters. In summary, social risk assessment is widely used in engineering practice.

2.3. Research on Risk Assessment Method

With the acceleration of globalization and the widespread application of complex systems, uncertainty risk has become a common challenge across various fields. Numerous scholars have conducted extensive research on risk assessment methods. Wang [23] proposed a modified social model, which was applied to evaluate the conflict risk between pedestrians and bicycles on both a straight road and at an intersection on a campus. Zhang et al. [24] introduced an analysis method for assessing the safety of population distribution in potential impact zones of major accidents. Tsang et al. [25] proposed a rational and universal approach for evaluating the adequacy of structural safety requirements by

comparing societal risk functions based on probabilistic loss assessment with a proposed regulatory requirement that aims to limit the mortality rate to “as low as reasonably practicable (ALARP).” Zhan et al. [26] presented a novel FMEA method based on social network analysis, enhancing the gained and lost dominance score (GLDS) for the risk assessment of submarine pipelines with improved reliability. Wang et al. [27] proposed a new framework and system for identifying and evaluating the main risks in the GSCAP from the perspective of agricultural enterprises. McDougall et al. [28] introduced a risk assessment tool for comparing the landslide risk faced by a group of people with the tolerable risk. Zhang et al. [29] utilized social media data to assess urban flood risk through a Bayesian network. Existing research primarily focuses on methods for transforming qualitative perspectives into quantitative calculations, and weight allocation often relies on the subjective views of experts. The superimposed and coupled effects of risk are challenging to represent quantitatively.

Existing research on risk assessment in lock scheduling faces three key limitations: (1) static deficiency: traditional methods struggle to quantify the dynamic evolution of risks triggered by changes in scheduling strategies; (2) subjective dependence: weight allocation and risk threshold setting overly rely on expert experience; (3) dimensional constraints: existing models cannot effectively characterize the coupled effects of multiple risk factors. The improved Two-Dimensional Cloud Model proposed in this paper utilizes a dynamic cloud parameter generation algorithm to achieve dynamic mapping of risk levels as scheduling rules change, thereby significantly enhancing the effectiveness of risk warnings.

3. Conceptual Connotation of the Inland Waterway Lock Reservation Scheduling Mode

Navigation scheduling and management for inland waterway locks are characterized by stringent safety requirements, complex operational procedures, and broad systemic impacts. Accordingly, the design of lock scheduling modes should follow well-defined principles to ensure scientific soundness and practical rationality. Against the backdrop of the fact that the current lock capacity supply cannot fully accommodate the growing demand for vessel lockage, whether the proposed scheduling mode can safeguard fairness in vessel passage and improve users’ perceived experience and satisfaction during lock transit is directly related to the credibility of navigation management authorities. Moreover, building on the advantages of the existing queue-based scheduling mode while promoting scheduling innovation in a phased and progressive manner to adapt to emerging development needs is an essential requirement for ensuring the stable and sustainable development of inland waterway lock operations.

This study integrates reservation-based and queue-based scheduling rules and proposes a hybrid scheduling mode based on priority reservation and declaration-based queuing. The lockage process under this mode is illustrated in Figure 1. Specifically, the proposed mode represents a combined scheduling mechanism that gradually embeds reservation rules into the full process of lock navigation management while retaining the fundamental logic of the existing queue-based system. Through advance planning and pre-arranged scheduling, originally stochastic vessel arrival demand can be transformed into an orderly and controllable arrival process, thereby reducing logistics costs, improving waterborne transport efficiency, enhancing the service level of dam-crossing navigation, and ensuring greater predictability for the lock transit of priority vessels.

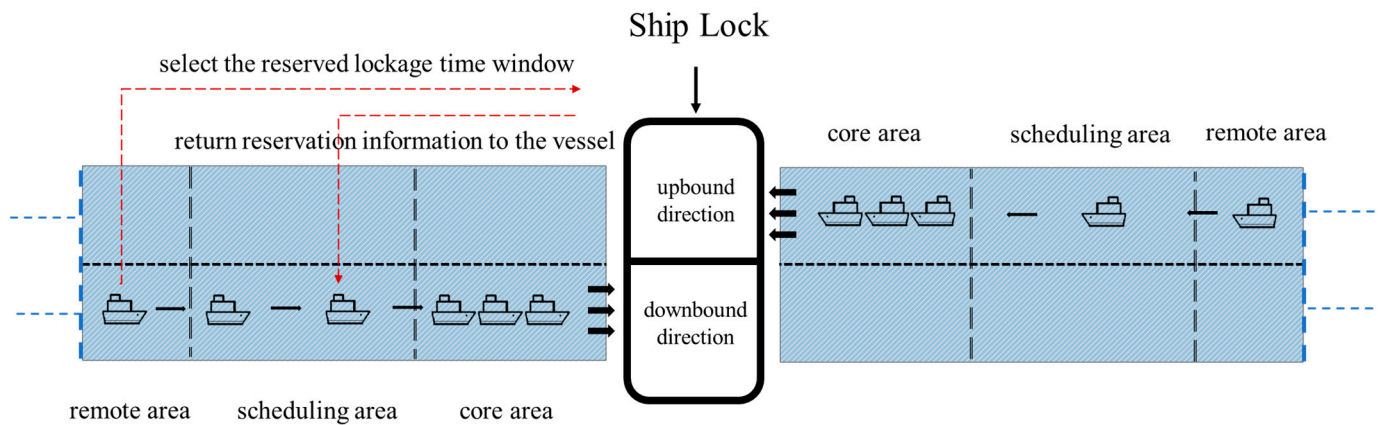


Figure 1. Schematic of vessel transit under the reservation-based scheduling rule.

From the perspective of scheduling organization, the priority reservation and declaration-based queuing mode can be divided into five stages: lockage resource allocation, vessel reservation/declaration, coordinated water-area control, anchorage and safety inspection, and sequenced vessel lockage. The overall operational process is shown in Figure 2. This process reflects the operational logic by which the reservation mechanism is embedded into the existing declaration-based queuing framework. Specifically, while preserving the declaration-based queuing pathway for ordinary vessels, a dedicated reservation channel is established for priority vessels. Through advance resource allocation, coordinated process control, and dynamic sequencing at the terminal stage, the proposed mode enables the coordinated matching between vessel lockage demand and lock service capacity.

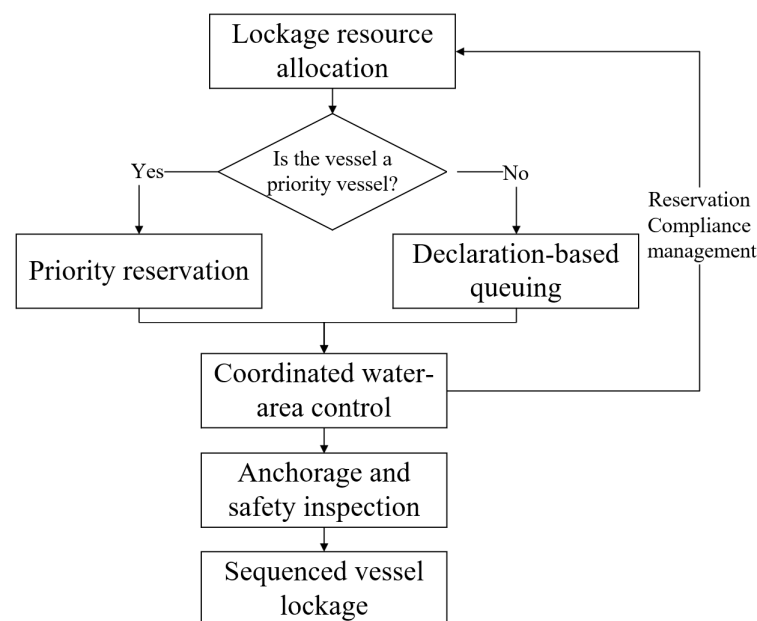


Figure 2. Overall flowchart of the priority reservation and declaration-based queuing mode.

At the initial stage of the voyage, vessels first obtain information on the lockage resources released by the lock authority. Based on such information, each vessel submits a lockage application by considering its voyage plan, loading and unloading arrangements, and estimated time of arrival. After completing the reservation or declaration process, vessels gradually approach the regulated scheduling waters in accordance with the feedback information and their own navigation progress, while being subject to coordinated control

arrangements. Once entering the core water area, vessels proceed to the waiting and on-site operational preparation stage. They are required to enter the designated anchorage areas according to scheduling instructions and complete anchorage berthing, safety inspection, certificate verification, and vessel condition confirmation in sequence. After completing the on-site inspection and meeting the required lockage conditions, vessels formally enter the lockage organization stage.

Overall, this mode uses reservation-based resource allocation as the front-end guidance mechanism, coordinated control as the process constraint, and dynamic sequencing as the terminal implementation approach, thereby forming a scheduling process that is more planned and coordinated than the traditional on-site queuing mode.

