

Research on Collaborative Rescue Schemes and Strategies of Multi-Carrier in Flood Disasters

Wei Yang, Siyuan Xu, Ying Gong

School of Management Science and Engineering, Chongqing Technology and Business University, Chongqing 400067, China

Abstract

Against the backdrop of global climate change, flood disasters exhibit the characteristics of frequent occurrence, wide coverage and high destructiveness, evolving into a complex "chain-breaking" crisis. The traditional single-carrier rescue mode is confronted with efficiency bottlenecks and structural defects, which make it difficult to meet the practical rescue demands. Based on the differentiated scenarios of floods, this paper constructs three three-dimensional collaborative schemes, namely Truck-Drone collaboration in urban waterlogging, Truck-Boat intermodal transport in basin floods, and Air-Ground integration in communication-interrupted areas. It also formulates three supporting strategies including dynamic grading based on urgency, rolling robustness in response to uncertainty, and collaborative linkage of official and social forces, thus establishing a multi-carrier collaborative rescue system featuring integration of space-air-ground, interconnection of water-land-air carriers, and collaboration of military-government-society. Simulation data show that this system has achieved a more than 30% improvement in material delivery efficiency, effectively solving the problems of rescue path blockage and resource misallocation. The research further puts forward policy recommendations such as equipment standardization and the construction of digital infrastructure, providing key support for the modernization optimization of the emergency management system.

Keywords

Flood Rescue; Multi-Carrier Collaboration; Rescue Schemes; Rescue Strategies.

1. Introduction

1.1. Research Background

1.1.1. The Normalized Trend of Disasters

At present, extreme hydrological events caused by global climate change show the characteristics of frequent occurrence, wide coverage and high destructiveness. According to the relevant statistical data from the United Nations Office for Disaster Risk Reduction and the Ministry of Emergency Management of China, flood disasters have become the type of natural disaster causing the most severe direct economic losses and the largest affected population. The 7.9-magnitude earthquake in Myanmar in 2025 and the secondary barrier lake breach disaster it triggered, as well as the extremely heavy rainstorm in Zhengzhou, Henan Province and the Zhuozhou flood disaster caused by extreme heavy rainfall in the Beijing-Tianjin-Hebei region in recent years in China, all indicate that modern floods are no longer a single water conservancy issue, but have evolved into a complex "chain-breaking" crisis integrating road blockage, communication paralysis and power outage.

In such disasters, the affected areas are often divided into multiple physically isolated nodes. However, the traditional rescue mode relies heavily on the ground transportation network. Once the water depth exceeds the usual wading limit of 0.5 meters for vehicles, or

bridges and culverts collapse, the rescue channels are immediately interrupted. This physical spatial barrier prevents rescue forces from reaching the core affected areas through conventional means within the golden 72 hours, resulting in a structural contradiction where rescue resources are backlogged at distribution centers while the affected points are in extreme shortage of materials.

To intuitively demonstrate this severe situation, the following figure counts the trends of the affected scale and frequency of global and Chinese flood disasters in the past five years based on historical data and recent disaster models, as shown in Figure 1.

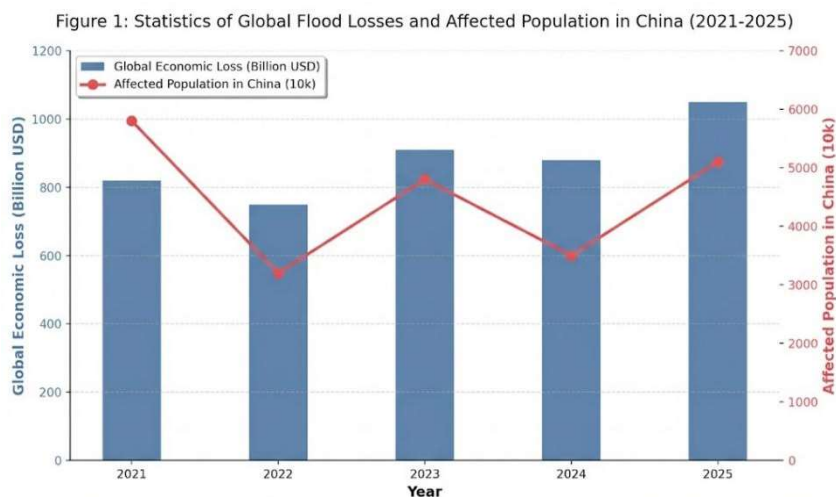


Figure 1. Statistical Trends of Global Flood Economic Losses and China's Affected Population (2021-2025)

1.1.2. Urgent Demand for Transformation

Faced with the above challenges, the limitations of the single-carrier operation mode have become increasingly prominent. Trucks cannot wade through water, ships cannot land, and aircraft are restricted by take-off and landing conditions and load capacity. Therefore, constructing a multi-carrier collaborative rescue system that can dynamically switch according to water level, terrain and disaster situation has become a key scientific issue in the field of emergency management. This not only requires the seamless connection of trucks, ships and aircraft at the physical level, but also the unified scheduling across departments and levels at the management level.

1.2. Literature Review

This paper conducts a systematic review of the relevant core literatures in academia. According to the different research focuses, the existing achievements can be divided into three main schools: System Architecture and Command Decision-Making, Heterogeneous Carrier Routing Optimization Algorithm (LRP) and Social Collaboration and Multi-Dimensional Constraints.

1.2.1. Research on System Architecture and Command Decision-Making

Such research focuses on the macro-level platform construction and information flow. Zhong Guihui et al. (2024) designed a command decision-making system integrating meteorological monitoring and flood simulation functions in view of the weak infrastructure in rural and town areas, emphasizing the coupling of pre-disaster early warning and in-disaster scheduling [1]. Lou Yang (2025) expanded the vision to the whole domain and proposed an intelligent collaborative scheduling architecture of space-air-ground integration, which solved the situation awareness problem at disaster sites by integrating satellite remote sensing and ground Internet of Things data [2]. Xu Jianhua (2026) took transnational earthquake rescue as an example to discuss the multilateral coordination mechanism in international humanitarian

assistance, providing a theoretical reference for inter-organizational collaboration in complex environments [3].

