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Comprehensive analysis of waterlogging control and carbon emission reduction for optimal LID layout

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Abstract

Under the background of global climate change, flooding is causing devastating impacts on the balance of the regional water resources system. The campuses are typical built-up areas with high building density and are also disturbed by waterlogging. How to transform the campus rainwater system into sponge city reconstruction is the key problem to be solved. Based on the MIKE FLOOD platform, the urban waterlogging model is established, the causes of waterlogging are analyzed in this study. Low impact development (LID) measures are added according to the current situation. The carbon emission reduction capacity and economic benefit of each scenario are calculated and evaluated. The Analytic Hierarchy Process (AHP) is used to comprehensively evaluate the LID combination scenario to further explore a reasonable solution to mitigate urban waterlogging. The results show that the current rainwater pipe network built has a small pressure load on the campus, which cannot well respond to heavy rainfall conditions, resulting in a high risk of waterlogging in the campus. After setting up LID measures, the runoff control rate can be increased by 26.15-42.84%, and the waterlogging area above 15cm can be reduced by 72.87-100%. If the energy conservation and emission reduction benefits and costs are considered at the same time, the layout scenario of 9% bioretention facility +3% green roof+3% permeable pavement can achieve the best benefits. The research can provide a reference for planning and reconstruction of ‘sponge campus’ and old residential areas.

Introduction

In recent years, China's urban floods have occurred frequently, and the waterlogging disasters have brought challenges to the current urban development and people's lives and property, which is the comprehensive embodiment of ‘urban disease’ (Wu et al. 2018). The construction of ‘sponge city’ can not only effectively mitigate ion urban waterlogging problems, enhance the climate resilience of urban and rural areas, and make the city flexibly adapt to environmental changes and natural disasters(Zhang et al. 2021; Baek et al. 2015). It can also further realize the green and low-carbon economy (Liu et al. 2017; Nguyen et al. 2020; Taghizadeh et al. 2021), and help China to achieve the goal of ‘carbon peak’ and ‘carbon neutralization’. Therefore, it is of great significance to plan LID measures through urban stormwater models to evaluate waterlogging reduction and carbon emission reduction(Darnthamrongkul et al. 2021; Baek et al. 2015). Hydrological models such as SWMM model can effectively simulate the process of urban regional rainfall runoff. Hydrodynamic model such as MIKE model is more detailed than hydrological model to characterize the surface flood process (Bisht et al. 2016). Tansar et al. (2020) used MIKE FLOOD to assess the flood disaster in the lower reaches of *Lower Ping River* Basin, Thailand. The study indicated that the model could effectively simulate the flood risk and provide management methods for disaster reduction. Patro et al. (2009) coupled 1D-2D hydrodynamic to generate a flood model, which simulated the flood inundation extent and flooding depth in the delta region of *Mahanadi River* basin in India. The model has good accuracy. Liu et al. (2016) used the MIKE URBAN model for the stormwater quantity and coupled with the water quality models for pollutants built-up and wash-off analysis through ABC. Similarly, Liang et al. (2019) and Liu et al. (2020) attempted to simulate the efficiency of stormwater control using LID measures and evaluate the effectiveness of different combination scenarios by using SWMM. Li et al.(2017) established a comprehensive benefit evaluation system for LID, including environmental, economic, and social benefits.They found that the preferential order of LID single measures based on the comprehensive benefit was: bioretention > rain barrels > low-elevation greenbelt > green roofs > permeable pavement. Liang et al. (2017) took Shenzhen City as the research object and used SUSTAIN to simulate the effectiveness of different LID measures in various scenarios. They evaluated the benefits of these LID facilities in view of water quantity control and implementation cost. Although the environmental benefits are key factors when choosing an LID measures, the cost-effectiveness are equally important in decision making for‘Sponge city’construction in China. From the above literature, a majority of the existing studies mainly focus on the flood evolution process and flood control and drainage in large river basins by MIKE series models. A very few studies have investigated the waterlogging and comprehensive benefit of combined LID measures in university. ‘Sponge campus’ is a typical ‘small sponge’, which is a new concept for campus stormwater management. It is necessary to build a ‘green campus’ to solve the problems of water security and water environment on campus.

The objectives of this paper are as follows:(1) A one-dimensional drainage network model(MIKE URBAN) and a two-dimensional surface runoff model (MIKE 21)are established, simulating the waterlogging process and analyzing the waterlogging causes in a university from Xi 'an;(2) To design different LID scenarios for waterlogging mitigation according to the causes of waterlogging;(3) To select the optimal scenario for comprehensive economic benefits, environmental benefits, and energy conservation and emission reduction benefits by AHP method. This study provides a reference for the construction of ‘sponge campus’.

Materials And Methods

Study area

Xi 'an is a core city in the central Guanzhong Plain. The urban area has an elevation of 400–450 meters and annual precipitation of 522.4-719.5mm, increasing from north to south. Precipitation is mainly concentrated from July to September. This study selects a university in Xi 'an as the research object. The campus is located near the road section of *Jinhua South Road*, *East Second Ring Road* in Xi 'an, covering an area of about 27.1554 hm^2. The five land use types are squares, buildings, green spaces, traffic roads and water area, which account for 37.68%, 31.55%, 20.99%, 9.62%, and 0.15%, respectively, of the total area of the campus. The distribution of land use types is shown in Fig. 1. This campus is a typical old campus with high density of building and high proportion of impervious pavement. The drainage system of the campus is old, and some areas are seriously waterlogged, which affects the lives of teachers and students.

Establishment of study area model

MIKE URBAN is a 1D drainage network model, which is composed of water supply and drainage system. The drainage system mainly includes rainfall runoff module, pipe flow module. MIKE URBAN provides four runoff models: Time-Area Method, Non-Linear Reservoir Method, Linear Reservoir Method, Unit Hydrograph Model. Among them, Non-Linear Reservoir Method is based on kinematic wave calculation, and the surface runoff is calculated as an open channel flow. Taking into account the factor of Horton infiltration, the physical concept is clearer. It is suitable for sponge city simulation in small areas with high precision requirements. Therefore, Non-Linear Reservoir Method with high precision is used to describe this confluence calculation model.