4. Social Risk Assessment Indicator System for Inland Waterway Lock Reservation Scheduling Mode Considering Stakeholder Perspectives

The establishment of the inland waterway lock reservation scheduling mode social risk assessment indicator system needs to be based on systems thinking, considering the mechanism and path of influence on the social system from the stakeholder perspective [30,31]. Taking into account the interconnections and directions of action of the factors, the influencing factors are categorized according to the guidelines of different dimensions based on the social amplification of the risk framework to achieve scientific, objective, and rational evaluation.

4.1. Evaluation Dimension Determination

To ensure the scientific rigor and objectivity of the social risk assessment indicator system for the reservation scheduling mode of inland waterway locks, the evaluation dimensions are developed with reference to China's Interim Measures for Social Stability Risk Assessment of Major Fixed Asset Investment Projects issued by the Development and Reform Commission. Accordingly, the social risks associated with inland waterway lock reservation scheduling are categorized into four primary dimensions, namely legality, rationality, feasibility, and controllability, which are adopted as the first-level indicators as shown in Figure 3.

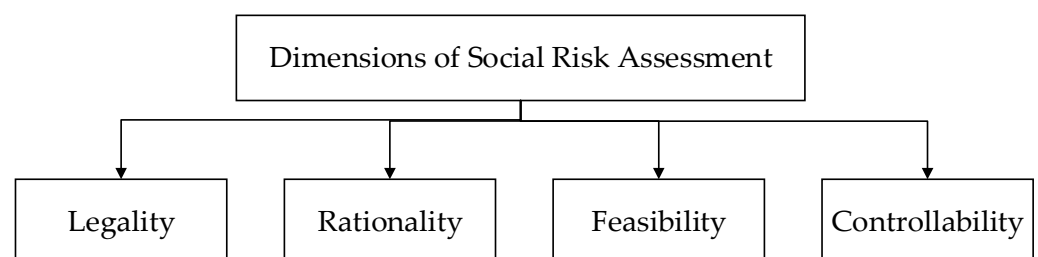


Figure 3. Dimensions of social risk assessment.

Legality refers to whether the formulation and implementation of lock scheduling rules conform to established institutional and procedural requirements. The legality assessment is therefore conducted from three aspects: the decision-making subject, decision-making content, and decision-making procedure. In social risk assessment, the clarity of the decision-making subject and the legitimacy of its decision-making authority are critical to the organization and coordination of risk management.

Rationality emphasizes whether the proposed scheduling rules are consistent with the interests of the majority of stakeholders and whether they can ensure fairness and reasonableness in resource allocation. Considering the practical objective of optimizing navigation scheduling rules for inland waterway locks, the rationality assessment should account for the impacts on both the management authority and regulated stakeholders.

Specifically, it should examine the effects of rule adjustment on lockage safety, lockage efficiency, and lockage fairness.

Feasibility refers to the practicability of implementing the proposed scheduling rules under actual operational conditions. Its assessment aims to systematically identify the favorable and unfavorable factors that may arise during rule implementation and to determine whether the optimization scheme can be carried out in accordance with the intended requirements. In this sense, feasibility assessment provides a practical basis and reliable support for decision-making regarding rule optimization.

Controllability reflects whether the potential risks induced by rule optimization can be effectively prevented, mitigated, and resolved. The construction of controllability indicators should focus on the demands and attitudes of shipowners and shipping enterprises, the response strategies and regulatory measures adopted by government departments and competent authorities, and the evolution of public opinion. The purpose is to evaluate the extent to which possible risk events arising from scheduling rule optimization can be effectively controlled.

4.2. Social Amplification of Risk Framework

The theory of risk amplification was first proposed by Kasperson in 1986 to explore various types of risks and risky events [32–34]. It is an evolutionary process of how risk events are interpreted in ways that amplify or weaken risk perceptions, leading to risk outcomes. Traditional risk analysis primarily focuses on the objective probability of risks and the quantification of their consequences, whereas the social amplification of risk framework emphasizes that risk perception is a socially constructed process in which social factors along the communication chain exert a substantial influence on the final form of risk experience.

The social amplification of risk framework argues that risk is not a static quantity that can be measured purely in technical terms, but rather a dynamic process in which risks are continuously amplified or attenuated through information transmission and social interaction. As risk events pass through multiple communication nodes, including experts, the media, institutions, and the public, risk-related information is filtered, reconstructed, and reinforced, ultimately shaping public perceptions and behavioral responses that may far exceed the results of technical assessments. This amplification process may generate cascading social consequences that go well beyond physical damage, making it an indispensable theoretical framework for understanding risk communication and governance in modern society.

Thus, by focusing on stakeholders, communication nodes, and the chain of social responses, the social amplification of risk framework provides a structured basis for identifying risk factors. The subsequent indicator system therefore not only captures impacts on safety and efficiency, but also covers key components of social stability risk, such as public opinion, collective behavior, and institutional trust.

4.3. Identification of Factors Influencing Social Risk

After the primary dimensions have been determined, it is necessary to further identify the key factors that may trigger social risks by considering the operational mechanisms of lock reservation scheduling and the demands of relevant stakeholders. Against the background of supply–demand imbalance and changes in scheduling organization, this section extracts specific indicators from the interactive relationships among management authorities, shipping enterprises, local governments, and other stakeholders.

The fundamental cause of vessel congestion at lock hubs lies in the fact that, within a given period, the service supply capacity of the lock is insufficient to meet vessels' lockage

demand. Therefore, to avoid supply–demand imbalance, it is necessary to manage the waiting sequence of vessels through dynamic regulation, thereby alleviating congestion in the dam area. The reservation scheduling mode proposed in this study regulates the arrival time windows and lockage sequences of different vessel types across daily time periods by classifying and allocating reservation resources. This enhances the predictability of vessel lockage time and is conducive to achieving a peak shaving and off-peak balancing effect.

Compared with the existing queuing-based scheduling mode, the reservation mode can more effectively balance the navigation demands of priority vessels and ordinary vessels. While ensuring the efficient allocation and rational utilization of navigation resources, it can reduce the time loss caused by vessel queuing and waiting. Meanwhile, by improving the predictability of lockage time, it also takes into account the gradual and stable adjustment of scheduling rules.

For inland waterway locks, scheduling rules are formulated and implemented by navigation scheduling management authorities. Their core role in the system network is to formulate and issue relevant policies and rules and to allocate channel and navigation facility resources in a rational manner. The stakeholders most directly affected by scheduling rules are shipping enterprises and shipping companies, which comply with relevant policies and rules within the operational network and organize production activities according to their own business conditions. Local governments along the waterway are responsible for promoting regional economic development and supporting related industries, and therefore also pay close attention to adjustments in scheduling rules.

Compared with the existing scheduling mode, the inland waterway lock reservation scheduling mode introduces changes in six key aspects: the declaration and reservation process for dam-crossing, the identification of priority vessels, vessel sequencing, reservation modification and cancelation, default handling, and the supporting management systems of relevant departments. These changes reshape the operational procedures, resource allocation logic, and responsibility boundaries among stakeholders. Since different stakeholders vary in their concerns and practical demands, social conflicts may emerge or be intensified during the formulation of scheduling modes, the release of policies, and the implementation of schemes. Accordingly, based on the above six aspects and the opinions of seven experts with long-term experience in shipping management, this study identifies 17 influencing factors related to risk perception and organizational complexity, as shown in Table 1.

Table 1. Screening of influencing factors from a stakeholder perspective.

Focus Point	Influencing Factors	Focus Point	Influencing Factors
Reservation process	Sufficiency of Rule Optimization Basis; Compliance with Rule Modification, Approval and Release	Determination of key ships	Competitiveness of key ships; lock transit plan compliance rate; proportion of reserved resources
Ship sequencing	Navigation Order of Ships; Single-Voyage Duration; Cost of Operations	Rescheduling and cancelation	The convenience of the reservation operation; reservation success rate
Breach-of-contract handling	Propensity for Risky Navigation Behavior; Coverage Rate of Safety Management Strategies; Mass Incident Susceptibility; Negative Opinion susceptibility	Supporting management system	Support technical guarantee level; recognition by the management department; impact on water ecological environment

The focus points in Table 1 refer to the key operational links in which the reservation scheduling mode differs from the traditional declaration-based queuing mode. They are not evaluation dimensions, but practical entry points for identifying potential risk sources

during the implementation of reservation scheduling rules. Specifically, changes in the reservation process, determination of priority vessels, vessel sequencing, rescheduling and cancelation, breach-of-contract handling, and supporting management systems may reshape resource allocation, procedural fairness, operational convenience, and stakeholder expectations. Therefore, Table 1 serves as an intermediate step for extracting influencing factors from the operational process of reservation scheduling.

The indicators measure the fairness of resource allocation, the acceptance of the system, the feasibility of the operation, and the perceived risks by the stakeholders. “Competitiveness of priority vessels” refers to the possibility that eligible priority vessels compete for limited reserved lockage resources, which may lead to perceived unfairness if the eligibility criteria, allocation rules, or approval process are not sufficiently transparent. “Proportion of reserved resources” reflects the social risk caused by an inappropriate allocation ratio between reserved resources and ordinary queuing resources; an excessively high proportion may reduce the opportunity for ordinary vessels, whereas an excessively low proportion may weaken the effectiveness of the reservation mechanism. “Reservation success rate” represents the extent to which vessels can successfully obtain reserved lockage slots under the proposed rules. A low success rate may increase dissatisfaction among shipping enterprises and vessel operators and reduce trust in the reservation system. In this study, these indicators are measured through stakeholder and expert scoring from two aspects: the probability of risk occurrence and the severity of risk consequences.

