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Research on the Proactive Prevention and Control System for Outdoor Adventure Accidents in China Empowered by Intelligence

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Abstract: In recent years, with the vigorous development of outdoor adventure sports in China, related safety incidents have occurred frequently, posing a serious threat to people's lives and property. Traditional emergency management models that focus on "post-incident response" have struggled to meet the increasingly complex safety demands of outdoor adventures. This paper systematically explores the spatiotemporal distribution characteristics, causative mechanisms, and risk evolution patterns of outdoor adventure accidents through a comparative analysis of accident data from two distinct periods: 2015–2019 and 2021–2024. The study finds that getting lost, being trapped, and slipping are the primary types of outdoor adventure accidents, with a notable seasonal and geographical distribution. Against the backdrop of heterogeneous data sources, this paper highlights the differences and commonalities in accident characteristics across different periods and addresses the limitations of small-sample statistics. Building on this, the paper introduces the concept of "proactive management" and constructs a four-pronged proactive prevention and control system for outdoor adventure accidents in China, integrating smart technologies such as the Internet of Things, big data, and artificial intelligence. This system, encompassing "smart perception—intelligent early warning—precise intervention—collaborative governance," aims to achieve early risk identification, dynamic assessment, and proactive intervention through technological empowerment, thereby effectively reducing accident rates. The research not only enriches the theoretical connotations of tourism safety management but also provides practical references for government departments and relevant institutions to enhance their outdoor adventure safety governance capabilities.

Keywords: Outdoor adventure; Tourism safety; Proactive management; Smart empowerment; Prevention and control system; Big data

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1. Introduction

With the rapid development of China's economy and society and the continuous improvement of people's living standards, mass tourism demand has become increasingly diversified and personalized. In this context, outdoor adventure sports, as an emerging industry that integrates sports, tourism, and leisure, are gaining popularity among more and more people. However, outdoor adventure activities, typically conducted in natural environments, are characterized by high levels of uncontrollability and danger. In recent years, frequent outdoor adventure accidents in China have not only resulted in severe casualties and property losses but also triggered widespread social concern. According to the *2024 Annual Report on Outdoor Adventure Accidents in China* released by the China Exploration Association, there were 335 outdoor adventure accidents in China in 2024, involving 1,126 individuals, with 84 fatalities, 92 injuries, and 11 missing persons [1]. Despite a decrease in the total number of accidents compared to 2023, hidden risks remain severe.

Faced with frequent outdoor adventure accidents, traditional safety management models have revealed numerous shortcomings. For a long time, tourism safety management in China has primarily focused on "post-incident response," involving emergency rescue and aftermath handling following accidents. While this approach can mitigate accident consequences to a certain extent, it fails to fundamentally prevent accidents from occurring. With the rapid development of smart tourism, new-generation information technologies such as the IoT, big data, and AI offer new opportunities for tourism safety management. Through smart empowerment, achieving a transition from "post-incident response" to "pre-incident prevention," namely "proactive management," has become an inevitable choice for enhancing the effectiveness of outdoor adventure safety governance. In January 2025, the General Administration of Sport of China and other departments issued the *Opinions on Promoting the High-Quality Development of Outdoor Sports*, explicitly proposing to "improve the safety management system for outdoor sports and enhance the level of smart management" [2], providing important policy support for this study.

This paper aims to conduct an in-depth analysis of the occurrence patterns and causative mechanisms of outdoor adventure accidents in China through a comparative analysis of accident data from two distinct periods: 2015–2019 and 2021–2024. Combining smart technologies, it constructs a proactive prevention and control system for outdoor adventure accidents in China. The research not only contributes to enriching the theoretical framework of tourism safety management but also provides decision support for relevant departments in formulating scientific and reasonable safety management policies.

2. Literature review and theoretical foundations

2.1. Research on outdoor adventure and tourism safety management

The safety issues associated with outdoor adventure sports have consistently been a focal point of academic attention. Scholars have conducted in-depth research on the causes, characteristics, and prevention and control strategies of outdoor adventure accidents from various perspectives. Huang [3] analyzed 178 typical mountain tourism accidents based on grounded theory, revealing that the causal factors of accidents, ranked by proportion, are human, environmental, facility, and management factors, with human factors accounting for the highest proportion at 57.3%. Lin [4] constructed a theoretical framework for the standardized development of sports tourism from the perspective of industrial ecology, emphasizing the need to establish safety management standards based on safety risk orientation, with a hierarchical and classified approach. Chen [5] built a network for the evolution of tourism safety accidents, identifying tourism traffic accidents as key node accidents, and proposed safety management recommendations from the three dimensions of "human-machine-environment." Liu [6] proposed a risk assessment method for mountain-type scenic spots, evaluating risk probability through a fuzzy Bayesian network model, providing a quantitative tool for scenic spot safety management. Chen [7] explored the causes and countermeasures of rafting tourism accidents in China based on 55 official reports of rafting tourism accidents, finding that insufficient safety awareness among tourists and illegal operations by operators are the main causes. Wang [8] analyzed the spatiotemporal characteristics of marine tourism safety accidents in China, revealing that accidents exhibit clustering and imbalance in distribution, with summer and the eastern coastal regions being high-incidence periods and areas. Huang

[9] analyzed safety risk incidents involving Chinese tourists traveling to ASEAN regions and proposed the establishment of a long-term risk prevention and control system.

2.2. Research on smart tourism and safety empowerment

Smart tourism, as a new trend in tourism development, plays an increasingly prominent role in enhancing tourism experiences, optimizing resource allocation, and strengthening safety management. Deng [10] explored the basic characteristics of smart tourism development in China, emphasizing the need to prioritize ethics in the digital and intelligent innovation of the tourism industry to prevent the risk of technological abuse. Yan [11] studied the safety risks of digital economy empowerment for high-quality tourism development and proposed the introduction of a technology-economy-society-politics coupling governance model. Liu [12] discussed the application of big data in tourism crisis management and the challenges it faces, pointing out that big data plays a positive role in tourism crisis warning, handling, and epidemic control, but data silos and privacy protection remain major obstacles. Luan [13] outlined the connotation of smart tourism management and proposed strategies for constructing a big data-based smart tourism management model, emphasizing the core position of data sharing platform construction. Peng [14] used policy tool analysis and the LDA2Vec machine learning method to analyze the evolution of China's smart tourism policies, finding that the policy focus is shifting from infrastructure construction to service innovation and safety management. Jiang [15] verified through a quasi-natural experiment that smart tourism construction significantly promotes the high-quality development of urban tourism economies, while also pointing out that the role of smart technologies in enhancing safety management effectiveness requires further empirical testing.