According to the urban planning map and the layout of rainwater pipe network, CAD and ArcGIS are used to analyze the underlying surface. The 1D drainage network model is established in the study area. This method is called the Thiessen polygon method, the study area is divided into 105 sub-catchment areas. In the model, 106 drainage pipes are established, with the total length of 2.913km and the pipe diameter range from 100 to 800 mm. There are 108 nodes in total, including 105 inspection wells and 3 drainage outlets (Fig. 2).

The 2D surface runoff model is a planar two-dimensional free surface flow model. The control equations are composed of shallow water equations and momentum equations, which are solved by the finite volume method of alternating direction implicit (ADI) (Darama et al. 2021). The data of 892 elevation points in CAD are extracted. The digital elevation model (DEM) of the study area is obtained by interpolation calculation using ArcGIS. When building and road are superimposed on the basic terrain, the elevation of building and road should be appropriately changed to ensure the stability of simulation results. In this study, it is assumed that the building will be raised 10 m and the road elevation is 0.15 m lower than the surrounding ground. According to the current situation of the study area and the precision requirements of the model, the grid size is determined to be 4⊆4 m. The interaction between the drainage system and the catchment area can be described by dynamically coupling MIKE URBAN and MIKE 21on the MIKE FLOOD platform. The coupling model takes the inspection well as the coupling point to couple with the 2D surface calculation grid. It can obtain the change process of overflow and backflow, and surface waterlogging in the study area under certain rainfall conditions. And it can more accurately reflect the interaction between the urban drainage pipe network and surface water flow.

Model calibration and validation

(1) Calibration of uncertain parameter

Owing to the lack of measured data, the model cannot calibrate the parameters through the measured value and simulated value of outlet runoff. This work adopts the parameter calibration method of urban rainfall runoff model based on runoff coefficient (Liu et al. 2014). To ensure that the model has good stability under different rainfall events, the precipitation with the return period of 1 year and 10 years is used to calibrate the parameters. According to the simulation results, the comprehensive runoff coefficients of the two designed rainfalls are 0.663 and 0.759. Both results can meet the requirements of the comprehensive runoff coefficient of 0.6 ~ 0.8 in the densely built central area.

(2) Model validation

Rainfall events on July 18,2021 and August 31, 2021 are selected as the research objects (referred to as 20210718 and 20210831) to conduct an empirical study on stormwater simulation. The simulation results are verified by maximum water depth survey method. After repeated reconnaissance and investigation, the data of rainfall runoff depth of typical waterlogging points in the region were collected. The location of typical waterlogging points in the study area is shown in Fig. 3. The maximum water depth of the waterlogging point is counted, and the relative error is analyzed between the measured value and the simulated value. The error of the four waterlogging points is within the allowable range of the application specification (-20%-10%)(Su et al. 2020). The comparison results of maximum water depth are shown in Table 1.

Table 1
Comparison results of maximum water depth at typical points of 20210718 and 20210831 rainfall events

Waterlogging point number	Location	20210718 rainfall event			20210831 rainfall event		
		Measured value (cm)	Simulated value (cm)	Relative error (%)	Measured value (cm)	Simulated value (cm)	Relative error (%)
1	South side of the library	3.90	4.30	0.10	3.20	3.60	0.13
2	Duxing Road	3.90	4.20	0.08	2.70	2.90	0.07
3	West side of teaching building six	2.60	3.10	0.19	2.10	2.40	0.14
4	North side of the fourth dormitory building	4.30	40	0.07	2.80	2.60	0.07

Scenario setting

Rainfall condition design

The Chicago rainfall pattern is used as the equation for calculating rainstorm intensity in this study area(Yang et al. 2021;Zhang et al. 2021). The intensity of rainstorm is calculated by the following Eq. (1):

$$q = \frac{2210.87(1 + 2.915lgP)}{(t + 21.933)^{0.974}}$$

1

Where q is the storm intensity; P is the rainfall return period, year; t is the rainfall duration, min.

The designed rainfall duration is 2h, the rainfall return periods are 1,3,5,10, 20 years. The time step is one minute, and the rain peak coefficient is empirical value 0.4 (Liu et al. 2020;Li et al. 2019). The design rainfalls are 12.775mm, 30.537mm, 38.797mm, 50.015mm, 61.221mm, respectively.

LID combination scenarios

MIKE URBAN provided two LID simulation methods: (1) Hydrological generalization based on catchment areas. (2) Hydrodynamic generalization method based on pipe network. This study adopts Soakaway of hydrodynamic generalization method, which is defined as permeable node in MIKE URBAN. Soakaway can represent many different LID measures and can also be directly connected to the drainage system. The study area is old urban with dense buildings. There are many cement roads with impervious, and the green space accounts for 20% of the total area. Considering the factors such as surface type and vegetation coverage rate, three LID measures are set up in the study area, including bioretention facilities, green roofs and permeable pavement. The planning area of LID measures is 4.073 hectares, accounting for 15% of the study area. The three LID combination scenarios are as follows: Scenario A:3% bioretention facility + 3% green roof + 9% permeable pavement. Scenario B:9% bioretention facility + 3% green roof + 3% permeable pavement. Scenario C:3% bioretention facility + 9% green roof + 3% permeable pavement.

Comprehensive benefit analysis

(1) Economic benefit

Owing to the lack of relevant information, this study mainly considers the construction cost, design cost and operation and maintenance cost as the estimation indexes of economic benefits of LID measures. The construction cost, design cost and maintenance cost of different LID measures are shown in Table 2.

Table 2
Reference cost of LID measures

LID measures	Construction cost (yuan/ m^2)	Design cost (yuan/ m^2)	Operation and maintenance cost (yuan/ m^2)
Bioretention facility	400	40	30
Permeable pavement	150	20	10
Green roof	200	25	20

(2) Environmental Benefit

LID measures can effectively improve the water ecology and water environment in the study area. This study mainly considers the runoff control rate and the reduction of overflow nodes as the estimation indexes of environmental benefits of LID measures.

