Decrease process analysis of urban system resilience based on the extreme flood simulation

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Abstract. Urban flood is growing worldwide due to climate change, rapid urbanization and population increase. Although the concept of resilience is an effective tool to deal with urban flood, urban flood resilience remains difficult to put into practice nowadays. The attenuation process of urban flood control capacity under the influence of flood is still a challenge. And the stage damage of flood resilience is strongly linked with the recovery of urban system to floods. But current studies failed to capture the change characteristic of flood resilience in time stage. Therefore, this study made stage damage analysis based on flood simulation and modelling in Jianye and Gulou District. Results reveal that Jianye has the higher inundated area and exposed population and asset to flood. Gulou shows more resilience to urban flood with flood return periods of 100 years. Moreover, the stage damage curve benefits the comprehensive understanding of loss and recovery process. This study provides a theoretical support for effective adaptive strategy to urban flood.

1. Introduction
Climate change has become more challenging and led to serious damage around the world [2]. The more frequent and intense extreme rainfall events result in the increase of flood disasters. Floods have accounted for the nearly half of the weather disasters over two decades worldwide [5]. In particular, urban flood is becoming one of the most common hazards in cities and induces plenty of harm to urban infrastructure, human life and social economy. Furthermore, the conflict between cities and urban flood will be particularly significant and more severe in the future [4] [5]. Despite the inevitability of urban flood, the concept of resilience is incorporated in urban flood management and provides the solution ideas of pre-disaster prevention and post-disaster recovery from the systematic perspective[1]. Urban flood resilience refers to the capacity of urban system to maintain function and structure, and resist the floods over a period of time during the flood events.

Flood resilience is difficult to operationalize [1] and one of the challenges is how flood resilience decreases with the impact of urban flood, since the stage damage of urban flood resilience is closely associated with the recovery and adaption of cities. The current studies related to stage damage of flood resilience primarily focused on the measurement of historical data and statistics after flood, but failed to reveal the time characteristic of flood resilience. The application of flood simulation and modelling could solve the limitation, and benefits to the comprehension of urban flood time characteristic. Geographic Information System (GIS) is widely used and could effectively reduce the uncertainty in the flood simulation [8]. Meanwhile, most studies paid less attention to the system characteristic of urban flood resilience and considered the city as the simple individual. But a city involves the complicated connection of different urban systems, and each subsystem also contributes to the
improvement of resilience, especially the infrastructure system [9]. Infrastructure not only survives from floods to maintain the function of urban system, but also covers losses caused by disasters, participating in post-disaster reconstruction and development [6]. Furthermore, the breakdown of infrastructure will pose the serious threat and lead to great losses during extreme flood events.

Nanjing has been affected by flood and suffered the considerable losses in recent years. It is urgent and necessary to deal with the conflict between floods and urban development. This study selected Jianye and Gulou District of Nanjing as the study area. We aimed to: (1) conduct the flood simulation and modelling based on the flood return periods of 100 years; (2) assess the urban flood resilience with different rainfall durations; (3) identify the damage factor of urban infrastructure during flood events and drew the stage damage curve of urban flood resilience. The findings of this study help to the comprehensive understanding of damage change in flood resilience and promote the effective adaptive strategy.

Figure 1. Study area.

2. Materials and Methods

2.1. Flood simulation and modeling

This study considered the extreme rainfall events in Nanjing and made urban flood simulation based on the return periods of 100 years. The design of extreme rainfall events originated from the rainstorm intensity equation in “China Outdoor Drainage Design Code” [8]. For the flood with 100-year return periods:

\[
q = \frac{10716.700(1+0.837 \cdot \log_{10} p)}{(t+32.900)^{1.011}} \text{ (1)}
\]

Where, \(q\) is the storm intensity (L/(s·hm²)), \(p\) is the return period (a), the value range is 2a~200a; \(t\) is the rainfall duration (min).

The rainfall durations of 0.5, 1, 1.5, 2, 2.5 and 3 h were for design in this study. Furthermore, inundation volume was calculated combined with region areas. Based on GIS, this study accomplished the flood simulation and modelling, and identified the flood depth and inundated area.

2.2. Calculation of urban flood resilience

Urban flood resilience measures the ability of urban system to maintain function and resist flood [7]. \(I_{UFR}\) consisted of two aspects, \(I_H\) and \(I_E\), and each aspect was calculated by the result of flood simulation and modelling. The equation is following:

\[
I_{UFR} = 1 - I_H^{n_1} \cdot I_E^{n_2} \text{ (2)}
\]
3. Where, $I_{URB}$ is Urban flood resilience, $I_H$ is Hazard, $I_E$ is Exposure, $n_1$, $n_2$ are the exponential weights: $n_1 + n_2 = 1$ ($n_1 = n_2 = 0.5$).

Hazard expresses the probability of being affected by flood consequence [1] and uses the rate of inundated area to the region area.

$$I_H = \frac{S_{\text{Flood}}}{S_{\text{Region}}} \quad (3)$$

Where, $I_H$ is Hazard, $S_{\text{Flood}}$ is the inundated area, $S_{\text{Region}}$ is the region area.

Exposure describes the impaired population and asset during flood events and reflects the relative loss degree in flood [3]. The built-up and arable land are the main exposed elements in urban areas.

$$I_E = \frac{S_{\text{Built-up}}+S_{\text{Arable}}}{S_{\text{Flood}}} \quad (4)$$

Where, $I_E$ is Exposure, $S_{\text{Built-up}}$ is the inundated built-up land, $S_{\text{Arable}}$ is the inundated arable area.

