Hierarchical management scheme of urban waterlogging risk based on critical rainfall level: a case study of Xining City

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Abstract. With the global climate change and the intensification of human activities, urban waterlogging caused by rainstorm is becoming more prominent, and the problem of urban waterlogging needs to be solved. According to different return periods and drainage standards, a new hierarchical management scheme of urban waterlogging risk is proposed, which is composed of micro source runoff control system, minor drainage transmission system, major waterlogging prevention system and resilience improvement system. Based on long series short duration precipitation data, different critical rainfall levels are calculated considering the relevant drainage and waterlogging prevention standards. The calculation results show that the rainfall level for micro source runoff control system is 15.8mm (i.e. point A). For minor drainage control system, the rainfall level are 20.6 mm and 26.9 mm respectively (i.e. point B and B’). For major waterlogging prevention system, the rainfall level is 53.5mm (i.e. point C). According to these segmentation points, four interconnected urban waterlogging risk management strategies are proposed, i.e. strategy 1.0 focuses on micro scale and aims to promote source runoff control by ‘green infrastructure’, 2.0 focuses on minor scale aims to conduct drainage optimization of ‘grey infrastructure’, 3.0 focuses on major scale aims to improve waterlogging prevention by ‘blue infrastructure’ and 4.0 aims to deal with disaster mitigation by ‘red infrastructure’. Furthermore, the rainfall characteristics, the influence degree and objectives and measures for each strategy are given in detail.

1. Introduction

With the global climate change and the intensification of human activities, the frequency of extreme weather increases[1], the urban waterlogging phenomenon caused by rainstorm is prominent, and the urban waterlogging problem needs to be solved. Therefore, it has become a research hotspot in recent years to analyze the causes of urban waterlogging and take targeted solutions to the causes of urban waterlogging[2,3,4]. At present, the research on the causes mainly focuses on four aspects[5,6]: natural factors, planning factors, engineering construction factors and management factors.

Among them, most of the researches focus on LID and Sponge City[7], trying to break the deadlock of urban water problem. For example, Huang miansong et al. [8] took Guyuan City as an example to simulate the effect of sponge measures on reducing ponding area; Wang leizhi et al. [9] compared and analyzed the rain flood control indexes at home and abroad, which provided guidance for the verification of each construction stage; Wang Hao et al. [10] started from the three essential connotations of Sponge City, established the corresponding coupling balance of sponge city construction, and based on solving the three major water problems of the city. However, some studies
have found that in some cases, it is difficult to rely on LID, Sponge City and other measures alone to alleviate urban waterlogging [11]. Therefore, some scholars began to study the urban waterlogging prevention and control strategy of dual-construction [12], multi-scale [13], multi-level [14], and achieved certain results. However, the relationship between different levels of the established multi-scale and multi-level strategy system is not clear and needs further study.

2. New hierarchical scheme for urban waterlogging risk management

For a long time, Xining city mainly relies on the traditional rainwater pipe network for drainage, lack of systematic and scientific drainage system design. Based on the characteristics of rainfall process and drainage system in Xining City, the waterlogging risk control scheme based on critical rainfall is proposed, as shown in Figure 1. It mainly includes four dynamic parts:

1) Micro-scale runoff control system: O-A is the source control system, which is mainly realized by various decentralized LID facilities or Sponge City construction, and the design standard is the 24h rainfall corresponding to the total runoff control rate;

2) Minor-scale drainage transmission system: A-B (or B') is the rainwater conduit system, and the rainwater runoff beyond the treatment capacity of the source control system enters the system, where B is the return period of rainfall with a return period of 2 years and B' is the return period of rainfall with a return period of 5 years; According to the Code for design of outdoor wastewater engineering (GB 50014-2006), the design standard of urban storm sewer is generally 2-10 years rainfall;

3) Major-scale waterlogging prevention system: B-C refers to the rainwater runoff exceeding the drainage capacity of storm sewer system and entering into the excessive rainwater storage and drainage system;

4) Resilience improvement system: C-D is excessive rainfall. In recent years, urban resilience research[15,16] has been carried out worldwide to implement rainfall and disaster prevention and reduction management so that reduce the harm caused by excessive rainfall.

