Comparing Engineering and Resilience Strategies for urban Flood Control: A Case Study of the "23·7" Flood in Mentougou, Beijing

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ABSTRACT

Frequent extreme rainfall due to global climate change has heightened challenges for urban flood control. The "23·7" extreme rainfall in July 2023 in Beijing's Mentougou District caused severe mountain flash floods. Post-disaster analysis suggests that enhancing flood control systems, such as building peripheral flood interception ditches, and adopting resilience strategies like improved urban vertical planning, can boost flood response and reduce losses. Using 2-D shallow water numerical model associated with measured data from the "23·7" rainfall event and high-resolution terrain models, this study revisits the disaster in the Mentougou River Basin and simulates the effects of engineering measures (e.g., flood interception ditches) and resilience strategies (e.g., urban vertical planning). Simulations reveal that both strategies reduce urban flood impacts, but the engineering approach alters water catchment patterns in urban area, significantly increasing downstream peak flows for rapid discharge, while the resilience strategy mainly modifies the spatial distribution of flood-affected areas with minimal impact on catchment characteristics. Furthermore, the paper discusses the applicability of various flood control strategies in urban flood planning based on the findings.

KEYWORDS: Extreme rainfall; Urban flood disasters; Engineering solutions; Resilience strategies

1 INTRODUCTION

Under the combined influence of Typhoon Doksuri moving northward and a cold air mass, from late July to early August 2023, the Haihe River Basin, which is located in northern China and encompasses megacities such as Beijing and Tianjin, experienced heavy rainfall, leading to a basin-wide catastrophic flood. The cumulative areal rainfall reached 155.3 mm, with 22 rivers in the Haihe River Basin exceeding warning levels, and 8 rivers recording their highest flood levels since data collection began. This event marked the largest flood in the Haihe River Basin since 1963(Web-1).

From 20:00 on July 29 to 07:00 on August 2, Beijing encountered an exceptionally heavy rainstorm lasting 83 hours, with an average rainfall of 331 mm across the city, accounting for 57% of its multi-year average annual rainfall of 585 mm. The extreme rainfall triggered historic floods in multiple tributaries and main streams of river basins, including the Yongding River, Dashi River, and Juma River. The floods were characterized by rapid onset, high volume, and peak intensity. For instance, the flow discharge at Lugou Bridge on the Yongding River surged from 1,000 m^3/s to a peak of 4,650 m^3/s within just two hours, exceeding the once-in-50-year flood standard and marking the highest peak flow recorded since 1925 (Web-2, Junmei et al., 2024).

The Mentougou District, which is a distant suburb in western Beijing, with mountainous areas accounting for 98.5% of its total land area (Web-3), was severely affected by the catastrophic "23·7" flooding. The catastrophic torrential rains caused comprehensive damage across all 178 administrative villages and 126 residential communities in Mentougou District. Approximately 310,000 people were affected, accounting for about 77% of the district's total population. A total of 7,787 houses collapsed, with an additional 12,925 severely damaged (Mentougou District People's Government of Beijing Municipality, 2024). In the urban area of Mentougou, gullies served as flood discharge channels, causing severe damage to river courses, roads, buildings, and other infrastructure along both sides, flatter areas with lower elevation experienced varying degrees of inundation.

Post-disaster assessment indicated that, a major engineering shortcoming was the lack of a comprehensive flood interception system, particularly on the upstream side of the urban built-up area. In the absence of functional interception ditches, floodwaters from the mountains flowed directly into the urban area along natural drainage channels and roads, causing severe damage. Furthermore, resilience measures such as the urban grading and emergency management were insufficient, roads intersecting the river channel essentially functioned as flood dispersal pathways once overtopping occurred. The failure to implement timely emergency interventions, such as deploying barriers at critical road-river intersections, allowed floodwaters to spread unchecked into the urban area, thereby expanding the impact.

