Zoning based cascade infrastructure system design for urban waterlogging prevention

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Abstract. With the development of global climate change and urbanization in China, urban waterlogging caused by rainstorm has a serious impact on the safety of people's life and property and the development of social and economic. Based on the hydraulic model, taking Xining City as an example, a set of multi-layer flood prevention infrastructure construction technology system is proposed, in which the microscale-drainage-system mainly includes the sponge transformation of building blocks, the construction of sponge park; the mesoscale-drainage-system mainly includes the transformation of pipe system for different return periods, the transformation of combined flow and separate flow system; the macroscale-drainage-system mainly includes utility tunnel system, natural and artificial storage facilities. Through quantitative evaluation of rainstorm with 50 year return period, under the construction of microscale-drainage-system and mesoscale-drainage-system with different return period index, the total drainage capacity increased from 1.407 million m$^3$ to 1.573 million m$^3$ and 1.830 million m$^3$. The total accumulated water is 1.073 million m$^3$ and 0.816 million m$^3$ respectively, which are less than 1.173 million m$^3$ of macroscale-drainage-system new storage capacity.

1. Introduction
With the continuous progress of global climate change and urbanization in China, the frequency of extreme weather increases [1], and urban waterlogging caused by rainstorm has a serious impact on people's life safety and social economic development [2]. Therefore, the problem of urban waterlogging has been widely concerned by the government, society and scientific research scholars. At present, the common urban waterlogging prevention strategies include engineering-non engineering measures, planning-construction-management [3], etc., but the sub-system architecture of each level is not clear, and the quantitative correlation between each level needs to be further studied.

For engineering construction measures, there are two major problems. First, the existing urban waterlogging control standard connection is not perfect. For example, the code for design of outdoor drainage (GB 50014-2006) [4] and the technical code for prevention and control of urban waterlogging (GB 51222-2017) [5] put forward different requirements for the return period of waterlogging prevention design. Although developed countries have adopted major-minor dual drainage systems [6] to a certain extent, the construction and application of major drainage systems in China is still in the exploratory stage, and minor drainage systems are still the main ones [7,8]. It directly leads to the limited ability to cope with extreme rainstorm events in high recurrence period under the application of existing standards [9]. Second, because China still takes sponge city and minor drainage system construction as the main flood prevention measures, in the long run, the
problem of urban waterlogging still cannot be systematically eradicated [10]. On the one hand, although the runoff control effect of sponge City [11,12,13] and pollutant reduction [14,15,16] have become the research hotspots in recent years, due to the great differences between cities and projects, it is difficult for some areas to rely on LID, Sponge and other measures alone to alleviate urban waterlogging [17]. On the other hand, although some scholars [18,19] have proposed a large number of reconstruction strategies for the design and planning of the drainage system, it is difficult to form an effective flood prevention linkage system among various engineering construction projects [20].

Aiming at the problems of the above-mentioned urban waterlogging prevention engineering construction measures, this paper takes Xining City as an example for analysis and application. Combined with the geographical conditions of the study area, using the constructed hydraulic model, and through the coordinated use of some existing feasible waterlogging prevention facilities, a set of more perfect multi-level urban waterlogging prevention infrastructure construction technical system is proposed.

2. General outline

![Fig 1. Drainage zone](#)

![Fig 2. Cascade infrastructure system framework](#)
Fig 3. Water balance judgment framework

According to the following basic principles, the drainage zone of Xining city is divided: 1) follow the drainage planning and drainage system of Xining city; 2) Taking advantage of the favorable topography, ditches and other characteristics and convenient conditions of Xining city; 3) The original urban rainwater drainage facilities should be fully reserved and utilized, and the administrative areas and river courses should be divided as far as possible; 4) According to the management and control division of sponge City, the management and construction of rainwater division are carried out. The main urban area of Xining city is divided into 36 drainage zones, including 10 in the west, 9 in the north, 10 in the East and 7 in the south, as shown in Figure 1.

Based on the division of drainage zone, a set of Cascade Infrastructure System design for urban waterlogging prevention is proposed (as shown in Figure 2), including expansion of Micro drainage system construction, optimization of Minor drainage system construction and implementation of Major drainage system construction. The system mainly aims at the main problems of urban waterlogging prevention system, i.e., the lack of micro drainage system, low standard of minor drainage system and lack of major drainage system. The three drainage systems form an organic whole, and they are connected and work together. Based on the results of drainage zoning and hydraulic model simulation, targeted construction is carried out to make the comprehensive infrastructure of the study area reach a higher standard of waterlogging prevention.