Fig 1. Hierarchical management scheme of urban waterlogging in Xining City

3. Critical rainfall level calculation

3.1. Segmentation point A

The design standard of source control is 24h rainfall corresponding to the total runoff control rate of sponge city. Based on the daily rainfall data of Xining city from 1954 to 2018, the accumulated daily rainfall less than or equal to 2mm is deducted and sorted from low to high. Deducting the rainfall of ≤ 2mm, the daily value of rainfall is sorted according to the rainfall from low to high, and the ratio of the total rainfall less than a certain rainfall (the total rainfall less than the rainfall is calculated according to
the real rainfall, and the total rainfall greater than the rainfall is calculated according to the rainfall, and the cumulative sum of the two) in the total rainfall is counted. The rainfall (daily value) corresponding to this ratio (i.e. annual total runoff control rate) is the design rainfall. The annual total runoff control rate is one-to-one corresponding to the design rainfall.

According to the Technical Guide for Sponge City Construction, Xining city is located in zone 1 (a ≥85%), and the designed rainfall value corresponding to 85% total control rate is used as the control index (as shown in Figure 2 below), and the 24-hour designed rainfall of corresponding source control system is 12.6 mm.

Fig 2. Relationship between runoff control rate and rainfall of Xining city

3.2. Segmentation point B and B’

According to the falling rainfall values in different return periods (as shown in Table 1 below), the return periods of Xining drainage system are 2-year return period and 5-year return period, and the design rainfall is 15.79 mm and 20.61 mm respectively. According to the proportion of rainfall in each hour of 24-hour design rainfall pattern in Xining City, it is allocated to the maximum 2 hours. Based on the same proportional distribution method, the other 22 hours of rainfall are expanded and summed, and the 24-hour design rainfall of rainwater conduit system is 29.48 mm and 38.48 mm, as shown in Table 2 below.

In the actual operation condition of pipe network drainage system, the rainwater inlet and pipeline are easy to be clogged, especially in the peak rainfall condition. In order to make the calculation results more in line with the reality, the attenuation coefficient of 0.7 is taken to reduce the 24 h theoretical design rainfall of the rainwater pipe system. Finally, the actual 24-hour rainfall of Xining drainage system is 20.6 mm (2-year return period) and 26.9 mm (5-year return period).

| Duration of rainfall (min) | 2-year return period | 5-year return period |
|---------------------------|----------------------|----------------------|
|                           | Accumulated rainfall (mm) | Rainfall intensity (mm/h) | Accumulated rainfall (mm) | Rainfall intensity (mm/h) |
| 60                        | 0.32                  | 0.32                  | 0.42                  | 0.42                  |
| 120                       | 0.69                  | 0.37                  | 0.89                  | 0.48                  |
| 180                       | 1.12                  | 0.44                  | 1.46                  | 0.57                  |
| 240                       | 1.67                  | 0.55                  | 2.18                  | 0.71                  |
| 300                       | 2.43                  | 0.76                  | 3.17                  | 0.99                  |
| 360                       | 3.83                  | 1.40                  | 5.00                  | 1.83                  |
| 420                       | 16.53                 | 12.70                 | 21.57                 | 16.57                 |

Table 1. Rainfall fall in different return periods of Xining city (unit: mm)

Table 2. Calculation of the dividing points of different return periods of Xining city
Table: Rainfall Characteristics and Impact Levels

| Rainfall Intensity | Impact Level | Objectives and Measures |
|-------------------|--------------|-------------------------|
| Light/Moderate    | 20-30%       | Improve green infrastructure to manage rainfall effectively |
| Severe            | 30-40%       | Implement grey infrastructure to control and manage rainfall |
| Extreme           | 40-50%       | Enhance grey infrastructure for optimal control and management |

3.3. Segmentation point C

The standard for urban logging prevention in Xining city is once in 50 years, and the corresponding 24-hour rainfall is 53.5mm. Based on the principle of water balance, the return period of the drainage system in Xining city is 2-year return period and 5-year return period, and the 24-hour rainfall of the excessive rainwater storage and drainage system under the waterlogging control standard is 32.9 mm and 26.6 mm respectively.

