

Article

Managing Extreme Rainfall and Flooding Events: A Case Study of the 20 July 2021 Zhengzhou Flood in China

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Abstract: On 20 July 2021, an extreme rainstorm battered Zhengzhou in China's Henan Province, killing 302 people, including 14 individuals who drowned in a subway tunnel and 6 who drowned in a road tunnel. As the global climate warms, extreme weather events similar to the Zhengzhou flood will become more frequent, with increasingly catastrophic consequences for society. Taking a case study-based approach by focusing on the record-breaking Zhengzhou flood, this paper examines the governance capacity of inland cities in North China for managing extreme precipitation and flooding events from the perspective of the flood risk management process. Based on in-depth case analysis, our paper hypothesizes that inland cities in North China still have low risk perceptions of extreme weather events, which was manifested in insufficient pre-disaster preparation and prevention, poor risk communication, and slow emergency response. Accordingly, it is recommended that inland cities update their risk perceptions of extreme rainfall and flooding events, which are no longer low-probability, high-impact “black swans”, but turning into high-probability, high-impact “gray rhinos.” In particular, cities must make sufficient preparation for extreme weather events by revising contingency plans and strengthening their implementation, improving risk communication of meteorological warnings, and synchronizing emergency response with meteorological warnings.

Keywords: climate change; extreme rainfall events; flood control; climate risk management; emergency response; China



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1. Introduction

Human-induced greenhouse gas emissions have led to global warming of 1.09 °C above 1850–1900 in 2011–2020 [1]. Since global temperature records began, the ten warmest years have all occurred since 2010, with the last nine years (2014–2022) ranking as the nine warmest years on record [2]. As the global climate warms, multiple extreme weather events have also become more frequent and intense, including heavy rainfalls and the resulting floods, which are the focus of this paper. According to the IPCC Sixth Assessment Report, the frequency and intensity of heavy precipitation and pluvial floods (surface water and flash floods) have likely increased on a global scale over a majority of land regions with good observational coverage, on a continental scale over North America, Europe, and Asia, and in selected regions in other continents, including Northern Australia, East Southern Africa and West Southern Africa, and South-Eastern South America [3].

Given their high population densities, extensive infrastructures, and their proximity to rivers, lakes, and coasts, cities are arguably the most important sites for managing the risk of extreme precipitation and flooding events [4,5]. In recent years, megacities around

the world such as London, Hong Kong, and New York have been hit hard by extreme rainfall-induced flooding. In July 2021, two extreme rainfall events caused flash flooding across London and Essex, resulting in more than 1500 properties reporting flooding [6]. Hong Kong experienced a “1-in-500-year” rainstorm from the night of 7 September to 8 September 2023. The Hong Kong Observatory Headquarters registered a record-breaking hourly rainfall of 158.1 mm and daily rainfall of over 638.5 mm, about a quarter of the normal annual total rainfall of Hong Kong [7]. The torrential rain brought the city to a standstill, causing widespread traffic disruption (including the closure of several railway stations) and damage to infrastructure, a temporary shutdown of power and water supply in some places, and at least two deaths and more than 140 cases of injury. Only three weeks later, New York City experienced similar downpours (the greatest rainfall totals ranged from 100 mm to 230 mm) and flash flooding on 29 September 2023, leading to a suspension of bus services and shutdown of half of the city’s subway system as well as flight delays or cancellations at the LaGuardia Airport and the Kennedy Airport [8].

China has millennia of experience in enduring and taming floods, the most common meteorological disaster in the country [9]. Three floods with the highest casualties in Chinese history are the 1887 Yellow River flood, the 1931 Yangtze–Huai flood, and the 1938 Yellow River flood, respectively, each leading to deaths of over 900,000 [10]. In the modern period, although casualties from floods have significantly decreased, economic losses have increased as flood basins become more densely populated. For instance, the catastrophic floods in the Yangtze and Songhua–Liao river basins in 1998 inundated more than 2.5 million hectares of land, damaged 7 million houses, killed 3500 people, and resulted in USD 30 billion economic losses [11]. It is estimated that the average annual losses caused by floods is equivalent to about 1% of the GDP. Each additional 0.5 °C of global warming will increase China’s flood losses by USD 60 billion per year [12]. Today, 67% of the national population lives in flood-prone areas, and more than 640 Chinese cities face varying degrees of flood risks [13]. In the next three decades, urbanization will continue at a high speed and at a large scale, with an additional 255 million residents settling in cities, further increasing cities’ exposures to flood risks [14].

Since the 1960s, particularly over the past decade, Chinese cities have witnessed a growing number of extreme precipitations and flooding events. While historically these events usually occurred in Southern China, particularly in coastal regions, recent years have seen a growing number of extreme precipitations and severe flooding events hitting inland regions in North China, such as the 21 July 2012 Beijing Flood, the 20 July 2021 Zhengzhou Flood in Henan Province, and the most recent flood in the Beijing–Hebei region, from late July to early August in 2023 [15]. Compared to coastal regions in Southern China, inland cities in North China are ill-prepared for extreme rainfall and flooding events in terms of both structural and non-structural measures, because most of these cities are defined as arid or semiarid regions according to the Aridity Index of China [16,17]. These extreme flooding events in North China are usually not only due to the regular influence of the East Asian monsoon, making the second half of July and the first half of August the main flood season, but are also compounded by a trend of more typhoons heading north [18]. The 20 July 2021 Zhengzhou Flood in Henan Province provides a case in point (the most recent Beijing–Hebei flood in late July and early August 2023 is another example). As a result of the airflow from Typhoon In-fa combined with the Western North Pacific Subtropical high, total rainfall during the 17–20 July period amounted to nearly 4 billion cubic meters of water, making it the most extensive and most intense rainstorm process since meteorological record-keeping began in Zhengzhou [19]. On 20 July alone, Zhengzhou received 624.1 mm of precipitation, equivalent to the average annual precipitation in the city (640.8 mm). The maximum hourly precipitation (201.9 mm), which occurred from 16:00 to 17:00 on 20 July, is equivalent to approximately 4 months of precipitation in Zhengzhou, breaking the record for hourly precipitation in China. Flooding during this rainstorm, which is a “1-in-1000-year” event, has far exceeded the drainage design standards in Zhengzhou (Zhengzhou’s drainage standard will reach a 1-in-50-year level (24-hour precipitation of

199 mm) by 2030, which is far below the intensity level of the Zhengzhou flood) and caused 302 deaths and direct economic losses of more than CNY 40.9 billion [19,20]. Given that extreme precipitation and flooding events will become more frequent and intense in the future and may occur in other unexpected regions in the world, it is imperative that cities in China (particularly the inland cities in North China) and other parts of the world draw lessons from past urban flooding events such as the 20 July 2021 Zhengzhou Flood to improve their flood risk management capacity [21,22].

