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A latent risk factor analysis guiding policy interventions for inland maritime safety

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ABSTRACT

Inland waterway safety is a pressing policy priority in China's transport sector, where effective regulation and targeted interventions are vital to managing accident risks in the world's busiest inland shipping network. While policymakers have increasingly focused on this issue, the causal mechanisms shaping accident severity remain insufficiently understood. This study applies Structural Equation Modeling (SEM) to quantify the influence of four latent constructs, Ship Characteristics, Environmental Conditions, Operational Risk, and Crew & Equipment, on inland maritime accident outcomes. Constructs were validated through principal component analysis, and the model achieved excellent fit (χ^2/df = 1.363; RMSEA = 0.022; CFI = 0.94). Results show that Operational Risk (β = 0.84) and Crew & Equipment (β = 0.70) are the strongest predictors of severity. These insights highlight that the policy needs to strengthen operational oversight, crew training, and equipment standards. The proposed framework provides a transferable, evidence-based tool for enhancing safety governance in inland waterway transport both within China and globally.

1. Introduction

Inland waterway transportation is a vital component of global trade and regional commerce, offering a cost-effective and high-capacity mode for moving goods and passengers. However, these benefits come with significant safety challenges. Around the world, busy rivers and canals continue to witness marine accidents that result in loss of life, property damage, and environmental harm (Mou et al., 2019; Bačkalov et al., 2023). Recent analyses of waterway accidents in Asia indicate that such incidents frequently occur and often lead to high casualties, with seasonal peaks (particularly in autumn and winter) and geographic hotspots in regions like South and Southeast Asia (Peng et al., 2023; Mia et al., 2021; Utomo and Mateo-Babiano, 2015). Ensuring the safety of inland navigation has therefore become a priority concern for industry stakeholders, policymakers, and transport authorities, as it directly affects the resilience and efficiency of national transport systems. Numerous studies over the past decade have underscored that human factors remain the dominant cause of maritime accidents, an estimated 75–96% of marine incidents are attributable to human error (Allianz, 2018). This trend holds true on inland waterways as well, where the human element (e.g. crew mistakes or rule violations) is implicated in the majority of accidents (Deng et al., 2022). At the same time, technical failures, adverse environmental conditions, and organizational shortcomings also contribute to inland shipping accidents, underscoring the multi-faceted nature of maritime safety risk (Bačkalov et al., 2023; Justace et al., 2024; Askari et al., 2025). For policy and governance, this implies that accident reduction strategies must integrate operational, regulatory, and infrastructural measures rather than focus on single-factor interventions.

Globally, a growing body of literature has emerged in the last 5–10 years examining the causes and characteristics of inland waterway accidents. Researchers have analyzed accident data in various regions to identify prevalent accident types and risk factors. For example, Bačkalov et al. (2023) conducted a comprehensive study of around 700 inland waterway accidents in Europe (Austria and Serbia) over 15 years, finding that collisions with fixed objects (allisions) and machinery

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failures were among the most common accident types (Bačkalov et al., 2023). Intriguingly, their results suggested that removing human operators (through automation) would only marginally improve safety unless issues like vessel maintenance and waterway infrastructure are also addressed (Bačkalov et al., 2023). This highlights that while human error is critical, it is not the sole determinant of accidents; vessel condition and external hazards play a significant role as well. Similarly, an analysis of inland shipping accidents in Bangladesh found that accidents stem from a combination of human, technical, and external factors (Askari et al., 2025). Overloading of vessels, machinery failures, and collisions with fixed structures were identified as the most influential contributors to riverine accidents in that context (Askari et al., 2025). These findings led the authors to call for stricter enforcement of safety regulations, improved vessel maintenance, better navigational aids, and enhanced crew training (Askari et al., 2025). Such recommendations align with international best practices, where evidence-based regulatory oversight, investment in navigation infrastructure, and enforcement of technical standards are recognized as core policy levers for safety improvement in inland waterways. Taken together, global studies suggest that inland waterway accidents commonly arise from a nexus of factors: mistakes or unsafe actions by crew, poor safety awareness, inadequate vessel upkeep or equipment malfunction, challenging environmental conditions (e.g. fog, currents, extreme weather), and lapses in safety management systems (Deng et al., 2022; Xia et al., 2023). There is broad agreement that most accidents are multi-causal; indeed, an analysis of 922 Chinese maritime accidents (inland and coastal) showed most incidents involved more than two contributing factors (Deng et al., 2022). From a policy perspective, acknowledging this multi-causality is essential to designing integrated safety frameworks that combine operational, regulatory, and capacity-building measures.

1.1. Inland waterway safety in China

China presents a particularly important case for studying inland maritime safety. The country possesses one of the world's largest and busiest inland waterway networks, including the Yangtze River, which is the world's busiest inland river by cargo volume (Peng et al., 2025; Wu et al., 2022). The Yangtze alone carried about 3 billion tons of cargo in 2020 (China, 2020), far exceeding the freight on other major rivers. This enormous traffic density on Chinese rivers heightens the potential consequences of any safety failure. Unfortunately, China has experienced numerous inland waterway accidents, some of them catastrophic. A stark reminder was the *Eastern Star* cruise ship disaster in June 2015, when the vessel capsized on the Yangtze River during a severe storm. The tragedy claimed 442 lives (CGTN, 2015), making it one of China's worst boating disasters in decades. The investigation revealed that freak weather (a sudden squall) precipitated the accident, but also found significant human and management failings – the captain was unprepared and failed to issue timely evacuation orders, among other deficiencies (CGTN, 2015). This incident underscored how gaps in safety management and emergency response can turn a hazardous situation into a mass-casualty event. It also served as a catalyst for Chinese authorities to strengthen inland waterway safety policy, prompting reforms in navigation governance, vessel inspection regimes, and emergency preparedness planning. It also galvanized Chinese authorities to pay greater attention to inland navigation safety. Over the past few years, the government has introduced measures such as modernizing navigation aids, tightening vessel inspections, and cracking down on illegal operations on the rivers. Despite these efforts, accidents on China's inland waterways continue to occur, though some data suggest improvements. For instance, studies of the Yangtze River indicate that overall accident frequencies have been on a downward trend in the last decade (Guo et al., 2018) , even as traffic has increased – a positive sign that safety initiatives may be yielding results. Nevertheless, collisions remain the most common type of incident on the Yangtze and other Chinese inland waterways (Guo et al., 2018; Deng et al., 2022), and recent analyses show that human errors and rule violations are involved in the vast majority of inland accidents (Deng et al., 2022). From a policy standpoint, these trends point to the need for sustained regulatory oversight and adaptive governance mechanisms to ensure that improvements in safety performance are maintained over time. Clearly, there is no room for complacency, and a deeper understanding of accident causation in the Chinese context is needed to further reduce the toll of inland waterway accidents.

Several research studies have begun examining the characteristics of maritime accidents in China's inland waters. In this regard, a study analyzed two decades of vessel traffic accidents in the busy waters of Shenzhen (South China) and developed a set of safety indices to quantify risk levels in port areas (Mou et al., 2019). Their work demonstrated the value of long-term accident data in identifying high-risk periods and locations, allowing authorities to set proactive safety thresholds (for example, using a *Safety Warning Index* to trigger interventions when risk rises) (Mou et al., 2019). Such data-driven safety metrics, when embedded into port and river management systems, can provide regulators with timely triggers for intervention, enhancing the effectiveness of safety governance. More recently, a study performed a time-series analysis of Yangtze River accident data from 2011 to 2020, investigating temporal patterns and potential causative factors in China's busiest waterway. Their study found that collision incidents accounted for a large share of accidents and highlighted seasonal fluctuations in accident occurrence, correlating certain peak accident periods with navigation conditions and traffic density on the Yangtze (e.g. increased traffic during winter fog season) (Sui et al., 2023). In addition to statistical trend analyses, Chinese scholars have applied advanced risk modeling techniques to inland water transport. Another study proposed a novel risk assessment framework combining text mining of accident reports with a Belief-Rule Bayesian Network model, and applied it to a case study on the Songhua River (Northeast China) (Xia et al., 2023). This approach enabled them to quantitatively rank risk influence factors for inland navigation. Significantly, they found that among human-related factors, "mis-observation" (failure to perceive or interpret the situation correctly) and "poor safety awareness" were the most critical contributors to accidents on the Songhua River (Xia et al., 2023). From a policy lens, these findings reinforce the importance of mandatory crew competency standards, periodic refresher training, and stricter enforcement of navigation rules.