(3) Social Benefit

The construction of sponge cities can not only effectively mitigate urban waterlogging and reduce the urban heat island effect, but also further realize carbon emission reduction. LID measures have an effect on energy conservation and emission reduction. The carbon emission reduction benefits of LID measures are quantitatively analyzed by using the evaluation index of carbon emission reduction. The urban greening and bioretention facility can sequester carbon and release oxygen through plants photosynthesis or rainwater infiltration retention. The carbon sequestration capacity is affected by the external environment, vegetation type and size. The carbon absorption is calculated by the following Eq. (2). Water can also absorb part of carbon. The chemoautotrophs in water can fix inorganic carbon to absorb CO_2 from the atmosphere (Eugenio et al. 2017). The carbon absorption is calculated by the following Eq. (3):

$$C_{sf1} = A_1 \times S_1$$

2

$$CI_{water} = C_{unit-water} \times A_{water}$$

3

Where C_{sf1} is the carbon uptake of vegetation, t/a;A_1 is the green area, m^2;S_1 is the photosynthetic carbon absorption unit area, and the bioretention facility is 2.715t/hm^2·a (Guan et al. 1998),0.948229 t/hm^2·a for ordinary green space. CI_{water} is the amount of carbon absorbed by water area, t/a; $C_{unit-water}$ is the carbon sequestration rate of rivers and lakes,0.567t/hm^2·a (Duan et al. 2008);A_{water} is water area.

A lot of ready-mixed concrete is required for laying cement roads, and a large amount of CO_2 will be emitted in the whole process of concrete production. Paving permeable pavement can reduce the use of concrete. Moreover, it has good infiltration capacity, which can reduce surface temperature and supplement groundwater, etc. The carbon emission is calculated by the following Eq. (4):

$$J_s = N \times V_G / T_G$$

4

Where J_s is used to reduce concrete consumption and carbon emission, t/a;N is carbon emission per unit cubic meter of concrete,0.22t/m^3 (Sanal 2017); V_G is the reduced concrete usage, m^3;$T_G$is the service life of road, 50 years.

Green roof can effectively reduce the total amount of roof runoff and has the role of energy conservation and emission reduction(Fan et al. 2020). One is carbon sequestration through plant uptake and soil substrate. The carbon reduction capacity is affected by vegetation type, soil matrix type and soil thickness (Chen et al. 2018; Zhang et al. 2015). The carbon absorption of vegetation is calculated by the following Eq. (5). On the other hand, energy consumption can be reduced by lowering the building temperature and protecting the roof structure, and ultimately carbon emissions can be reduced (Jim et al. 2012). The carbon emission reduction and energy conservation of building is calculated by the following Eq. (6):

$$C_{sf2} = A_2 \times S_2$$

5

$$J = E \times S$$

6

Where $C_{sf2}$is the carbon uptake of vegetation, t/a; A_2 is green roof area, m^2;S_2 is the photosynthetic carbon absorption per unit area,0.948229t/ hm^2·a (Xie et al. 2008); J is the amount of building energy conservation carbon emission reduction, t/a;E is the energy consumption reduced by green roof per unit area,10.002Kg/ m^2·a (Cai et al. 2019);S is green roof area, m^2.

(4) Comprehensive Benefit

Analytic Hierarchy Process (AHP) method is a multi-objective decision analysis method combining qualitative analysis and quantitative analysis, which is suitable for dealing with problems that are difficult to quantify (Lee 2015). AHP is used to evaluate three LID combination scenarios in this study. A screening system for optimal layout of LID combination scenarios is established based on the above mentioned method (Fig. 4).

Results And Discussion

Simulation result analysis

Effect of runoff control

Annual total runoff control rate is generally adopted as the control target for LID rainwater system. Under the five rainfall return periods, the reduction effect of the three stormwater control scenarios on total external discharge is shown in Table 3. It can be seen from the table that Scenario B has the best effect on runoff control in each return period. The difference of control rate between Scenario B and Scenario C is stable within 5%. With the increase of the return period, the stormwater control effect of the three LID scenarios decreases obviously. The reason is that LID measures quickly reach saturation when the rainfall intensity is high. The soil infiltration capacity is weak, so the subsequent water volume cannot be regulated.This resultis in accordance with the literature that suggests that the storage effect of LID measures decreases with the increase in rainfall intensity(Rong et al. 2021).For the rainfall return period of 3 years, the total runoff control rate under the currentdevelopment scenario is 17.44%. After adding the LID measures of Scenario B, the control rate increased to 58.02%.

Table 3
Statistical results of the total runoff amount

Rainfall return period	Total water amount (m^3)		Total outflow amount (m^3)	Percentage control (%)
1a	Current	3469.90	2276.00	34.41
	Scenario A		1,209.80	65.13
	Scenario B		840.00	75.79
	Scenario C		1,361.20	60.77
3a	Current	8292.50	6846.10	17.44
	Scenario A		4,245.40	48.80
	Scenario B		3481.60	58.02
	Scenario C		4,677.50	43.59
5a	Current	10535.50	9,009.70	14.48
	Scenario A		5,491.80	47.87
	Scenario B		4,769.20	54.73
	Scenario C		5,929.90	43.72
10a	Current	13581.80	11,962.70	11.92
	Scenario A		6,987.80	48.55
	Scenario B		6,332.80	53.37
	Scenario C		7,223.60	46.81
20a	Current	16624.80	14923.50	10.23
	Scenario A		8,217.80	50.57
	Scenario B		7801.70	53.07
	Scenario C		8,419.20	49.36

Node overflow and pipe network load

(1) Node overflow analysis

Rainfall with high intensity in cities often leads to overloaded drainage pipelines. When the runoff in the study area exceeds the drainage capacity of the drainage pipe, the surface will produce overflow node (inspection well). The overflow of nodes in the study area under five rainfall conditions are presented in Table 4.

Table 4
The statistics table of overflow node

Rainfall return period	Rainfall Depth (mm)	Overflow discharge (m³)		Overflow reduction rate (%)	Number of overflow nodes	Overflow node percentage(%)	Overflow node reduction rate (%)
1a	12.778	Current	1.04		6	5.71	
		Scenario A	0.00	100.00	0	0.00	100.00
		Scenario B	0.00	100.00	0	0.00	100.00
		Scenario C	0.00	100.00	0	0.00	100.00
3a	30.537	Current	22.39		61	58.10	
		Scenario A	2.23	90.04	7	6.67	88.52
		Scenario B	0.48	97.86	2	1.90	96.72
		Scenario C	3.85	82.80	16	15.24	73.77
5a	38.797	Current	32.71		79	75.24	
		Scenario A	4.98	84.78	16	15.24	79.75
		Scenario B	1.57	95.20	10	9.52	87.34
		Scenario C	7.17	78.08	21	20.00	73.42
10a	50.015	Current	43.65		88	83.81	
		Scenario A	8.81	79.82	28	26.67	68.18
		Scenario B	4.49	89.71	17	16.19	80.68
		Scenario C	11.02	74.75	29	27.62	67.05
20a	61.221	Current	52.00		94	89.52	
		Scenario A	14.31	72.48	40	38.10	57.45
		Scenario B	8.88	82.92	31	29.52	67.02