1.2.2. Research on Heterogeneous Carrier Routing Optimization Algorithm (LRP)

This is a current research hotspot in the field of emergency logistics, whose core is to solve the spatial relay and coordination of different means of transportation. (1) Truck-Drone Collaboration: Zhang Yali (2025) and Zhang Zefeng (2023) conducted in-depth research on the operation mode of trucks as mobile take-off and landing platforms. Among them, Zhang Yali focused on the path response problem under the dynamic change of customer locations in mega cities [4]; while Gong ying (2025) introduced the robust optimization method into the Location-Routing Problem (LRP) to cope with the volatility of truck travel time [5]. (2) Truck-Boat Collaboration: Aiming at the water-land interweaving environment, Zhou Yufeng (2025) constructed a Truck-Boat collaborative search and rescue model containing a scarcity cost function, and improved the solution efficiency through the Improved Tabu Search (ITS) algorithm [6]; Cheng Jiahao (2025) discussed the multi-objective trade-off between material distribution and satisfaction rate for mountainous terrain [7]. (3) Air-Ground Integration: Zeng Jingxiang (2024) and Lv Zheng (2025) analyzed the high-low matching mode of helicopters and UAVs in communication relay and material delivery [8,9].

1.2.3. Research on Social Collaboration and Multi-Dimensional Constraints

This type of research focuses on the soft constraints in the rescue process and the organization of social forces. Tian Wanfang (2025) pointed out the disorder problem of social emergency forces in on-site coordination based on the practice of the Zhuozhou rescue, and put forward an optimization scheme of the government-led coordination mechanism [10]. Xu Bingbing (2025) quantified and graded the emergency demand urgency by using the Grey Relational Analysis method [11]. Liu Changshi (2025) innovatively introduced the rescue utility index, regarding material distribution and disaster victim transfer as a two-way coupling process [12]. Table 1 presents a classified review of the core literatures related to multi-carrier collaborative rescue.

Table 1. Classified Review Table of Core Literatures Related to Multi-Carrier Collaborative Rescue

Research Dimension	Representative Authors	Core Contributions	Limitations/Unsolved Problems
System Architecture	Zhong Guihui Lou Yang	Established a multi-level command information platform architecture from rural and town areas to space-air-ground, solving the problem of "situation awareness".	Focus on the technical realization of information flow, with less involvement in the specific scheduling strategies of physical carriers.
Routing Algorithm	Gong ying Zhou Yufeng Zhang Yali	Proposed mathematical models (LRP/VRP) and improved algorithms (ITS/INSGA-II) for Truck-Drone and Truck-Boat collaboration.	Most models are based on idealized assumptions, with insufficient consideration of complex tactical processes and sudden interruptions in actual combat.
Social Strategy	Tian Wanfang Liu Changshi	Revealed the drawbacks of the lack of coordination mechanism for social forces, and introduced soft evaluation indicators such as rescue utility.	Belong to qualitative analysis or single-link optimization, lacking systematic integration with physical collaborative schemes.

1.2.4. Research Commentary and the Research Entry Point of This Paper

Based on the above literature review, the existing research has made remarkable progress in micro routing algorithms and macro system architecture, but there are still the following disconnections:

First, the disconnection between algorithms and actual combat. A large number of studies focus on improving heuristic algorithms to shorten calculation time, but ignore the design of physical processes such as carrier switching and material transfer in actual rescue.

Second, the disconnection between single mode and comprehensive scenarios. Most existing models aim at a single combination of Truck-Drone or Truck-Boat, lacking a comprehensive solution to cope with the whole process of complex floods, from waterlogging to basin floods and then to isolated islands.

Finally, the disconnection between official and social forces. Physical models often assume that all carriers are under unified command and control, ignoring the self-organization characteristics of social rescue forces.

In view of this, based on the perspective of engineering management, this paper is not only pursuing the mathematical optimality of algorithms, but also committed to constructing a comprehensive rescue system covering physical schemes, management strategies and social collaboration.

2. Current Situation of Multi-Carrier Collaborative Rescue in Flood Disasters

2.1. Development Bottlenecks

In China's current emergency rescue system, although the equipment level has been significantly improved, in the face of extremely complex flood disasters, the current multi-carrier collaborative rescue is faced with severe physical limit challenges brought by the single-carrier operation mode, as well as the slow development caused by the differences in connection schemes of each single carrier and the lack of relatively complete schemes and strategies.

2.1.1. The "Route-Breaking" Dilemma of Land Rescue

Heavy trucks and off-road vehicles are the main force of emergency logistics, undertaking more than 90% of material transportation tasks. However, as pointed out by Zhang Yonghua (2024) in his research on railway emergency rescue, land transportation is extremely vulnerable in the face of floods [13].

(1) Wading depth limit: The maximum wading depth of ordinary military trucks is usually about 0.8 meters, and that of civil freight trucks is only 0.4-0.5 meters. Once the flood overflows the embankment or urban waterlogging is severe, the land transportation line is immediately paralyzed.

(2) Secondary disaster blockage: Mountain floods are often accompanied by mudslides and landslides, leading to complete road damage. In this case, not only materials cannot be delivered, but a large number of trucks are stranded on the way and become new rescue targets.

2.1.2. The Environmental Constraints of Water Rescue

Assault boats and rubber boats are the core tools for water rescue, but their operation environment has high selectivity.

(1) Shallow water area risk: Gong ying's (2024) research shows that when the water depth is less than 0.5 meters or there are a lot of building ruins underwater, such as collapsed walls, guardrails and submerged vehicles, the propeller of the outboard engine of the assault boat is extremely prone to bottom damage, resulting in power loss [14].