By contrast, organizational factors (like management or policy deficiencies) had a lower risk priority in their analysis (Xia et al., 2023). This suggests that improving the alertness and hazard perception of crew through training and strict adherence to navigation rules could substantially enhance safety on Chinese inland waterways (Xia et al., 2023). Another study focused on the Yangtze River mainstream, analyzing 238 accidents from 2016 to 2021 using a combined interpretive structural modeling and Bayesian network approach (Guo et al., 2024). Their results underscored the importance of vessel and environmental factors: the most sensitive factors affecting accident occurrence were the location of the incident (e.g. river section), the type and age of the vessel, the condition of the ship's hull, and the channel/environmental conditions (Guo et al., 2024). In essence, older ships in poor condition operating in challenging river sections were found to significantly elevate accident risk, alongside the ever-present influence of human error. A broader examination of 20 years of accident investigation reports in China (2000–2020) further reinforces these findings, as reported that over 90% of all maritime accidents in Chinese waters (inland and coastal) involve human factors, followed in prevalence by vessel-related factors and management factors (Deng et al., 2022). Notably, their analysis revealed that certain unsafe practices are even more pronounced in inland river accidents than in coastal waters: for example, *lack of safety awareness* among crew was the second most frequent human failure in inland accidents (much higher ranking than in marine accidents) (Deng et al., 2022). Similarly, overloading and missing inspections (neglecting vessel maintenance) were found to be more common in inland incidents compared to at-sea incidents (Deng et al., 2022). These nuances highlight that while the general categories of causation are similar everywhere, the specific risk profile of China's inland waterways may differ in degree from open-sea contexts, likely due to factors like the operating environment (river currents, congested channels), vessel types (many smaller or older ships on rivers), and perhaps regulatory enforcement gaps in the inland sector. These nuances underline the necessity for targeted, river-specific safety regulations and enforcement strategies, recognizing that inland waterways present distinct operational, vessel, and governance challenges compared to maritime transport at sea.

1.2. Research gap and rationale

Although the importance of inland shipping safety in China is evident and some studies have begun to shed light on its aspects, there remain significant gaps in the literature. From a *Policy* perspective, most inland-waterway papers to date emphasize growth, operations, and infrastructure management rather than accident causation and safety governance (e.g., China's inland-waterway growth drivers; lock/throughput management; restricted-waterway capacity; fleet sizing under hydrological constraints). This leaves a clear niche for policy-oriented, empirically grounded analyses of *safety causation* in inland waterways (Lu et al., 2023; Deng et al., 2021; Chen et al., 2025; Wang et al., 2025). First, compared to the extensive research on ocean-going maritime safety, studies focusing specifically on China's inland waterway traffic are relatively scarce and fragmented. Many of the investigations in Chinese contexts have concentrated on particular regions (e.g., the Yangtze or Pearl River) or on specific issues (such as collision risk modeling or time-series trends), with limited integration of all the interacting factors that drive accidents. Within *Policy domain*, inland-waterway contributions have tended to address *capacity, emissions, and operational policy* (e.g., modal shift to waterways in Zhejiang; optimal inland fleet sizing) rather than *multi-factor accident causation*. A policy-relevant safety model that integrates human, technical, environmental, and organizational dimensions is therefore missing (Jiang et al., 2024; Wang et al., 2025).

Second, a systemic analytical approach remains underused in the inland-waterway safety literature, even though multivariate methods, such as SEM, are increasingly applied to safety and behavior studies in other transport modes (e.g., safety at rail grade crossings via SEM; SEM in freight ownership decision-making). This demonstrates clear methodological relevance for applying a SEM-based framework to inland-waterway safety, which is rarely seen in existing studies (Sahu et al., 2022; Vivek et al., 2024). Third, governance-focused and evidence-based safety analysis is essential for translating empirical findings into actionable policy (e.g., benchmarking institutional safety frameworks; evaluating willingness-to-pay for targeted safety improvements). However, inland-waterway safety governance, particularly in China, has not been examined with comparable empirical depth. Bridging this gap requires studies that quantify how risk factors interact to shape severity and that translate findings into regulatory levers such as training standards, operational oversight, and equipment regimes (Randall et al., 2024; Subhan et al., 2023).

Key questions, therefore, remain insufficiently addressed: (i) How do human, technical, environmental, and organizational factors jointly influence accident likelihood and severity on inland waters? (ii) To what extent do factors identified on the Yangtze generalize to other Chinese river systems and to global inland networks (e.g., constrained/restricted waterways)? (iii) How effective are current safety-management practices and oversight mechanisms, and which policy levers yield the highest marginal safety gains? The existing studies suggest that human errors (such as lapses in lookout or rule violations) are a crucial problem, and also point to issues with vessel integrity and oversight, yet there is a need to integrate these findings to see the full picture. For example, poor safety awareness and insufficient training have been identified as persistent issues in China's inland shipping sector (Deng et al., 2022), but there is a lack of detailed research on their root causes, such as organizational culture, regulatory shortcomings, or economic pressures on vessel operators. While operational research exists on areas such as convoy/lock management and optimal fleet sizing, there is little that links these operational contexts to a causation-to-policy chain for improving safety performance (Chen et al., 2025; Deng et al., 2021; Wang et al., 2025).

Given these gaps, the necessity of the present research becomes clear. Inland water transport in China is expanding rapidly, not only on major arteries like the Yangtze but also across networks of smaller rivers and canals supported by national and provincial policy initiatives to boost domestic logistics capacity. Ensuring safety in this sector is crucial for protecting lives, safeguarding the environment, and maintaining the efficiency of supply chains. Each serious accident can have far-reaching impacts, from tragic human costs to disruptions in trade and public confidence. Yet the complex interplay of factors behind inland waterway accidents is not yet fully understood in the Chinese context, and there is an urgent need for research that moves beyond documenting patterns to identifying the most salient risk factors, how they interact, and where gaps in the current safety regime allow accidents to occur. This study addresses these needs by applying a SEM framework to quantify the relative and interactive effects of four latent constructs, Ship Characteristics, Environmental Conditions, Operational Risk, and Crew & Equipment, on accident severity. Grounded in recent accident data and informed by global safety research, the framework is designed to produce evidence-based, policy-ready levers such as improved operational oversight, enhanced crew training standards, and stricter equipment maintenance requirements (Chen et al., 2025; Deng et al., 2021; Wang et al., 2025; Vivek et al., 2024; Sahu et al., 2022). In doing so, it supports the development of integrated, governance-focused safety strategies that are transferable to other inland contexts, including restricted canals and lock-constrained corridors (Lu et al., 2023; Chen et al., 2025; Wang et al., 2025).

1.3. Contribution of this study

This study contributes to inland waterway safety research by linking empirical accident analysis to evidence-based transport governance. First, it narrows the spotlight onto China's inland waterways, a context under-represented in scholarly literature, thereby extending global understanding of maritime safety into a region of intense activity and unique challenges. Drawing on accident case data and applying rigorous analytical methods, the study will identify the major factors that statistically influence accident occurrence and severity in Chinese inland navigation. In doing so, it integrates human, technical, environmental, and organizational dimensions, offering a more holistic view than many prior studies that examined these factors in isolation. The study also aims to highlight any distinctive patterns in China's inland accidents (for example, particular risk factor combinations or systemic issues) that have not been reported elsewhere. This can help ascertain whether lessons from international maritime safety research apply equally to inland China or if tailored strategies are required. Furthermore, the research addresses practical gaps by highlighting areas for viable improvements.

From the policy perspective, by pinpointing critical safety weaknesses (such as training deficiencies, regulatory enforcement gaps, or technological needs in vessel traffic management), the findings will directly inform policymakers and industry practitioners on where to focus safety improvements. Ultimately, the value of this work lies in its potential to save lives and reduce accidents through better understanding. By justifying and undertaking an in-depth examination of inland waterway traffic accidents in China, this study not only advances academic knowledge but also serves the tangible goal of enhancing maritime safety. It builds on prior studies but goes further to synthesize and apply insights in a new context, thereby contributing a fresh perspective that will enrich global discourse on inland water transport safety governance and support China's ongoing efforts to achieve safer, more sustainable inland navigation.

In summary, this study advances inland waterway safety research in three interrelated ways. First, it develops and empirically tests a structural equation model for inland accident severity using accident reports from across all of China, first from a national perspective to handle the challenging issue with increasingly important, beyond the state-of-the-art studies, which focus more on specific rivers/canals, making the results less representative and the generality of the analysis more arguable. This model jointly represents four latent domains, including Ship Characteristics, Environmental Conditions, Operational Risk, and Crew & Equipment, using a multi-year accident dataset, rather than treating these factors in isolation or through purely descriptive analyses. Second, it quantifies the strength and direction of each domain's effect on severity and identifies key mediating paths between them, thereby turning qualitative diagnoses from prior case-based studies into a ranked set of statistically supported risk drivers. Third, it explicitly maps these model outputs onto concrete governance levers, such as targeted oversight of high-risk operating profiles, competence-based crew training and certification, and minimum equipment and stability requirements for specific vessel segments, providing a traceable link from accident data to policy design for China's inland waterways and other constrained river and canal systems, but conceptually transferable to other constrained river and canal systems where similarly integrated, governance-oriented safety models remain scarce.

