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Effects of heavy rainfall and outer river level on urban waterlogging in hilly areas of South China: a case study of Nanhu Port, Changsha City

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ABSTRACT

With the renewal of urban construction, disasters caused by heavy rainfall caused by urban waterlogging risk is more and more high, seriously affecting the safety of people's lives and property, causing the "city to see the sea" spectacle. Most of the hilly areas in southern China belong to the subtropical monsoon climate, and heavy rains are usually concentrated from May to August. During this period, there is a significant positive correlation between external river level and heavy rainfall. This study comprehensively evaluates the influence of external river level change on the overflow capacity of urban drainage system by superimposing different external river level and different rainfall intensity. It provides the basis for the operation, construction and reconstruction of urban drainage system. The results showed that the total water volume of the region increased by 54.47%–111.17% as the outer river level increased from 25.50 to 38.34 m. When the outer river level was higher than 36.15 m, the maximum variation range of urban waterlogging water was 26.13%. As the rainfall return period changed from one in 100 y to one in 10 y, the regional total water volume decreased by 77.78%–152.09%. Therefore, the main reason of urban waterlogging risk lies in heavy rainfall rather than external river level, but the design of urban drainage pipe network should consider the influence of external river level in combination with actual development and surrounding environment.

Keywords: InfoWorks ICM; Drainage network; Outer river level; Urban waterlogging

1. Background and introduction

In recent years, under the background of global climate system warming, extreme climate events such as heavy rain occur frequently [1]. According to incomplete statistics, more than 300 cities in China have suffered from waterlogging disasters of varying degrees and urban waterlogging has been widely valued by the society [2]. In Changsha, Wuhan and other cities along rivers and rivers, the ground elevation in most places is below the high outer river level, so urban flood control is also an important issue. The main measures of urban flood control include the construction of river and lake embankments, the construction of reservoirs upstream for storage and dispatch, the protection of polders, and the separation of flood floods for flood storage and detention [3]. The main measures for urban waterlogging control include reasonably reserving blue and green space in urban construction, giving play to the role of stagnant storage, implementing source emission reduction within the plot, and building drainage pipe networks, drainage pumping stations, reservoirs and other engineering facilities [4]. Therefore, the water level and rainfall intensity of the outer river have a huge impact on the phenomenon of urban waterlogging, and of course, the pumping station also plays an important role in the urban drainage system. The drainage capacity of the pump directly affects the peak drainage

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capacity of the entire area. Reasonable water pumps can often offset the water level support caused by the growth of the river level outside the city, and the failure of the pump station often brings serious urban waterlogging disasters [5]. Therefore, for cities in the hilly areas of southern China, they often receive greater influence from the water level of the outer river due to the rivers and lakes. The degree of urban waterlogging will receive a combination of rainfall intensity and the water level of the outer river [6]. Since urban waterlogging is often affected by the combination of multiple variables, it is necessary to simulate and analyze the impact of multiple variables on waterlogging by establishing an urban rainwater model, and simulate the comprehensive effect of multiple variables on this basis. The main purposes of this study are as follows: (1) Based on the variation characteristics of rainfall in Nanhu Port area of Changsha City and the variation characteristics of river level in Juzizhou hydrological station of Xiangjiang River, the hydrodynamic model of InfoWorks ICM was used to simulate the supporting effect of different external river levels on urban drainage network, and to reveal the relationship between external river level changes and urban waterlogging; (2) To evaluate the influence degree of different rainfall intensity and outer river level on urban waterlogging, and to provide theoretical reference for urban planning and construction schemes in combination with waterlogging risk situation.

2. Research methods

2.1. Basic data collection, collation and model building

Through the collation and collection of meteorological data and hydrological data of Changsha city, the long-duration rain pattern of once in 10~100 y and the outer river level of once in 10~200 y were determined. Meanwhile, the two extremely heavy rain patterns of September 10, 2017 and 2021.8.17 of Juzizhou Hydrology Station near Nanhu Port area of Changsha City were collected and sorted out. The details are shown in Table 1.