2.3. Research on proactive management theory

Proactive management refers to a management model that eliminates risks in their infancy or minimizes their impact through systematic planning, monitoring, warning, and intervention before risk events occur. In the field of tourism safety, proactive management emphasizes identifying and controlling risks from the source. Tian [16] constructed a proactive management model for the relationship between border tourism and national security through a case study of Daluo Town in Yunnan Province, emphasizing the pre-positioning of safety risk assessment in the tourism product development stage. Hu [17] proposed algorithms for instantaneous safety capacity and daily safety capacity considering evacuation time based on the spatiotemporal distribution characteristics of crowd gathering, providing proactive quantitative means for preventing stampede incidents. Wang [18] studied the spillover effects of post-disaster tourism destination environmental risks on tourism attraction elements, emphasizing the importance of pre-disaster risk perception management and pointing out that proactive risk communication can effectively reduce tourists' risk perception. Hao [19] discovered through knowledge graph visualization analysis that tourism disaster management research mainly focuses on risk assessment and disaster impact, calling for strengthened proactive research on tourists' risk perception. Lv [20] constructed a safety risk evaluation system for internet-famous attractions and proposed targeted safety risk management strategies, emphasizing the integration of safety risk assessment into the daily operational management processes of scenic spots.

In summary, existing research has achieved fruitful results in the causes of outdoor adventure accidents, the application of smart tourism, and proactive management, laying a solid theoretical foundation for this study. However, research on the deep integration of smart technologies and proactive management to systematically construct a prevention and control system for outdoor adventure accidents in China is still scarce, which is precisely the research entry point and innovation of this paper.

3. Analysis of the characteristics and risk evolution of outdoor adventure accidents in China (2015–2024)

3.1. Data sources and processing explanation

The data in this article primarily originate from two periods: the traditional era of tourism-related safety (2015–2019) and the era of explosive mass adventure (2021–2024). The data from 2015 to 2019 mainly reference the *China Tourism Safety Blue Book* [21] published by the China Tourism Academy. This blue book focuses on "tourism-related accidents and disasters," with a statistical scope covering travel agency liability accidents, tourism traffic accidents, scenic spot safety incidents, etc. The data scope is relatively macroscopic. The data from 2021 to 2024 are sourced from the *China Outdoor Adventure Accident Report* [1] published by the China Adventure Association. This report concentrates on "outdoor adventure accidents," with the statistical subjects being outdoor sports enthusiasts and a scope more focused on adventure activities in natural environments such as mountains, water bodies, and high altitudes. The data scope is more microscopic. Given the significant differences in statistical subjects, scope, and reporting channels between the two datasets, it is scientifically inadequate to forcibly splice them together for trend analysis in a single time series.

Therefore, this article adopts a segmented comparative analysis method, treating the data from these two periods as independent samples reflecting the characteristics of outdoor safety risks under different era backgrounds. When comparing accident types, efforts have been made to cross-reference and reclassify the accident classification standards in the two datasets to achieve comparability within a limited scope.

3.2. Total accident volume and risk evolution trends

As shown in **Figure 1**, the total volume of outdoor adventure accidents in China from 2015 to 2024 exhibits characteristics of "high volatility" and demonstrates different evolution trends under the two era backgrounds.

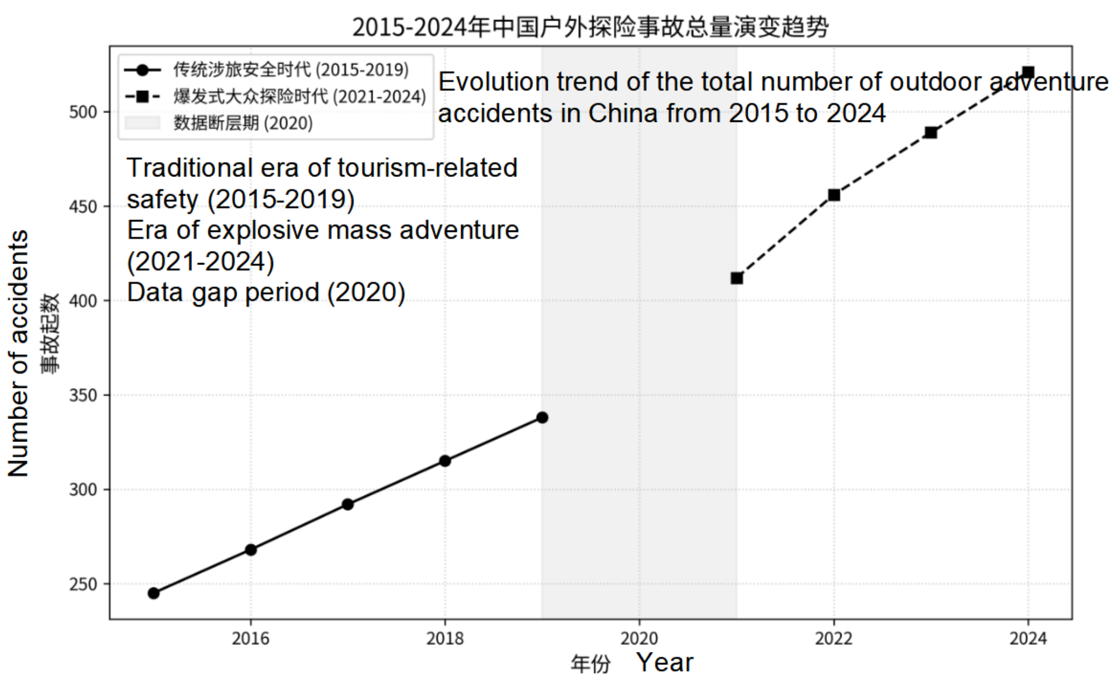

Figure 1. Evolution trend of the total number of outdoor adventure accidents in China from 2015 to 2024

During the traditional era of tourism-related safety (2015–2019), the total number of accidents remained relatively stable, with an average of around 100 incidents per year and a declining trend in fatalities or missing persons [21]. During this period, tourism safety management primarily focused on safety issues within traditional tourism sectors, such as travel agency liabilities and transportation safety. Accident causes were mostly associated with inadequate tourism infrastructure and insufficient safety management systems.