1.4. Approach viability

SEM is a multivariate statistical approach that combines a measurement model (linking observed indicators to latent constructs) with a structural model (linking those constructs to each other and to an outcome) (Othman and Naintin, 2016; Thakkar, 2020). In our case, each of the four latent factors, including Ship Characteristics, Environmental Conditions, Operational Risk, and Crew & Equipment, is measured by several observed variables, and such variables, together with their parent four factors are then related to accident consequence through a system of paths. SEM estimates all of these relationships simultaneously while accounting for measurement error, making it well-suited to accident causation problems where multiple interdependent risk dimensions have to be modeled in a single coherent framework. It is worth reflecting on the methodological choice of using SEM for this analysis, as it adds rigor and depth to the findings. SEM was chosen because it enables simultaneous examination of multiple latent constructs and their interrelationships with the outcome, which is well-suited to the complex, multi-causal nature of maritime accidents. Traditional statistical methods (like simple regression or bivariate correlations) would have struggled to capture the systemic interactions at play, for example, how ship design, crew preparedness, operations, and environment collectively influence accident severity. In contrast, SEM allowed for integration of a path analysis of causal effects with a confirmatory factor analysis of latent variables in one unified model. As observed by recent studies, for example (Hu et al., 2019; Vivek et al., 2024), the SEM approach combines the strengths of factor analysis and path analysis while accounting for measurement errors, thereby providing a more realistic modeling of causation in safety studies. Indeed, SEM does not require the unrealistic assumption that variables are measured without error; instead, it explicitly models the error terms and thus yields more reliable estimates of the true relationships (Xu et al., 2021; Othman and Naintin, 2016).

In our context, this meant we could confidently quantify, say, the effect of an abstract concept like "Operational Risk" on accident outcomes because that concept was measured by multiple observed indicators (watchkeeping, danger recognition, etc.) with the measurement inaccuracies accounted for. Additionally, unlike isolated regressions, SEM can assess inter-factor correlations and indirect effects. This is crucial in accident causation research, where factors often interplay. As one methodological study notes, *"the structural equation model can also quantitatively analyze the relationship between causes, not just their individual effect on the result"* (Hu et al., 2019). By using SEM, we can gain insight that, for example, even after accounting for environmental and ship factors, operational/human factors retain a strong, unique influence, highlighting those as genuine high-priority areas rather than an artifact of co-correlation. In summary, SEM provided a robust, theory-driven framework to test our hypotheses about accident causation. This approach has been gaining traction in maritime safety research (Wahid et al., 2024).

Recent studies have shown that SEM is increasingly used to analyze complex, multi-factor safety problems in maritime domains. For example, it has been used to link latent maritime security threats (such as piracy, kidnapping, and oil theft) to blue-economy development indicators in Nigeria, demonstrating how security-related constructs can be quantified and connected to macro-level outcomes (Uchenna et al., 2025). It has also been applied to inland rivers to build a risk-evolution model for ships carrying dangerous goods (Qin et al., 2024). Similarly, SEM has been used to examine how technical and non-technical factors jointly shape the implementation of safety management systems in traditional shipping, highlighting the role of latent organizational and human elements (Wahid et al., 2024). Taken together, these studies underscore that SEM is well-suited for capturing interacting human, technical, environmental, and managerial influences in maritime and inland-waterway safety. Our use of SEM to model accident severity on Chinese inland waterways follows this trajectory, but focuses specifically on quantifying how ship characteristics, environmental conditions, operational risk, and crew–equipment factors combine to shape inland accident consequences. The good fit indices (CFI, RMSEA, etc., as reported in the Results) further indicate that SEM is an appropriate choice to represent such data. Using SEM thus strengthens the credibility and generalizability of the findings, giving us a high degree of confidence in the identified cause–and–effect linkages.

2. Methodology

2.1. Data collection and processing

Accident records were comprehensively collected from multiple authoritative sources to build a robust dataset of inland maritime incidents in China. Data compilation drew on official maritime authorities and credible industry and research outlets. In particular, accident reports and statistics were obtained from the China Maritime Safety Administration (MSA) (the national authority overseeing maritime safety) (http://www.msa.gov.cn/) and the Yangtze River Navigation Affairs Administration Bureau (which supervises navigation on the Yangtze River) (https://cjhy.mot.gov.cn/). These provided foundational data through published investigation reports and annual bulletins. To supplement national data, provincial maritime authorities' bulletins were consulted – for example, provincial MSA offices like Guangdong (http://gd.msa.gov.cn/) regularly publish local accident notices. Industry sources, such as the China Port and Waterway Association (http://www.chinaports.org/), were also utilized to gather any reported port and waterway incident data and to cross-check statistics. Furthermore, a thorough search was conducted in the CNKI research databases (China National Knowledge Infrastructure) (https://www.cnki.net/) to identify reports, academic studies, and theses that document inland shipping accidents, ensuring inclusion of historical or otherwise unpublicized cases. Finally, reports from reputable Chinese news outlets such as Xinhua News Agency (http://www.xinhuanet.com/) and People's Daily (http://www.people.com.cn/) were reviewed to capture additional incident details and any accidents that might not appear in the official records. All sources were cross-referenced to maximize coverage and accuracy.

After compiling the raw data from these sources, rigorous processing steps were undertaken to ensure data quality and consistency in compliance with concurrent literature (Khan et al., 2021, 2022, 2023; Liu et al., 2025; Yin et al., 2024, 2025). Each accident entry was cross-verified across the different sources. This cross-checking validated key details (date, location, vessel name/type, etc.) and helped reconcile any discrepancies. When the same incident appeared in multiple sources (for instance, an MSA report and a news article), duplicate entries were identified and de-duplicated so that each accident is represented only once in the final dataset. In cases of conflicting information, priority was given to official investigation reports from MSA or provincial agencies as the most authoritative accounts, while other sources were used to fill in missing details (such as specific causes or context). A total of 355 accident reports were finalized for the period 2008–2024.

2.1.1. Exploratory data trends and basic accident dynamics

Before specifying the SEM, we examined how accident consequences distribute across key observable factors (Figs. 1–3). These exploratory trends help to contextualize the later SEM results and show why multiple dimensions, ship, environment, and operations, need to be modeled simultaneously in order to capture the associated risks more accurately.

Fig. 1 plots gross tonnage against consequence level. As expected, the central tendency of tonnage shifts upward from Minor to Major and Critical consequences: the median for Critical and Catastrophic cases lies in the higher tonnage bands (2001–5000 GT and >5000 GT), whereas Minor and Major accidents show a wider spread across the smaller classes. At the same time, the interquartile ranges overlap substantially across all four consequence categories, and a few Catastrophic events involve very small vessels. This pattern indicates that larger vessels are more *exposed* to high-consequence outcomes, simply because of higher kinetic energy, cargo value, and potential for secondary damage, but tonnage alone is not determinative. Small ships can still generate catastrophic losses when unfavorable environmental and operational conditions align, reinforcing the need to analyze interactions rather than treating size as a stand-alone predictor.

Fig. 2 shows the distribution of consequences by ship type. General cargo vessels dominate the sample in every consequence class, reflecting their numerical dominance in the inland fleet and the diversity of trades and operating patterns they represent. However, "Other" vessels contribute a disproportionate share of Critical and Catastrophic accidents relative to their overall numbers, suggesting that heterogeneous missions, ad-hoc operating procedures, and less standardized safety management can contribute to higher severity when accidents occur. Container ships, tankers, and passenger ships appear less frequently overall but are present across all consequence levels, which confirms that high-severity events are not confined to any single ship class and that safety governance must address the full mix of inland vessel types.

Fig. 3 examines visibility at the time of the event. Minor accidents are common under all visibility conditions, but the composition of severe outcomes changes markedly as visibility degrades. Under good visibility, the distribution is skewed towards Minor and Major consequences, whereas poor or restricted visibility shows a higher proportion of Critical and Catastrophic accidents. This is consistent with navigation in narrow channels and congested reaches, where reduced sight distance compresses reaction time and amplifies the effect of any lapse in lookout, speed control, or rule compliance. In reliability terms, visibility acts as an exposure-intensifying factor: it does not create hazards by itself but increases the probability that existing human and operational weaknesses escalate into high-impact outcomes.

In light of the above analysis, these descriptive patterns support the modelling choice made in this study. Severity on Chinese inland waterways is shaped jointly by ship characteristics (tonnage and type), environmental conditions (e.g., visibility), and operational/behavioral factors, rather than by any single variable in isolation. This motivated the subsequent structural equation framework, which treats these dimensions as interacting latent constructs rather than simple one-to-one predictors of accident consequence.

Here, it is important to clarify that these figures were developed on the initial data before factor loading and SEM analysis.