The rainfall and corresponding external river levels in Changsha on 10 September 2017 and 17 August 2021 are shown in Fig. 1. The peak rainfall on that day, 10 September 2017, was 100 mm/h, and the river level was maintained at 38.0 m. The peak rainfall on the day of 7 August 2021 was 163 mm/h and the river level was maintained at 32.0 m.

In this study, the InfoWorks ICM model developed by HR Wallingford, UK, provides the simulation calculation of urban drainage system, the simulation of hydrological process of urban water cycle, etc. Through the collection of planning data such as land use planning, special drainage planning, water system planning, flood control and drainage planning and water function regional planning, import inspection well data and pipeline data from the data import center of ICM, and then organize the pipe network by deleting, trimming, merging and supplementing. Combined with ArcGIS and CAD to check the integrity of data and the accuracy of upstream and downstream node attributes, the system types of nodes and pipelines were checked, and the geophysical data were supplemented and repaired. By collating and collecting the basic terrain data, drainage facility data, hydraulic building data and river, lake and reservoir data of the area, the 1D drainage digital model of Changsha Nanhu Port Area is constructed, as shown in Fig. 2.

2.2. Parameter selection and model coupling

After the network arrangement generalization and the installation of municipal facilities such as the storage tank of the pumping station, the drainage network model of the study area is generalized. After the generalization, there are 1,257 model nodes and about 1,243 pipeline connections. The Manning coefficient of all pipelines is 0.04, and that of the river is 0.02. Subsets of hydrological model According to the research content, Tyson polygon is mainly used to divide the whole Nanhu port area of Changsha City, and a total of 982 subsets of water are drawn.

The current flow generation models commonly used in InfoWorks ICM include Wallingford fixed runoff model, New Britain (variable) runoff model, American SCS model, Green-Ampt seepage model, Horton seepage model and fixed seepage model. Referring to the conclusion of Bestselling Wallingford's fixed runoff model was adopted for roads, buildings and water bodies under extreme working conditions, and Horton's infiltration model was adopted for the calculation of current green areas' runoff production, which was expressed as a function of rainfall time [7]. The confluence calculation models include bilinear reservoir Wallingford model, large contribution area runoff model, Sprint runoff model, Desbordes runoff model and SWMM runoff model. According to the requirements of Kim et al. SWMM model was selected for confluence calculation, and combined with the fixed runoff model and the Horton flow production model [8]. The surface runoff wizard tool in the model was used to sort out key parameters such as initial infiltration and ultimate infiltration, and different production and confluence parameters were constructed, as shown in Table 2.

After the above steps, the 2D model was constructed. 52,633 pieces of the 1:2000 urban topographic map of Nanhu

Table 1
Scene table of rainstorm and outer river level

Rainfall intensity (mm)	Return period	Once in 10 y	Once in 20 y	Once in 30 y	Once in 50 y	Once in 100 y	
	24 h rainfall	162.09	192.43	210.18	232.54	262.88	
Outer river level (m)	Free flow	Constant water level of outer river	Once in 20 y	Once in 30 y	Once in 50 y	Once in 100 y	Once in 200 y
	25.5	29.50	36.15	36.66	37.30	37.72	38.34

