



# Performance assessment of coupled green-grey-blue systems for Sponge City construction

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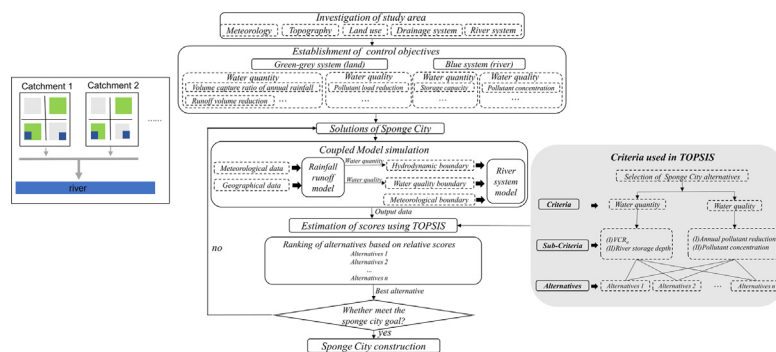
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## HIGHLIGHTS

- An integrated framework is proposed to assess green-grey-blue systems.
- Sponge City performance assessment should consider receiving water bodies.
- The performance of Sponge City strategies increases with larger scale deployment.
- The effectiveness of the framework was demonstrated using a case study.

## GRAPHICAL ABSTRACT



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## ABSTRACT

In recent years, Sponge City has gained significant interests as a way of urban water management. The kernel of Sponge City is to develop a coupled green-grey-blue system which consists of green infrastructure at the source, grey infrastructure (i.e. drainage system) at the midway and receiving water bodies as the blue part at the terminal. However, the current approaches for assessing the performance of Sponge City construction are confined to green-grey systems and do not adequately reflect the effectiveness in runoff reduction and the impacts on receiving water bodies. This paper proposes an integrated assessment framework of coupled green-grey-blue systems on compliance of water quantity and quality control targets in Sponge City construction. Rainfall runoff and river system models are coupled to provide quantitative simulation evaluations of a number of indicators of land-based and river quality. A multi-criteria decision-making method, i.e., Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is adopted to rank design alternatives and identify the optimal alternative for Sponge City construction. The effectiveness of this framework is demonstrated in a typical plain river network area of Suzhou, China. The results demonstrate that the performance of Sponge City strategies increases with large scale deployment under smaller rainfall events. In addition, though surface runoff has a dilution effect on the river water quality, the control of surface pollutants can play a significant role in the river water quality improvement. This framework can be applied to Sponge City projects to achieve the enhancement of urban water management.

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## 1. Introduction

Rapid urbanization has resulted in increased impervious surfaces that significantly affect natural hydrologic and ecological processes. Many cities in China experienced frequent flooding events and water quality in receiving water bodies, which lead to high economic and human life losses (O'Driscoll et al., 2010; Paule-Mercado et al., 2017; Randhir and Raposa, 2014). To ease the problems, Sponge City construction, as a comprehensive stormwater management measure, has received increasing attention in recent years (Jia et al., 2017).

Traditional storm water management relies on grey infrastructures such as storm sewers, pipes, detention basins (Tavakol-Davani et al., 2016). However, the limitations of grey infrastructure make them unable to adapt to the evolving social and ecological systems (Jones et al., 2012; Kallis, 2007). An extensive adoption of green infrastructure to supplement traditional drainage systems is required. The combination of green and grey systems could offer win-win solutions especially in a long-term perspective (Renaud et al., 2013). Examples of new approaches to achieve green-grey systems include Best Management Practices (BMPs) in the United States, Water Sensitive Urban Design in Australia, Sustainable Drainage System (SuDS) in the United Kingdom (Fletcher et al., 2014). A multifunctional approach—green and blue infrastructure (GBI) which can enhance the resilience of cities to cope with environmental risks was emerged (Alves et al., 2019). Resilience based urban storm water management strategies have received attention globally. Since 2014, China has been implementing the Sponge City construction. Sponge City refer to a city that can absorb, store and purify rainwater as a sponge and then naturally filter the rainwater through the soil, allow it to reach urban aquifers, and release it for reuse when needed. Compared to conventional urban stormwater management, Sponge City relies on natural based solutions, and it is expected it can improve the resilience of stormwater systems, which is normally defined as the ability to maintain their services and recover from extreme events (Ding et al., 2019). Compared with Resilience City (Admiraal and Cornaro, 2019) which emphasizes the ability of the complex city system to adapt to changing conditions, Sponge City is considered a specific practice to improve the resilience of cities with respect to water and environmental system management. Actually, Sponge City is a typically green-grey-blue system that includes LID (green infrastructure) at the source, the drainage pipe system (grey infrastructure) at the midway and receiving water bodies (blue system) at the terminal (Li et al., 2019). Rainfall runoff is firstly treated by LID practices, the outflow from LIDs is conveyed to the drainage system and then transported to the receiving water bodies (i.e. river) (LeFevre et al., 2010). In a plain river network area, which is a typically flat area that is covered with dense river branches, rainwater pipe systems with numerous outlets, rainfall runoff could flow into the river via these outlets and result in a great influence on water environment (Lai et al., 2016; Wang et al., 2017b). River is not only the final outlet of an urban rainwater system, but also an important component that contribute to water management. Green infrastructure, pipe network and rivers are not isolated but should be considered as an integrated system in urban water management (Depietri and McPhearson, 2017).

