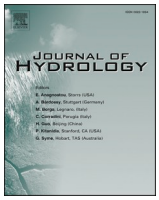
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Research papers

Optimizing the deployment of LID facilities on a campus-scale and assessing the benefits of comprehensive control in Sponge City

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ABSTRACT

Rapid and intense urbanization has brought a wide range of serious issues like flooding and water pollution, which have become a great concern in a lot of cities. In response to these problems, Sponge City (SPC) has emerged as a potential solution. This study utilized the Stormwater Management Model (SWMM) to simulate urban runoff and determine an optimal combination of Low Impact Development (LID) strategies for reconstructing the study area. Upon analyzing the existing rainwater drainage system and revealed that it could only meet the design return period of 2-*years*, and identified the vulnerable flood-prone area and the maximum overflow node. After comprehensive consideration of various factors, the sponge reconstruction scenario selected four LID facilities combination: Porous pavement, Rain garden, Sunken green belt, and Green roof. Results indicated that when P = 1-*yr*, 5-*yr*, 10-*yr* and 20-*yr*, the total runoff in the LID scenario decreased by 43.91 %, 43.93 %, 45.95 % and 47.11 %, respectively. LID facilities substantially mitigate stormwater runoff and peak flows during moderate to light rainfall events. These LID facilities prove effective in reducing pollutant concentrations (reduction rate is all over 42 %), with notable reductions in Chemical Oxygen Demand (COD) and Suspended Solids (SS). This paper offers valuable insights that can serve as a reference for the construction or renovation of SPC, shedding light on effective strategies and considerations for managing stormwater and mitigating the impact of urbanization.

1. Introduction

As the global population continues to grow, urbanization and climate change persist, the sustainability of water resources is becoming a growing concern (Jiang et al., 2018). Since 2000, the scale of urban construction in China has continuously expanded (Jiang et al., 2022b). In 2020, China's urban area reached 186,628.87 km^2, of which the built-up area of cities reached 60,721.32 km^2, with an urbanization rate of 63.89 % (Li et al., 2022). As cities grow, more green spaces are being replaced with gray concrete (Guan et al., 2021). The massive use of impermeable materials such as asphalt, cement concrete, and tiles has caused the permeability of the city to decrease and the original natural water cycle to be destroyed (Zha et al., 2021). When it rains, the rainwater can't flow away, store, and infiltrate in time, which leads to the advance of runoff peak time and the increase of surface runoff (Chan et al., 2018a; Liberalesso et al., 2020). Simultaneously, it leads to an increase in pollutant concentration within rainwater runoff in urban areas, which leads to river water pollution and deterioration of the urban water environment (Jia et al., 2013; Ma et al., 2018; Movahedinia et al., 2019).

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The incidence of heavy precipitation events or sustained precipitation events produces a substantial volume of rainwater runoff that rapidly accumulates within the drainage pipe infrastructure, surpassing its overflow handling capacity (He et al., 2019). Consequently, the city experiences flooding or waterlogging calamities, which is commonly referred to as urban flooding (Chan et al., 2018b; Qin, 2020). In April 2021, China issued the "Implementing Opinions of the General Office of the State Council on Strengthening Urban Waterlogging Control" (GOSCC, 2021). The government and the public are concerned about finding effective and sustainable solutions to urban flooding (Liu et al., 2022). Urban drainage capacity is limited by the return period of the drainage pipe network design (Andrés-Doménech et al., 2018). Urban expansion has not brought about the synchronous upgrading of municipal drainage pipe networks, and the direct causes of urban waterlogging are the lower design return period standard, aging pipelines, and even unreasonable design of pipe networks (Qin et al., 2013). Urban flooding is becoming a common phenomenon in many cities (Mignot et al., 2019). According to the data from the China Ministry of Water Resources, in 2016, 192 cities in China suffered from flooding hazards (Xu et al., 2018). In July 2021, several areas in China's Henan Province suffered heavy rainfall, with Zhengzhou receiving up to 201.9 *mm/h* of rainfall on July 20 (16:00–17:00). This super heavy rainfall caused serious floods and had an irreversible impact on people's safety of life and property (Peng and Zhang, 2022). Urban flooding has a high incidence (Qin, 2020). From 2016 to 2020, Pingxiang City, Jiangxi Province, experienced 16 internal flooding disaster events in four years, an average of four times a year (Wang et al., 2022b). Urban flooding seriously hinders urban traffic, threatens the operation of urban infrastructure, greatly reduces the well-being of residents, and even threatens people's lives in serious cases (Abass et al., 2022).

Under the combined influence of climate change and urbanization, natural disasters occur frequently, and it is not uncommon for cities to have disastrous weather once in 50-years or even once in 100-years (Cea and Costabile, 2022). The frequency and intensity of extreme weather events are likely to increase significantly, and the probability of urban flooding will also increase (Clarke et al., 2022). To solve these urban water problems and promote the transformation to a sustainable urban development pattern, it is crucial to focus on managing urban water effectively, realizing the scientific regulation of rainwater runoff, and recognizing and utilizing the resource attribute and value attributes of rainwater (Chao, 2020; Ma and Jiang, 2023; Pervin et al., 2020). As a matter of fact, since ancient times, China has followed the philosophical theory of "Goodness is like water, water conserves all things without contention", and has had the awareness of rainwater resource utilization since a very early time (Xu et al., 2018). With the development of modernization, China gradually began to focus on managing urban rainwater in the 1990 s, and taking inspiration from the methods used in developed countries such as the USA, Germany and Japan (Yin et al., 2022). For example, the concept of Low Impact Development (LID) from the USA was introduced in Beijing, and the research on the design methods of green infrastructure such as sunken green space and rain garden and the effect of runoff control gradually increased. LID was initially applied in Maryland, and then gradually spread throughout the USA (Eckart et al., 2017). Its core objective is to mitigate the impacts of urban development on natural hydrological processes by replicating, as closely as possible, the hydrological processes that existed before urbanization, and by preserving and restoring natural hydrological features (Koc et al., 2021). LID was incorporated into China's national "Twelfth Five-Year" major water project in 2011(Casey and Koleski, 2011). This provided a clearer definition of the concept, objectives, and design methods of LID at a theoretical level. It has facilitated the engineering application of LID in various domains, and has established the groundwork for the subsequent development of Sponge City (SPC) (Jia et al., 2017b). In 2013, China initiated the development of SPC based on summarizing ancient wisdom of water management and drawing on the advanced experience of developed countries. Thirty cities were chosen to start pilot construction in 2015 (Yin et al., 2021).

SPC, is a new generation of urban stormwater management concept in China, which means that the city has good "resilience" in adapting to environmental changes and coping with natural disasters caused by stormwater (Che et al., 2015; Jia et al., 2017a). It needs to take six measures of "infiltration, retention, storage, purification, utilization and discharge" to reduce the impact of urban development and construction on the ecological environment (Nguyen et al., 2019; Ren et al., 2017). LID focuses more on the control of small and medium rainfall events. It takes the total runoff as the control target and adopts source, dispersion, and small-scale green technical measures. SPC aims to transform urban development concepts and build a sustainable urban development mode. SPC construction follows the guiding principle of LID, which emphasizes protecting the original ecosystem and implementing ecological restoration and repair. Its core concept is consistent with LID, which is to establish a multi-objective modern urban stormwater control system that combines green and gray infrastructure (Jia et al., 2022; Jiang et al., 2018). Many achievements have been made in the research and application of SPC based on LID theory (Jiang et al., 2022c). Jia et al. (2015) discussed the LID-BMPs (Low Impact Development Best Management Practices) planning principle of urban runoff control based on an example of LID-BMPs planning in the urban environment of southern China. Leng et al. (2022) proposed a general simulation–optimization framework for refined LID-BMPs spatial allocation incorporating receiving water area responses. At the same time, there are increasing studies on the comprehensive benefits of SPC based on evaluation methods such as life cycle assessment (LCA) and numerical simulation models such as hydrology and hydrodynamic water models (Liu et al., 2023). Zhu et al. (2023) established an index quantification system based on LCA from three aspects: environment, economy and society, and adopted the monetary approach to quantify the benefits of green infrastructure.

Old urban area typically has a high population density and infrastructure that has aged over time. Their drainage pipes often have issues due to backward design concept, serious aging and difficult reconstruction. Some old urban areas even face the problem of pollution caused by sewage overflows (Guo et al., 2019). It is more meaningful to conduct research on SPC reconstruction for old urban areas, which are highly urbanized and densely populated (Xu et al., 2022). Based on the construction goal of sponge city and LID technology, how to build a LID engineering system of "source reconstruction, middle pipe network improvement, and end pollution interception" to solve the comprehensive problems of overflow pollution and urban flooding in old urban areas is an important research direction (Dong and Gao, 2019; Yang et al., 2022).

This study focuses on a university campus as a typical research area, and the Storm Water Management Model (SWMM) is used to investigate the rainwater runoff and the drainage network carrying capacity in different return periods, and to determine the hydrological information such as flood-prone areas. Combined with comprehensive evaluation method and SWMM, a set of multi-objective evaluation system composed of runoff control ability, cost, economic and environmental benefits is established to optimize the deployment scenario of LID facilities. Comparison between the original scenario and LID scenario was conducted to evaluate the effect of rainwater regulation and pollutant removal. The Objective is to explore the optimal configuration and combination design of LID facilities. The results are instructive to the deployment of sponge facilities and the construction of "Sponge Campus" in arid and semi-arid areas.

