Time-Series Analysis of Urban Precipitation and Waterlogging Risks in Railway Culvert Areas: A Case Study of Zhengzhou

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Abstract

Urban flooding has become an increasingly pressing issue under the combined influeces of climate change and urbanization. This study focues on Urban flood in Zhengzhou, a city as major transportation hub in China, where railway culverts represent critical infrastructure prone to waterlogging during extreme storm events. Utilizing ten years(2015-2024) of hourly precipitation data obtained from NASA, this study conducts a comprehensive time-series analysis to explore seasonal and interannual trends in rainfall intensity and frequency. A disaster model was developed to simulate flood formation processes in culvert areas, integrateing precipitation, land use, drainage, and terrain data. The model identifies a consistent temporal pattern: in most flood events, waterlogging occurred when 30–50% of the total rainfall duration had elapsed. The well-known July 20, 2021 ("7·20") event was found to be an outlier, but overall, the frequency of extreme precipitation has shown signs of increase in recent years. These findings offer a new perspective for characterizing extreme rainfall and provide reference values for early warning systems and urban flood resilience planning.

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CCS Concepts

• **Computing methodologies** → Modeling and simulation; Simulation evaluation.

Keywords

Urban floods, Precipitation data, Zhengzhou railway culverts, Disaster analysis

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1 Introduction

With the development of global climate change and urbanization, the risk of urban floods has increased [1]. Most scholars believe that climate change is the main cause of urban floods. The water cycle is significantly affected by climate change, leading to the occurrence of extreme weather events in recent years, especially extreme rainfall [2]. Furthermore, there are many studies on analyzing climate change to predict the water cycle. Some scholars believe that the cause of urban floods can be attributed to unreasonable urban planning, as the service level of the urban drainage system cannot meet some heavy rainfall [3-4]. Some hydrodynamic models have been established to simulate or predict flood disasters [5-6]. In 2023, Volos, Greece, suffered two storms within 15 days - Daniel (September 4-9) and Elias (September 24-28), which severely damaged infrastructure, caused transportation disruptions, and exacerbated already tense urban systems [7]. Jingxuan Zhu et al. studied Lishui, China's urban area, linking flood-induced traffic disruptions to rainfall duration and congestion time through simulation data [8]. From a flood risk management perspective, urban resilience—the system's capacity to predict, absorb, adapt to, and recover from flood impacts—has driven proposals like Sponge City Plans (SCPs) and green infrastructure [9]. However, these remain generalized and lack quantitative specificity.

Zhengzhou has not only become a bridge for north-south transportation, but also a hub for east-west communication, bringing tremendous impetus to the local economy [10]. The appearance of the Zhengzhou 720 catastrophic flood has attracted more and more researchers' attention to the city of Zhengzhou [11]. Zhengzhou is a city with strong transportation, and the impact of floods on it is significant, which also puts higher demands on the road construction in Zhengzhou [12]. The high-speed railway is an important transportation construction in Zhengzhou, which makes its railway culverts of high research value.

Existing flood related research mainly focuses on analyzing precipitation processes and intensities separately [13-14], or improving urban infrastructure structures through model predictions [15]. There is basically no analysis of precipitation processes through disaster simulation. This study evaluates precipitation data through disaster analysis of railway culverts in Zhengzhou, and defines extreme precipitation from another perspective.

This study analyzes the ten-year (2015-2024) precipitation data of Zhengzhou city. This study developed a disaster model that simulates flood processes by integrating rainfall data with land use, drainage infrastructure, and terrain information, with a particular focus on high-risk railway culvert areas. This study further imported time-series precipitation data for dynamic simulation, and analyzed the precipitation data in reverse from the simulation results. This study introduces a new perspective and analyzes the proportion of time from rainfall to waterlogging, providing practical reference for early warning systems and urban planning decisions in future extreme climate situations.

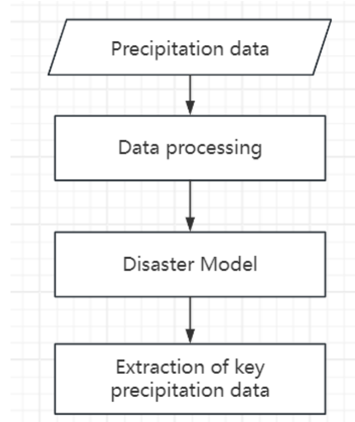

Figure 1: Research framework.