In the era of explosive mass adventure (2021–2024), driven by the post-pandemic surge in outdoor adventure enthusiasm, the total number of accidents increased significantly, with the average annual number of incidents far exceeding that of the previous period. Although the total number of accidents decreased somewhat in 2024, the absolute number remained substantial [1]. During this period, accident causes were more closely related to the adventurers' lack of skills, weak risk awareness, and blind challenges to unknown environments. The gray area in Figure 1 clearly marks the data gap period in 2020, reminding readers to note the transition in data sources when interpreting the trend.

3.3. Accident type structure and "low-frequency, high-loss" risks

As shown in **Figure 2**, there are significant differences in the accident type structure across different eras, but "low-frequency, high-loss" risks remain a focal point in outdoor safety management.

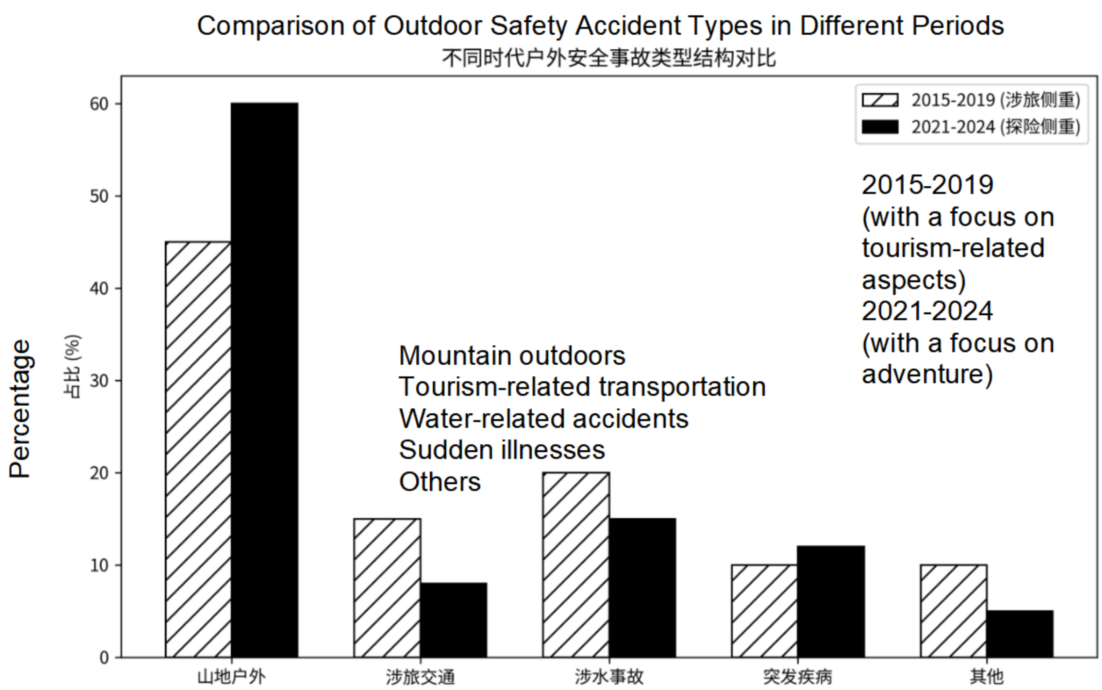

Figure 2. Comparison of the structural composition of outdoor safety incident types across different eras

In the era of traditional tourism-related safety (2015–2019), traditional tourism risks such as tourism-related transportation incidents and water-related accidents accounted for a relatively high proportion of incidents. Although mountain outdoor sports accidents also occurred, their proportion within the overall tourism-related incidents was relatively low. Notably, tourism-related traffic accidents often resulted in a high number of fatalities, exhibiting characteristics of "low frequency but high damage."

In the era of explosive mass adventure (2021–2024), the proportion of mountain outdoor sports incidents (such as getting lost, being trapped, and slipping and falling) significantly increased, becoming the primary type of incident. Although the proportion of tourism-related traffic accidents decreased, their inherently high fatality rate remained unchanged. This indicates that with the popularization of outdoor adventure, mountain outdoor sports have become a high-frequency source of risk, while tourism-related transportation remains a "low-frequency but high-damage" type with a high fatality rate, posing a dual challenge to outdoor safety.

3.4. Interactive analysis of fatality risk and incident types

As shown in **Figure 3**, through an interactive analysis of the number of incidents and the number of fatalities, the differences in fatality risk among different incident types can be understood more intuitively.

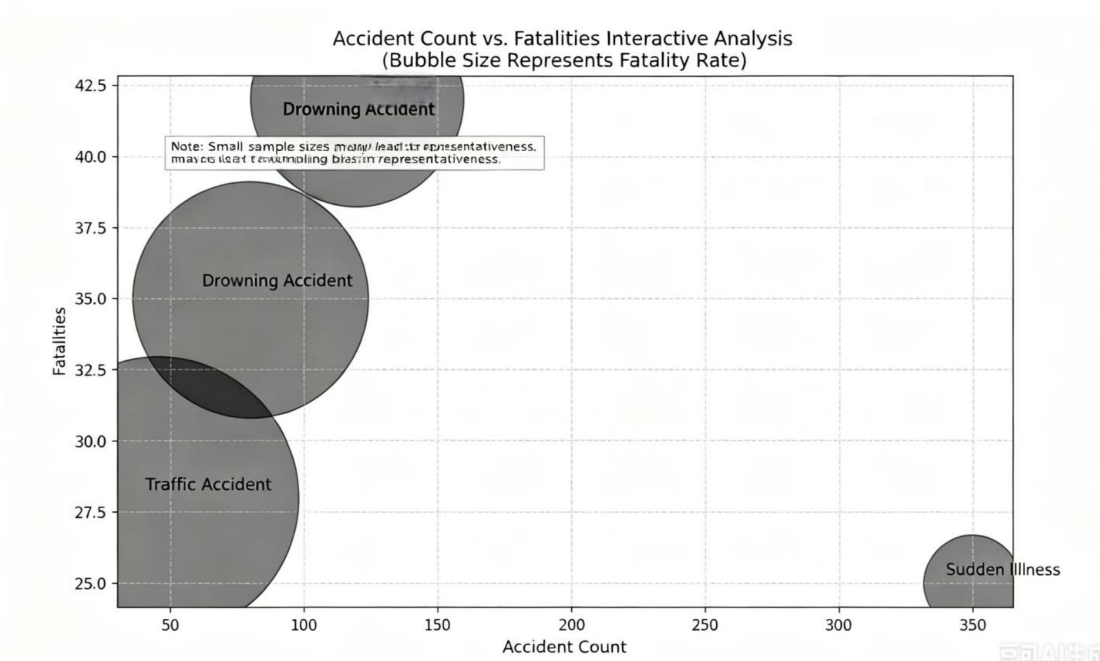

Figure 3. Interactive analysis of incident count vs. fatality count (bubble size represents fatality rate)