2. Materials and methods

2.1. Study area

The study area is the "Beiyuan" campus of Chang'an University, Beilin District, Xi'an, with a total area of about 25 ha. Xi'an locates in the

middle of the Guanzhong Plain in the Yellow River Basin in the hinterland of mainland China (E107°40′ ~ 109°49′ and N33°39′ ~ 34°45′). Fig. 1 shows the specific location and land use types of the study area.

"Beiyuan" campus is located in the core urban area of Xi'an, which is representative and has a simple land type, including roads, green space, and construction land. As shown in Fig. 2, the overall terrain appears mostly level, with a higher elevation in the north and lower in the south, with a gradient of 0.3 % to 0.5 %. Additionally, there is an autonomous drainage system that connects to the local municipal rainwater pipe network via the southwest water outlet.

Xi'an has a warm temperate continental monsoon climate. As shown in Fig. 3, the precipitation in Xi'an varies from year to year and is unevenly distributed within the year, showing strong seasonal characteristics. The multi-year average annual precipitation in Xi'an over the past 20 years is 554.98 mm. July-September has a large amount of precipitation, accounting for 49.05 % of the annual precipitation. January, February, and December have less precipitation. According to Wang et al. (2022a) the precipitation in Shaanxi Province generally shows a decreasing trend, while that in Xi'an City tends to be stable. However, extreme rainfall events, floods and other water security problems should be vigilant. According to the statistics of relevant departments, there are thirteen flood-prone areas, with more overpass tunnels and suburban joints (Hou et al., 2020a).

Table 1 is a list of the data used in this study.

2.2. Urban stormwater management model

Storm Water Management Model (SWMM) is a precipitation-runoff dynamic simulation model developed by the United States Environmental Protection Agency in the 1970s, which can be used to simulate runoff generation and confluence, pollution load of single or long-term (continuous) precipitation in urban areas (Huber et al., 2005). It can simulate the surface runoff process, water quality and drainage network transportation under retrofitting scenarios by adding an LID control facility. Based on the principle of the water balance equation, SWMM drives the rainwater storage relationship among various structural layers (Fig. 4), including the moisture change relationship of rainfall, evaporation, runoff, and infiltration, and realizes the simulation of LID facility (Gironás et al., 2010).

2.2.1. SWMM model construction

The "Beiyuan" campus primarily uses surface catchments for drainage and has a well-established pipe network for the same purpose. The drainage network was extracted and sub-catchments were delineated using the planning drawings and HS-Data (*https://www.info-water.com.cn/product/product*) plug tool in AutoCAD. HS-Data tool can export processed drainage networks and sub-catchments as "*.inp*" format files, which can be easily imported into SWMM. As shown in Fig. 5, there are 358 sub-catchments, 66 rain pipe sections, 66 check wells and 1 drainage outfall of the drainage pipe network.

2.2.2. Model parameter setting and calibration

The parameters of SWMM are shown in Table 2, in which the characteristics parameters of the sub-catchment and drainage pipe network are obtained from the planning drawings. Other parameters, such as infiltration coefficient, and manning coefficient can infer from the SWMM operation manual, related literature research and project implementation plan. The model parameters are optimized by the Nash-Sutcliffe Efficiency Coefficient (NSE) (Rosa et al., 2015):

$$R_{NS} = 1 - \frac{\sum_{i=1}^{n} (Q^s - Q^o)^2}{\sum_{i=1}^{n} (Q^o - Q^{ao})^2}$$

where, R_{NS} – Nash-Sutcliffe Efficiency Coefficient; Q^s, Q^o, Q^{ao} – simulated values at moment i; measured values at moment i; average of measured data. When R_{NS} is infinitely close to 1, it means that the model simulation results are close to the measured values and have high confidence. When R_{NS} is infinitely close to 0, it represents that the model has a large error. When$R_{NS} > 0.75$ (Paule-Mercado and Lee, 2017), the model simulation effect is considered to be more accurate, and the parameter can be used for subsequent study.

We selected precipitation and runoff data on August 12, 2021, to calibrate the model parameters, and continuously iterated to adjust the parameter values to make the model simulation values more consistent with the measured values (Fig. 6-A). After calculation, R_{NS}=0.83, the calibrated model parameter values have high confidence. Model parameters after calibration are shown in Table 2. Of course, selected precipitation and runoff data on September 24, 2021, to verify the model parameters (Fig. 6-B). $R_{NS} = 0.89$. This set of parameters can be used for subsequent simulations.

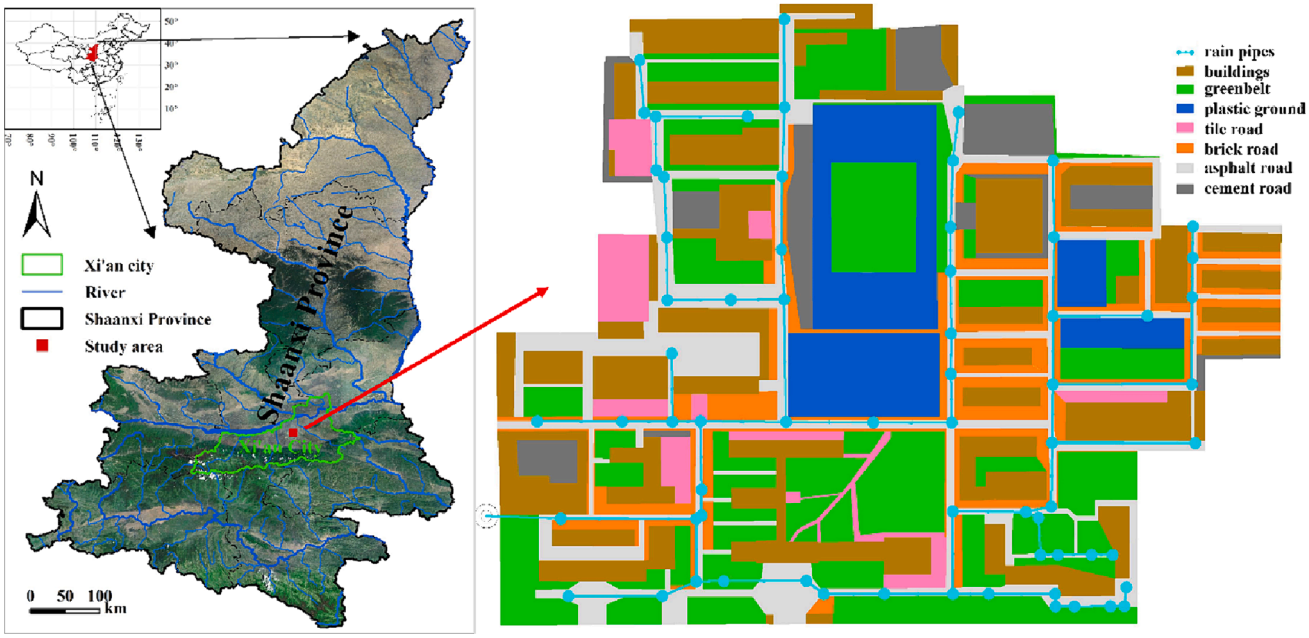


Fig. 1. Location and land use map of study area.

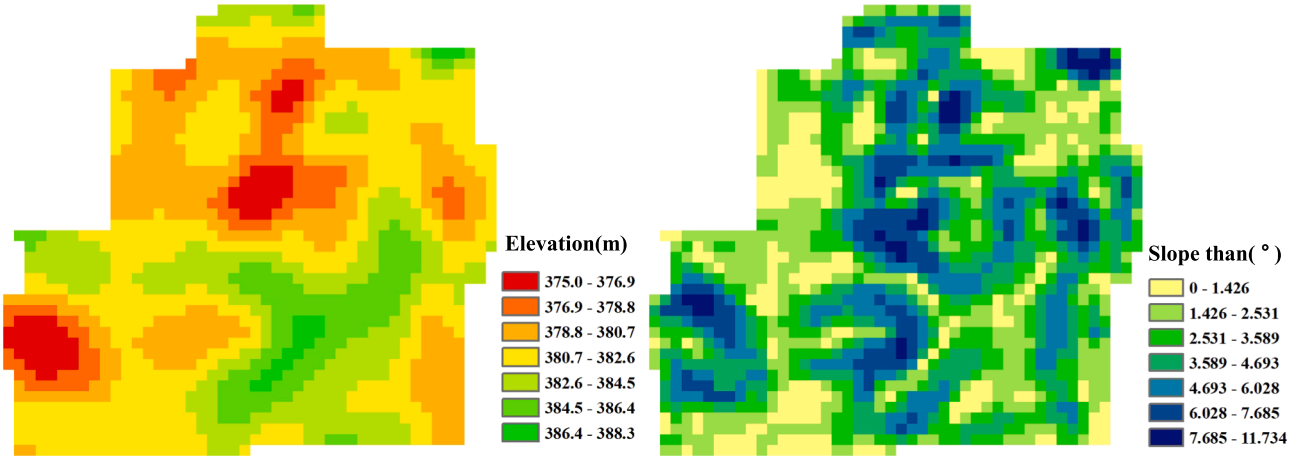


Fig. 2. Elevation and slope of the "Beiyuan" campus.