2 Research method

2.1 Research framework

The research framework of this study is shown in Figure 1. This study preprocesses precipitation data to form time-series data and imports it into a disaster model, extracting key precipitation data through the disaster model.

2.2 Disaster model

This is the framework of the disaster model, divided into four levels: **data preparation**, **data processing, model simulation**, and **result analysis**, as shown in Figure 2.

In the **data preparation** phase, collect precipitation data, drainage system data, building data, and land type data, where precipitation data comes from hourly precipitation data recorded by NASA satellites (2015-2024).

In the **data processing** stage, the study area is divided into sub basins using terrain and hydraulic connectivity, and key parameters (infiltration rate, runoff coefficient, slope gradient) are assigned.

The **model simulation** phase involves importing processed datasets into disaster models to simulate rainfall runoff processes. This study imported time series precipitation data into the model. Through model simulation, the time period of flood occurrence can be analyzed, such as the extreme precipitation period in July 2021.

Finally, the **result analysis** phase evaluates and visualizes flood dynamics, the start time and space of flooding, and evaluates their applicability in early warning and infrastructure planning.

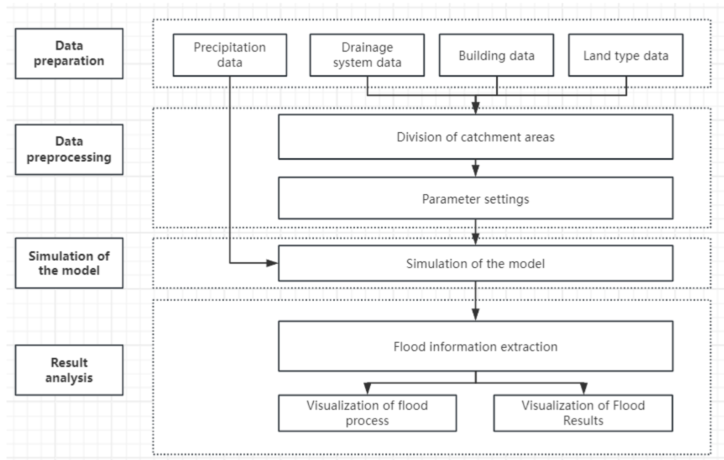

Figure 2: Disaster Model.

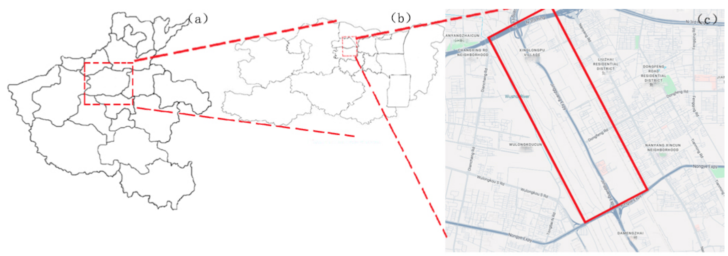

Figure 3: The research area:(a)Henan Province, (b)Zhengzhou City, (c)The research area.

2.3 Time series analysis algorithm for precipitation data

According to this study, Algorithm 1 is a simple process principle algorithm. It provides a precipitation data time series analysis algorithm that can extract specific precipitation data time periods that may lead to flood disasters.

Algorithm 1 Time series analysis algorithm for precipitation data

Start
  Hourly rain check
  No rain ⟶ Check if recording
   Rain detected ⟶ Record data
    First rain ⟶ New record
      Ongoing rain ⟶ Append data
      Trigger flood check
        Exceeds terrain storage ⟶ Flood
          Exceeds drainage limit ⟶ Flood
    Rain stops ⟶ Save data if flagged

3 Case study

3.1 Target site analysis

3.1.1 The research area. Zhengzhou has gathered seven high-speed railways, including the Beijing Guangzhou high-speed railway, Zhengzhou West high-speed railway, Zhengzhou Xuzhou high-speed railway, Zhengzhou Chongqing high-speed railway, Zhengzhou Hefei high-speed railway, Zhengzhou Jinan high-speed railway, and Zhengzhou Taiyuan high-speed railway, making Zhengzhou's transportation status even more important.

The research area is located in the urban area of Zhengzhou, covering an area of approximately 7631360 square meters. and depicted in Figure 3.

3.1.2 Railway culvert. Due to the existence of railway, vehicles and pedestrians can only pass through low-lying railway culverts to reach the other side of the railway. So railway culverts are a key area of research and also a high-risk area for disasters.