Figure 3 illustrates the distribution of different incident types in terms of incident count and fatality count, with bubble size representing the fatality rate. From the figure, it can be observed that although tourism-related traffic incidents have a relatively low count, their fatality count and fatality rate are significantly higher than those of other types, reaffirming their characteristic of "low frequency but high damage." In contrast, mountain outdoor incidents have a higher count but a relatively lower fatality rate.

To verify the statistical differences in fatality risk among different incident types, this paper conducted a Kruskal-Wallis H test on incident data from 2015 to 2019 (see **Table 1**).

Table 1. Results of Kruskal-Wallis H test on fatality counts for different incident types

Accident type	Sample size (*n*)	Mean rank	H statistic	Degrees of freedom	Asymptotic significance (*P*)	η^2
Mountain outdoor		12.40	16.854	3	0.001	0.656
Travel-related traffic		18.60				
Water-related accident		8.20				
Sudden illness		4.80				

Note: Due to the small sample size of annual observations ($n = 5$), the results of statistical tests are highly susceptible to interference from extreme values, limiting their robustness and academic credibility. They are only provided as supplementary references for trend analysis. In contrast, mountain outdoor incidents occur more frequently but have a relatively lower fatality rate.

3.5. In-depth analysis of the causal mechanisms of accidents

Based on the accident causation chain theory and the "human-machine-environment-management" system model, this paper conducts an in-depth analysis of the causal mechanisms of outdoor adventure accidents. Accidents often result not from a single factor but from the interplay and coupling of multiple factors.

Human factors: The compounded effects of weak safety awareness and insufficient skills. A significant number of accidents are caused by the adventurers themselves. Some adventurers blindly pursue thrills, lacking essential outdoor survival skills and knowledge of self-rescue and mutual aid. Without professional training, they rashly attempt difficult adventure routes, making them prone to getting into trouble. Some adventurers underestimate their physical capabilities, leading to exhaustion. In long-distance hikes or high-altitude climbs, a sharp decline in physical stamina can severely impair judgment and reaction speed, increasing the likelihood of accidents. Others ignore safety warnings and enter undeveloped or unopened "wild attractions" or "secret realms," which typically lack basic safety facilities and rescue support, making the consequences of accidents unimaginable.

Environmental factors: The uncontrollability of extreme weather and complex terrain. Outdoor adventure activities are greatly influenced by the natural environment. Sudden heavy rain, thunderstorms, flash floods, mudslides, and other extreme weather conditions often catch adventurers off guard. For example, in mountainous areas, localized severe convective weather can lead to a sudden increase in rainfall, triggering flash floods that trap adventurers in river valleys or canyons. Additionally, steep cliffs, dense forests, underground rivers, and other complex terrains are direct causes of accidents. In these terrains, adventurers are prone to getting lost, falling, or being attacked by wildlife. The uncontrollability of environmental factors requires adventurers to possess a high degree of vigilance and adaptability.

Material factors: The hidden dangers of improper equipment and lack of facilities. Adventurers who do not carry professional outdoor equipment (such as navigation devices, warm clothing, first aid supplies) or whose equipment fails during use are highly susceptible to emergencies. For example, in cold environments, insufficient warm clothing can lead to hypothermia; in complex terrains, the failure of navigation devices can easily result in getting lost. Meanwhile, some remote adventure areas lack well-established communication base stations, directional signs, and emergency shelters. Poor communication prevents adventurers from sending distress signals promptly when in danger; the absence of directional signs increases the risk of getting lost; and the lack of emergency shelters leaves adventurers with nowhere to hide in extreme weather conditions.

Management factors: Systemic defects in regulatory blind spots and delayed rescue. The dispersed, concealed, and spontaneous nature of outdoor adventure activities poses significant challenges to government regulation. Some regions lack clear regulations and standards for outdoor adventure management, leading to unclear regulatory bodies and inadequate implementation of responsibilities. Some "wild attractions" remain unmanaged for long periods, becoming high-risk areas for accidents. Additionally, due to complex terrain and poor communication, professional rescue forces often struggle to reach the scene promptly in the event of an accident. Delayed rescue not only increases the life risk of those trapped but also significantly raises the cost and difficulty of rescue operations. Furthermore, the integration and coordination mechanisms for social rescue forces are still imperfect, resulting in inefficient rescue efforts.

4. Construction of a proactive prevention and control system for outdoor adventure accidents enabled by smart technologies

In response to the aforementioned accident characteristics and causes, this paper proposes the construction of a four-in-one proactive prevention and control system for outdoor adventure accidents in China, namely the "Smart Perception-Intelligent Warning-Precise Intervention-Collaborative Governance" system (hereinafter referred to as the "PCG-OAS system"). Supported by smart technologies such as the Internet of Things (IoT), big data, and artificial intelligence, this system aims to achieve early risk identification, dynamic assessment, and proactive intervention. The construction of this system represents not only a disruptive innovation in traditional safety management models but also an inevitable choice to address the increasingly complex safety challenges of outdoor adventures.

4.1. Technology-driven proactive governance logic model

The occurrence of outdoor adventure accidents often results from the systemic failure chain of "human-machine-environment-management." The core logic of smart technology-enabled proactive governance lies in effectively cutting off this failure chain through a closed loop of "real-time perception-intelligent warning-precise intervention." Specifically:

Real-time perception (eliminating spatial barriers): Utilizing technologies such as the IoT, sensor networks, and satellite positioning, this system achieves all-around, high-precision real-time data collection on adventurers, the environment, and facilities and equipment. This breaks the spatial limitations of traditional management, making risk information ubiquitous and providing a data foundation for subsequent warnings and interventions.

Intelligent warning (compressing time redundancy): Based on big data analysis and artificial intelligence algorithms, this system conducts in-depth mining and pattern recognition of real-time perception data to predict the occurrence of potential risks. This significantly compresses the time redundancy from risk emergence to discovery and response, transforming "post-event response" into "pre-event warning."

