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Optimized Collaborative Scheduling of Unmanned Aerial Vehicles for Emergency Material Distribution in Flood Disaster Management

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Abstract: The effective allocation of emergency supplies is crucial in the aftermath of flood disasters, as it directly impacts response times and mitigates casualties and property losses. Traditional methods of material distribution predominantly rely on ground-based transportation, which often proves inefficient and inflexible under the dynamic conditions of a disaster. This study explores the potential of unmanned aerial vehicles (UAVs) as a transformative solution to the challenges associated with emergency material dispatch. Factors influencing UAV scheduling, including environmental constraints, payload capacity, and flight dynamics, are analyzed in depth. Optimization measures for improving UAV collaborative operations are proposed, with a focus on enhancing the efficiency and adaptability of disaster response systems. The integration of reinforcement learning (RL) is examined as a theoretical framework for optimizing UAV collaborative scheduling, facilitating autonomous decision-making in real-time scenarios. An empirical analysis is presented based on the "7-20" rainstorm and flooding disaster in Zhengzhou, illustrating the practical application of collaborative UAVs in disaster relief. The results demonstrate the significant optimization potential of UAV technology, with a notable reduction in response times and improved logistical coordination. Furthermore, the role of UAVs in future disaster relief operations is discussed, with emphasis on the integration of blockchain and smart dispatch systems to enable decentralized, autonomous coordination. These advancements are expected to enhance the overall efficiency of emergency material distribution and better address the complex challenges posed by post-disaster environments. The findings underscore the potential for UAV systems to revolutionize disaster management and contribute to more resilient, responsive strategies in future flood events.

Keywords: Emergency material dispatch; Unmanned aerial vehicle (UAV); Optimization measures; Cooperative UAV technology

1 Introduction

In recent years, with the aggravation of climate change and the continuous progress of urbanization, flood disaster has gradually become one of the global research hotspots [1]. Flooding disasters have strong destructive power and high uncertainty [2], and have become an important research topic in the field of emergency management. These disasters not only cause building collapses and infrastructure damage directly. They also often trigger secondary disasters, such as mudslides. This further intensifies the threat to the ecological environment, economic development, and the safety of people's lives and property. According to the United Nations Disaster Assessment Report, floods in 2023 directly killed an estimated 12,000 people worldwide. About 100 million people were affected, facing evacuation, homelessness, or worsening living conditions. Additionally, the economic damage caused by floods is estimated to exceed $30 billion, as shown in Figure 1. In this context, how to quickly restore social order and effectively protect the lives and properties of people in the affected areas has become a critical issue for scholars and practitioners to address [3, 4].

Emergency supplies are important resources used for emergency rescue and relief, relief of affected people and post-disaster recovery when responding to various types of emergencies (e.g., natural disasters, accidental catastrophes, public health incidents, social security incidents). Emergency logistics refers to logistics activities triggered by emergencies. The lead times are very short in emergency logistics and thus need efficient logistics and transportation networks to support the most important stake, i.e., human lives [5]. The core characteristic of emergency supplies is "rapid deployment and efficient use". However, after floods occur, issues such as inaccurate information, slow emergency response times, and the insufficient professional capabilities of emergency personnel in material distribution and scheduling arise. These problems can lead to severe consequences, including delays in the optimal rescue timing [6].

In recent years, with the rise of IoT and 5G, UAVs stand out with their low cost, high performance and speed. Since UAV distribution of materials is not limited by geographical factors and other restrictions, application practices have been realized globally: e.g., UAVs have opened up the last mile of commercial transportation [7], and UAVs were utilized to airlift medicines during COVID-19 [8]. These successful practices show that UAV applications in the field of material movement are feasible and effective.

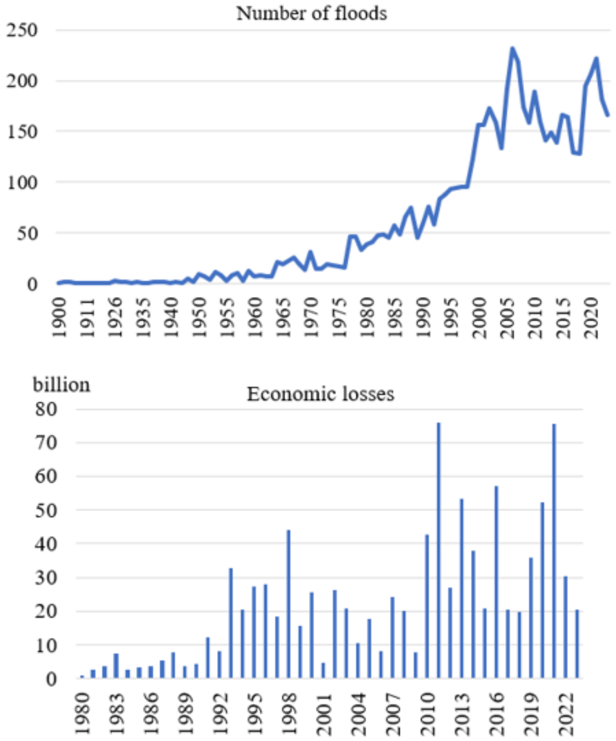

Figure 1. Number of floods and economic losses due to floods

Source: https://ourworldindata.org/natural-disasters

2 Related Work

A number of studies have been conducted to explore how to minimize the impacts of floods at the theoretical level. Rehman et al. [9] used systems thinking approaches, such as Causal Loop Diagrams (CLD) and the Driver-Pressure-State-Impact-Response (DPSIR) framework, to formulate policy recommendations for flood disaster coping strategies. These recommendations were based on information gathered from expert interviews with key government officials. Price et al. [10] introduced the concept of a digital city as a methodology for capturing, analyzing, and applying information about urban areas, services, and city design and operation. This concept integrates the management of the urban stormwater cycle with urban planning to protect the interests of all stakeholders, incorporating both structural and non-structural strategies to mitigate flood risks. Dieperink et al. [11] had outlined potential processes and mechanisms for coordinating the activities and capacities of actors involved at different levels and sectors of flood risk governance. This includes the implementation of individual strategies and the coordination of overall strategies, which have been empirically shown to improve the efficiency of flood relief efforts.

There are also some studies that provide insights into the problem from the perspective of model construction. Khan et al. [12] proposed a novel Flood Disaster Management (FDM) system using the Full Life Cycle Disaster Event Model (FLCNDEM), which is an abstract model based on function super-objects. This model provides a comprehensive flood management framework to improve emergency response. Zhang et al. [13] developed the iCRESTRIGRS model by integrating the coupled wiring and excess STorage (CREST) model with the physically based Transient Rainfall Infiltration and Grid-Based Regional Slope Stability (TRIGRS) models. Koks et al. [14] proposed an integrated direct and indirect flood risk model for small- and large-scale flooding events, which allows for the dynamic modeling of total economic losses, from the flood event to full economic recovery, and for the development of the iCRESTRIGRS model. Economic losses are modeled dynamically, providing specific practices for responding to floods. These theories and models provide an effective foundation for decision-making. However, they focus more on macro-level planning and strategies, neglecting how to quickly and effectively deliver on-site relief during a disaster. The integration of theory and practice remains a challenge, particularly in the rescue process, where choosing the appropriate means of transportation and technology has become a key factor affecting the efficiency of the rescue efforts.