In this work, a 2-D flood simulation is carried out to revisit the disaster in the Mentougou River Basin, Urban area of Mentougou. Furthermore, effects of engineering measures (e.g., flood interception ditches) and resilience strategies (e.g., urban vertical planning) on resisting "23·7" flood are tested.

2 SIMULATION

2.1 Basin information

In this work, we focus on the Mentougou River Basin in the middle of the Mentougou urban area, as shown below in Figure 1. Mentougou River is a tributary of Yongding River, it's also one of the four main flood rivers of Mentougou urban area. Mentougou River Basin is isolated by mountains around on the north, west and south, and the east of the basin stands the right bank of the Yongding River. Mentougou River flows from west to the east, river length is 10.3 kilometers, river slope ranges from 1‰ to 5‰, basin area is 22 square kilometers,

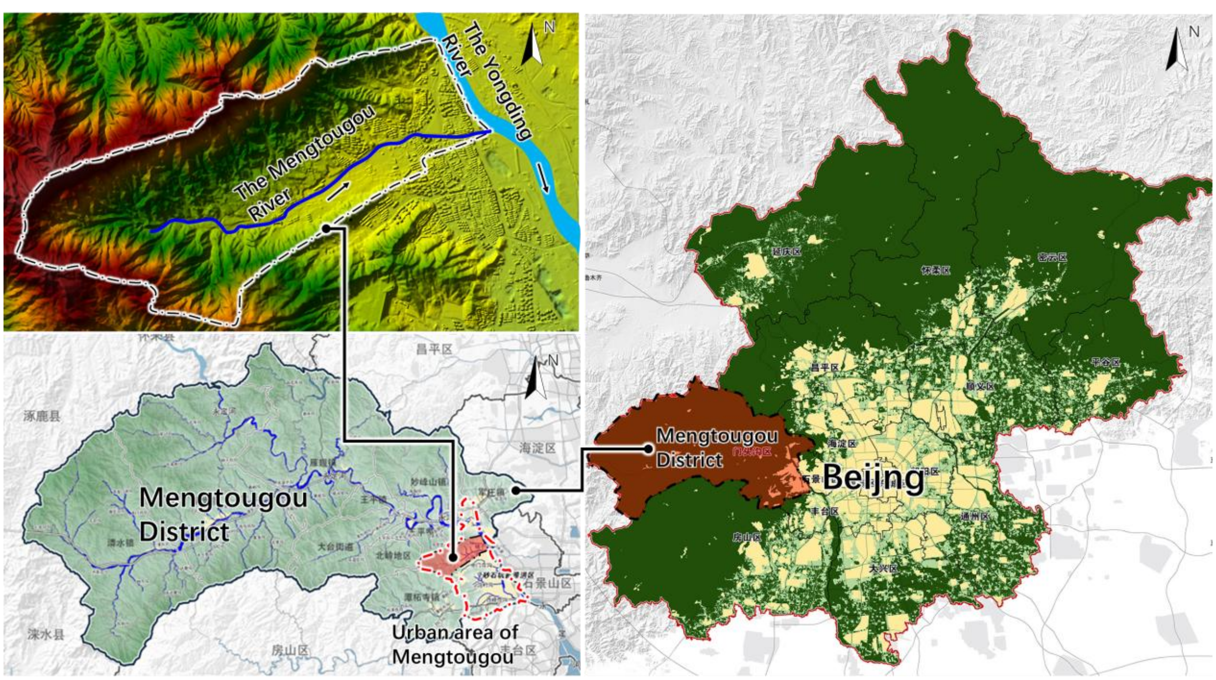

Figure 1: Mentougou river base and it's location in Beijing (Web-4)

According to the rainfall data of the Beijing Geological Hazard Monitoring Rainfall Stations, during the "23·7" extreme rainfall, the 24 hours and 72 hours averaged rainfall in the urban area of Mentougou are 426 mm and 595 mm, and the maximum rainfall occurred at the Dongxinfang station (Mentougou River basin), with average accumulations amounting to 665 mm in 24 hours and 928 mm in 72 hours. Heaviest rainfall happened at about 10:45, July 31st, 2023.

