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Evaluating Urban Emergency Rescue Accessibility from a Supply-Demand Coordination Perspective: A Case Study of the July 20, 2021 Torrential Rainstorm in Zhengzhou

GAN Jing[1,2], LING Yun[1,2], LI Jian[3]

1. College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China;
2. Key Laboratory of Spatial Intelligent Planning Technology, Ministry of Natural Resources of the People's Republic of China, Shanghai 200092, China;
3. College of Transportation Engineering, Tongji University, Shanghai 201804, China

Abstract: Increasingly frequent torrential rainstorms have progressively severe impacts on cities, necessitating urgent attention to the evolving characteristics of emergency rescue demand and the corresponding level of emergency rescue accessibility, so as to enhance the dynamic response capability of urban emergency rescue. Taking the central urban area of Zhengzhou as an example, this paper uses social media data to identify rescue request points and road blockage points and analyzes the spatiotemporal distribution features of emergency rescue demand during the July 20, 2021 torrential rainstorm. From a supply-demand coordination perspective, the paper employs the Gaussian Two-Step Floating Catchment Area method to evaluate urban emergency rescue accessibility. The results show that emergency rescue demand exhibits dynamic concentration patterns, while the rescue accessibility demonstrates a mismatch between supply and demand. Finally, optimization strategies are proposed from three perspectives, including improving emergency rescue corridor networks, establishing an intelligent accessibility evaluation platform, and optimizing the spatial arrangement of emergency rescue resources. **DOI:** 10.13813/j.cn11-5141/u.2024.0505-en

Keywords: resilient transportation; emergency rescue accessibility; supply-demand coordination; torrential rainstorm; Gaussian Two-Step Floating Catchment Area method; Zhengzhou

0 Introduction

In the context of global climate change, unexpected weather disasters frequently occur and cause serious impacts on cities such as torrential rainstorms, super typhoons and extremely high temperatures. Owing to the increasing complexity and uncertainty of these climate disasters [1], it is urgent to improve the dynamic response capability of emergency rescue, which attaches importance to quick response and timeliness during the disaster. In reality, the emergency rescue facilities are configured based on the service radius and service area according to traditional methods. For example, "Construction Standard for Urban Fire and Rescue Stations" (Construction Standard 152-2017) stipulates that fire and rescue stations should be arranged according to the principle of "arriving at the edge of the jurisdiction within 5 minutes after receiving dispatch instructions" [2]. However, urban spatial elements exhibit the features of spatial aggregation, mixed functions and dynamic changes; meanwhile, the dynamic aggregation of population during sudden disasters can form demand gradient differences, which means that the existing spatial configuration model may lead to delayed rescue in the area with high emergency rescue demand, and unbalanced timeliness of emergency rescue due to information asymmetry [3]. Therefore, the dynamic response of emergency rescue should pay more attention to supply-demand coordination, which means the ability to deliver necessary resources to the emergency rescue demand-side according to demand changes in actual disaster scenarios.

Accessibility is both the main evaluation indicator of the resource delivery capability of public service facilities [4-5], and an important measure indicator of emergency rescue response capability [6]. From the perspective of supply-demand coordination, emergency rescue accessibility should pay attention to not only the spatial range of emergency rescue within a certain time (the delivery capability of emergency rescue resources), but also the dynamic change of emergency rescue demand (the actual demand for emergency rescue during the disaster). Therefore, the concept of emergency rescue accessibility can be defined as “emergency rescue suppliers providing sufficient service to the emergency demand side according to demand changes within a certain period of time”. The accessibility of emergency rescue facilities is usually measured with the Gaussian Two-Step Floating Catchment Area method [6-9]. Li et al. evaluated the accessibility of emergency rescue services

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in the central urban area of Shanghai during a 100-year pluvial flood [6]. Green et al. conducted a study on the emergency responder accessibility in Leicester, UK, under flood scenarios of various magnitudes (1 in 20-year, 1 in 100-year and 1 in 1 000-year recurrence intervals) [7]. Current studies always take the densely populated area or the area with high flood vulnerability as the location of scenario analysis on emergency rescue demand, lacking the analysis on changeable location and quantity of emergency rescue demand. This leads to the imprecise matching of emergency rescue accessibility and practical emergency rescue demand and results in a spatial mismatch between supply and demand.

