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ABM-based emergency evacuation modelling during urban pluvial floods: A "7.20" pluvial flood event study in Zhengzhou, Henan Province

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Abstract Increasing urban pluvial flood disasters due to climate change and rapid urbanisation have been a great challenge worldwide. Timely and effective emergency evacuation is important for reducing casualties and losses. This has become a bottleneck for emergency management. This study aimed to develop a commonly used Agent-Based Mode (ABM) for pluvial flood emergency evacuation at the city scale, exploring the cascading impacts of pluvial flooding on human behaviour and emergency evacuation. The July 2021 pluvial flood event in Zhengzhou, Henan Province, claiming 380 lives and 40.9 billion yuan in direct losses, was selected as this case study. A raster-based hydraulic model (ECNU Flood-Urban) was used to predict flood inundation (extent and depth) during an event in Zhengzhou's centre. Moreover, a comparative analysis of emergency evacuations was conducted before and after the pluvial flood event. The results showed that crowd behaviour plays an important role in an emergency evacuation, and extensive flooding leads to an 11–83% reduction in the number of evacuees. This study highlights the importance of risk education and contingency plans in emergency response. The ABM model developed in this study is proven to be effective and practical and will provide support for decision-making in urban flood emergency management.

Keywords Pluvial flood, Emergency evacuation, Agent-based model, Crowd behaviour, Extreme rainfall in Zhengzhou

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1. Introduction

Urban pluvial flooding is one of the most common natural hazards in many regions around the world. Recent work by the latest Intergovernmental Panel on Climate Change (IPCC) assessment report has established that the globally observed heavy precipitation frequency has had an obvious increasing trend, especially in China (mainly in northern regions), and extreme precipitation occurrences have been expected to continue increasing (IPCC, 2021). With rapid urbanisation, human influence has weakened cities' ability to regulate and respond to climate change and pluvial flooding. Dwindling rivers, increasing impervious surfaces, lagging drainage networks, and delayed emergency responses have increased the risk of sudden pluvial flooding. Heavy rainfall and flooding in Beijing (July 2012) and Zhengzhou (July

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2021) caused 79 deaths and 11.64 billion yuan of damage and 380 deaths and 40.9 billion yuan of damage, respectively. One of the main reasons for the increase in flood losses is the lack of awareness of non-engineering measures, which are constraints on human behaviour and have a much greater effect in the long term.

Increasingly severe urban floods have attracted considerable attention from governments, international organisations, and academia, and exploring people-oriented, non-engineered flood prevention measures have become a continuing concern (Xia and Chen, 2021). In 2015, the third United Nations World Conference on Disaster Reduction adopted the Sendai Framework for Disaster Risk Reduction 2015–2030. In "Enhancing disaster preparedness for effective response", one of the four priorities for action, proposed that the ability of local government to evacuate residents in disaster prone areas must be strengthened. Some countries, such as the UK and the US, are establishing and optimising flood emergency evacuation plans for major urban areas. China has generated suggestions for the development of key technologies for monitoring, warning, and responding to earthquakes, typhoons, rainstorms, floods, and geological disasters in the Medium- and Long-Term Science and Technology Plan of China (2006–2020) (State Council of the PRC, 2005). Furthermore, China aims to establish and optimise the layout of emergency shelters according to the 14th Five-Year Plan (2021–2025) for the National Emergency System Plan (State Council of the PRC, 2021). Consequently, the study of emergency evacuations for urban disasters has become the forefront of international scientific research.

Recently, emergency evacuation researchers have shown an increased interest in computer simulation modelling. He (2018) proposed a flood crowd evacuation model based on cellular automata. Moreover, there is a growing body of literature that recognises the changeable psychology and behaviour of evacuees during disasters. Helbing et al. (2000, 2005) proposed a social force model that used physical force to describe the psychological changes of people facing disasters. Hu et al. (2009) improved the social force model and applied it to evacuation processes. Lim et al. (2019) adopted the discrete choice model to analyse the different response characteristics of crowds to flood events. Among the various types of behaviour simulation modelling techniques, Agent-based modelling (ABM) regards individuals as self-thinking agents who are able to make decisions and respond to their surroundings and is widely used in evacuation modelling (Zhuo and Han, 2020). Dawson et al. (2011) considered crowd response under flooding through ABM modelling and carried out a simulation of flood emergency evacuation in Towyn, UK.

Existing international experience in disaster risk reduction research recognises the critical role played by timely and effective evacuation. To increase the flood emergency evacuation efficiency and minimise the pluvial flooding casualties and losses, targeted countermeasures and strategies should be comprehensively optimised via high resolution numerical flood simulation and evacuation modelling, which can analyse the risk and exposure to flood disasters and assess emergency evacuation demands and shortcomings. However, few studies have been able to draw on any systematic research into complete emergency evacuation under flood situations in China. Up to now, far too little attention has been paid to flood evacuation theoretical approaches and empirical studies. By focusing on typical cases, this paper therefore set out to conducted research on emergency evacuation modelling for urban pluvial flood disasters and proposed a human behaviour-based ABM evacuation simulation model to rebuild the entire process of evacuation. The work offers some important insights into theoretical and methodological system for emergency evacuation and support for decision-making in urban flood emergency management.