2.1.2. Variables definition

The consolidated data were then standardized and organized into a structured database for analysis. A consistent set of variables based on the data was defined for every accident. For example, accident types were categorized (e.g., collision, grounding), and vessel categories (ship type, tonnage class) were standardized based on industry conventions to

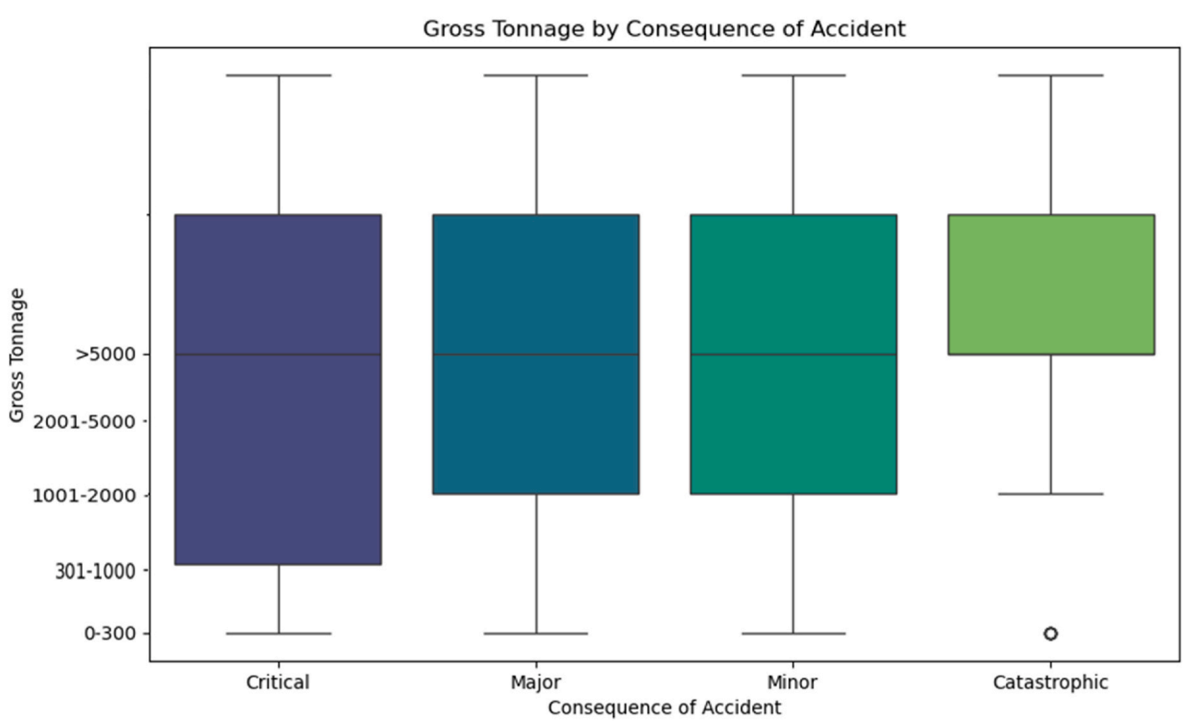

Fig. 1. An exploratory distribution of the gross tonnage of ships against accident consequences.

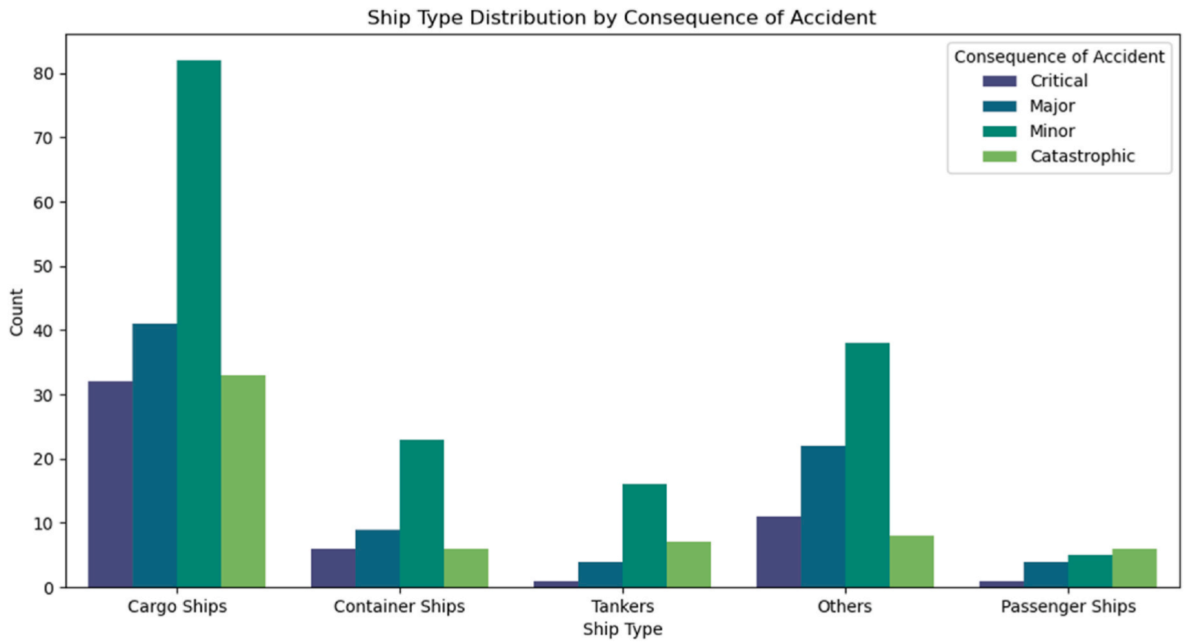

Fig. 2. A distribution of ship types against the accident consequences.

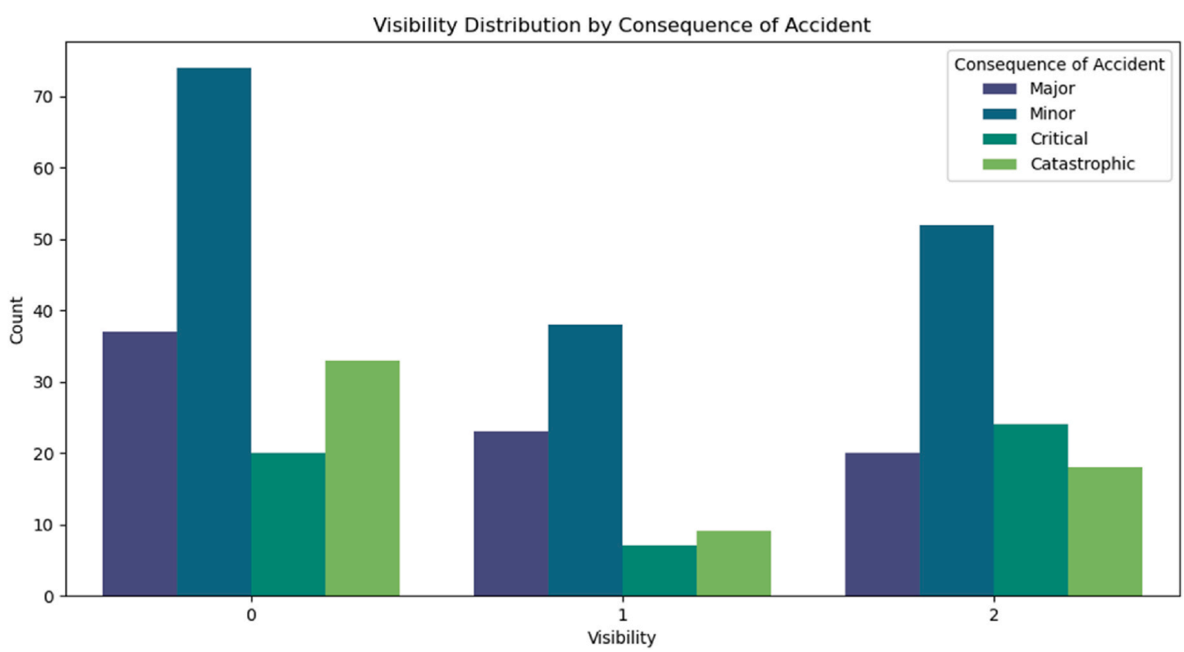

Fig. 3. Accident consequence distribution against the observed visibility conditions of the accidents.

ensure comparability. Descriptive information from narrative reports (such as causes or contributing factors) was coded into quantitative or categorical variables; for instance, human factors, weather conditions, and regulatory violations were each coded into standardized fields. This careful normalization of variables ensured that data from different sources could be meaningfully combined. Finally, the dataset was reviewed for completeness and internal consistency, resulting in a clean, verified collection of inland waterway accident cases ready for statistical analysis. These steps, from source triangulation to variable standardization, were crucial in constructing a reliable dataset and minimizing biases or errors in the subsequent analysis.

The final set of variables and their corresponding states extracted based on the finalized data are presented below in Table 1. The variables states are coded as 0,1,2, 3 (and 4 where applicable) based on the number of states for each variable.