The choice of transportation is crucial in the rescue process in floods. Traditional means of transportation, such as rescue vehicles, are effective under certain conditions, but they are often limited by factors such as road damage, weather changes, and geographic conditions. Al-Qadami et al. [15] noted that during floods, vehicles are often affected and can be easily swept away when the flow velocity and depth of the water exceeds specific thresholds. Moreover, the available equipment for providing safety threshold warning signals during floods is inherently predictive and based on complex technologies that are both cumbersome and quite expensive, thus undermining its attractiveness to low economic societies in developing countries [16]. In addition, the use of rescue vehicles is prone to secondary injuries: a study by Han [17] showed 570 vehicle-related flood fatalities, with almost all fatal accidents resulting in 1 death. These deaths accounted for 58% of the total number of flood deaths. Therefore, exploring new types of transportation, especially technologies that can overcome the limitations of traditional transportation, has become a necessary path to improve the efficiency of disaster relief.

UAVs, as an emerging mode of transportation, show great potential in flood disasters. First of all, compared to traditional means of transportation, UAVs can provide important support in the event of communication disruptions in disaster areas. They are able to operate flexibly in complex geographic environments. This allows them to provide victims with fast, cost-effective, easy-to-deploy, and secure wireless communications [18]. The use of UAVs is critical in emergency situations as they allow for the quick and easy deployment of micro and miniature cellular base stations when needed to supplement or replace traditional communications infrastructure [19]. This provides a necessary prerequisite for post-disaster relief. In addition, UAV technology combined with other means can better empower disaster relief and rescue. Munawar et al. [20] combined UAVs with convolutional neural networks (CNNs) to extract flood-related features from images of the disaster area to prompt a rapid disaster management response to minimize damage to infrastructure. Furthermore, they used UAVs to develop an automated imaging system for identifying flooded areas identified in aerial images. This real-time floodplain system will help in transforming the disaster management system according to modern smart city plans [18]. Hashemi-Beni et al. [21] investigated the quality of UAV-based DEMs for spatial flood assessment mapping and used it to assess the extent of flooding events during hurricanes. Thus, it can be seen that the application of UAVs to the field of emergency material dispatch has endless potential.

3 Emergency Material Scheduling

3.1 Influencing Factors of Material Scheduling

In the existing research, scholars have considered multiple indicators, such as cost, the number of rescue points, the number of demand points, and the reliability of the path. In this paper, combined with the new perspective of UAV application, the pre-influencing factors affecting material dispatch are categorized into time factor, infrastructure condition, emergency coordination, and information-sharing mechanism, as shown in Table 1.

Table 1. Factors affecting resource scheduling

Time Period	
Pre-disaster phase	Time factor: Saving lives and reducing casualties
	Infrastructure conditions: Vehicles such as trucks, trains, UAVs, etc.
	Emergency coordination and information sharing mechanism: Establishing a unified and powerful information-sharing system
Post-disaster phase	Types of supplies: Transition from single flood-related emergency supplies to a diverse range of needs
	Budget: Rebuilding the disaster area's cultural and ecological aspects, boosting morale
	Disaster recovery capacity: The post-disaster reconstruction capacity of the region, directly impacting the speed and quality of recovery

(1) In terms of the time factor, during the early stages of a flood disaster, the speed at which emergency supplies can be delivered is the primary focus of the emergency response. Regardless of the type of natural disaster, saving the lives of the injured and reducing casualties are the foremost priorities after the disaster occurs. On one hand, it is necessary to quickly mobilize emergency medicines, medical equipment, and professional medical

personnel to reach the disaster area and provide emergency medical assistance to the injured. On the other hand, efficient disaster assessment technology must be utilized to quickly evaluate the distribution of the disaster situation, providing a reliable basis for the deployment of subsequent rescue resources. Additionally, it is essential to prioritize transportation channels to ensure that materials and personnel can rapidly reach the affected areas. The ability to seize the golden rescue time is directly related to saving lives and minimizing losses, making it the most urgent task in disaster relief efforts. In this context, UAVs can significantly reduce transportation and distribution times. Studies have shown that, in urban GIS simulation models, UAVs arrived before vehicles in 32% of cases, saving an average of 1.5 minutes. In rural areas, UAVs arrived before vehicles in 93% of cases, saving an average of 19 minutes [22].

(2) In terms of infrastructure conditions, transportation equipment such as trucks, trains, airplanes, and other carriers is indispensable, as it can greatly improve transportation efficiency and significantly reduce transportation time. However, compared to these carriers, UAVs have the advantage of avoiding congested road traffic, especially in areas that are inaccessible or have been damaged by disasters. UAVs do not rely on ground transportation networks and can directly reach their target locations even in complex terrain. Furthermore, UAV flights do not require large-scale infrastructure construction, which not only reduces construction costs but also eliminates concerns about the impact of post-disaster infrastructure damage on UAV operations. In a study conducted by Yakushiji et al. [23], UAVs assisted in transportation 12 times by detouring to avoid obstacles and ascending or descending from lowlands to plateaus. The transported cargo included a 17 kg DMAT canvas backpack, a glucometer, a drug-integrated insulin syringe, needles, and sterilized cotton. The cargo was ultimately delivered to a narrow destination point, where the UAV landed safely at the endpoint.

(3) With regard to emergency coordination and information-sharing mechanism, the establishment of a unified and powerful information-sharing mechanism can better coordinate and adjust logistics operations. Emergency material dispatching is usually cross-field and involves multiple departments, and after a disaster occurs, multiple special plans are activated at the same time, and each special command needs to form a linkage. In this case, UAVs can play a huge role in emergency coordination, especially in information acquisition and dissemination. Liao's team's research shows that UAV cooperation based on information exchange can significantly improve performance. For example, target neutralization time (TNT) was reduced by almost 70% when UAVs changed from no communication to communicating within a small transmission range of 10 units, or from communicating every 16-time steps to communicating every 4 steps [24]. This result proves that UAVs can effectively facilitate information transfer and sharing in the process of disaster relief and establish a more efficient information-sharing mechanism, thus improving coordination efficiency.