(2) Insufficient transport capacity: Compared with land transportation, the single carrying capacity of assault boats is extremely small, usually only able to carry 6-8 people or several hundred kilograms of materials, showing a "drop in the bucket" transport capacity gap when meeting the living material needs of thousands of affected people.

2.1.3. The "Blind Spot" Limitations of Air Rescue

Air rescue is regarded as the "last line of defense", but it is not omnipotent in actual combat.

(1) Helicopter limitations: Zeng Jingxiang (2024) pointed out that helicopters have strict requirements for take-off and landing sites, requiring a hard open area with a diameter of more than 15 meters, and cannot take off under severe weather conditions such as rainstorms, heavy fog and strong winds. Helicopters have extremely high safety risks when conducting low-altitude hovering rescue in the canyon of high-rise buildings in cities [8].

(2) UAV shortcomings: Li Xiong (2025) analyzed that the currently widely used consumer-grade or light industrial-grade UAVs, although flexible in deployment, have a general endurance time of less than 30 minutes and a low wind resistance level. Without the support of ground mobile platforms, their operation radius is limited to the visual range, and cannot achieve continuous coverage in the far depth [15].

2.1.4. The "Matching" Dilemma of Multi-Carrier Collaborative Rescue

At present, scholars in academia have conducted research on the coordination of various carriers in flood disasters. For example, Zhou Yufeng et al. (2025) studied the problem of Truck-Boat collaborative rescue from the perspective of optimization [6], and Gong ying et al. (2025) further considered the coupling of flood search and rescue and tasks from the perspective of water-land-air transportation [16]. However, to fully promote the implementation of the coordination of various carriers in flood rescue, the defects such as the low wading depth of land rescue, the weak transport capacity of water rescue and the harsh basic conditions of air rescue need to be balanced with each other; the transformation of water-land-air rescue forms also needs a unified connection and transformation scheme.

2.2. Structural Defects

Compared with the shortcomings of physical equipment, the division in the management mechanism has a more hidden and fatal impact on rescue efficiency.

2.2.1. Decision Delay Caused by "Information Silos"

At disaster sites, there is often a phenomenon of "having eyes in the sky but no way on the ground". A typical scenario is: UAVs detect the location of trapped people, but due to the lack of a unified data link for data sharing, these high-precision coordinate images can only be stored locally or transmitted back to the pilot terminal, and cannot be synchronized in real time to the assault boat team searching in the nearby waters. This break in the information flow leads to the failure of the command center to form a global situation awareness for multi-carrier coordination, and often can only rely on fragmented telephone alarms for passive scheduling [17].

2.2.2. Unordered Influx of Social Forces and Resource Misallocation

In recent years, social emergency forces such as the Blue Sky Rescue Team and the Gongyang Rescue Team have developed rapidly and become an important supplement to government rescue. However, Tian Wanfang's (2025) review research on the Zhuozhou flood disaster shows that due to the lack of a standardized coordination mechanism, a large number of civil teams swarmed in the early stage after the disaster, leading to serious negative effects:

(1) Traffic congestion: Thousands of private cars and rescue vehicles blocked the few life channels, resulting in the failure of military vehicles carrying heavy pontoon bridge equipment to enter the site.

(2) Coexistence of repeated operations and blind spots: In areas with high media exposure, more than a dozen teams conducted repeated searches; while in remote villages with interrupted communication, no one cared for several consecutive days.

(3) Communication interference: Each team used intercom equipment of different frequency bands, and even UAVs flew randomly in the same airspace, causing signal interference and even crash accidents [10].

2.2.3. Lack of Dynamic Adaptation between Tasks and Carriers

The current scheduling mode is mostly "static assignment", that is, once the task is issued, it is rarely adjusted according to the real-time road conditions. For example, a truck is assigned to deliver goods to a certain village, and the road is suddenly interrupted by water accumulation on the way. The truck can only wait in place or turn back. At this time, if the nearby UAV can be dispatched in real time for relay, the task can be completed. The existing system lacks such dynamic task switching capability based on real-time status [18].

3. Schemes of Multi-Carrier Collaboration in Flood Disasters

In view of the differentiated spatial characteristics presented in the evolution process of floods, a single rescue method can no longer meet the demand of global coverage. Based on the above analysis of the physical characteristics of heterogeneous carriers such as trucks, ships, unmanned aerial vehicles (UAV) and helicopters, this paper constructs three standardized collaborative operation schemes according to the submergence depth of disaster scenarios and the damage degree of infrastructure.

3.1. Truck-Drone Collaboration Mode under Urban Waterlogging

3.1.1. Scenario Characteristics and Operation Difficulties

Urban waterlogging usually occurs in high-density built-up areas. Its typical characteristic is "interlaced water and land": the water depth under overpasses, at the entrances of underground garages and in low-lying alleys reaches 1-2 meters, forming physical barriers; while viaducts, main roads and highland communities remain dry. In this scenario, trucks cannot cross deep water areas to reach trapped communities, and small UAVs cannot take off directly from remote bases to cover the whole city due to the limitation of battery life (usually < 30 minutes).

3.1.2. "Mobile Landing Platform - Terminal Penetration" Operation Architecture

This scheme establishes a collaborative mode with heavy trucks as the mobile landing platform carrying rotor UAV swarms for short-distance and high-frequency operations. The focus of this mode is to break the path dependence of traditional logistics and UAV closed flight, and realize dynamic release points and accompanying relay.

Traditional logistics relies on fixed distribution centers (DC), while in floods, the optimal release points change dynamically. According to Zhang Zefeng's (2023) model, trucks should drive along the unsubmerged main roads, and use vehicle-mounted lidar or wading sensors to detect the real-time road conditions ahead to realize the decision logic of dynamic release points. The specific implementation path is as follows.

(1) Setting of release threshold: When detecting that the water depth ahead exceeds 0.4 meters (the safety limit of civil freight trucks) or 0.6 meters (the limit of military trucks), the vehicle immediately brakes and is locked as a temporary release point.