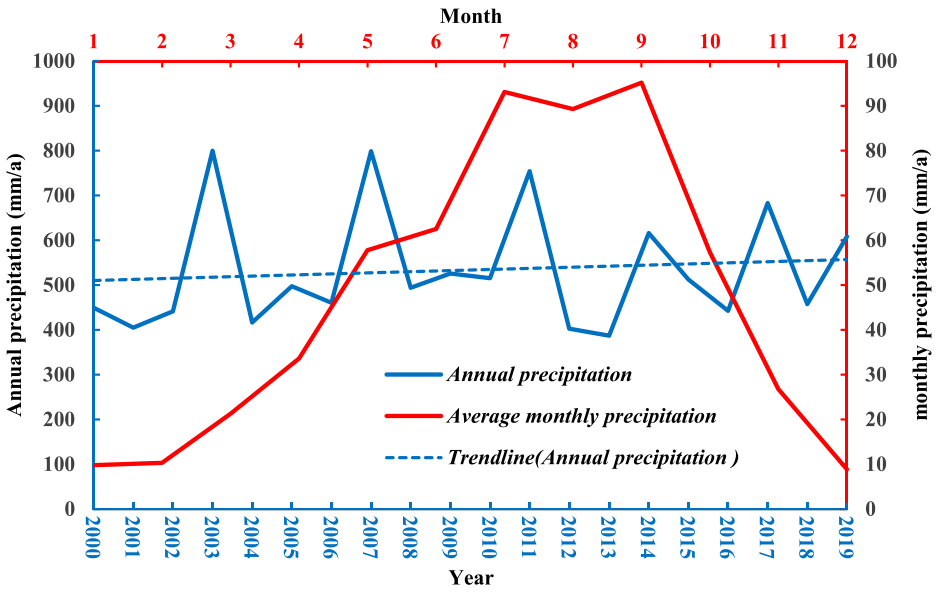


Fig. 3. Annual precipitation and monthly average precipitation in Xi'an for the past 20 years.

Table 1
Data list.

No.	Data type	Data source
1	DEM image data	Resources and Environmental Sciences and Data Center, Chinese Academy of Sciences (GF2_PMS1_E108.9_N34.2_20170412_L1A0002303198)
2	Planning documents(CAD drawing, etc.)	School Planning Office; School archives (Beiyuan planning CAD drawing, V.2011)
3	Runoff data	HQ-610 Ultrasonic Doppler non-full tube Flowmeter ("Beiyuan" campus) (Real-time monitoring data). National Bureau of Statistics of China (Data source: https://www.stats.gov.cn/tjsj/ndsj/)
4	Meteorological data	WCDMA wireless weather station (Yanta campus) (Real-time monitoring data); Design precipitation
5	Water quality data	Water sample collection (Aug. 12, 2021 and Sep. 24, 2021) and testing (Flood Disaster Monitoring and Simulation Laboratory, Chang'an University)

The water quality parameters in the model were preset according to the existing literature, and then the field monitoring data on August 12, 2021, were used for rate determination. The water quality indicators are COD (Chemical Oxygen Demand), TP (Total Phosphorus), TN (Total Nitrogen) and SS (Suspended Solids). The pre-set parameter combinations were modeled, and the calculated results were compared with the monitoring results to determine the optimal values of the parameters applicable to the study area with the principle of minimizing the relative deviation. According to the cumulative flushing characteristics of surface pollutants in the study area, the saturation growth curve was selected for the cumulative model and the exponential flushing function was used for the flushing model. The results are shown in Table 3.

2.3. Precipitation event design

Precipitation data is an important input data for hydrological model simulation. The selection of design precipitation type is related to the evaluation of hydrology and water quality. Typically, Short-term precipitation exhibits a single peak in precipitation, with the peak value rainfall intensity occurring towards the front and middle of the precipitation. After the short-term rainfall event, the surface will rapidly catch up and runoff will rapidly increase to its peak value, which is more suitable for the study of runoff reduction than long-term precipitation. Therefore, we choose two-hour short-term design precipitation data and choose the Chicago rain pattern combined with Xi'an rainstorm

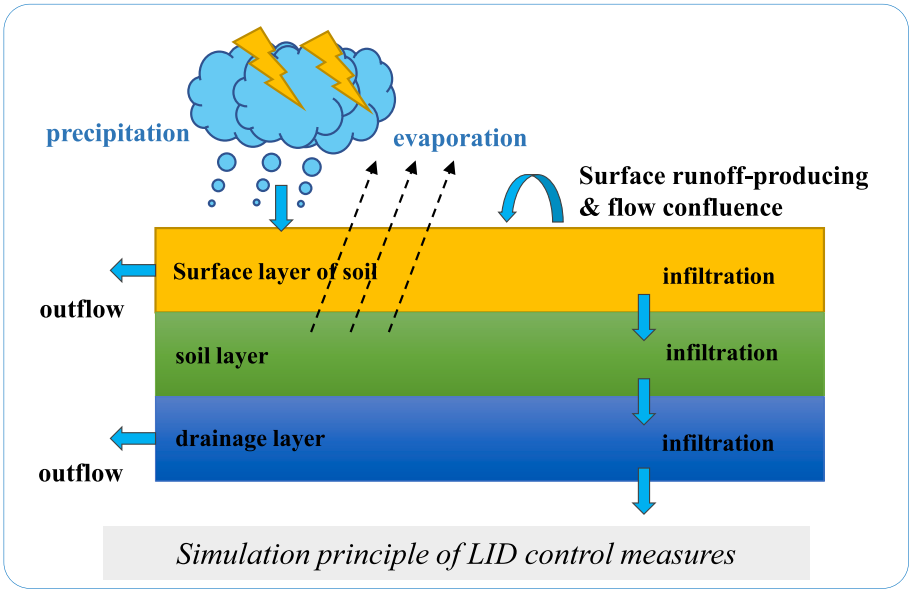


Fig. 4. The simulation principle of the LID control facility in SWMM.

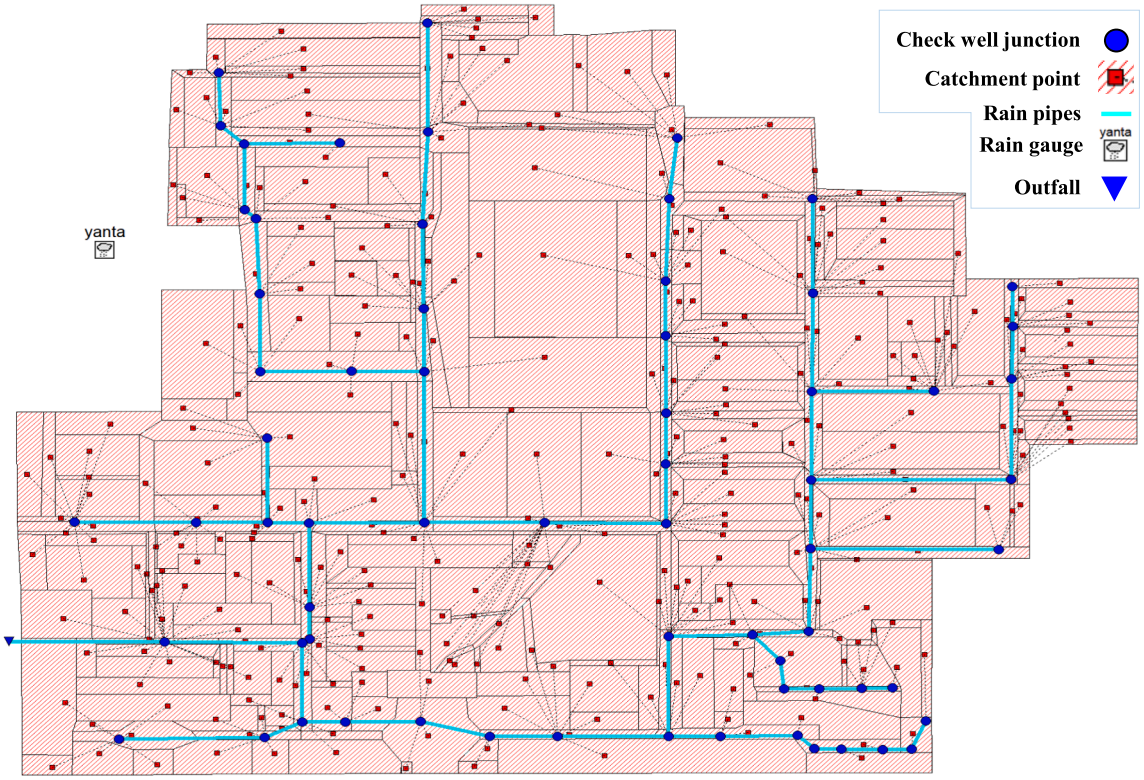


Fig. 5. Drainage network extraction and sub-catchment delineation of the "Beiyuan" campus.

intensity formula to design rainstorms with different return periods (Li et al., 2018).

According to relevant studies, the design storm equation for Xi'an is as follows:

$$i = \begin{cases} \dfrac{6.041(1+1.475\log P)}{(t+14.72)^{0.704}} (P < 20yr) \\ \dfrac{15.2(1+1.125\log P)}{(t+21.5)^{0.87}} (P > 20yr) \end{cases}$$

where, i – designed rainstorm intensity (mm/min); t – rainfall duration (min); P – return period (yr).