As shown in Figure 4(a), the red part represents the high-speed railway, and the blue part represents the road below the railway. As shown in Figure 4(b and c), the government built a culvert to allow vehicles and pedestrians to reach the other side of the railway. In order to avoid the hazards caused by steep slopes, the culvert has a long slope, which results in a large area of sub catchment in this region.

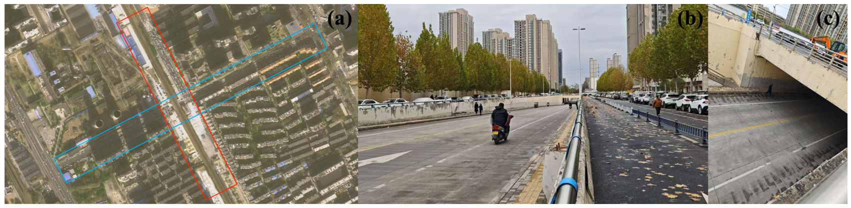

Figure 4: (a)Satellite image of Songzhai South Street Culvert; (b and c)Songzhai South Street Culvert.

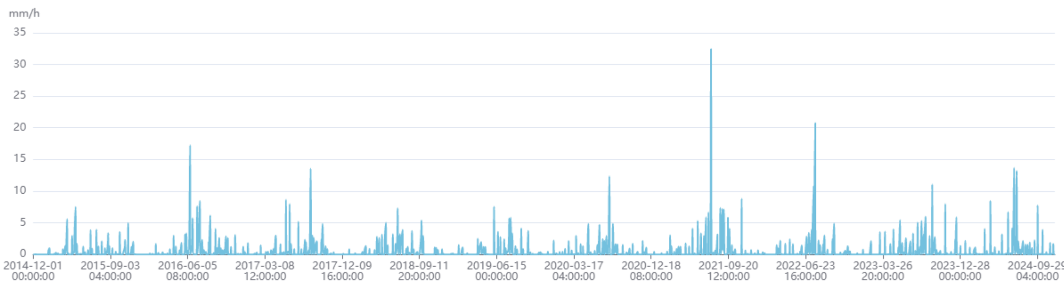

Figure 5: Precipitation data.

Table 1: Information of Songzhai South Street Culvert.

Item	Value
length	630m
width	15m
depth	4.1m
gradient	1.30%

Table 2: Precipitation data.

Item	Value
Data sources	NASA
Location	(113.633 E, 34.7825 N)
Time	2015 to 2024 (10 years)

Table 1 shows the information of the culvert on Songzhai South Street, which facilitates the construction of a disaster model in this study.

3.2 Precipitation data

3.2.1 Data sources. As shown in Table 2, this study collected precipitation data from NASA for 10 years from 2014 to 2024. The reduced dimensional coordinate is 113.633 E, 34.7825 N.

As shown in Figure 5, precipitation shows a 10-year cyclical pattern with higher summer and lower winter levels, while notable peaks post-2021 require further refined analysis.

3.2.2 Statistics by hour. This study compiles precipitation data by the hour and categorizes the larger amounts of precipitation.

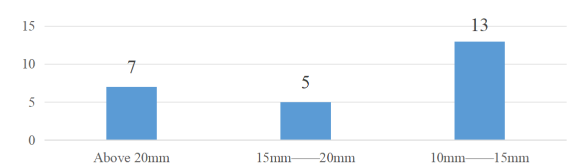

Figure 6: Statistics of hourly precipitation.

As shown in Table 3, there were 7 instances of hourly precipitation exceeding 20mm. There are 5 instances of precipitation between 15mm and 20mm, and 13 instances of precipitation between 10mm and 15mm.

It can be seen that there are a total of 25 times when the hourly precipitation exceeds 10mm, and 7 times when it exceeds 20mm.

3.2.3 Statistics by day. This study summed the precipitation data for each day and obtained the results shown in Figure 7.

As shown in Figure 7, the highest daily precipitation was on July 20, 2021, at 310.59mm. Next are July 8th, 2024 and July 21st, 2021, which are 107.55mm and 99.67mm respectively.