2. Emergency evacuation modelling

2.1 Evacuation behaviour simulation

Crowd evacuation behaviour is influenced by both subjective and objective factors during the flood evacuation period. Subjective behaviour refers to the ability of agents to make decisions and respond to disasters, such as whether to evacuate, when to evacuate, evacuation routes, and destination. Objective constraints indicate environmental constraints, including inundation depth, traffic congestion, and shelter capacity. In this study, the agents' behavioural rules were formulated from both objective and subjective factors, including evacuation decision-making, response, and activity. Figure 1 shows a logit flow chart of the model.

2.1.1 Decision-making of agents

An individuals' ability to make their own evacuation decisions when they perceive or are informed of danger is crucial for a successful evacuation. Relevant theories and practices indicate that people tend to respond in two distinct ways when faced with a sudden disaster. Some individuals stay calm and make evacuation decisions such as escape routes and shelters quickly without being influenced by the behaviour of other evacuees during the evacuation process. Only objective constraints (e.g., roads closed owing to flooding and shelter overload) would change their evacuation decisions. This study refers to this group of evacuees with decision-making capacity as decision makers, while the other group of individuals tends to panic when faced with a sudden disaster and are easily influenced by those around them during the evacuation process, resulting in group behaviour

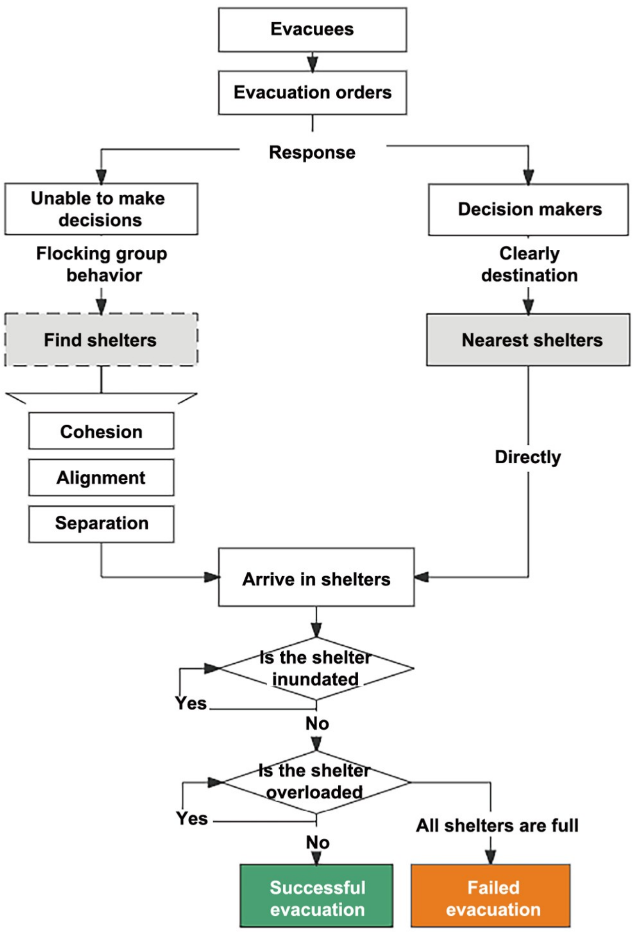

Figure 1 Flowchart of evacuation behaviour modelling during urban pluvial flooding.

such as blind others-following, competition, or synergy. We regard these agents as non-decision makers. However, individual decision-making usually depends on a personal cognitive level, disaster warning, and government emergency guidance. As the evacuation process is a group movement process, individual decision-making psychology and behaviour influences the evacuation performance of the group. Accordingly, the percentage of decision-makers is critical to group evacuation efficiency. This study considered the proportion of decision-makers as a model variable to simulate various evacuation scenarios with different proportions of decision-makers.

2.1.2 Evacuation response rates

The evacuation response rate is particularly important for the efficiency of large-scale evacuation, which is the embodiment of individual evacuation psychology. It is affected by many factors, including the distance from the dangers, subjective judgment of risk, the surrounding environment and the information they can attach through social media. (Murray-Tuite and Wolshon, 2013). To quantitatively determine the evacuation response rate, researchers have used statistical methods to fit numerous evacuation event data during disasters and found that the time spent responding to a warning often follows S-curves (Sorensen, 2000). These curves also include the actual response observed during Hurricanes Katrina and Opal (Murray-Tuite and Wolshon, 2013). Consequently, the typical S-curve rates were chosen to represent the evacuation response rate of the agents.