The standard of flood prevention in Xining city is once in 50 years. Using the constructed hydrodynamic model, the waterlogging situation of each system construction in the main urban area under different rainfall scenarios was simulated, the waterlogging risk assessment was carried out, and the effect of different measures was evaluated. On this basis, through the calculation of precipitation, drainage, storage and ponding, the water balance analysis is carried out, and the effect of waterlogging prevention and control construction in the main urban area of Xining is quantitatively evaluated. The water balance judgment framework is shown in Figure 3.
3. Zoning based cascade infrastructure system design for urban waterlogging prevention

3.1. Case study area
Xining city is located in the east of Qinghai Province, located in the middle reaches of Huangshui basin, surrounded by mountains and three rivers. It is the capital of Qinghai Province and the largest city in Qinghai Province. It is also the center of politics, economy, science and technology, culture and transportation, and the main industrial base.

According to the relevant data of Xining City, the research scope includes the East District, the middle district (including the South New District), the West District, the North District, the Haihu New District and the national economic development zone. The total area of the study area is 380 km$^2$. The study area is an urban construction intensive area, mainly residential housing and commercial land. The total impervious ground accounts for nearly 66.5% of the total area, and the green space rate is only 26.8%.

3.2. Expansion of micro drainage system construction
The construction of micro drainage system in Xining City, based on the pilot project of sponge city construction, according to the site conditions, combined with green space and landscape, constructs various small and decentralized rainwater control and utilization facilities, such as green roof, infiltration pavement, rainwater garden, terrain green space, rainwater bucket, etc., which plays the role of emission reduction, peak shaving and purification for a large number of small and medium-sized rainfall.

1) The recommended area for building sponge city

Combined with the hydrodynamic model simulation results of Xining city constructed in this study, it is suggested that 154 residential, commercial and square blocks in 14 districts and 101 blocks of the main urban area should be sponge transformed. The green roof and permeable pavement are used to enhance the infiltration capacity, absorb the runoff generated by the surrounding impervious hardened area, and control the rainwater runoff.

2) Green space construction

The rainwater utilization is promoted in the main urban area of Xining city. Through the construction of sunken green space and parks, the rainwater is accumulated and utilized to effectively change the situation of ponding after rain and the difficulty for tourists to travel, reduce the rainfall discharged, and reduce the pressure of urban drainage and waterlogging prevention.

The specific name of the land for reconstruction is shown in Table 1, and the spatial distribution is shown in Figure 4 and Figure 5.
Table 1. Name of sponge city reconstruction block

| Drainage Zone | Number | Location | Area (ha) | Sponge city transformation | Area (ha) | Green space construction | Area (ha) |
|---------------|--------|----------|-----------|---------------------------|-----------|--------------------------|-----------|
| 1             | 1      | HEYUEJU  | 3.09      |                           |           |                          |           |
|               | 2      | Transportation Luyuan Community | 4.24 |                           |           |                          |           |
|               | 3      | Qaidam Road 3&4 Factory Community | 8.48 |                           |           |                          |           |
| 4             | 4      | Fuyuan Community | 1.50 |                           |           |                          |           |
| 5             | 5      | Mafang Village Community | 1.18 |                           |           |                          |           |
| 6             | 6      | Hetaiju Community | 14.54 |                           |           |                          |           |
|               | 7      | Lilac Community | 12.39 |                           |           |                          |           |
|               | 8      | Hengda Community | 29.16 |                           |           |                          |           |
|               | 9      | Mafang Community | 10.98 |                           |           |                          |           |
|               | 10     | Mafang petroleum Community Xiadu Community Qinghai Engineering | 6.09 |                           |           |                          |           |
|               | 11     | Jinzuoyayuan Phase 3 | 9.10 |                           |           |                          |           |

3.3. Optimization of Minor drainage system construction
Combing the combined rainwater pipe network in the old urban area, making clear its location, pipe length, pipe diameter and other attributes, in principle, the original combined rainwater pipe will be
used as sewage pipe, and new rainwater pipe will be arranged. In areas that can not meet the needs of rainwater drainage, some rainwater pipes should be included in the underground utility tunnel. In the areas that can not meet the drainage needs and the land demand is tight, it is considered to upgrade the original pipeline that can not meet the requirements. According to the simulation calculation, 1) 127.28 km of rainwater pipelines need to be reconstructed in Xining City, which are mainly distributed in 22, 20, 6 and 33 drainage zones, accounting for 37.2% of the reconstruction length; 2) 56.95 km of rainwater and sewage combined pipeline needs to be reconstructed, mainly distributed in 22, 7, 12 and 11 drainage zones, accounting for 71.3% of the reconstructed length; 3) The newly-built rainwater pipes should be mainly distributed in the units with low network density, such as units 7, 20, 22, 30 and 31.