As shown in Figure 8(Left), the number of days with daily precipitation between 50-60mm is 3, and the number of days with daily precipitation between 60-70mm is 5. In addition, the number of days with daily precipitation between 80-90mm, 90-100mm, 100-110mm, and greater than 150mm is 1. This study analyzed the distribution of years with daily precipitation exceeding 50mm, as shown in Figure 8(Right). It can be seen that there were 2 occurrences in 2016, the highest in 2021 with 5 occurrences, 1 occurrence in 2022, 3 occurrences in 2023, and 1 occurrence in 2024. It can be seen that since 2021, the number of rainstorm in recent years has become more.

Table 3: Hourly precipitation.

Hourly precipitation	Number of hours	Year
Above 20mm	7	2021(6), 2022(1)
15mm-20mm	5	2016(1), 2021(4)
10mm-15mm	13	2016(1), 2017(1), 2020(1), 2021(3), 2022(3), 2024(3)

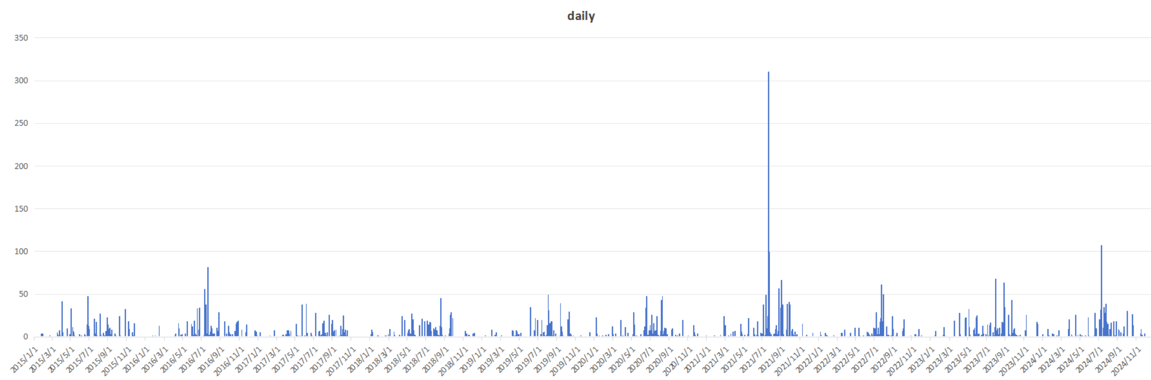

Figure 7: Daily precipitation.

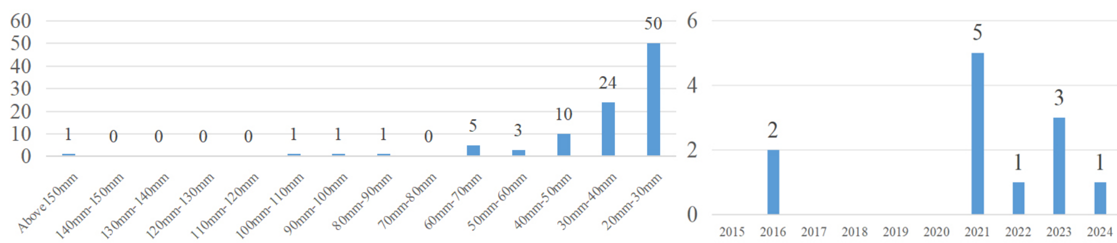

Figure 8: (Left) Daily precipitation statistics, (Right) Daily precipitation statistics by year.

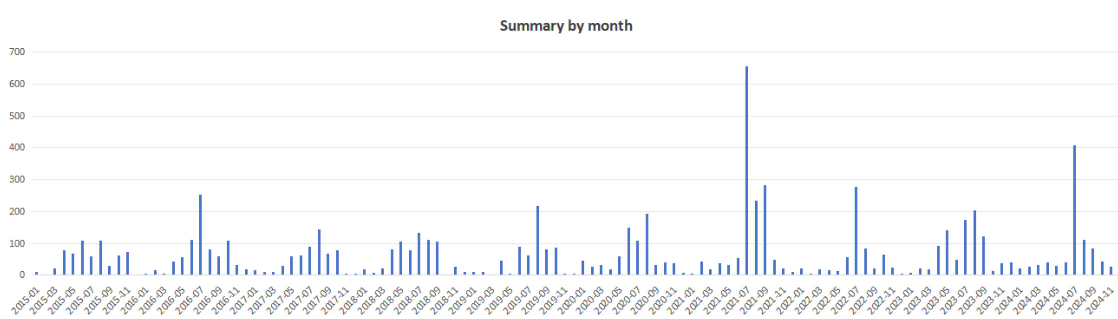

Figure 9: Monthly precipitation statistics.