4.4. Construction of the Indicator System

To facilitate subsequent weighting and comprehensive evaluation, the identified indicators should be classified according to unified criteria, with their hierarchical structure and logical relationships further clarified. Within the four-dimensional framework, this section systematically organizes the 17 indicators and constructs a social risk assessment indicator system that can support weight calculation and integration with the cloud model.

Establishing an indicator system for assessing the social risks associated with lock reservation scheduling requires a systems-thinking perspective, with particular attention to the mechanisms and pathways through which stakeholder perspectives affect the social system. By comprehensively considering the interrelationships and directions of influence among different factors, the influencing factors are screened based on the social amplification of risk framework and classified according to the criteria of different dimensions, thereby ensuring a scientific, objective, and reasonable evaluation.

Based on the extraction of evaluation dimensions and the analysis of influencing factors presented in the previous section, a social stability risk assessment indicator system for lock reservation scheduling is constructed from four dimensions: legality, rationality, feasibility, and controllability, as shown in Figure 4. On the basis of the influencing factors identified from the operational focus points in Table 1, the factors are further reorganized into a formal social risk assessment indicator system. The logic of this transformation is as follows: Table 1 identifies where social risks may arise in the reservation scheduling process, whereas Figure 4 explains how these risks are evaluated from the perspective of social stability risk assessment. Legality reflects risks related to institutional basis and procedural compliance; rationality reflects risks related to resource allocation, operational efficiency, cost, and perceived fairness; feasibility reflects risks related to the practical implementation of the reservation process and supporting conditions; and controllability reflects risks related to safety behavior, public response, emergency management, and environmental impact.

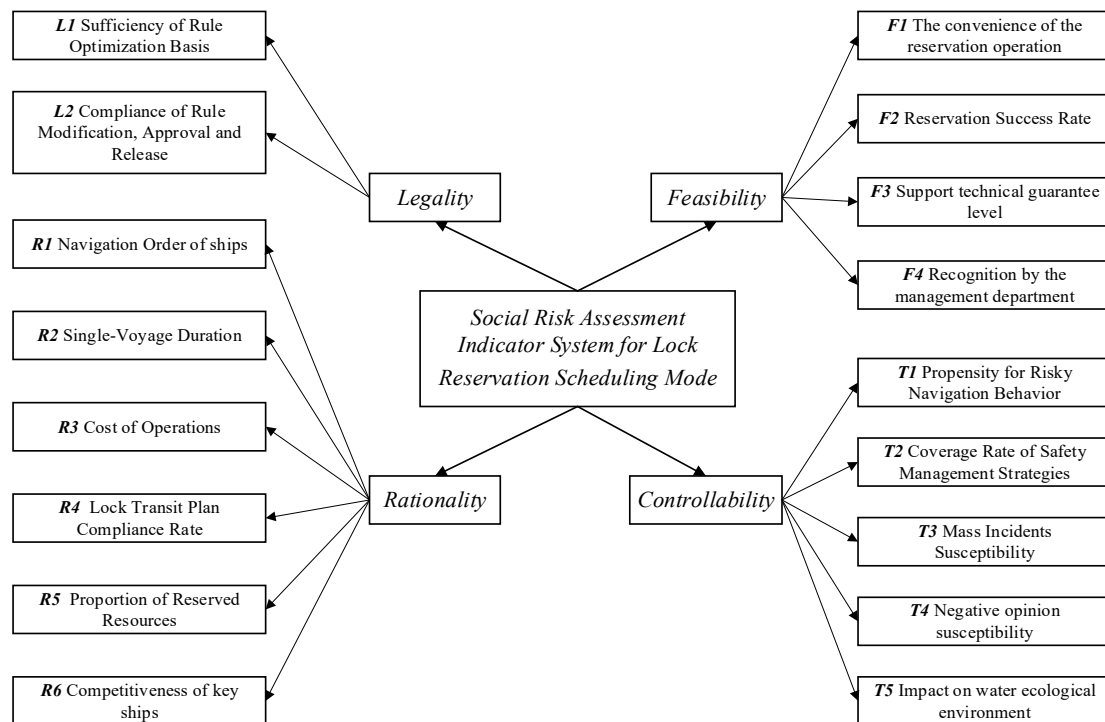


Figure 4. Social risk assessment indicator system for lock reservation scheduling mode.

The legality dimension emphasizes the procedural compliance and institutional authority of system design and implementation, serving as the institutional foundation for the smooth implementation of scheduling rules. The rationality dimension focuses on the comprehensive effects of reservation scheduling on navigation efficiency, fairness, and economic performance, and thus constitutes the core basis for evaluating institutional effectiveness. The feasibility dimension concerns the operational feasibility of the system, as well as the technical and organizational conditions required for its implementation, which determine whether the reservation scheduling mode can be stably implemented in practice. The controllability dimension reflects the extent to which potential negative effects arising from institutional implementation can be managed and constrained, including safety risks, social risks, public opinion risks, and ecological and environmental impacts.

These four dimensions are complementary and progressively structured, jointly forming a comprehensive evaluation framework for identifying the influencing factors of social risks associated with lock reservation scheduling. This framework provides a solid foundation for subsequent indicator quantification, weight determination, and comprehensive risk assessment.

5. Two-Dimensional Cloud Model for Social Risk Assessment

After the indicator system has been established, expert scores and operational-state information need to be transformed into comparable comprehensive risk levels. This section integrates dynamic weighting with the Two-Dimensional Cloud Model. Specifically, dynamic weights are first used to highlight state-dependent changes in key risk factors, and the Two-Dimensional Cloud Model is then employed to achieve comprehensive representation, visualized comparison, and quantitative classification in the two-dimensional space of probability and consequence.

Before presenting the calculation procedure, it should be clarified that the variables used in the proposed assessment model are mainly derived from expert and stakeholder

evaluation scores. Therefore, most variables do not have physical engineering units. Instead, they are expressed as dimensionless scores, normalized weights, or ordinal risk levels.

5.1. Dynamic Weighting Model

To more realistically characterize the evolution of the importance of social risk factors under the inland waterway lock reservation scheduling mode, this study develops a Dynamic Weighting Model based on traditional static weights.

The dynamic weights consist of two components. The first component is the standard weight derived from expert weighting, which serves as the baseline weight and reflects the relative importance of each risk indicator under general conditions and in a long-term statistical sense. The second component is a weight multiplier introduced to dynamically revise the standard weight, thereby capturing changes in the intensity and direction of indicator effects caused by variations in risk information and process differences across different scheduling modes or operational stages. Through the organic integration of these two components, the indicator weights can maintain overall stability while responding promptly to changes in actual risk states, thereby improving the objectivity and sensitivity of social risk assessment results.

5.1.1. Determination of Standardized Weights

Traditional static weighting methods represent one of the most fundamental and widely used approaches for weight determination in comprehensive evaluation. Their core feature is that the weights remain unchanged once determined. Such methods can effectively reflect the relative importance of indicators in a general sense and are suitable for comprehensive evaluation problems involving system-level structures and long-term stable states. Common static weighting methods characterize indicator importance from different perspectives. Subjective methods emphasize expert experience and cognitive judgment, objective methods focus on the information contained in the indicator data, while combined weighting methods integrate the advantages of both. A traditional comprehensive evaluation model can generally be expressed as Equations (1) and (2):

$$F = \sum_{m=1}^M \eta^m \lambda^m \quad (1)$$

$$\sum_{m=1}^M \eta^m = 1, \quad \eta^m \geq 0 \quad (2)$$

Based on the social stability risk assessment indicator system for lock reservation scheduling, experts in the shipping field are invited to score the influence of each factor on the social risks associated with the inland waterway lock reservation scheduling mode through questionnaire surveys and other approaches, thereby obtaining the standard weights.

Suppose that the evaluation indicator system contains M indicators, and L experts from the fields of shipping and navigation management are invited to score the importance of each indicator. The average score can be expressed by Equation (3).

$$\bar{a}_m = L^{-1} \sum_{j=1}^L a_{jm} \quad (3)$$

To eliminate the influence of measurement scales and ensure that the weights of all indicators satisfy the normalization condition, the average scores are standardized according to Equations (4) and (5).

$$\eta^m(0) = \frac{\bar{a}_m}{\sum_{k=1}^M \bar{a}_k} = \frac{\sum_{j=1}^L a_{jm}}{\sum_{k=1}^M \sum_{j=1}^L a_{jk}} \quad (4)$$

$$\sum_{m=1}^M \eta^m(0) = 1, \eta^m(0) \geq 0 \quad (5)$$

The standard weights reflect the relative importance of each risk indicator to the social stability risk of lock reservation scheduling under normal operating conditions, and serve as the basis for subsequent dynamic weight calculation.