The majority of the literature on extreme urban flooding events in China focuses on impact assessment, vulnerability and risk assessment, and attribution [17,23–27]. For instance, Dong et al. [28] applied hydrodynamic modeling to assess the risk for people and vehicles during the 20 July 2021 Zhengzhou Flood. Within attribution studies, most discussions have primarily revolved around meteorological and climatic factors behind the disasters, with only a cursory discussion of the human contribution to disaster impacts [29]. In the case of the Zhengzhou Flood, although some scholars have investigated some aspects of the management loopholes that contributed to the disaster, very few have systematically evaluated the effectiveness of each stage of the flood management process in a systemic and holistic manner. For instance, scholars have investigated how rapid urbanization compounded by inadequate green space and drainage pipelines contributed to the disaster impacts [29], the metro company's violation of regulations in changing the design of the subway parking lot and the mistakes of the subway commanders in emergency dispatching [30], the fragmented emergency regulations and fragmented organization and the resulting fragmented information [31], as well as the low level of post-disaster resilience one year after the event [32].

This paper contributes to the existing literature by employing a case study-based approach to demonstrate the existing loopholes in urban flood risk management system in inland cities in North China. Based on the case of the record-breaking 20 July 2021 Zhengzhou Flood, the authors hypothesize that inland cities in North China still have low risk perceptions of extreme weather events. The urban meteorological disaster risk management system is weakened by insufficient pre-disaster preparation and prevention, poor risk communication, and slow emergency response. Accordingly, this paper recommends that inland cities in North China as well as cities worldwide in general update risk perceptions of extreme precipitation events and make sufficient preparation for extreme weather events by revising contingency plans and strengthening their implementation, improving risk communication of meteorological warnings, and synchronizing emergency response with meteorological warnings. The authors will investigate the hypothesis in the context of multiple case studies that they are conducting or plan to undertake in the future.

This paper is structured as follows. Section 1 introduces the background, aim, and significance of this study as well as in what way this study would contribute to the existing literature and inform policy decision-making. Section 2 provides an overview of the governance system responding to extreme precipitation and flooding events in China, including the institutional setup and the key policy documents that guide flood risk management. Section 3 introduces the research methods, data collection process, and the limitations of this study. Section 4 explains the analytical framework based on the key phases of the flood risk management process. Section 5 analyzes the government response during the 20 July 2021 Zhengzhou Flood and identifies the key weaknesses in each phase of the flood risk management process. Section 6 discusses the roles and shortcomings of other policy initiatives in China that may also contribute to the management of extreme weather events. Section 7 concludes this paper.

2. Flood Management System in China

At the national level, the central coordinating agency and the highest authority of China's flood management system is the State Flood Control and Drought Relief Headquarters (SFCDRH), first established in 1950s [21,33]. While the Ministry of Water Resources (MWR) used to be the lead agency for flood control, mainly in charge of water conser-

vancy projects such as building river channels, dams, and dykes, its leading role was replaced by the newly established Ministry of Emergency Management (MEM) following the government reorganization in 2018. (The MWR still supports the MEM in playing many important roles in flood control management, such as organizing the preparation and implementation of flood and drought disaster prevention plans and protection standards and undertaking the monitoring and early warning of water and drought conditions.) The National Committee for Disaster Reduction (NCDR) is in charge of disaster relief during and after flooding events. In addition, the China Meteorological Administration (CMA) provides weather forecasts and early warning services to aid flood control management.

The municipal-level institutional arrangements for flood risk management mimic their national-level counterparts. All cities in China have established flood control and drought relief headquarters, often referred to as flood control headquarters (FCHs) for short, which coordinate the relevant departments that manage water affairs, hydrology, natural resources and planning, and ocean monitoring to jointly perform flood control duties. Mayors serve as the commanders-in-chief of municipal FCHs, demonstrating the level of importance attached to this issue. Many municipalities also establish special sub-headquarters in charge of flood control in risk-prone sectors such as road traffic and urban underground pipelines.

Flood control contingency plans (FCCPs) are the most important policy documents guiding flood prevention and control in China. The FCCPs specify the command system and responsibilities of the FCHs and the sub-headquarters as well as the procedures to be followed in each step of the flood control process. At the national level, the State Flood Control Contingency Plan (SFCCP) has shaped flood risk management in China since 2005. At the municipal level, almost all municipal emergency management bureaus have prepared FCCPs and regularly revised them. In addition to municipal-level FCCPs, lower levels of governments (e.g., county governments) as well as relevant government bureaus (e.g., urban tunnel management and maintenance centers) are also required to prepare corresponding FCCPs for their respective jurisdictions.

3. Methodology

3.1. A Case Study Approach

The overall research design roadmap is illustrated in Figure 1 below. This study investigates how well inland cities in North China are coping with extreme precipitation and flooding events and thus evaluate the extent to which they are prepared for increasingly frequent and intense extreme weather events in the future. Because the research questions are “how” questions about a contemporary phenomenon, we chose a case study-based approach and followed one of the most cited methodology books in the social sciences, the sixth edition of the *Case Study Research and Applications: Design and Methods* by Robert K. Yin [34].

This study focuses on the particular case of the extreme flooding event that happened in Zhengzhou City in central China’s Henan Province on 20 July 2021. Single-case studies can be extremely valuable when the single case has any of five characteristics: being a critical, extreme or unusual, common, revelatory, or longitudinal case [33]. This particular case of the 20 July 2021 Zhengzhou Flood was chosen primarily because this is a “revelatory case” that reveals an important social problem not systematically studied within a comprehensive framework: loopholes in each stage of the flood risk management process in inland cities in North China. In particular, the tragic event of the flooding of a subway train during the flood provides an appropriate lens through which to observe man-made causes of the disaster, which could be rectified, thereby avoiding casualties in the future. As previously alluded to, compared to their counterparts in South China, inland regions in North China are much less prepared for and slower in response to flooding events [29,35]. This case study may serve as a wake-up call to inland cities in North China to improve flood risk management loopholes in order to minimize the impact of such disasters caused by extreme weather events in the future. Another reason making the study of the 20 July

2021 Zhengzhou Flood particularly valuable is that it is one of the most recent extreme rainfall and flooding events in inland regions in North China and has received widespread attention from policymakers as well as scholars. The timeliness of the event allows us to draw lessons to inform policymaking in the near future.