With the extensive application of mobile communication technologies in recent years, social media has become an important platform for publishing disaster information, and more and more scholars apply social media data to analyze the disaster situation [10-13], which has brought social media to be an important data source for the analysis on dynamic changing characteristics of emergency rescue demand. In fact, social media data contains relatively comprehensive information, including rescue request content, emergency degree and geographic location [14], which can effectively represent the characteristics of the disaster [15-16]. Therefore, it is helpful to more accurately analyze the spatial characteristics of rescue demand with the use of identifying distress information published on social media. In this context, this paper takes the July 20, 2021 torrential rainstorm in Zhengzhou as an example to analyze the characteristics of emergency rescue demand based on social media data, and evaluate the accessibility of emergency rescue from the perspective of supply-demand coordination. Accordingly, this paper proposes optimization strategies to enhance the urban emergency response capability and provides a reference to a more efficient urban emergency rescue system in the context of extraordinary rainstorms and floods.

1 Empirical study

1.1 Study area This paper intends to explore the application of emergency rescue accessibility based on the July 20, 2021 torrential rainstorm in Zhengzhou. Considering the affected area and limited data, this paper focuses on the central urban area of Zhengzhou, including Erqi District, Jinshui District, Zhongyuan District, Guancheng District, and Huiji District.

The fire and rescue team is the main body of emergency rescue in China. The "14th Five-Year Plan for National Fire and Rescue" proposes to improve the emergency rescue capabilities for all types of disasters and extreme conditions, to fully utilize the Internet of Things and modern information technology, and to promote the construction of digital, visual, and intelligent contingency plans [17]. During extreme weather disasters, fire and rescue forces often take on responsibilities (personnel search, personnel rescue, personnel evacuation), and cooperate with other departments of disaster prevention and mitigation to ensure the safety of cities and residents. According to the Notice of the General Office of the People's Government of Zhengzhou on Issuing the Emergency Plan for Meteorological Disasters (Document No. 68 of 2022), the fire and rescue team should mobilize rescue personnel to carry out emergency response work, including such as personnel search, personnel rescue, and personnel evacuation [18]. Therefore, this paper takes the fire and rescue team as the main research object.

1.2 Data sources The research data includes rescue request points (166 in total) and road blockage points (175 in total) during the July 20, 2021 torrential rainstorm in Zhengzhou, location of fire and rescue stations (51 in total), population distribution and road network. All the data sources are shown in Tab. 1.

Tab. 1 Data sources

Data types	Data sources
Rescue request points (RRPs)	Rescue request information from July 21 to July 28, 2021 is collected from Sina Microblog1), and rescue request points are distinguished from the address in rescue request information2)
Road blockage points (RBPs)	Road blockage points are collected through the official account of Sina Microblog of "Zhengzhou Traffic Police" during the July 20, 2021 torrential rainstorm in Zhengzhou, including urban waterlogging positions, road collapse positions, the positions of dangerous road sections, and the positions of traffic control sections
Location of fire and rescue stations	Location of fire and rescue stations is distinguished through Gaode Maps and Baidu Maps
Population distribution	Population distribution in 2020 is collected from WorldPop website (https://hub.worldpop.org/)
Road network	OpenStreetMap website (https://www.openstreetmap.org/)

1) Although the July 20, 2021 torrential rainstorm in Zhengzhou ended on July 21, 2021, the secondary disasters such as urban waterlogging and invalid road systems lasted for a week. Therefore, emergency rescue was ongoing. 2) During the disaster, urban residents published rescue request information through Sina Microblog, including rescue request content and address, which can be used to analyze the spatial distribution characteristics of emergency rescue demand.

2 Research method

Based on the analysis of the spatiotemporal distribution characteristics of emergency rescue demand, this paper evaluates urban emergency rescue accessibility during the July 20, 2021 torrential rainstorm in Zhengzhou with the Gaussian Two-Step Floating Catchment Area method.

1) Analysis on the spatiotemporal distribution characteristics of emergency rescue demand

This paper analyzes the time and location of rescue request information based on organizing rescue request information on Sina microblog published by disaster-affected residents, identifying the spatial locations of rescue request and road blockage, and distinguishing the time of rescue request information.