5.1.2. Determination of Dynamic Weights

However, social risks associated with lock operation are characterized by pronounced dynamics and state sensitivity. Under different scheduling rules, the influence intensity of various risk factors on lock operational safety is not identical, and their relative importance may change accordingly. In particular, when certain key indicators become abnormal or change sharply, their impact on the overall social risk may exhibit an amplification effect, and may even dominate the system risk state within a short period. Since the weights in a static weighting model remain unchanged, such models have difficulty highlighting the importance of abnormal indicators in a timely manner. As a result, the comprehensive evaluation results may be insufficiently sensitive to abrupt risk changes, thereby weakening their practical value for risk warning and decision support. Meanwhile, in the assessment of social risks associated with lock operation, the evaluation results are often expected to support real-time scheduling risk analysis and the investigation of social risk evolution patterns. Relying solely on static weights is therefore no longer sufficient to meet the requirements of dynamic management and refined decision-making.

Therefore, it is necessary to introduce a dynamic weighting method that can adaptively adjust according to changes in indicator states, so as to overcome the limited adaptability of static weights under complex dynamic conditions. The Dynamic Weighting Model is a comprehensive evaluation method developed on the basis of traditional weighting principles. In this model, indicator weights are no longer treated as constants, but are dynamically adjusted with changes in the operational states of indicators or the states of evaluation objects, making the weights functions of indicator states. The Dynamic Weighting Model can be further expressed as shown in Equation (6).

$$F(n) = \sum_{m=1}^M \eta^m(n) \lambda^m(n) \quad (6)$$

In the process of lock scheduling operations, the direction and intensity of the risk indicators will change with the natural conditions or scheduling mode, and thus their weights will be updated on the basis of the universal standard weights. In this paper, weight multipliers are introduced for the calculation of dynamic weights, and the calculation method is shown in Equations (7) and (8), where $\lambda^m(n)$ is the weight multiplier for the n th update of the m th indicator, $s^m(n)$ is the score value for the n th update of the m th indicator,

n is the number of updates of the dynamic weights, and $\eta^m(n)$ is the dynamic weight after the n th update of the m th indicator.

$$\lambda^m(n) = 1 + |s^m(n) - s^m(0)| \quad (7)$$

$$\eta^m(n) = \frac{\eta^m(0) \times \lambda^m(n)}{\sum_{k=1} \eta^k(0) \times \lambda^k(n)} \quad (8)$$

In these equations, the expert score represents the perceived importance or state-deviation degree of a given risk indicator and is a dimensionless ordinal score. The standard weight represents the baseline relative importance of the indicator under normal conditions, while the weight multiplier reflects the change in indicator importance caused by the updated operational state. The dynamic weight is obtained by revising the standard weight with the corresponding weight multiplier and is then normalized.

Through the improvement introduced by the Dynamic Weighting Model, the stability of the weight structure derived from expert experience and long-term statistical significance is retained. Meanwhile, the importance of indicators can be dynamically adjusted according to real-time changes in the operational state of lock reservation scheduling and social risk information. As a result, the social risk assessment outcomes can better reflect actual operating conditions and provide stronger practical explanatory power.

5.2. Construction of Two-Dimensional Cloud Model

The Two-Dimensional Cloud Model [35] is based on probabilistic and fuzzy mathematical theories, is a theory that reflects the vagueness and randomness of concepts in the human knowledge system, and studies the conversion between uncertain information and quantitative indicators. It is generally used for the comprehensive evaluation of stochasticity and uncertainty problems under the combined effect of two influencing factors, and centers on the mapping between qualitative concepts and quantitative data through the construction of a cloud generator. The social risk of the inland waterway lock reservation scheduling mode is determined by the probability of risk and the degree of harm of the consequences together, so the use of the Two-Dimensional Cloud Model to establish the risk pre-assessment type is scientific and effective.

5.2.1. One-Dimensional Cloud Model

Many phenomena in the real world obey or approximate a normal distribution, so normal cloud is the most general and important theory in cloud modeling. One-Dimensional Cloud Models typically express qualitative concepts quantitatively in terms of numerical features (Ex , En , He). Assuming that F is a random function obeying a normal distribution, expected value (Ex) reflects the center value of the argument, entropy (En) reflects the range of the argument, and hyper-entropy (He) reflects the uncertainty of En . The expectation curve determined by the numerical characteristics of the cloud model is:

$$\mu_i = \exp \left[-(x_i - Ex)^2 / 2F(En, He)^2 \right] \quad (9)$$

where μ_i is the degree of affiliation and x_i is the indicator value.

The One-Dimensional Cloud Model is essentially a model that organically integrates probability distributions with membership functions. By introducing the randomness of entropy, the membership function itself is endowed with stochastic characteristics, thereby overcoming the excessive boundary rigidity of traditional fuzzy membership functions. In this way, the model can more realistically represent the uncertainty in human cognition, where fuzziness and randomness coexist.

5.2.2. Two-Dimensional Cloud Model

Building on the One-Dimensional Cloud Model, the Two-Dimensional Cloud Model extends uncertainty representation to a two-dimensional space by depicting the joint uncertainty of two correlated indicators through cloud drop distributions. It provides a multidimensional framework for characterizing the uncertainty of a qualitative concept jointly determined by two interrelated quantitative indicators, while establishing the mapping relationship between qualitative concepts and quantitative measures. The spatial distribution of cloud drops enables an intuitive representation of how a qualitative concept is distributed within the quantitative domain.

Assuming that a is a random function obeying a normal distribution, the more complex transformation between qualitative and quantitative indicators is described using the two-dimensional expected value (Ex), entropy (En), and hyper-entropy (He) as its numerical characteristics, where expected value (Ex_1, Ex_2) is the position of the form center on the projection surface; entropy (En_1, En_2) denotes the boundary curve of the projection, i.e., ambiguity; and hyper-entropy (En_1, En_2) reflects the thickness of the Two-Dimensional Cloud Model, i.e., stochasticity and discretization.

As shown in Equations (10)–(12), the cloud model constituted by cloud drops $drop(x_i, y_i, \mu_i)$ is a two-dimensional normal cloud model, and the cloud drops are the core carriers and intuitive embodiments of the model, where x_i, y_i is the cloud drop coordinate, P_x, P_y is the conditional cloud drop coordinate, and μ_i is the degree of affiliation.

$$(x_i, y_i) = F(Ex, Ey, En_x, En_y) \quad (10)$$

$$(P_{xi}, P_{yi}) = F(En_x, En_y, He_x, He_y) \quad (11)$$

$$\mu_i = \exp\left(-\left[\frac{(x_i - Ex)^2}{2En_x^2} + \frac{(y_i - Ey)^2}{2En_y^2}\right]\right) \quad (12)$$

In the Two-Dimensional Cloud Model, the two coordinates of a cloud drop correspond to the risk probability level and the risk consequence level, respectively. Both coordinates are ordinal evaluation values rather than physical quantities. The expected values represent the central positions of the risk cloud on the probability and consequence axes, while entropy and hyper-entropy describe the dispersion and uncertainty of the cloud drop distribution on the same evaluation scale. The membership degree is a dimensionless value between 0 and 1, indicating the degree to which a cloud drop belongs to a given qualitative risk level.

Cloud modeling primarily utilizes a cloud generator to establish mapping relationships between qualitative and quantitative interconnections. The two-dimensional cloud generator allows for planar cloud model generation. It is specifically divided into a forward cloud generator and backward cloud generator. The principle of a 2D multi-rule generator is shown in Figure 5.

5.2.3. Composite Risk Cloud

In the inland waterway lock reservation scheduling mode, the likelihood of a social risk occurring and the consequences resulting from the occurrence of the risk together reflect the level of risk. Therefore, a risk indicator can be used as a metric, and probability level and consequence level can be taken as the two base variables for risk assessment. According to the indicator system proposed in this study, the scores of the probability level and consequence level of each risk indicator form cloud drops, respectively, and the risk probability cloud and risk consequence cloud composing the indicator are collectively referred to as the two-dimensional composite risk cloud, and Equations (13)–(16) show its

calculation, where x_k is the rating value for group k , S^2 is the variance, and q is the number of expert groups. The eigenvalues of probability and consequence clouds are generated by the backward cloud generator,

$$Ex = q^{-1} \sum_{k=1}^q x_k \quad (13)$$

$$En = \sqrt{\frac{\pi}{2}} \times q^{-1} \sum_{k=1}^q |x_k - Ex| \quad (14)$$

$$S^2 = \frac{1}{q-1} \sum_{k=1}^q (x_k - Ex)^2 \quad (15)$$

$$He = \sqrt{|S^2 - En^2|} \quad (16)$$

as shown in Equation (11). The eigenvalue matrices of the indicator layer probability cloud and consequence cloud are calculated with the corresponding weight vector matrices, respectively, to obtain the eigenvalues of the criterion-layer probability cloud and consequence cloud, and then the eigenvalues of the 2D composite risk cloud, where Ex' , En' , He' are the expected value, entropy and hyper-entropy of the higher level metrics, respectively.

$$C = (w_1, w_2, \dots, w_n) \begin{pmatrix} Ex_1 & En_1 & He_1 \\ \vdots & \vdots & \vdots \\ Ex_n & En_n & He_n \end{pmatrix} = (Ex', En', He') \quad (17)$$

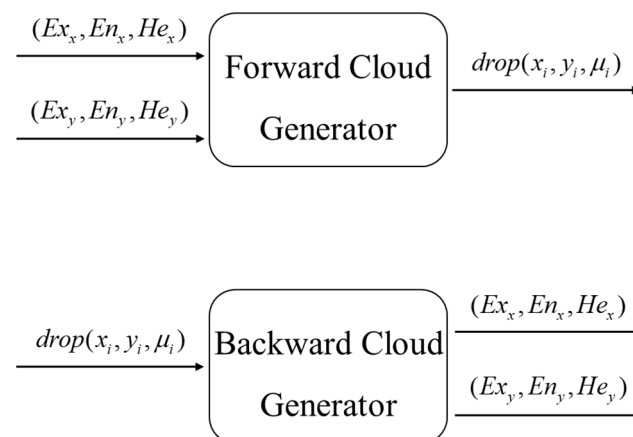


Figure 5. Two-dimensional cloud generator.