Chicago rain pattern is a rainfall process line with uniform rainfall intensity based on the storm intensity formula proposed by Keifer and Chu, which is widely applicable and can be used for precipitation design for any recurrence period and arbitrary rainfall calendar time (Keifer and Chu, 1957). Rainfall peak coefficient r is determined by the climatic conditions of the study area, and $r = 0.4$ is defined in this study (Su et al., 2019). We set six different return periods (Fig. 7): 1-year return period (1-yr), 2-years return period (2-yr), 5-years return period (5-yr), 10-

Table 2
Setting of model parameters.

Parameter name		Value Range	Defined value	Calibration value
Infiltration coefficient	Maximum infiltration rate (*mm/h*)	10–100	76.2	74.2
	Minimum infiltration rate (*mm/h*)	0–10	3.6	3.3
	Attenuation constant (h^{-1})	0–7	4.14	2
	Drain time (*day*)	1–7	7	7
	Decay (*mm*)	2–4	3	3
Manning coefficient	Manning coefficient of impervious zone	0.011–0.033	0.013	0.012
	Manning coefficient of permeable zone	0.05–0.8	0.24	0.24
	Manning coefficient of pipeline	0.011–0.024	0.013	0.013
Accumulation of depression	Impervious zone (*mm*)	0.2–10	1.27	1.78
	Previous zone (*mm*)	2–10	3.8	5.08
Percentage of water storage impermeable without depression (%)		1–100	–	25

years return period (10-*yr*), 20-years return period (20-*yr*), and 50-years return period (50-*yr*).

3. LID facility benefits analysis of SPC

3.1. LID scenario design

In the sponge reconstruction process, the selection of different LID facilities is according to their control functions. Usually, different combinations of LID facilities can be selected to achieve multiple runoff control objectives in the reconstruction area (Garbanzos and Maniquiz-Redillas, 2022). When designing the LID scenario scheme, this study adopts a comprehensive analysis method to consider the site demand, environmental demand, construction cost and other factors of the study area. In the selection of LID facilities, soil status, spatial layout, environmental and runoff control objectives in the study area were considered. Comprehensive adoption of "runoff, infiltration, catchment, storage, purification, release" and other technical ideas, to maximize the maintenance of the campus's original ecological environment of the natural circulation system, optimize and upgrade the campus spatial layout, improve its rationality.

The first step is to identify the vulnerable flood-prone areas in the study area by SWMM.

3.1.1. Identification of flood-prone areas

Runoff simulations were conducted at different precipitation return periods (P = 1-*yr*, 2-*yr*, 5-*yr*, 10-*yr*, 20-*yr*, and 50-*yr*) under the original scenario. Because this study area is moderate in size and there is no external water or rivers and lakes, so not considered other surface runoff inflow and rainfall evaporation. Table 4 shows the simulation results of hydrological characteristics in different return periods. All the continuity errors were less than 0.05 and the results were reliable. Total rainfall and total runoff are positively correlated with the precipitation return period. The peak runoff time under each return period occurred

Table 3
Calibration results of water quality simulation parameters.

Land use type	Project	Parameter	COD	TN	TP	SS
Road	Cumulative parameter	Maximum cumulant	165	6	0.2	283
		Half-saturation constant	10	10	10	10
	Flushing parameter	Flushing index	0.006	0.004	0.002	0.008
		Flushing coefficient	1.8	1.7	1.7	1.8
Roof	Cumulative parameter	Maximum cumulant	76	4	0.2	135
		Half-saturation constant	10	10	10	10
	Flushing parameter	Flushing index	0.006	0.004	0.002	0.007
		Flushing coefficient	1.8	1.7	1.7	1.8
Greenbelt	Cumulative parameter	Maximum cumulant	35	10	0.6	75
		Half-saturation constant	10	10	10	10
	Flushing parameter	Flushing index	0.0035	0.002	0.001	0.004
		Flushing coefficient	1.2	1.2	1.2	1.2

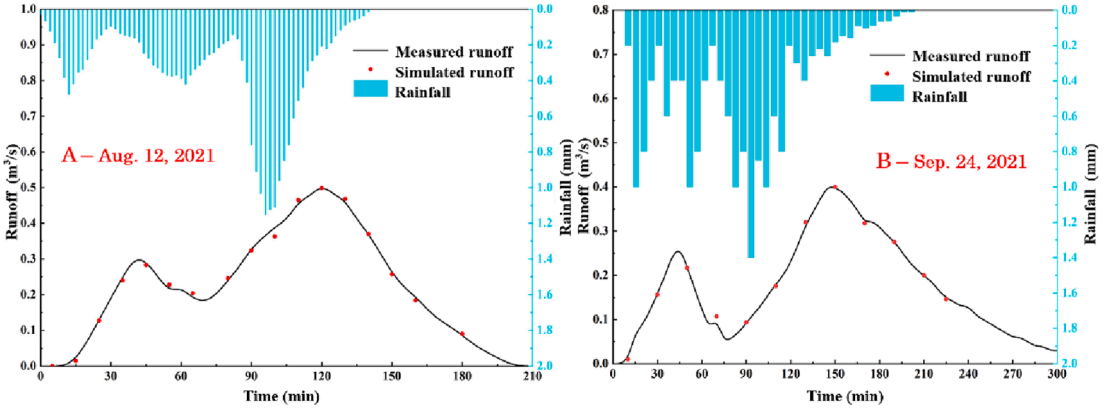


Fig. 6. Comparison between measured runoff and simulation results.

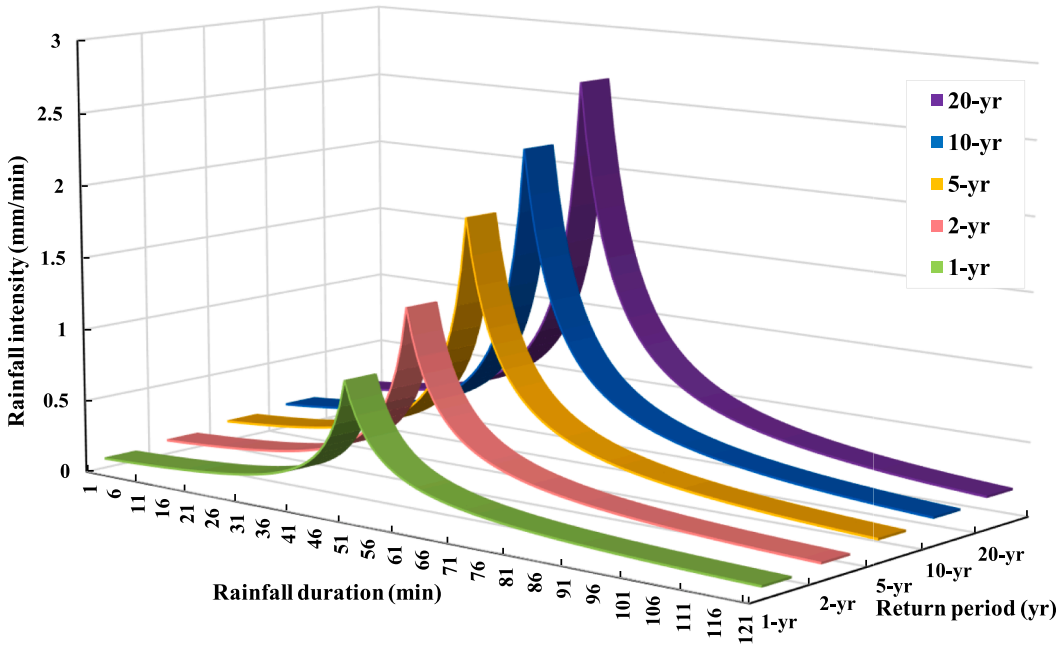


Fig. 7. Precipitation process curves of different precipitation return periods.

Table 4
Simulation results of hydrological characteristics in different return periods.

Return period (*P*)	1-*yr*	2-*yr*	5-*yr*	10-*yr*	20-*yr*	50-*yr*
Precipitation (*mm*)	23.1	33.3	46.9	57.	60.7	71.7
Infiltration (*mm*)	5.7	8.6	11.3	11.9	11.9	12.2
Surface runoff (*mm*)	16.	24.0	34.5	44.1	47.7	58.4
Peak time (min)	45	45	45	45	45	45
Continuity error (%)	−0.020	−0.020	−0.021	−0.024	−0.025	−0.026

around 45 min. With the increase in return period, the increase of peak runoff is greater than that of total runoff, because the infiltration capacity of soil will not increase after reaching the maximum value, and the water capacity of the pipe network will reach saturation, but the runoff coefficient will still increase. Therefore, the carrying capacity of the pipe network system to the peak flow needs to face a greater test in the event of precipitation in a larger precipitation return period.

The sub-catchment runoff, check the well ponding depth and water delivery amount of the pipe network at the peak precipitation time is shown in Fig. 8. P = 1-*yr* a and P = 2-*yr*, the drainage condition was good, and there was no ponding water on the ground. P = 5-*yr*, the nodes and pipes were heavily loaded, most of the pipes were running at full capacity, and some areas were slightly waterlogged. When P = 10-*yr*, 20-*yr* and 50-*yr*, the drainage network was heavily loaded, and the ground surface showed large areas of waterlogging and widespread internal flooding.