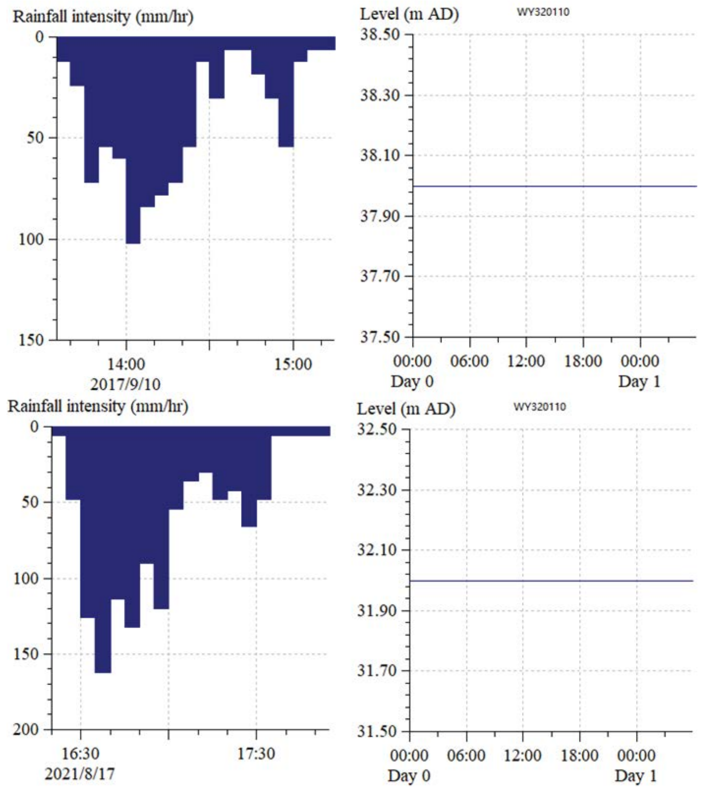

Fig. 1. Rainfall and corresponding external river level map from September 10, 2017 to September 17, 2021.8.17.

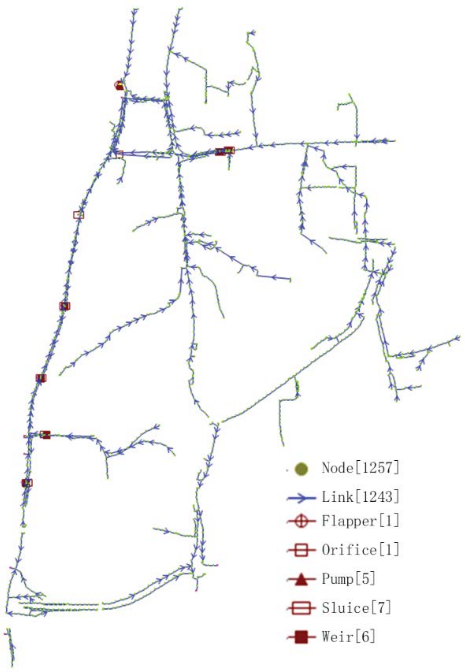

Fig. 2. Digital model of pipe network in Nanhu Port area.

Port area in Changsha City and 52,633 pieces of rainwater olivier elevation data were extracted from each inspection well and geophysical survey, which were preprocessed in ArcGIS and imported into InfoWorks ICM to complete the construction of the ground model. Considering that elevation point data came from topographic map of 1:2000, excessive error may cause adverse impact on simulation results. Therefore, the corresponding elevation of all buildings was raised by 0.25 m in ICM, and the roadside stones were reflected while the buildings were raised. Grid elevation intervals were set for parking lots and green Spaces according to the topographic map, and detailed terrain was divided. Finally, the flood type of 1D model was changed to 2D before coupling, and the digital model construction of Nanhu Port area in Changsha was completed.

2.3. Model calibration verification

In order to ensure the accuracy and reliability of the modeling, the rainfall, external river level data and related waterlogging data of September 10, 2017 and August 17, 2021 were used in this study to calibrate and verify the model. Five waterlogging prone points in the region were selected according to the waterlogging data and evaluated according to the Nash coefficient [9]. The calculation formula is shown as follows:

$$E_{\text{NS}} = 1 - \frac{\sum_{i=1}^{n}\left(S_i - O_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}$$

where O_i is the measured water level, m; S_i is the simulated water level, m; $\bar{O}$ is the average measured water level, m; i is the time step number. n is the total

Table 2
Main parameter selection list

Surface type	Confluence model	Confluence type	Confluence parameter	Current producing surface type	Runoff type	Type of initial loss	Initial loss value (m)	Runoff coefficient	Initial infiltration mm/h	Limiting infiltration mm/h	Attenuation factor1/h
Road	SWMM	Rel	0.012	Watertight	Fixed	Slope	0.00071	0.90			
Commercial building	SWMM	Rel	0.015	Watertight	Fixed	Slope	0.00071	0.75			
Residential building	SWMM	Rel	0.017	Watertight	Fixed	Slope	0.00071	0.80			
Green space	SWMM	Rel	0.010	Permeable water	Horton	Slope	0.00071		200	12.7	4

number of time steps. Using the above evaluation methods, the calibration verification results of main waterlogging points are obtained as shown in Table 3.