4. Risk control strategies based on different critical rainfall levels

Based on the calculation of the critical rainfall of each partition point, a hierarchical waterlogging risk management and control scheme is proposed, and four risk management strategies are proposed for Xining city. Among them, strategy 1.0 is mainly aimed to promote sponge facilities construction at micro scale, strategy 2.0 mainly aims to promote the construction of conduit facilities at minor scale, strategy 3.0 focuses on the construction of storage facilities at major scale, and strategy 4.0 focuses on construction of risk management system. The details are given as follows:

4.1. Strategy 1.0: Micro-scale source runoff control by ‘green infrastructure’

Rainfall characteristics: Light and moderate rainfall accounts for about 80-90% of the total annual rainfall, and the 24-hour rainfall is less than 12.6 mm.

Impact degree of rainfall: The impact of rainfall on people, such as wet shoes and mud, is inconvenient and uncomfortable, thus affecting the livability of the city.

Objectives and measures: ‘Green infrastructure’ can coordinate various natural ecological processes to play the role of nature in regulating water quantity and quality, through exploring new construction mode. Highlight the convenience and livability, through the construction of micro-scale drainage system, promote the new ecological waterlogging control and utilization measures, including low impact development facilities (LID), realize the natural infiltration, purification and accumulation of rainwater, strengthen the vertical management and control, and carry out urban waterlogging risk management.

4.2. Strategy 2.0: Minor-scale drainage optimization of ‘grey infrastructure’

Rainfall characteristics: The standard of conduit construction is once every 3-5 years, and the rainfall in 24 hours is less than 20.6 mm. It is used to exclude rainfall within 10 years of return period, accounting for about 10% of the total annual rainfall.

Impact degree of rainfall: Rainfall has a great impact on people's production and life, causing traffic congestion, damage to cars and other life and property losses.
Objectives and measures: ‘Grey infrastructure’ is a traditional municipal infrastructure which is mainly based on drainage. Highlight safety and economy. Optimize and perfect ‘minor-scale drainage system’, scientifically improve the design standard of pipe and channel system, timely improve the quality of the pipe and channel for the backward areas, upgrade the existing pipe and channel infrastructure, especially in the old urban areas with limited conditions to strengthen daily management and maintenance. In the new urban area, the higher system design standard should be selected as far as possible, and the control facilities of water conservancy facilities (gates, dams and pumping stations) should be added. For important areas, further improve the construction standard of rainwater conduits to 10-year or 30-year return period to reduce the impact of urban waterlogging.

4.3. Strategy 3.0: Major-scale waterlogging prevention by ‘blue infrastructure’
Rainfall characteristics: The runoff exceeding the design capacity of minor drainage system is excluded, and the rainfall with return period of 10-100 years is mainly dealt with. The standard of waterlogging prevention and control in Xining city is once in 50 years, the 24-hour precipitation is less than 53.5mm, and the occurrence frequency is low.

Impact degree of rainfall: Rainfall has a great impact on people's production and life, causing more serious traffic congestion, damage to cars and other life and property losses.