Rainfall return period	**Rainfall Depth (mm)**	**Overflow discharge (m^3)**		**Overflow reduction rate (%)**	**Number of overflow nodes**	**Overflow node percentage(%)**	**Overflow node reduction rate (%)**
		Scenario C	15.71	69.79	44	41.90	53.19

Table 5
Submerged range at diferent water depths

Rainfall return period	Submerged area (m^2)	Submergence water depth					
		0.05-0.15m	0.15–0.2 m	0.2–0.3 m	[illegible] 0.3m	Total	More than 0.15 m waterlogging depth percentage (%)
1a	Current	64	0	0	0	64	0.00
	Scenario A	0	0	0	0	0	0.00
	Scenario B	0	0	0	0	0	0.00
	Scenario C	0	0	0	0	0	0.00
3a	Current	9648	1136	656	96	11536	0.70
	Scenario A	1120	32	48	0	1200	0.03
	Scenario B	224	0	0	0	224	0.00
	Scenario C	1360	48	48	0	1456	0.04
5a	Current	13248	3856	1776	688	19568	2.33
	Scenario A	1936	144	160	0	2240	0.11
	Scenario B	1168	96	0	0	1264	0.04
	Scenario C	4000	224	192	16	4432	0.16
10a	Current	21680	5136	3824	2048	32688	4.05
	Scenario A	4896	736	624	16	6272	0.51
	Scenario B	2224	560	128	0	2912	0.25
	Scenario C	6688	1136	816	32	8672	0.73
20a	Current	31504	4000	6256	5904	47664	5.95
	Scenario A	7264	1616	1248	160	10288	1.11
	Scenario B	5184	704	784	112	6784	0.59
	Scenario C	7312	2640	1408	336	11696	1.61

It can be seen from Table 4 and Fig. 5 that the number of overflow nodes and overflow discharge is positively correlated with rainfall intensity in the two development scenarios. With the increase of return period, the number of overflow nodes and overflow discharge also gradually increase. It is consistent with the research conclusions of other scholars (Hernes et al. 2020). The reduction rate of overflow nodes in the three LID scenarios is 53.19–100.00%. The reduction rate of overflow is 69.79–100.00%. And the degree of reduction will gradually decrease with the increase of return period. When the rainfall return period is 1 year, the reduction rate of overflow discharge and overflow node number in the three scenarios reaches 100% This phenomenon demonstrates that under high frequency rainfall events, LID measures can give full play to their functions of water seepage, storage and drainage. And it can effectively regulate the drainage capacity of pipeline network. In the case of low frequency rainfall events, LID measures are quickly filled with the initial rainwater, resulting in the decrease of its efficiency in absorbing rainwater. Scenario B has the best reduction effect on overflow discharge and overflow node, Scenario A is the second, and Scenario C is the weakest.

(2) Drainage capacity of rainwater pipeline network

When the node overflows, the nearby pipe must be in full flow status. The load of the pipes connected to the nodes that have not overflowed may also exceed the design standard. In MIKE URBAN, the index to evaluate the return period of pipe network is the pipe filling degree, and it is calculated by the following Eq. (7). When F > 1.0, it means that the water level exceeds the top of the pipeline, that is, it exceeds the design capacity of the pipeline drainage; When F ≤ 1.0, it means that the water level does not exceed the top of the pipe, which meets the drainage design capacity of the pipe.

$$F = \frac{W_{level} - P_{inertlevel}}{P_{height}}$$

7

Where F is the pipe filling degree; W_{level} is water level elevation, m; $P_{inertlevel}$ is the pipe bottom elevation, m; P_{height} is the height of the pipe, m.

To evaluate the pressure load capacity of drainage pipe in detail, the load state is divided into four grades to count the simulation results of the drainage network. As can be seen from Fig. 6: the design return period of pipe network in the study area does not exceed 3 years. With the increase of rainfall intensity, the length of overloaded pipe network increases and the pressure of drainage system is large. When the return periods are 3,5,10 and 20years, the load of most pipe networks is greater than 1, indicating that the design standard of the campus pipeline is at a low level. The LID measures have a better optimization effect on the drainage capacity of the rainwater pipe network, which can effectively increase the pipe length that meets the requirements. However, when the return period is 10 years and above, the reduction is obviously weakened. Comparison of the optimization capabilities of each scenario: Scenario B > Scenario A > Scenario C. Under the same rainfall scenario, the proportion of overloaded pipe network is larger than that of overflow nodes. This shows that some nodes do not occur overflow, but the pipe connected to the node is in a high load operation status, which has a high risk of overflow.

Effect of waterlogging control

Based on the 2D surface flow model coupled with MIKE FLOOD to extract the maximum water depth simulation results, it can be seen the surface flooding situation of the study area after the addition of LID measures. By comparing with the spatial distribution of the current maximum waterlogging depth, the mitigating effect of LID measures on campus waterlogging is analyzed under different rainfall return periods. The waterlogging results of 5 years and 20 years design rainfall events under the two development scenarios are selected for comparison(Fig. 7 and Fig. 8).

The waterlogging situation of the study area under the current scenario is simulated. Combined with the basic data and survey results, the waterlogging problems are divided into three types: area waterlogging, road waterlogging and point waterlogging.

From these results, it can be concluded that the waterlogging area is mostly concentrated in the northwest corner of the study area. Because that the school as a whole presents a terrain of high east and low west, high south and low north. And one of the outlets is located in the northwest corner of the lowest terrain. Under the condition of heavy rainfall, the runoff increases and the drainage capacity of the pipe network is insufficient. Rainwater cannot be drained in a timely and effectively excluded, and nodes occur overflow, resulting in waterlogging in the area. In the west of the study area, the surface hardening is serious and the building density is high. The density of rainwater pipe network is high, but the water load is large. Although there is a large green area in the east, the density of rainwater pipe network in the whole region is low and the pipe diameter is small. The surface runoff can only flow downstream along the road, resulting in serious waterlogging on *Zheng qi Road, Du xing Road* and other roads. There are some single points of waterlogging in the study area. After many field surveys, it is found that some of the waterlogging points are low-lying points. The surface runoff that cannot enter smoothly the rainwater system spreads to the low topography, presenting the phenomenon of depression detention.