(2) UAV swarm distribution: The truck unfolds the side compartment panels and releases 3-5 carrying multi-rotor UAVs. Each UAV carries first-aid medicines, communication terminals or compressed dry food (single UAV load 5-10kg), crosses the water accumulation section and flies to the affected points within a radius of 2-5 kilometers [19].

To break through the UAV endurance bottleneck, this scheme adopts the "accompanying support" tactic to realize the accompanying relay of "non-return to the original point". The specific steps are as follows.

- (1) Step 1 (Separation): At point A, the UAV takes off to perform the delivery task.
- (2) Step 2 (Movement): During the UAV operation, the truck does not wait in place, but turns around to detour or go to the next dry area with high terrain (point B).
- (3) Step 3 (Recovery): After completing the delivery, the UAV does not return to point A, but directly flies to point B and lands on the top of the truck according to the real-time positioning signal.
- (4) Step 4 (Preparation): The driver or automatic robotic arm completes the UAV battery replacement and material reloading within 2 minutes, preparing for the next round of take-off. This mode of "truck moving and UAV flying, off-site recovery" transforms the radiation radius of fixed bases into a strip-shaped coverage area flowing along the traffic line, effectively solving the problem of material delivery under the complex road network in cities [5].

3.2. Truck-Boat Intermodal Transport Mode under Basin Floods

3.2.1. Scenario Characteristics and Boundary Definition

Basin floods involve a large area of submerged farmland and villages, with a vast water area and drastic changes in water depth. The core contradiction in this scenario is the dynamic movement of the water-land boundary. The relevant boundary information is shown in Table 2.

Table 2. Table of Water-Land Boundaries and Bearing Capacity

Boundary Type	Water Depth	Bearing Capacity
Land Transport Boundary	< 0.5m	Accessible for trucks
Soft Contact Zone (Transfer Area)	0.5m-1.0m	Inaccessible for trucks, prone to bottoming for assault boats
Water Transport Boundary	> 1.0m	Free navigation area for assault boats

3.2.2. "Land Transport Distribution - Water Transport Relay" Operation Process

This scheme constructs a Truck-Boat intermodal transport system based on dynamic transfer hubs, and focuses on solving the problem of physical transfer efficiency of materials and personnel between heterogeneous carriers through the site selection and establishment of dynamic transfer hubs combined with a two-way logistics mechanism.

The transfer hub is no longer a permanent wharf in the traditional sense, but a temporary node that moves with the advance and retreat of floods. To construct a dynamic transfer hub, the following key points need to be focused on:

- (1) Site selection strategy: Select highways and their extensions with gentle terrain and no underwater reefs as docking points.
- (2) Operation specifications: The truck reverses to a water depth of 0.3 meters, and the assault boat beaches at a low speed until the bow touches the ground. Using portable roller tables or floating bridge modules, the modular material boxes on the truck are directly slid into the cabin to avoid manual wading handling, reducing the single ship loading time from 20 minutes to 5 minutes [7].

In response to the supply and demand mismatch problem proposed by Tu Manman (2025) [18], this scheme constructs a two-way logistics mechanism of "in and out balance" and enforces the two-way carrying standard:

(1) Inbound: Assault boats are fully loaded with living materials (water, food, tents) and go deep into isolated island villages.

(2) Outbound: After unloading, assault boats are not allowed to return empty. They must use the vacated cabin space to carry the wounded, the old, the weak, women and children or important archives and property back to the transfer hub.

(3) Closed loop: After returning to the hub, the wounded are immediately transferred to the waiting ambulances or empty trucks, realizing an efficient closed loop of "materials in, personnel out".

To intuitively show the efficiency difference between this collaborative mode and the traditional single mode, the following figure compares the task completion time of the single assault boat round trip and the Truck-Boat relay mode in a typical mountain flood scenario based on the simulation data of Cheng Jiahao (2025) and Zhou Yufeng (2025), as shown in Figure 2. The data intuitively shows that in a typical scenario with a transportation distance of 30km, the Truck-Boat collaborative mode has a significant improvement of about 33% in time efficiency compared with the single assault boat mode, verifying the necessity of the relay scheme.

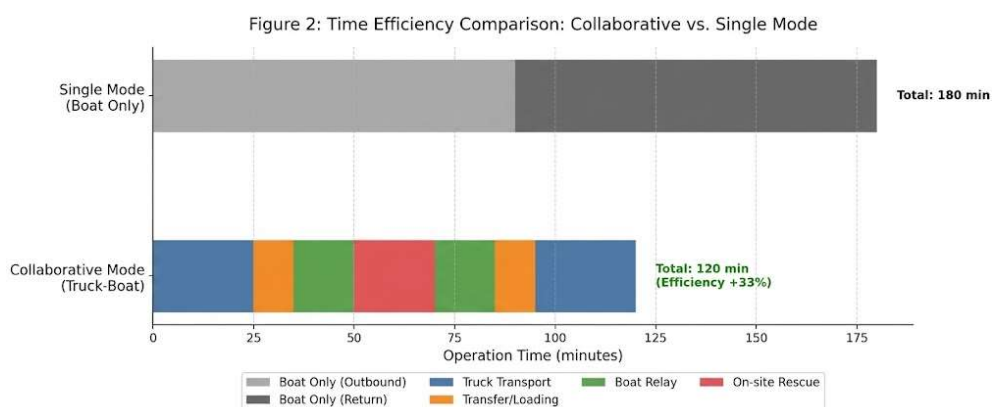


Figure 2. Time Efficiency Comparison: Collaborative Mode vs Single Mode

3.3. Air-Ground Integration Mode in Communication-Interrupted Areas

3.3.1. Scenario Characteristics and Pain Points

In barrier lake breaches triggered by earthquakes or extreme heavy rainstorms, infrastructure often suffers devastating damage, forming an isolated island with three breaks, namely road break, power outage and communication interruption. At this time, ground forces cannot enter, and the command center has no knowledge of the internal situation of the disaster area due to the lack of communication signals, making conventional rescue methods completely invalid.