The status of the check-well node in the pipe network at peak runoff time is shown in Table 5. Combined with the attribute parameters of each check-well node, the check-well node, overload or overflow, can be judged. (Overload in a stormwater drainage system refers to a situation in which the capacity of drainage pipes or networks cannot accommodate the volume of rainwater during rainfall or heavy rain events. Overflow in a stormwater drainage system occurs when rainwater or wastewater exceeds the capacity of drainage pipes or collection facilities during periods of hydraulic overload.)

After conducting simulations and a thorough analysis of sub-catchment, node water depth, and pipe network capacity, it has been determined that the stormwater pipe network in the study area has a designed precipitation return period of 2 years. Flood-prone areas are shown in Fig. 9. The maximum overflow node is **J59** indicated in the figure. The main causes of flood-prone are inadequate drainage capacity of the pipe network and overloading of drainage tasks. This is a consequence of the inadequate design return period of the pipe network and the poor capacity of pipe section intersections to carry runoff.

3.1.2. *LID scenario scheme*

According to the flood-prone areas simulated above, runoff control objectives and pollution control objectives (Campus general construction plan and Xi 'an SPC Project construction guideline), while referring to the SPC construction guideline and the experience of sponge reconstruction examples (Ji and Bai, 2021). The comprehensive analysis method is used to compare and select the appropriate type and scale of LID facilities. In the end, a combination of 4 LID facilities – Rain Garden (2.45424 ha), Green Roof (0.90294 ha), Porous Pavement (2.41488 ha), and Sunken Green Belt (1.00006 ha) – was chosen. The design scheme is shown in Fig. 10.

The model setting parameters of the LID facility are shown in Table 6.

3.2. *Comparative analysis of runoff control effect*

3.2.1. *Runoff simulation comparison*

As shown in Table 7, with the increase in return period, the rainfall gradually increases, and the accompanying runoff and runoff coefficient keep rising. In the LID reconstruction scenario, runoff, infiltration, and runoff coefficient were reduced to varying degrees, and the runoff occurrence time and peak time were extended. Under different return periods, the decreasing rates of runoff were 43.78 %, 43.90 %, 45.73 % and 47.10 % successively. The runoff occurrence time-lagged by 5 min, 3 min, 3 min and 3 min in turn.

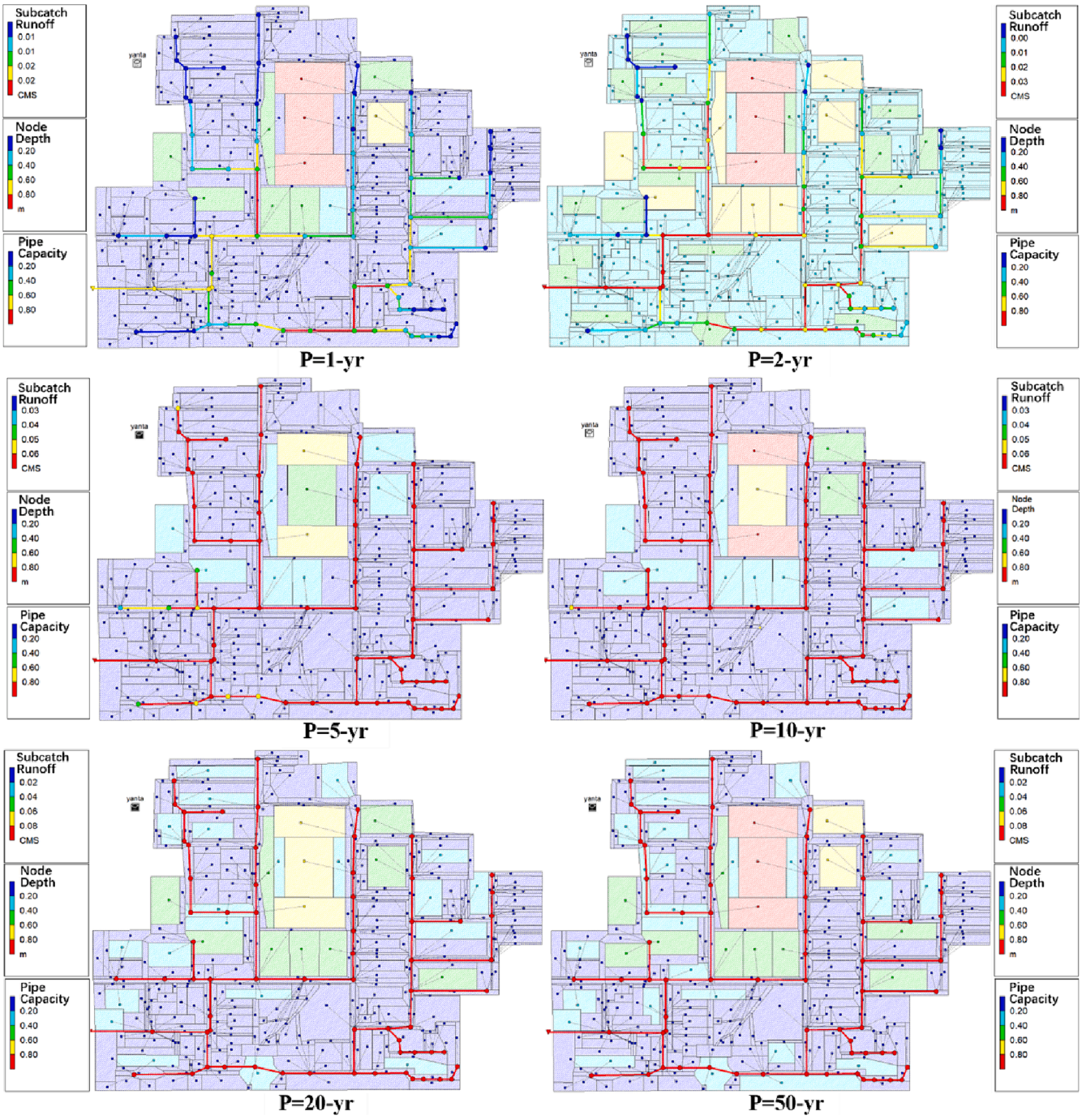


Fig. 8. Runoff simulation in the study area under different return periods.

Table 5
Overload and overflow of rainwater pipe network nodes.

Return period (*P*)		1-*yr*	2-*yr*	5-*yr*	10-*yr*	20-*yr*	50-*yr*
Overload	amount	0	18	25	36	50	66
	Overload rate (%)	0	27.3	37.9	54.5	75.6	100
Overflow	amount	0	6	14	26	38	59
	Overflow rate (%)	0	9.1	21.2	39.4	57.6	89.4

3.2.2. *Runoff discharge change at the outlet **OUT01***

The change process curve of the runoff flow of OUT01 in the LID scenario and original scenario is shown in Fig. 11. When rainwater falls to the ground to form runoff, it needs to go through the process of surface biological interception, depression water storage, surface soil storage and other processes. Rainfall intensity and rainfall increase to a certain extent, runoff will slowly form. Therefore, the discharge curve at drainage outlet OUT01 showed a delay compared to the rainfall curve, causing the peak discharge time to be later than the time of peak rainfall intensity. Compared with the original scenario, when P = 1-*yr*, 5-*yr*, 10-*yr* and 20-*yr*, the total runoff in the LID scenario was reduced by 43.91 %, 43.93 %, 45.95 % and 47.11 %. The reduction rate of peak runoff was 47.37 %, 43.56 %, 36.36 %, and 31.91 % respectively. The peak flow time-lagged 1 min, 1 min, 3 min and 5 min, respectively.

Runoff occurrence time was positively correlated with the precipitation return period. From P = 1-*yr* to P = 20-*yr*, runoff occurrence time

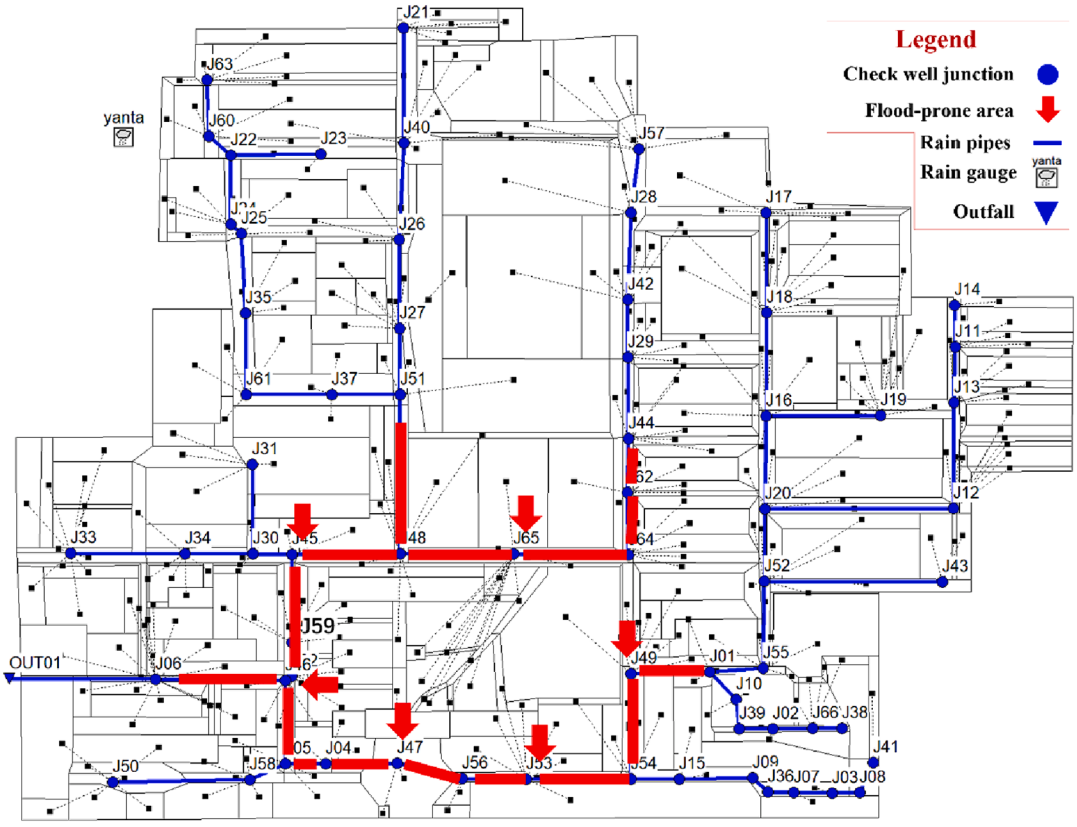


Fig. 9. Distribution of flood-prone areas.