In the later stages of the flood disaster, the demand for materials no longer focuses solely on the supply of emergency relief materials. Emergency supplies in the early stages mainly met the basic needs of the people in the affected areas, such as drinking water and emergency food. However, with the change of the disaster situation, the later material demand began to shift to environmental restoration and temporary resettlement. Especially after the flood, the occurrence of secondary disasters such as mudslides further aggravated the needs of the disaster areas. As a result, later material dispatch involves more diversified materials, such as durable tents, mobile homes, portable toilets, etc., which play a crucial role in the survival and recovery of the disaster area; in terms of the funding budget, a reasonable allocation of funds is crucial, which should cover all aspects of post-disaster reconstruction, including such areas as public health protection, economic recovery, psychological assistance, and so on. Adequate and efficient use of funds can ensure that residents in the affected areas can resume normal life as soon as possible, and lay a solid foundation for social stability and economic revival in the aftermath of the disaster; in terms of post-disaster recovery capacity, the degree of impact and recovery capacity of different regions varies, so the way in which supplies are dispatched needs to be adapted to local conditions. In areas with strong recovery capacity, conventional means of transportation, such as roads and railroads, can ensure the smooth distribution of materials. In areas with poorer recovery capacity, due to transportation and logistics disruptions, it may be necessary to rely on special emergency response means, such as air transport and UAVs, to ensure that supplies can be delivered in a timely manner. Differences in recovery capacity determine the flexibility and contingency of post-disaster material dispatch.

3.2 Characteristics of Emergency Material Scheduling

Emergency material scheduling belongs to the problem of logistics planning in operations research, so it has the characteristics of global systems, dynamics, cost control, and benefit maximization. However, emergency material scheduling is more complex than logistics planning. Due to its practical significance, it is also characterized by timeliness, resource limitation and prioritization, fairness, and public synergy, as summarized in Table 2.

(1) Time sensitivity: Flood disasters are characterized by instantaneous and destructive force. After the outbreak of flooding, the demand for emergency supplies is also urgent. Dispatch of emergency supplies need to follow the "golden 72 hours" principle of rescue, during this time, the use of UAVs with high mobility can be transported to the disaster area as soon as possible, so that the rescue work can be carried out.

Table 2. Characteristics of emergency resource allocation

Characteristics	
Time sensitivity	The emergency response and resource allocation need to be completed in the shortest time possible after a disaster in order to maximize lives saved and minimize losses.
Resource constraints and priorities	In the case of limited emergency resources, resources should be allocated reasonably based on the urgency of the disaster area's needs and the extent of the damage, with priority given to life-saving assistance and critical needs.
Fairness	During the emergency resource scheduling process, it is important to ensure the fairness of resource distribution across different affected areas and populations, avoiding disparities caused by regional, demographic, or social status differences.
Public cooperation	The ability and level of efficient collaboration, resource integration, and information sharing among governments at all levels, social organizations, businesses, and the public during disaster response and recovery to collectively achieve emergency management goals.

(2) Resource constraints and prioritization: In the wake of a flood disaster, it will not be entirely possible to achieve sufficient emergency resources. Emergency resources here include necessary supplies such as drinking water, transportation resources, personnel resources, and funds and budgets. UAVs can dynamically prioritize based on real-time data, damage in the disaster area, and material needs. UAVs can quickly assess the specific needs of the disaster area and make precise distribution of supplies based on this data. Due to resource constraints, the following priorities are usually delineated: human life priority. In the aftermath of a disaster, the most urgent task is to safeguard lives. Therefore, priority is given to delivering medical supplies, first-aid equipment, emergency medicines, and life support materials to severely affected areas to ensure that the injured are treated in a timely manner. Then priority is given to the worst-hit areas: according to the extent of the disaster, it is possible to assess which areas have the most urgent need for supplies. Priority is given to transporting relief supplies to these areas. Finally, priority is given to socially sensitive groups: special groups such as the elderly, children, pregnant women, and the disabled are given priority in the allocation of resources to ensure that their basic needs are met, as the survival and safety of these groups require extra attention.

(3) Fairness: In the early stage of emergency relief, the supply of materials is in short supply, and it is difficult to meet all the needs of the affected areas. At the same time, due to the difference in the amount of material distribution and delivery time, as well as poor information and other factors, the affected area will produce a psychological "sense of unfairness" [25]. However, in order to apply the minimum resources to realize the maximum economic effect, relative fairness should be achieved. In the process of material dispatch, fairness first requires that distribution be based on the actual needs of each region and group. For example, some of the most severely affected areas may need more medical resources, while other areas may need more food and water. This requires a dispatch system that can assess the differences in needs between locations based on real-time data to ensure that supplies are distributed according to need. Equity in emergency supplies dispatch needs to be balanced with efficiency. In a situation of extreme resource scarcity, the pursuit of fairness may sacrifice some of the efficiency, while over-optimization in the pursuit of efficiency may result in some groups being neglected. Therefore, in the dispatch process, it is important to find a balance between fairness and efficiency, and to ensure basic fairness while maintaining rapid and efficient material dispatch.

(4) Public cooperation: Public synergy emphasizes the coordination, cooperation and resource sharing of different subjects in disaster response. The loss of interests caused by urban flooding for the society and the public has certain public characteristics; therefore, it is necessary for all groups in the whole society to participate in the emergency response to such events to jointly resist the disaster and eliminate the adverse effects [25]. UAVs are able to work in concert with other emergency resources to form an integrated emergency response system with multi-party collaboration. Through the command and control platform of UAVs, multiple rescue teams can share information and coordinate the distribution of materials, maximizing public synergy.

In August 2017, the southeastern United States experienced extensive flooding due to hurricanes Harvey and Irma. In order to minimize the impact of the flooding, the CRASAR team employed UAV technology. The CRASAR team conducted a large-scale UAV deployment after the hurricanes, completing 119 flights, which provided government officials with timely videos and maps of the flooding inundation and damage assessment [26]. This rapid data acquisition capability allowed rescuers to quickly understand the disaster situation and develop timely rescue plans and material transportation programs. Second, in the aftermath of a disaster, UAV resources are relatively limited and need to be allocated appropriately to meet the needs of different regions. Government officials identify and prioritize public assets and assign these targets to UAV teams for missions. The UAV teams rationalize their flight routes and times based on mission priorities, prioritizing material transportation and information support for the most severely affected and in-need areas. Again, the CRASAR team conducted UAV flights to several affected counties after Hurricane Harvey, providing detailed damage assessment data to government officials and rescue organizations in different regions [26]. These data help rescuers understand the damage situation in each region, rationally allocate relief supplies, and avoid unfair resource allocation due to geographic remoteness or information asymmetry. Finally, the application of UAVs in flood relief involves the synergistic cooperation of multiple parties such as governments, enterprises, non-governmental organizations and volunteers. After Hurricane Harvey, the CRASAR team collaborated with Florida State University, Kovar Associates LLC, Lone Star UASC, and other organizations on UAV missions. Each of these partners had their own roles to play, working together to provide damage assessment and material transportation support to the affected areas. At the same time, government officials, rescuers, volunteers, and others worked closely with the UAV team to share information and coordinate actions, creating an efficient relief network. Texas handled this flood disaster perfectly by accurately grasping the dispatch characteristics of emergency supplies while taking advantage of UAVs.