5.2.4. Standardized Risk Cloud

The evaluation interval is divided into several standard rating intervals according to a certain law, and the cloud eigenvalues corresponding to each interval of the inland waterway lock reservation scheduling mode social risk probability class and consequence class can be obtained from Equations (18)–(20).

$$Ex'' = \frac{S_j^{\max} + S_j^{\min}}{2} \quad (18)$$

$$En'' = \frac{S_j^{\max} - S_j^{\min}}{6} \quad (19)$$

$$He'' = \left[\frac{Ex}{100}, \frac{En}{10} \right] \quad (20)$$

5.2.5. Risk Level Cloud Diagram

The eigenvalues of the final obtained 2D composite risk cloud and the eigenvalues of the standard risk cloud are input to the MATLAB 2022b forward cloud generator to obtain the 2D composite risk cloud diagram with the standard risk cloud diagram. The level of risk is determined by comparing and analyzing the relationship between the composite risk cloud and the level 5 standard risk cloud, and by judging how close they are to each other. The two-dimensional composite risk cloud is initially identified as the risk level for which the results of the composite evaluation are closer to the five levels of the standardized risk cloud. The principle for this is mainly through the comparison of the standard risk cloud and composite risk cloud eigenvalues in the cloud between the expectation of the proximity of the social risk level of the lock reservation scheduling mode and the expectation of the risk cloud diagram that is reflected in the highest point of the cloud diagram projected in the coordinate region corresponding to the value of the coordinate axis.

5.2.6. Proximity

Due to the similarity between the derived composite risk cloud and the standard risk cloud, the 2D cloud diagram for the 3D view may cause some visual errors. Therefore, in order to determine the risk level more accurately, proximity was utilized to calculate the closeness of the composite risk cloud to the standard cloud. Larger proximity indicates that the assessment results are closer to the standardized risk level corresponding to that proximity, and Equation (21) shows the calculation method of proximity N . Ex, Ey are the expected values of the probability and consequence classes of the composite risk cloud, respectively; Ex'', Ey'' are the expected values of the probability and consequence classes of the standard cloud, respectively.

$$N = \frac{1}{\sqrt{(Ex - Ex'')^2 + (Ey - Ey'')^2}} \quad (21)$$

The proximity value is also dimensionless. It is used to measure the closeness between the comprehensive risk cloud and each standard risk cloud. A larger proximity value indicates that the assessment result is closer to the corresponding standard risk level.

In summary, this section organically integrates the Dynamic Weighting Model with the Two-Dimensional Cloud Model through a complete procedure involving dynamic weight determination, composite risk cloud construction, standard risk cloud setting, risk cloud diagram comparison, and quantitative proximity testing. This integrated approach can not only characterize the uncertainty of social risks in terms of both probability and consequence, but also achieve a unified visualization and quantification of risk level identification. It therefore provides a systematic, rigorous, and highly engineering-applicable technical pathway for the scientific assessment of social risks associated with lock reservation scheduling.

6. Case Study

In this study, model validation is carried out for the Three Gorges locks, which are double-lane, five-stage locks, the largest in the world, and are capable of passing a fleet of 10,000-ton ships, with a designed one-way annual throughput capacity of 50 million tons. In 2011, the gate freight volume through the Three Gorges locks exceeded 100 million tons, marking the achievement of the design throughput capacity 19 years ahead of schedule. In 2024, the freight volume through the gate exceeded 159 million tons.

6.1. Sample Data

In order to alleviate the regular problem of backlogs of ships in the dam area caused by a serious imbalance between supply and demand, the Three Gorges locks are proposed to adopt reservation scheduling rules to optimize the method of transport organization. The Three Gorges locks were operated, on a trial basis, in reservation mode for six months in 2024. During the trial operation period, the hydrological conditions of the waterway remained relatively stable. During this period, the research team conducted thematic discussions and field investigations in Wuhan, Yichang, Chongqing, and other locations, and subsequently carried out a targeted questionnaire survey among relevant stakeholders. The respondents mainly included personnel from navigation management departments, local transport authorities, managers of shipping enterprises, experienced crew members, and researchers from scientific institutions. These respondents have long been engaged in lock scheduling management, transport organization, or related research, and therefore possess strong professional expertise and representativeness in judging the social stability risk indicators associated with the reservation scheduling mode of the Three Gorges lock.

The distribution of questionnaire respondents is presented in Table 2. The sample covers multiple stakeholder groups, including management authorities, enterprises, crew members, and researchers, thereby providing a sound basis for capturing heterogeneous perceptions during the implementation of reservation scheduling rules.

Table 2. Composition of questionnaire respondents.

Category	Number of Samples	Percentage
Navigation management departments	31	16.2%
Local transport authorities	19	9.9%
Shipping enterprises	67	35.1%
Crew members/shipowners	48	25.2%
Research institutes/universities	26	13.6%
Total	191	100%

A total of 191 questionnaires were collected. After excluding 18 invalid responses, 173 valid questionnaires were obtained, yielding a validity rate of 90.58%. Given the relatively large sample size, Table 3 only presents the processed data from three respondents as illustrative examples.

Table 3. Expert scores and dynamic risks (partial).

Risk Indicators	Expert 1		Expert 2		Expert 3	
	Probability $p_1 + p_d$	Consequence $c_1 + c_d$	Probability $p_1 + p_d$	Consequence $c_1 + c_d$	Probability $p_1 + p_d$	Consequence $c_1 + c_d$
L_1	88	86	90	90	80	85
L_2	90	90	92	92	95	95
R_1	81 + 12	80 + 8	75 + 12	76 + 7	72 + 15	70 + 18
R_2	68	72	75	75	70	72
R_3	80	83	81	82	85	85
R_4	79	75	80	82	85	78
R_5	75 + 10	76 + 8	80 + 5	85 + 5	82 + 8	76 + 10
R_6	78 + 5	78 + 5	82 + 2	80 + 2	83 + 6	83 + 8
F_1	80	83	85	85	80	80
F_2	70 + 8	77 + 8	75 + 5	75 + 5	78 + 2	76 + 3
F_3	85	86	80	88	76	78
F_4	75	78	85	86	90	90
T_1	53 + 12	48 + 18	60 + 10	55 + 12	65 + 15	60 + 13
T_2	82	76	80	80	75	70
T_3	60 + 8	62 + 6	55 + 10	45 + 12	50 + 7	50 + 8
T_4	50 + 18	45 + 20	60 + 5	62 + 7	55 + 12	53 + 7
T_5	80	80	85	82	81	83

In the model validation process, stakeholder feedback was incorporated through both the questionnaire survey and thematic discussions. The questionnaire scores provided

the basis for estimating the probability and consequence levels of each risk indicator, while the discussions helped interpret the practical meaning of the evaluation results under the reservation scheduling scenario. Differences in stakeholder concerns were also observed. Navigation management departments paid more attention to rule compliance, safety control, and emergency response, whereas shipping enterprises, crew members, and shipowners were more concerned with reservation fairness, operational convenience, waiting time, and cost changes. These heterogeneous perceptions were not treated as simple inconsistencies, but were incorporated into the assessment through the cloud model, in which entropy and hyper-entropy were used to reflect the dispersion and uncertainty of stakeholder judgments. Therefore, the validation process retained, rather than ignored, the diversity of stakeholder views regarding the social risks of lock reservation scheduling.

6.2. Dynamic Weight Calculation

As can be seen from Table 3, since the Three Gorges locks are piloting a reservation scheduling mode, this is a major difference from the traditional queuing system for crossing the locks. A total of seven indicators, R_1 , R_5 , R_6 , F_2 , T_1 , T_3 , and T_4 , are strongly influenced by the reservation rules, so the dynamic adjustment of the weights of the indicators should be fully considered.