2.1.3 Agents evacuation behaviours

Massive evacuees are thrown into panic when a disaster strikes. In crowded conditions, interpersonal interactions become more frequent, showing significant group behaviour characteristics (Zhang and Zhu, 2021). Reynolds (1987) proposed the classical flocking behavioural rule for group motion inspired by the social behaviour of bird flocking, fish schooling, and land animal herding, which consists of three main basic rules: (1) “Cohesion” indicates an individual attempting to stay close to nearby individuals (unless another individual is too close); (2) “Separation” represents individuals that avoid collisions with nearby individuals that get too close; (3) “Alignment” signifies that an individual attempts to match velocity and direction with nearby moving individuals. However, these flocking rules do not work for all evacuees, and decision-makers with clear goals are not easily influenced by group behaviours to change their evacuation plans. However, non-decision-makers are affected by the surrounding environment and face a series of selective problems, such as the choice of evacuation routes and shelters. Accordingly, this study applies flocking rules to the evacuation process of non-decision-makers. For decision makers, the nearest shelter will be selected and will not be changed unless the shelter capacity is full.

2.2 ABM for evacuation

The emergency evacuation of large-scale crowds is highly complex, dynamic and uncertain. ABM focuses on the exploration of geographic objects and phenomena (Chen et al., 2021), which can better analyse geographic simulation and reveal the dynamic process of crowd evacuation (Yu et al., 2017). As a result, this study utilises an ABM model to rebuild the large-scale crowd evacuation process under urban pluvial flood scenarios to assess the applicability of evacuation plans and shelters and propose reasonable emergency evacuation strategies. We considered evacuees and shelters; there are two groups of evacuees, namely decision-makers and non-decision-makers, which are randomly generated by the model according to the input proportion. In addition, the attributes of evacuees' include origin, pop_-depth, response rate, destination, and speed. The moving speed during flooding was determined from the water depth-speed curves and the road speed limit in the study area (Pregnolato et al., 2017; Lee et al., 2019). Thus, when there is no inundation, the initial speed assigned to the evacuee agent is the road speed limit, whereas, with inundation, the initial speed is assigned according to the water depth-speed curves. We also defined a simple traffic congestion rule for the model to signify realistic traffic congestion scenarios, that is, when two or more agents are in the same position, they will randomly slow down and immediately return to their original speed when separated. For shelter individuals, location, shelter depth, and capacity were the main attributes for modelling. The evacuation ABM model is conducted based on the Flocking algorithm criterion (http://ccl.northwestern.edu/netlogo/models/Flocking) (Wilensky, 1998), and is built on the NetLogo platform with the Logo language compiled.

3. Case study

3.1 Study area

Within this study, the "7.20" Extreme Rain Disaster in Zhengzhou, Henan Province was selected as an empirical case study. Zhengzhou is located in the north-central part of Henan Province, and its topography decreases from west to east. Zhengzhou has a north temperate continental monsoon climate, with an average annual precipitation of approximately 650 mm. Owing to strong monsoon control, the rainfall in Zhengzhou is concentrated in summer, accounting for 45–60% of the total annual rainfall. In the last decade, Zhengzhou City has suffered from varying degrees of heavy precipitation almost every year. From 8:00 on July 17 to 8:00 on July 21, 2021, the Zhengzhou National Meteorological Observation Station recorded 624.1 mm of precipitation (on July 20, 2021), and the cumulative daily rainfall in some areas exceeded the local annual average rainfall. In terms of short-term rainfall, the maximum hourly rainfall at Zhengzhou National Meteorological Observatory reached 201.9 mm (16–17 h on the 20th), breaking the historical extreme value of hourly rainfall in Chinese mainland (198.5 mm, Linzhuang, Henan, August 5, 1975). Sudden extreme rainstorms caused widespread severe inundation in Zhengzhou City, resulting in 380 deaths and 40.9 billion yuan of direct economic losses due to the untimely activation of emergency response (Disaster investigation team of the State Council of China, 2022). To reconstruct the evacuation situation, the downtown area of Zhengzhou was chosen as the study site, which mainly includes Zhongyuan, Erqi, Jinshui, Guancheng, and Huiji districts, covering an area of approximately 891 km^2.

3.2 Data availability and processing

The data used for the study mainly included 1-hour precipitation data, 5-m digital surface model (DSM), grid population data, roads, and shelter basic data from the centre of Zhengzhou. Precipitation data were obtained from the hourly rainfall recorded by the Chinese Central Meteorological Station for the July 20, 2021 event. High resolution DSM dataset was generated by the fusion inversion of various satellite images (stereo pairing method), which includes the Resource 3 satellite. The county-level grid population data of the study were derived from the results of the Sixth Census Data of China, specifically including sex and age structure. The vector population were then converted to 100 m grid population distribution data by resampling. The basic GIS information for the road network were obtained from OpenStreetMap (https://www.openstreetmap.org) and manually corrected to match the topological data. For shelters data, the Code for Design of Disasters Mitigation Emergency Congregate Shelter (GB 51143-2015) indicate that shelters are preferably located in public facilities that are flat and high and conducive to drainage, such as parks, green spaces, squares, schools, and stadiums. Since the existing shelters in Zhengzhou are mainly outdoor spaces for earthquake disasters, they do not meet the requirements of flooding shelters. Therefore, this study obtained the basic GIS location for 137 stadiums and schools in the study area through the national point of interest information database as temporary emergency shelters for urban pluvial flooding.