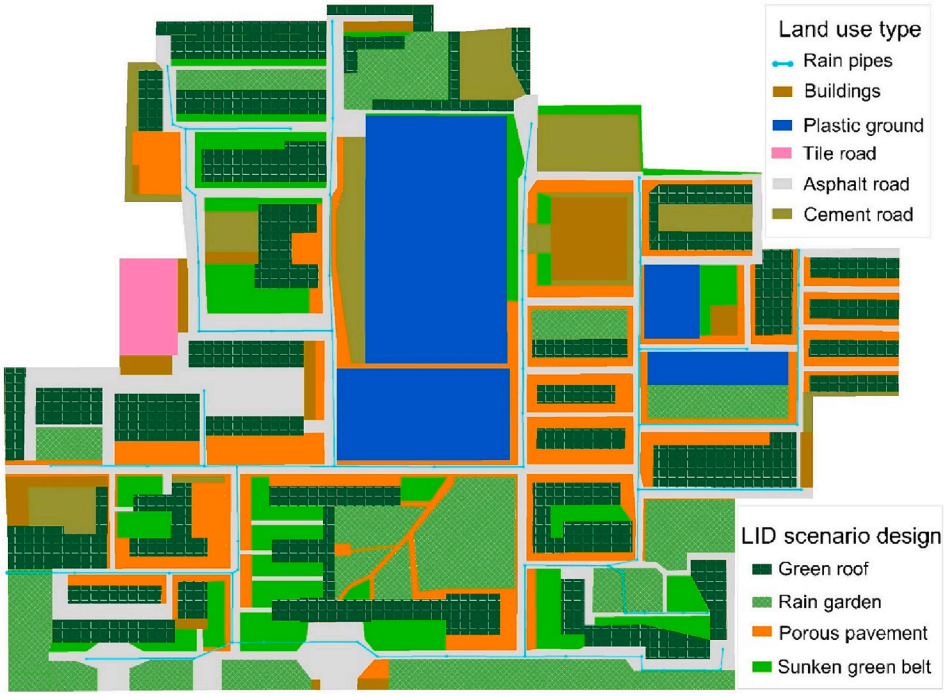


Fig. 10. LID facilities design scheme.

was 10 min earlier, and runoff duration also increased synchronously. The use of LID facilities can significantly reduce runoff, which is not only reflected in the lag time of runoff occurrence and the decrease of runoff but also the slowing down of the peak speed of runoff. It is observed that the peak runoff in the LID scenario is delayed compared to the original scenario. This delay can provide some protection to the pipe network.

Fig. 12 shows the water elevation profile at peak runoff time (55 min) of the pipeline (J46-OUT01) near the discharge outlet OUT01. When P = 5-*yr*, J46, J06 and OUT01 in the original scenario appear to be overloaded, and the pipeline load overpressure. In the LID scenario,

Table 6
Parameters of LID facility.

	Parameter	Green roof	Rain garden	Penetrative pavement	Sunken green belt
Surface layer	Water storage depth (*mm*)	200	300	5	400
	Volume coverage of vegetation (%)	0.2	0.1	0	0.1
	Roughness coefficient of surface	0.4	0.24	0.014	0.24
	Surface slope (%)	0.5	0	1.5	0
Soil layer	Thickness (*mm*)	300	400	–	400
	Porosity	0.463	0.463	–	0.463
	Field water holding capacity	0.232	0.232	–	0.232
	Wilting moisture content	0.116	0.116	–	0.116
	Soil infiltration coefficient (*mm/hr*)	3.3	13	–	13
	Water conduction slope	10	10	–	10
	Suction height (*mm*)	88.9	88.9	–	88.9
Paving layer	Thickness (*mm*)	–	–	60	–
	Porosity	–	–	0.21	–
	Impervious surface proportion	–	–	0	–
	Permeability (*mm/hr*)	–	–	800	–
Water storage layer	Thickness (*mm*)	50	300	250	400
	Porosity	0.5	0.5	0.5	0.5
	Hydraulic conductivity (*mm/hr*)	–	2	5	2
Culvert	Flow coefficient (*mm/hr*)	–	1.443	1.318	1.443
	Flow index	–	0.5	0.5	0.5
	Offset height (*mm*)	–	0	250	300

nodes and pipelines are adequately loaded. When P = 10-*yr*, nodes and pipelines in the original scenario and LID scenario are overloaded. However, in the LID scenario, the three nodes (J46, J06 and OUT01) are only slightly overloaded, and the overloaded water head is far lower than that in the original scenario. This shows that LID facilities play a role in reducing, slowing, and stagnating flow.

3.3. Analysis of pollutant reduction effect

The pollutant concentration at the water outlet OUT01 is shown in Table 8. With the increase of precipitation return period, the concentration of pollutants increased gradually. Compared with the original scenario, the concentration of pollutants in the LID scenario decreased. When P = 1-*yr*, the reduction rate of TN, TP, COD and SS are 42.56 %, 43.90 %, 42.56 % and 42.49 %, respectively. When P = 5-*yr*, the reduction rates of pollutants are 42.75 %, 42.35 %, 42.74 % and 42.71 %. When P = 10-*yr*, the reduction rates of pollutants are 44.49 %, 44.95 %, 44.49 % and 44.49 %. When P = 20-*yr*, the reduction rates of pollutants are 45.92 %, 45.86 %, 45.92 % and 45.92 %.

In Fig. 13, for the LID scenario, the pollutant concentration of the drainage outlet OUT01 decreased in different degrees at each precipitation return period, while delaying the occurrence time of peak concentration. Among them, COD and SS showed more improvements that are significant. The COD's peak concentrations diminished by 10.3 %, 14.3 %, 11.1 %, and 10.2 % sequentially. Likewise, the peak concentrations of SS also reduced by 12.6 %, 15.4 %, 13.3 %, and 12.4 %, respectively. Notably, the peak concentrations of TN and TP experienced a marginal increment compared to the original scenario. Nonetheless, the total amount of pollutants had reduced. This reduction is attributed to diverse factors such as land use, LID type, surface runoff, and runoff flushing in the study area. LID facilities have the ability to mitigate pollutants through techniques such as plant retention and slow-flow sedimentation. Nevertheless, the effectiveness of different LID facilities in reducing pollutants may vary, and the extent to which a particular pollutant can be reduced may differ across various facilities. At the beginning of rainfall, the concentration of pollutants will gradually rise with the increase in rainfall time. This is because rainwater runoff washes part of the surface pollutants into the drainage pipe, resulting in the sharp rise of pollutant concentration in the early period of rainfall. With the increased rainfall time, the final concentration of pollutants in the pipe will slowly decline and stabilize around a certain value. LID facilities have a beneficial effect on reducing common pollutants, COD and SS are more obvious.

3.4. Cost-effectiveness of SPC

Life Cycle Costing (LCC) refers to all costs incurred during the entire life cycle of a product (Xu et al., 2019). The LCC of SPC mainly includes construction cost, operation cost and the recovery value of the facility. Construction costs include material costs, installation costs and labor costs. Operating cost refers to the cost of maintenance inspection and labor management during the normal operation of the facility. Recovery value refers to the recovery cost of the facility. Calculating the LCC of a

Table 7
Simulation results of total runoff under different precipitation return periods.