3.3 Emergency Resource Scheduling Optimization

(1) Simplify the scheduling process to improve emergency material delivery timeliness: The traditional scheduling process involves “layers of approval”, meaning that in the event of a disaster, approval must pass through multiple layers, such as county, city, and provincial deployment planning. While this process helps ensure the flow of information to some extent, the “layers of approval” are too cumbersome, significantly delaying the delivery of emergency materials. In this regard, the local government can be given a certain degree of scheduling authority. An automated distribution system can be introduced to adjust material supply in real time based on the urgency of demand. Additionally, distributed material reserve centers should be built in high-risk areas, staffed with professional emergency management teams. This way, in the early stages of a disaster, these stockpile centers can provide a “first response” to the affected region, reducing reliance on central government resources.

(2) Allocate resources in the first instance and set priorities: First, establish a strategy centered around distribution centers, supported by individual distribution points. This strategy should clearly prioritize the allocation of resources to ensure that critical materials, such as life-saving supplies, drinking water, and medical resources, reach the most urgent disaster areas as a priority. Second, the bottleneck caused by the damaged transportation network should be solved through a multi-channel transportation system, combining air and water transportation. In addition, a distributed stockpile system should be established to ensure that disaster areas can quickly access the necessary resources at the initial stage and shorten the rescue response time. Emergency supplies should be distributed rationally, following prioritization principles. These principles should focus on preserving human life, addressing the needs of hard-hit areas, and prioritizing socially vulnerable groups.

(3) Promote relative fairness in post-disaster material distribution: In the aftermath of a disaster, the people’s suffering mood is obvious, and the atmosphere at the scene is depressed. Therefore, promoting fairness in the dispatch of emergency supplies becomes the key to restoring people’s confidence. To improve the fairness of dispatching, it is necessary to fully consider the needs of different affected regions and groups of people. A prioritized distribution system should be established based on the urgency of demand and the special needs of affected groups. At the same time, post-disaster monitoring departments should be set up as far as possible to avoid corruption and waste of resources and to ensure that all regions receive supplies in a relatively equitable manner. Through these measures, it will help to avoid localized shortages or waste of resources and improve the efficiency of emergency response and social justice.

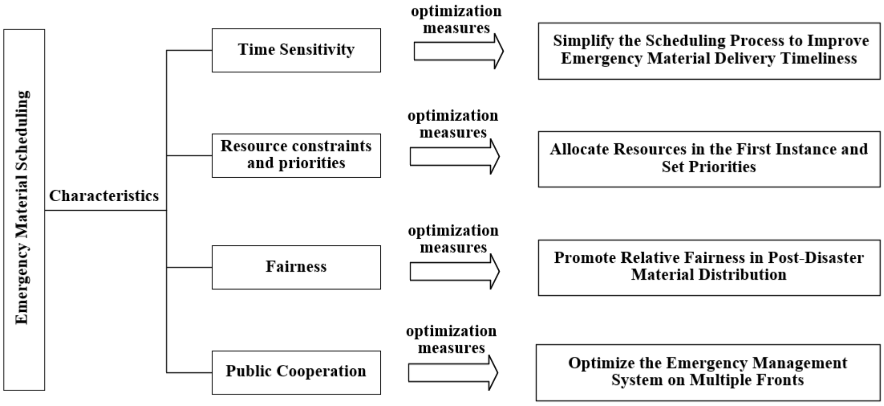

Figure 2. Emergency resource dispatch optimization measures based on emergency resource dispatch characteristics

(4) Optimize the emergency management system on multiple fronts: Among the existing dispatch modes, there are one-to-one, one-to-many, many-to-one, and many-to-many. Among the above material dispatching modes, the fourth mode, i.e., many-to-many (multiple supply points to multiple demand points), is more adaptable to the complex reality of the emergency response system. First, establish a cross-sectoral coordination mechanism, set up an emergency coordination center to coordinate resources and actions, and clarify the division of responsibilities to avoid duplication and omission. Second, implement a regional linkage mechanism, establish inter-regional resource sharing and rapid support networks, and enhance cross-regional collaboration capabilities. At the same time, it is important to strengthen public awareness of collaboration and enhance disaster preparedness through publicity and education. The public should be encouraged to actively participate in emergency response efforts. A comprehensive emergency response system with multi-party coordination should be built to provide strong support for disaster response.

Figure 2 summarizes the optimization measures based on the characteristics of emergency resource dispatch, to comprehensively enhance the efficiency and fairness of emergency response.

3.4 Emergency Resource Scheduling Process

The emergency dispatch process for floods is a complex and rigorous system that covers a number of links from the mobilization of materials to their final distribution. First, the sources of emergency supplies mainly include emergency supplies reserves, social donations and purchased relief supplies. These materials are quickly classified and distributed through centrally managed distribution centers after a disaster occurs. The distribution center plays a central role in resource integration and efficient scheduling. It ensures accurate distribution based on the actual needs of different regions, preventing uneven distribution of materials or the waste of resources. At this stage, the types and quantities of materials need to be adjusted in real time according to the extent of the disaster, the distribution of the population and transportation conditions.

Second, information flow plays a key role in the whole emergency dispatching process. The monitoring platform is responsible for collecting real-time information of the affected area, including the assessment of the disaster, the distribution of the affected population and the feedback of material demand. This information not only provides a scientific basis for the decision-making of the distribution center, but also guides the warehousing department to carry out reasonable inventory management and prepare the required materials in advance. At the same time, the two-way flow of information ensures dynamic adjustments in the distribution process, such as the optimization of transport routes, the adjustment of material categories, and the re-prioritization of disaster sites. The monitoring platform also needs to coordinate with multiple departments to ensure timely and transparent information sharing at every stage, providing a guarantee for the efficiency improvement of overall dispatching.

Finally, the supplies are sent from the distribution points to the affected areas and shelters through the transportation sector. Throughout the entire process, the transportation department needs to conduct dynamic planning based on road conditions, weather impacts, and the performance of transportation methods. This ensures that relief materials reach the front line as quickly as possible. In addition, during the final stage of material delivery, the distribution in shelters should follow a prioritized order to ensure that vulnerable groups are served first. At the same time, a feedback mechanism should be implemented to monitor the actual use of materials and further improve subsequent scheduling. Through the efficient synergy of material flow and information flow, the entire emergency dispatch system can respond quickly to the needs of floods and minimize the losses and impacts of disasters. A specific emergency resource network structure and scheduling diagram is shown in Figure 3.