3.3 Pluvial flood simulation

Pluvial flood modelling was performed using a 2D hydrodynamic model (ECNU Flood-Urban) (Yu and Coulthard, 2015; Yang et al., 2020), which couples hydrological processes (e.g., infiltration, evapotranspiration) and a 1D drainage module with a raster-based 2D surface flood inundation model. The model has already been applied and validated in some urban pluvial flooding cases and has performed well in flood simulations. In this study, we simulated the inundation scenario for the worst six hours of rainfall in the study area (15–20 hours on July 20, 2021), and due to the lack of detailed drainage network data for Zhengzhou, the urban design drainage capacity standard (0.2 m day^{-1}) was implemented. Figure 2 shows the max inundation map during the event, and the statistics indicated that 59.6% of Zhengzhou's central urban area was flooded, which is consistent with the Investigation Report on "7.20" Extreme Rain Disaster in Zhengzhou, Henan Province that "more than half of the underground community spaces and infrastructure in the downtown area were flooded" (State Council of China, 2022).

3.4 Human vulnerability identification

Vulnerable groups, such as the elderly, children, and people with poor health, are disproportionately affected by flooding disasters because of their limited information judgement and

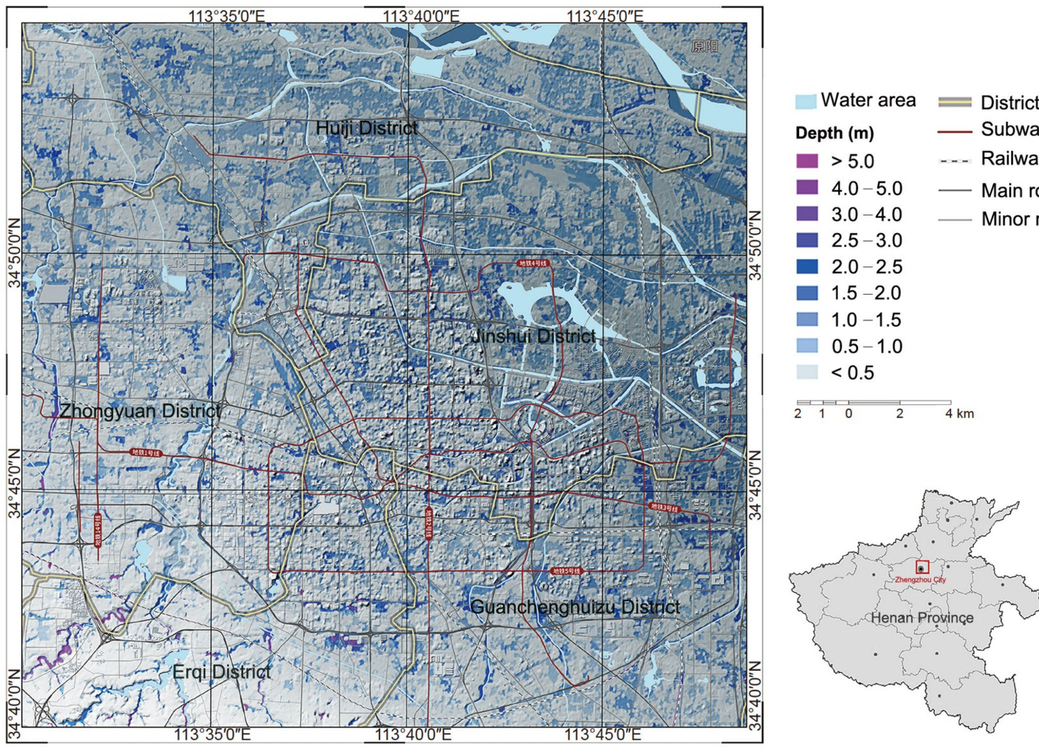

Figure 2 The simulated inundation map for "7.20" pluvial flood event in Zhengzhou downtown.

mobility (Yu et al., 2020; Yin et al., 2021). An experimental study demonstrated that a water depth exceeding 0.5 m will seriously affect the evacuation speed, especially for vulnerable groups such as the elderly and children, as it is difficult to maintain standing and walking (Lee et al., 2019). As a result, this study regards individuals over 65 and under 14 years old as high-risk groups that need to evacuate. However, evacuees can be evaluated relatively easily by overlaying hazard maps using grid population data. Summary statistics indicate that the population in the study area is approximately 3,797,200, of which 234,800 are over 65 years old, 520,800 are under 14 years old, and 193,300 are targeted evacuate individuals in inundation with water depths greater than 0.5 m. Moreover, spatial patterns show that the majority of evacuees (66.72%) were in areas flooded to a depth from 0.5 to 1.5 m; 30.85% evacuees with depths of 1.5 to 2.5 m; and 2% were in inundation with severe depths over 2.5 m.

3.5 Evacuation process simulation

After determining the evacuee individuals (population over 65 years old and under 14 years old), considering the actual situation of evacuation in Zhengzhou and the limited judgement of the elderly and children, we assumed 20% of decision-makers and the remaining 80% of non-decision-makers, Moreover, 137 schools and stadiums were selected as shelter agents. As it is difficult to obtain the capacity data of temporary shelters in Zhengzhou, the capacity limits of the shelters were temporarily excluded from the modelling process.

