



Network Structure Optimization Method for Urban Drainage Systems Considering Pipeline Redundancies

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Abstract Redundancy is an important attribute of a resilient urban drainage system. While there is a lack of knowledge on where to increase redundancy and its contribution to resilience, this study developed a framework for the optimal network structure of urban drainage systems that considers pipeline redundancies. Graph theory and adaptive genetic algorithms were used to obtain the initial layout and design of the urban drainage system. The introduction of additional water paths (in loop)/redundancies is suggested by the results of complex network analysis to increase resilience. The drainage performances of the urban drainage system with pipeline redundancies, and without redundancies, were compared. The proposed method was applied to the study area in Dongying City, Shandong Province, China. The results show that the total overflow volume of the urban drainage system with pipeline redundancies under rainfall exceeding the design standard (5 years) is reduced by 20–30%, which is substantially better than the network without pipeline redundancies.

Keywords China · Pipeline redundancies · Structure optimization method · Urban drainage systems · Urban hydrology · Urban resilience

1 Introduction

The urban drainage system is one of the important infrastructures for a modern city. How to optimize the design of urban drainage systems economically and technically is a crucial research topic. Previously, a summary of the main layout optimization processes was provided by Bakhshipour et al. (2019) and Duque et al. (2020). A variety of optimization methods have been proposed for pipe hydraulic design: simulated annealing (Yeh et al. 2013); modified particle swarm optimization algorithm (Navin and Mathur 2016); a Storm Water Management Model (SWMM)-based algorithm (Shao et al. 2017); and ant colony optimization (Moeini and Afshar 2017). Sustainable urban drainage systems (SUDS) are promising options that can facilitate flood management, while enhancing the quality of stormwater runoff (La Rosa and Pappalardo 2019; Chen et al. 2021). However, SUDS also have some restrictions. For example, SUDS reduce the runoff, according to Mentens et al. (2006), Carter and Jackson (2007), and Mora-Melià et al. (2018). But these strategies are ineffective during extreme rain events. Implementation of mitigation measures such as Low Impact Development (LID) in urban areas to reduce flood volume has benefits that are more apparent when there is a shorter return period of heavy rainfall (Sun et al. 2021).

Climate change has led to an increase in the number and severity of extreme precipitation events in many parts of the world, and the resulting rainstorms and flood disasters have had a significant negative impact on communities and assets (Cheng et al. 2020). As flood volumes increase, urban drainage networks encounter more difficulties, raising the possibility of infrastructure failure. In order to reduce the magnitude and duration of flood hazards, the concept of resilience has been applied to numerous urban infrastructures (Hu et al. 2020; Fu et al. 2021; Sen et al.

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2021). The adaptability of cities could be considerably increased by building a resilient drainage system. The analysis on the resilience of a system focuses on identifying and quantifying the system's reaction to extreme stress. Research on the resilience of urban drainage systems can help mitigate urban flood hazards (Wang et al. 2019). Redundancy is an important feature of urban water system resilience (Mugume, Diao, et al. 2015; Mugume, Gomez, et al. 2015). Redundancy implies having multiple components that provide similar functions or having alternative elements to reduce the likelihood of a system failure overall (Hesarkazzazi et al. 2020; Farahmand et al. 2021).

In urban drainage systems, resilience is defined as the degree of stability and recoverability of the system under extreme conditions that exceed the design standard (Butler et al. 2018). Improving urban drainage system resilience through redundancy (Ke et al. 2016) can be accomplished in three ways by: (1) implementing best management practices, such as building storage facilities like reservoirs and rainwater tanks; (2) replacing critical pipes; and (3) optimizing the rainwater network topology, such as the introduction of parallel pipes or loops to increase redundancy (Mugume, Diao, et al. 2015; Mugume, Gomez, et al. 2015; Hesarkazzazi et al. 2020). Numerous investigations have been conducted on the first and the second methods (Tao et al. 2014; Bartos and Kerkez 2019; Jia et al. 2019; Ngamaliou-Nengoué et al. 2019; Wang et al. 2021). Therefore this study focused on the third method—the introduction of loops in the urban drainage system to increase redundancy. Using this method, it is necessary to consider where to introduce additional pipes to better improve the resilience of the urban drainage system. According to Hesarkazzazi et al. (2020), adding redundant pipelines downstream can make the water flow out effectively. However, it is yet unclear how to locate additional pipes with accuracy.

Typically, a complicated system is a research object that can be transformed into a complex network. Currently, urban water system studies and social sciences, biochemistry, transportation, and communication research, for example, all make extensive use of complex network analysis (Jenelius and Mattsson 2015; Sitzenfri et al. 2020). Complex network analysis is a useful technique for studying complicated systems. In order to determine vulnerability, it has, for instance, been used to model flood control infrastructure as a directed graph (Farahmand et al. 2021). Sitzenfri (2021) enhanced the evaluation of water quality in extensive water distribution networks by employing a complex network analysis-based approach. Due to the spatial and temporal behavior of pipe networks based on the structure and the interaction of the edges (pipes) and nodes (manholes), the urban drainage system is typically quite complicated. The analysis of a complex network is helpful for examining structural stability, determining the

crucial nodes of the pipe network, and facilitating network structure optimization.

This study developed a method for determining the specific location of additional pipelines for improving the redundancy of the urban drainage system. We also analyzed the contribution of the increased redundancies to the improvement of the resilience of the system.

2 Methodology and Datasets

This section introduces the methods used including layout selection, hydraulic design, and complex network analysis, and then applies them to a study area in Dongying City of Shandong Province in China.

2.1 Overview

The research framework is shown in Fig. 1. The proposed framework primarily consists of three steps: (1) determine the initial layout of the urban drainage system by applying graph theory algorithm; (2) obtain the optimal hydraulic design according to the adaptive genetic algorithm; and (3) determine the crucial nodes for increasing loop and redundancy based on the complex network analysis, and evaluate the resilience performance. The evaluation mainly focuses on the performance of urban drainage systems when subjected to functional failure. Thus, two indicators were selected: total overflow volume (TOV) and mean flood duration (MFD) (Mugume, Gomez, et al. 2015). The TOV is the volume of stormwater that flows out of the drainage channel when the runoff discharge is more than the drainage capacity.

2.2 Methodology

The urban drainage system network is created using layout selection and hydraulic design as a foundation, and complex network analysis is used to further optimize the network structure.

2.2.1 Layout Selection

Layout selection mostly involves determining the position and quantity of manholes, choosing the pipes involved, and determining the water flow direction. In general, graph theory algorithms are used to choose layouts (Navin and Mathur 2016; Turan et al. 2019). A graph is a collection of vertices and edges. Manholes and pipelines are analogous to vertices and edges, respectively. As the foundational graph, all potential pipes are connected. The loop-by-loop cutting algorithm forms a feasible tree layout by cutting the undirected base graph step-by-step (Haghighi 2013). Figure 2 is a summary