Let us take the example of indicator T_4 : negative opinion susceptibility. From the Expert 1 scores in Table 3 in Section 6.1, the standard probability score for this indicator is 50 and its dynamic score is +18, which gives a revised final score of 68. This rating reflects this expert's opinion that under standard conditions, lock scheduling may be prone to negative public opinion due to longer delays and less efficient navigation. After the implementation of the reservation rule, the lock scheduling organization is more orderly, the probability of negative public opinion is reduced, and its score increases. After synthesizing the probabilistic evaluation scores of 173 experts for indicator T_4 , it is known that the weight multiplier λ is taken to be 2.34, and its probabilistic dynamic weight η_{T_4} to be 0.096. Similarly, we can get the dynamic weight values of the remaining indicators, as shown in Table 4.

Table 4. Dynamic weights of indicators (probabilities and consequences).

Risk Indicators	η_p	η_c	Risk Indicators	η_p	η_c
L_1	0.046	0.048	L_2	0.065	0.073
R_1	0.059	0.064	R_2	0.03	0.016
R_3	0.031	0.036	R_4	0.029	0.031
R_5	0.062	0.061	R_6	0.073	0.074
F_1	0.06	0.063	F_2	0.084	0.089
F_3	0.056	0.032	F_4	0.059	0.052
T_1	0.023	0.031	T_2	0.082	0.087
T_3	0.093	0.099	T_4	0.096	0.105
T_5	0.052	0.039			

6.3. Composite Risk Cloud

After obtaining the dynamic weights of the 17 risk indicators, we need to calculate the numerical eigenvalues of the risk cloud corresponding to the indicators.

Take the legality dimension as an example. Based on the combined evaluation scores of 173 experts for the two indicators L_1 and L_2 under the legitimacy dimension and using the backward cloud generator, the eigenvalues are computed for the probability and consequence clouds of the indicators under all expert scoring outcomes:

$$L_1 : [C_{L_1}^p(Ex, En, He), C_{L_1}^c(Ex, En, He)] = [(80.20, 2.71, 0.54), (80.60, 5.21, 0.37)]$$

$$L_2 : [C_{L_2}^p(Ex, En, He), C_{L_2}^c(Ex, En, He)] = [(93.20, 2.82, 0.63), (90.40, 2.41, 0.57)]$$

According to the calculation principle of the Dynamic Weighting Model, the weights and eigenvalues of criterion legality L can be calculated based on the weight values and eigenvalues of the lower indicators L_1 and L_2 of criterion legality L legitimacy:

$$(\eta_L^p, \eta_L^c) = (0.111, 0.121)$$

$$[L_p, L_c] = [(87.82, 2.77, 0.59), (86.51, 3.52, 0.49)]$$

Similarly, the weights and cloud eigenvalues of the rationality, feasibility and controllability dimensions of the remaining three criteria layers can be calculated in the same way. The eigenvalues of the composite risk cloud can then be derived, as shown in Table 5.

Table 5. Indicator risk cloud eigenvalues.

Composite Risk Cloud		Criterion Risk Cloud				
Probability	Consequence	Criterion	Weights η_p	Probability	Weights η_c	Consequence
(77.62, 3.14, 0.61)	(77.12, 2.98, 0.67)	L	0.111	(87.82, 2.77, 0.59)	0.121	(86.51, 3.52, 0.49)
		R	0.284	(79.26, 3.17, 0.69)	0.282	(78.47, 2.83, 0.71)
		F	0.259	(82.71, 3.12, 0.57)	0.236	(85.62, 3.05, 0.76)
		T	0.346	(69.19, 3.26, 0.59)	0.361	(67.36, 2.86, 0.65)

6.4. Standard Risk Cloud

To map the comprehensive risk cloud into interpretable and comparable risk levels, it is necessary to construct standard risk clouds as a unified reference. Based on the grading principles of social stability risk assessment and the interval division of the rating scale, this section establishes a five-level standard risk cloud system, which provides a benchmark for cloud-map comparison and closeness testing.

In accordance with the classification principles for assessment levels in the Interim Measures for Social Stability Risk Assessment of Major Water Conservancy Construction Projects issued by the Ministry of Water Resources of China, the social risk level of the Three Gorges locks' reservation and dispatch mode can be divided into five grades, namely low risk, moderately low risk, medium risk, moderately high risk, and high risk, which are sequentially ranked from 1 to 5. We therefore averaged the interval $[0, 100]$ into five standardized rating intervals, which also echoed the classification principle of the Likert scale. The cloud eigenvalues corresponding to each interval of the inland waterway lock reservation scheduling mode social risk probability class and consequence class are shown in Table 6.

Table 6. Risk level classification and standard risk cloud characteristic values.

Risk Level	Risk Degree	Probability Level Description	Consequence Level Description	Score Range	Cloud Characteristic Values
Level 1	low	Almost never	Negligible	[80,100]	(90,3.3,0.5)
Level 2	moderately low	Rare	Minor	[60,80)	(70,3.3,0.5)
Level 3	medium	Sometimes	Moderate	[40,60)	(50,3.3,0.5)
Level 4	moderately high	Often	Major	[20,40)	(30,3.3,0.5)
Level 5	high	Very frequent	Catastrophic	[0,20)	(10,3.3,0.5)

The standard risk cloud system establishes a clear correspondence among risk levels, risk intervals, and cloud characteristic parameters, enabling the comprehensive risk cloud to be classified within a unified evaluation scale.

6.5. Risk Level Assessment Based on Cloud Diagrams

According to the calculation results in the previous section, after obtaining the cloud eigenvalues of the indicator dynamic weights, composite risk cloud and standard risk

cloud, we use matlab2022b to draw a 2D cloud diagram. The model and algorithm script are derived from the actual tests of the Three Gorges ship lock, which can be downloaded at <https://github.com/LR-yyy/2D-cloud-model> (accessed on 4 August 2025). The social risk level assessment of the Three Gorges lock reservation scheduling mode is carried out by combining the proximity values of the cloud diagram.

6.5.1. Criterion Risk Cloud Assessment

To identify the sources of variation in social risk across different dimensions, it is necessary to conduct a comparative analysis of the criterion-layer risk clouds corresponding to legality, rationality, feasibility, and controllability. The risk level and relative intensity of each dimension can be interpreted through the positional relationships and projection patterns of the cloud maps.

The degree of risk impact varies across different evaluation dimensions. The characteristic parameters of the risk probability cloud and consequence cloud, together with those of the standard risk clouds, are input into the MATLAB forward cloud generator to obtain comparative cloud maps between the comprehensive risk clouds and the standard clouds. These maps are used to reflect the social risk levels and intensities of the Three Gorges lock reservation scheduling mode across the four criterion dimensions of legality, rationality, feasibility, and controllability, as shown in Figure 6.

The cloud scatter plot on the left side of Figure 6 presents the relative positions of the criterion-layer risk clouds within the standard risk cloud system. The right side shows the plan-view projection of the risk clouds, from which the proximity between each criterion-layer cloud and the corresponding standard risk level can be intuitively observed.

The visual comparison in Figure 6 provides an intuitive basis for identifying dimension-specific management priorities. A risk cloud located closer to a higher-level standard cloud indicates that the corresponding criterion requires greater managerial attention, while a more dispersed cloud drop distribution reflects stronger uncertainty or disagreement in stakeholder judgments. From this perspective, legality and feasibility mainly indicate whether the reservation scheduling rules are institutionally acceptable and operationally implementable, whereas rationality and controllability are more directly related to stakeholder perceptions, resource allocation fairness, safety control, and public response. Therefore, the criterion-layer cloud diagrams do not merely provide a graphical risk classification, but also help decision-makers to identify which dimensions should be prioritized when refining reservation rules.

Since the Three Gorges locks' reservation scheduling rules significantly impact all stakeholders, the management emphasizes procedural propriety and legal standardization. Extensive research and consultations were conducted before the project, securing basic approval from ship transportation companies. Figure 6a,b illustrate the risk profile of the legality criterion, showing that the legality risk cloud is very close to the standard risk cloud of level 1, with the projected shapes of the two clouds mainly overlapping from the top view. This indicates that the social risk related to legality is low.

Part of the priority ship reservation program for this trial at the Three Gorges locks has not been synchronized with the optimization of the navigation and scheduling rules for ordinary ships, resulting in a decrease in goodwill towards the policy for ship types that do not enjoy the reservation policy, and also affecting the production and operation strategies of the shipping companies. Figure 6c,d reflect the risk profile of the rationality criterion, and we can see that the rationality risk cloud is in the middle of the standard risk cloud of levels 1–2, but it is difficult to determine precisely which level it is closer to. Further class assessment based on the proximity value is needed. The optimization of scheduling rules needs to focus on the consideration of undesirable competitive behaviors of key ships

in the reservation process, regulate the reservation behaviors, and avoid the reservation resources being monopolized or maliciously occupied.