UAVs play a crucial role in emergency material dispatching. In terms of material flow, the advantages of UAVs are mainly reflected in the efficient and precise distribution from the distribution point to the disaster site, which has been discussed in detail in 3.1 and will not be repeated here. What deserves more attention is the unique role of UAVs in information flow: first, after a disaster, UAVs can quickly establish communication signal stations by virtue of their flexibility and mobility, which is difficult to be achieved by traditional means of transportation. In the flooding caused by the extremely heavy rainfall in Henan, China, the Pterodactyl-2H emergency disaster relief UAV was successfully used to restore communications in the disaster area. This UAV can restore mobile public network communications over an area of 50 square kilometers and establish an audio-visual communication network covering 15,000 square kilometers. It provides timely communication services to affected individuals, enabling them to contact the outside world, request help, or report their safety. In addition, after the delivery of emergency supplies, UAVs can also undertake the task of supervising the distribution of supplies to ensure the fairness and transparency of the distribution process. For example, in the Hurricane Harvey and Irma floods in the southeastern United States, the image materials taken by UAVs were widely disseminated to show the actual situation of material distribution in the disaster areas through social media and news media. This not only improved the efficiency of resource allocation, but also enhanced the community's trust in the relief efforts, creating a more favorable environment for subsequent rescue operations. The versatility of UAVs makes them indispensable in emergency dispatch, and also demonstrates the great potential of technology in disaster relief.

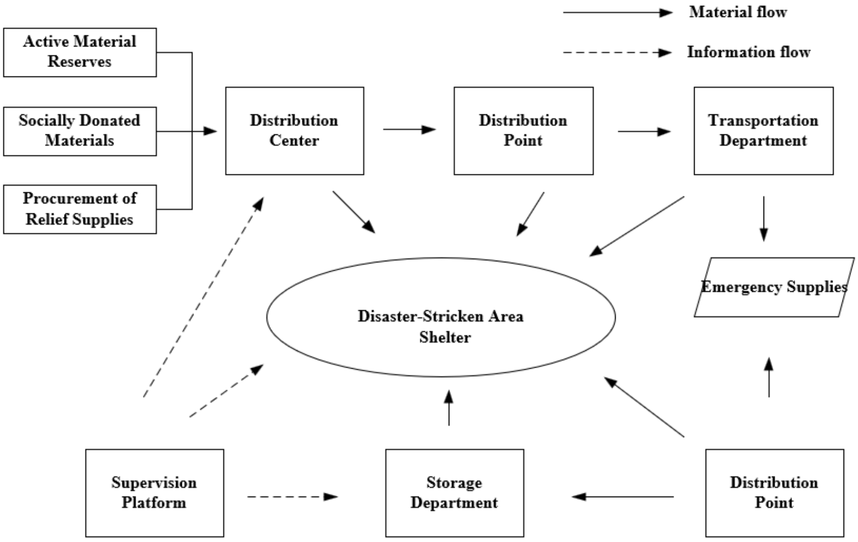

Figure 3. Emergency supplies network structure and dispatch diagrams

3.5 Co-Scheduling of UAVs

3.5.1 Theoretical support for collaborative UAVs in emergency material scheduling

In emergencies such as floods, the complexity and urgency of the material dispatching task require a system that can make decisions and coordinate flexibly and precisely. The application of cooperative UAVs in material dispatching provides a new idea to solve this problem. UAVs can maximize scheduling efficiency through precise path planning and real-time communication to achieve collaborative operations between multiple UAVs. However, how to achieve efficient coordination among multiple UAVs and how to deal with complex task allocation and scheduling problems is a challenging task. RL, as an intelligent decision-making method, can provide theoretical support for collaborative UAV scheduling by simulating complex environmental interactions and optimizing the decision-making process. Through RL, the UAS can learn itself in a dynamic environment and gradually improve its performance in emergency material dispatching, thus effectively improving the efficiency and accuracy of task execution.

The RL process can be abstracted as a Markov process. It contains five variables: <S, A, T, R, done>. Where S denotes the set of states of the system, A denotes the set of operations allowed by the UAV in any state $S \in S$, and T denotes the model of the environment for transitioning from one state to another as in Eq. (1).

$$T\left(s_t, a_t, s_{t+1}\right)=P\left(s_{t+1} \mid s_t, a_t\right) \tag{1}$$

where, $T\left(s_t, a_t, s_{t+1}\right)$ denotes the probability that the system moves to the next state S_{t+1} after taking action a_t in state S_t. R denotes the total gain of the model, and done is the sign of whether the model is updated or not. RL has the concepts of environment and agent. Specifically for emergency material dispatching, environment refers to the external conditions and state of the system, including the operation of the UAV, the geographic information of the affected area, and the material demand. These external factors determine the flight path of the UAV. These environmental factors keep changing as time pushes forward, and the intelligent body needs to obtain this information and make decisions in real time. Agent refers to the UAV system that performs the task of material dispatching. Each UAV can be regarded as an independent intelligent body, which needs to select appropriate actions to accomplish the task based on the current state. The intelligent body makes decisions by sensing the environment and based on RL algorithms. In emergency material dispatching, each UAS maximizes its own reward value through continuous “trial and error” R to make optimal dispatching decisions.

Policy update: after each interaction with the environment, the RL algorithm evaluates the rewards gained based on the current state and actions taken, and updates its decision-making policy based on this feedback. In exploration, the ε search strategy is utilized: actions are randomly selected for exploration with a certain probability ε and the current optimal action is selected for exploitation with a probability $1-\varepsilon$. The strategy π is a function that decides which action to take in a certain state. In multi-UAV material scheduling tasks, policy updating is usually performed by methods such as gradient descent. The goal of policy updating is to maximize the cumulative return, as shown below:

$$\pi_{t+1}=\pi_t+\alpha \nabla_\pi E\left[R_t\right] \tag{2}$$

where, α is the learning rate and $\nabla_{\pi} E\left[R_t\right]$ is the gradient of the strategy, indicating how the current strategy can be adjusted to improve future rewards.

Value function update: RL algorithms maintain a value function to measure the long-term payoff of taking an action in a certain state. In multi-UAV scheduling, the update of the value function is evaluated based on the feedback of individual states and actions, aiming to improve the decision-making efficiency of the system through the accumulation of long-term gains. The update formula is as follows:

$$Q\left(s_t, a_t\right) \leftarrow Q\left(s_t, a_t\right) + \alpha\left[r_t + \gamma \max_{a} Q\left(s_{t+1}\right) - Q\left(s_t, a_t\right)\right] \tag{3}$$

where, γ is the discount factor indicating the weight of future rewards.