2.1.3. Indicator format and SEM specification

All variables entering the SEM were originally recorded as categorical accident descriptors (Table 1). Gross tonnage, ship type, navigation condition, visibility, wind, watch behavior, danger recognition, response measures, stability, device condition, and sailor-related variables were coded into ordered categories based on regulatory or domain-relevant thresholds. For the SEM, multi-category variables were represented as sets of binary (0/1) indicators for each relevant category, such that higher-risk categories (e.g., poor visibility, low sailor competence, improper loading) load positively on their corresponding latent

Table 1
A description of the variables and corresponding states.

Risk factor	Variable	Threshold/ category	State code	Reason
Ship	Gross tonnage	0–300 t	0	Gross tonnage is the international indicator of ship size. Larger ships contain more subsystems, so the probability of failure generally increases with tonnage.
		301–1000 t	1	
		1001–2000 t	2	
		2001–5000 t	3	
		>5000 t	4	
	Ship type	Cargo ships	0	Previous studies show that ship type is related to safety level. In China's inland waterways, more than 70% of ships are cargo vessels, followed by container, passenger, and tanker ships.
		Container ships	1	
		Passenger ships	2	
		Tankers	3	
		Others	4	
Equipment	Stability	Good stability	0	Lack of stability (interaction of center of gravity, center of buoyancy and metacenter) is a significant cause of ship accidents.
		Improper ballast	1	
		Insufficient anti-wind capsizing ability	2	
		Overloading or improper loading	3	
	Device condition	Both (Failure and Shortage)	0	Defective devices pose a major threat to navigation safety. Device failure or age (such as old circuit devices) may cause a fire, leading to an accident. Ineffective devices (such as the device for updating navigation maps) may also have serious consequences.
		Device failure	1	
		Device shortage	2	
		None	3	
Environment	Navigation condition	Dangerous segment	0	The conditions of China's inland waterways are complex. Locations have a variety of features, including stone beds, dangerous beaches, curved channels, narrow river surfaces, rapid current flows, thick fog, strong winds, and ice. During the flood season, recirculation, vortexes, and strong cross-flow phenomena can occur. These conditions are not favorable for the stability and maneuverability of the ship, and make it prone to hitting rocks and becoming stranded.
		Dense traffic	1	
		Good navigation condition	2	
		Rough current/ wave/tide	3	
	Wind	>7 (Beaufort scale)	0	Different wind levels have diverse impacts on navigation safety; the classification follows the Beaufort wind scale.
		4–7	1	
		<4	2	
	Visibility	Clear	0	Poor visibility can slow or stop a ship and seriously aggravate traffic congestion.
		Not so clear	1	
		Bad	2	
Crew	Sailor	Both adequate	0	The competence level of many inland river sailors is low; emergency response capacity is insufficient, and risk awareness is weak.
		Low quality	1	
		Insufficient staffing	2	
		None	3	
	Watch	Negligence	0	A high rate of catastrophic accidents is related to watch negligence (failure to judge danger or maintain appropriate speed).
		Careful watch	1	
Operational risk	Danger recognition	Correct judgment	0	Timely and accurate danger recognition is critical for preventing accidents.
		Incorrect judgment	1	
	Measure	Delayed action	0	“Measure” refers to steering or maneuvering the ship in time to avoid danger.

(continued on next page)

Table 1 (*continued*)

Risk factor	Variable	Threshold/ category	State code	Reason
		Effective and timely	1	
Accident	Consequence of accident	Catastrophic	0	The consequence of the accident variable captures the severity of the event.
		Critical	1	
		Major	2	
		Minor	3	

constructs. This yields a measurement model with categorical indicators and continuous latent variables for Ship Characteristics, Environmental Conditions, Operational Risk, Crew and Equipment, and Consequences of Accident. The model was estimated using covariance-based SEM with the robust weighted least squares estimator with mean and variance adjustment (WLSMV), which is specifically recommended for models with categorical indicators and ordered outcomes.

2.2. SEM framework

SEM was employed to analyze the latent relationships among factors contributing to inland maritime accident severity. SEM allows simultaneous modeling of measurement and structural relationships, enabling a robust analysis of both latent variable estimation and their interconnections (Lee et al., 2018). The modeling procedure followed a two-phase approach. First, an initial exploratory reduction of dimensionality was conducted using Principal Component Analysis (PCA) to guide the definition of latent constructs. Second, SEM was used to validate the measurement structure and estimate directional effects among constructs.

The general SEM framework is defined as follows:

Measurement model:

$$Y = \Lambda_\eta \eta + \varepsilon \tag{1}$$

Structural model:

$$\eta = \beta\eta + \Gamma\xi + \zeta \tag{2}$$

where:

- Y represent observed indicators for exogenous and endogenous latent variables,
- η and ξ are exogenous and endogenous latent variables,
- Λ_η are loading matrices,
- η: Vector of latent variables
- ε are measurement errors,
- β, Γ are the matrix of regression paths,
- ζ represents the structural disturbances.

The latent constructs modeled in this study include *Ship Characteristics*, *Environmental Conditions*, *Operational Risk*, and *Crew and Equipment*, with *Consequence of Accident* as the dependent latent variable. Observed variables for each construct were finalized through factor loading analysis, discussed in Section 3.1.

3. Results

3.1. Factor loading and model finalization

The initial selection and grouping of observed variables were informed by an exploratory factor analysis using principal components extraction with varimax rotation. Components with eigenvalues greater than 1.0 were retained and interpreted based on the pattern of loadings, and a loading threshold of 0.60 was adopted as the criterion for including indicators in a construct, in line with common recommendations (Comrey and Lee, 2013; Hair, 2009; Hair et al., 2014, 2019; Stevens, 2002). The consequence dimension was conceptually treated as a unidimensional latent construct representing accident severity, reflected by life-loss and financial-loss indicators.

Before extraction, the suitability of the data for factor analysis was confirmed using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's test of sphericity. The KMO value of 0.81 and a Bartlett test p-value <0.001 indicated adequate sampling adequacy and sufficient inter-item correlations for factor extraction. Varimax rotation, a widely used orthogonal rotation technique, was applied to obtain a clearer and more interpretable loading structure by maximizing the variance of squared loadings within each factor and reducing cross-loadings across factors.

Categorical variables with multiple sub-levels (e.g., Navigation Condition, Ship Type) were represented through binary indicator coding for each category (e.g., “dense traffic”, “dangerous segment”, “good navigation conditions”). This allowed the factor analysis to capture distinct contributions of specific categories to the underlying latent constructs, rather than forcing them into a single ordinal scale. Observed variables were initially grouped according to theoretical expectations (ship, environment, operational risk, crew/equipment), and the rotated component matrix was then used to confirm or adjust these groupings.

The rotated solution revealed four coherent latent dimensions that aligned well with the conceptual framework and prior literature: Ship Characteristics, Environmental Conditions, Operational Risk, and Crew & Equipment. Indicators were assigned to constructs based on their highest rotated loadings, retaining only those with loadings $\geq$0.60 (Comrey and Lee, 2013; Hair, 2009; Hair et al., 2019; Stevens, 2002). Variables exhibiting substantial cross-loadings (above 0.40 on more than one factor) were reviewed and, where necessary, removed to improve discriminant clarity between constructs. In the subsequent SEM measurement model, standardized loadings for retained indicators were all above 0.70, providing support for convergent validity of the constructs.

The final construct compositions are presented as follows in Table 2:

All retained indicators loaded highly and cleanly onto their respective constructs, reinforcing their theoretical and empirical coherence. Composite reliability and Average Variance Extracted (AVE) values for all latent constructs exceeded recommended thresholds, confirming strong internal consistency and convergent validity.

3.2. SEM analysis

The SEM was estimated using a robust weighted least squares estimator with mean and variance adjustment (WLSMV), which is well suited to models with categorical and binary indicators and does not rely on multivariate normality of the observed variables. The SEM analysis provides valuable insights into the factors influencing the consequences of maritime accidents. As evident from Fig. 4, Ship Characteristics exhibited strong loadings from Gross Tonnage (0.88) and Ship Type (0.65), indicating that larger ships and specific vessel types are highly

Table 2
Standardized factor loadings for latent constructs.