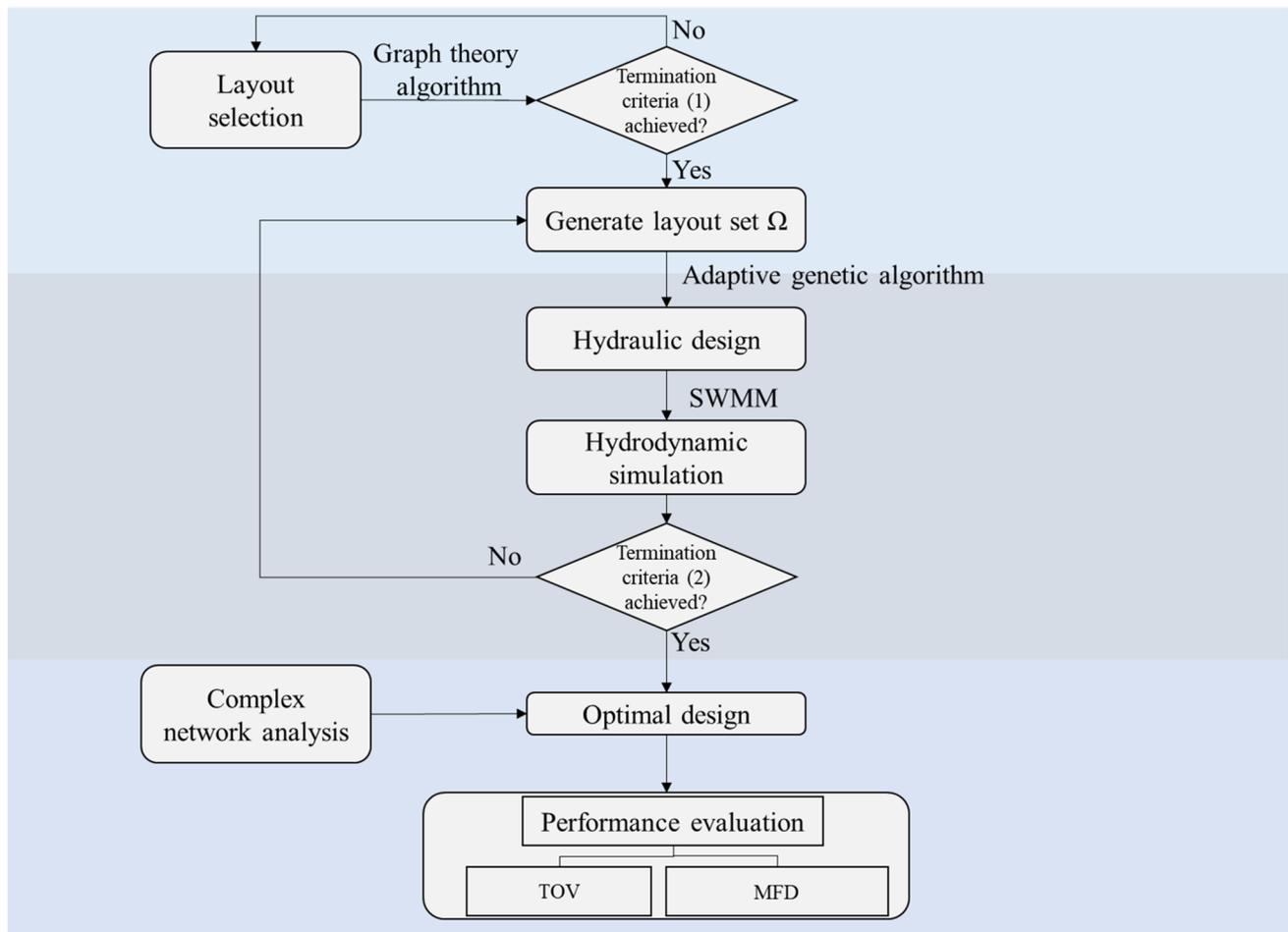


Fig. 1 Overview of the proposed research framework. Termination criteria (1): get all the subgraphs; termination criteria (2): all layouts in Ω are hydraulically designed. *SWMM* storm water management model; *TOV* total overflow volume; *MFD* mean flood duration

of the layout selection methodology used in this study: (1) to construct the base graph $G(V, E)$, where V is the collection of vertices and E is the collection of edges, and identify all the loops in the base graph; (2) to take any loop, remove an edge in the loop, and update the remaining edges (maintain connectivity during the edge removal process); (3) to check if there are still loops in the graph, and if so, go back to (2), if not, go to (4); and (4) to get all subgraphs that do not have loops (Fig. 2).

2.2.2 Hydraulic Design

The hydraulic design is mainly used to determine the diameter and slope, with the criteria of avoiding the use of pumping stations and pressurized pipes.

(1) Objective function

The problem of optimization of an urban drainage system may be expressed as:

$$\text{Minimize } F = \sum_{i=1}^N C_i(D_i, H_i) \times L_i \tag{1}$$

where F is the objective function; N is the total number of pipes; C_i is the construction cost of pipe i ; D_i is the diameter; H_i is the buried depth; and L_i is the length of the pipe.

(2) Design constraints

The hydraulic design of the urban drainage system needs to meet the corresponding pipe diameter constraints, flow velocity constraints, and buried depth constraints:

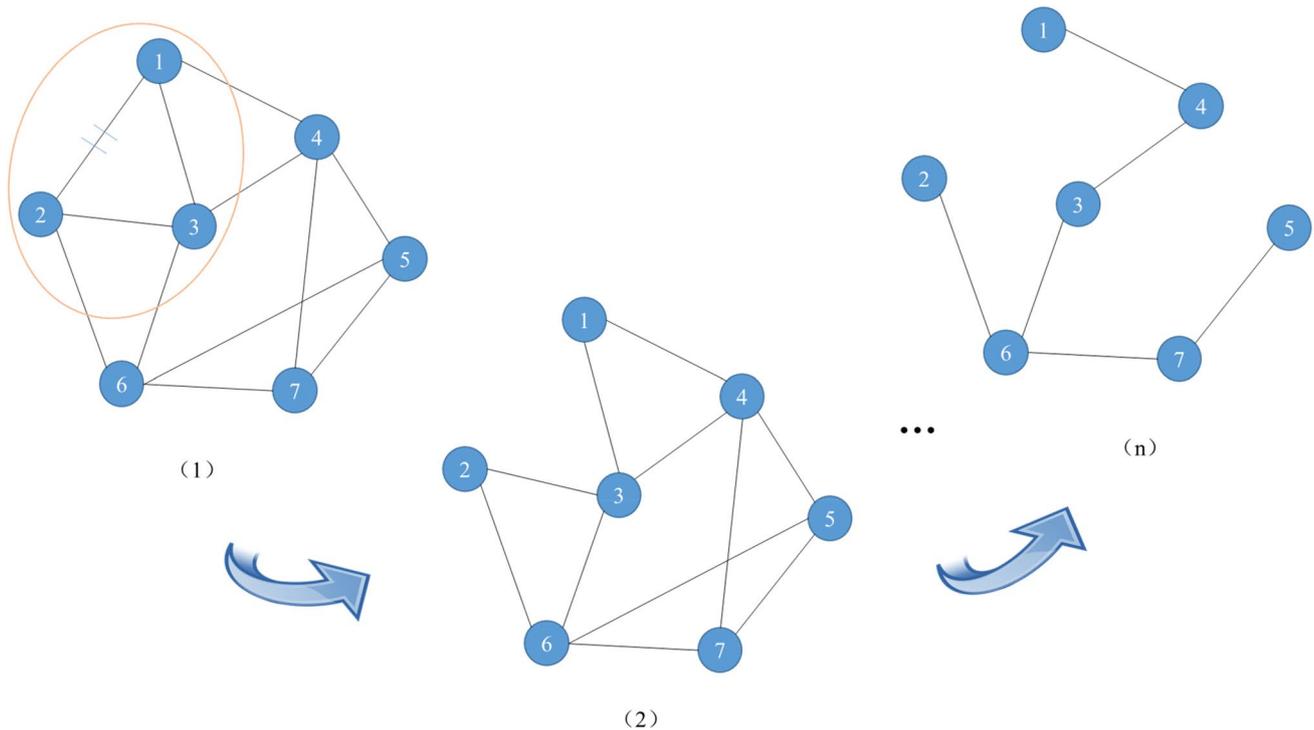


Fig. 2 Layout selection

$$D_{\min} \leq D \leq D_{\max} \tag{2}$$

$$D_{\text{down}} \geq D_{\text{up}} \tag{3}$$

$$D \in D_s = \{D_1, D_2, D_3, \dots, D_Z\} \tag{4}$$

$$v_{\min} \leq v \leq v_{\max} \tag{5}$$

$$dh_{\min} \leq H \leq dh_{\max} \tag{6}$$

where D_{\min} is the minimum pipe diameter; D is the pipe diameter; D_{\max} is the maximum pipe diameter; D_{down} is the downstream pipe diameter; D_{up} is the upstream pipe diameter; D_s is an optional set of pipe diameters; v is the flow velocity; v_{\min} is the minimum flow velocity; v_{\max} is the maximum flow velocity; dh_{\min} is the minimum buried depth; H is the buried depth; and dh_{\max} is the maximum buried depth.