Figure 1. Flowchart of this study.

3.2. Data Collection and Analysis

In order to collect thorough data, the authors performed a thorough review of publicly available information to track events before, during, and after the flood. Key sources of data included official newspapers, such as Zhengzhou Daily and Henan Daily, and the Weibo accounts of relevant municipal and provincial bureaus and agencies, such as the Zhengzhou Municipal Meteorological Bureau (ZMMB), the Henan Provincial Meteorological Bureau (HPMB), the Propaganda Department of Zhengzhou Municipal Party Committee (PDZMPC), the Emergency Management Department of Henan Province, and the Zhengzhou Metro (Zhengzhou Metro is a rapid transit rail network serving the urban and suburban districts of Zhengzhou. It is operated by the state-owned Zhengzhou Metro Group), as well as official documents, including the State Council's Investigation Report of the 2021.07.20 Extreme Torrential Rain Disaster in Zhengzhou (on 2 August 2021, the State Council set up an investigation group led by the MEM to investigate the 20 July 2021 rainstorm disaster in Zhengzhou, Henan. The group released its final investigation report on 21 January 2022, which concluded that although the Zhengzhou flood was above all a natural disaster, the responses to it revealed critical mistakes that led to "casualties that should not have happened", e.g., the flooding of the Subway Line 5 train and the Jingguang North Road Tunnel [19]) and FCCPs of Zhengzhou City, Henan Province, as well as other municipalities. Due to strict travel restrictions under COVID-19 and the sensitivity of the issue under study, the authors have not been able to conduct field interviews with relevant stakeholders in Zhengzhou to collect first-hand data (the first author's affiliation with a

Hong Kong-based university has made it particularly hard to get access to local government officials in mainland China). However, the first author still managed to conduct four interviews with researchers with expertise in climate adaptation and risk management. Two online interviews were conducted on 30 July 2021, one with a climate change researcher at Zhengzhou University and the other with an engineer at the Zhengzhou Municipal Meteorological Bureau. Both interviewees had extensive expertise in climate change science and experienced the Zhengzhou flood personally. Two in person interviews were conducted with senior researchers on climate risk management, one from the Chinese Academy of Agricultural Sciences, and the other from Beijing Normal University, on 18 October 2023. All interviews were conducted on an anonymized basis in order to protect interviewees' identities.

To analyze case data, the authors applied the technique of processing tracing, one of the most commonly used analytical tools for within-case analysis based on qualitative data [36,37], and closely followed [38] to draw descriptive and causal inferences. The analysis of the case is framed by the flood risk management process, described in detail in Section 4.

3.3. Limitations of this Research

The authors recognize the limitations of using a single case study to make broader generalizations about the ability of inland cities in North China to manage extreme precipitation events. We consider this exploratory study to be the starting point for a set of multiple case studies. Our ultimate goal is to generalize the set of case study results to form a broad theory about whether the traditional flood management system and processes can still prove effective in the face of climate change and rapid urbanization. A manuscript is currently being prepared to compare and contrast the flood management weaknesses revealed in three recent floods in North China, namely the 21 July 2012 Beijing Flood, the 20 July 2021 Zhengzhou/Henan Flood, and the most recent Beijing–Hebei Flood from late July to early August 2023.

Moreover, the authors recognize the limitations of relying only on official data sources, which may be biased and even misleading, to draw conclusions about meteorological disaster risk management in Zhengzhou and to make inferences about such management in other cities in North China. However, given limited data access, particularly access to reliable data sources, the authors believe that their observations and insights are still valuable for policy-making at all levels of government in China and in other parts of the world to prevent “casualties such as those that should not have happened in Zhengzhou” [19].

4. Analytical Framework: Flood Risk Management Process

This paper develops a multi-stage flood risk management process framework (see Figure 2 below) to analyze the case of the 20 July 2021 Zhengzhou Flood, in reference to the IRGC risk governance framework as well as the commonly used 2P2R (prevention–preparation–response–recovery/resilience) framework in disaster management [39]. The flood risk management process mainly consists of four phases, namely pre-disaster prevention and preparation, meteorological forecasting and warnings, emergency response, and post-disaster policy learning, recovery, and reconstruction. Since recovery and reconstruction following the Zhengzhou flood is still ongoing, this paper mainly focuses on the first three phases of the flood risk management process as well as post-disaster policy learning, while recovery and reconstruction will be studied in the next phase of this research (on 14 March 2022, the NDRC officially released the “Overall Plan for Recovery and Reconstruction after Heavy Rainstorms and Floods in Zhengzhou, Henan and Other Places” (hereinafter referred to as the “Plan”). The Plan proposes that within one year, the restoration of water conservancy projects, the repair and reinforcement of damaged houses, the reconstruction of the original site of rural residents' self-built houses, and the infrastructure, such as transportation, energy, communication, education, and medical and health services, will be basically completed. Within three years, the post-disaster

recovery and reconstruction tasks should be fully completed, and the disaster prevention and mitigation capabilities of the disaster-stricken areas significantly improved).

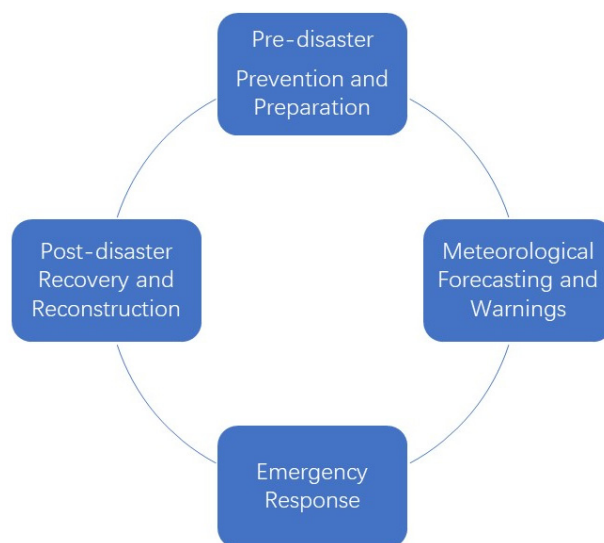


Figure 2. Flood risk management process framework.