Objectives and measures: ‘Blue infrastructure’ is a large-scale storage facility mainly composed of underground space and surface channel, which ensures the drainage of excessive rainwater. Highlighting safety and economy. The construction of ‘major-scale drainage system’, namely surface drainage channel, includes natural formed channels and artificial channels, such as low-lying land in town, water system of potpond River and lake, underground large discharge facilities (such as depth), safe flood area on the ground and storage facilities (such as wetland) and other ‘storage and drainage’ systems. The natural drainage channel of rainwater should be established, and the waterlogged water will eventually flow to the natural or artificial receiving water body or facilities for discharge. It is necessary to add storage facilities in suitable areas to provide space for rainwater storage and drainage. In the process of urbanization, the landform should not be changed at will, the natural depressions should be retained as far as possible, the curved shape of the river should be restored as far as possible, the water ecology inside the river should be restored, the resistance of the river bank to flood should be enhanced, and the River should be dredged in time to prevent blockage. Wetland not only increases the regulation and storage of runoff, but also plays an active role in purifying water body.

4.4. Strategy 4.0: Resilience improvement by ‘red infrastructure’
Rainfall characteristics: The design return period is 50-100 years. It mainly deals with excessive rainstorm or extreme rainstorm exceeding the design standard of minor drainage system, and extreme rainstorm with low probability.

Impact degree of rainfall: excessive rainfall has a disastrous impact on people's production and life, causing great social and economic harm and loss.

Objectives and measures: ‘Red infrastructure’ is mainly through the construction of remote monitoring system such as Smart Water Platform and Intelligent Pipeline Network to realize the joint regulation of multi-process and multi-facilities, so as to maximize the rainstorm storage and drainage capacity. Highlighting stress emergency and adaptability. Building ‘resilience system’ emphasizes that in the face of various uncertain factors, the system has the ability to adapt to complex changes and respond to external shocks, and enhance the overall coordination ability and disaster response ability of the city. It mainly includes the restriction of land development and utilization, traffic guidance, forecast and early warning, emergency rescue, etc., the management of waterlogging emergencies, avoiding or reducing the impact of disasters, recovering from disasters as soon as possible after disasters, and realizing the ‘soft landing’ of excessive rainfall. The resilience of urban flood control system is to describe that the urban system can still operate after being attacked by rainstorm and flood. Flood has serious impact and disaster on the city, but the city can still maintain normal operation; The
impact and disaster of flood can rely on the ability of urban system itself to recover the original function of urban system.

The characteristics of different strategies and their corresponding technologies and management systems are shown in Table 3.

Table 3. Technological characteristics corresponding to different strategies in Xining City

| Catagory | Rainfall Frequency | Implementation scale | Measures focus |
|----------|-------------------|----------------------|---------------|
| Strategy 1.0 | <=15.8mm | Micro-scale runoff control system 80%~90% | Mainly micro drainage system | Sponge facilities And LID development |
| Strategy 2.0 | >15.8mm or 20.6mm | Minor-scale drainage control system 5%~10% | Micro-minor drainage system | Transmission network optimization |
| Strategy 3.0 | >20.6mm or 26.9 | Major-scale waterlogging prevention system 2%~5% | Micro-minor-major drainage system | Storage facilities construction |
| Strategy 4.0 | >53.5mm | Resilience improvement system 1%~2% | Micro-minor-major drainage system & resilience improvement | Risk management |

5. Conclusions

According to the current situation of Xining City in the study area, a hierarchical management scheme of urban waterlogging risk is proposed, which is composed of micro-scale runoff control system, minor-scale drainage transmission system, major-scale waterlogging prevention system and resilience improvement system. Through the quantitative classification, the combination solution strategy under different return period rainfall is provided for Xining City scientifically, systematically and pertinently. It makes up the blank of Xining in this aspect.

The core of this management scheme is the critical rainfall level, which will have influence on the degree of urban ponding. Based on long series short duration precipitation data, different critical rainfall levels are calculated considering the relevant drainage and waterlogging prevention standards. Results show that the critical rainfall point A is 15.8mm, the critical rainfall point B is 20.6 mm and B ’is 26.9 mm for the different construction strategy sections with 2-year return period and 5-year return period, and the critical rainfall point C is 53.5mm.