Iterative process: With multiple rounds of training and continuous accumulation of data, the performance of the RL model will gradually improve. In each round of iteration, the system learns how to make optimal decisions under different mission requirements and environmental changes by adjusting the strategy and updating the value function. For multi-UAV material scheduling, as the algorithm iteration deepens, the efficiency of collaborative scheduling, the accuracy of material placement, and flight safety will be gradually improved.

RL provides a theoretical framework for collaborative UAV scheduling, and in practical applications, it can support multiple aspects of multi-machine collaboration, path planning optimization, and task allocation, solving the challenges that cannot be addressed by traditional methods. Therefore, the theoretical support lays the foundation for the next practical implementation. Next, how collaborative UAVs are specifically realized in emergency material dispatch will be discussed in detail.

3.6 Application of collaborative UAVs in emergency resource scheduling

A UAV is an aircraft that does not require a pilot and is operated by radio remote control and an autonomous control system, with the advantages of small size, low cost, ease of control, and adaptability to complex environments. It is able to enter areas that are difficult for personnel to reach, thus effectively avoiding danger to personnel. At the same time, UAVs can realize rapid ground mapping and real-time data transmission, ensuring the timeliness and intuition of information acquisition. Therefore, UAVs are widely used in the field of disaster rescue and emergency response. According to the number of UAVs, relevant studies are mainly categorized into two main categories: single UAV deployment and multi-UAV cooperative deployment. A single UAV performs well in regional, single-task scenarios. However, in the context of flood emergency material dispatch, the load capacity, flight time, and dispatch efficiency of a single UAV may not be sufficient to meet the demand. Therefore, the application of collaborative UAVs in emergency material dispatch is discussed in Figure 4.

(a) UAV (b) Remote controller terminal

Figure 4. UAV equipment configuration

(1) Pre-flight preparation: When using UAVs for operations, it is important to understand the relevant policies in advance, such as whether they are in no-fly zones and whether they meet local privacy regulations. At the same time, it is important to check the hardware equipment of the UAV, and the check includes the integrity of the airframe, battery power usage, the condition of the flight control device, and software update issues.

(2) Material preparation and load configuration: In flood emergency material dispatching, the materials to be prepared are usually food and drinking water, rescue equipment such as lifebuoys, emergency lights, and communication equipment such as walkie-talkies. When preparing emergency supplies, it is important to consider the load capacity of each UAV. The weight of each parcel should be controlled to 70-80% of the UAV's load capacity to avoid overloading and ensure flight stability. By reasonably preparing supplies and configuring loads, the UAV emergency supply distribution task can proceed smoothly, while maximizing distribution efficiency and flight safety.

(3) On-site image acquisition. On-site image acquisition refers to the acquisition of real-time images or videos of a specific area through the camera or other sensors carried by the UAV. In flood emergency material dispatch refers to the utilization of UAVs to obtain the disaster situation, the number of people in distress, and so on. In on-site image acquisition, certain skills are required. For example, Setting the UAV flight altitude between 300 and 500 meters is

more conducive to wide-range monitoring or tasks that require a broad field of view. Maintaining a moderate flight speed during operation and flying in open airspace are also recommended for optimal performance. This is more conducive to obtaining high-definition, first-hand data resources, providing accurate support for emergency material dispatch.

(4) Material placement and precise landing. First of all, through GPS supplemented by radar and other technologies, accurately determine the delivery area to ensure that the UAV can always know its accurate position during the flight process and can accurately fly to the delivery target area. Then, the distribution route is reasonably planned, and the position, speed, heading, and altitude of the vehicle are accurately calculated to ensure that the materials are stabilized during the flight process and ultimately accurately placed.

(5) Multi-aircraft coordinated delivery. In the dispatch of emergency supplies for flooding, multiple UAVs are often required to work in concert. Each UAV is placed separately in different target areas according to the division of labor of the task. In order to ensure that no collision or interference occurs between multiple UAVs, flight intervals and coordination mechanisms are usually used. For scenarios where a large amount of materials needs to be rapidly delivered in an emergency, multiple UAVs may perform the material delivery task at the same time. With the Soft Actor-Critic (SAC) algorithm in RL, multiple UAVs can be synchronised according to preset times, paths and tasks to maximise allocation efficiency.

(6) Image data post-processing. After the UAV completes the task of collecting images and material delivery, it needs to transmit the images back to the distribution center to transform the large amount of raw data collected into valuable information. These processed data can provide reliable data support for post-disaster relief work and government decision-making.

Hurricane Ian was an extremely destructive Category 4 hurricane that struck the U.S. state of Florida in September 2022. This hurricane brought huge storm surges, flooding, and strong winds that caused at least 146 deaths and up to $40 billion in property damage. Multi-UAS played an important role in this disaster. In terms of on-site image acquisition, the UAS team flew 34 missions and collected more than 636 GB of data during the rescue operation in Florida [27], which became crucial for the rescue. In terms of coordinated multi-aircraft delivery, UAVs were assigned to different delivery areas according to the severity of the disaster and the urgency of the need in the disaster area. One part of the UAVs focuses on delivering basic necessities to densely populated communities, while the other provides emergency medical supplies to remote areas. Rescue teams organized “UAV drop queues” to deliver supplies to multiple shelters in a sequential manner [27]. Multiple UAV groups worked together to ensure that all affected locations received supplies, avoiding missed or duplicated deliveries. During the Hurricane Ian flood relief operation, the multi-UAV drop technology: the arrival time of supplies was reduced by about 40%, especially in areas that were difficult to reach by traditional transportation; and the multi-UAV fleet completed more than 300 mission cycles per day, which greatly improved the overall efficiency of the relief effort.

3.6.1 The potential of collaborative UAVs in emergency material scheduling

From the above discussion, it is clear to see the incomparable advantages of UAVs in terms of efficient timeliness in emergency material dispatch, precise material delivery, real-time data collection and evaluation, adaptation to a variety of material distribution needs, and enhancement of public collaboration and cooperation. In addition to these advantages, UAVs have the following potentials under the wave of technological development.

(1) UAV clusters and disaster area autonomy: The application of UAV clusters, combined with the concept of disaster area autonomy, can establish an independent and flexible rescue network in disaster areas. Specifically, drone clusters can, in the event of destruction of traditional communication facilities, establish a temporary material distribution and communication network and act as a temporary data transmission and communication relay station. Future UAV clusters can realize self-sufficiency through their own solar panels, charging equipment, etc., reducing dependence on ground power facilities, which is particularly suitable for long-duration, long-distance post-disaster rescue.