3.2.4 Statistics by month. This study calculates precipitation on a monthly basis and obtains the data shown in Figure 9.

From Figure 9, it can be seen that within 10 years, the highest precipitation occurred in July 2021 and July 2024, with precipitation rates of 656.37mm and 407.10mm, respectively. This study further averaged the monthly precipitation and obtained Figure 10.

As shown in Figure 10, the highest precipitation occurs in July each year, with an average of 221.88mm.

3.2.5 Statistics by year. This study calculates the annual precipitation and obtains Figure 11.

As shown in Figure 11, the annual precipitation is relatively average, around 600mm-900mm, with a higher amount of 1443.80mm in 2021.

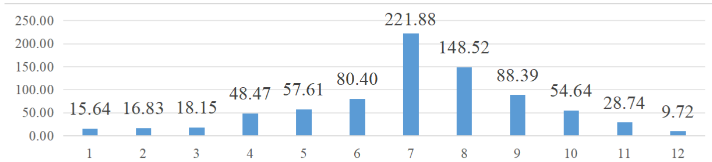

Figure 10: Average monthly precipitation.

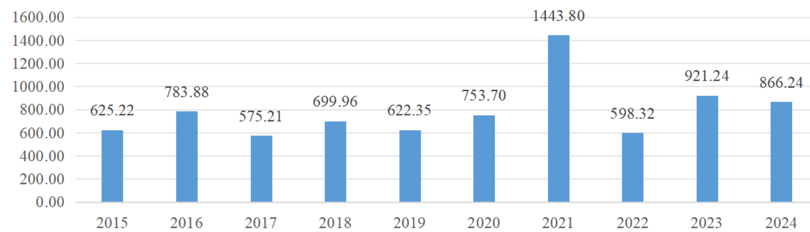

Figure 11: Annual precipitation.

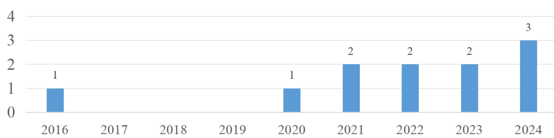

Figure 12: Annual precipitation.

4 Results

4.1 Precipitation Characteristics Over 10 Years

We conducted a multi-scale analysis of rainfall patterns using precipitation data from 2015 to 2024: **Hourly Rainfall**: There are a total of 25 instances where the speed exceeds 10mm/h, with 7 instances exceeding 20mm/h. Specifically, six of them occurred on July 20, 2021, confirming the severity of the "7 20" incident (Table 3, Figure 6). **Daily Rainfall**: The highest single-day precipitation was recorded on July 20, 2021 (310.59 mm), followed by July 8, 2024 (107.55 mm, Figure 7). **Monthly Distribution**: Rainfall was most concentrated in July and August, the average rainfall in July is 221.88mm, but July 2021 recording the highest monthly precipitation (656.37 mm). (Figure 9–10). **Annual Trend**: The overall annual precipitation remained within a stable range of 600-900 mm, but the annual precipitation in 2021 was 1443.8 mm, indicating an extreme value for that year (Figure 11).

4.2 Flood Simulation and Waterlogging Frequency

In the flood disaster model, this study sets terrain parameters to further adjust the sub catchment area. After importing the time-series precipitation data, we captured the precipitation segments where waterlogging occurred.

According to Figure 12, the frequency of waterlogging mostly occurs after 2020, with the highest number occurring in 2024, which is 3 times.

4.3 Temporal Dynamics of Rainfall to Waterlogging

4.3.1 Precipitation time series image. This study drew images based on the obtained precipitation data, as shown in Figure 13.

These 11 line segments represent the temporal distribution of precipitation data for 11 waterlogging events. This green line is the 720 event, which can be seen to have at least two peak precipitation periods. As shown in Figure 14, the impact of the three precipitation events on August 1, 2020, July 17, 2021, and August 28, 2021 was significant and long-lasting. Among them, the largest event on July 17, 2021.

4.3.2 Time analysis before waterlogging. The proportion of time before waterlogging is worth studying. This study calculated the proportion of time before 11 waterlogging events. This metric may serve as a valuable input for early warning systems, helping authorities anticipate when waterlogging is likely to occur during extreme precipitation.

As shown in Figure 14, there is a time lag between the onset of precipitation and the formation of waterlogging. The majority proportion is 30%, with 2 incidents at around 54% and 1 incident at 76.0%.