The cycle of flood risk management starts with pre-disaster prevention and preparation, which should be carried out on a regular basis even before the flood season. This involves first and foremost the formulation and revision of a comprehensive system of FCCPs, developed by each level of government and relevant bureaus and organizations. The staff in charge of flood control are also supposed to conduct regular preparatory work such as troubleshooting and remediation of hidden dangers, dredging of drainage pipes, maintenance of equipment, and emergency plan drills.

With the advent of the flood season, municipal meteorological bureaus should work closely with provincial bureaus as well as the Central Meteorological Observatory (CMO) to monitor weather conditions, make forecasts, and issue **warning signals** to the public via various platforms such as television and SMS notifications (see [] for the conditions for activating the four levels of rainstorm warnings and the corresponding defense measures). Following the transmission of warning signals, FCHs may decide to activate the appropriate level of **warning response** (*yujing xiangying*) for all or part of a city based on judgments about the severity and impact of a flood. There are usually four levels of warning response, ordered in decreasing severity of disaster impacts, i.e., red, orange, yellow, and blue, corresponding to the four levels of meteorological warning signals. For instance, in Beijing, when the municipal meteorological bureau issues a red rainstorm signal, the municipal flood control headquarters may decide to activate the red warning response [40]. When activating the highest level(s) of a warning response, the flood control headquarters may announce that the entire city or parts of the city enter an “emergency flood control season” (*jinji fangxunqi*), which means that the headquarters or designated parties have the discretion to mobilize all necessary resources and to take emergency measures. For example, public security agencies and traffic management bureaus may implement land and water traffic control.

In addition to warning responses, a municipal government may activate a corresponding level of **emergency response** (*yingji xiangying*) when rainstorm-induced emergencies have occurred (e.g., flooded river basins, water accumulation on roads, collapse of houses, flooded underground facilities, trapped tourists, or geological disasters). A municipal FCCP usually defines the specific scenarios where each level of emergency response can be activated. For instance, one scenario for activating a Level I (the highest level) emergency response in Zhengzhou is when major accidents have occurred in the Changzhuang Reservoir [19]. The municipal FCHs shall be in overall charge of the command and coordi-

nation of the emergency response work. Commanders in charge of different industries and relevant bureaus need to rush to the scene of the accident to organize the rescue.

5. Case Study

5.1. Study Area: Zhengzhou in Henan Province

Zhengzhou is the capital of and the largest city in Henan Province (see Figure 3 below). With a population of over 12 million, it is one of the most populated cities in China. Zhengzhou is also a major transportation hub, with railways connecting it to other major Chinese and even European cities and the large Zhengzhou Xinxing International Airport.

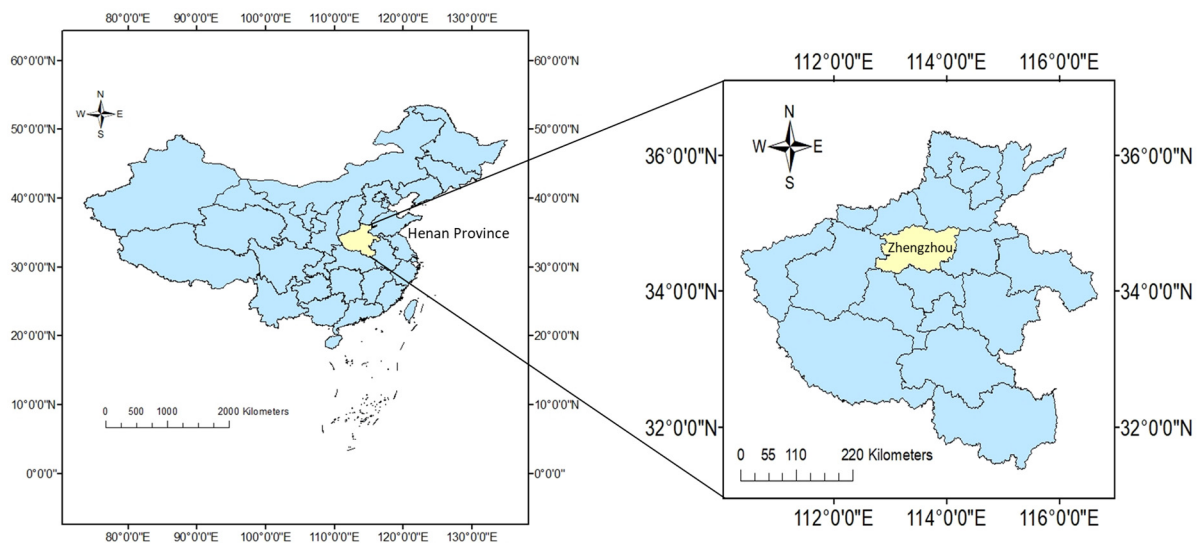


Figure 3. Location of Zhengzhou, Henan Province in China.

The average annual precipitation of Zhengzhou in the period of 1984–2020 was 627 mm, approximately the same as the average national precipitation in China. Under the influence of the monsoon lows in the summer, Zhengzhou's flood season lasts from July to September every year, and its precipitation accounts for 60~70% of Zhengzhou's total annual precipitation [27]. As in other cities in Northern China, most floods in Zhengzhou, including the 20 July 2021 flood, occur in the second half of July and the first half of August, i.e., the so-called main flood season.

5.2. Case Analysis

This section applies the flood risk management process framework to examine and evaluate the Zhengzhou government's response in each phase of the event, which allows us to form hypotheses about weaknesses in the urban flood risk management system in inland cities in North China. Figure 4, below, illustrates the timeline of major events during the flood. The most noteworthy points about this timeline are the gap between the advanced rainstorm signals sent by the meteorological stations and the much-delayed upgrades of emergency response levels by the flood control headquarters, and the gap between the early signs of flooding in the subway and the underground tunnel and the delayed decisions to shut down operations of the subway and the tunnel, which will be analyzed in detail in this section, particularly in Sections 5.2.2 and 5.2.3.