The evacuation departure times of the individuals were calculated according to the response rate curves established by the US Army Corps of Engineers (1999), which include fast, medium, and slow types (Figure 3a). We classified these evacuation response rates according to the water depth by referring to the Water Conservancy Trade Standard (SL 483–2017), i.e., when the water accumulation is between 0.5–1.5 m, it corresponds to slow response rate; between 1.5–2.5 m, it corresponds to medium response; and over 2.5 m, it corresponds to fast response.

For agent evacuation behaviour simulation, decision makers follow the proximity principle, while others who are unable to make decisions follow flocking group behaviour rules compiled and designed by Reynolds (1987) and Wilensky (1998). Furthermore, the moving speed of agents in flooding was determined from the water depth-speed curves and the road speed limit in the study area (Pregnolato et al., 2017; Lee et al., 2019) (Figure 3b). Meanwhile, road closure for driving occurs at a depth of over 30 cm (Yin, 2017).

We modelled pre- and post-disaster evacuation scenarios for 24 h to reveal the flood impact on emergency evacuation. For the pre-disaster evacuation process, it is assumed that residents will receive meteorological warnings and evacuation orders 24 h before flooding, which is ideal for reducing casualties and property damage. The post-disaster scenario

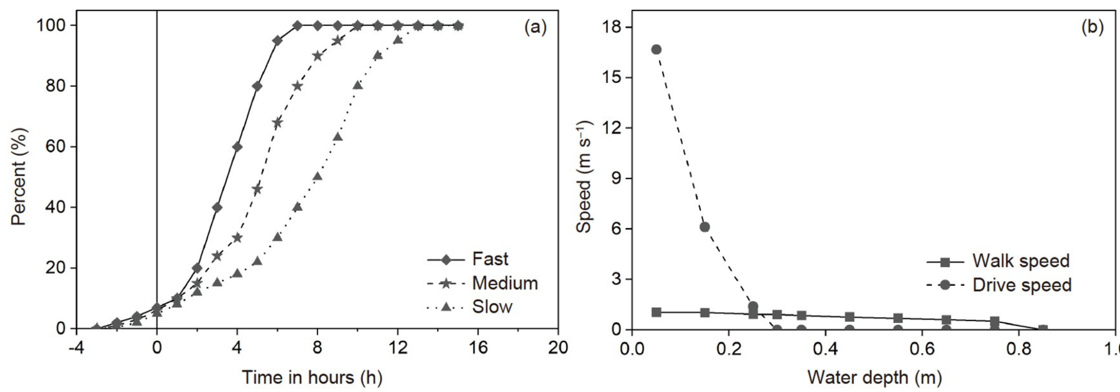

Figure 3 Evacuation behaviours of individuals during pluvial flooding. (a) Evacuation response rates; (b) water depth-speed curves.

assumes that evacuation orders are issued by governments after flooding, which is more consistent with the actual situation in Zhengzhou City during the "7.20" pluvial flooding disaster. Figure 4a and 4b shows the ABM model interfaces for the two scenarios.

3.6 Results

Figure 5 compares the dynamic evacuation process of pre- and post-scenarios. In terms of the pre-disaster scenario (Figure 5a–5d), without inundation, evacuees followed the fastest road speeds to find the nearest shelter. Statistics reveal the successful evacuation rate, in the early evacuation process, the majority of crowds didn't response, with only 13,000 individuals evacuated in the first eight hours, accounting for 6.8% of all evacuees. During the second eight hours, more individuals began to respond to the evacuation order. Nevertheless, with the low proportion of decision-makers, most individuals still have no clear planning, and just 28,000 (14.6%) individuals reached the shelters. In the last eight hours, the crowd evacuation rate decreased, with only 15,000 (7.9%) individuals successfully evacuated. Post-disaster evacuation scenarios are shown in Figure 5e–5h. Compared to pre-disaster evacuation, evacuation success rates were significantly reduced in post-disaster situations, with the majority of individuals trapped in heavily flooded areas, and less than 10,000 individuals successfully evacuated within 24 h. Among them, 2,000 (1.0%) individuals were successfully evacuated in the first 8 h, 4,200 (2.2%) individuals were evacuated in 8–16 h, and only 2,400 (1.3%) individuals succeeded in the last 8 h. Overall, 56,500 (29.3%) evacuees were evacuated within 24 h during the pre-disaster situation. In contrast, just a minority of individuals (4.5%) was successfully evacuated in the post-disaster scenario (Figure 6a). Taken together, these results suggest that untimely evacuation was one of the main causes of this serious casualty in Zhengzhou. Detailed statistics on evacuation rates are illustrated in Figure 6b, which suggests that the peak evacuation period was between 8 and 16 h after the orders were issued, and six to eight times more individuals evacuated successfully before the disaster.