P	Scenario setting	Precipitation (*mm*)	Runoff (m^3)	Infiltration (*mm*)	Runoff occurrence time (min)	Peak runoff time (min)	Runoff coefficient (*cms*)
1-*yr*	Original scene	23.072	16.301	5.650	20	56	1.09
	LID scene		9.164	3.462	25	57	0.65
5-*yr*	Original scene	46.858	34.480	11.261	13	53	2.02
	LID scene		19.344	5.620	16	57	1.14
10-*yr*	Original scene	57.103	44.057	11.934	11	51	2.20
	LID scene		23.910	7.336	14	56	1.40
20-*yr*	Original scene	67.348	53.894	12.341	10	51	2.35
	LID scene		28.509	7.781	13	57	1.60

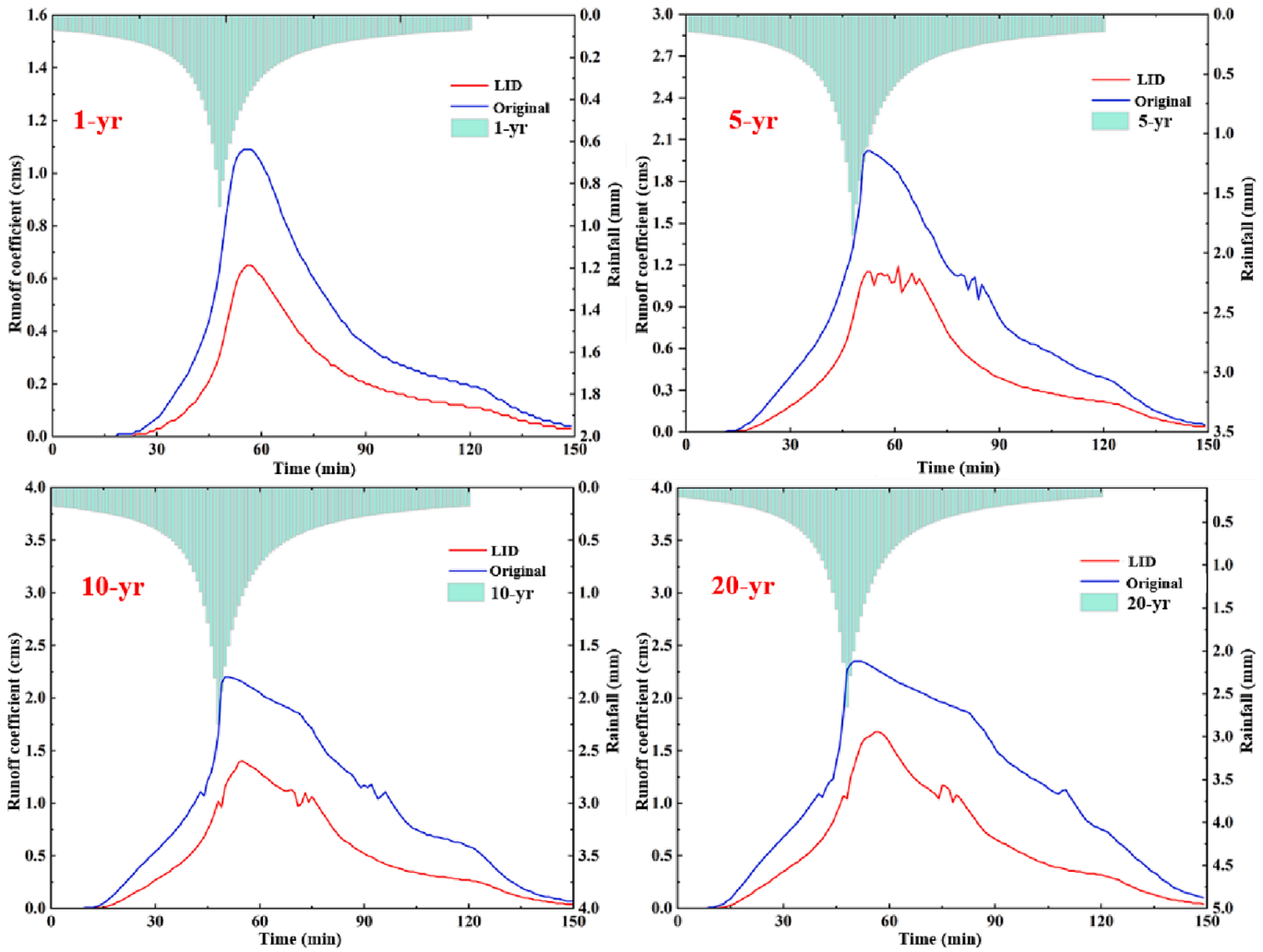


Fig. 11. Process curve of runoff flow at outlet during different precipitation return periods.

project can be used to analyze its economic benefits (Zhu et al., 2022). The following formula can calculate the costs and benefits of a LID facility in t year of operation:

$$LCC = I_0 + M_0 \times \frac{(1+\mathrm{i})^t - 1}{\mathrm{i}(1+\mathrm{i})^t} - S \times PV$$

$$PV = \frac{1}{(1+5\%)^t}$$

where: I_0: construction cost (ten thousand yuan), M_0: operating cost (ten thousand yuan), S: recovery value (ten thousand yuan), PV: present value, i: device discount rate ($i = 5$ %).

This study considered the cost of materials, operation, and maintenance, while labor and other costs are temporarily ignored. The price is based on the price standard of Xi'an City. The cost range and calculated cost of each LID facility are shown in Table 9.

The 30-years cost of the LID transformation scenario in the study area is 10.06 million yuan, and the cost of each LID measure is shown in Table 9.

4. Discussion

With the continuous development of SPC in China, it is increasingly important to evaluate their comprehensive benefits. From an economic viewpoint, rainwater stored by a sponge facility can be used as municipal water to save water. The operation of a sponge facility can effectively protect the urban drainage network and relieve the pressure of urban waterlogging and drainage. SPC construction improves urban infrastructure, improves environmental quality, and increases city core competitiveness (Yuan et al., 2022). As for ecological environment aspects, SPC construction can reduce surface runoff and runoff pollutants, improve urban water environmental capacity and environmental carrying capacity, and achieve the purpose of improving the environment (Han et al., 2021). From the social standpoint, after the reconstruction of the SPC, improves and optimizes the living environment, and then improves the residents' happiness index and social cohesion, so the comprehensive strength of the city can be enhanced (Kumar et al., 2021).

The selection of LID facilities comprehensively considered environmental, economic, and social benefits in this study. As far as possible, considering the reconstruction design based on the original terrain can reduce the construction amount, reduce the time of disturbing people, and save the cost. Rain gardens can not only enhance the infiltration of rain but also effectively remove runoff harmful substances. Reasonable plant allocation, can enrich the plant species of campus, and improve the campus microclimate. At the same time, it provides a place for leisure, giving people a new landscape perception and visual feeling (Kasprzyk et al., 2022). Green roof improves the green coverage of the city, create the longitudinal landscape of the city, and reflect its landscape benefits. It can relieve rain overflow, absorb dust to reduce noise and act as insulation (Fleck et al., 2022). Porous pavement can relieve the water on

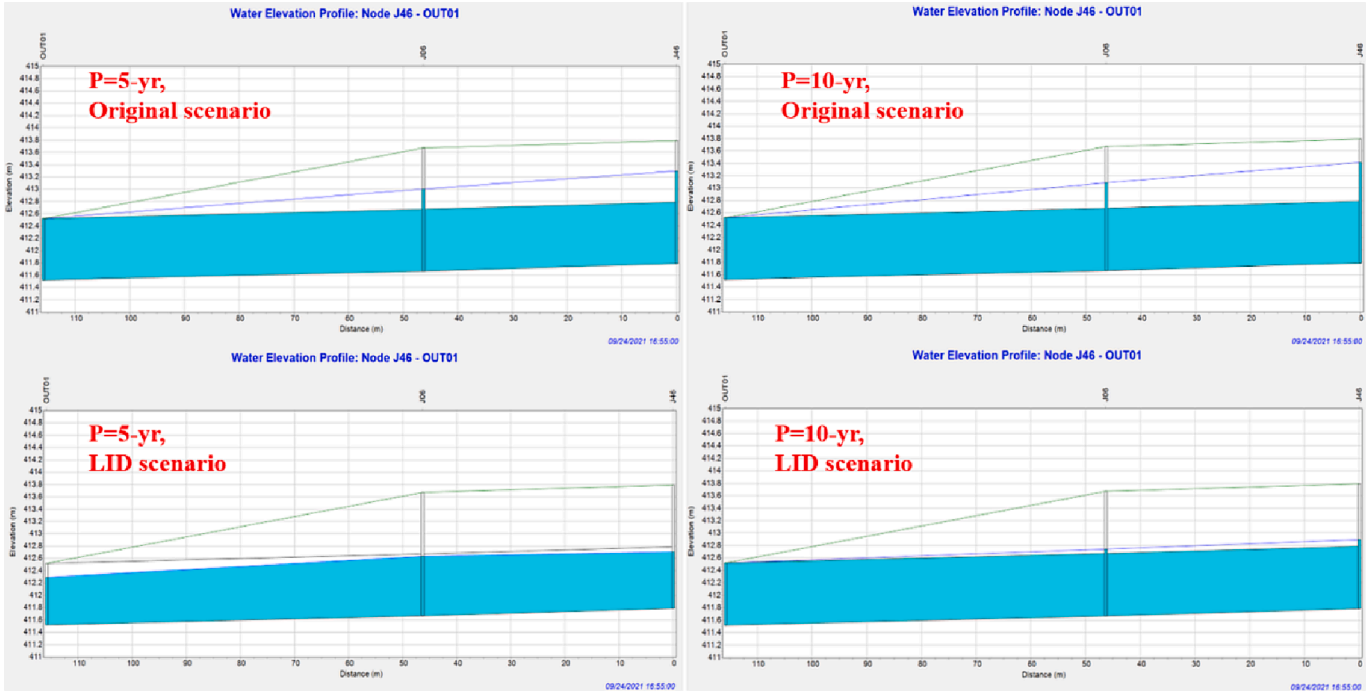


Fig. 12. Water elevation profile at peak runoff time (55 min) of pipeline near discharge outlet (J46-OUT01).