(2) Blockchain-based material tracking and transparency: Blockchain is a distributed ledger technology that records data or transaction information in a decentralized, tamper-proof, transparent and traceable manner. The core feature of blockchain is that data is jointly maintained by multiple nodes, with its security and consistency ensured through cryptographic technology. The distribution process of all supplies can be recorded on the blockchain, ensuring that the entire journey of each piece of material, from the warehouse to the disaster area, is traceable. Incorporating UAVs into blockchain technology not only improves the transparency of material management but also ensures that materials are fairly distributed to every corner of the disaster area. The non-tamperability of the blockchain ensures the fairness of the distribution of supplies, prevents any improper distribution behavior from occurring, and increases the public’s trust in the management of relief supplies.

(3) Automation and intelligent dispatch systems: The rapid advancement of technology has led to the rapid iteration of UAVs. It has been shown that UAVs can automatically optimize transportation paths after a disaster based on specific weather, affected areas, and the number of people trapped, avoiding the inefficiencies and errors of manual intervention [28]. The intelligent scheduling system can dynamically adjust the scheduling strategy, such

as automatically reallocating resources to the most urgent areas when a sudden disaster occurs. It can also share the transportation pressure among multiple UAVs working together, achieving the lowest cost and maximizing the realization of benefits. The UAV utilizes high-resolution cameras and computer vision algorithms for real-time identification of materials. After the images captured by the camera are processed, the AI model can recognize the categories of supplies, such as food, medical supplies, tents, etc. The UAV classifies and labels the supplies through a deep learning model, which is able to automatically identify the type of supplies needed from the warehouse and indicate the location where the supplies are stored. Various packages of medicines, rescue equipment, etc., are recognized through a trained neural network. This improves sorting efficiency while reducing the pressure of manual sorting. During the process of distributing emergency supplies, UAVs can generate disaster-specific datasets to improve the quality of UAV distribution. The datasets are transmitted to the decision-making system to form real-time reports for decision-makers.

3.7 Empirical Analysis

Zhengzhou is located in the central plains of China, on the lower reaches of the Yellow River, and has a temperate monsoon climate with rainy summers and dry winters. From July 17th to 20th, 2021, Henan Province was hit by extreme rainfall, which was particularly severe in Zhengzhou, and was known as the “once-in-a-millennium” rainstorm. On July 20, the 24-hour rainfall in Zhengzhou was as high as 624.1 mm, of which 201.9 mm fell in one hour from 16:00 to 17:00, which was three times the amount of rainfall at the Zhengzhou National Weather Station (Source: Investigation Report on the “7.20” Extraordinarily Heavy Rainfall Disaster in Zhengzhou, Henan Province). As shown in Figure 5. According to official statistics, the storm caused 302 deaths, 50 missing people, and direct economic losses of more than 120 billion yuan. During the disaster, urban transportation was paralyzed and a large amount of flood water surged into Metro Line 5, killing 14 people. In addition, some villages were besieged by floodwaters, and people were trapped for dozens of hours. The extraordinarily heavy rainstorm led to severe urban flooding, subway inundation, collapsed houses, and infrastructure damage, making it one of the worst urban rainstorm disasters in China in recent decades. Given the suddenness of the event and the destructive nature of the disaster, this flood can be used as an important typical case to study the optimization of emergency management and rescue in flood disasters.

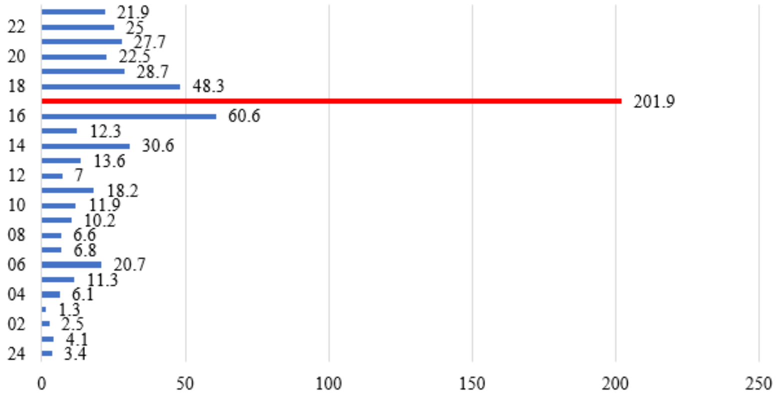

Figure 5. Hourly rainfall in Zhengzhou on July 20 (Unit: mm)

Source: https://weibo.com/ttarticle/p/show?id=2309404793649128146050

The occurrence of the “7-20” rainstorm in Zhengzhou in 2021 is closely related to the superposition of extreme natural conditions and human factors. In the context of global climate change, extreme weather events occur frequently, especially in summer, when the atmospheric water content increases and the intensity of rainstorms increases significantly. The rainfall was caused by the combined influence of the subtropical high pressure and the low vortex system, with the center of heavy rainfall remaining steady over the Zhengzhou area. The concentrated rainfall exceeded historical limits. Zhengzhou City is located in the lower plains of the Yellow River, where the terrain is relatively flat. This terrain causes rainfall to quickly accumulate in a short period of time. Additionally, the Jinshui River and other major river basins have limited capacity, unable to withstand the impact of heavy rainfall that exceeds design standards by several times, resulting in poor rain drainage and further exacerbating urban flooding. Meanwhile, the north bank of the Yellow River north of Zhengzhou was also badly affected. According to the comparative analysis of satellite images in Figure 6, before and after July 20, large areas of the northern bank of the Yellow River (indicated by the red-circled area in Figure 6) were inundated by floodwaters, with the water body area significantly enlarged. This indicates that the heavy rainfall not only worsened the urban flooding situation but also caused serious impacts on the river systems in the surrounding areas. The Yellow River itself serves as a crucial water regulation resource, and the increased rainfall in its upstream areas further exacerbated the complexity of flooding downstream. This highlights the destructive nature of regional extreme weather events.

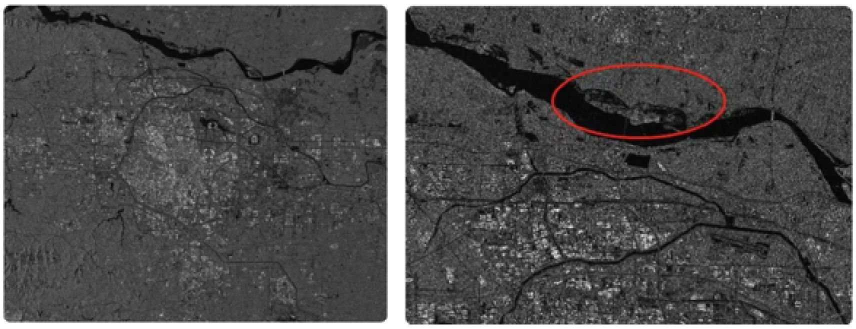

Figure 6. Satellite map changes in the north bank of the Yellow River partly north of Zhengzhou around July 20
Source: https://baijiahao.baidu.com/s?id=1706002383466507039&wfr=spider&for=pc