5 Conclusion and Discussion

From the precipitation data, the annual precipitation in Zhengzhou has not changed much in the past 10 years, except for a relatively high amount in 2021. The precipitation data is highest in July and August, with less precipitation in winter.

This study conducted time series analysis on precipitation data from 2015 to 2024. Based on the analysis results, this study obtained time series precipitation data that may lead to floods.

First, this study evaluates precipitation data through disaster analysis of railway culverts in Zhengzhou, and defines extreme precipitation from another perspective. In terms of heavy rainfall, it was found that the 720 event in 2021 was just a special case. In recent years, extreme precipitation has existed but not frequently,

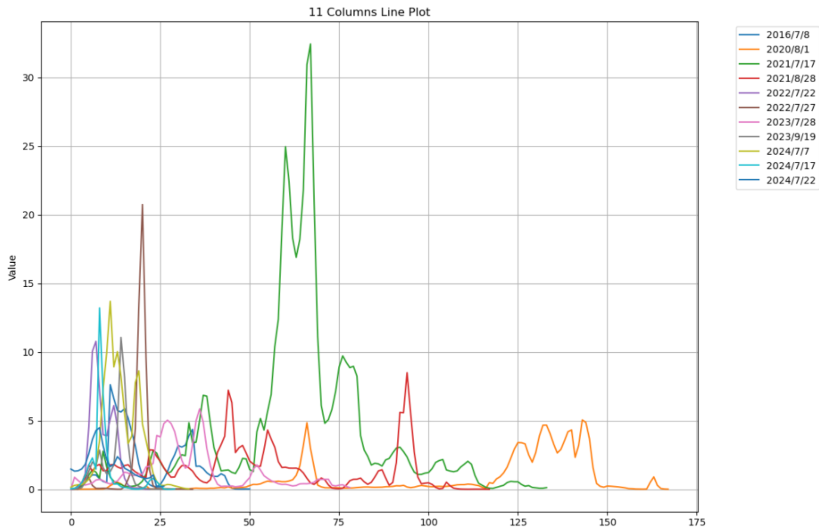

Figure 13: Precipitation time series image.

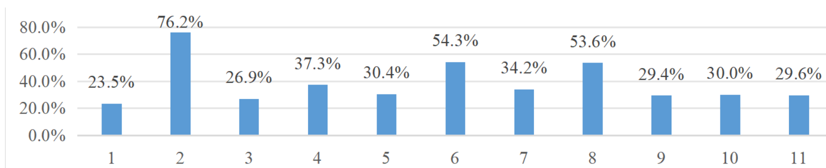

Figure 14: Precipitation time series image.

and there is no apparent trend of growth. However, based on the results of this study, combined with the specific impact of flood models, except for the 720 event in 2021, extreme precipitation has increased in recent years.

Second, from the beginning of precipitation to the occurrence of waterlogging, the proportion of time is mostly between 30-50%, which has certain reference significance for future disaster prevention.

Third, flood simulation display for the culvert area (especially Songzhai South Street). The culvert design is slender and low-lying, which not only increases the sub catchment area but also increases the risk of water accumulation. This indicates that in future climate scenarios, particular attention should be paid to regions with such structures.

However. the disaster model in this study is not comprehensive enough, as it does not cover the entire drainage system and does not consider situations such as backflow. The flood and waterlogging model used in this study did not specifically calculate its economic or social impacts. In future research, the disaster model will be improved.

This study can support urban planners and emergency management officials in revising drainage design specifications, improving real-time warning systems, and enhancing the resilience of infrastructure under climate change conditions. Regarding flood control of railway culverts, urban planners can focus on the surrounding areas of railway culverts based on Sponge City Planning (SCP) and build more green infrastructure near them. By improving the terrain structure near railway culverts, such as raising the elevation of the entrance to the railway culvert, the area of the divided secondary catchment will be reduced, and some of the original catchment will be incorporated into other areas. Policy makers can analyze and predict disasters, detect their occurrence in a timely manner, and intervene in traffic near railway culverts in a timely manner (for example, before the total precipitation duration reaches 30%). Although this method cannot change the occurrence of floods, it can minimize the damage caused by floods to transportation as much as possible.

Future work will expand the disaster model to include a wider geographic scope, incorporate real-time hydrodynamic responses, and assess economic losses from flood events. These improvements will enhance the practicality of the model in comprehensive urban flood risk management.

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