4. Discussion

4.1 Impact of decision-maker ratio on evacuation

This study proposed a novel concept for evacuation decision-makers and non-decision-makers during evacuation processes. To investigate the influence of the evacuation decision-maker ratio on emergency evacuation efficiency, four pre-disaster and post-disaster evacuation scenarios with 100%, 80%, 50%, and 0% decision-maker ratios were simulated to carry out a sensitivity analysis (Figure 7). The most obvious finding to emerge from the analysis is that the percentage of evacuation decision-makers greatly affects evacuation efficiency compared to the eight evacuation results. When the decision-maker ratio was 100%, all individuals can be successfully evacuated within 24 h in the pre-disaster scenarios. Whereas only 12% of evacuees succeeded under no-decision-maker situation. In terms of post-disaster scenarios, most evacuation routes were closed by severe inundation, and the proportion of decision-makers did not have a major influence on evacuation efficiency at this time, with only 17% of the individuals successfully evacuating even in a 100% decision-maker scenario. Comparative results suggest that decision makers are vital to increasing emergency evacuation efficiency (especially in pre-disaster situations). As a result, disaster risk education and emergency evacuation plans may contribute to better evacuation efficiency during flood disasters.

4.2 Impact of response level on evacuation

Another index of evacuation behaviour involved in the model is the evacuation response rate, which can bring significant differences to the evacuation results. In this study,

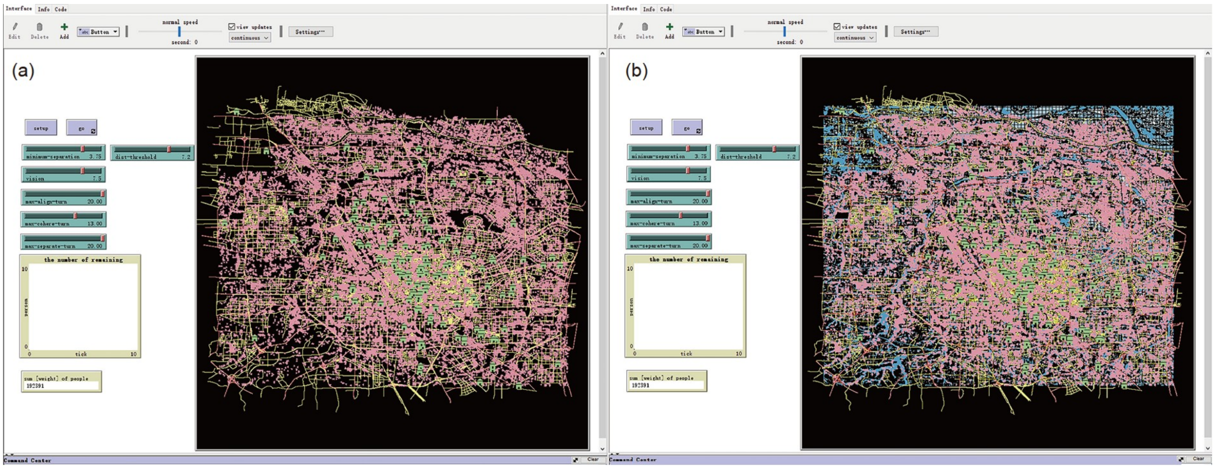

Figure 4 ABM model interfaces for flooding evacuation. (a) Pre-disaster evacuation scenario; (b) post-disaster evacuation scenario; red dots represent evacuee individuals, green dots represent shelters, yellow lines represent roads, and blue areas represent simulated flooding maps.