2) Evaluation of emergency rescue accessibility

The accessibility of emergency rescue is analyzed from the overall and peak of rescue request information, and the specific analysis steps are as follows.

① Based on the Network Analyst tool in ArcGIS, this paper establishes an origin-destination cost matrix, calculates the rescue distance from fire and rescue stations to the RRPs avoiding RBPs, and selects rescue routes (rescue distance ≤ 5 km). Considering that the extremely heavy rainstorm caused urban waterlogging and rescue vehicles to be blocked, this paper takes 30 km/h as the speed and 10 min as the time threshold according to existing literature [6], which means the rescue distance threshold is 5 km.

② The Gaussian equation is used to calculate the emergency rescue supply-demand ratio of fire and rescue stations, and the calculation formula is as follows:

$$R_i = \frac{S_i}{\sum_{d_{ij} \in \{d_{ij} \le d_0\}} G(d_{ij}, d_0) P_j},$$

$$G(d_{ij}, d_0) = \begin{cases} \dfrac{e^{-\left(\frac{1}{2}\right) \times \left(\frac{d_{ij}}{d_0}\right)^2} - e^{-\left(\frac{1}{2}\right)}}{1 - e^{-\left(\frac{1}{2}\right)}}, & d_{ij} \le d_0 \\ 0, & d_{ij} > d_0 \end{cases},$$

In the formula, R_i represents the emergency rescue supply-demand ratio of fire and rescue station i, which is the ratio of emergency rescue supply to total rescue demand; S_i represents the emergency rescue supply of fire and rescue station i, and the number of fire and rescue vehicles is used as an indicator of the emergency rescue supply; d_{ij} represents the rescue distance from fire and rescue station i to rescue request point j; d_0 represents the rescue distance threshold (5 km); G represents the Gaussian equation; P_j represents the potential population at rescue request point j, obtained based on the population distribution published on the WorldPop website.

③ According to the emergency rescue supply-demand ratio of each fire and rescue station, the Gaussian equation is used again to calculate the emergency rescue accessibility of each rescue request point, and the calculation formula is as follows:

$$A_k = \sum_{d_{kl} \in \{d_{kl} \le d_0\}} G(d_{kl}, d_0) R_l,$$

$$G(d_{kl}, d_0) = \begin{cases} \dfrac{e^{-\left(\frac{1}{2}\right) \times \left(\frac{d_{kl}}{d_0}\right)^2} - e^{-\left(\frac{1}{2}\right)}}{1 - e^{-\left(\frac{1}{2}\right)}}, & d_{kl} \le d_0 \\ 0, & d_{kl} > d_0 \end{cases},$$

In the formula, A_k represents the emergency rescue accessibility of the rescue request point k. d_{kl} represents the rescue distance from the fire and rescue station l to the rescue request point k. R_l represents the emergency rescue supply-demand ratio of fire and rescue station l.

④ The interpolation method of inverse distance weighted (IDW) is used to spatially interpolate emergency rescue accessibility of each rescue request point, which can obtain the spatial distribution of emergency rescue accessibility in the central urban area. In fact, the principle of IDW is similar to the characteristics of emergency rescue. In other words, emergency rescue accessibility is high where RRPs are close to fire and rescue stations, while emergency rescue accessibility is low where RRPs are far from fire and rescue stations. Therefore, IDW is appropriate for this paper to perform spatial interpolation analysis.

3) The analysis on supply-demand coordination in emergency rescue accessibility

The degree of supply-demand coordination in emergency rescue is analyzed by comparing emergency rescue demand with the spatial distribution of emergency rescue accessibility, and targeted suggestions are proposed according to the current situation of supply-demand coordination.

3 Research results and analysis

3.1 Characteristics of emergency rescue demand

The July 20, 2021 torrential rainstorm in Zhengzhou is a typical meteorological disaster caused by extreme weather events in recent years. During this disaster, urban residents publish rescue request information on Sina microblog. It can be seen from Fig. 1 that RRPs are mainly concentrated in the area within the third ring road and the eastern area outside the third ring road, while a small number of RRPs are distributed in the western area within the third ring road. The RBPs are densely distributed within the third ring road which is similar to the high-density area of RRPs. The RBPs are scattered outside the third ring road (Fig. 1). There are the most disaster-affected areas within the third ring road and the eastern area outside the third ring road.