Precise intervention (correcting behavioral deviations): On the basis of intelligent warnings, this system employs technical means such as intelligent navigation, remote dissuasion, and pre-positioned deployment of emergency supplies to proactively and precisely intervene in risks. This aims to promptly correct adventurers' behavioral deviations, make up for environmental deficiencies, and repair equipment failures, thereby blocking the further evolution of accidents.

Through the above logic, the PCG-OAS system aims to prevent accidents at the source, achieving a fundamental transformation from "mending the fold after the sheep are stolen" to "taking precautions before trouble arises." Meanwhile, "collaborative governance" serves as a guarantee mechanism to ensure the effective operation and continuous optimization of the entire system.

4.2. Smart perception: A multi-dimensional data collection network across the entire area

Smart perception is the foundation of proactive prevention and control. By deploying a multi-dimensional data collection network across the entire area, this system achieves real-time monitoring of adventurers, the natural environment, and facilities and equipment, providing precise data support for subsequent warnings and interventions.

Adventurer behavior perception and physiological state monitoring: Utilizing smart wearable devices (such as smartwatches and GPS locators) and smartphone apps, this system collects real-time data on adventurers' location trajectories, physiological signs (such as heart rate and blood oxygen), and movement states. These devices not only record adventurers' travel routes but also automatically trigger alarm mechanisms when adventurers experience physiological crises such as abnormal heart rates or low blood oxygen levels. Through electronic fence technology, this system monitors whether adventurers deviate from established routes or enter dangerous areas. Once adventurers cross safety boundaries, the system immediately sends warning messages to them and simultaneously notifies the management backend.

Natural environment perception and meteorological and geological disaster monitoring: Deploying IoT sensors such as meteorological monitoring stations, geological disaster monitors, and hydrological monitoring stations in key adventure areas, this system collects real-time environmental data such as temperature, humidity, wind speed, rainfall, and soil displacement. These sensors can work continuously 24 hours a day, capturing minute changes in the environment. Combined with satellite remote sensing and drone patrols, this system achieves macroscopic monitoring of large-scale natural environments. For example, through satellite remote sensing technology, it can monitor forest fire risk levels and vegetation coverage in real-time; through drones equipped with high-definition cameras and infrared thermal imagers, it can quickly discover trapped personnel and potential geological disaster hazards.

Facility and equipment perception and operational state monitoring: This system conducts digital transformations of key facilities in adventure areas, such as communication base stations, emergency shelters, and rescue supply storage depots, to monitor their operational states and supply reserves in real-time. By installing smart sensors on these facilities, management departments can grasp information such as equipment battery levels, signal strengths, and supply consumption at any time. Once equipment failures or supply shortages are detected, the system automatically generates maintenance work orders, reminding staff to handle them promptly to ensure that these facilities can function normally in emergencies.

4.3. Intelligent warning: Dynamic risk assessment based on big data

Intelligent warning is the core of proactive prevention and control. Through in-depth mining and analysis of massive perception data, this system achieves dynamic assessment and precise prediction of safety risks.

4.3.1. Construction of an outdoor adventure risk assessment indicator system

To achieve precise warnings, the PCG-OAS system constructs a multi-dimensional risk assessment indicator system (see **Table 2**), covering four core dimensions: human, machine, environment, and management.

Table 2. Outdoor adventure risk assessment indicator system and weight directions

Dimension	Evaluation indicator	Data source	Weight direction	Early warning trigger logic
Individual (Personal Risk)	Physiological signs (heart rate/ oxygen saturation)	Smart wearable devices	High	Deviation from baseline >30%
	Movement trajectory (deviation)	GPS/Beidou positioning	Medium	Deviation from planned route >500m
Equipment/ Facilities	Outdoor experience and skill level	User profile big data	Low	Skill level does not match route difficulty
	Equipment integrity/battery level	IoT sensors	Medium	Critical device battery <20%
	Communication signal strength	Base station/satellite link	Medium	Signal interruption >15 minutes
Environmental Risk	Weather changes (precipitation/ wind speed)	Weather station/ satellite	High	Sudden extreme weather warning
	Terrain complexity/geological stability	GIS/geological monitor	Medium	Detection of soil displacement or landslide signs
Management Risk	Regional visitor flow density	Video surveillance/ heatmap	Low	Exceeds instantaneous capacity 90%
	Rescue force coverage distance	Rescue dispatch system	Low	Distance to nearest rescue point >2 hours travel

4.3.2. Construction of risk assessment model and application of machine learning

Based on the aforementioned indicator system, the PCG-OAS system employs machine learning algorithms to achieve dynamic risk assessment. The logical flow of its algorithms is shown in **Figure 4**.

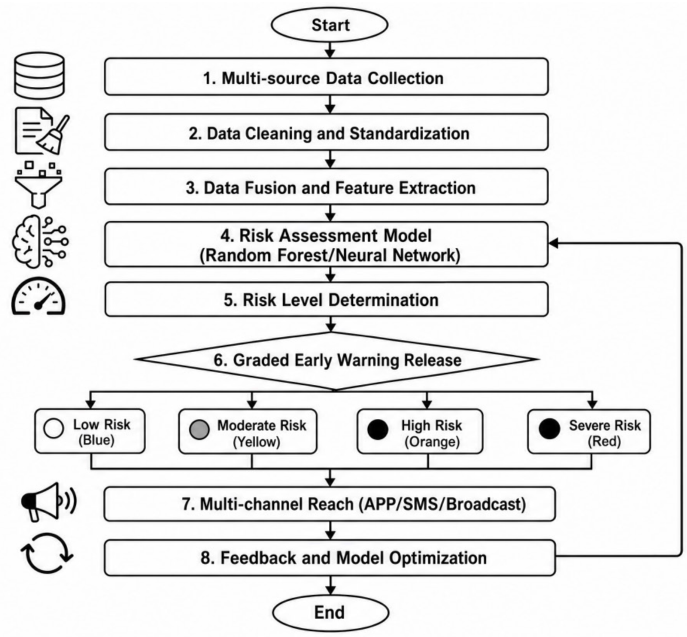

Figure 4. Logic flow diagram of intelligent early warning algorithm

(1) Data cleaning and standardization

Raw sensor data (e.g., GPS trajectories, physiological signs, environmental sensor data) often suffer from issues such as noise, missing values, and inconsistent formats. Initially, data preprocessing techniques (e.g., outlier removal, interpolation, normalization) are employed to clean and standardize the data, ensuring data quality and consistency.