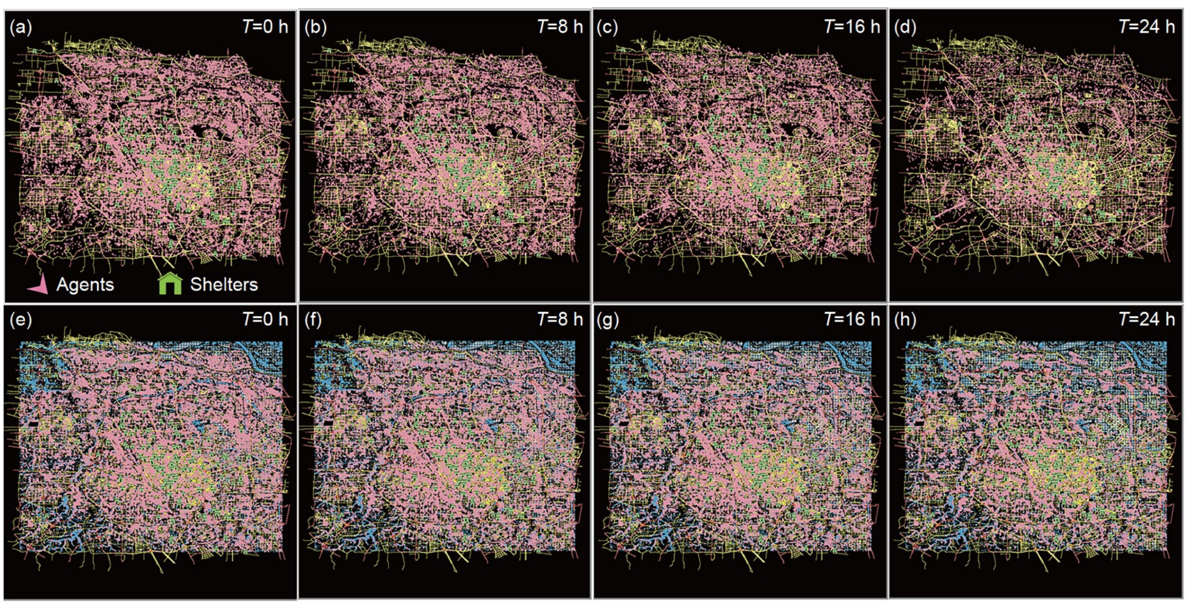

Figure 5 Time series results of evacuation simulation in urban pluvial flooding. (a)–(d) Pre-disaster scenario results every 8 h; (e)–(h) post-disaster scenario results every 8 h.

evacuation response rates were classified into fast, medium, and slow levels according to different inundation depths, and the comparison of statistical average evacuation times for each evacuation response led to two main findings. First, the average evacuation time for individuals in the fast response rate level was approximately 2.67 h (pre-disaster scenario with 20% decision makers) and 3.27 h (post-disaster scenario with 20% decision makers) less than the time taken in the slow response rate area, respectively. Second, there is little change between pre- and post-disaster average evacuation times for the same response rate level, with the slow response areas having an average post-disaster evacuation time that was less than the pre-disaster scenarios, as the number of successful evacuees plummeted after the flood, suggesting that the effects of flooding inundation on evacuation exceed the impact of response rates. The three evacuation response curves used in the model are based on the statistics of multiple hurricane evacuation events in the United States, whereas further localised research and validation are required for the applicability of emergency evacuation in urban flooding disasters. Furthermore, the classification standard for evacuation response rate levels must be further investigated for actual emergency response situations.

4.3 Impact of shelters on evacuation

The spatial distribution and capacity of shelters are important factors that affect emergency evacuations as well. As there are no flooding shelters in Zhengzhou, some schools and

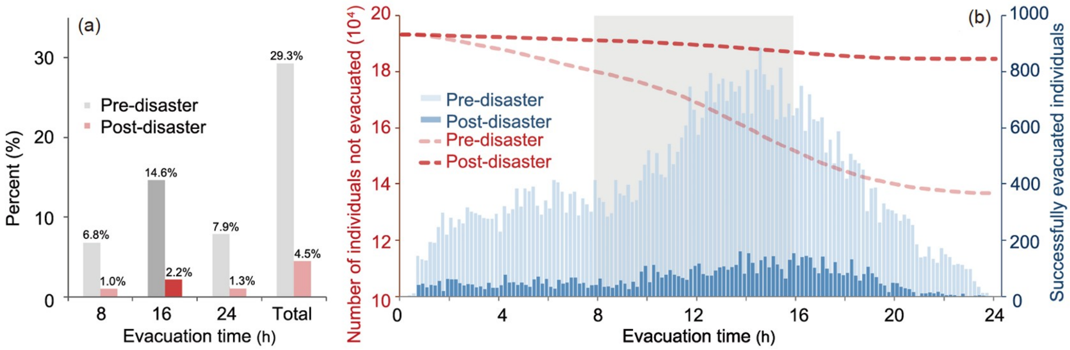

Figure 6 Comparison of evacuation rates in urban pluvial flooding. (a) Percentage of successful evacuations every 8 h; (b) time series of successfully evacuated individuals.

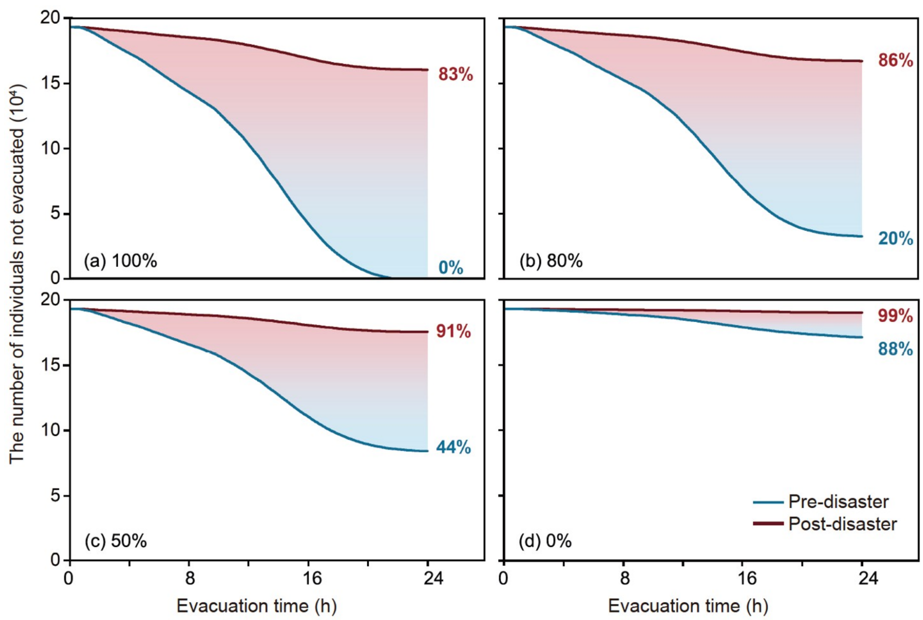

Figure 7 Evacuation scenarios with different decision-maker ratios. (a)–(d) Denote evacuation 100%, 80%, 50%, and 0% decision-maker ratios, respectively.