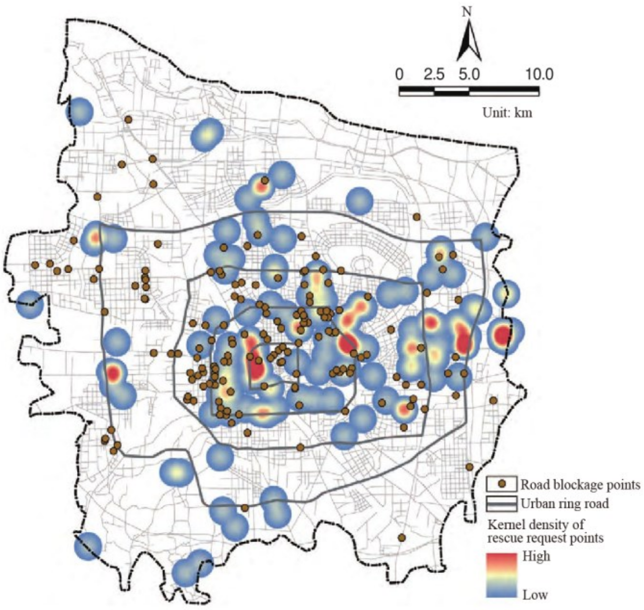

Fig. 1 Kernel density of rescue request points and spatial distribution of road blockage points during the July 20, 2021 torrential rainstorm in Zhengzhou

1) Time distribution

There are two peak periods of rescue requests, including the peak day (July 22, 2021) and the secondary peak day (July 24, 2021 to July 25, 2021). From July 21 to July 23, 2021, the number of rescue request information firstly increases and then decreases, concentrating on July 22, 2021. Meanwhile, the rescue request time is concentrated from 9:00 am to 11:00 am. From July 23 to July 28, 2021, the number of rescue requests firstly increases and then decreases, concentrating on July 24, 2021 and July 25, 2021. Meanwhile, rescue request information presents a relatively mean distribution starting from 8:00 am (Fig. 2)

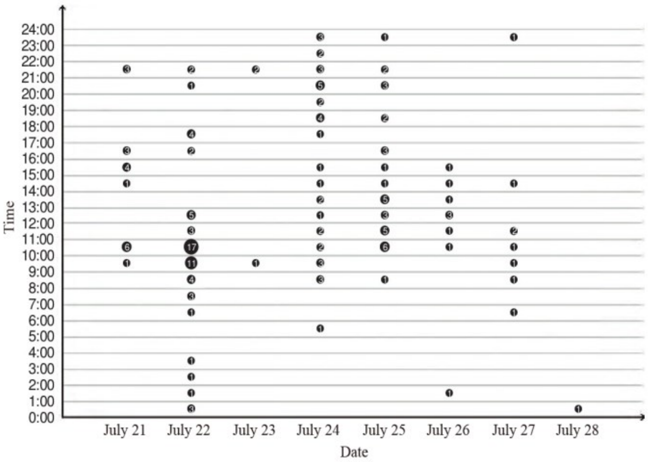

Fig. 2 Volume distribution of rescue request information during the July 20, 2021 torrential rainstorm in Zhengzhou

2) Spatial distribution

On the peak day (July 22, 2021) and the second peak day (July 24, 2021 to July 25, 2021), RRPs are relatively concentrated. While, on the other days, RRPs show a scattered distribution. In terms of the peak day, it shows similar characteristics on the spatial distribution of RRPs comparing peak hours (9:00 am to 11:00 am) with off-peak hours, and RRPs mainly distribute in the area within the third ring road and the eastern area outside the third ring road. However, the distribution range of the RRPs on peak hours is wider than the distribution range of the RRPs on off-peak hours (Fig. 3)

3.2 Characteristics of emergency rescue accessibility

3.2.1 Overall emergency rescue accessibility

The research results show that emergency rescue accessibility is relatively high in the northwest and southwest areas around the third ring road in the central urban area, while it is low within the third ring road. Regarding the emergency rescue supply-demand ratio of fire and rescue stations, it shows a characteristic of a small amount of high value and a general low value: the emergency rescue supply-demand ratio of most fire and rescue stations is lower than 1, except the fire and rescue station in the Jingnan Seventh Road (> 4) and the fire and rescue station in the high-tech zone (> 3) (Fig. 4). This phenomenon indicates that the fire and rescue stations may have insufficient supply under the background of torrential rainstorm.