Latent construct	Indicator	Factor loading
Ship Characteristics	Gross tonnage	0.88
	Ship type	0.69
Environmental Conditions	Visibility	0.68
	Wind	0.72
Operational Risk	Danger recognition	0.76
	Watch	0.78
	Risk mitigation measure	0.85
Crew & Equipment	Stability	0.78
	Device condition	0.66
	Sailor expertise	0.81

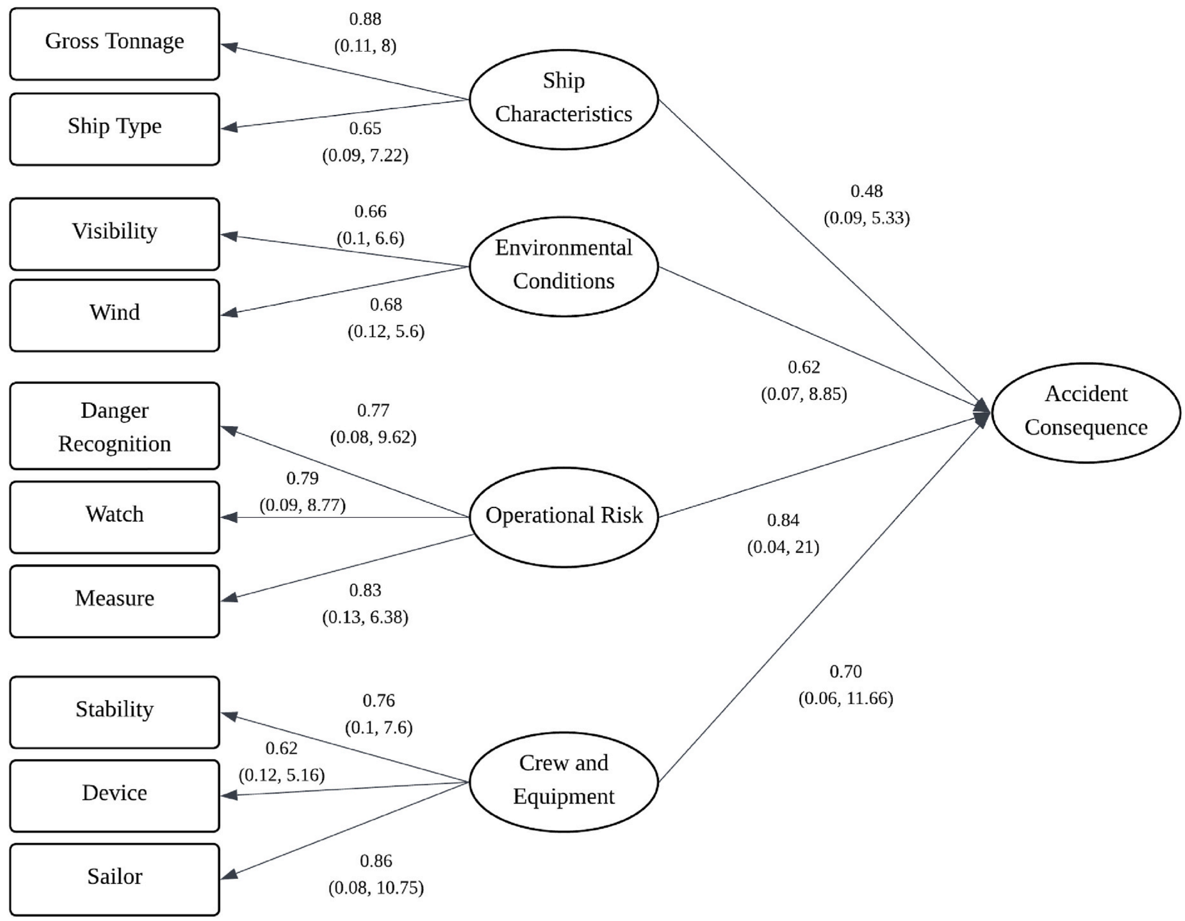

Fig. 4. The final SEM model with numeric results for the inland shipping.

influential attributes in defining this latent factor. Environmental Conditions, characterized by variables such as Visibility (0.66), Wind (0.68), also demonstrated strong contributions, highlighting the significant role of weather and navigational complexity in accident contexts.

Operational Risk emerged as the latent construct with the highest path coefficient towards the Consequence of Accident (0.84), underscoring those operational deficiencies such as Danger Recognition (0.77), Watch (0.79), and Measure (0.83) are critical contributors to accident severity. This finding aligns with previous research emphasizing the predominance of operational factors in accident causation. Similarly, Crew and Equipment Factors like Stability (0.76) and Device Condition (0.62), and most importantly, Sailor (0.86), revealed strong loadings, suggesting that crew competencies and onboard equipment integrity significantly shape safety outcomes.

In terms of direct effects on the consequences of accidents, Operational Risk had the strongest influence (0.84), followed by Crew and Equipment (0.70), Environmental Conditions (0.62), and Ship Characteristics (0.48). These results collectively emphasize that while environmental hazards are unavoidable to some extent, human and operational factors offer significant intervention points for enhancing maritime safety. Training programs, better operational protocols, and improved ship design targeting the most influential factors could substantially mitigate accident consequences.

3.3. Model fit assessment

The SEM demonstrates a strong overall goodness-of-fit, as reflected by multiple fit indices. The model was estimated using the robust weighted least squares mean and variance adjusted (WLSMV) estimator, which is appropriate for models with categorical or ordinal indicators and provides robust chi-square and fit indices. The chi-square goodness-of-fit test yielded a χ^2/df ratio of 1.363, which is well below the commonly recommended upper limit (around 2 to 3) for an acceptable model fit (McNeish, 2018, Zheng and Bentler, 2025). Such a low normed chi-square indicates that the discrepancy between the model and the observed data is minimal relative to model complexity. This suggests the model fits the sample covariance matrix closely, although it is worth noting that the chi-square can be sensitive to sample size and thus is often interpreted alongside other indices.

The RMSEA (Root Mean Square Error of Approximation) for the model is 0.022. This value is considerably below the conservative threshold of 0.05 for a close fit (Kenny et al., 2014), and well under the 0.08 mark typically used to denote a reasonable error of approximation (Rigdon, 1996). An RMSEA of 0.022 indicates an excellent fit, implying that the model's approximate error in reproducing the population covariance matrix is very low. The 90% confidence interval for RMSEA (not provided here, but likely very narrow around 0.022) would presumably confirm that the true RMSEA is below 0.05, reinforcing the conclusion of a good fit. Such a low RMSEA, combined with a non-significant test of close fit ($p > 0.05$) if reported, would strongly indicate that the model's residuals are within an acceptable range.

The comparative fit indices also support the model's adequacy. The CFI (Comparative Fit Index) is 0.94, exceeding the conventional 0.90 cutoff for acceptable fit (Mousavi et al., 2023) and approaching the more stringent criterion of 0.95 for good fit (Mousavi et al., 2023). Similarly, the TLI (Tucker–Lewis Index) is 0.92, also above 0.90 (Alruwaili and Xie, 2024). Both CFI and TLI compare the specified model to a null model, with values closer to 1.0 indicating better fit. Values in the mid-0.90s are often desired; thus, a CFI of 0.94 and TLI of 0.92 reflect a robust fit, albeit just shy of the highest standards (e.g., Hu and Bentler's 0.95

threshold). These indices suggest that the model explains a large proportion of the covariance in the data relative to an independence model, with only modest room for improvement remaining.

Finally, the model's RMR (Root Mean Square Residual) is 0.00074, effectively zero. The RMR (or its standardized variant, SRMR) should be below 0.08 to indicate a good fit of the model in terms of residuals (Alruwaili and Xie, 2024). The virtually zero RMR observed here signifies an almost perfect correspondence between the observed covariance matrix and that predicted by the model. In practical terms, this negligible residual indicates no substantial discrepancies left unexplained. Additional absolute and incremental fit indices support the same conclusion. The standardized root mean square residual (SRMR) is 0.010, well below the commonly used 0.08 guideline, indicating that average standardized residuals between observed and model-implied correlations are very small. The goodness-of-fit index (GFI = 0.96) and adjusted goodness-of-fit index (AGFI = 0.94) both exceed the 0.90 threshold, suggesting that the model reproduces the observed variance–covariance structure to a high degree. Likewise, the normed fit index (NFI = 0.95) and incremental fit index (IFI = 0.93) satisfy the ≥0.90 criterion generally adopted in covariance-based SEM, indicating that the specified model substantially improves on the null model (Lomax, 2004).

Taken together, all fit metrics meet or surpass accepted standards, pointing to an excellent model fit. The combination of a low χ^2/df, very low RMSEA, high CFI/TLI, and negligible RMR provides strong evidence that the SEM model is an appropriate and well-fitting representation of the data on inland maritime accident severity in China.

Table 3 presents a summary of the key fit indices alongside their conventional benchmark criteria for good model fit, illustrating that each index falls within the recommended range for an adequate to good fit.

4. Discussion

4.1. Key findings and model dynamics

The SEM results highlight that all four latent constructs, Ship Characteristics, Environmental Conditions, Operational Risk, and Crew & Equipment, have statistically significant impacts on Accident Consequence, with varying degrees of influence. Notably, Operational Risk emerged as the most potent driver of accident outcomes, showing the highest path coefficient (β ≈ 0.84) to Accident Consequence. This suggests that deficiencies in operational practices (e.g., poor watchkeeping, failure to recognize danger, inadequate safety measures) are strongly linked to more severe accident consequences. In practical terms, a one-standard-deviation increase in the Operational Risk factor corresponds to approximately a 0.84 standard deviation increase in accident severity, marking it as the dominant predictor in the model. This finding aligns with extensive maritime safety research attributing the majority of accidents to human and operational errors (Zhao et al., 2025; Deng et al., 2022; Chowdhury et al., 2024). It reinforces that lapses like not maintaining proper watch or misjudging risks can drastically worsen the outcomes of inland waterway accidents.