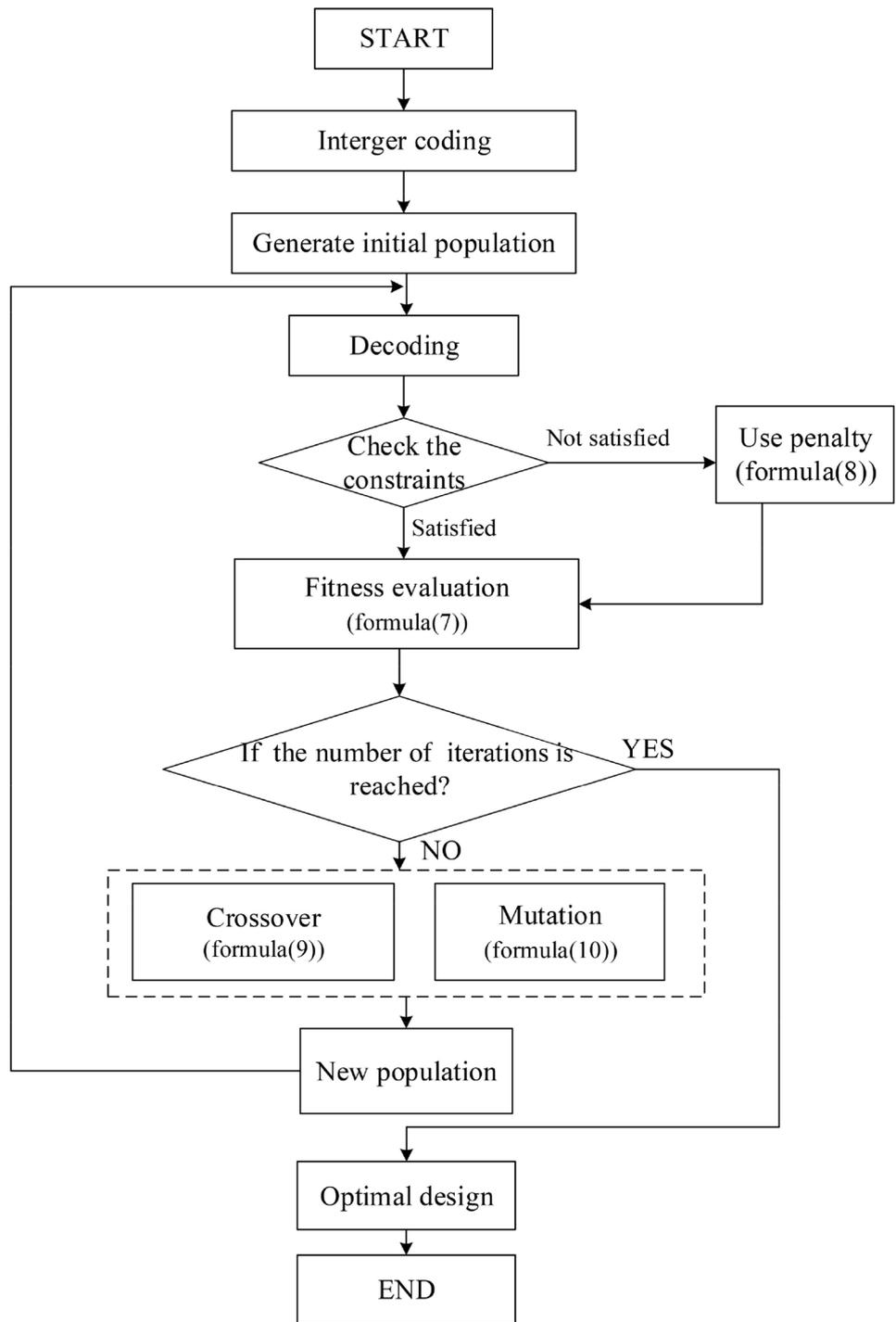
(3) Adaptive genetic algorithm for optimization
Genetic algorithm was originally proposed by Holland (1975), and it is often used to solve combinatorial optimization problems with particularly large solution space after development. Genetic algorithm origi-

nated from Darwin’s theory of biological evolution. It searches for optimal solutions by simulating the process of natural selection and biological evolution. Genetic algorithms are used for optimal hydraulic design optimization (Palumbo et al. 2013; Hassan et al. 2018). Figure 3 illustrates the steps of adaptive genetic algorithm for hydraulic optimization.

- Integer coding. Integer encoding can improve computational efficiency.
- Generate initial population. The initial population is the initial solution generated according to the coding rules. The individuals in the initial population are the parameters of the pipes.
- Decoding. The related parameters are decoded for the hydraulic calculation of the pipes.
- Fitness evaluation. The selection of the fitness function directly affects the convergence speed of the genetic algorithm and whether the optimal solution can be found. Every time fitness is calculated, it will be sorted from largest to smallest. In this study, the reciprocal of the cost of the network is selected as the objective function. The fitness function is expressed as:

$$f = \frac{a}{F(x) + G} \tag{7}$$

Fig. 3 Flowchart of adaptive genetic algorithm



$$G = P_i \times N \times C_{\max} \times L_{\max} \tag{8}$$

where f is the fitness; G is the penalty function, when the constraints are not met, $P_i = 1$, and the penalty function is executed on the fitness; a is the coefficient (mainly because the construction cost of the drainage

pipe network is relatively high, to avoid the reduction of the optimization potential due to inadequate adaptation to obtain a local optimum).

- Crossover. Adaptively adjust the crossover probability. The crossover probability calculation formula is:

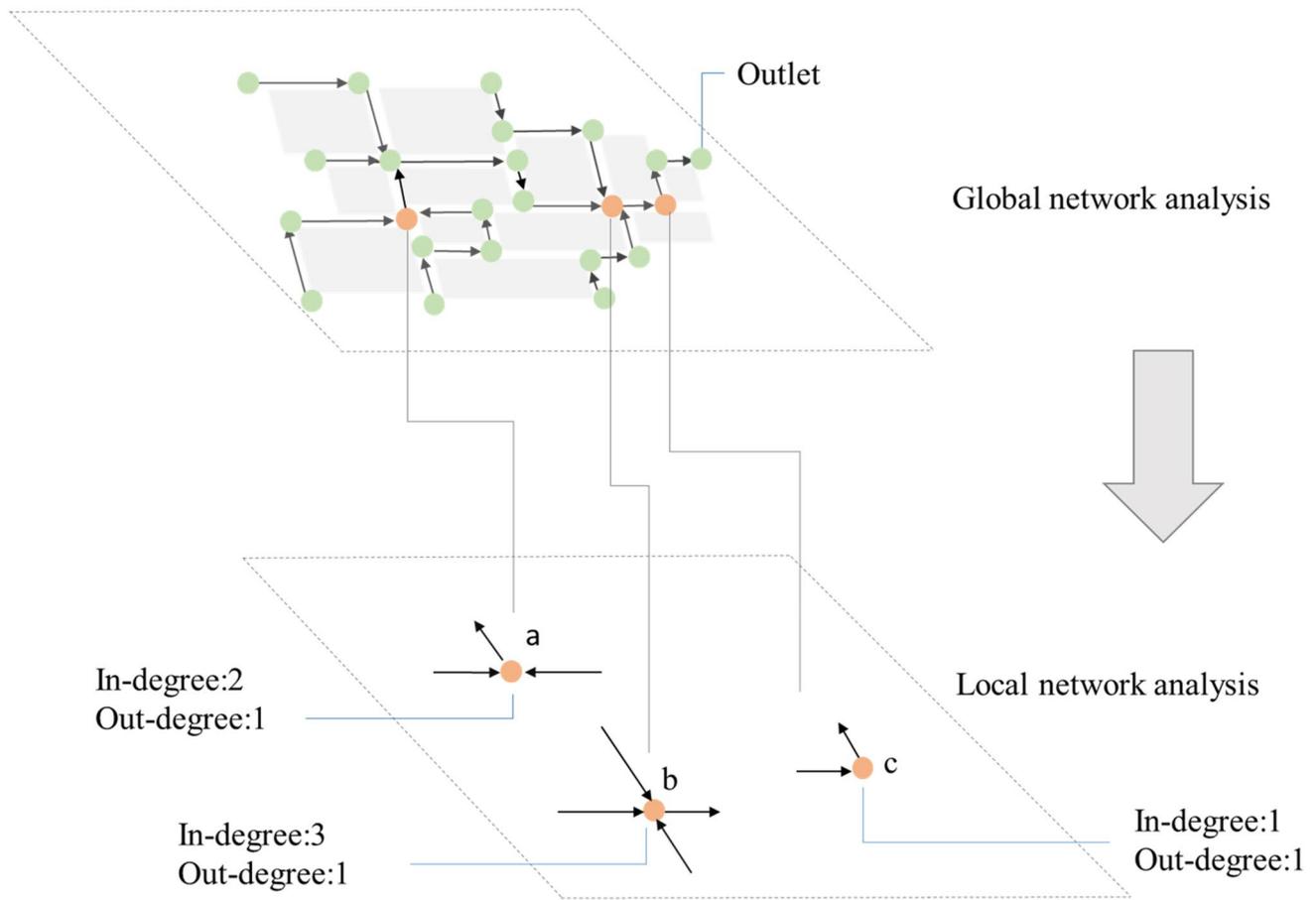


Fig. 4 Relationship between the global network analysis and the local network analysis