(2) Data fusion and feature extraction

Cleaned multi-source heterogeneous data are fused to construct a unified data view. Based on this, features highly relevant to outdoor adventure risks are extracted, such as the adventurer's position change rate (speed), heart rate variability, blood oxygen saturation decline trend, meteorological mutation indicators (e.g., sudden wind speed increase, abnormal rainfall), terrain slope, and communication signal stability. These features serve as inputs to machine learning models.

(3) Risk assessment model construction

Using machine learning algorithms such as Random Forest, Support Vector Machine, or Deep Neural Networks, a multi-dimensional risk assessment model is constructed. The model learns the complex relationships between risk factors and accident occurrences from historical accident data to predict real-time risk probabilities under current conditions. For example, the model can output risk indices for adventurers getting lost, suffering from hypothermia, or falling in the near future.

(4) Risk level determination and hierarchical early warning

Based on the risk indices output by the risk assessment model and predefined thresholds, risks are classified into four levels: red (extremely high), orange (high), yellow (medium), and blue (low). The system automatically triggers corresponding early warning mechanisms according to different risk levels and disseminates early warning information to adventurers, management departments, and rescue agencies through multiple channels such as APP notifications, SMS messages, vibrations from smart wearable devices, and scenic area broadcasts. Meanwhile, the early warning information includes specific risk types, locations, and recommended countermeasures to achieve precise early warnings.

(5) Feedback and model optimization

The operational effectiveness of the early warning system is continuously evaluated through actual accident occurrences and user feedback. The model continuously learns from new data and feedback information for iterative optimization to improve the accuracy and timeliness of early warnings, forming a self-adaptive, self-learning closed-loop system. Through the aforementioned algorithm logic, the PCG-OAS system can achieve dynamic assessment and precise prediction of safety risks, transforming from being "wise after the event" to being "prophetic before the event."

(6) Hierarchical and classified early warning dissemination and multi-channel reach

Based on risk assessment results, early warning levels are classified into red, orange, yellow, and blue, corresponding to extremely high, high, medium, and low risks, respectively. Early warning information is disseminated to adventurers, management departments, and rescue agencies through multiple channels such as SMS messages, APP notifications, vibration alerts from smart wearable devices, and scenic area broadcasts. To ensure the timeliness and effectiveness of early warning information, the system should possess intelligent routing capabilities to automatically select the optimal communication channel based on the adventurer's network environment. For example, in areas without mobile network coverage, early warning information can be sent through the Beidou Short Message Service.

4.4. Precise intervention: Interrupting the accident evolution chain

Precise intervention is key to proactive prevention and control. After early warning information is disseminated, proactive intervention measures are taken through technical means to interrupt the accident evolution chain and resolve risks in their infancy.

4.4.1. Proactive prevention and control of tourism-related traffic accidents

Based on the previous analysis of the "low-frequency, high-damage" characteristics of tourism-related traffic accidents, the prevention and control focus of the PCG-OAS system should shift to the "first kilometer" of adventurers traveling to the base. This includes:

Smart traffic big data fusion: Break down data silos among cultural tourism, sports, and traffic police departments and integrate traffic flow, road condition information, vehicle trajectories, and driver behavior data. Utilize big data analysis models to conduct real-time assessment and prediction of traffic risks for adventurers traveling to outdoor adventure areas by self-driving or chartered vehicles. For example, identify high-risk behaviors such as fatigued driving, speeding, and abnormal vehicle trajectories.

"First kilometer" smart intervention: Before adventurers set off, provide "safe travel recommendations" based on real-time traffic data and weather warnings through APPs and SMS messages, including optimal routes, hazard avoidance sections, and extreme weather warnings. For high-risk vehicles or drivers, remote reminders or mandatory rest can be issued. Deploy smart monitoring equipment on high-risk road sections such as mountain roads to monitor vehicle driving status in real-time and immediately issue warnings and notify relevant departments for intervention upon detecting abnormalities.

Cross-departmental collaborative response: Establish a joint emergency response mechanism involving cultural tourism, sports, traffic, public security, and other departments. When traffic risk warnings reach a certain level, relevant departments can collaboratively take measures such as traffic control, road diversion, and police force pre-positioning to ensure adventurers' safety during the traffic segment.

4.4.2. Smart route planning and dynamic navigation guidance

Based on GIS technology and real-time road condition data, provide personalized smart route planning services for adventurers. When planning routes, the system not only considers distance and time but also comprehensively evaluates terrain, weather, and safety facilities along the way. When adventurers deviate from safe routes or encounter dangers ahead (e.g., sudden mountain floods, road collapses), the system automatically replans safe routes and guides adventurers to avoid hazardous areas through voice and visual navigation. This dynamic navigation guidance can effectively reduce accidents caused by getting lost and venturing into dangerous areas.

4.4.3. Virtual barriers for remote dissuasion and electronic blockade

When detecting that adventurers are attempting to enter unopened "wild attractions" or high-risk areas, management departments can dissuade them through drone shouting, remote broadcasting, and other means. Drones can not only quickly reach areas difficult for personnel to access but also convey clear warning messages to adventurers through onboard loudspeaker equipment. Meanwhile, utilize electronic fence technology to blockade dangerous areas in virtual space. When adventurers' smart devices detect entry into blocked areas, they automatically emit strong alarm sounds and restrict certain device functions, forcing adventurers to leave dangerous areas.

4.4.4. Pre-positioning of emergency supplies and drone delivery

Utilize operations research and optimization algorithms to establish a pre-positioning model for emergency supplies. Based on historical accident distributions and real-time tourist flow heat maps, pre-position first aid kits, communication relay equipment, warmth supplies, etc., in accident-prone areas and key nodes. This pre-positioning can significantly shorten rescue response times and improve rescue success rates. In emergencies, large cargo drones can also be used to precisely deliver urgently needed medical supplies, food, and drinking water to trapped individuals, buying precious time for subsequent ground rescues.

4.5. Collaborative governance: An ecosystem with multiple stakeholders

Collaborative governance is the guarantee for proactive prevention and control. Outdoor adventure safety management involves multiple stakeholders such as governments, enterprises, social organizations, and adventurers. It is essential to construct a collaborative governance ecosystem with multiple stakeholders participating to form a concerted effort.