According to the calculated critical rainfall value, four different strategies are put forward. Among them, strategy 1.0 mainly aims at promoting sponge facilities construction (i.e.green infrastructure). Strategy 2.0 mainly aims at promoting drainage network optimization (i.e.grey infrastructure). Strategy 3.0 mainly aims at focusing storage facilities construction (i.e.blue infrastructure). Strategy 4.0 mainly aims at building resilience improvement system in order to achieve the disaster reduction (i.e. red infrastructure).

Although a relatively complete hierarchical management scheme is given, due to the lack of detailed pipe network data and the uncertainty of specific waterlogging prevention responsibility, some studies need to be further improved.In addition, in the scope of the study area, the specific construction content under the four strategies should be studied in detail, so as to achieve the simulation quantification and suit measures to local conditions.

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References

[1] Zhang D D, Yan D H, Wang Y C, et al. (2014) Research progress on risk assessment and integrated strategies for urban pluvial flooding. Journal of Catastrophology, 29(01): 144-149.

[2] Zhang J Y, Song X M, Wang G Q, et al. (2014) Development and challenges of urban hydrology in a changing environment I: Hydrological response to urbanization. Advances in Water Science, 25(04): 594-605.

[3] Liu J H, Wang J, Wang H, et al. (2020) Effectiveness of urban inundation control system in sponge city construction. Advances in Water Science, 31(04): 611-618.

[4] Wang W C, Chen Y C, Kang A Q, (2019) Analysis of Causes and Risk Assessment of Urban Waterlogging Based on GIS—Taking the Main City of Fuzhou as an Example. Journal of Water Resources Research, 08(03): 224-233.

[5] Jiao S, Ma B, Li B. (2019) Review on Causes and Control Strategies of Waterlogging in China. Ecological Economy, 35(07): 92-97.

[6] Zhou H, Liu J, Gao C, et al. (2018) Analysis of Current Situation and Problems of Urban Waterlogging Control in China. Journal of Catastrophology, 33(03): 147-151.

[7] Ning Y F, Dong W Y, Lin L S, et al. (2017) Analyzing the causes of urban waterlogging and sponge city technology in China. IOP Conference Series: Earth and Environmental Science.

[8] Huang M S, Yang S X, Qi W C, et al. (2019) Numerical simulation of urban waterlogging reduction effect in Guyuan sponge city. Water Resources Protection, 35(05): 13-18+39.

[9] Wang L Z, Yun Z D, Hu Q F, et al. (2021) Comparison and enlightenment of urban stormwater management index system at home and abroad. Water Resources Protection.

[10] Wang H, Mei C, Liu J H. (2017) Mesoscale numerical simulation analysis for temperature distribution in early-age concrete. Journal of Hydraulic Engineering, 48(09): 1009-1014+1022.

[11] Chen N, Chen A Z, Ma B, et al. (2021) Stormwater management path in Fenghuang, Hunan. Acta Geographica Sinica, 76(01): 153-166.

[12] Ren J C, Xie S B, Liu H, et al. (2020) Research on urban waterlogging prevention and control strategy under the background of sponge City. Water Resources Planning and Design, 2020, (11): 35-38-105.

[13] Ding S Y, Zeng J, Wang N, et al. (2019) Study on the strategy of prevention and control for internal heel under the intelligent sponge system: take Xiamen as an example. Water & Wastewater Engineering, 55(11): 67-73.

[14] Nie J K. (2021) Study on the causes of flood and waterlogging in urban river network concentrated areas and the Countermeasures. Water Resources Planning and Design, (01): 36-39+94.

[15] Tayyab M, Zhang J Q, Hussain M, et al. (2021) GIS-Based Urban Flood Resilience Assessment Using Urban Flood Resilience Model: A Case Study of Peshawar City, Khyber Pakhtunkhwa, Pakistan. Remote Sensing, 13(10): 1864-1864.

[16] Russo, B., Velasco M., Locatelli L., et al. (2020) Assessment of Urban Flood Resilience in Barcelona for Current and Future Scenarios. Sustainability, 12(14): 5638.