3.3.2. Hierarchical Three-Dimensional Operation Architecture

Referring to the research of Lou Yang (2025) and Zeng Jingxiang (2024), this scheme constructs a three-layer three-dimensional operation architecture of "space-air suppression, dimensionality reduction strike", and strictly follows the logical sequence of "first communication connection, then reconnaissance, and finally rescue".

The first layer is the link layer of air-based communication relay. In the first hour after the start of the rescue operation, the primary task is not material delivery, but the restoration of the information link. The key of the air-based communication relay lies in equipment configuration and the determination of operation objectives.

(1) Equipment configuration: Deploy long-endurance fixed-wing UAVs or tethered UAVs to hover at an altitude of 3000 meters or 200 meters above the disaster area, carrying a communication power equipment (CPE).

(2) Operation objective: Establish a temporary communication network with a coverage radius of 30-50 kilometers, enabling the mobile phones of affected people to access signals to send distress messages and ensuring the real-time online of the BDS terminals of ground rescue teams [9].

The second layer is the eye layer of low-altitude reconnaissance and guidance. After the communication is restored, small multi-rotor UAVs are used to play the role of "perspective eye". The key of low-altitude reconnaissance and guidance lies in the realization of tactical actions and data fusion.

(1) Tactical actions: UAVs penetrate through heavy fog or forest gaps to conduct ultra-low altitude (< 50 meters) close reconnaissance of the affected points. Focus on identifying the degree of building collapse, the density of personnel distribution and potential helicopter landing sites.

(2) Data fusion: Transmit the reconnaissance images back to the command center in real time to generate a 3D disaster situation heat map, providing accurate coordinates for the input of heavy forces [15].

The third layer is the hand layer of heavy equipment precise delivery. Based on the information support of the first two layers, manned helicopters or heavy transport are put into use. The key of heavy equipment precise delivery lies in the realization of high-low matching.

(1) High-low matching: According to the reconnaissance results, helicopters are responsible for hoisting heavy equipment such as excavators and pontoon bridges and transferring critically ill wounded; if there are no landing conditions, UAVs guide helicopters to carry out rappelling operations. This hierarchical coordination avoids the safety risk of blind maneuver of helicopters in unknown environments and maximizes the efficiency of air rescue [8].

4. Strategies of Multi-Carrier Collaboration in Flood Disasters

In the actual combat environment of flood rescue, the effectiveness of physical schemes is highly dependent on the scientificity of command strategies. Faced with the explosive growth of demand at affected points, the rapidly changing hydrological environment and the complex situation of multi-subject participation, static scheduling instructions often become invalid in an instant. Based on the theory of management science, this paper constructs a comprehensive strategy system covering dynamic response, robust control and social coordination.

4.1. Dynamic Graded Response Strategy Based on Urgency

Under the premise of limited total resources, the essence of rescue is an "ethical choice". The traditional strategies of "first come, first served" or "nearest first" are very likely to lead to irreversible life losses in remote severe disaster areas due to long waiting time. Therefore, it is necessary to establish a differentiated response mechanism with the maximization of life rescue utility as the core.

4.1.1. Multi-Dimensional Portrait and Grading of Demand Urgency

Referring to the Grey Relational Analysis model of Xu Bingbing (2025), we abandon the single index of "affected population" and construct a three-dimensional evaluation system including life risk coefficient (whether there are the elderly/critically ill wounded), resource exhaustion time (duration of water/power outage) and environmental deterioration trend (speed of water level rise). According to real-time data, the system divides all affected points into three response levels of red, yellow and green [11]. The relevant standards are shown in Table 3.

Table 3. Graded Response Standard Table for Flood Rescue Demand Urgency

Response Level	Color Identification	Judgment Characteristics(Meet any one)	Resource Allocation Strategy	Time Window
Level 1 Response	Red	① There are critically ill wounded/pregnant women in need of transfer② There is a risk of building collapse③ Food and water shortage for more than 48 hours	Direct delivery right: Mobilize helicopters or high-performance UAVs to implement point-to-point airdrop or rappelling, regardless of cost and without transit.	Immediate execution(Response delay < 1 hour)
Level 2 Response	Yellow	① Infrastructure damaged but buildings stable② Lack of medicines but with basic food③ Slow water level rise	Cluster supply: Use assault boat fleets to carry out batch material delivery along the main water routes, balancing efficiency and coverage.	Priority execution(Response delay < 6 hours)
Level 3 Response	Green	① Personnel safe, only in need of living material supplement② Normal communication, with self-rescue capability	Queued service: Included in the conventional truck transportation plan, to be implemented after the relief of Level 1/2 tasks.	Planned execution(Response delay < 12 hours)

4.1.2. "Zero Waiting for Empty Carriers" Task Coupling Mechanism

In response to the collaborative problem of material distribution and disaster victim transfer proposed by Liu Changshi (2025) [12], this strategy introduces the time window game rule at the execution level. In Truck-Boat intermodal transport or helicopter rescue, there is often a contradiction between "fast unloading" and "slow transfer of the wounded". To avoid the invalid idleness of transport capacity resources, the strategy stipulates:

(1) Two-way locking: The command system gives priority to assigning orders to nodes with "dual demands" of both materials and evacuation.

(2) Fuse jump point: If the personnel assembly time of a certain node exceeds the preset threshold, for example, more than 10 minutes of the unloading time, the carrier commander has the right to trigger the fuse mechanism, abandon the current personnel transfer task, immediately go to the next node to deliver materials, and downgrade the point for re-queuing. This seemingly "ruthless" strategy is actually to maximize the global rescue efficiency.

To more intuitively show the complete decision-making chain from receiving demand to final execution, especially the three-level diversion of red/yellow/green and the fuse jump point logic based on the "time window", the following figure simulates the logical judgment path of the command system when facing sudden demand, as shown in Figure 3.