The 1-dimensional to 2-dimensional coupling of ponding conditions is shown in Fig. 3, which visualises the distribution of ponding, with the blue portion indicating the location of the ponded water.

As can be seen from the above table, in the simulation results of the two measured rainfall, ENS values of the five waterlogging points are all higher than 0.70. It is believed that the 2D inundation depth results under the two rainfalls have a small error, and the simulated results are close to the measured water depth. Therefore, it can be considered that the accuracy and reliability of the coupling model are good, and the model can basically reflect the actual situation of the area.

3. Analysis and results

3.1. Influence analysis of outer river level

According to the rainstorm type of Changsha City, the once-in-a-century rainfall (262.88 mm) was selected as the input condition. By studying the variation of the Waihe River at 25.50–38.34 m, the water accumulation in the area and the flow capacity of the pipe network were analyzed. The increasing trend of the water volume in the area is shown in Fig. 4. When the outer river level is lower than 29.50 m, the regional waterlogging volume changes little, at this time, the end of the pipe network flow capacity is larger, with good drainage capacity. As the external river level continues to rise, the regional waterlogging volume reaches an inflection point when the external river level is 36.15 m. Compared with the previous two working conditions, the total amount of waterlogging volume in this area changes from 70,360.89 to 117,808.06 m^3, an increase of about 67.43%. As the outer river level continued to rise to 37.72 m, the waterlogging volume in this area showed a linear change, and the maximum total water volume increased by about 13.82% compared with the former, with a small increase. When the external river level reaches 38.34 m (once in 200 y), the rise of the external river level has the greatest impact on the increase of waterlogging volume in the area. At this time, the total waterlogging volume in the area is 148,458.38 m^3, an increase of about 110.99% compared with the original condition. For urban areas with high flood control requirements, this flood control standard should be guaranteed.

In order to study the influence of the external river level on the overflow capacity of the area, the change law of the overflow capacity and overflow of the end pipe without pump and with pump was studied for the high and low discharge area. The results are shown in Fig. 5. Fig. 5a shows that the overflow capacity of the high-discharge pipe network in the area decreases successively with the increase of the external river level, while the low-discharge pipe network is mainly affected by the change of the external river level due to the mechanical discharge of the pumping station, and the sensitivity of the external river level is low. As shown in Fig. 5b, with the increase of the external river level, the regional total overflow increases slightly and then decrease. The main reason for the increase is the increase of regional water accumulation caused by the decrease of the

Table 3
Model calibration verification results

Waterlogging point	2017.09.10 rainfall			2021.08.17 rainfall		
	ENS	Survey water depth/m	Simulated water depth/m	ENS	Survey water depth/m	Simulated water depth/m
Near the tunnel on Nanhu Road	0.89	0.50	0.58	0.76	0.50	0.67
Shuyuan Road – Trade Street junction	0.96	0.40	0.44	0.84	0.40	0.51
Tuxin community	0.95	1.40	1.55	0.84	2.00	2.40
Chiling Road junction	0.84	0.30	0.36	0.77	0.30	0.40
Changpo First Street	0.75	0.20	0.31	0.88	0.30	0.35

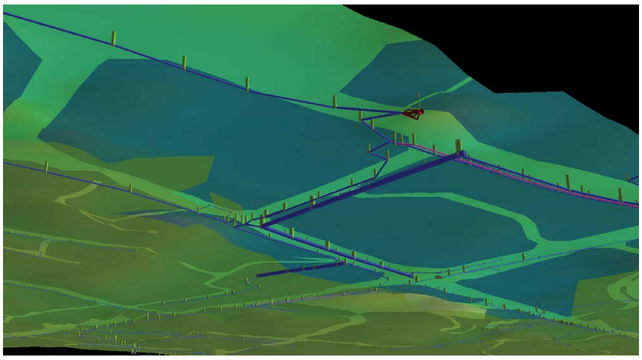

Fig. 3. Schematic diagram of 1D-2D model coupling.