2.2 Model and parameters

The Hec-Ras 2-D flow model (Hydrologic Engineering Center, 2024) is chosen to carry out the simulation of the "23·7" flood in Mentougou River Basin. Terrain DEM of Mentougou River Basin with 2-meter resolution is applied in the model. Basic calculation mesh scale in the model is about 100 m * 100 m, while mesh along the river and roads are refined to 2 m * 2 m to get a better simulation detail. About 125 thousands meshes in total are used in the calculation.

In this work, the simulation directly incorporates rainfall data recorded by the Beijing Geological Hazard Monitoring Rainfall Stations. This dataset has a 5-minute temporal resolution and covers the period from 00:00 on July 29th to 24:00 on August 2nd. The Thiessen polygon method is used to determine the areal distribution of rainfall. The Deficit and Constant loss method is used for runoff calculation, loss rate is calculated according to the *Beijing Hydrologic Manual* (Beijing Water Authority, 2005), which is 5mm/h in this work.

Land use in the basin is divided into 3 types and related roughness coefficients are listed below.

Table 1 Land use classification and related roughness coefficients in Mentougou Basin

Land use classification	**roughness coefficients**
Urban development land	0.015~0.035
Forest land	0.035~0.25
River and water land	0.035

2.3 Validation

Due to the limited hydrological monitoring facilities in Mentougou District during the disaster, data on inundation depth and flow discharge collected from post-disaster investigations were used to calibrate the model.

Quantitative water depth measurements were unavailable during the flood event, although qualitative calibration of this model was conducted based on the video footage and photographs documenting the inundation extent and depth (Yi et al. (2024)). However, a post-disaster field survey identified a flood level marker at the entrance of a downstream community along the Mentougou River, which recorded the maximum inundation depth from the "23·7" event. This recorded depth (0.75 m) was subsequently used as a benchmark for the quantitative calibration of the model, by comparison with the simulated depth at the same location.

As shown in Figure 2, the simulated inundation depth at the community gate peaked at 11:20 on July 31st, exhibiting a lag of approximately half an hour behind the rainfall peak. The maximum simulated depth is approximately 0.86 m, showing good agreement with the post-disaster measurement of 0.75 m.

The flow hydrograph for the outlet section of the Mentougou Basin was also used to calibrate the model. The simulated flow hydrograph at the outlet section of the Mentougou Basin is shown in

Figure 3. The simulated peak flow occurred at about 11:40 am July 31st, 2023, reaching 452.5 m^3/s. This value is close to the post-disaster estimate of 512.6 m^3/s by Jiahong et al. (2024). Considering the complexity of the actual underlying surface conditions, the discrepancy is within an acceptable range, demonstrating that the models and parameters used in this study are reliable for reproducing the flood event.