Figure 3: Logic Flow of Dynamic Priority Response Strategy

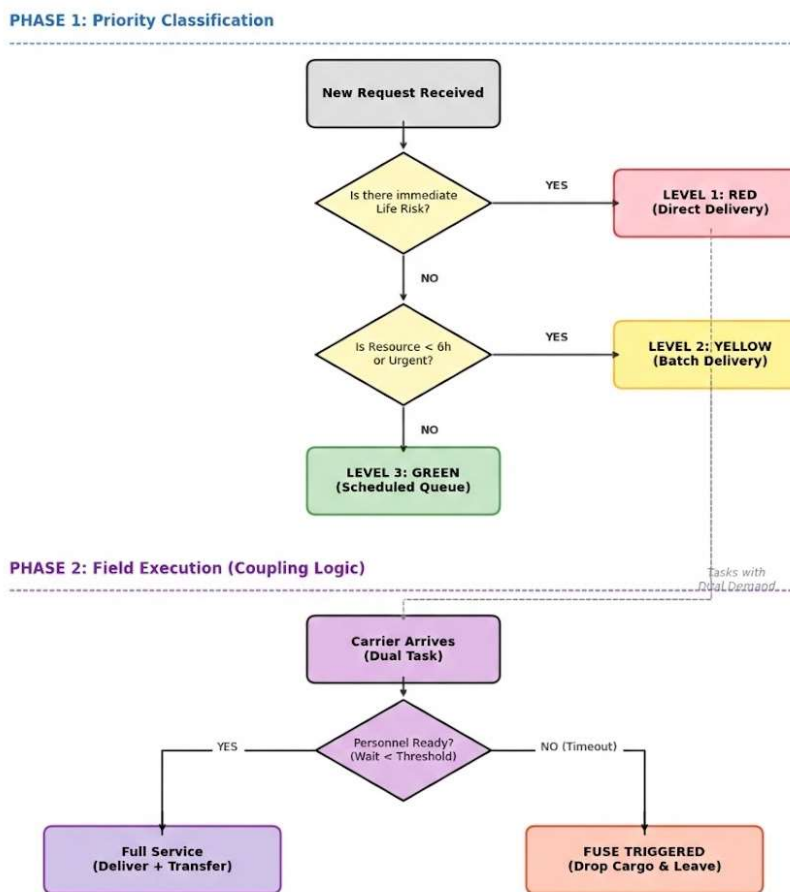


Figure 3. Logic Flow of Dynamic Priority Response Strategy

4.2. Rolling Robust Strategy for Addressing Environmental Uncertainty

The essence of the flood environment is "unstructured". Academic research has pointed out that in the scenario where the water depth changes in real time, any static global optimal path generated at time T0 may become infeasible at time T+1 due to the sudden interruption of a road. Therefore, it is necessary to introduce the idea of rolling horizon control (RHC).

4.2.1. Introducing Time Buffer of "Scarcity Cost"

At the algorithm level, the core of robust optimization is to deal with the fluctuation of parameters. At the management level, we transform this mathematical processing into a flexible schedule.

(1) Scarcity cost control: The victims' pain perception increases exponentially with the waiting time. The strategy requires commanders to introduce scarcity cost as a penalty item when formulating plans, that is: it is better to let the carriers run empty than to make them spend an indefinite time on a road section with extremely high unknown risks.

(2) Setting of safety redundancy coefficient: In response to the path robustness problem proposed by Gong ying (2025) [5], we stipulate that when calculating the travel time of any wading road section, a safety redundancy coefficient of 1.2 to 1.5 times must be multiplied. For example, if the expected travel time is 20 minutes, 30 minutes must be reserved on the scheduling table. This 10-minute buffer is used to absorb the possible time of vehicle trapping, detour or communication debugging, ensuring that the entire rescue chain will not produce a domino effect due to the delay of a single node.

4.2.2. "Advancing Step by Step" Rolling Re-Planning

In addition to reserving buffers, more importantly, dynamic adjustment is required. This strategy implements the T+30 rolling decision-making mechanism:

- (1) Lock the present: Only lock the vehicle instructions in the execution domain within the next 30 minutes to ensure the stability of front-line execution.
- (2) Look into the future: Based on the latest water situation map transmitted back by UAVs every 30 minutes, conduct a comprehensive recalculation of all unexecuted tasks in the prediction domain after 30 minutes.

This strategy that attaches equal importance to the current situation and prediction can effectively avoid command errors caused by excessive weight of the current situation, and ensure that the rescue path always avoids the latest submerged areas [4].

4.3. Collaborative Linkage Strategy of Official and Social Forces

In response to the chaos of "thousands of troops and horses blocking the road" that occurred in the Zhuozhou rescue [10], the core of this strategy is to establish a standardized collaboration interface under government leadership. The collaborative division of labor between official and social rescue forces is shown in Table 4.

Table 4. Collaborative Division of Labor Matrix between Official and Social Rescue Forces

Dimension	Official Forces	Social Forces	Collaborative Interface/Control Means
Operation Area	Core severe disaster areas, rapid current areas, air corridors	Shallow water submerged areas, community interior, peripheral resettlement sites	Geo-fencing
Core Tasks	Breach blocking, severe case transfer, hazardous chemical disposal	Life search, material distribution, transfer of the old and the weak	Task list allocation system
Communication Authority	Have full-band command right, priority use of satellite links	Use designated civil frequency bands, access to public network intercom	Unified frequency communication protocol
Equipment Level	Heavy pontoon bridges, helicopters, large UAVs	Kayaks, off-road vehicles, consumer-grade UAVs	Equipment recognition and fuel supply

4.3.1. "Trunk-Microcirculation" Spatial Division of Labor

The government command center should not attempt to micromanage each civil team, but should establish a clear spatial dividing line.