In the LID layout scenario, the surface submerged depth and submerged area are effectively controlled. In the low return period rainfall, the maximum water depth is basically controlled below 0.3m in Scenario A and Scenario B, and there is no obvious waterlogging in the study area. In the high return period rainfall, although the maximum water depth of a few pavements is still above 0.3 m, there is no large area of waterlogging in the whole study area compared with the current situation. Among the three scenarios, Scenario B has the best reduction effect.

According to the spatial distribution of the maximum water depth, the submerged area and flood duration in the study area after setting LID measures is counted and compared with the current conditions(Table 5and Table 6).

Table 6
Submerged range at different flooding durations

Rainfall return period	Submerged area (m^2)	Submerged duration					
		0-20min	20–40 min	40–60 min	60-80min	>80min	Total
1a	Current	3760	384	448	960	0	5552
	Scenario A	0	0	0	0	0	0
	Scenario B	0	0	0	0	0	0
	Scenario C	0	0	0	0	0	0
3a	Current	9264	9536	14096	25760	0	58656
	Scenario A	560	928	1968	2960	0	6416
	Scenario B	2096	1536	992	1024	0	5648
	Scenario C	2464	2064	3024	5536	0	13088
5a	Current	11840	8304	19872	35392	832	76240
	Scenario A	3056	2208	5520	5296	0	16080
	Scenario B	5488	3296	1328	4144	0	14256
	Scenario C	3184	6208	8560	9728	0	27680
10a	Current	25504	13888	15280	47104	2048	103824
	Scenario A	6640	4208	8960	11584	0	31392
	Scenario B	10512	5328	3280	9104	0	28224
	Scenario C	11600	6576	12384	17968	0	48528
20a	Current	23136	18384	11344	52256	6544	111664
	Scenario A	8400	6960	13680	20912	0	49952
	Scenario B	10560	10704	12640	14960	0	48864
	Scenario C	8944	10800	13984	23904	80	57712

As can be seen from Table 5and Table 6, with the increase of rainfall, the submerged area expands and the duration of waterlogging increases, and the risk of waterlogging on campus increases. The three LID scenarios have a significant effect on reducing campus waterlogging. When the rainfall return period is 1 year, the reduction effect of sponge facilities on the waterlogging reaches 100% in the study area, indicating that LID measures can better play the role of detention and storage under the condition of low rainfall return period. Under the condition of rainfall with high return period of 10 years, the reduction rates of the three scenarios for the area above 0.15m of water depth are 87.4%, 93.8% and 81.9%, respectively. In Scenario B, the submerged area and the submerged duration is relatively minimum, and the risk of waterlogging is weak.

Both the reduction rate of the submerged area and the shortening of the submerged duration by LID measures are positively correlated with the change of rainfall intensity. The study results of Li et al. (2018) on Xi'an in Shanxi Province, rainstorm waterlogging simulation show that the reduction effect of LID mode decreases with the increase in rainfall intensity.

Comprehensive benefit analysis

According to the construction cost, design cost and maintenance cost of different LID facilities in Table 2, the cost comparison of three LID scenarios is presented in Table 7. The preferential order of LID measures based on economic cost is as follows: Scenario A > Scenario C > Scenario B.

Table 7
Economic costs of different scenarios

Cost (million yuan)	Scenario A	Scenario B	Scenario C
Construction cost	855.60	1222.90	937.05
Design cost	101.86	130.44	110.00
Operation and maintenance cost	65.19	89.68	81.48
Total	1022.65	1443.02	1128.53

Cities are areas where human energy activities and carbon emissions are concentrated. The university campus is the community of the city. Campus carbon output mainly includes fossil fuel combustion, vegetation and soil respiration, human and animal respiration, wastewater carbon emissions, waste decomposition (Svirejeva et al. 2008). In the currentdevelopment scenario, carbon reduction measures mainly include urban common greening and water area in the campus. Carbon input includes natural vegetation photosynthesis, water carbon absorption, etc. In the LID layout scenario, the new carbon reduction measures include bioretention facility, permeable pavement and green roof. As discovered in the literature (Emad et al. 2018), carbon input includes rainwater storage, plant absorption and energy conservation of sponge facilities. According to statistical calculation, the comparison of carbon emission reduction benefits of the study area under the two development scenarios is shown in Table 8.

Table 8
Comparison of carbon emission reduction benefits

Carbon emission reduction (t/a)	Current	Scenario A	Scenario B	Scenario C
Plant uptake	5.405	2.986	7.414	4.530
Water absorption	0.024	0.000	0.000	0.000
Energy Conservation and consumption reduction	0.000	115.6876	44.012	60.305
Total	5.429	118.673	51.425	64.835

Scenario A has the highest efficiency of energy conservation and emission reduction, which can reduce118.673 t CO_2 in a year. Compared with the current development scenario, the carbon emission reduction is increased by 21.85 times. Because of the largest proportion of permeable pavement in Scenario A, accounting for 9% of the total study area. The results indicate that permeable pavement can effectively reduce energy consumption and greenhouse gas emissions. Spatari et al. (2011) and McIntyre et al. (2009) have reported similar conclusion. Scenario B has the best plant absorption effect, as the proportion of bioretention facilities are the largest in Scenario B. Because of the diversity of plants and rich soil matrix, the carbon sequestration and oxygen release capacity of bioretention facilities is higher than that of ordinary green spaces (Haaland et al. 2015).

By analyzing the 1D and 2D simulation results, it is determined that the comparison effect of each scenario is the most obvious under the rainfall return period of 3 years. Therefore, the simulation results of the rainfall event are selected to determine the judgment matrix(Table 9). After calculation, the construction cost weight is 0.1709, the design cost weight is 0.0747, the operation and maintenance cost weight is 0.0652, the runoff control rate weight is 0.3700, the number of overflow weight is 0.1233, the waterlogging control weight is 0.1305, and the carbon emission reduction weight is 0.0653.