Government-led and legislation-perfected top-level design

Government departments should play a leading role, accelerate the formulation and improvement of laws, regulations, and industry standards related to outdoor adventure safety management, clarify the rights and responsibilities of all parties, and establish cross-departmental joint law enforcement and emergency response mechanisms. For example, the "Regulations on the Management of Outdoor Adventure Activities" can be introduced to regulate the organization, participation, and rescue segments of adventure activities. Meanwhile, the government should increase investment in smart safety infrastructure to provide solid material support for the operation of the proactive prevention and control system.

Enterprise participation and market-driven technological innovation

Encourage technology companies, outdoor equipment manufacturers, and tourism platforms to participate in the construction of the smart prevention and control system. Through public-private partnership (PPP) models, increase R&D investment in core technologies such as the Internet of Things, big data, and artificial intelligence to promote the application and transformation of scientific and technological achievements in the field of outdoor adventure safety. For example, technology companies can develop lighter and more durable smart wearable devices; tourism platforms can be required to provide safety risk warnings and skill tests when users book adventure products.

Social collaboration and integration of professional rescue forces

Give full play to the roles of social organizations and professional rescue agencies such as the China Adventure Association and Blue Sky Rescue Team. Establish a diversified rescue system combining government professional rescue with social volunteer rescue. The government can support the development of social rescue forces through service purchases and subsidies. Meanwhile, promote a mandatory outdoor adventure insurance system and use insurance mechanisms to diversify risks. Insurance companies can implement differentiated premium rates based on adventurers' risk assessment results and use economic levers to guide adventurers to travel safely.

Adventurer self-discipline and internal motivation for safety education

Adventurers are the primary responsible parties for their own safety. Strengthen safety education and skill training for adventurers through a combination of online and offline methods. Establish an adventurer credit evaluation system and impose credit penalties for non-compliant adventure behaviors, such as restricting the purchase of specific tourism products and prohibiting entry into specific scenic areas. Through these measures, guide adventurers to establish correct safety concepts and enhance self-protection awareness and capabilities.

5. Typical case analysis: Practical exploration of smart empowerment for proactive prevention and control

To further verify the effectiveness and feasibility of the "smart perception-intelligent early warning-precise intervention-collaborative governance" proactive prevention and control system, this paper selects several representative cases in outdoor adventure safety management in China for in-depth analysis. These cases cover different types of adventure activities such as mountain scenic areas, unmanned area traverses, and high-altitude mountaineering, demonstrating the enormous potential of smart technologies in practical applications.

5.1. Case 1: Huangshan Scenic Area's "scenic area brain" and proactive tourist flow early warning

As a typical mountainous world heritage site with precipitous terrain and changeable climate, Huangshan Scenic Area has seen a continuous increase in annual tourist volume, reaching 5.168 million inbound tourists in 2025 [22]. Facing the huge tourist flow and complex natural environment, Huangshan Scenic Area took the lead in introducing the "Scenic Area Brain" system, built more than 30 application systems, and was selected as one of the first batch of national "5G+Smart Tourism" application pilot projects [23], achieving proactive management of tourism safety.

Omnidirectional perception and data aggregation: Huangshan Scenic Area deployed thousands of high-definition cameras, meteorological monitoring stations, and tourist flow counting devices throughout the mountain to construct an omnidirectional perception network. These devices collect real-time data on tourist distribution, movement trajectories, and meteorological conditions such as wind speed and rainfall and transmit the data to the "Scenic Area Brain" platform in real time. The scenic area has an approved daily maximum carrying capacity of 50,000 people (normal conditions), adjusted to 30,000 people in winter and 40,000 people during peak seasons [22]. Through smart perception, precise tourist flow control is achieved.

Intelligent early warning and dynamic flow limitation: Based on historical data and real-time tourist flow, the "Scenic Area Brain" can accurately predict tourist flow density at various scenic spots in the next few hours.

When predicting that tourist flow at a certain scenic spot is about to reach the safety threshold, the system automatically triggers an early warning mechanism. The scenic area management department takes dynamic flow limitation measures in advance based on the early warning information, such as suspending ticket sales and guiding tourist diversion, effectively avoiding crowded stampede accidents. Tourist satisfaction reached 94% during the 2023 National Day Golden Week, a record high [24].

Precise intervention and emergency response: Before the arrival of extreme weather (e.g., thunderstorms, ice and snow), the "Scenic Area Brain" issues safety tips to tourists and plans safe shelter routes through SMS messages, broadcasts, and APP notifications. Meanwhile, the scenic area pre-positions emergency rescue teams and supplies at key nodes to ensure a rapid response in the event of emergencies. Through smart empowerment, Huangshan Scenic Area has achieved a remarkable record of no forest fires for 46 consecutive years [25] and no major work safety accidents for 27 consecutive years, providing valuable reference experience for other mountainous scenic areas with its proactive management model.

5.2. Case 2: Beidou navigation and electronic blockade in the Hoh Xil Unmanned Area

The Hoh Xil Unmanned Area, with its unique natural scenery and mysterious allure, attracts a large number of adventure enthusiasts. However, the area's high altitude, low oxygen levels, complex terrain, and wildlife presence make it prone to fatal accidents such as getting lost, hypothermia, and wildlife attacks. To strengthen the management of adventure activities in the unmanned area, the local government introduced Beidou navigation systems and electronic blockade technology.

Beidou navigation and trajectory tracking: Legal adventure teams entering Hoh Xil must be equipped with Beidou navigation terminals. These terminals not only provide high-precision positioning services but also maintain communication with the outside world through short message functions in areas without mobile network coverage. Management departments can track the trajectories of adventure teams in real-time through backend systems and immediately initiate verification mechanisms upon detecting deviations from predetermined routes or prolonged immobility.

Electronic blockade and drone patrols: To address "wild tourism" behaviors involving illegal traverses of the unmanned area, management departments set up virtual electronic fences at the unmanned area's boundaries. The system automatically issues alarms when detecting unauthorized vehicles or personnel attempting to enter. Meanwhile, long-endurance drones are used for regular patrols to promptly detect and dissuade illegal traversers.

Collaborative governance and joint law enforcement: The Hoh Xil Administration Bureau has established a joint law enforcement mechanism with public security, environmental protection, emergency response, and other departments to crack down on illegal traverse behaviors severely. Meanwhile, information sharing and regional collaboration with neighboring provinces are strengthened to form a cross-regional prevention and control network. The application of Beidou navigation and electronic blockade technologies has significantly reduced illegal traverse incidents and safety accidents in the Hoh Xil Unmanned Area, effectively protecting adventurers' life safety and the local ecological environment.