$$P_c = \begin{cases} P_{c \max} - \frac{(P_{c \max} - P_{c \min})(f - f_{\min})}{f_{\max} - f_{\min}}, & f \geq f_{\text{avg}} \\ P_{c \max}, & f < f_{\text{avg}} \end{cases} \quad (9)$$

where P_c is the crossover probability; $P_{c \max}$ is the maximum crossover rate; $P_{c \min}$ is the minimum crossover rate; f_{\max} is the maximum fitness; f_{\min} is the minimum fitness; and f_{avg} is the average fitness.

- Mutation. Adaptively adjust the mutation probability. The probability of mutation is calculated as:

$$P_m = \begin{cases} P_{m \max} - \frac{(P_{m \max} - P_{m \min})(f - f_{\min})}{f_{\max} - f_{\min}}, & f \geq f_{\text{avg}} \\ P_{m \max}, & f < f_{\text{avg}} \end{cases} \quad (10)$$

where P_m is the probability of mutation; $P_{m \max}$ is the maximum rate of mutation; and $P_{m \min}$ is the minimum rate of mutation.

The termination criterion of the algorithm is to achieve the preset number of iterations.

2.2.3 Complex Network Analysis

Two-layer complex network analysis is developed, consisting of a global network analysis for all nodes and a local network analysis applied individually for each node (Fig. 4).

(1) Global network analysis

Global network analysis is applied to find the crucial nodes in the urban drainage system. The role of particular nodes in the graph and their effects on the network may be determined using centrality, which can aid in the identification of significant nodes. Betweenness centrality and closeness centrality are essential in network analysis (Freeman 1977; Brandes 2001). In a big water distribution system, demand was indicated by the betweenness centrality (Sitzenfrei 2021). The edge betweenness centrality for sewage systems was adjusted by Hesarkazzazi et al. (2020) to reflect how frequently an edge is included in the shortest path from the source vertices to the

outlet. In this study, customized modifications are introduced: betweenness centrality refers to the frequency at which a node appears on the shortest path in the network; closeness centrality represents the average distance from a node to the outlet:

$$C_B(v) = \sum_{s \neq t \neq v \in V} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{11}$$

$$C_C(v) = \frac{1}{\sum_{t \in G} d_G(v, t)} \tag{12}$$

$$I = w_1 \times C_B(v) + w_2 \times C_C(v) \tag{13}$$

where $C_B(v)$ is the betweenness centrality; s, v, t are nodes; V is node set; $\sigma_{st}(v)$ is the number of shortest paths from s to t through v ; σ_{st} is the number of shortest paths from s to t ; $C_C(v)$ is the closeness centrality; G is the graph; $d_G(v, t)$ is the minimum length of any path connecting nodes v and t in G ; I is node value; and w_1 and w_2 are weights determined by the Analytic Hierarchy Process. In this study w_1 is 0.2, w_2 is 0.8. The Analytic Hierarchy Process analysis was done according to Zhang et al. (2022).

(2) Local network analysis

Local network analysis, which includes degree (d), in-degree (d_{in}), out-degree (d_{out}), and maximum degree (d_m), is a focused investigation of nodes with higher values derived from global network analysis. Degree describes how many edges are connected to a node; in-degree describes how many edges enter the node; out-degree describes how many edges leave the node; and maximum degree describes how many edges can connect to the node:

$$d = d_{in} + d_{out} \tag{14}$$

If $d < d_m$, the redundancy can be increased, and if $d = d_m$, the redundancy cannot be increased. Take node c in Fig. 4 as an example, where its maximum degree is 3; the current in-degree is 1; the out-degree is 1; there is room to increase redundancy. There is no room to add redundancy at node b because it can only have a maximum degree of 4, while the in-degree and out-degree are already 3 and 1, respectively.

2.3 Study Area and Datasets

The study area is located in the eastern part of the Dongying City center, Shandong Province, China, with an area of 8.916 km² (Fig. 5). The Storm Water Management Model (SWMM) was used for hydraulic simulation (Rossman 2015). The characteristics of the subcatchment and original stormwater engineering were obtained through a digital elevation model dataset and current status. The elevation of

the study area is high in the south and low in the north. The impervious coverage rate is 90.9%. We used elevation data with a resolution of 30 m × 30 m, and land use data with a resolution of 10 m × 10 m (Fig. 6). The total length of the original drainage pipe is 25,142 m, and the pipe density is 2.82 km/km². The pipe diameter ranges from 300 to 2000 mm. The research area has monitoring equipment for ponding points as well as a rain gauge station nearby. The rainfall data were recorded by the rain-gauge station from 18 to 20 August 2018, and the data of the three waterlogging points' flooding depth are used to calibrate the parameters (Fig. 7a). The model is acceptable because all errors are within 10% (Table 1). The final calibration parameter values of SWMM are shown in Table 2.

The verification results show that the coefficient R_e is greater than 0.9, indicating that the validity and accuracy of the model are acceptable (Table 1). The calibrated values of the parameters for SWMM are shown in Table 2.

There is a strong correlation between street networks and urban water infrastructures—around 80% of total sewer networks correlate with 50% of the street networks (Mair et al. 2017). Subcatchments are divided according to the distribution of buildings and streets in the study area. The digital elevation model is subjected to a spatial analysis to ascertain the flow direction. The design return period of drainage pipes in important areas is 3–5 years. The study area belongs to the northern residential area of Dongying City, which is a relatively densely populated residential area. The return period for design pipes is fixed at 5 years for safety concerns. For the hydraulic assessment of the urban drainage system, rainfall with 10-year and 20-year return periods is used (see Fig. 7b). The rainfall of 10-year and 20-year return periods is 80.7 mm and 92.3 mm, respectively. According to the rain-storm intensity formula of Dongying City (Di et al. 2017), the rainfall design is shown in Fig. 7b.