In recent years, assessing the benefits of Sponge City applications has been studied (Jia et al., 2017; Li et al., 2019; Li et al., 2016; Mei et al., 2018; Qingmu and Hsueh-Sheng, 2018). However, the majority of existing studies has an emphasis on the use of indicators of urban drainage system to measure the performance of Sponge City facilities, e.g. peak value of runoff, runoff volume reduction, pollutant load. (Damodaram and Zechman, 2013; Yang and Best, 2015). River water indicators are not taken into consideration. For an integrated assessment of green-grey-blue system, indicators should not be confined to rainfall runoff control effects. It is high time to incorporate the receiving water bodies into the assessment framework which is equally important in decision making for Sponge City construction.

Simulation models have long been used as value tools to quantify the environment benefits, and thus can best assess the far-reaching effects of various planning and management options (Achleitner et al., 2007). To obtain the indicators of different part of green-grey-blue system, a coupled model is imperative for an integrated assessment. The search for optimal configurations of green infrastructure represents a great challenge for practices (Alves et al., 2018; Her et al., 2017). It is necessary to integrate a rainfall runoff model with a river system model to quantify the impact of Sponge City facilities on urban water environment.

In the study, we take a typical plain river network area of Suzhou, in China as a case example, propose an integrated assessment framework to quantify the performances of different solutions of Sponge City. We adopt a rainfall runoff model coupled with a river system model to analysis the water quantity and quality in a green-grey-blue system. Four indicators—volume capture ratio of annual rainfall ( $VCR_a$ ), pollutant load reduction, river storage depth, and river pollutant concentration—are selected to conduct a Multi-Criteria Decision Making (MCDM) with the use of Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS). Besides, a statistical approach is developed to help evaluate the effectiveness of LID in receiving water bodies, enabling urban managers to fully understand the performance of various interventions during the decision-making process. The assessment framework offers significant rational information for decision makers when choosing among different solutions, as a guide to Sponge City construction in the practical projects.

## 2. Materials and methods

### 2.1. Integrated assessment framework

To maximise the benefits of Sponge City solutions, an integrated management system will help the planners in evaluating the performance of various interventions to determine the optimal strategy to develop and implement the Sponge City measures. However, the existing approaches for assessing the performance do not incorporate the effectiveness of Sponge City applications in receiving water bodies. To address this limitation, we propose a novel framework for a comprehensive analysis of the performance of Sponge City facilities to support the strategic planning in green-grey-blue system for sustainable management.

The overall framework (Fig. 1) includes four main parts: Part I: Control objectives; Part II: Model simulation; Part III: Decision making.

#### 2.1.1. Control objectives

Sponge City facilities can provide multiple environmental benefits in various impact categories. These benefits are often quantified using a range of performance indicators. In China, the construction of Sponge City is regulated by the *Sponge City Development Technical Guide: Low Impact Development* (MHURD, 2014) to meet the requirements for reducing runoff volume and pollution. Traditionally, most studies consider several categories of environment impacts, including water quantity control, pollutant load abatement. Certain performance indicators are used for each impact category. The Volume Capture Ratio of Annual Rainfall ( $VCR_a$ ) and runoff volume reduction are often used to characterize the water quantity control impact. For example,  $VCR_a$  is used in (Randall et al., 2019) to compare the hydro-environmental benefits of LID scenarios with varying degrees of implementation of rain gardens, permeable pavements and green roofs. Runoff volume reduction is used in (Petrucci et al., 2013) to examine the hydrological impact of different storm water management strategies. The  $VCR_a$  is presented as key index in guideline which is the cumulative annual control (i.e. volume not directly discharged) of the total annual rainfall by means of natural and artificial measures, such as infiltration, detention, storage, and evaporation. The guideline has delineated five geographic areas within the country, each