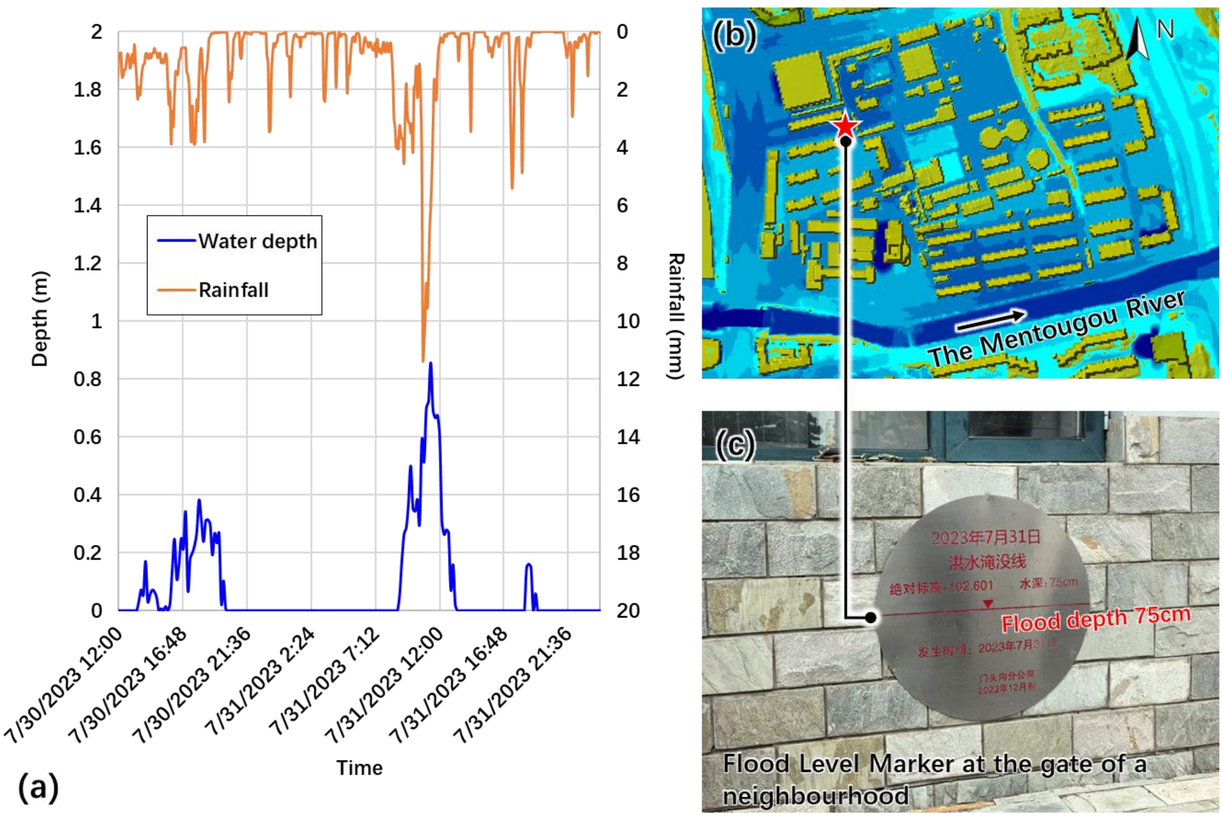

Figure 2: (a) Temporal variation of simulated flood depth and rainfall at a flood level marker during the "23·7" flood in the downstream of Mentougou River. (b) Location of the flood level marker. (c) The picture of the flood level marker.

2.4 Case study

During the "23·7" flood event, the lack of flood interception ditches allowed mountain floodwaters to flow directly into adjacent built-up areas. Meanwhile, roads perpendicular to the river acted as conduits for flood dispersal, channeling water toward the city center. Therefore, constructing flood interception ditches around built-up areas, and elevating key road junctions near rivers to prevent flood ingress, would be effective in reducing flood damage.

This study investigates the performance of engineering measures (e.g., flood interception ditches) and resilience strategies (e.g., urban vertical planning) during the "23·7" extreme rainfall event. To this end, two simulation scenarios are established, as illustrated in

Figure 3.

Case 1: Implementation of planned ditches. Flood interception ditches, which were planned but not constructed before the disaster, are added to the model around the built-up area of the Mentougou River Basin to control mountain floodwaters.

Case 2: Deployment of temporary barriers. As a resilience strategy to modify local topography and block flood ingress, 1-meter-high temporary barriers are placed around the most flooded downstream region as well as the nearby road intersections with the river channel.

The inundation area with maximum flood depth in

Figure 3 (a) to (c) is 3.2 km^2, 3.5 km^2 and 3.8 km^2, respectively. The flood interception ditches in case 1 effectively direct mountain floodwaters into the downstream river, resulting in less inundation compared to both the original scenario and Case 2; On the other hand, the flood barriers in case 2 also perform well in protecting the core built-up area. Flood barriers around core built-up area altered the flow direction, reducing the inundation area from 0.89 km² in the original case to 0.76 km² in Case 2. Furthermore, the maximum flood depth decreased by approximately 0.2-0.6 m within areas surrounded by flood barriers, as shown in Figure 4.