Considering the large amount of investment, space constraints and other factors, two pipe network transformation schemes are proposed. 1) According to the standard of 2-year return period, the spatial distribution of rainwater pipeline and rainwater sewage diversion pipeline is shown in Figure 6. The construction standard meets the requirements, the investment of pipeline reconstruction is relatively small, but the ability to cope with the Extreme Rainstorm Weather in the future is limited. 2) According to the standard of 5-year return period, the spatial distribution of rainwater pipeline and rainwater sewage diversion pipeline is shown in Figure 7. The scheme has strong ability to cope with the Extreme Rainstorm Weather in the future, but it has high construction standard, relatively large number of reconstruction and high investment cost.

1) For the reconstruction measures of rainwater pipeline system in Xining City, priority should be given to the pipeline reconstruction of existing ponding points. The reconstruction measures are shown in Table 2 and Figure 8. 2) The reconstruction measures of combined pipeline system in Xining city are shown in Table 3 and Figure 9.
Table 2. Reconstruction measures of rainwater pipeline in ponding point

| Drainage Zone | Number | Location                      | Rainwater pipeline transformation measures                      |
|---------------|--------|-------------------------------|-----------------------------------------------------------------|
|               |        |                               | Change the rainwater pipe diameter of Gonghe Road from Kunlun Avenue intersection to Xiadu Avenue to DN1200. |
| 20            | 1      | Gonghe Road                   | Change the diameter of rainwater pipeline to DN800.              |
| 22            | 1      | Huangzhong Road to Boya Road  | Section                                                        |
|               |        |                               | Rainwater pipe into the underground utility tunnel of Bayi Road.|
|               |        | Boya Junction to Minhe Junction| Section                                                        |
|               |        |                               | Change the diameter of rainwater pipeline to DN800.              |

Table 3. Reconstruction measures of combined pipeline in ponding point

| Drainage Zone | Number | Location                          | Rainwater pipeline transformation measures                      |
|---------------|--------|-----------------------------------|-----------------------------------------------------------------|
| 31            | 1      | Martyrs' Cemetery intersection    | Increase the water intake at the intersection of martyrs' cemetery and improve the standard of rain grate at the water intake. Improve the drainage pipe between Xijiu highway and Nanchuan East Road, and the drainage pipe diameter of Nanchuan East Road should be DN1400. |

Fig 8. Reconstruction of rainwater pipeline

Fig 9. Reconstruction of combined sewer
3.4. Implementation of major drainage system construction

The construction of major drainage system in Xining city mainly includes the super-high part of the ditch, the surrounding green belt, the farmland and the water body of the end ecological garden, etc. in the event of heavy rain, it will play an important role in storage and drainage, in order to cope with the rainfall exceeding the flood prevention standard in the region. When the rainstorm of drainage standard comes, the water discharged from the pipe network will be discharged through roads, slopes, natural ditches, water bodies and other ways, forming a "major drainage system".

3.4.1 Rainwater pipeline enter the utility tunnel system

The comprehensive development of Xining and some long-term reservation are considered in the research cycle of the utility tunnel. In line with the layout principle of "high efficiency, economy, moderation and practicality". The key research areas of the utility tunnel are as follows: 1) high density development zone, where pipelines are connected frequently and where expansion is possible; 2) Roads with concentrated pipelines (especially in combination with high voltage power pipelines). Combined with the development intensity of urban commercial land, new roads and old city reconstruction, the network space layout of comprehensive pipe gallery formed in the near and long term is conducive to Xining city building into an ecological, green, low-carbon and intensive modern new city and adapting to the development situation of Xining city.

3.4.2 Construction of storage facilities

The planning of rainwater storage space should give priority to urban wetland, park, sunken green space and sunken square, which should be combined with all kinds of construction activities in the process of urban development.

1) Urban wetland and water body improvement. Urban wetland is a natural "sponge" for water storage and waterlogging control. Through the regulation of wetland, excessive water from rainfall and river can be stored, so as to avoid the occurrence of waterlogging disaster. This study suggests that the wetlands in the construction area should be reasonably utilized to build a waterlogging control system in Xining City, so as to alleviate the urban drainage problem in flood season. The specific location is shown in Figure 10.

2) Artificial reservoir construction. In the area with serious road water accumulation, artificial reservoirs are built along both sides of the road, which can stabilize the peak value of rain and flood, reduce the downstream pipeline, and realize the multi-function of rainwater reuse and pollution reduction. The construction of artificial reservoir should be selected in combination with the overall urban planning, and its storage capacity should be reasonably determined. The specific location is shown in Figure 11 below. Among them, Huzhu road and Chaidamu road are located at the main ponding points.