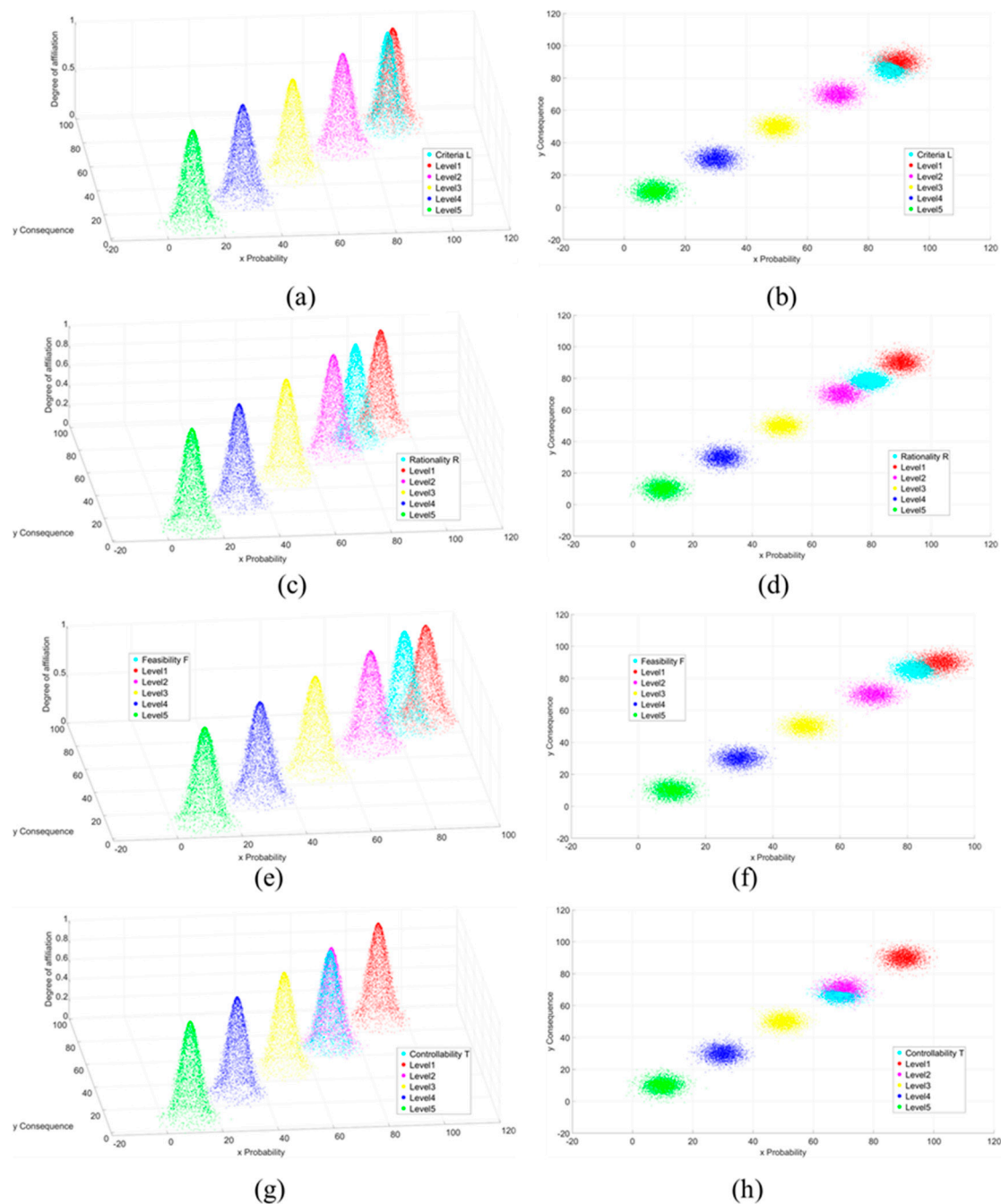


Figure 6. Risk cloud diagram and its top view under the four guidelines.

Figure 6e,f reflect the risk profile for the feasibility criterion, and similar to the legitimacy criterion, we can see that the feasibility risk cloud has a high degree of overlap with the level 1 standard risk cloud. Therefore, a preliminary feasibility criterion risk rating of 1 can be determined, with a degree of low risk. The reservation mode breaks the tradition, and the navigation management department needs to update the workflow of reservation, security inspection, mooring and other operations in time to strengthen the synergy between different functional units under the implementation of the new rules.

Safety is the red line of Three Gorges lock scheduling, and the safety management strategy of the container reservation mode needs to be designed according to the status

quo to prevent the occurrence of personal extreme events for the crew of ships crossing the locks. Figure 6g,h reflect the risk profile of the controllability criterion. From the overlap of the clouds, we can see that the controllability criterion is the most risky of the four criterion dimensions, and is between the standard risk clouds of levels 2–3 and is closer to the standard risk cloud of level 2. The management should follow the objective law of the market and rationalize the proportion of resources for reservation of key ships. While maintaining credibility, they should scientifically guide the direction of public opinion and improve their ability to withstand risks to social stability.

6.5.2. Indicator-Level Key Risk Identification

The criterion-layer risk cloud assessment provides an overall judgment of the risk intensity of legality, rationality, feasibility, and controllability. However, criterion-layer results alone cannot fully reveal the specific sources of social risk embedded in the 17 lower-level indicators. Therefore, it is necessary to further interpret the indicator-layer results in order to identify the key risk points that require priority attention in the implementation of reservation scheduling.

Based on the dynamic weights of the 17 indicators, stakeholder evaluation scores, and the criterion-layer risk cloud results, the key risks are mainly concentrated in the rationality, feasibility, and controllability dimensions. In the rationality dimension, the proportion of reserved resources and the competitiveness of priority vessels are particularly important. These indicators reflect whether the allocation of limited lockage resources between reserved vessels and ordinary queuing vessels is perceived as fair and whether competition among eligible priority vessels may induce dissatisfaction or strategic behavior. If the proportion of reserved resources is set improperly or the eligibility criteria for priority vessels are not sufficiently transparent, ordinary vessels may perceive a loss of lockage opportunity, while priority vessels may compete for limited time-window resources.

In the feasibility dimension, reservation success rate and operational convenience are key indicators affecting stakeholder acceptance. A low reservation success rate may weaken stakeholders' confidence in the reservation system, while complicated application, modification, or cancelation procedures may reduce the willingness of shipping enterprises and vessel operators to comply with the new rules. These risks indicate that the reservation scheduling mode should not only be technically feasible for the management authority, but also practically convenient and predictable for users.

In the controllability dimension, negative public opinion susceptibility, mass incident susceptibility, coverage of safety management strategies, and propensity for risky navigation behavior represent the most management-sensitive risks. These indicators are directly related to whether dissatisfaction caused by rule adjustment can be effectively prevented, communicated, and controlled. In particular, if reservation compliance management is weak or stakeholder expectations are not properly guided, individual dissatisfaction may be amplified through information diffusion and group interaction, thereby increasing public opinion pressure or collective behavioral responses.

Overall, the indicator-layer analysis shows that the main social risks of the Three Gorges locks' reservation scheduling mode are not derived from institutional legality or basic technical feasibility, but from the fairness of resource allocation, the acceptability of the reservation process, the transparency of priority rules, and the controllability of stakeholder responses. Therefore, the subsequent risk management should focus on reserved resource allocation, priority vessel qualification rules, reservation success feedback, compliance management, safety control, public opinion guidance, and emergency response.

6.5.3. Comprehensive Risk Assessment

Based on the criterion-layer analysis, it is necessary to further determine the overall social risk level of the reservation scheduling mode. This section identifies the overall risk level according to the comparison between the comprehensive risk cloud and the standard risk clouds, and further explains its practical implications.

A comprehensive social risk assessment of the Three Gorges lock reservation scheduling mode was conducted based on the assessment of the four dimensions of legality, rationality, feasibility and controllability. The input of the composite risk cloud eigenvalues in Table 5 and the standard risk cloud eigenvalues in Table 6 to the MATLAB forward cloud generator results in a cloud diagram of the composite risk cloud against the standard cloud, as shown in Figure 7. We can see that the composite risk cloud is in the middle of the level 1–2 standard risk cloud. According to the top view of the cloud drop projection in Figure 8, we can see that the composite risk cloud is closer to the level 2 standard risk cloud. This preliminary result indicates that the social risk level of the Three Gorges locks' reservation scheduling mode is level 2, corresponding to a moderately low risk level. The reservation scheduling rules can meet the needs of the Three Gorges lock scheduling management and ship navigation.