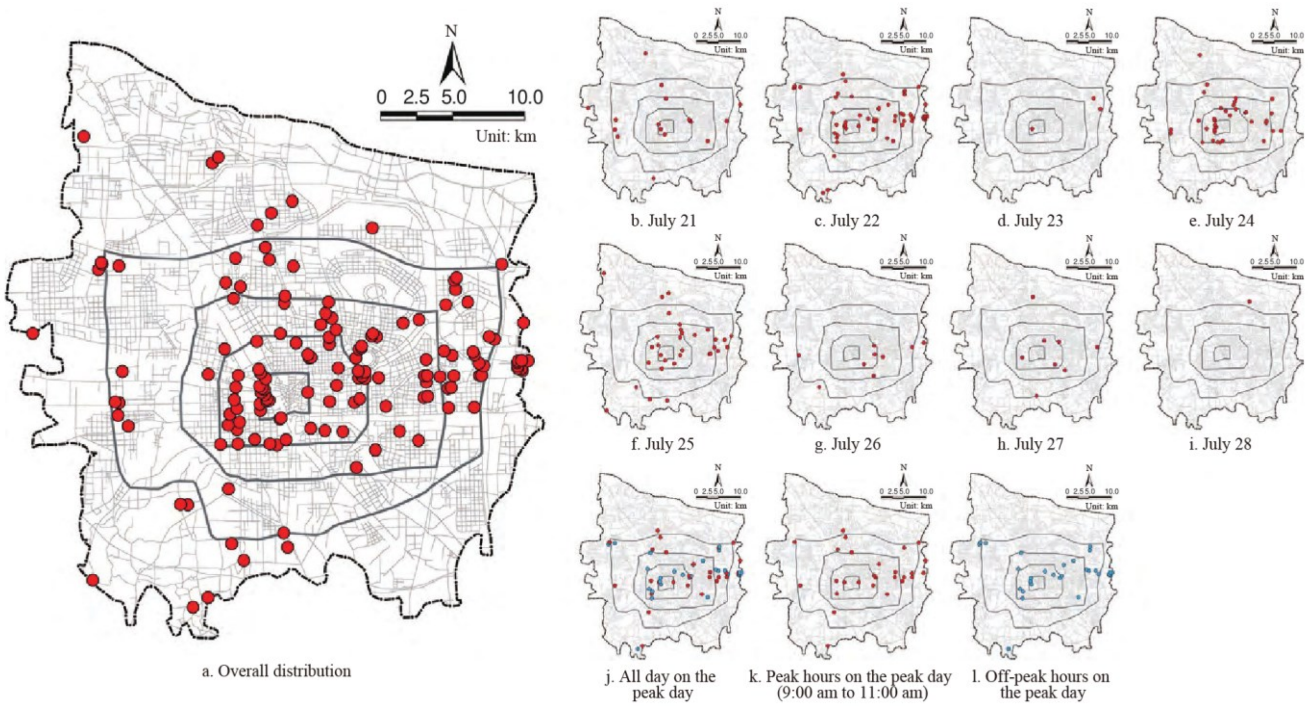

Fig. 3 Spatial distribution of rescue request information during the July 20, 2021 torrential rainstorm in Zhengzhou

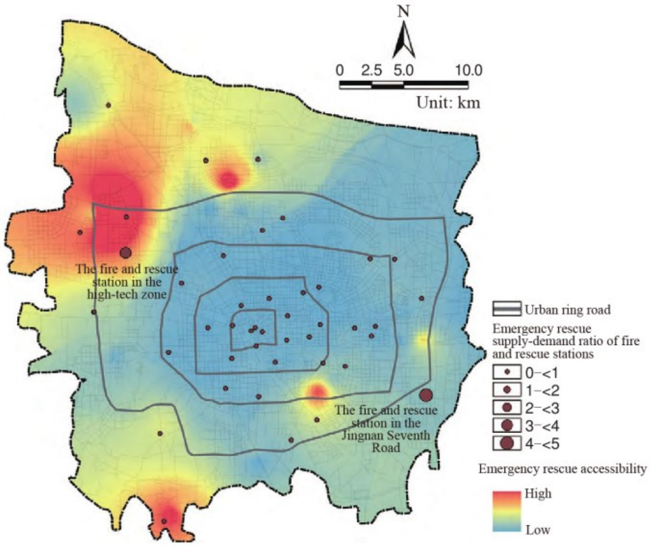

Fig. 4 Overall emergency rescue accessibility during the July 20, 2021 torrential rainstorm in Zhengzhou