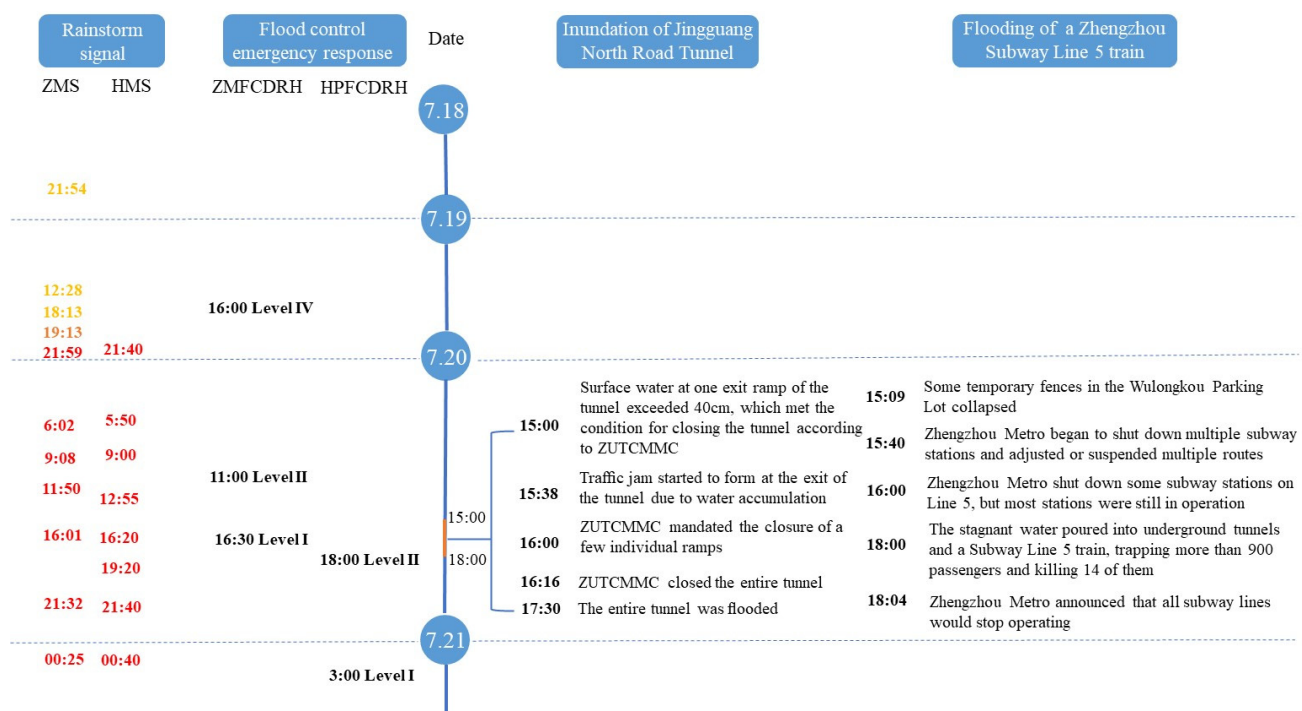


Figure 4. Timeline of major events during the 20 July 2021 Zhengzhou Flood (18–21 July 2023). Note: 1. ZMS stands for Zhengzhou Meteorological Station, and HMS stands for Henan Meteorological Station. The different colors of the times—yellow, orange, and red—represent different levels of the rainstorm signal issued by the meteorological stations (please refer to Appendix A for explanations of the corresponding rainfall forecast for each rainstorm warning signal). 2. ZMFCDRH stands for Zhengzhou Municipal Flood Control and Drought Relief Headquarters, and HPFCDRH stands for Henan Provincial Flood Control and Drought Relief Headquarters. 3. ZUTCMMC stands for the Zhengzhou Urban Tunnel Comprehensive Management and Maintenance Center.

5.2.1. Pre-Disaster Prevention and Preparation

The two most reported and controversial tragedies during this torrential rainstorm are the inundation of the Jingguang North Road Tunnel and the flooding on a Zhengzhou Subway Line 5 train (see Figure 4). In the former, approximately 300,000 cubic meters of water filled the Jingguang North Road Tunnel, which is 1835 m long and 6 m high, within three hours, flooding 247 vehicles and drowning six victims (the Jingguang North Road Tunnel is located on the Jingguang Express, a main road that runs through the north and south of Zhengzhou. Along this road, there are several important transportation hubs in Zhengzhou City, including the Zhengzhou North Railway Station in the north and the Zhengzhou Bus Terminal in the south. The area just above this tunnel is adjacent to the west square of Zhengzhou Railway Station). The flooding on a Zhengzhou Subway Line 5 train also occurred during the heaviest hour of precipitation on the afternoon of 20 July, drowning 14 individuals.

As alluded to in Sections 2 and 4, at the core of flood prevention and preparation is a thorough contingency plan, which serves as a “battle map.” However, comparing the FCCPs of Zhengzhou and Beijing reveals many weaknesses in the former regarding meteorological warnings and government responses, foreshadowing the flooding of the road tunnel and subway train in the 20 July 2021 Zhengzhou Flood (see Table 1 below). For instance, the Zhengzhou FCCP is ambiguous about the administrative details of meteorological warnings, such as who has the authority to issue meteorological warnings, who needs to approve such warnings, and what channels these warnings are released through. Our interview with an anonymous staff member at ZMMB suggests that the ZMMB has the discretion to issue red rainstorm signals without approval from the ZMFCDRH. In contrast, the Beijing FCCP specifies that the Beijing Meteorological Bureau must obtain approval

from the commanders-in-chief of the FCDRHs before releasing a warning signal. This ensures that the FCDRHs are updated about meteorological conditions and thus cognizant of the earliest opportunities to prevent casualties, for instance by announcing the closures of schools, businesses, and underground transportation infrastructures.

Table 1. Comparison between the flood control contingency plans of Beijing and Zhengzhou.

Category	Beijing Flood Control Contingency Plan (2019)	Zhengzhou Flood Control Contingency Plan (2015)
Meteorological warning	Before issuing a red rainstorm signal, the municipal meteorological bureau must consult the municipal flood control office, which reports to the executive deputy commander-in-chief and the commander-in-chief of the municipal flood control headquarters for approval. Once a red rainstorm signal is approved, it is released through the municipal early warning center.	The contingency plan does not mention the administrative details of issuing warnings.
Disaster scenario forecast	The subway is mentioned seven times in the contingency plan. It explicitly considers the disaster scenario of waterlogging in underground transportation facilities (including the subway) during extreme rainstorm events.	Underground transportation facilities are barely mentioned in the contingency plan. The “subway” is mentioned only once in the “Key Protection Objects” section. It does not explicitly mention the scenario of flooded underground transportation facilities.
Allocation of responsibility for the transportation committee	The responsibilities of the special sub-headquarters for road traffic flood control (commanded by the municipal transportation committee) are clearly specified.	The responsibility of the municipal transportation committee is only to “provide support for the transportation of flood control materials” under a Level I emergency response.

Sources: [40,41].