The flood flow volume hydrographs for all three cases are also presented in

Figure 3 (d). As we can see, the engineering measures implemented in case 1 significantly altered the watershed confluence characteristics. At the outlet section of Mentougou river, the peak discharge and flood volume in case 1 is 753.8 m^3/s and 8,672.1 m^3, respectively, representing increases of approximately 66% and 62% compared to the original scenario. This is because the ditches directed floodwaters from the upstream mountainous areas to the downstream river more efficiently, resulting in a substantial increase in both peak discharge and total flood volume.

In contrast, the resilience strategies in case 2 had little effects on the flood hydrograph, both the maximum discharge and flood volume in case 2 are comparable to those of the original simulation.

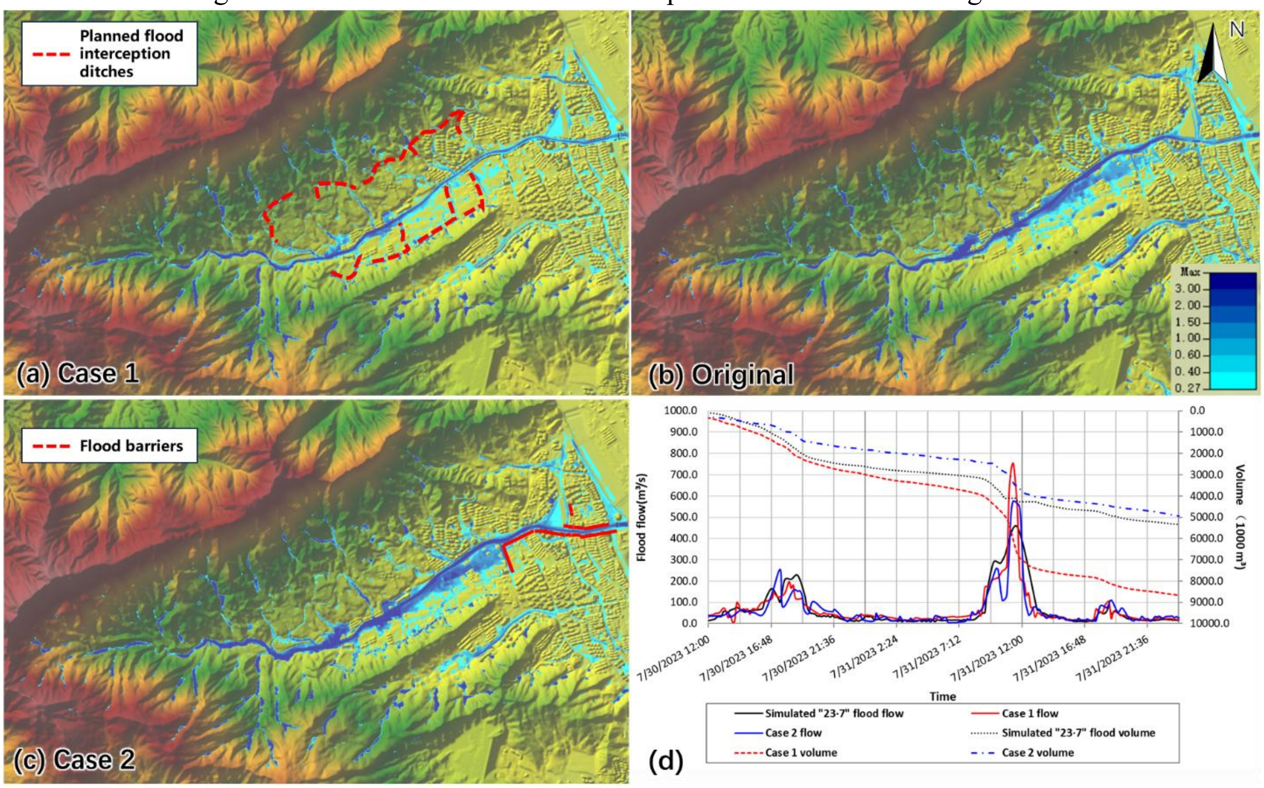

Figure 3: Simulation results of case 1 & 2, and the comparison with original "23·7" flood simulation. (a) ~ (c) are the maximum inundation depth maps of Mentougou river basin in case 1, original "23·7" flood simulation and case 2, respectively. (d) Comparison of flood flow volume hydrographs at the outlet section of Mentougou river between these cases.