2.3. Stage damage analysis of urban flood resilience

Urban infrastructure was selected for stage damage analysis of urban flood resilience. Infrastructure was classified into seven sectors[9]: Energy, Transportation, Information and Communication, Water Supply and Treatment, Education, Health and Medical and Emergency Response in this study.

This study captured the relationship of flood depth, inundated area and urban flood resilience with different rainfall durations. Furthermore, the damage factor (inundation rate) of seven sectors was obtained by flood simulation. Regression analysis was used to analyse the relationship among urban flood resilience and flood depth, inundated area and damage factor with rainfall durations from 0.5 to 3.0 h, and this study drew the stage damage curve on this basis.

3. Results & Discussion

3.1. Flood depth and inundated area

Figure 2 shows the result of flood simulation, and Figure 3 presents the flood depth and inundated area of Jianye and Gulou District with flood return periods of 100 years. At the rainfall duration of 0.5 h, the inundated area in Jianye and Gulou is 34.60 and 13.28 km², respectively, and flood depth is 0.08 m. At 1.0 h, the inundated area covers 54.51 and 20.30 km², and flood depth reaches 0.14 m. At the rainfall duration of 1.5 h, the inundated area occupies 63.14 and 23.48 km², and flood depth achieves 0.18 m. At 2.0 h, inundated area in Jianye and Gulou takes up 67.66 and 25.36 km² and flood depth reaches 0.22 m. At the rainfall duration of 2.5 h, the inundated area accounts for 70.36 and 26.82 km², and flood depth achieves 0.24 m. At 2.0 h, inundated area in Jianye and Gulou makes up for 72.46 and 28.05 km².
and flood depth reaches 0.27 m. The more inundated area in Jianye means the more exposed population and asset to flood, which could result in the higher damage and loss and reflect the difference between two regions.

Figure 3. Flood depth and inundated area of Jianye (left) and Gulou District (right).

### 3.2. Damage factor of urban infrastructure

Figure 4. Damage factor of infrastructure in Jianye (left) and Gulou District (right). Figure 4 exhibits the damage factor of infrastructure in Jianye and Gulou. With the rainfall duration from 0.5 to 3.0 h, the damage factor shows the increasing trend together and gradually levels off in the end. Overall, the damage factor of infrastructure in Jianye is more than Gulou, which reveals the higher inundation rate and loss potential. Furthermore, transportation infrastructure has the largest damage factor in Jianye, and energy and emergency response infrastructure are the other two primary types. Local governments should pay attention to the protection and rehabilitation of transportation, energy and emergency response infrastructures to adapt to urban flood. And information and communication, water supply and treatment, and transportation infrastructure are the three dominating types of damage
factor in Gulou. Two districts should attach importance to the function operation of transportation infrastructure altogether during flood events.

3.3. Urban flood resilience

Figure 5. Damage factor of infrastructure in Jianye (left) and Gulou District (right).

Figure 5 shows the trend of urban flood resilience with different rainfall duration in Jianye and Gulou District. Overall, urban flood resilience decreases with the increase of rainfall duration. Urban flood resilience exhibits the gradual downward trend and finally flattens out. This decline process reflects the reduction in the resistance, adaption and recovery of urban system to flood. Furthermore, the lowest value of flood resilience, at the rainfall duration of 3.0 h, reveals that city reaches the limit state of bearing capacity to disaster. There are the differences on the initial and final state of flood resilience, which further illustrate the interregional heterogeneity in Jianye and Gulou. Combined with Jinaye District, Gulou District is more resilient to urban flood and heterogeneity between two regions remains indispensable to further explore.

3.4. Stage damage analysis

Figure 6. Stage damage curve of Jianye (left) and Gulou District (right).

Figure 6 presents the comparison between urban flood resilience and fitting curve in Jianye and Gulou District. Overall, the fitting effect of stage damage curve is good. Stage damage curve reveals the change of urban flood resilience in the different time stage. And the stage damage curve is strongly linked with the inundation area, flood depth and damage factor in regions and reflects the characteristics of the stage changes in these factors. Furthermore, according to stage damage curve, the decreasing process of flood resilience corresponds to the loss process of urban system affected by flood. Two points on the curve at different stages reflect the different degrees of flood interference and damage, and the corresponding recovery process requires the different measures and methods.
4. Conclusions
This study selected Jianye and Gulou District and conducted the stage damage analysis for urban system. We made the flood simulation and modelling, evaluated urban flood resilience with different rainfall durations and drew the stage damage curve based on flood return periods of 100 years. Results indicate that inundated area in Jianye covers 34.60, 54.51, 63.14, 67.66, 70.36 and 72.46 km². Inundated area in Gulou occupies 13.28, 20.30, 23.48, 25.36, 26.82 and 28.05 km² and flood depth reaches 0.08, 0.14, 0.18, 0.22, 0.24 and 0.27 m, respectively. Transportation, energy and emergency response infrastructure shows the higher damage factor in Jianye while information and communication, water supply and treatment, and transportation infrastructure exhibits the higher damage factor in Gulou. Urban flood resilience presents the gradual downtrend and finally flattens out altogether. Finally, the stage damage curve deserves much attention and associates closely with the recovery process. Future study can explore the factors that cause the regional heterogeneity and formulate the recovery strategy.

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