3.2.2 Emergency rescue accessibility during the peak day

On the peak day (July 22, 2021), there exhibits the highest emergency rescue accessibility in the northwest area outside the third ring road, while emergency rescue accessibility is generally low within the third ring road where rescue points are dense (Fig. 5). According to further analysis on peak hours of the peak day (9:00 am to 11:00 am), the highest emergency rescue accessibility distributes in the northwest and southwest area outside the third ring road. In addition, a single point with high emergency rescue accessibility appeared in the eastern area within the third ring road, while emergency rescue accessibility is relatively low within the second ring road and in the eastern area outside the third ring road (Fig. 6).

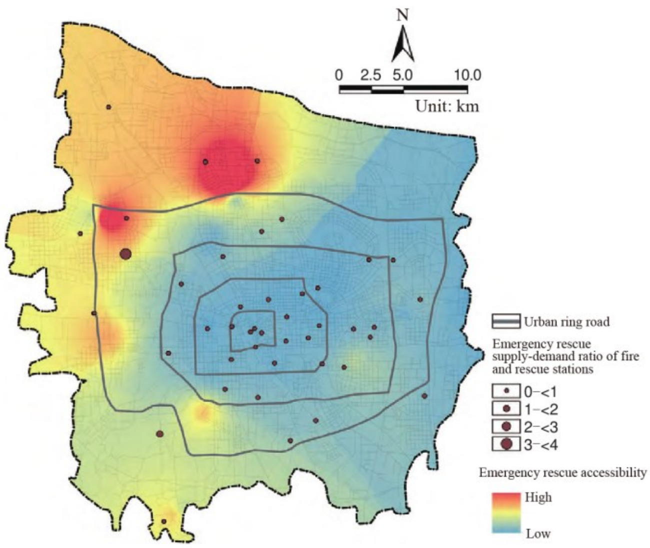

Fig. 5 Emergency rescue accessibility on the peak day of rescue requests during the July 20, 2021 torrential rainstorm in Zhengzhou

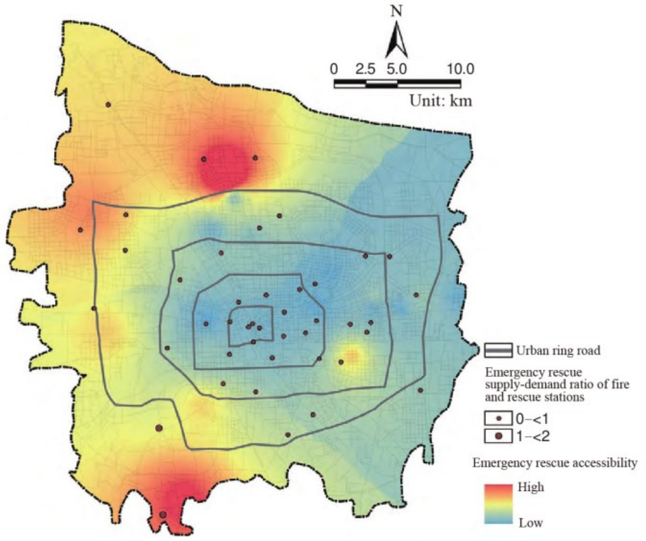

Fig. 6 Emergency rescue accessibility during peak hours on the peak day of the July 20, 2021 torrential rainstorm in Zhengzhou

3.3 Supply-demand Coordination of emergency rescue accessibility

From the above analysis, it can be seen that high emergency rescue accessibility is mainly distributed in the area outside the third ring road, while low emergency rescue accessibility is distributed within the third ring road. Although there is a dense road network in the central urban area, urban waterlogging and road collapse caused by rainstorms are mostly concentrated in the area within the third ring road of the central urban area. Therefore, rescue vehicles must re-plan their routes to reach the RRPs, which will increase the rescue difficulty.