The Crew & Equipment factor is the second strongest predictor (β ≈ 0.70), underscoring the critical role of vessel material condition, maintenance, and crew proficiency in accident severity. Even when operational practices are sound, shortcomings in crew training or equipment reliability can significantly heighten accident consequences. This supports the well-documented contribution of technical failures and crew errors to maritime accidents, for example, the International Maritime Organization (IMO) has reported that roughly one-quarter of maritime accidents stem from mechanical failures of ships or equipment (Islam et al., 2018a, 2018b). Consistently, studies find that ship-specific factors (like machinery condition or crew competency) are closely linked to accident severity (Zhao et al., 2025). Our model's inclusion of Stability, Device reliability, and Sailor (crew competence) as indicators for this latent construct proved meaningful: high ratings on this factor (indicating better stability, reliable equipment, and skilled crew) correspond to markedly lower accident impacts. Conversely, weaknesses in these areas (e.g., an unstable or older vessel, malfunctioning devices, or an under-skilled crew) can aggravate the consequences when an incident occurs (Chen et al., 2019a). This dynamic resonates with analyses of maritime casualties showing that aging vessels and poor maintenance tend to correlate with more severe accidents (Antão et al., 2023; Chen et al., 2019b). For instance, a study found that ship factors like inadequate machinery upkeep in older vessels significantly heighten incident severity (Kimera and Nangolo, 2022). These parallels suggest that the strong effect of the Crew & Equipment construct in our model reflects a general truth: robust crew training and well-maintained ships are fundamental to mitigating accident outcomes worldwide.

The Environmental Conditions construct also demonstrated a significant influence (β ≈ 0.62) on Accident Consequence. As expected, adverse environmental factors, such as poor visibility and high winds, which were the indicators in our model, increase the likelihood of severe accidents. This is consistent with international studies that have quantified how harsh weather amplifies maritime risk. For example, empirical analyses show that accident severity tends to rise under strong winds, heavy seas, strong currents, and even paradoxically under unusually good visibility (which often corresponds to riskier behavior) (Maternová and Svabova, 2024). In other words, extreme or rapidly changing conditions can overwhelm even well-prepared crews, leading to collisions or groundings with worse outcomes. Our findings mirror those of (Jon et al., 2021) and others who underscore the significant influence of environmental conditions on accident severity (Zhao et al., 2025). Notably, Visibility had a substantial loading on the Environmental Conditions factor, which dovetails with prior observations that low visibility (fog, nighttime darkness) sharply increases the probability of accidents (Chen et al., 2023; Ding et al., 2025). Wind conditions likewise are known to affect vessel maneuverability; strong winds can push ships off course or hinder stopping, contributing to incidents (Heij and Knapp, 2015; Maternová and Svabova, 2024; Wang et al., 2021). The fact that Environmental Conditions ranked third in path strength in our model indicates that, while human factors dominate, natural conditions remain a critical contributing cause, a finding aligning with the broader maritime safety literature that identifies weather and waterway conditions as important though generally secondary risk factors (Deng et al., 2022; Magklasi, 2022).

Finally, Ship Characteristics had the smallest (yet still significant) effect on Accident Consequence (β ≈ 0.48). This factor, defined by attributes such as Gross Tonnage and Ship Type, captures how the physical and design features of vessels influence accident outcomes. The positive path coefficient suggests that certain ship profiles (for instance, higher tonnage vessels or particular types of ships) are associated with more severe accident consequences. One interpretation is that larger ships or high-capacity vessels, when involved in accidents, tend to cause greater damage or loss (due to momentum or cargo hazards), thus raising the "consequence" severity. Conversely, smaller vessels might be nimbler but could also be more vulnerable, indeed, statistics indicate that

Table 3
Summary of model fit indices and conventional thresholds.

Fit Index	Value	Standard Threshold
Chi-square/df	1.363	<3.0 (good fit)
RMSEA	0.022	<0.05 (good fit)
CFI	0.94	≥0.90 (acceptable)
TLI	0.92	≥0.90 (acceptable)
RMR	0.00074	<0.08 (good fit)
SRMR	0.010	<0.08 (good fit)
GFI	0.96	≥0.90 (acceptable)
AGFI	0.94	≥0.90 (acceptable)
NFI	0.95	≥0.90 (acceptable)
IFI	0.93	≥0.90 (acceptable)

smaller craft like fishing boats and yachts often suffer disproportionately severe outcomes in accidents (Maternová and Svabova, 2024; Wang et al., 2021). Our finding is in line with studies that examine accident severity by vessel type: for example, an analysis in this regard found that fishing vessels and pleasure craft were most involved in higher-severity accidents, likely reflecting their design limitations and operational patterns (Maternová et al., 2022; Maternová and Svabova, 2024). Additionally, older or poorly equipped ships (traits partly captured by our Ship Characteristics latent variable) have been linked with higher incident rates and severity (Lin et al., 2023, Kimera and Nangolo, 2022). The relatively lower influence of Ship Characteristics in our model (compared to human factors) suggests that while vessel attributes do matter, they are often overshadowed by how the ship is operated and managed. In essence, even a well-built ship can be steered into disaster by human error, whereas a less ideal ship in capable hands and benign weather might avoid serious accidents. This hierarchy of influences, human/operational factors outweighing ship design, echoes findings in global maritime accident investigations (Deng et al., 2022; Zhang et al., 2024; Chowdhury et al., 2024).

It is important to note that these four factors in the model are not entirely independent in real-world scenarios. In practice, maritime accidents often result from a *combination* of circumstances (for instance, an inexperienced crew navigating a heavily loaded ship in foggy conditions). Our SEM, by design, isolates the unique contribution of each latent construct to the accident outcome, controlling for the others. The significant coefficients for all paths indicate that each factor adds explanatory power; none can be neglected when assessing accident causation. Moreover, the latent constructs likely correlate with each other to some extent (e.g., vessels with poor equipment may also have less trained crews, or adverse weather might exacerbate operational mistakes), though the model treats them as separate predictors of consequences. The high path loadings of the observed indicators on their respective constructs (all loadings ≥0.62 in the SEM diagram) also give confidence that our latent variables were well-defined and captured the intended risk dimensions. Overall, the model's driving dynamics suggest a scenario where Operational Risk acts as the primary catalyst of accidents, but its ultimate impact on consequences is modulated by the vessel's characteristics, the crew/equipment state, and the environmental context. This holistic insight is one of the strengths of using SEM for our analysis.

4.2. Comparison with global accident patterns and generalizability

Our findings from China's inland waterways show a striking convergence with international maritime accident research, supporting the generalizability of the results beyond the immediate study context. Decades of global data have established that human and organizational factors are the predominant causes of marine accidents across regions. In our model, the two human-centric constructs (Operational Risk, and Crew & Equipment) collectively had the largest influence on accident outcomes, a pattern echoed by many studies worldwide. For instance, analyses of marine casualties in Western shipping consistently attribute 75–80% or more of accidents to human error or unsafe actions (Chowdhury et al., 2024; Zhao et al., 2025). Another study noted that despite advances in technology, human failures remain the root cause in roughly 80% of maritime accidents (Fan et al., 2020) . Similarly, a recent comprehensive study reported that over 80% of accidents result from crew errors or inappropriate crew responses to hazards (Zhao et al., 2025). These figures align extremely well with what our China-focused SEM indicates, namely, that improving human performance and decision-making is paramount to reducing accidents. The dominance of the Operational Risk factor (encompassing behaviors like inadequate watchkeeping and hazard recognition) is consistent with case investigations from around the world. For example, a study found that in Nigerian maritime companies, nine distinct human-related issues (such as poor crew coordination, fatigue, excessive speed, and flawed judgment) were major causes of accidents (Oluseye and Ogunseye, 2016). Several of those human failures (e.g., lapses in lookout or decision errors) map closely to the elements of our Operational Risk construct, reinforcing that the same unsafe acts and conditions plague maritime safety across both developing and developed contexts. Likewise, a study of Tanzanian inland waterway accidents observed that nearly 70% were attributable to human error, underlining the universal criticality of the human factor even in inland shipping (Justace et al., 2024).