- (1) Official forces (firefighting, military): Responsible for the trunk of rescue. Use heavy pontoon bridges and helicopters to tackle key problems in rapid current areas, dam breach areas and fixed-point hospital transfer.
- (2) Social forces (Blue Sky, Gongyang, etc.): Responsible for the microcirculation of rescue. Use their own kayaks and off-road vehicles to go deep into the waterlogged community interior for dragnet search and living material distribution. This division of labor not only gives play to the tackling advantages of official forces, but also utilizes the flexibility of social forces, realizing efficiency complementarity.

4.3.2. Digital Access and Geo-fencing

Relying on the command platform proposed by Zhong Guihui (2024) [1], implement digital management and control.

- (1) Electronic registration: All social vehicles entering the disaster area must register and file on the APP to obtain a unique ID.
- (2) Geo-fencing: The system demarcates red zones (no-entry zones) and blue zones (operation zones) on the map according to water level risks. If civil teams stray into the dangerous red zones of official operations, such as under the helicopter take-off and landing routes, the terminal will immediately alarm and force them to leave.
- (3) Frequency communication mechanism: Uniformly stipulate the emergency communication frequency bands, and strictly prohibit civil teams from "occupying the frequency" in the official rescue frequency bands to ensure the unimpeded flow of command instructions.

5. Policy Recommendations

Based on the research and deduction of the flood multi-carrier collaborative rescue system in this paper, to break the practical bottlenecks in the implementation of multi-carrier collaborative rescue and promote the modernization of China's emergency management system and capacity, combined with the actual combat needs of flood rescue and the current development of the industry, the following targeted policy recommendations are put forward:

- (1) Construct a standardized system for rescue equipment and promote the construction of heterogeneous carrier interoperation. Issue unified national standards for military and civil emergency rescue carriers, standardize technical indicators such as UAV take-off and landing platform specifications, modular material box sizes and physical interfaces of water-land connection equipment, so as to realize the seamless connection of heterogeneous carriers such as trucks, ships and aircraft; establish a performance detection and cross-subject recognition mechanism for rescue equipment, laying a hardware foundation for multi-carrier collaborative operations.
- (2) Build an integrated digital infrastructure for emergency command and break the information barriers in disaster rescue. Accelerate the construction of interconnection of the four-level emergency command platforms at the ministry, provincial, municipal and county levels, open up multi-source data links such as meteorological hydrology, geographic information, traffic road conditions and disaster monitoring, and realize the real-time fusion and sharing of dynamic disaster data with the location of social rescue forces and equipment resource information; build a space-air-ground integrated emergency data transmission network to fundamentally solve the problem of information silos at disaster sites.
- (3) Carry out practical drills of multi-carrier collaboration and improve the collaborative disposal capacity of emergency teams. Incorporate multi-carrier collaborative rescue into the core subject of flood control and drought relief emergency drills, focus on simulating the extreme isolated island disaster scenario of three breaks in roads, power and communication, organize and carry out cross-departmental, cross-regional and military-government-society linked collaborative practical drills, and temper the dynamic scheduling capacity of command personnel and the practical operation capacity of front-line teams in carrier connection and task switching.
- (4) Improve the standardized cultivation and institutionalized management system for social emergency forces. Establish a digital access, filing and hierarchical management system for social emergency forces, and support it with standardized control means such as geo-fencing management and control and unified emergency communication frequency protocol; set up special support funds for the development of social emergency forces, carry out standardized

operational skill training, promote the upgrading and transformation of their equipment, and give full play to the supplementary role of social emergency forces in the microcirculation link of rescue.

(5) Increase support for the research, development and transformation of key emergency rescue technologies. Issue special policies to support universities, research institutes and enterprises in carrying out research and development of core technologies such as long-endurance UAVs, swarm intelligence and water-land-air rapid connection equipment, and promote the transformation of scientific research achievements into practical rescue equipment; give financial and policy inclinations to the research and development projects of anti-interference and high-adaptability rescue equipment adapted to extreme flood environments, so as to improve the practical adaptability of emergency rescue equipment.

6. Conclusion

6.1. Research Summary

Based on the severe reality of frequent and severe flood disasters under global climate change, this paper deeply analyzes the structural failure of the traditional single rescue mode in coping with the isolated island effect, communication interruption and complex water conditions. Through the systematic deconstruction and reorganization of relevant cutting-edge literatures, this paper constructs a flood multi-carrier rescue system featuring integration of space-air-ground, interconnection of water-land-air carriers, and collaboration of military-government-society.

The main research conclusions are as follows:

- (1) Three-dimensional physical schemes: The three proposed modes of mobile landing platform based Truck-Drone collaboration, dynamic transfer hubs based Truck-Boat intermodal transport and air-ground hierarchical suppression have successfully broken through the physical performance bottlenecks of single carriers. Simulation data show that compared with the traditional mode, the collaborative mode has achieved a more than 30% improvement in material delivery efficiency in mountainous and urban waterlogging scenarios.
- (2) Resilient management strategies: A three-level response mechanism based on urgency and a rolling robust control strategy based on rolling horizon control (RHC) have been constructed. Transforming the "robustness" in mathematical algorithms into "time buffer" and "fuse mechanism" in management, effectively solving the problem of command decision-making in unstructured environments.
- (3) Standardized social collaboration: The "trunk-microcirculation" division of labor logic between official and social forces has been clarified, and the pain point of on-site unordered competition has been solved through digital fencing technology.

6.2. Research Limitations

Restricted by research conditions, this paper still has certain limitations. For example, the collaborative schemes are mostly deduced based on theoretical models and have not been fully verified in large-scale actual combat; the anti-interference control technology of UAVs under extreme rainstorms and strong winds is less involved.

6.3. Future Research Prospects

With the progress of the times and science and technology, the future research direction of flood multi-carrier rescue should pay more attention to the dual development of quality and quantity to meet the further requirements of improving rescue efficiency. Therefore, this paper holds that the research can focus on the following two aspects:

- (1) Swarm intelligence: Explore the autonomous game and collaborative control of heterogeneous unmanned swarms based on local perception in a completely communication-free network environment.
- (2) Underwater-indoor global expansion: With the maturity of technology, expand the collaborative territory from water-land-air to underwater (search and rescue robots) and indoor (building search), realizing all-weather and all-dimensional life protection.