The fire and rescue stations are configured based on factors such as rescue time and responsibility zone according to the relevant requirements of the "Construction Standards for Urban Fire and Rescue Stations" (Construction Standard 152-2017). Therefore, the spatial distribution is relatively balanced which can meet the emergency rescue demand within the construction standards. However, in the background of torrential rainstorms, it is the decline of road traffic capacity caused by urban waterlogging and the increase of rescue demand that affect the actual emergency rescue accessibility of fire and rescue stations, leading to a supply-demand mismatch. Therefore, the supply-demand coordination for emergency rescue accessibility needs to consider not only the emergency rescue supply capacity of fire and rescue stations, but also the changing characteristics of emergency rescue demand under different disaster scenarios and the traffic capacity of road networks.

4 Conclusions and recommendations

This paper applies social media data to analyze the spatiotemporal distribution characteristics of emergency rescue demand and emergency rescue accessibility in the context of the July 20, 2021 torrential rainstorm in Zhengzhou. The main conclusions are as follows.

1) Emergency rescue demand exhibits dynamic concentration patterns

In terms of time distribution, emergency rescue demand presents the peak day and the secondary peak day. In terms of spatial distribution, emergency rescue demand is mainly concentrated in areas within the third ring road.

2) Emergency rescue accessibility demonstrates a mismatch between supply and demand

Torrential rainstorm disasters have caused increasingly serious harm to cities, and there is a supply-demand mismatch of emergency rescue accessibility in the context of torrential rainstorm disasters. According to the analysis results, the distribution of emergency rescue demand is dense in the area within the third ring road where emergency rescue accessibility is relatively low. While the distribution of emergency rescue demand is relatively sparse in the area outside the third ring road where the accessibility of emergency rescue is high.

From the people-oriented perspective, the allocation of basic public services should maintain the conditions of residents' healthy and orderly living to the greatest extent [19]. Therefore, this paper proposes the following optimization strategies from the perspective of supply-demand coordination.

1) Improving emergency rescue corridor networks

The traffic capacity of the road network is an essential factor affecting emergency rescue accessibility. Urban waterlogging caused by extreme climate disasters will obstruct the normal passageways of residents, make the optimal rescue paths invalid, and make rescue more complex and difficult. Therefore, the emergency corridor networks should be improved with higher flood prevention standards according to the evaluation results of emergency rescue accessibility, so as to serve as a rapid emergency rescue corridor during disasters.

2) Establishing an intelligent accessibility evaluation platform

Emergency rescue demand exhibits dynamic concentration patterns, and it is difficult to meet the complex and changing emergency rescue demand only through static emergency rescue facility planning. Therefore, intelligent technology (including big data, artificial intelligence, mobile Internet, and cloud computing) can be combined to establish an intelligent accessibility evaluation platform that can integrate multi-source disaster data to identify RRPs and risk, to analyze the spatiotemporal characteristics of emergency rescue demand and road traffic capacity, and to evaluate the accessibility level of emergency rescue. At the same time, the evaluation results can be fed back to the decision-makers to timely clear blocked roads and uniformly deploy emergency rescue resources.

3) Optimizing the spatial arrangement of emergency rescue resources

The spatial arrangement of emergency rescue resources should be optimized in the areas with low emergency rescue accessibility. Based on the case study of Zhengzhou, it is the area within the third ring road, characterized by high population mobility and density, are not only hotspots for emergency rescue demand but also regions with relatively low emergency service accessibility. Therefore, the density of fire and rescue stations should be appropriately increased in this area, and small stations with greater flexibility can be taken into consideration when the configuration space is limited for large stations.

This paper applies social media data to provide strong support for more accurate identification of emergency rescue demand information such as the content of the rescue request and the location of disaster-affected areas. In further research, mobile signaling data can also be used to make a more accurate analysis of the disaster-affected groups of people, making up for the shortcomings of social media data (such as incomplete user coverage and the inability to determine the disaster-affected population), and provide more comprehensive data support for emergency rescue accessibility research.

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