In addition, in Zhengzhou City, there is a long-standing problem of insufficient capacity of the drainage system; this problem is particularly significant in this rainstorm. Zhengzhou's drainage network was mostly built at the end of the last century, and its design standards are much lower than the current demands for extreme weather. Most of the drainage facilities are only capable of handling daily rainfall or small- to medium-sized rainstorms. In the face of extreme weather events like the "7-20" rainstorms, the network's capacity is seriously insufficient, resulting in large areas of the city being unable to quickly discharge water. Especially in some low-lying areas, such as the city center and the old city area, historical reasons have led to outdated drainage facilities and poor maintenance. As a result, rainwater quickly accumulated, causing severe flooding. In many streets, the water level even exceeded 1.5 meters, severely impacting residents' daily lives and transportation. Worse still, some key areas such as subway stations and tunnels failed to take timely closure measures during the heavy rainfall, resulting in rapid back-up of water, with disastrous consequences ensuing. For example, the section of Metro Line 5 from Shakou Road Station to Beach Temple Station was unable to operate normally because the drainage facilities were washed out by floodwaters. Rainwater poured directly from the ground into the railroad tracks, trapping a large number of passengers inside the carriages and compartments. Additionally, the Jingguang North Road Tunnel was not closed in time, causing water to quickly pour in. The water level in the entire tunnel reached over 4 meters at one point, trapping a large number of vehicles and preventing passengers from being evacuated in time, resulting in major casualties.

Immediately after the flooding, Zhengzhou City activated its emergency response mechanism and organized a multi-departmental joint operation. This operation focused on assessing casualties, the extent of housing damage, infrastructure damage, and the specific material needs of the affected areas. Due to the extensive damage caused by the torrential rain and the huge demand for supplies, the government prioritized the distribution of basic necessities such as medical supplies, emergency food, and drinking water. Special focus was placed on the most severely affected areas, including subway stations, tunnels, and low-lying communities. Residents in these areas are in urgent need of emergency supplies due to transportation disruptions and infrastructure destruction.

The State General Administration of Flood Control (SGFC) launched the flood control level III emergency response at 20:00 on July 20 and raised the response level to level II at 03:00 the next day. The Ministry of Emergency Management (MEM) quickly deployed to the disaster area to guide flood control, rescue, and relief efforts. At 5:00 p.m. on July 21, MEM received a request for support from the Fire and Rescue Bureau. To monitor the disaster situation in real-time and assess post-disaster damages, the National Disaster Reduction Center (NDRCC) of MEM urgently activated the "Major Disasters UAV Emergency Monitoring Cooperative Mechanism". The mechanism retrieved the location information and equipment of more than 100 cooperative teams across the country through the UAV Emergency Response Cloud Platform, and screened out the most suitable teams to carry out this emergency response mission. Immediately afterward, three UAV emergency response teams were mobilized from Kaifeng, Xuchang and Xingyang in Henan Province, while four UAV volunteer teams were deployed locally from Zhengzhou. These teams carried fixed-wing and rotary-wing UAVs to the disaster area to carry out post-disaster remote sensing monitoring and provide efficient disaster assessment and subsequent reconstruction support. The Pterodactyl UAV used by the operator in the "7-20 Zhengzhou Heavy Rainstorm" rescue was a large-scale backhaul UAV communication method. In this emergency rescue, based on the large-scale backhaul UAV stalling time of 5 hours, the directional restoration of 50 km^2 of mobile public network communications, the establishment of audio and video communications network can cover 15 000 km^2, the cumulative total of 3,572 users, generating a traffic volume of 2,089.89 M, the maximum number of users accessed in a single time of 648 users, for the disaster area in a timely manner to provide mobile communications security.

In addition to the application of a single UAV, multiple crews collaborated to carry out a wide range of continuous

UAV remote sensing monitoring. At 10:46 a.m. on July 21, the first UAV team arrived at Zhengzhou Hi-Tech Zone to start the mission, followed by other UAV crews that arrived at Changzhuang Reservoir, Guojiazui Reservoir, Gongyi Miehe Township, and seven other areas with serious disaster conditions to carry out remote sensing monitoring. By collecting high-definition images and data, these UAVs transmitted back the situation in the disaster areas in real time, providing key support for the subsequent rescue and post-disaster assessment. At 15:00 on the same day, the first batch of post-disaster remote sensing data was successfully transmitted back to the National Disaster Reduction Center (NDRC) to help assess the disaster situation in a timely manner. Until July 29, NDRCC's UAV remote sensing monitoring had covered five cities, Zhengzhou, Xinxiang, Weihui, Gongyi, and Xingyang, and along three rivers, the Jialu River, the Suo River, and the Qili River, with a total monitoring area of more than 1,400 square kilometers. Through the acquired image data, as shown in Figure 7. The NDRCC provided accurate decision support for the command of the Ministry of Emergency Management (MEM), the Henan provincial government, and the cities of Zhengzhou and Xinxiang. These data not only provided the forward command with essential information for on-the-ground rescue but also equipped the fire brigade with efficient tools for tasks such as flood management and road clearing. This significantly improved the timeliness and accuracy of the emergency response.

Figure 7. Pictures of the disaster acquired through coordinated UAVs

4 Conclusion

This thesis focuses on the optimization of emergency material dispatching in flood disasters and systematically discusses the related problems of post-disaster material dispatching. The study takes the "7-20" rainstorm and flooding disaster in Zhengzhou as a classic case, analyzes the key factors affecting emergency material dispatching in depth, and puts forward a feasible optimization method in combination with the specific needs of post-disaster dispatching. In the case study section, the key influencing factors in the pre-disaster period are first discussed in detail, focusing on time pressure, infrastructure availability, emergency coordination mechanism, and the effectiveness of the information sharing system. In the post-disaster period, on the other hand, factors such as the type of materials, financial budget, and recovery capability of the disaster area directly affect the rationality and executability of material dispatch. In the scheduling process, the evaluation and confirmation of material demand, material procurement and deployment, logistics transportation and distribution, as well as post-supervision and feedback management, should not be overlooked. The effective connection and implementation of each link are crucial for ensuring the overall scheduling efficiency.On this basis, the optimization strategy section proposes an optimization path for flood emergency material dispatching. Through the use of cooperative UAV technology, dynamic adjustment of material distribution paths, rational allocation of limited resources, and optimization of the coordination and information-sharing mechanism in the scheduling process, the timeliness and accuracy of material supply in the disaster area can be effectively improved.

This paper has the following improvement points that can be improved in the next work. First, in practical application, how to harmonize the complexity of practical operation and break down the barriers that hinder information sharing is an urgent problem to be solved. Second, due to the concurrency of disasters, none of the disasters are single; therefore, future research can further explore the construction of a generalized optimization model so that the method can be applied to multiple types of disasters and achieve good results in dispatching in different areas.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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