Table 9
Simulation results of LID scenario under once-in-3-years rainfall return period

LID scenario	Construction cost (million yuan)	Design cost (million yuan)	Operation and maintenance cost (million yuan)	Runoff control rate control (%)	Number of overflow nodes	Waterlogging control (%)	Carbon emission reduction (t/a)
Scenario A	855.60	101.86	62.19	48.80%	7	0.03%	118.67
Scenario B	1222.90	130.44	89.68	58.02%	2	0.00%	51.43
Scenario C	937.05	110.00	81.48	43.59%	16	0.04%	64.84

For multi-objective decision-making, all objectives need to be standardized, using a normalization method. For each objective, the optimal and the worst scenarios are taken as the boundary, and they are defined as '1' and '0', respectively. The judgment values of other scenarios are calculated by interpolation method, and the values are between 0 and 1. The simulation results are standardized, and the weighted summation method is used to sum each index. The benefits of the three LID combination scenarios are presented in Table 10.

Table 10
Benefit of LID scenario under once-in-3-years rainfall return period

LID scenario	Economic cost	Environmental Benefit	Social Benefit	Comprehensive Benefit
Scenario A	0.311	0.213	0.098	0.622
Scenario B	0.000	0.493	0.131	0.624
Scenario C	0.206	0.000	0.013	0.219

It can be observed from Table 10 that the comprehensive benefits of Scenario B (9% bioretention facilities + 3% green roof + 3% permeable pavement) is the highest, and that of Scenario C (3% bioretention facilities + 9% green roof + 3% permeable pavement) is the lowest. For Scenario B, the economic costs are relatively low, but the environmental benefits and social benefits are remarkable, which is in accordance with the literature (Li et al. 2017).

Conclusions

Based on Mike model, this paper evaluates the drainage capacity and waterlogging situation of the study area in the current stage. Three LID combination scenarios are constructed. The scenarios are compared and selected based on carbon emission reduction benefits, environmental benefits and economic benefits. The research results can provide references for sponge reconstruction of similar campuses or old residential areas. The study draws the following conclusions:

1. The MIKE FLOOD model can effectively simulate the waterlogging status of the campus and provide security assessment for the rainwater system. The old campus pipelines have low design standards. Under the condition of high return period rainfall, the road waterlogging area is large and the waterlogging risk on campus is high.
2. The three LID combination scenarios have remarkable effects on waterlogging control. After comparison and selection by AHP, the combination scenario of 9% bioretention facilities + 3% green roof + 3% permeable pavement (Scenario B) has the highest comprehensive benefits. In the return period of 3 years rainfall, the runoff control rate of the currentdevelopment model is only 17.44%. There are 99.31% overload rainwater pipelines. After setting LID measures, runoff control rate can be increased by 40.57%. The proportion of overload pipelines can be reduced by 44.29% and the phenomenon of waterlogging is completely eliminated.
3. Comprehensive benefit of Scenario A is lower than that of Scenario B. And Scenario A is the combination of 3% bioretention facilities + 3% green roof + 9% permeable pavement. The scenario has the highest carbon emission reduction benefits, with an annual emission reduction of 118.673 t CO_2 and the lowest cost, which can be used as an alternative option.

Because of the site limitation, the LID area in this study only accounts for 15% of the total study area. The proportion and location of sponge facilities can be optimized according to local conditions and drainage capacity to achieve the best effect.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Authors' contributions

JS and JL contributed to the study conception and design. Material preparation, data collection, and analysis were performed by XG, YY and CJ. The first draft of the manuscript was written by JS. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The datasets generated and analyzed during the current study are not publicly available due [REASON WHY DATA ARE NOT PUBLIC] but are available from the corresponding author on reasonable request.