stadiums capable of evacuation were selected as temporary evacuation sites in this study. Figure 8 shows the number of evacuees arriving at shelters in the pre- and post-disaster scenarios. During the pre-disaster evacuation scenario, the number of individuals received in temporary shelters in the central area was mostly approximately 500–1,000, while the capacity is greater than 1,500 (or greater than 2,000 in the suburbs, which make a great burden on suburb evacuation shelters). A possible explanation for these patterns might be explained by the unevenly distributed of shelters in Zhengzhou. In contrast to the post-disaster evacuation scenario, the number of individuals received in shelters dropped sharply, with most of them having less than 500, some having a reduction of over 90% in capacity, and some having no applicable individuals. Therefore, a well-designed spatial distribution of flood evacuation shelters is crucial for emergency evacuations. Evacuation demands and efficiency must be considered when optimising the distribution of evacuation shelters.

5. Conclusions

This study proposes a novel ABM emergency evacuation simulation model for urban pluvial flooding that considers decision-making psychology, group movement behaviours, and flood constraints on evacuation. We then applied the ABM model and a 2D inundation model to simulate the evacuation scenario of the “7.20” pluvial flood event in Zhengzhou. The results of this empirical study revealed that: (1) the proportion of decision makers is important to emergency evacuation in disasters, and there is a nonlinear relationship between the increasing proportion of decision makers and evacuation rates; (2) evacuation response rates

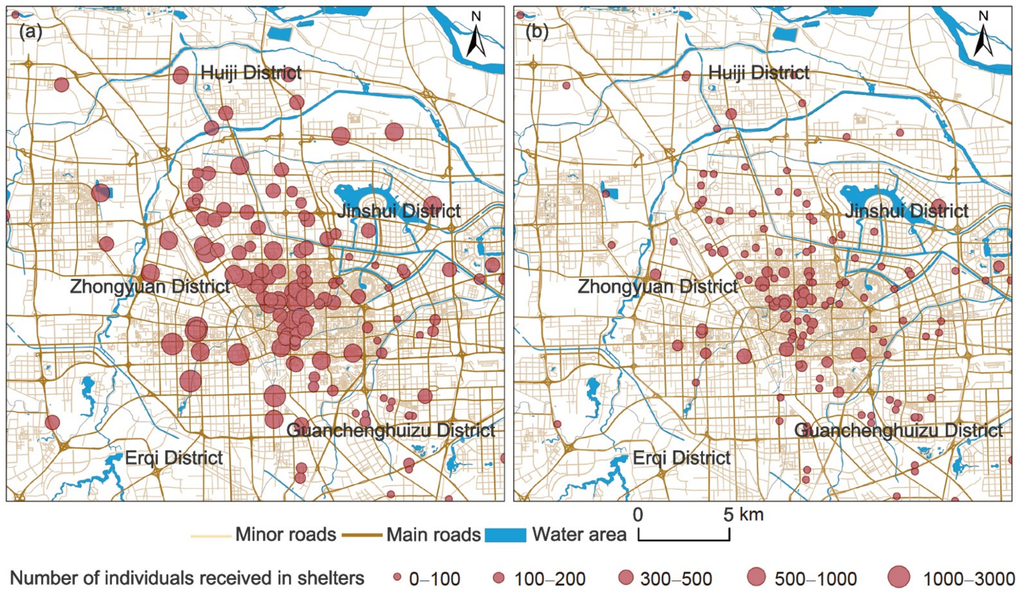

Figure 8 Comparison of the number of individuals received in shelters. (a) The pre-disaster scenario, (b) the post-disaster scenario.

directly influence the emergency evacuation rate, which does not grow continuously, but shows a slow-fast-slow characteristic; and (3) the spatial distribution and capacity of shelters are also important factors, which are especially significant in suburban areas. The methodology proposed herein can be adopted for applications in other large-scale urban flooding evacuation situations. These detailed results may contribute to the optimisation of flood emergency plans and emergency efficiency.

Emergency evacuation during urban pluvial flooding is a complex and dynamic process with high uncertainty and spatial and temporal variability. To arrive at more robust conclusions, this study could be improved in the following aspects: (1) the impact of dynamic flooding changes on evacuation behaviours needs to be considered, and form a research paradigm for the whole process of emergency evacuation before, during, and after the disaster; (2) future studies should consider using big data (e.g., traffic and mobile phone signals) to provide more realistic spatio-temporal observation and verification data for evacuation modelling; (3) urban important and vulnerable infrastructure such as subways and tunnels are also critical focus indices during flood evacuation processes. With climate change and urbanisation, further studies should be conducted to simulate extreme evacuation situations under future pluvial flooding scenarios, and the findings of these studies have a number of important implications for future flooding risk management.

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