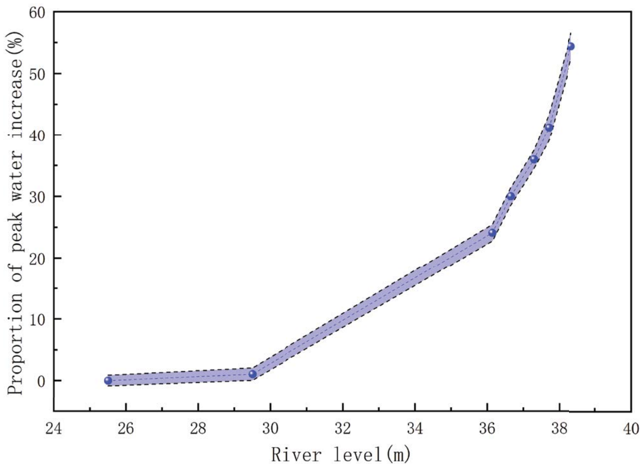

Fig. 4. Variation chart of outer river level and peak water volume.

overflow capacity of the high drainage network. Combined with Bernoulli equation [10], the increased water accumulation increases the head of water. The total over discharge in the low discharge area shows a monotonously increasing trend. The main reason is that the high-water level of the outer river drains part of the current backflow water of the outer river and the waterlogging water in the low discharge area due to the topographic flow. In urban design, the scale of the front pool of the pump station should be appropriately increased to ensure the normal operation of the pump station. For the high discharge area without pump, the influence of the external river level on the area should be considered comprehensively, and the appropriate boundary between high and low should be formulated to prevent the backfilling of the external river.

3.2. Analysis of rainfall impact

In view of the influence of rainfall intensity on the area, when the outer river level is selected as free outflow (25.5 m), the waterlogging water is analyzed under different operating conditions of once-in-10 y to once-in-100 y rainfall. The results are shown in Fig. 6. The peak water volume of the area increased from 70,360.90 to 175,996.4 m^3, increasing by about 150.13%, showing a monotonically increasing trend. Therefore, in the formulation of waterlogging prevention program should be strictly according to the specification of the highest rainfall standard, to achieve the effect of waterlogging prevention and control.

By comparing the end-pipe network flow capacity of low-discharge (with pumps) and high-discharge (without pumps) in the area under different rainfall intensities, the results are shown in Fig. 7. Fig. 7a shows that when the external river level is constant, the overflow capacity of the high-discharge pipe network in the area basically does not change, indicating that the overflow capacity of the high-discharge pipe network in the area has reached its limit, exceeding the rainwater flowing into the low-discharge or locally low-lying through surface runoff. The flow change of the pumping station of the low-discharge pipe network indicates that with the increase of rainfall intensity, the area receives the inflow of high-discharge rainwater and the increased rainfall of low-discharge. And since the pump station is 8.71 m^3/s, there is still room for improvement. Fig. 7b shows that the total amount of high and low overflows in the area presents a strict positive correlation with rainfall intensity, indicating that as the rainfall process enters the later stage, there is gradually no rainfall in the area, and the current drainage system discharge urban waterlogging water. Therefore, when designing the urban drainage pipe network, the influence of water regression time should be considered in combination with standards, and appropriate rainfall intensity standards should be formulated to prevent over-development and construction.