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Figures

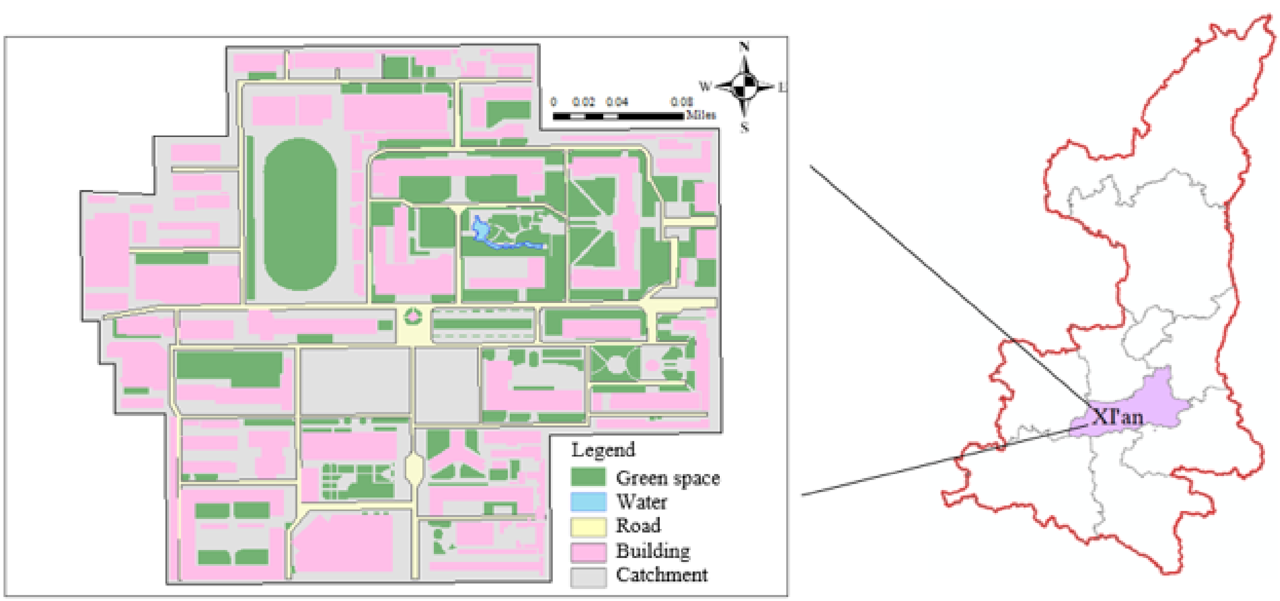

Figure 1

Location and land use map of the study area

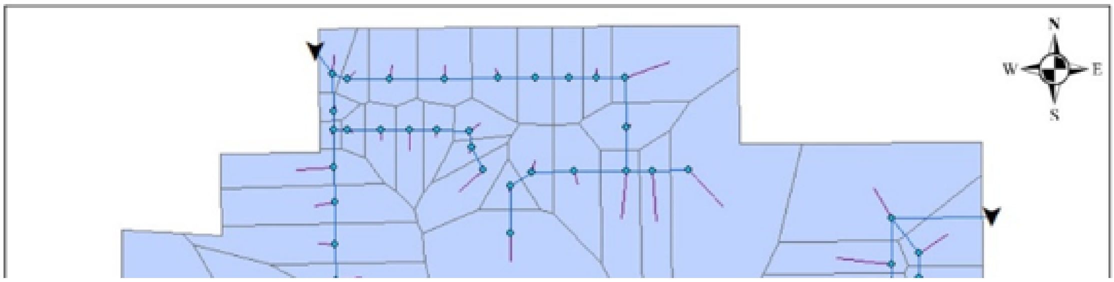

Figure 2

Models of 1D drainaged

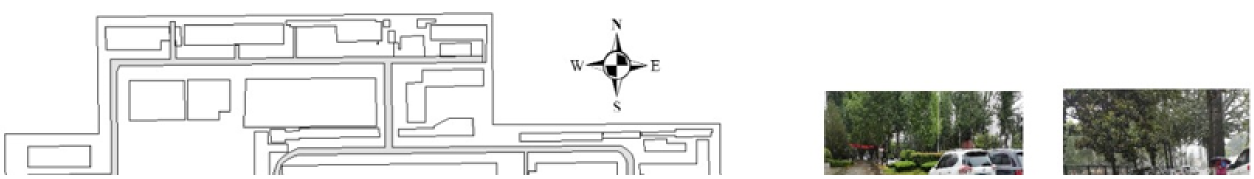

Figure 3

Location of waterlogging prone points in the study area

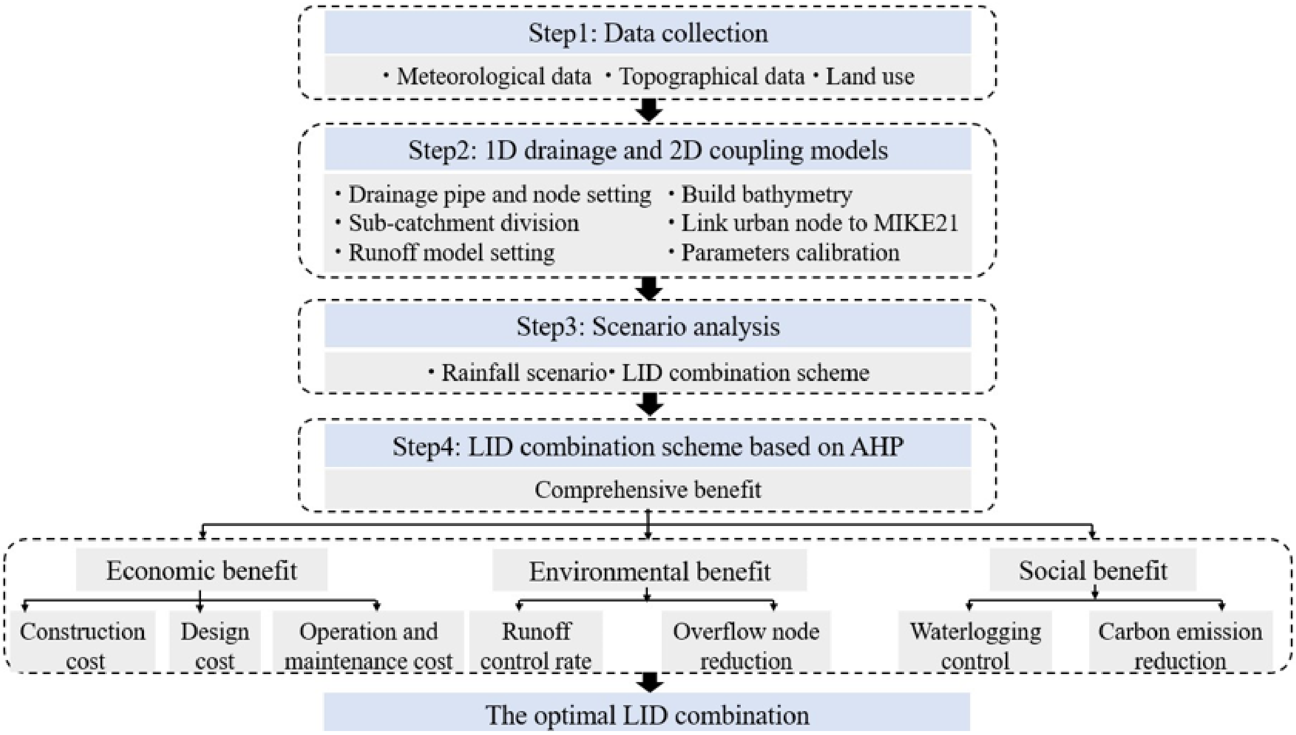

Figure 4

The optimal layout screening system of LID combination scenarios

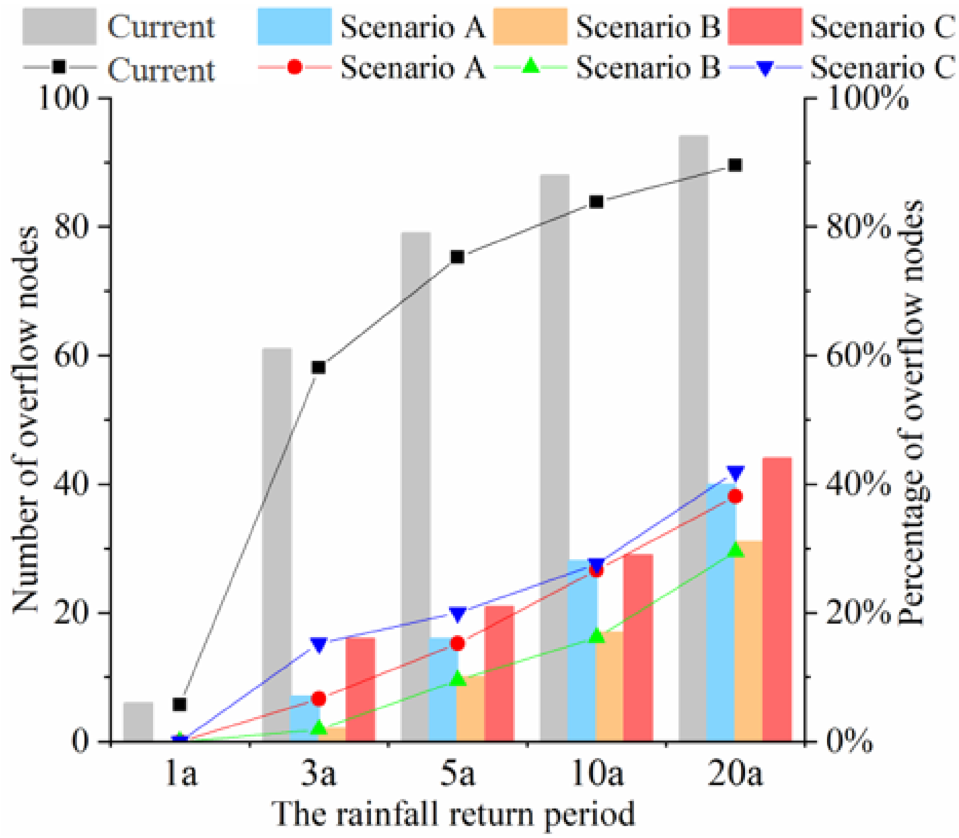