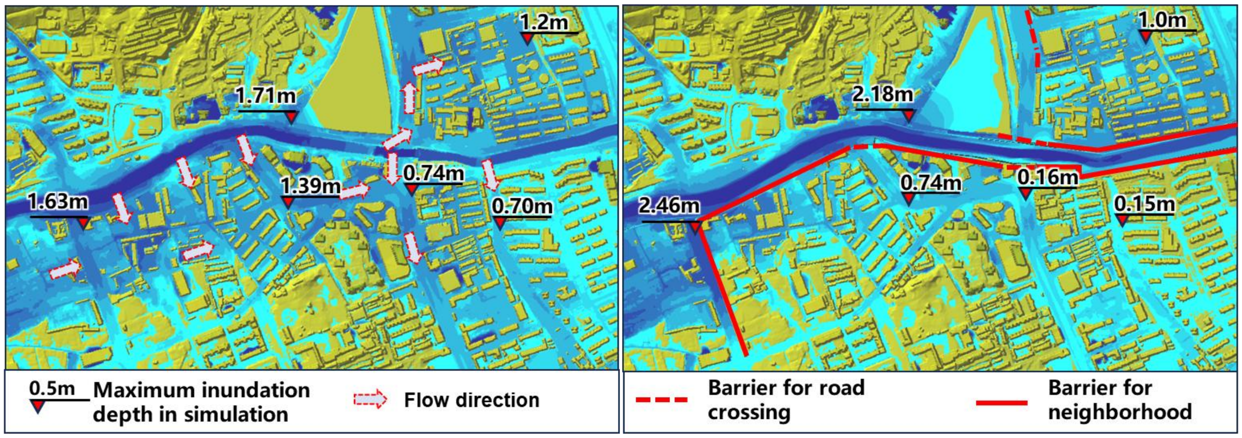

Figure 4: Simulation results in downstream built-up area of Mentougou: (left) original "23·7" flood simulation and (right) Case 2.

3 DISCUSSION AND CONCLUSION

In this work, engineering measures (e.g., flood interception ditches) and resilience strategies (e.g., urban vertical modification) are simulated to mitigate the "23·7" flood in the simulation. Both prove effective in reducing the inundation area and maximum flood depth in built-up areas. However, the flood interception ditches reduced flow resistance, allowing mountain flood to drain into the downstream river more easily. This led to a significant increase in peak discharge and flood volume downstream. In contrast, setting flood barriers around the most severely flooded built-up region—acting as a temporary elevation barrier—successfully blocked the flood but raised the local water depth, as shown in Figure 4.

The simulation results indicate that engineering measures such as flood interception ditches around built-up areas are more effective for flood risk mitigation in general. However, their implementation must be incorporated into an integrated flood control strategy, which requires concurrently strengthening the downstream flood defence system. On the other hand, resilience strategies like blocking flood by temporary flood barrier may be more suitable for areas with sufficient surrounding open space, given their potential to cause adverse impacts on adjacent zones.

In this study, the spatial configurations of the two simulation cases were determined based on the layout of flood interception ditches as planned in the urban flood control plan and the spatial distribution of urban built-up areas. Specifically, the engineering measures were primarily concentrated in the mountainous areas of the upstream basin, while the resilience strategies were mainly focused on the concentrated built-up areas in the downstream basin. The impact of this spatial disparity in the two types of measures on the hydrological processes of the river basin has not been fully explored in this paper and warrants further investigation in future research.

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