Moreover, the Zhengzhou FCCP does not recognize that underground transportation infrastructures are the Achilles’ heel of any city during an extreme precipitation event, as the Zhengzhou flood revealed. In fact, the Zhengzhou FCCP barely mentions underground transportation infrastructures, let alone the scenarios of subway flooding, nor does it specify the responsibilities of the municipal transportation commission (MTC) during a flood. In contrast, the Beijing FCCP establishes sub-headquarters for road traffic flood control, commanded by the MTC, and specifies their responsibilities during extreme precipitation events. The Beijing FCCP also explicitly considers the disaster scenarios involving flooded underground transportation facilities, including subways.

5.2.2. Meteorological Forecasting and Warnings

As the timeline in Figure 4 shows, meteorological forecasting and warnings for the 20 July 2021 Zhengzhou Flood were relatively timely and accurate. Although the earliest forecast was inaccurate in terms of intensity and timing, within the next two days, the weather forecasts became increasingly accurate (the earliest weather forecast for the rainstorm appeared on the afternoon of 17 July. At 17:00 on 17 July, the ZMS forecasted that 19 July would be a cloudy day with heavy and torrential rains, locally severe torrential rains, and strong convective weather, such as short-term heavy precipitation and short-term strong winds; 20 July would entail only heavy rains. In reality, however, the heaviest rain fell on 20 July instead of 19 July, and the actual grade of precipitation, namely, extreme torrential rain, was higher than initially expected, i.e., torrential rains and locally severe torrential rains). Between the first red rainstorm signal at 21:59 on 19 July and the flooding of the subway train and Jingguang North Road Tunnel on the afternoon of 20 July, ZMS and HMS had already issued at least eight red rainstorm signals. The timely meteorological forecasting and warnings provided Zhengzhou with more than fifteen hours to prepare for flooding accidents, which was sufficient to make arrangements such as the suspension of

schools and businesses and the closure of underground infrastructure, which unfortunately was not taken advantage of.

Despite the timely, accurate weather forecast and warnings, such information was not communicated effectively. First, the rainstorm signal messages sent by the ZMS and HMS lacked key information that would have created stronger perceptions of the risks associated with the extreme precipitation. Article 2 of the Measures for Issuance and Dissemination of Meteorological Disaster Early Warning Signals stipulates that meteorological warning signals must be composed of names, icons, standards, and defense guides [42]. The defense guides for red rainstorm signals clearly specify that schools should be suspended and businesses, with the exception for special industries, should be closed. However, the fifteen red rainstorm signals published on the official Weibo accounts of the ZMMB and HPMB and the SMS notifications only reminded the public to take precautions and did not specify any defense guides. (A red letterhead document for a red rainstorm signal, signed by director LI Kexing and issued by the ZMMB at 11:50 on 20 July 2021, has been widely circulated on the internet. Although this document contains defense guides, it was an internal document of the ZMMB and was not publicly published. The document was accidentally exposed by media on the internet after the flood happened. In other words, the public did not see this red letterhead document on 20 July 2021.)

Further weakening the warning effects of the red rainstorm signals, the first four signals that the ZMMB's Weibo published did not even include the red icons, the most eye-catching feature of a red rainstorm signal. For the general public not familiar with meteorology, a red rainstorm signal message that merely states that "cumulative precipitation will exceed 100 mm within the next three hours" without including any icons or defense guides probably has limited warning effects. Due to such incomplete risk communication, relevant government bureaus and the general public were not aware of the defensive advice of "suspending school and business" under red rainstorm signals, and went to work and school as usual, leading to casualties that could have been avoided.

In addition to lacking key information, the red rainstorm signals reached only a small audience due to the limited channels of communication and the low awareness of and poor timeliness of some communication channels. The red rainstorm warning messages were mainly sent through traditional media, such as TV broadcasts and SMS notifications [19]. The local TV stations only broadcast red rainfall signals in their regular weather forecast programs. Given the severity of the rainstorm, it was insufficient to send the red rainstorm signal only once through SMS. Although the official Weibo accounts of the ZMMB, HPMB, and PDZMPC all published warning signals, such messages were rarely read. For example, the three red rainfall signals published by the Weibo account of the ZMMB between 06:00 and 12:00 on 20 July were retweeted 11, 4, and 9 times, respectively. This very low readership implies that the official Weibo accounts of the meteorological bureaus are not effective channels for information dissemination. Moreover, the official WeChat (WeChat is a widely used messaging app, operated by Tencent Holdings in China) accounts of the ZMMB and HPMB did not publish any warnings about the extreme rainstorm. Considering the large user base of WeChat (1.2 billion monthly active users worldwide as of September 2021), particularly among middle-aged and elderly users in China, versus the relatively younger users of Weibo, Zhengzhou ignored a key platform for risk communication. In addition, a search of online news media shows that there was almost no news about the rainstorm until the afternoon and evening of 20 July, which suggests a poor timeliness of risk communication.

5.2.3. Emergency Response

The delayed emergency responses by the ZMFCDRH and other government agencies as well as the ZUTCMMC form a sharp contrast with the timely, accurate early warnings by the meteorological bureaus (see Figure 4). This is evidenced by the ZMFCDRH's disregard of the multiple earliest red rainstorm signals. After the ZMS released two red warnings, at approximately 08:00 on 20 July, the municipal government released the ZMFCDRH's

emergency notice, but by that time, most people were already at work or school. After the release of the third red warning, at 10:30, the Changzhuang Reservoir in Zhengzhou experienced a piping disaster, which qualified as the condition for activating a Level I emergency response according to the Zhengzhou FCCP. But in reality, the ZMFCDRH only upgraded the emergency response level from Level IV to Level II at 11:00 am instead of Level I. It was not until 16:30, i.e., during the maximum hourly precipitation and when the road tunnel and Subway Line 5 train had already partially flooded, that the ZMFCDRH decided to raise the emergency response level to Level I. However, this decision came rather late and did not leave much time for the relevant bureaus and organizations to make emergency arrangements. For instance, by 17:00, the Jingguang North Road Tunnel was seriously flooded and had trapped hundreds of cars and passengers. Even after the activation of Level I emergency response, the Zhengzhou municipal government never declared that the city had entered an “emergency flood season”, as stated in the FCCP.

The slow responses of Zhengzhou Metro and ZUTCMMC also severely delayed rescue. Even when early signs of danger (e.g., collapses of temporary fences on Wulongkou Parking Lot, flooding in several places on the Subway Line 5 train) appeared, the management team of Zhengzhou Metro never went to the Operating Control Center (OCC) or the site to command and carry out effective emergency response. The Subway Operation Branch was hesitant to completely shut down subway system operations and never activated emergency responses. They did not report the case to the Duty Office of Zhengzhou Metro until 19:48, when over 400 passengers had been trapped in the subway train for over one hour. Similarly, the ZUTCMMC did not follow the 2021 Tunnel Flood Control Emergency Plan and delayed the closure of the tunnel by over one hour.