Figure 5

Number of overflow nodes and percentage of overflow nodes

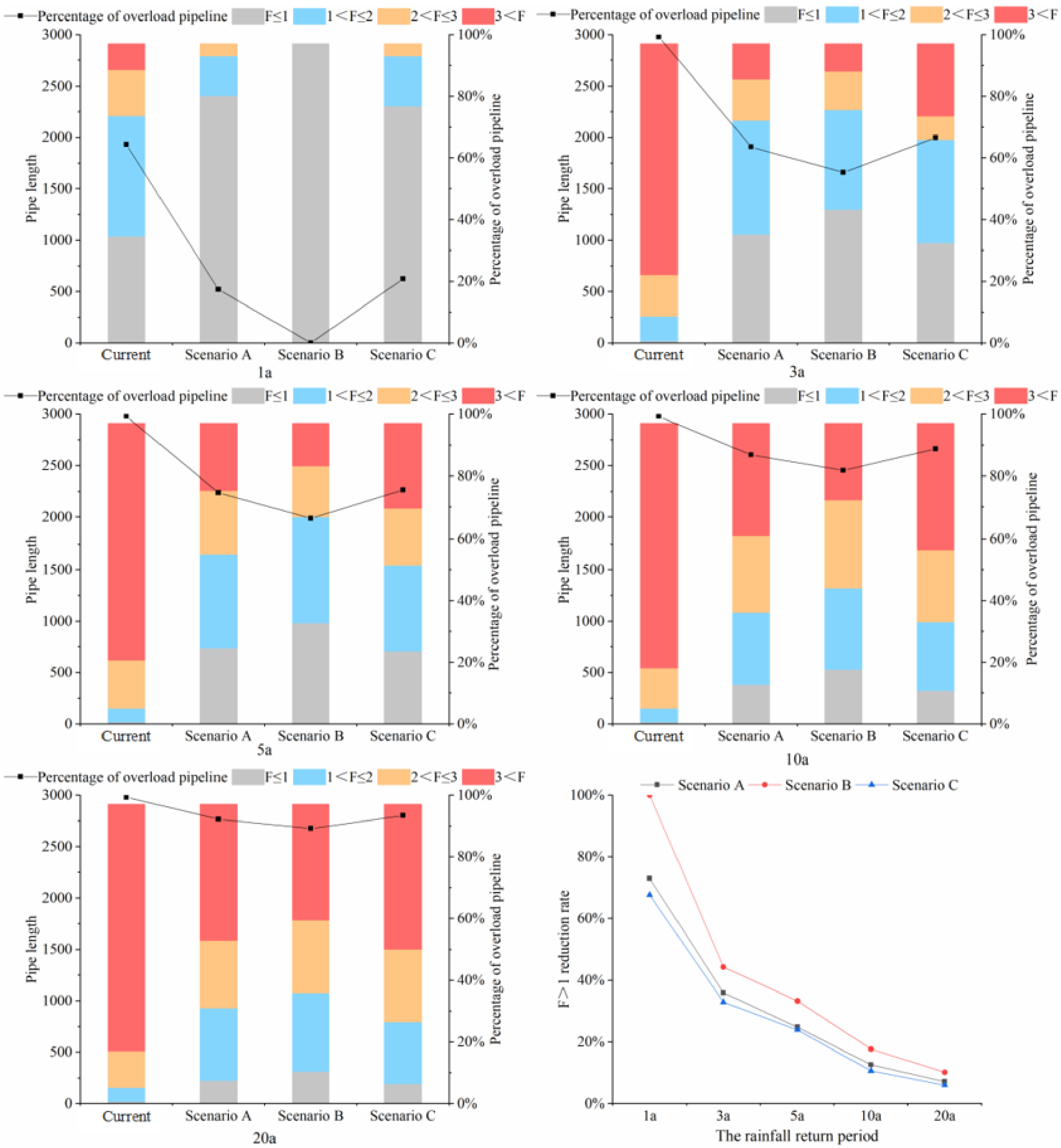

Figure 6

Load of pipe section under different rainfall return periods and pipe section reduction rate with F>1

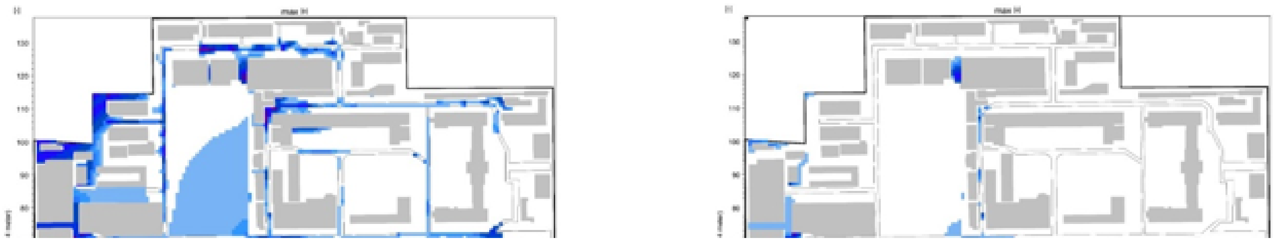

Figure 7

Distribution of rainstorm waterlogging during once-in-5-years rainfall return period under different scenarios

Figure 8

Distribution of rainstorm waterlogging during once-in-20-years rainfall return period under different scenarios