Table 8
Water quality simulation results of discharge outlet under different return periods.

P	Scenario setting	TN (*lbs*)	TP (*lbs*)	COD (*lbs*)	SS (*lbs*)
1-*yr*	Original scene	2.016	0.041	40.339	20.271
	LID scene	1.158	0.023	23.169	11.658
5-*yr*	Original scene	4.267	0.085	85.345	42.7
	LID scene	2.443	0.049	48.869	24.462
10-*yr*	Original scene	5.444	0.109	108.882	54.449
	LID scene	3.022	0.06	60.437	30.226
20-*yr*	Original scene	6.674	0.133	133.477	66.738
	LID scene	3.609	0.072	72.187	36.093

the road when it rains (Legret et al., 1996). Compared with traditional pavement, it has higher permeability, environmental protection, and aesthetics (Cheng et al., 2019). Sunken green belt is designed around the pavement according to the terrain, which can quickly absorb and store rainwater. The plants inside can play a role in beautifying the landscape (Azkarini et al., 2019; Wei et al., 2021).

According to a comprehensive analysis, LID facilities are effective in reducing runoff, extending runoff occurrence time, reducing peak discharge, and reducing flood peak discharge when the precipitation return period is small, such as moderate and light rain (Jiang et al., 2022a). However, with the increase in precipitation return periods, the capacity of runoff reduction also decreased. To some extent, LID facilities are not suitable for heavy rain events (Hua et al., 2018). Under different precipitation return periods, LID facilities can reduce a certain number of pollutants through the interception of plants, slow flow precipitation and other functions, among which COD and SS are more obvious (Baek et al., 2020). Different LID facilities have different reducing effects on pollutants, and the same LID facilities have different effects on the reduction of different pollutants (Allen et al., 2019; Li and Kim, 2022).

To successfully develop an SPC, one must consider the integration of environmental, economic, and social factors. It is important to maintain a positive feedback loop cycle of regional water environment and economic rationality, while also identifying any conflicting objectives between environmental, disaster control goals, and economic benefits. By maximizing the comprehensive benefits of an SPC, urban water problems can be effectively solved, and the virtuous cycle of SPC construction can be promoted (Bai et al., 2019; Hou et al., 2020b).

5. Conclusion

The implementation of sponge cities and the utilization of LID facilities hold immense importance in addressing the issue of rain-induced waterlogging. Based on the concept of an SPC, this paper conducted a relevant study in combination with the functionality and local suitability of LID facilities and provides certain references for LID planning and construction of the city. The “Beiyuan” campus of Chang’an University was taken as a study area, collected hydrometeorology data and pipe network planning data to build a rainstorm and flood management model based on SWMM. By designing scenarios of different precipitation return periods and the SWMM model to identify flood-prone areas in the study area. Based on the comprehensive consideration of the topographic terrain of the “beiyuan” campus and the cost-effectiveness of LID facilities, the sponge LID scenario was designed. Through SWMM model simulation, compared and analyzed the runoff regulation effect and pollutant concentration reduction effect between the original scenario and LID scenario.

Through the simulation and analysis of the study area by the SWMM model, it is concluded that the pipe network system can only meet the design return period of 2-years. The maximum overflow node is J59. The rain-flood regulation effect of LID facilities is affected by the change in rainfall characteristics. It has a good weakening effect on stormwater runoff and peak discharge in moderate and light rain precipitation events but has a deficient performance in heavy rain and rainstorm precipitation events. LID facilities have a certain effect on the removal of common water pollutants, and the reduction of COD and SS is obvious. When the return period increases gradually, the reduction rate of pollutants shows a downward trend. The comprehensive benefits of the LID reconstruction scenario tend to decline with the increase of the

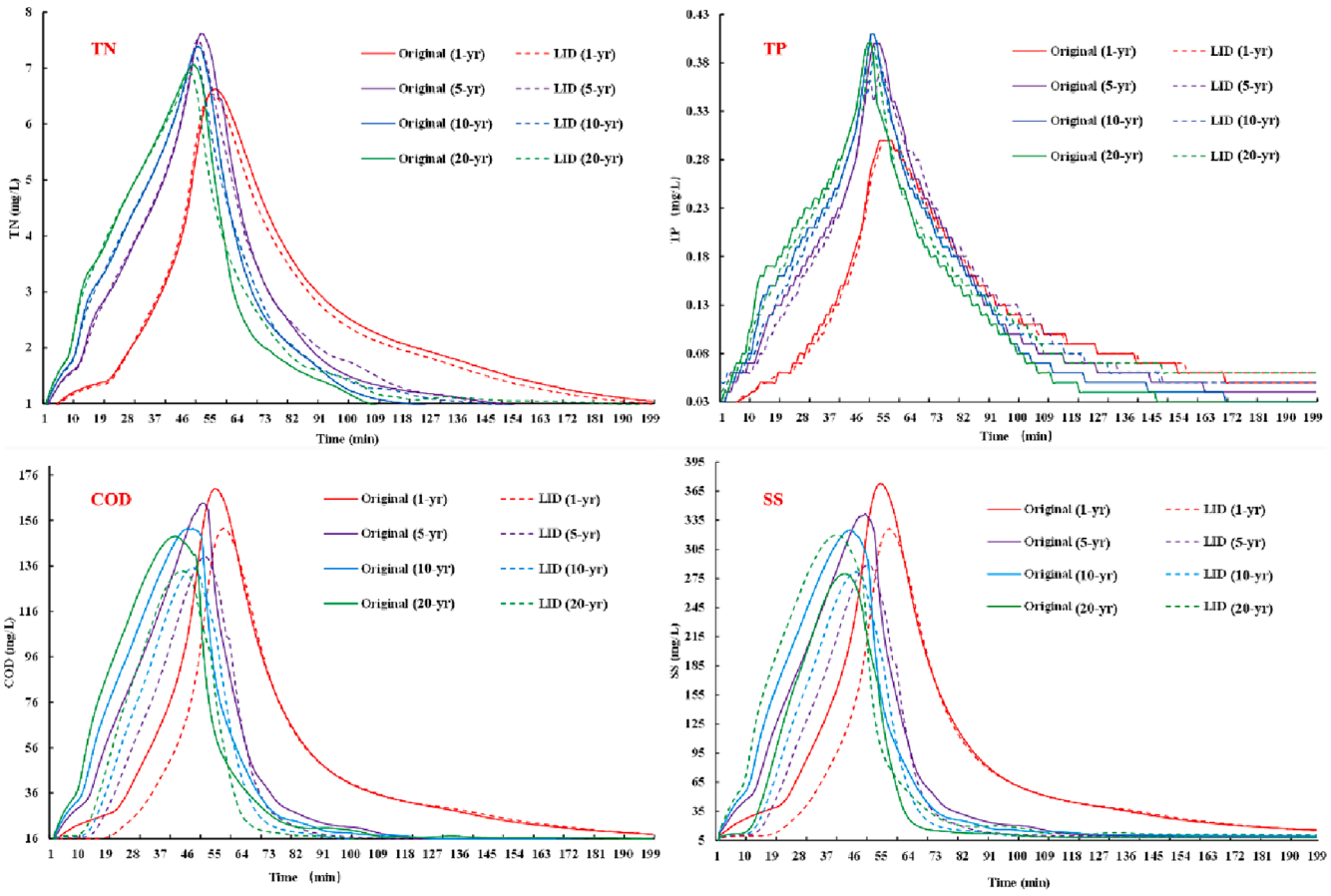


Fig. 13. Change curve of pollutant concentration at discharge outlet (OUT01).

Table 9
Cost calculation of LID facility.

LID type	Reference price range			Cost of operating for 30 years		
	I_0(*Yuan* /m^2)	M_0(*Yuan* /m^2/ *year*)	Construction area (m^2)	I_0(*Yuan* /m^2)	M_0(*Yuan* /m^2/ *year*)	30 years LCC (ten thousand yuan)
Rain garden	200–400	10–70	4542.4	240	10	179
Porous pavement	50–200	2–13	24148.8	95	5	415
Green roof	150–350	5–60	9029.4	180	6	246
Sunken green belt	50–180	3–4	10000.6	120	3	166

precipitation return period.

There are definite areas for improvement in this study, which will be addressed and enhanced in future studies. We will design rainfall process lines based on different methods (not only the Chicago rain pattern line) and will design rainfall scenarios with different rainfall durations. Meanwhile, design multiple LID scenarios according to land use types for comparative study.

CRediT authorship contribution statement

Xianbao Zha: Data curation, Software, Writing – original draft. **Wei Fang:** Formal analysis. **Wei Zhu:** Formal analysis. **Shuangtao Wang:** Data curation, Writing – review & editing. **Yong Mu:** Data curation, Writing – review & editing. **Xiaofeng Wang:** Data curation, Writing – review & editing. **Pingping Luo:** Conceptualization, Writing – review & editing. **Mohd Remy Rozainy Mohd Arif Zainol:** Data curation, Writing – review & editing. **Mohd Hafiz Zawawi:** Data curation, Writing – review & editing. **Khai Lin Chong:** Data curation, Writing – review & editing. **Apip Apip:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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