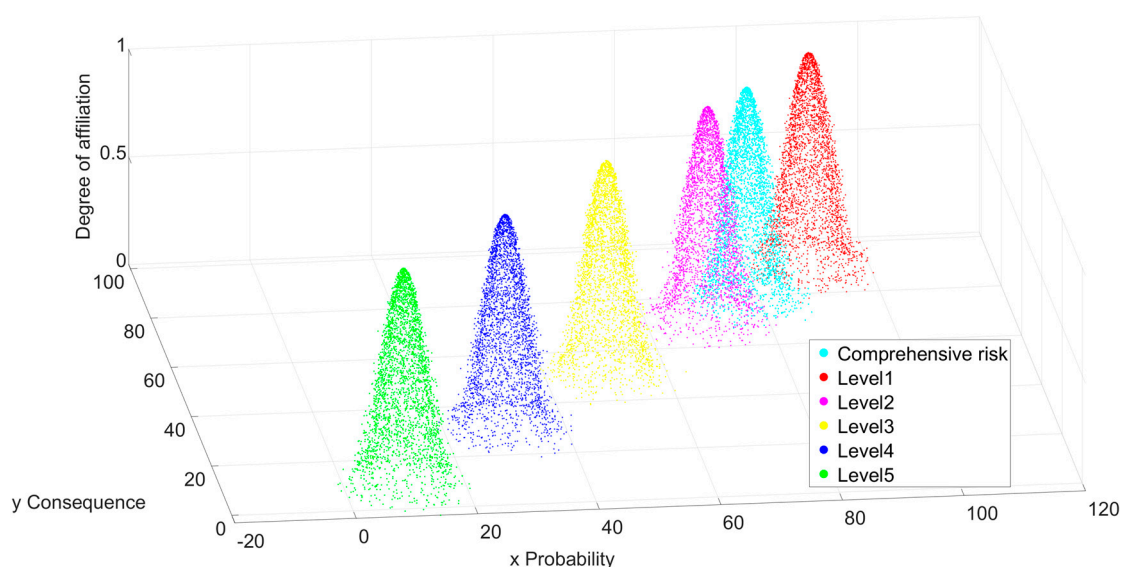


Figure 7. Schematic cloud diagram of comprehensive risk.

The practical implication of the level 2 result is that the reservation scheduling mode is generally acceptable and controllable under the current operating conditions of the Three Gorges locks, but it should not be interpreted as risk-free. The relative position of the comprehensive risk cloud suggests that the proposed rules can support orderly lockage organization and meet basic navigation management requirements. However, the overlap between the comprehensive risk cloud and adjacent standard clouds also indicates that risk may increase if reservation resources are improperly allocated, compliance management is weakened, or stakeholder expectations are not effectively guided. Therefore, continuous monitoring of reservation behavior, safety control, and public opinion response remains necessary during the implementation of reservation scheduling.

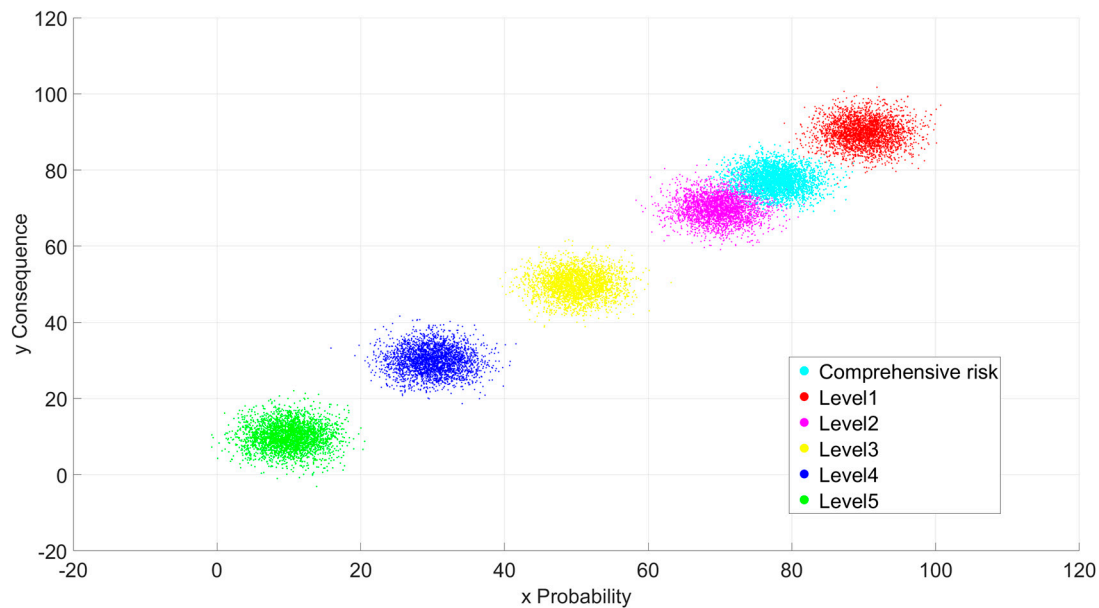


Figure 8. Top view of the composite risk cloud.

6.5.4. Proximity

Due to the similarity between the composite risk cloud and standard risk cloud, and the visual error caused by three-dimensional graphs, the risk level can only be determined initially, so this study carries out the social risk level assessment of the inland waterway lock reservation scheduling mode by introducing proximity. Substituting the eigenvalues of the composite risk cloud and the eigenvalues of the standard risk cloud can be used to calculate the proximity of the composite risk cloud to the standard risk cloud at each level, which is expressed by N_1 , N_2 , N_3 , N_4 , and N_5 , respectively. Table 7 presents the calculation results of the proximity.

Table 7. Proximity calculation situation.

	N_1	N_2	N_3	N_4	N_5
Proximity	0.056	0.096	0.026	0.015	0.010

From the above settlement results, the relationship between the magnitude of proximity is: $N_2 > N_1 > N_3 > N_4 > N_5$. Therefore, the social risk level of the Three Gorges locks' reservation scheduling mode is level 2, corresponding to a moderately low risk level.

This assessment is consistent with the results of the pre-project visit and research and the feedback from the trial run of the reservation mode at the Three Gorges locks. The respondents have a certain degree of acceptance of the fair and transparent management of the optimized rules in the revision, approval, release and implementation phases.

Although the results of the combined assessment are good, we can see that the controllability dimension has a relatively high level of risk. After the implementation of the reservation scheduling rule, the existing organizational system and navigation safety management methods of the navigation management department cannot match the new rule in time. Uncontrollable safety situations may arise, such as ships maliciously seizing reservation resources or adopting risky operational behaviors due to time constraints, or even social conflicts aggravating and triggering mass incidents. At the same time, there are some concerns about the updating of the declaration and reservation management system and the change in the philosophy and business habits of the shipowners.

The Three Gorges lock case demonstrates the applicability of the proposed framework in a complex inland waterway lock scheduling context. Beyond this specific case, the core procedure, including stakeholder identification, risk indicator construction, dynamic weight adjustment, and two-dimensional risk cloud evaluation, can also be adapted to other inland waterway locks, canal navigation systems, port scheduling systems, and infrastructure systems involving scarce resource allocation and multiple stakeholder interests. For different application contexts, the indicator system and weight parameters can be adjusted according to local operational rules, governance structures, data availability, and stakeholder characteristics. Therefore, the proposed framework provides a transferable analytical basis for assessing social risks associated with scheduling rule optimization and infrastructure operation management in broader contexts.

7. Conclusions and Future Work

This study can be summarized as follows: First, it examines how the stakeholder perspective influences the lock system. Using the social amplification of risk framework, it identifies the correlations and action paths of influencing factors under the reservation scheduling rule and categorizes them into four dimensions: legality, rationality, feasibility, and controllability. This leads to the development of a social risk indicator system for the inland waterway lock reservation scheduling mode. Second, a social risk assessment model for the inland waterway lock reservation scheduling mode is proposed. The model employs risk probability and risk consequence as key variables and combines data-driven and knowledge-driven approaches to create the evaluation dataset. By introducing weight multipliers to reflect the direction and strength of risk indicator impacts as scheduling rules change, it calculates two-dimensional dynamic weights for these indicators. Subsequently, a Two-Dimensional Cloud Model maps the composite risk cloud, providing an initial risk level interval. Analyzing the distribution of cloud drops allows an understanding of social risk extent, typical regions, and boundary transition properties. The proximity values are then compared to determine the overall risk level. Finally, the model is validated through an example involving the Three Gorges lock scheduling operation. Results indicate that the overall social risk level of the Three Gorges locks' reservation scheduling mode is level 2, corresponding to a moderately low risk level, which largely ensures the smooth policy implementation and management of ship navigation and scheduling at the Three Gorges locks. This confirms the scientific validity and effectiveness of the assessment model.

It is worth noting that the model proposed in this paper has two main limitations: (1) Although the Dynamic Weighting Model improves the traditional static weighting scheme, the determination of expert scores, risk-level thresholds, and cloud parameters still partly depends on expert judgment, which may introduce subjective bias into the assessment results. Future research will further reduce this dependence by incorporating data-driven approaches, such as historical lock operation records, vessel trajectory data, reservation compliance information, and machine learning-based parameter calibration, so as to improve the objectivity, robustness, and generalizability of the proposed framework. (2) The Two-Dimensional Cloud Model performs well in representing bivariate risks, but faces significant challenges when extended to high-dimensional scenarios: first, high-dimensional cloud droplet sampling is affected by the "curse of dimensionality," which can be addressed using Monte Carlo optimization or dimensionality reduction techniques; second, the computational complexity of multidimensional joint distributions grows exponentially, necessitating the design of parallel computing frameworks; finally, high-dimensional visualization difficulties impair interpretability, and solutions based on interactive visualization or feature importance ranking can be explored. Future research

should focus on overcoming these technical bottlenecks while enhancing the model's ability to capture dynamic risk evolution and complex semantic expressions.

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