5.3. Summary

The 20 July 2021 Zhengzhou Flood reveals critical loopholes in the city’s flood risk management system. Fundamentally, as an inland city in North China, the government of Zhengzhou still has low risk perceptions of extreme rainstorm and flooding events, which was manifested in insufficient pre-disaster prevention and preparation, poor risk communication, and slow emergency response. In terms of pre-disaster prevention and preparation, the comparison between the FCCPs of Beijing and Zhengzhou suggests that there is much room for improvement. In particular, the Zhengzhou FCCP lacks administrative details, does not fully consider all disaster scenarios, and has poor operability. The poor implementation of the FCCPs in Zhengzhou also implies that the flood control staff were not familiar with the content of the FCCP and that flood control drills were not conducted properly or frequently.

Moreover, many casualties during the Zhengzhou Flood could have been avoided had the red rainfall signals been communicated to all stakeholder groups in the first place. The warning messages should contain both meteorological forecasts and, more importantly, the defense guides, and be sent through a wider range of channels, including traditional and new media.

Last but not least, Zhengzhou did not take advantage of the relatively timely meteorological warning and delayed emergency responses. When the highest levels of meteorological warning signals were issued, the municipal government did not activate corresponding levels of emergency responses. The slow response of the Zhengzhou Metro reveals the habitual mindset of reporting to and waiting for orders from superior government agencies during extreme weather events, in this case awaiting orders from the MTC and/or the FCHs regarding whether to shut down subway operations. It is a typical phenomenon in a bureaucracy that lower levels of government avoid decision-making and wait for orders from superior levels of government. By acting as an implementer rather than a decision-maker, lower levels of government shirk the responsibility for making wrong decisions. Given the long chain of reporting in the bureaucracy, it can take a long time to obtain an order, which is a fatal deficiency in emergency management.

6. Discussion

Managing the risk of extreme precipitation and flooding events is systems engineering that requires not only speedy emergency response, as analyzed through the Zhengzhou case in this paper, but also long-term efforts to strengthen urban climate resilience. In recent years, the Chinese government has launched several policy initiatives such as the sponge city pilot program in 2015 and 2016 and the climate-resilient pilot city program in 2017. The Ministry of Housing and Urban–Rural Development (MOHURD) launched two batches of sponge cities in 2015 and 2016, respectively, which aims to enhance cities' resilience to flooding and waterlogging by renovating and building drainage infrastructures that act as sponges. In addition to the national-level sponge city pilot program, many provinces such as Henan, Sichuan, and Jiangsu have also launched provincial sponge city pilots. In 2017, the National Development and Reform Commission (NDRC) along with MOHURD launched the climate-resilient cities pilot program, which covered 28 pilot cities that represent different geographies, climates, and socioeconomic statuses. The goal is that by 2020, the pilot areas will have strengthened climate change adaptation infrastructure, improved adaptation capacity, and raised public awareness of climate adaptation. In 2021, the concept of “resilient cities” was written into the 14th Five-Year-Plan (2020–2025), for the first time in history, wherein resilience particularly refers to urban capacity for flood prevention and drainage. Both the sponge city and the resilient city pilot programs aim to improve urban resilience to extreme precipitation and mitigate waterlogging, although the climate-resilient pilot city program has a broader scope of addressing other types of climate risks too. Despite current limitations and shortcomings, sponge and climate-resilient city construction both have potential to contribute to the management of extreme weather events in China.

Under the sponge city pilot program, local governments in China have upgraded existing drainage designs and engineering standards, which has effectively mitigated urban waterlogging [43,44]. However, the program is crippled by many problems such as the lack of or slow construction of urban rainwater recovery system and storage facilities and data sharing platforms [45]. The 20 July 2021 Zhengzhou Flood raises further doubts about the effectiveness of sponge city construction in mitigating urban flooding and waterlogging, given that Zhengzhou was a provincial sponge city pilot in Henan Province in 2016, and the “Zhengzhou City Master Plan (2017–2030)” proposed to invest CNY 53.48 billion to construct a sponge city by 2020. Attributing the Zhengzhou disaster to sponge city construction reflects a common misunderstanding of the purpose of a sponge city. In China, the goal of sponge city construction is to achieve a total annual runoff control rate of 75–85%, mainly by controlling medium and small-size rainfall events with high frequency. The design standard for sponge city construction in China is to withstand 1-in-20-year or 1-in-50-year floods and to minimize damage caused by 1-in-100-year floods. According to the Zhengzhou City Sponge City Special Plan (2017–2030) issued in 2018, the design rainfall control standard for sponge city construction in various regions of Zhengzhou ranges from 15.7 to 26.5 mm [46]. Since the launch of sponge city construction, Zhengzhou has already improved its ability to cope with medium- and small-size rainfalls. By June 2021, the built-up area in Zhengzhou had not experienced any serious flooding disasters, and 125 flood-prone points had been eliminated, with an elimination rate of 77% [29]. However, during the Zhengzhou flood, the rainfall from 16:00 to 17:00 on July 20 alone reached 201.9 mm, which is nearly 10-times the amount of rainfall control standard designed for the sponge city. In other words, sponge city construction is not intended to prevent the risks of extreme torrential rains and floods such as the “1-in-1000-year” flood in Zhengzhou.

However, the Zhengzhou accident does warn cities of the importance of improving sponge city construction in the future to better respond to extreme rainfall events. At present, sponge city construction is usually limited to demonstration projects, which make up only a small proportion of the urban built-up area. Cities must significantly expand the scope of sponge city construction in order to mitigate the risk of waterlogging. Moreover, it is urgent to update the construction standards of sponge city construction and

to incorporate forward-looking climate information into infrastructure design instead of relying on historical trends only [47]. For instance, the current rainfall control standards in sponge city construction are based on 30 years of historical data, but as the future distribution of precipitation changes, the effect of a sponge city would be much reduced if the corresponding design standards were not updated.

Assessment of the first phase of the climate-resilient cities pilot program (2017–2020) suggests only moderate progress in pilot cities' capacity for climate adaptation and risk management. Despite progress in urban infrastructure development and ecological space optimization, pilot cities generally fall short of their capacity for meteorological monitoring, early warning, and disaster prevention and control [48,49]. It is therefore important to incorporate the learnings from the Zhengzhou Flood into the design of the second phase of the climate-resilient city pilot program.