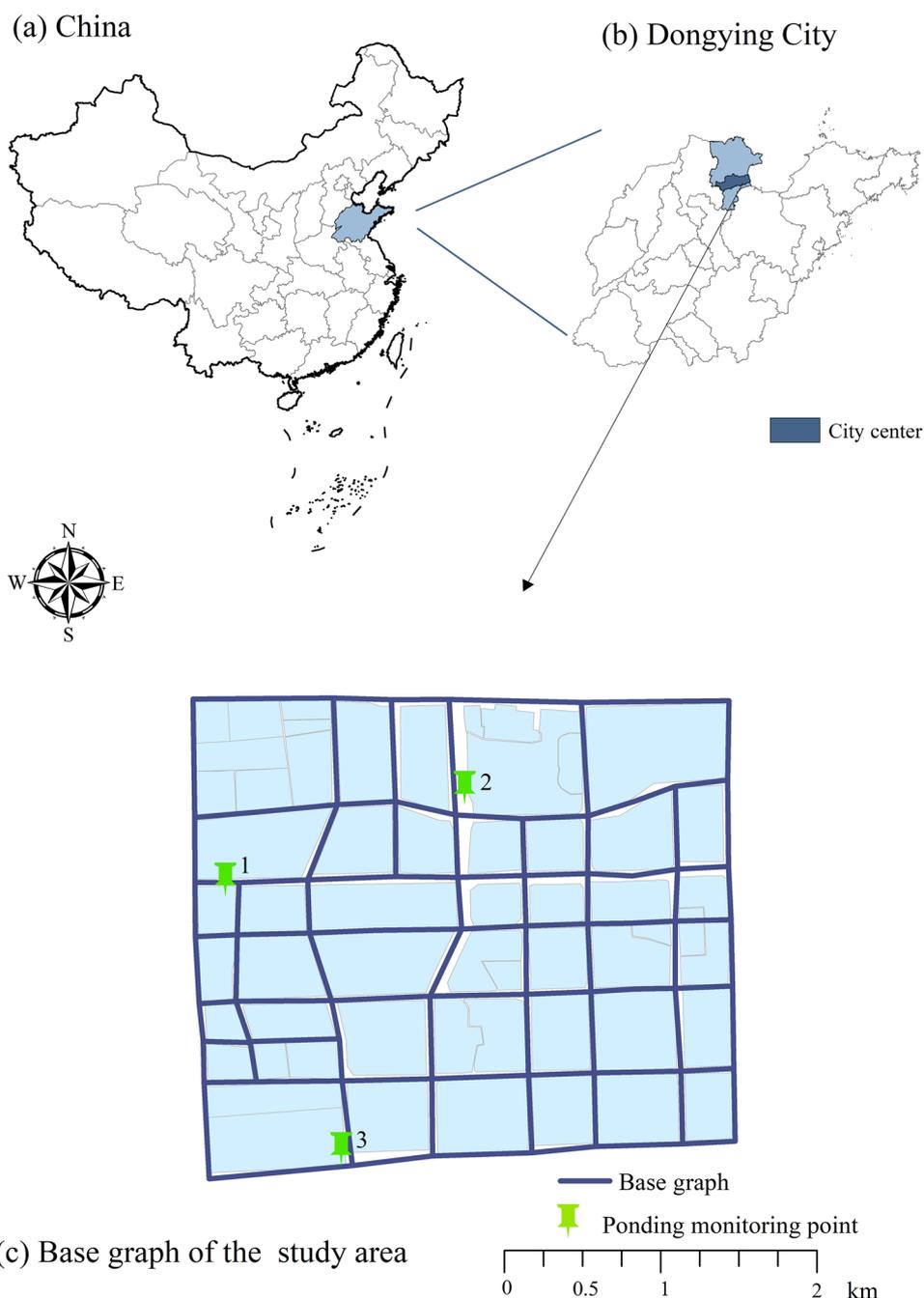
3 Results

The local drainage system's layout is first obtained using the methods and datasets described in Sect. 2; then, the hydraulic performance of the drainage system is assessed before and after optimization; and lastly, the system performance with or without redundancy is examined.

3.1 Layout of the Urban Drainage System

The base graph is a fully looped system in which all possible conduits are connected. The initial optimized layout obtained by applying the graph theory algorithm (see Sect. 2.2.1) and the adaptive optimization algorithm (see Sect. 2.2.2) is shown in Fig. 8b. The total length of the optimized network is 23,527 m, with one drainage outlet. The

Fig. 5 Location of the study area in Dongying City, Shandong Province, China. **a** China; **b** Dongying City; **c** Base graph of the study area



maximum diameter of the pipe used is 2000 mm, and the minimum diameter is 300 mm. The minimum buried depth and maximum buried depth of the manholes are 1.0 m and 6.0 m, respectively. The layout of the urban drainage system before optimization is shown in Fig. 8a.

3.2 Hydraulic Performance Assessment

A comparison of the hydraulic performance of the optimized urban drainage network with the original drainage network in the study area shows that the total overflow volume (TOV) of

the optimized network has a reduction of 65.7% and 59.6%, respectively, under the 10-year and 20-year rainfall scenarios. The mean flood duration (MFD) of the optimized drainage network is lower than that of the original network (Table 3).

Under the 20-year rainfall scenario, the pipes' surcharge rate is higher than it is under the 10-year rainfall scenario (Fig. 9). Most of the surcharged pipes of the two networks are distributed downstream. This is due to the fact that the flow through the pipe increases when water flow is focused downstream, which causes the pipes to be surcharged. As a result, it is conceivable to think about adding pipes