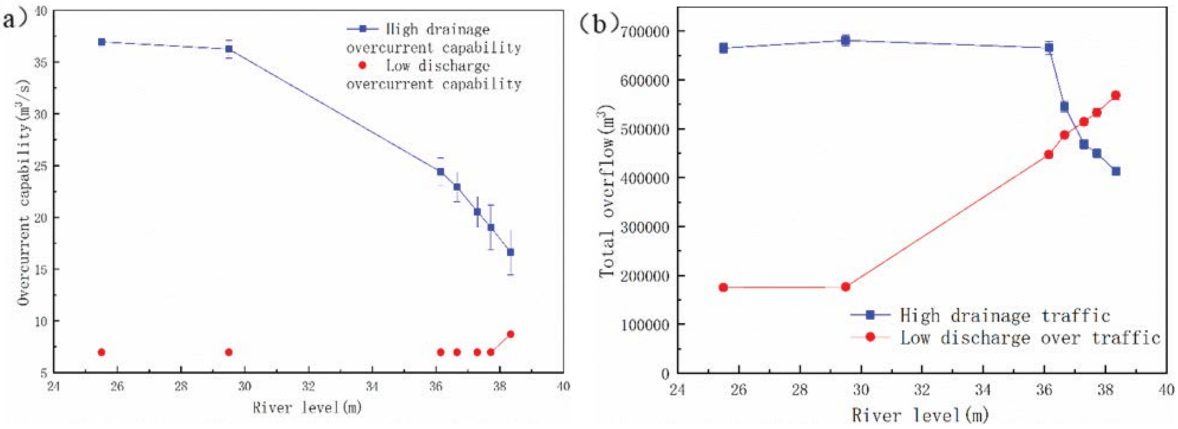

Fig. 5. Changes of outer river level and overcurrent capacity.

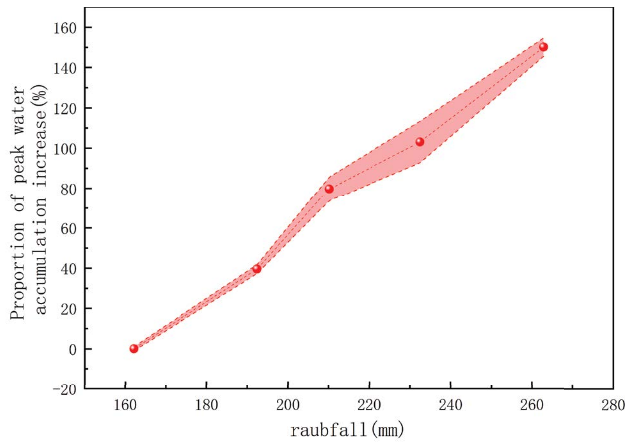

Fig. 6. Variation of rainfall and peak water volume.

3.3. Comprehensive comparative analysis

Higher water levels are usually accompanied by heavy rainfall events, and while the probability of simultaneous heavy rainfall and high-water levels is low, ignoring the increase in water levels in outer rivers caused by the intensity of heavy rainfall, resulting in the combination of heavy rainfall and high outer river water levels, may lead to a higher risk of waterlogging. During the heavy rainfall in Changsha, the high-water level of the river outside Juzizhou clearly shows that it is impossible to correctly assess the risk of urban waterlogging by considering only the intensity of rainfall or the water level of the outer river. Therefore, it is necessary to evaluate the combined impact of rainfall intensity and outer river water level on urban waterlogging. In this study, 30 different working conditions of once in 10 y (162.09 mm) ~ once in 100 y (262.88 mm) rainfall and free outflow (25.50 m) ~ once in 200 y (38.34 m) were selected, and the total accumulated water and duration of urban water accumulation under different rainfall intensity and water level combinations were simulated. The impact of rainfall intensity and river levels on urban waterlogging was assessed.

Matlab is used to comprehensively analyze the relevant data of rainfall, outer river level and area water, and the drawing results are shown in Fig. 8. According to the difference of water volume, the working condition of 25.50 m water level superimposed on 162.09 mm was taken as the baseline scenario, and it was concluded that when the water level increased from 25.50 m to 38.34 m, the regional total water volume increased by about 54.47%–111.17%. With heavy rainfall resumption period from once in 100 y to once in 10 y, the total water volume of the region decreased by