Beyond human factors, our inclusion of Ship, Environment, and Crew/Equipment factors also finds support in international literature, underscoring that maritime accidents have multifactorial causes in any setting. A study analyzed 922 accidents in Chinese waters (both inland and coastal) and identified four major cause categories, human, ship, environment, and management, which mirror the constructs in our model (Deng et al., 2022). In their findings, human factors were involved in over 90% of incidents, far outpacing the other causes (Deng et al., 2022). Ship-related factors were the next most frequent contributor (∼44% of accidents), followed by management (∼43%) and then environmental factors (∼23%) (Deng et al., 2022). Our SEM results align with that general ranking: the human element (Operational risk and Crew/Eqpt combined) clearly overshadows ship and environment factors in effect size. One minor difference is that our Environmental Conditions path coefficient (0.62) was somewhat higher relative to Ship Characteristics (0.48) than Deng et al.'s proportional counts suggest. This could be due to the specific nature of inland waterways in our study; environmental hazards like sudden fog, river currents, or wind gusts in narrow channels might have an outsized impact on accidents compared to open-sea conditions. Deng et al. indeed noted that for inland river accidents, human factors account for an even larger share of causes than at sea, while environmental factors play a relatively smaller role inland than in maritime waters (Deng et al., 2022). Regardless, both our model and international data clearly indicate that all these factors matter. The presence of significant paths from Ship Characteristics and Environmental Conditions to accident outcome in our model confirms what global statistics show: factors such as vessel type/age and weather conditions, even if secondary, still contribute meaningfully to accident causation (Islam et al., 2018b; Kimera and Nangolo, 2022; Antão et al., 2023; Chen et al., 2019b). For example, IMO reports attribute roughly one in four accidents to ship mechanical issues (Chen et al., 2019a), and studies have linked poor visibility or severe weather to spikes in collision and grounding incidents (Lin et al., 2023; Zhao et al., 2025). Our Chinese inland data thus behaves in accordance with these global trends, bolstering the relevance of our study to wider maritime safety discussions.

Another important point of comparison is the role of organizational and management factors, which often underpin human errors. While our SEM did not have a separate "management" latent variable, the Operational Risk construct inherently captures procedural and organizational safety lapses (e.g., inadequate safety measures or failure to adhere to best practices). International research similarly emphasizes that management quality and safety culture are key antecedents to accidents. An investigation in this regard found that management problems (e.g., poor safety oversight on offshore facilities) often underlie the root causes of accidents (Bhardwaj et al., 2022). Another study demonstrated that implementing effective safety assessment systems significantly reduces the occurrence of ship accidents (Kokotos and Linardatos, 2011). Likewise, one more study established a clear causal link between safety management practices and accident severity (Cao et al., 2023). These findings suggest that what we termed "Operational Risk" is often an indication of deeper organizational issues, and improving those organizational aspects can mitigate the risk. Our results, when viewed alongside such studies, imply that the inland shipping sector in China is no exception, fostering a stronger safety culture, better training, and stricter operating procedures (all management-driven actions) should yield safety improvements just as they have in international contexts.

The general alignment between our model's causal structure and those identified in global accident analyses gives confidence that our research is not an isolated case. Instead, it contributes to a growing body of evidence that maritime accidents, whether on Chinese rivers or the open ocean, arise from a common set of risk domains. This generalizability means that safety interventions informed by our findings (discussed below) are likely to have relevance not only for China's inland waterways but potentially for other regions' inland transport and even broader maritime operations.

5. Policy implications

The SEM results provide a clear hierarchy of where policy intervention can most effectively reduce accident severity of China's inland waterways. The two human–operational constructs, Operational Risk ($\beta \approx 0.84$) and Crew & Equipment ($\beta \approx 0.70$), exert the strongest influence on consequences, followed by Environmental Conditions ($\beta \approx 0.62$) and Ship Characteristics ($\beta \approx 0.48$). This ranking implies that governance measures aimed at how ships are operated, staffed, and equipped will yield the largest marginal gains in safety, while vessel design and environmental controls play important but secondary, enabling roles.

From a regulatory perspective, the dominant effect of Operational Risk points to the need for tighter oversight of everyday navigational practices. Priority measures include: (i) embedding structured watchkeeping, speed management, and hazard-recognition protocols into licensing, renewal, and recurrent training for inland masters and officers; (ii) introducing risk-based inspections and audits focused explicitly on bridge procedures (e.g., logbook checks, VDR/AIS track review, compliance with sailing instructions on hazardous reaches); and (iii) strengthening enforcement of rules on lookout, overtaking, and passing in narrow or congested channels. Inland Maritime Safety Administration units and river basin authorities can use these findings to refine supervision criteria, concentrating limited inspection resources on vessels, routes, and operators exhibiting high-risk operational profiles rather than spreading enforcement uniformly.

The strong influence of Crew & Equipment underscores that technical reliability and crew competence must be treated as a single safety governance axis. Policy tools here include mandatory, interval-based hull and equipment inspections linked to certification, with particular attention to stability conditions, loading practices, and critical navigation and communication devices. At the same time, competence-based crew training and certification should be calibrated to inland-specific hazards rather than adopting ocean-going standards wholesale. Regulators could also couple inspection outcomes and recorded deficiencies with targeted training requirements for operators and companies, creating a feedback loop in which poor safety performance directly triggers remedial capacity-building obligations.

Although Environmental Conditions are not directly controllable, their significant path coefficient suggests that policy can still meaningfully shape exposure. In practice, this means expanding and operationalizing real-time river information services: continuous visibility, water level, current, and wind monitoring on high-risk reaches; timely broadcasting of warnings; and the use of dynamic control measures, such as temporary speed limits, one-way traffic windows, or staggered lock entry, during fog, storms, or high-flow periods. Inland VTS centers and river management authorities can use these SEM insights to justify investments in such monitoring and control systems, especially in sections where historical accident data indicate that poor visibility and strong winds frequently coincide with severe outcomes.

Finally, while Ship Characteristics exert the smallest, yet still significant, direct effect, they remain important for limiting the upper tail of accident consequences. Policy attention should focus on high-tonnage and ageing vessels in constrained waterways, for example, through stricter stability criteria, enhanced structural and machinery inspection regimes, and, where necessary, targeted retrofit requirements (e.g., upgraded navigation and communication systems, redundancy in critical equipment). Differential standards or routing rules for specific ship categories (such as older high-tonnage cargo vessels transiting narrow bends or lock complexes) can help ensure that the physical risk profile of the fleet is aligned with the carrying capacity and safety envelope of the river system.

When being taken into account collectively and holistically, these findings can support an integrated safety-governance strategy in which (i) operational behavior and safety management systems are treated as primary levers, (ii) crew competence and equipment reliability are jointly strengthened through certification, training, and maintenance regimes, (iii) environmental monitoring and dynamic traffic management are used to dampen exposure during hazardous conditions, and (iv) vessel standards are calibrated to the specific risks of inland navigation. The SEM framework thus not only explains current accident severity patterns but also provides a structured, evidence-based map from empirical risk drivers to concrete regulatory and managerial interventions on China's inland waterways.

6. Conclusion

This study provides a robust, multi-dimensional analysis of inland maritime accident severity in China using SEM, integrating empirical accident data with a theoretically grounded factor structure for evidence-based governance implications. The primary finding is the dominant role of Operational Risk in determining accident outcomes, as evidenced by its highest path coefficient ($\beta = 0.84$). This confirms that procedural deficiencies, poor watchkeeping, and delayed hazard responses are critical determinants of severity in inland accidents. Such insights reinforce global literature that consistently identifies human and operational errors as the leading contributors to maritime incidents.

The significant influence of Crew & Equipment ($\beta = 0.70$) further highlights the need for improved crew competence, enhanced training, and regular maintenance of onboard systems. Indicators such as sailor expertise, vessel stability, and equipment functionality underscore the compound effect of crew readiness and technological integrity in accident mitigation. Environmental Conditions, including visibility and wind ($\beta = 0.62$), while largely uncontrollable, also amplify risk, emphasizing the need for adaptive navigation systems and real-time hazard detection in adverse scenarios. Ship Characteristics, though the least influential ($\beta = 0.48$), still matter, particularly when dealing with high-tonnage vessels and complex ship types operating in constrained waterways.

The model's strong fit (RMSEA = 0.022; CFI = 0.94; TLI = 0.92) validates its explanatory power and confirms the appropriateness of using SEM in this context. By disentangling the complex interplay of human, environmental, and technical factors, this study contributes a validated, data-driven framework that offers actionable insights for inland waterway safety management. It further demonstrates that inland maritime safety in China mirrors global accident trends, suggesting that international best practices in safety culture, training, and regulation could be effectively adapted to China's context.

However, this study is not without limitations. First, while comprehensive, the dataset remains geographically constrained to China, which may limit global generalizability. Second, some variables, such as organizational management or economic pressures, could not be explicitly modeled due to data limitations. Lastly, the model focuses on the severity of consequences but does not address accident prevention in probabilistic terms. Future research should aim to expand the model to include predictive accident frequency, incorporate qualitative organizational factors, and apply the framework to other inland and coastal regions to validate its broader applicability. Longitudinal analysis could also help in assessing how interventions alter risk dynamics over time.

CRediT authorship contribution statement

Jingbo Yin: Writing – review & editing, Visualization, Validation,

Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Rafi Ullah Khan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mujtaba Asad:** Writing – review & editing, Visualization, Validation, Software, Methodology, Data curation, Conceptualization. **Xinbo Wang:** Writing – review & editing, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Zaili Yang:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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Data availability

The authors do not have permission to share data.

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