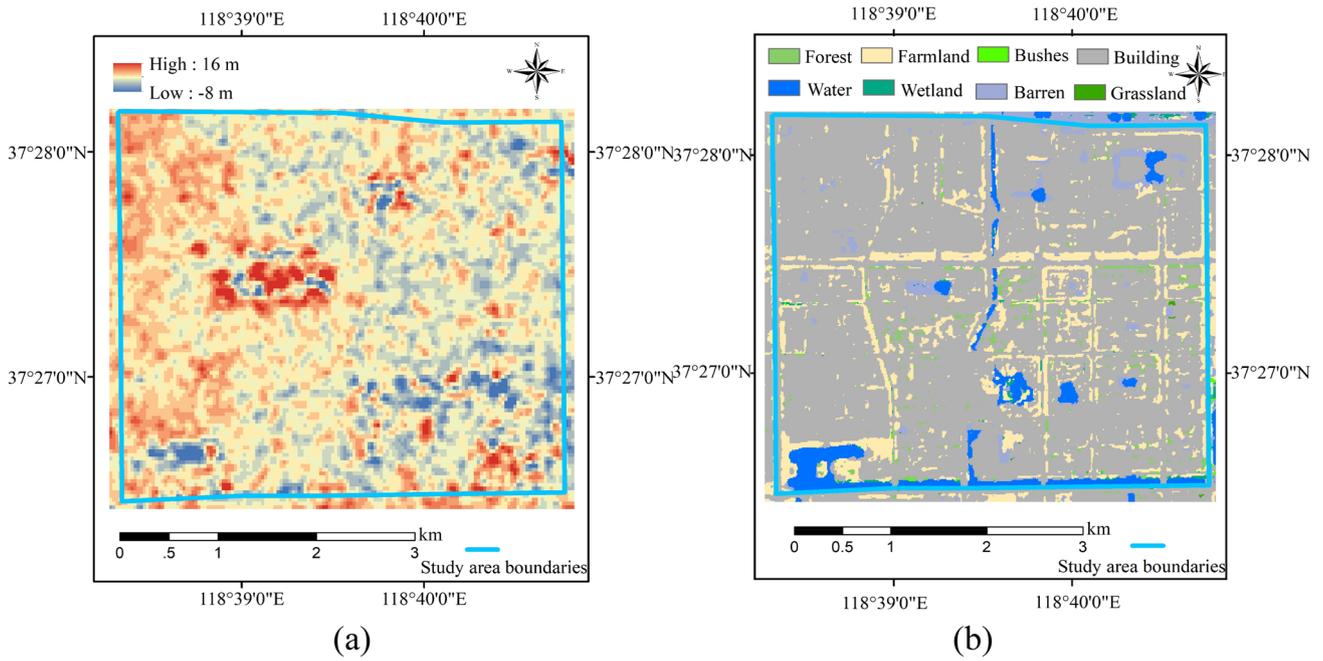


Fig. 6 Overview of the study area. **a** Ground elevation; **b** land use

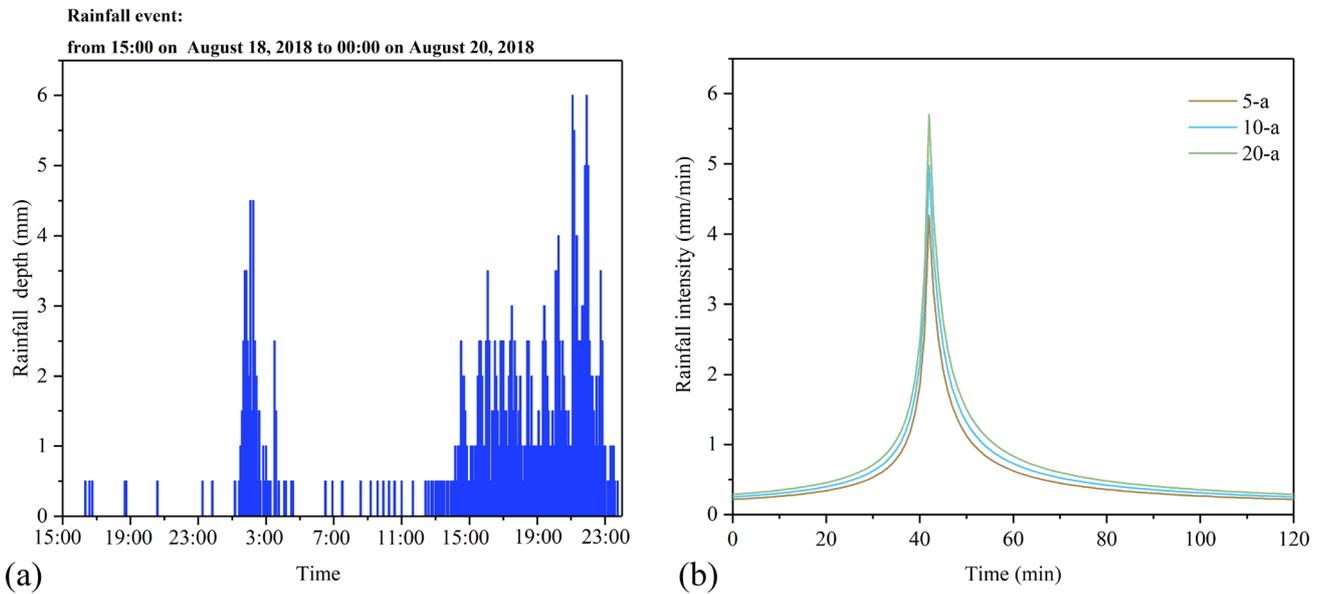


Fig. 7 Rainfall data used in the study. **a** Rainfall event used for calibration; **b** design storm under different return periods (5-year, 10-year, and 20-year): 2-h design hyetograph

downstream to improve redundancy and lower the downstream pipelines' drainage pressure.

3.3 Redundancy and Optimization

The software Gephi is used to show the data and perform complex network analysis of the urban drainage system

(Bastian et al. 2009). Gephi is free and open source software for graphics and network visualization.¹ The nodes' color shade represents the betweenness centrality, and the size of the nodes denotes the closeness centrality (Fig. 10).

¹ For download and installation, visit <https://gephi.org/>

Table 1 Flooding depth of the three waterlogging points

Waterlogging point	Observed value (m)	Simulated value (m)	$R_e = \frac{ V_{sim} - V_{obs} }{V_{obs}} \times 100\%$
1	0.255	0.261	2.4%
2	0.238	0.217	8.8%
3	0.200	0.219	9.5%

be increased. Figure 11a and b present the introduction of pipes with higher node values and lower node values, respectively.

According to the results of the complex network analysis, the network structure of the existing drainage system is optimized. To prove the effectiveness of the complex network analysis method, the position with lower node value is selected to increase the redundancy (Fig. 11).

Table 2 Calibrated values of the parameters for the storm water management model (SWMM)

Parameter	Description	Calibrated value
N-imperv	Manning's n for overland flow over the impervious portion of the subcatchment	0.015
N-perv	Manning's n for overland flow over the pervious portion of the subcatchment	0.28
Dstore-imperv (mm)	Depth of depression storage on the impervious portion of the subcatchment	1
Dstore-perv (mm)	Depth of depression storage on the pervious portion of the subcatchment	6
Maxrate (mm h ⁻¹)	Maximum infiltration rate on Horton curve	51
Minrate (mm h ⁻¹)	Minimum infiltration rate on Horton curve	3.3

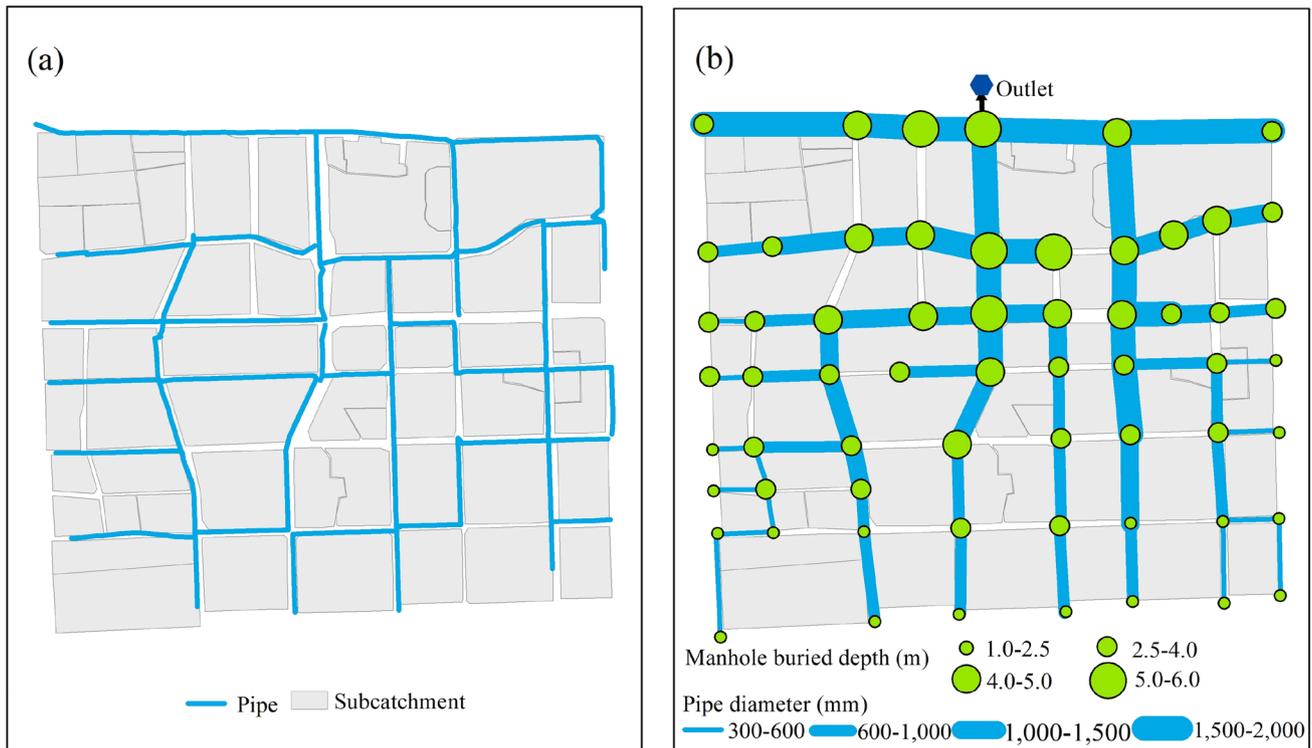


Fig. 8 Urban drainage network of Dongying City center. **a** Urban drainage network before optimization; **b** urban drainage network after preliminary optimization

Through global network analysis, nodes with higher index values are obtained. To facilitate comparison, the values are normalized, and the calculation results of the index value of each node are shown in Table 4. Local network analysis is applied to nodes with higher index values to determine the locations where pipeline redundancies can

In Table 5, the parameters of the introduced pipes are summarized. Network (a) adds a total length of 3245 m and a maximum pipe diameter of 1500 mm. Network (b) adds a total length of 3317 m and a maximum pipe diameter of

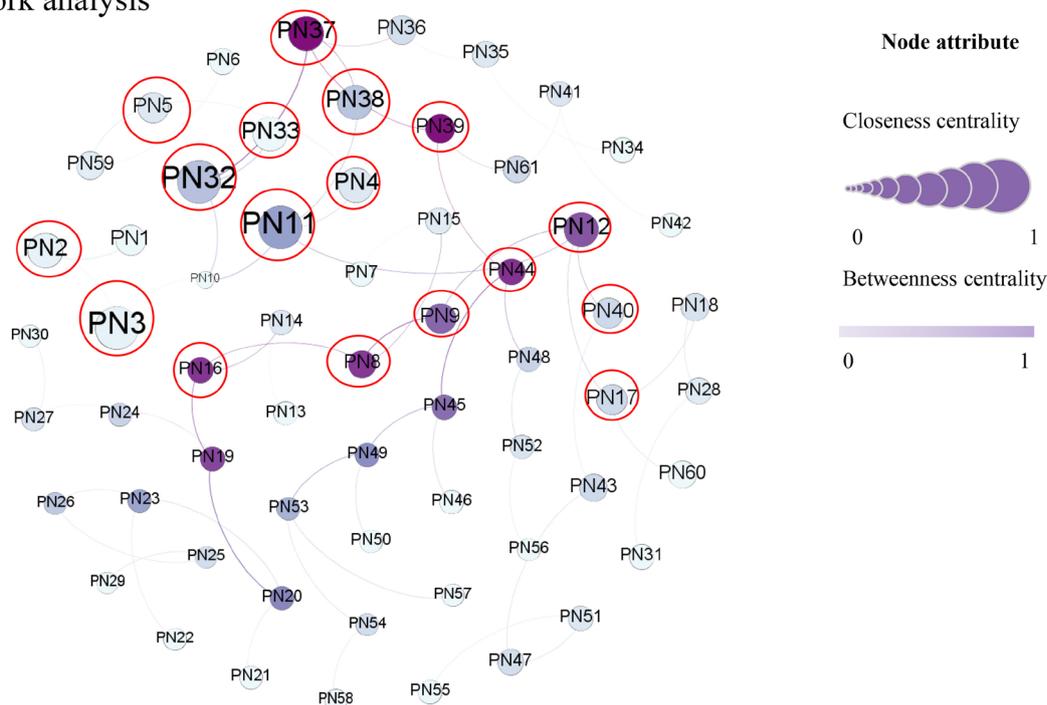
Table 3 The performance of the original urban drainage network and the designed network