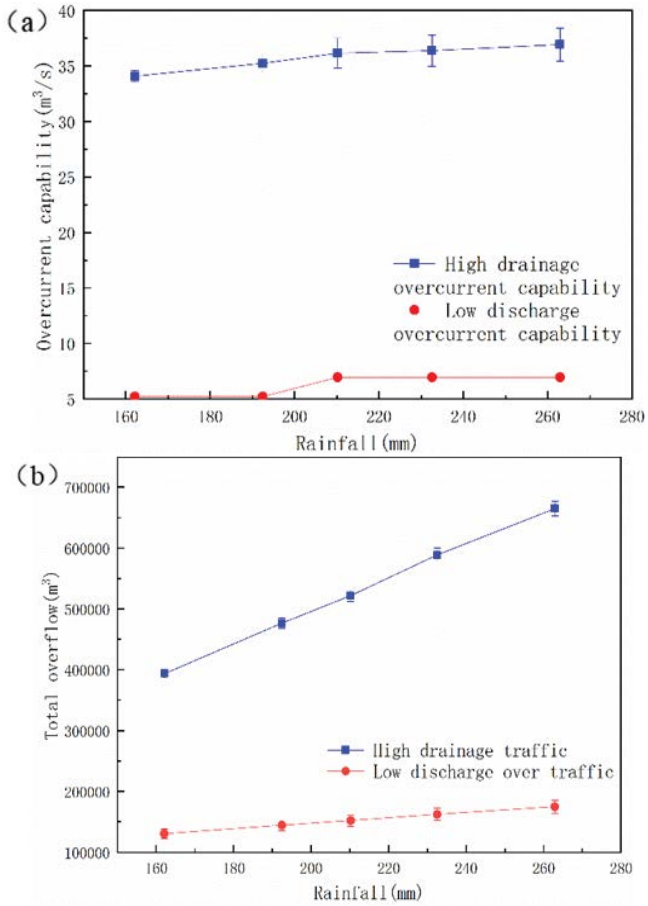

Fig. 7. Variation of rainfall intensity and flow capacity.

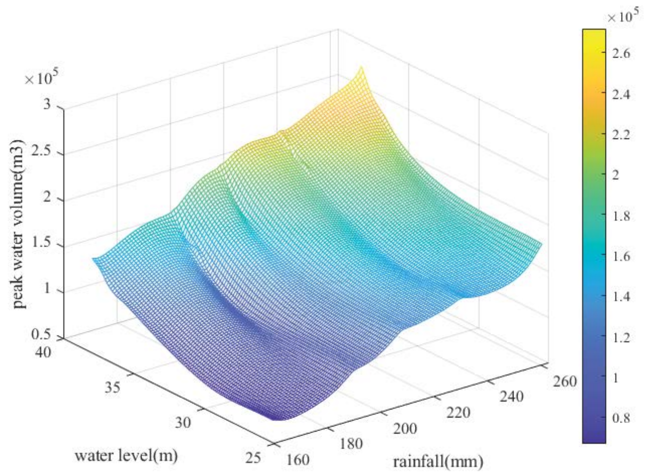

Fig. 8. Relationship between rainfall, outer river level and urban waterlogging.

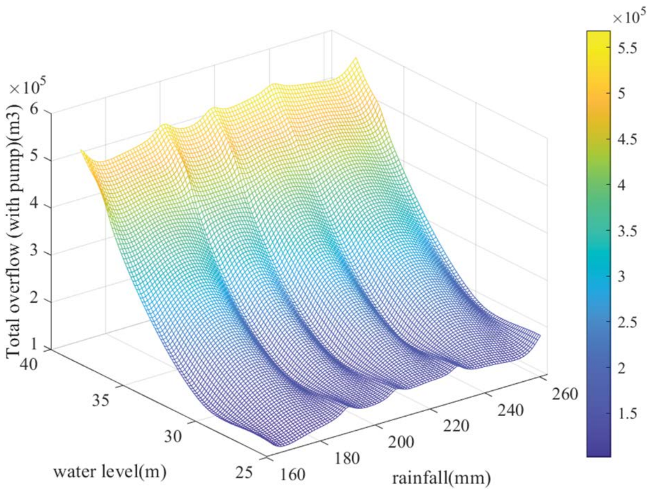

Fig. 9. Relationship between rainfall intensity, water level of rivers and total water accumulation in low areas.

77.78%–152.09%. The above analysis shows that regional waterlogging is mainly caused by heavy rainfall, and the rise of river level outside the confluence system will also have a certain adverse impact on urban waterlogging.

For cities along rivers, urban waterlogging is often caused by a variety of factors, including the intensity of heavy rainfall, the water level of the outer river, and the overflow capacity of the urban drainage system, etc., which will affect the total amount of water in the city and the time of water accumulation. Therefore, it is important to use the waterlogging model to simulate the combined effects of different factors on urban waterlogging. Since the drainage facilities in this area have high and low discharge conditions (i.e., with and without drainage pumps), the combined effects of heavy rainfall intensity, outer river water level and pumping station on urban waterlogging are evaluated in the simulation results, and the results are shown in Figs. 9 and 10.