5.3. Case 3: Smart wearable devices and physiological monitoring for high-altitude mountaineering on Siguniang Mountain

Siguniang Mountain is a well-known high-altitude mountaineering destination in China, attracting a large number of mountaineering enthusiasts. High-altitude mountaineering faces severe risks such as mountain sickness, avalanches, and falls. To enhance mountaineering safety guarantees, Siguniang Mountain Scenic Area has promoted the use of smart wearable devices and physiological monitoring technologies.

Real-time physiological sign monitoring: Mountaineers wear smart watches or smart bracelets during the climb to monitor key physiological indicators such as heart rate, blood oxygen saturation, and body temperature in real-time. These data are transmitted to the team leader's terminal device and the scenic area management backend through Bluetooth or low-power wide-area networks. Based on massive physiological data and medical models, the system can intelligently identify early symptoms of mountain sickness. When detecting that a mountaineer's blood oxygen saturation continuously falls below the safety threshold or heart rate abnormalities, the system immediately issues alarms, reminding the mountaineer to stop climbing, descend, or take emergency measures such as oxygen inhalation.

Precise positioning and rapid rescue: In the event of sudden accidents such as falls or avalanches, smart wearable devices can provide precise positioning information to help rescue teams quickly locate the individuals in distress. Meanwhile, the scenic area has pre-deployed medical supplies such as hyperbaric oxygen chambers and emergency medicines at various campsites to provide timely treatment for mountaineers suffering from altitude sickness. The application of smart wearable devices has transformed safety management in high-altitude mountaineering from traditional "experience-based judgment" to "data-driven" approaches, significantly reducing the mortality and severe illness rates associated with altitude sickness.

6. Implementation path and countermeasure suggestions

To ensure the effective implementation of the proactive prevention and control system of "smart perception—intelligent early warning—precise intervention—collaborative governance," this paper proposes the following implementation paths and countermeasure suggestions.

6.1. Accelerating the construction of new infrastructure and consolidating the foundation for smart perception

The government should increase investment in the construction of new infrastructure in key exploration areas such as remote mountainous regions and nature reserves. Expand the coverage of 5G networks and the Beidou Satellite Navigation System to address the issue of "communication blind spots." Deploy IoT monitoring nodes for meteorology, geology, hydrology, etc., on a large scale to construct an all-weather, comprehensive three-dimensional perception network. In particular, deploy special sensors with the capability to withstand harsh environments in high-risk areas to ensure data continuity and reliability.

6.2. Promoting data interconnection and establishing a national-level safety brain

Break down departmental barriers and promote data sharing and business collaboration among departments such as culture and tourism, emergency response, meteorology, public security, and forestry and grassland. Relying on the national government service platform, build a national-level big data center for outdoor exploration safety ("safety brain"). Develop unified data standards and interface specifications to achieve cross-regional and cross-level early warning linkage and command and dispatch. By introducing blockchain technology, ensure data security and immutability, enhancing the trust foundation for multi-party collaboration.

6.3. Strengthening the application of scientific and technological innovation to enhance precise intervention capabilities

Encourage universities, research institutes, and technology companies to collaborate in tackling key technologies such as high-precision positioning, low-power communication, and smart wearable devices in complex environments. Develop intelligent equipment such as drones for inspection and robots for rescue suitable for extreme environments. Promote the application of big data-based intelligent route planning and risk assessment algorithms to enhance the scientific and precision of intervention measures. Establish special scientific research funds to support key technology research and development and commercialization of research findings in the field of outdoor exploration safety.

6.4. Improving the legal and regulatory framework and establishing a long-term governance mechanism

Accelerate the introduction of specialized regulations such as the "Administrative Measures for Outdoor Exploration Activities" to clarify the access conditions, filing procedures, and safety responsibilities for outdoor exploration activities. Establish a "blacklist" system to prohibit explorers who repeatedly violate regulations or cause serious consequences from entering. Meanwhile, strengthen the qualification review and daily supervision of outdoor exploration business operators to regulate market order. Promote the comprehensive implementation of a mandatory insurance system for outdoor exploration, utilizing market mechanisms to disperse risks and protect the legitimate rights and interests of explorers and operators.

6.5. Strengthening safety education and cultural construction to enhance public risk awareness.

Popularize outdoor exploration safety knowledge and skills through multimedia platforms, public lectures, outdoor practices, and other forms. Advocate the concept of "responsible outdoor activities" and guide explorers to establish a safety mindset of "respecting nature and acting within their capabilities." Encourage social organizations to develop and promote outdoor safety education courses and train professional outdoor leaders and safety coaches. Incorporate outdoor safety education into the national education system, starting from youth, to enhance the public's ability to identify risks and provide self-rescue and mutual rescue.

7. Conclusion and outlook

Through a comparative analysis of outdoor exploration accident data in China from 2015–2019 and 2021–2024, this paper reveals the spatiotemporal distribution characteristics, causal mechanisms, and risk evolution patterns of accidents. Based on this, a four-in-one proactive prevention and control system for outdoor exploration accidents in China, namely "smart perception—intelligent early warning—precise intervention—collaborative governance," has been constructed. This system aims to achieve early risk identification, dynamic assessment, and proactive intervention through smart technology empowerment, thereby effectively reducing accident rates and enhancing outdoor exploration safety governance capabilities.

The innovations of this study lie in: first, conducting a segmented comparative analysis of heterogeneous outdoor exploration accident data for the first time, revealing the evolution characteristics of outdoor safety risks under different era backgrounds; second, deeply integrating smart technology with proactive management concepts to construct a systematic outdoor exploration accident prevention and control system and refine the logic of intelligent early warning algorithms and risk assessment indicators; third, verifying the effectiveness and feasibility of the PCG-OAS system through typical case analysis. However, this study also has certain limitations, such as the robustness issues of small-sample statistics and the limited depth of analysis due to the difficulty in obtaining some data. Future research can further expand data sources, introduce more complex machine learning models, and conduct empirical research to quantitatively assess the actual benefits of the PCG-OAS system.

Notes

It should be particularly noted that due to the heterogeneity of data sources, this paper cannot provide accident data for 2020, resulting in a "gap" in the time series.

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