The planned wetland construction and rainwater storage tanks in Xining is shown in Table 4.

| Drainage Zone | Wetland construction | Planned rainwater storage tanks |
|----------------|----------------------|---------------------------------|
| ...           | ...                  | ...                             |
| 5             | West Railway Station Wetland Park | 45.2 | Railway culvert at 1 and 3, Qaidam Road | 2500 |
| 6             | Huoshaogou Wetland Park | 32.6 | - | - |
| 9             | Wetland Park | - | Xiaqiao Street, Xiaqiao Cross Crossing of Spring detour Road and Ningda Road | 2500 |
| 15            | - | - | Road | 3000 |
4. **Evaluation of urban waterlogging prevention facilities construction**

The effect of zoning based cascade infrastructure system design for urban waterlogging prevention is quantitatively evaluated. The calculation results (Table 5) show that through the "Micro Minor Major" cascade infrastructure system, the adjustable water storage volume of the utility tunnel is about 267,000 m$^3$. The storage capacity of water storage facilities near main roads is about 19,000 m$^3$. About 253.7 hectares of storage wetlands or reservoirs are reconstructed and constructed, with a storage capacity of 887,000 m$^3$.

The accumulated rainwater storage capacity of the main urban area increased by 1.173 million m$^3$. In the event of a rainstorm with a return period of 50 years, without adopting the zoning based cascade infrastructure system of Xining City, the total rainfall in the main urban area of Xining city is 4.896 million m$^3$, the total drainage is 1.407 million m$^3$, and the total ponding is 1.764 million m$^3$. 1) 2 year return period scenario: Micro drainage system and Minor drainage system (in 2 year return period) were constructed, the total runoff was reduced to 2.646 million m$^3$, and the total drainage was increased to 1.573 million m$^3$. Under the construction of Major drainage system, a total of 1.173 million m$^3$ of storage capacity was increased, which was greater than the total water accumulation of 1.073 million m$^3$. 2) 5 year return period scenario: Micro drainage system and Minor drainage system (in 5 year return period) were constructed, the total runoff was reduced to 2.646 million m$^3$, and the total drainage was increased to 1.830 million m$^3$. Under the construction of Major drainage system, a total of 1.173 million m$^3$ of storage capacity was increased.
which was greater than total water accumulation of 0.816 million m³. Both schemes have achieved the expected effect overall.

### Table 5. Water balance in different return periods in Xining City (unit: million m³)

| Return period       | Total rainfall | Total runoff | Total ponding | Total drainage |
|---------------------|----------------|--------------|---------------|----------------|
| 50 year return period | 4.896          | 3.171        | 1.764         | 1.407          |
| Sewer in 2 year return period | 4.896          | 2.646        | 1.073         | 1.573          |
| Sewer in 5 year return period | 4.896          | 2.646        | 0.816         | 1.83           |

### 5. Conclusions

Urban drainage and waterlogging prevention infrastructure is an important part of urban infrastructure, which usually has natural monopoly, large capital investment, long life and far-reaching influence. It is the "hard foundation" to ensure the safety of urban drainage and waterlogging prevention. Considering the feasibility and capital investment of the construction of engineering measures, the paper proposes the reconstruction block and the standard pipe section by using hydraulic model simulation, and combines some built flood prevention infrastructure to make up the missing items of the original flood prevention infrastructure. Considering the scientific and systematic measures to solve the waterlogging problem in Xining City, this paper puts forward the technical system of urban waterlogging multi-level waterlogging prevention infrastructure construction, in which the micro drainage system mainly includes the sponge transformation of building blocks and the construction of sponge park green space; the minor drainage system mainly includes the transformation of pipe network system for different return periods and the transformation of combined flow and separate flow system; the major drainage system mainly includes utility tunnel system, natural and artificial storage facilities.

Finally, a 50 year return period rainstorm is evaluated quantitatively.

1) Under the construction of micro drainage system, the total runoff is reduced from 3.171 million m³ to 2.646 million m³.

2) Under the construction of two-year return period and five-year return period index Minor drainage system, the total drainage capacity increased from 1.407 million m³; the total amount of accumulated water decreased from 1.764 million m³ to 1.073 million m³ and 0.816 million m³ respectively.

3) Under the construction of Major drainage system, the adjustable water storage volume of the utility tunnel is about 267,000 m³; the storage capacity of main road water storage facilities is about 1,900 m³; about 253.7 hectares of wetland was constructed, with a storage capacity of 887,000 m³. The accumulated new storage capacity is 1.173 million m³, less than the total amount of ponding in each return period.

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