The total low-discharge overflow in Fig. 9 is an indicator describing the overflow capacity of the pumping station in rain and after rain. It can be seen from the figure that with the increase of rainfall recurrence period from once in 10 y to once in 100 y, the total overflow of the pumping station increases by about 4.18%–35.51%, indicating that the influence of pumping on waterlogging decreases with the increase of rainfall recurrence period. At the same time, when the water level of the pump station is too high, the overflow capacity will increase by 224%–317%, which indicates that the pump station plays an important role in the urban drainage system. In addition, when the outer river level is lower than 35 m, the difference of total overflow water between different recurrence periods is small, and when the outer river level is higher than 35 m, the difference becomes larger and larger. Therefore, when the outer river level is higher than 35 m, the drainage pump station can effectively reduce the risk of regional waterlogging. The high-discharge peak overflow capacity in Fig. 10 is an index describing the overflow capacity of the high-discharge system (without pump) during rainstorm. It can be seen from the figure that with the increase of the external river level from 25.50 to 38.34 m, the peak overflow capacity of the high-discharge network decreases by 53.39%–54.98%. The peak overflow capacity of high-discharge pipe network increases by about 4.68%–8.37%, indicating that the high-discharge pipe network has almost reached the peak flow capacity. In urban planning and design, the division of high and low zones should be properly considered, and some pipelines in high-discharge areas should be divided into low zones, which can effectively reduce the risk of external river backflow and ensure the overflow capacity of high-discharge pipe network, which is of great significance for urban drainage and waterlogging prevention projects.

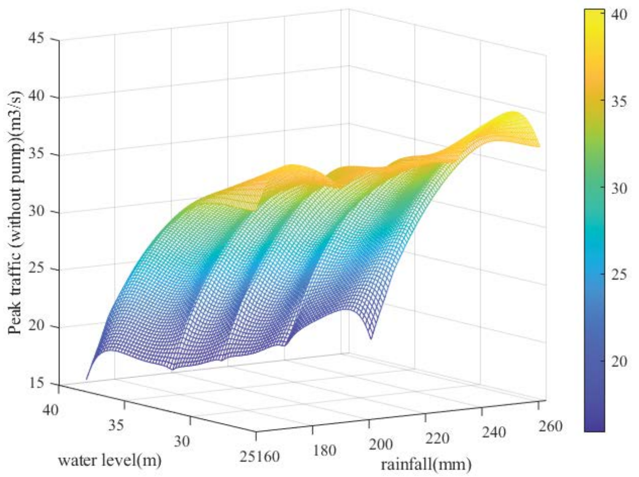

Fig. 10. Relationship between rainfall, outer river level and overflow capacity of high discharge area.

4. Conclusion

Urban waterlogging risk often changes with climate change, urban drainage and waterlogging prevention system should consider the comprehensive impact of heavy rainfall intensity and outer river water level, and build drainage facilities suitable for the urban geographical and hydrological environment to achieve the purpose of reducing urban waterlogging risk. In this study, the checked hydrodynamic model was used to simulate the comprehensive effects of rainfall, water level and pumping station on urban waterlogging, and the main conclusions are as follows:

(1) As the outer river level increased from 25.50 m to 38.34 m, the regional total water volume increased by about 54.47%–111.17%. When the outer river level was higher than 36.15 m, the maximum variation of urban waterlogging water was 26.13%. As the rainfall return period changed from one in 100 y to one in 10 y, the total water volume of the region decreased by about 77.78%–152.09%.

(2) With the rise of the outer river level, the effective role of the pumping station for urban drainage is gradually enhanced; With the increase of rainfall recurrence period, both high and low discharge pipe networks have overflow thresholds. In urban planning and design, proper consideration should be given to the division of high and low zones, which is conducive to rational utilization of construction resources and urban planning and design.

The results of this study can be used for the design of urban drainage system engineering in the southern hilly area, and the research results can provide a scientific basis for the establishment of water level in outer rivers and the setting of urban drainage system. During urban construction and development, by establishing standards for the prevention and control of water levels in outer rivers, the goal of distinguishing urban high-discharge and low-discharge zoning is completed, and the goal of drainage and risk elimination is completed by using topography and water pumps.

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