7. Conclusions

The revelatory case of the 20 July 2021 Zhengzhou Flood demonstrates that the current urban flood risk management system in Zhengzhou is no longer adequate to cope with extreme rainfall and flooding events and must be adapted to the fast-changing climate. Based on this case, the authors have generated the following hypothesis: four critical weaknesses exist in the current urban flood risk management system in inland cities in North China. Fundamentally, inland cities in North China have not yet recognized the immediate threat of global climate change. The low risk perceptions are manifested in three particular weaknesses in the flood risk management process, namely insufficient pre-disaster prevention and preparation, poor risk communication, and slow emergency response. Inland cities may be ill-prepared for extreme weather events before disasters happen, as reflected by Zhengzhou's incomplete flood control contingency plans and weak implementation of the plans. During the phase of meteorological warnings, risk communication about meteorological warning signals is often ineffective, lacking key information such as defense guides and reaching only a limited audience. Once emergencies have occurred, government agencies and other relevant organizations react slowly and passively, characterized by disconnections between the emergency response and meteorological warnings and the habitual mindset of waiting for orders from superior government, which delays rescue.

We believe that this case study serves as a good starting point for understanding the effectiveness of and areas of improvement in the existing flood management system in inland cities in North China. As suggested in the methodology section, the authors will investigate this study's hypothesis in the context of multiple case studies, one of which is the recent flood that hit China's Beijing–Hebei region from the end of July to early August 2023. The 2023 Beijing–Hebei flood confirms the findings from the Zhengzhou flood that local governments in inland cities in North China still retained low risk perceptions of extreme weather events, which again manifested in the lack of pre-disaster prevention and preparation. Despite there being more comprehensive contingency plans in Beijing compared to Zhengzhou, the flash flood drills organized by district governments in Beijing showed their underestimation of the intensity of flooding. For instance, prior to the flood, the Government of Changping District in Beijing had organized flash flood drills in seven flash flood geological disaster key-risk villages, but the simulation scenarios for these drills were only 50 mm or 70 mm precipitation within 3 h, while in reality the maximum hourly precipitation in many parts of the region ranged between 40–90 mm, or even above 100 mm [50]. Likewise, the 2023 Beijing–Hebei flood revealed that there was room for improvement in the risk communication and notification system. Although the meteorological early warning dissemination system in Beijing significantly improved since 2012 and proved effective during the 2023 flood, the huge economic losses incurred by businesses and residents in the flood detention basins in Hebei suggest the need for more timely coordination and risk communication among cities in the same river basin so that residents in flood detention areas can be informed of evacuation plans well in advance and businesses can make plans to transfer goods on time [51].

Amid global climate change, many cities will face a combination of intensifying climate change impacts and rapid urban developments in the coming decades, and the frequency of extreme weather events akin to the 20 July 2021 Zhengzhou Flood is likely to increase. Therefore, all cities could draw lessons from the Zhengzhou Flood case. This requires first and foremost updating risk perceptions of extreme weather events. Managing flooding risks is not unique to coastal cities; even inland cities with arid climates should be more alert to extreme rainfall and flooding events in the future. In particular, extreme rainfalls and floods are no longer low-probability, low-impact “black swan” events, but are turning into high-probability, high-impact “gray rhino” events. Once risk perceptions are updated, government agencies as well as other organizations will realize the importance of erring on the side of caution and exercising discretion when needed, e.g., immediately shutting down subway and tunnel operations when the highest levels of meteorological warning signals are sent or when early signs of danger appear, whichever happen first. Second, given the catastrophic impacts of extreme weather events, cities should devote most of their efforts to pre-disaster prevention and preparation rather than emergency response during the disaster and post-disaster recovery. The pre-disaster preparation work should start with the revision and implementation of contingency plans that fully consider possible disaster scenarios as well as explicitly specifying responsibilities of different agencies and actors. Third, managing the risk of extreme weather events requires timely and effective risk communication, especially during the phase of meteorological forecasting and warnings. Fourth, extreme weather events evolve quickly and leave very limited time for decision-making. Government agencies and relevant parties must respond in an agile manner and make immediate, resolute decisions, which might be achieved through synchronizing emergency responses with meteorological warnings.

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Appendix A Rainstorm Warning Signals in China

Rainstorm Signal	Icons	Activation Conditions	Defense Guides
Red		Precipitation in the next 3 h will exceed 100 mm or has already exceed 100 mm and is likely to continue.	1. The government and relevant departments shall carry out emergency and rescue work in accordance with their duties to prevent rainstorms; 2. Stop gatherings, classes, and business (except for special industries); 3. Carry out the prevention and rescue of disasters such as mountain torrents, landslides, and mudslides.

Rainstorm Signal	Icons	Activation Conditions	Defense Guides
Orange		Precipitation in the next 3 h will exceed 50 mm or has already exceeded 50 mm and is likely to continue.	1. The government and relevant departments should implement rainstorm prevention emergency work according to their duties; 2. Cut off the dangerous outdoor power supply and suspend outdoor operations; 3. Organizations in dangerous areas should suspend classes or business, and take special measures to protect the safety of students, infants and other workers who have arrived at school; 4. Carry out drainage of waterlogging in cities and farmland, and take precautions against possible disasters such as mountain floods, landslides, and mudslides.
Yellow		Precipitation in the next 6 h will exceed 50 mm or has already exceeded 50 mm and is likely to continue.	1. The government and relevant departments should carry out rainstorm prevention work in accordance with their duties; 2. The traffic management department shall adopt traffic control measures on heavy rainstorm sections according to the road conditions, and implement traffic guidance on the road sections with stagnant water; 3. Cut off dangerous outdoor power supplies in low-lying areas, suspend outdoor operations in open areas, and transfer people in dangerous areas and residents of dangerous houses to safe places to avoid rain; 4. Check the drainage system of cities, farms, and fish ponds, and take necessary drainage measures.
Blue		Precipitation in the next 12 h will exceed 50 mm or has already exceeded 50 mm and is likely to continue.	1. The government and relevant departments shall prepare for rainstorm prevention according to their duties; 2. Schools and kindergartens take appropriate measures to ensure the safety of students; 3. Drivers should pay attention to road water and traffic jams to ensure safety; 4. Check the drainage systems of cities, farmlands, and fish ponds, and prepare for drainage.

Source: [42].

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