Index	Return Period (year)	Original Drainage Network	Optimized Drainage Network
Total overflow volume (1000 m ³)	10	53.82	18.44
	20	64.90	26.20
Mean flood duration/maximum flood duration (hours)	10	0.80/5.78	0.64/4.17
	20	0.93/6.35	0.74/5.14



Fig. 9 Distribution of surcharged pipes. Pipe surcharge rate is the ratio of the length of the surcharged pipe to the total length of the pipe

(a) Global network analysis



(b) Local network analysis

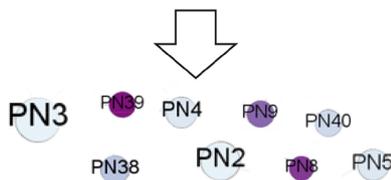


Fig. 10 Complex network analysis results (node attribute value visualization)

1200 mm. The performance of network (a) and network (b) are simulated under different rainfall scenarios.

In Fig. 12, the TOV of network (a) under the 10-year and 20-year rainfall scenarios is 12,610 m³ and 20,910 m³, respectively, which is 31.6% and 20.2% less than the preliminary optimized network. The TOV of network (b) is 16,690 m³ and 25,500 m³ under the 10-year and 20-year rainfall scenarios, respectively, which decreased by 9.5% and 2.7% compared with the network. In comparison to the preliminary optimized network, the mean and maximum flood duration of network (a) are both decreased, with the maximum flood duration decreasing more noticeably. The mean and maximum flood duration both drop in network (b), however the decrease is smaller than in network (a). It shows that the network that introduces pipes at higher node values has better resilience.

4 Discussion

Through the use of hydraulic design and layout selection, the preliminary optimum urban design network is created. The TOV and MFD of the preliminary optimized urban drainage network are reduced. The TOV of the urban drainage network after optimization is reduced by more than 50% compared with the urban drainage network before optimization. However, in conjunction with the surcharge position of the pipes in Fig. 9, it can be seen that, although the optimized drainage system performs better, its downstream pipes still bear great drainage pressure when faced with rainfall exceeding the design standard. Current urban drainage systems typically have dendritic layouts (Haghighi 2013; Steele et al. 2016; Kwon et al. 2021). The drainage pressure on the main pipes and

Table 4 Complex network analysis results (index values of nodes)

Node	Closeness centrality	Betweenness centrality	Value	Node	Closeness centrality	Betweenness centrality	Value
PN11	1.00	0.45	0.89	PN15	0.33	0.07	0.28
PN32	1.00	0.28	0.86	PN28	0.33	0.07	0.28
PN3	1.00	0.03	0.81	PN48	0.29	0.18	0.27
PN37	0.67	1.00	0.73	PN6	0.33	0.00	0.27
PN12	0.67	0.74	0.68	PN23	0.22	0.42	0.26
PN38	0.67	0.26	0.59	PN41	0.29	0.09	0.25
PN39	0.45	0.99	0.56	PN53	0.22	0.36	0.25
PN4	0.67	0.08	0.55	PN14	0.29	0.08	0.24
PN2	0.67	0.03	0.54	PN51	0.29	0.08	0.24
PN9	0.50	0.67	0.53	PN24	0.25	0.18	0.24
PN33	0.67	0.00	0.53	PN34	0.29	0.00	0.23
PN8	0.40	0.84	0.49	PN7	0.29	0.00	0.23
PN44	0.35	0.87	0.46	PN31	0.29	0.00	0.23
PN16	0.33	0.86	0.44	PN52	0.25	0.11	0.22
PN40	0.50	0.16	0.43	PN26	0.20	0.24	0.21
PN17	0.50	0.16	0.43	PN13	0.25	0.00	0.20
PN5	0.50	0.08	0.42	PN55	0.25	0.00	0.20
PN1	0.50	0.00	0.40	PN46	0.25	0.00	0.20
PN36	0.45	0.13	0.39	PN42	0.25	0.00	0.20
PN19	0.29	0.79	0.39	PN27	0.22	0.11	0.20
PN45	0.29	0.64	0.36	PN54	0.20	0.13	0.18
PN43	0.40	0.16	0.35	PN21	0.22	0.00	0.18
PN18	0.40	0.11	0.34	PN50	0.22	0.00	0.18
PN59	0.40	0.05	0.33	PN56	0.22	0.00	0.18
PN60	0.40	0.00	0.32	PN25	0.18	0.13	0.17
PN61	0.35	0.16	0.31	PN22	0.20	0.00	0.16
PN20	0.25	0.55	0.31	PN30	0.20	0.00	0.16
PN49	0.25	0.53	0.31	PN57	0.20	0.00	0.16
PN35	0.35	0.08	0.30	PN58	0.18	0.00	0.14
PN47	0.33	0.13	0.29	PN29	0.17	0.00	0.13

downstream will certainly increase as the water collects. As a result, the surcharge of the pipes frequently happens in these locations (Lu et al. 2021).

As shown in Fig. 12, when the rainfall exceeds the design standard, the stormwater pipe network (a) and network (b) perform better in terms of drainage than the network without taking redundancy into account. Some studies define redundancy as meshness (the number of pipes connected to the node in addition to the source node and the outlet node) (Reyes-Silva et al. 2020). A network with a higher meshness value has shorter flood duration and smaller node flood volume than a predominantly branched network. This is in line with the current findings.

Network (a) and network (b) both increase redundancy and provide additional water flow paths and storage capacity. The difference is that network (a) shows higher resilience than network (b). If there are not many differences between the two networks' storage capacities, it is

presumed that the improved resilience results from better flow distribution. Yang et al. (2019) mentioned in their study of stormwater drainage systems that the number of deteriorating pipes is not the decisive factor for node flooding, and the topological location has a considerable impact on performance. The introduction of parallel pipes at reaches with bottleneck problems to increase the loop has higher efficiency in terms of flood prevention (Yazdi 2017). In this study, introducing pipes at locations with higher node values can reduce TOV by 31.6% and 20.2%, respectively, under the 10-year and 20-year rainfall scenarios. This finding suggests that the topological position of the pipes, as opposed to their quantity or length, is more crucial to the drainage system's performance. This also suggests that adding extra pipes in the right place can improve system resilience. The performance of an urban drainage system depends on the properties of the fundamental components (such as pipes) and the interdependence between