Acknowledgments

Funding: This work was supported by the National Social Science Foundation of China (NSSFC) (Grant No. 25XGL054); the Chongqing Postgraduate Research and Innovation Project (Grant No. CYS25605); and the Scientific Research Startup Fund Project of Chongqing Technology and Business University (CTBU) (Grant No. 2555009).

References

- [1] Zhong,G.H.,&Liu,S.G.(2020). Emergency rescue and command decision-making system platform for flood disasters in village and town areas.China Rural Science & Technology, General Issue 303, 36-37.
- [2] Lou,Y.,&Xu,H.Z. (2025).A preliminary study on the space-air-ground integrated intelligent collaborative dispatching emergency rescue system.China Emergency Rescue,Issue6,General Issue 114,16-22.<https://doi.org/10.19384/j.cnki.cn11-5524/p.2025.06.007>
- [3] Xu,J.H.,Qu,M.H.,Wang,Z.F.,et al.(2026).Study on post-earthquake emergency response and post-disaster collaborative rescue mechanism of the 2025 Myanmar M7.9 earthquake.Journal of Seismological Research,49(1),17-26. <https://doi.org/10.20015/j.cnki.ISSN1000-0666.2026.0002>
- [4] Zhang,Y.L.(2025).Collaborative delivery routes optimization of air-ground integrated multiple transport tools with dynamic response to customer position in megacity [Master's thesis].Chongqing Jiaotong University, Chongqing,China.<https://www.cnki.net>
- [5] Gong,Y.,Tu,M.M.,&Zhou,Y.F.(2025).Truck-drone collaborated location-routing robust optimization problem for flood emergency response.Computer Engineering and Applications,61(14),307-321. <https://doi.org/10.3778/j.issn.1002-8331.2410-0289>
- [6] Zhou,Y.F.,Gong,Y.,Liu,X.C.,&He,J.Y.(2025).Robust optimization of vehicle-vessel coordinated search and rescue routing for flood-stranded individuals.Journal of Safety and Environment,25(4),1455-1465. <https://doi.org/10.13637/j.issn.1009-6094.2024.1593>
- [7] Cheng,J.H.,Hao,Z.D.,Li,G.Q.,&Liu,S.J.(2025).Multi-objective optimization of truck-speedboat coordination for emergency material distribution in mountainous floods.Journal of Transportation Systems Engineering and Information Technology,25(6),294-304.<https://doi.org/10.16097/j.cnki.1009-6744.2025.06.027>
- [8] Zeng,J.X.,Peng,W.,Xie,G.L.,Zhang,C.Y.,&Liu,G.H.(2024). Aviation emergency rescue mode of helicopter/UAV collaborative cooperation [Conference paper].Proceedings of the Annual Conference of the Emergency Rescue Branch of Chinese Society of Aeronautics and Astronautics,pp.1-8.
- [9] Lyu,Z.(2025).Practical research on the collaborative operation mode of UAVs and ground rescue forces in earthquake disaster rescue.China Plant Engineering,12(First Half),263-265.<https://www.cnki.net>.
- [10] Tian,W.F.,&Li,M.(2024).Optimization thoughts on the coordination mechanism of social emergency forces based on Zhuozhou flood rescue.City and Disaster Reduction.<https://www.cnki.net>
- [11] Xu,B.B.(2025).Research on optimization of emergency logistics routes for flood rescue considering demand urgency [Master's thesis].North China University of Science and Technology,Sanhe,China.<https://www.cnki.net>

- [12] Liu, C.S., Wan, C., Wang, F., Chen, B.X., & Yue, J.Y. (2025). Route planning relief delivery and victim evacuation based on rescue utility in flood disaster scenarios. *Journal of Transportation Systems Engineering and Information Technology*, 25(5), 320-332. <https://doi.org/10.16097/j.cnki.1009-6744.2025.05.029>
- [13] Zhang, Y.H., Liu, Y.X., Jiang, L.L., et al. (2023). Research on site selection and vehicle configuration strategy for railway emergency rescue bases based on multi-vehicle intermodal transport planning. *Railway Transport and Economy*, 45(6), 113-117, 124. <https://doi.org/10.16668/j.cnki.issn.1003-1421.2023.06.16>
- [14] Gong, Y. (2024). Research on optimization of emergency search and rescue and distribution with multi-transport collaborative operation in flood disasters [Doctoral dissertation]. Shanghai Maritime University, Shanghai, China. <https://www.cnki.net>
- [15] Li, X., & Zhou, H. (2025). Research on the application of unmanned aerial vehicles in emergency rescue. In *Proceedings of the 5th 2025 Unmanned Systems Summit Forum*, pp.8-10. <https://www.cnki.net>
- [16] Gong, Y., Zhou, Y.F., & Liu, C.S. (2025). Optimizing integrated search, rescue, and delivery routes during flood emergencies with coordinated land, water, and air transportation. *Journal of Safety and Environment*, Advance online publication. <https://doi.org/10.13637/j.issn.1009-6094.2025.0802>
- [17] Fan, M.Y., Zhao, S.H., & Fei, W. (2025). Application of unmanned aerial vehicles in emergency rescue scenarios. *China Disaster Reduction*, December (First Half), <https://www.cnki.net>
- [18] Tu, M.M. (2025). Optimization study of trapped personnel rescue routes and supplies distribution routes in the context of floods [Master's thesis]. Chongqing Technology and Business University, Chongqing, China. <https://www.cnki.net>
- [19] Zhang, Z. F. (2023). Research on optimization of cooperative distribution between truck and UAV under urban flood [Master's thesis, Logistics Engineering and Management]. Xi'an Technological University, Xi'an, Shaanxi, P.R.China. <https://www.cnki.net>