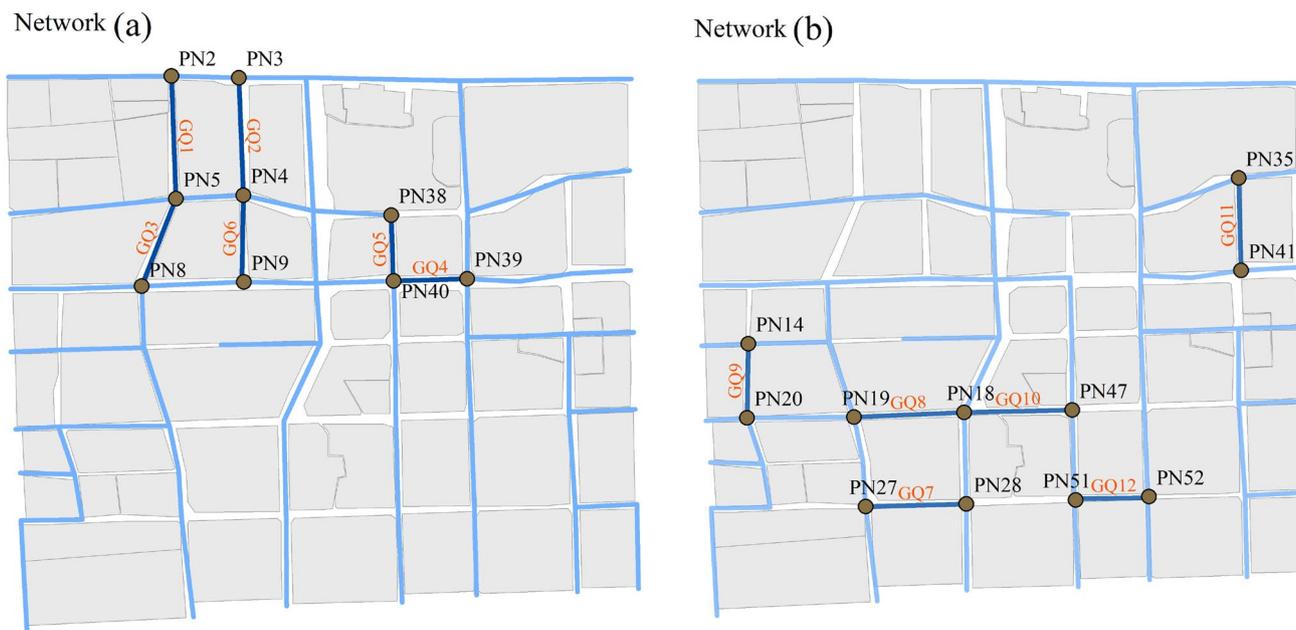


Fig. 11 Optimized structure considering pipeline redundancies. Network **a** introduces pipes where the node value is higher; Network **b** introduces pipes where the node value is lower. PN represents the pipeline node, and GQ indicates the pipe

Table 5 Parameters of the introduced pipes

Structure	Pipe	Length (m)	Diameter (mm)	Slope (%)
(a) Increase loops where the node value is higher	GQ1	713	1000	1.4
	GQ2	682	1500	3.4
	GQ3	542	1000	1.8
	GQ4	419	1000	2.4
	GQ5	387	1200	2.1
	GQ6	502	1200	2.0
(b) Increase loops where the node value is lower	GQ7	596	1000	4.2
	GQ8	654	1200	3.7
	GQ9	445	1000	3.3
	GQ10	639	1000	3.8
	GQ11	555	1200	4.1
	GQ12	428	1000	5.5

the functions of these various components, which is a system-level phenomenon. Complex network analysis identifies components that need to be prioritized to improve network performance from a system perspective.

5 Conclusion

Urban floods are becoming increasingly common as a result of urbanization and climate change, and the capacity of urban drainage systems to handle heavy

precipitation is crucial for flood management and catastrophe mitigation. How to optimize the network structure of urban drainage systems to have better performance and resilience is a fundamental scientific issue of urban hydrology. This study proposes an optimization method for the network structure of urban drainage systems, which combines graph theory algorithm, adaptive genetic algorithm, and complex network analysis. This method enables the identification of where to increase the pipeline redundancies accurately to optimize the network structure of urban drainage systems.

The initial optimum hydraulic design and layout can be obtained using graph theory and adaptive genetic algorithms. Complex network analysis is used to identify key nodes in the network and improve the resilience of the system by increasing the structural redundancy at locations with higher node values. The case study of an urban area demonstrates that increasing pipeline redundancies in the network can improve drainage performance. When compared to a structure that does not take redundancies into account, the one that does can cut TOV by 20–30% and the maximum flood duration by 2–3 h. According to the findings, a network with more pipeline redundancies is more effective at preventing flooding and has more potential to improve resilience.

Urban drainage systems are often very complex because pipe networks have different spatial and temporal behaviors through structure and interaction of edges and nodes. The complex network analysis enables the identification of the

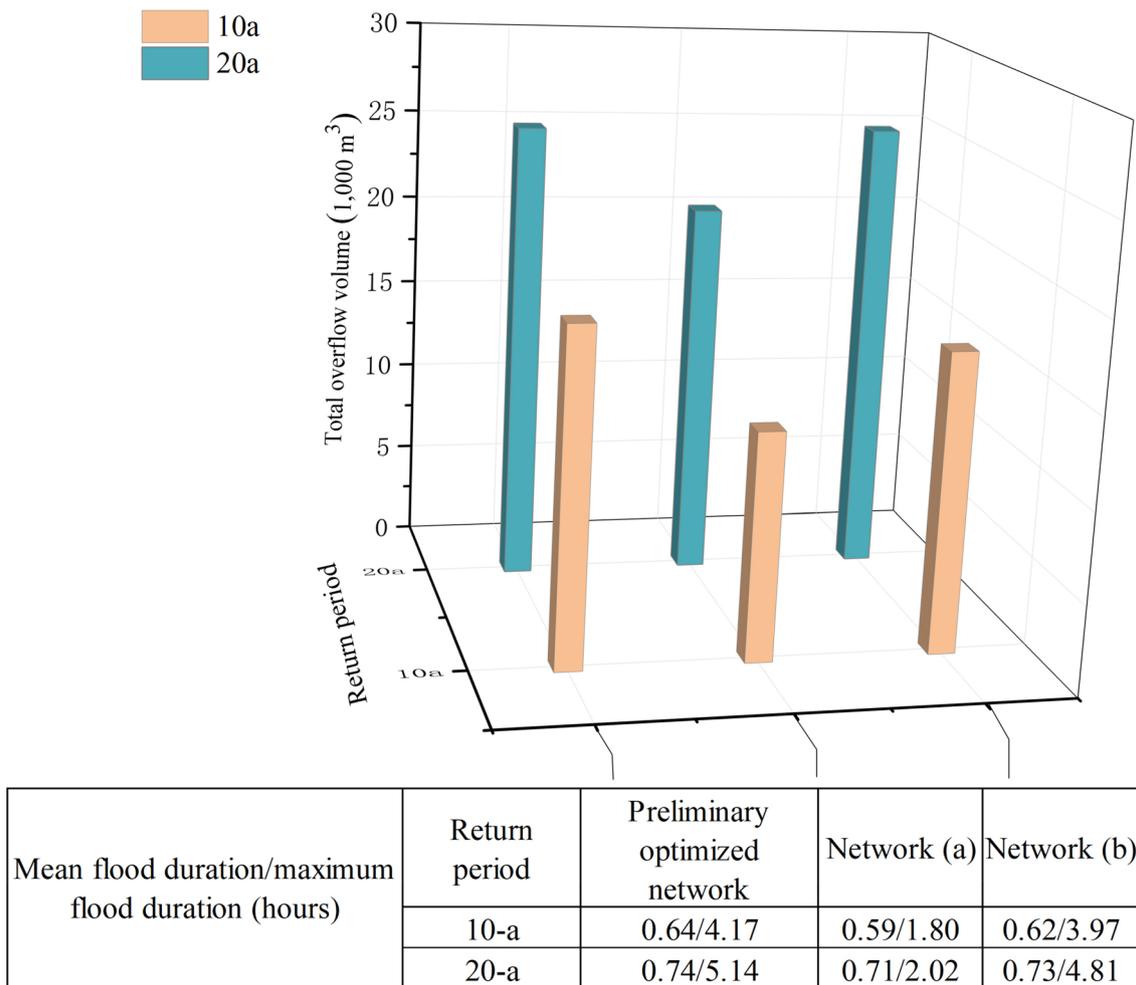


Fig. 12 Drainage performance comparison between the preliminary optimized network and the optimized networks for 10- and 20-year return periods

crucial nodes in the drainage network and then locates the location of additional pipes, which solves the problem of determining where to increase the loop. The developed network structure optimization method offers a way to increase pipeline redundancies and provides new opportunities for improving the resilience of urban stormwater systems. Future research should investigate the cost-effectiveness of increasing redundancy in improving the drainage efficiency of urban drainage systems. Additionally, resilience indices to evaluate the impact of redundancy on system resilience are recommended for future studies.

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