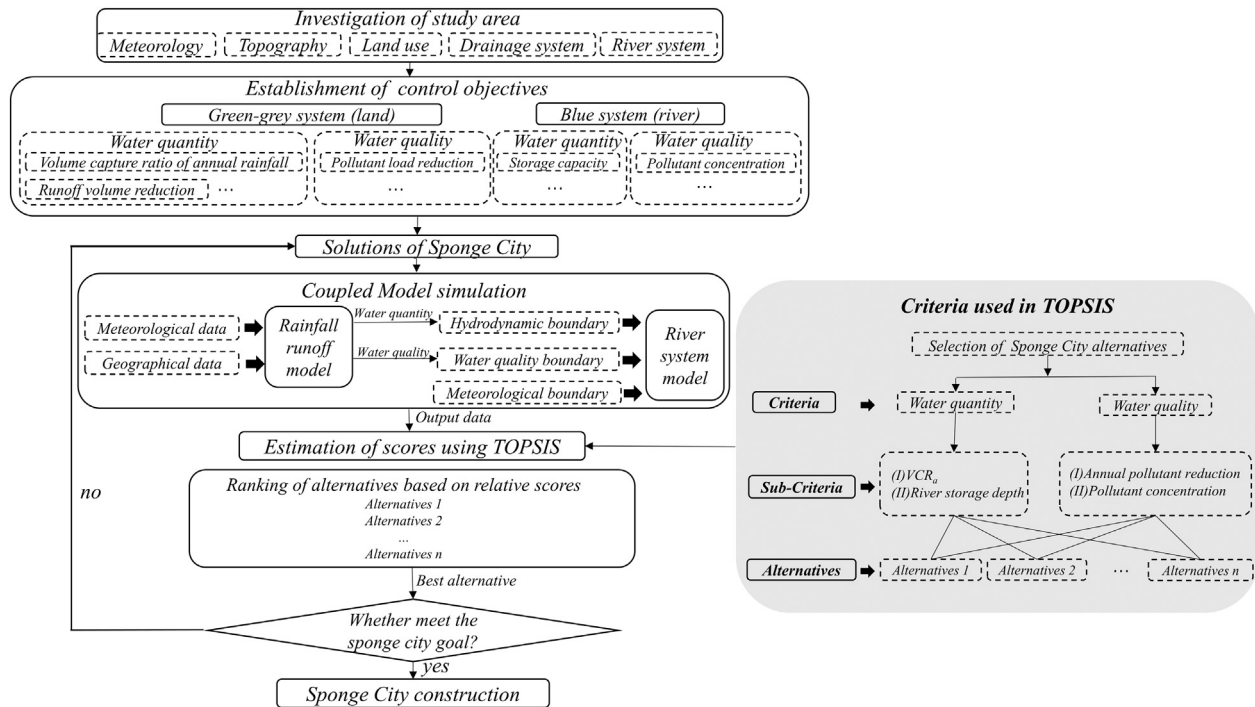


Fig. 1. Procedure of integrated assessment for Sponge City construction.

with a different range of acceptable  $VCR_a$  due to different climate, soil, topography and other environment conditions. For runoff volume reduction, LID design guideline has specified the runoff volume reduction targets or listed the estimated runoff volume reduction resulted from LID practices. Pollutant load reduction is often used to assess the surface runoff pollution abatement benefit of LID practices. To calculate pollutant load reduction, long-term continuous hydrologic modeling simulations should be conducted. It should be mentioned that the  $VCR_a$  is calculated for each scenario while runoff volume reduction is calculated as the difference between the simulated scenario and the benchmark case. So, runoff volume reduction is always used in scenarios optimization.

However, it has certain limitations that the performance assessment of Sponge City construction mainly focuses on the urban drainage system as these objectives are directly related to the output data of rainfall runoff model. In green-grey-blue system, integrated assessments are necessary to consider both the land-based indicators and the river-based indicators. This paper describes an attempt to incorporate the receiving water bodies into Sponge City assessment framework which points out that attention should be paid to the river water environment benefits provided by LID practices. Many different indicators may be considered to measure hydrological and water quality status depending on potential use of receiving water.

LID practices can provide environment benefits on receiving water bodies in various impact categories including hydrological and water quality improvement. River storage depth is used to assess the hydrological improvement impact refer to *Ad Hoc Plan of Sponge City Construction* (Shanghai Municipal Government, 2016). It is defined as the ratio of the water quantity from the rainwater outlet (the storage water volume of river) to area of the regional river. For instance, the area of river is  $A$  ( $m^2$ ), the outflow of rainwater outlet is  $V$  ( $m^3$ ). Assume that the river is separated from the outside water body by gates and dams, all gates are closed in the rainfall events. The rising height of water level  $H$  (m) can be estimated:

$$H = \frac{V}{A} \quad (1)$$

When the  $H$  lies within the target value of river storage depth, it can be concluded that the hydrological requirement is met. For river water quality, the assessment standard can refer to the Chinese Surface Water Environmental Quality Standards (GB3838-2002). According to the local planning, the pollutant concentration in the river should lie within the range specified in the standard.

### 2.1.2. Model simulation

To better facilitate effective decision making on Sponge City construction, establishing a quantitative cause-and-effect relationship through mechanistic mathematical modeling is necessary (Liu et al., 2014). The coupled model which consists of rainfall runoff and river model, respectively, were used in this research to simulate the water quantity and quality process in the sewer system and river. The most widely used rainfall runoff models include Storm Water Management Model (SWMM), the System for Urban Storm water Treatment and Analysis Integration (SUSTAIN) and Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID) Model (Huber et al., 1988, Liu et al., 2015). Researchers worldwide have used these models to assess the effectiveness of LID and BMPs practices in storm water management since the process considered in these models include surface runoff and wash-off, flow and pollutant transport in sewers (Ackerman and Stein, 2008, Avellaneda et al., 2010, Bhaduri et al., 2000, Damodaram et al., 2010, Elliott and Trowsdale, 2007, Jia et al., 2015, Newcomer et al., 2014).

River system models such as Environmental Fluid Dynamics Code (EFDC) model, Water Quality Analysis Simulation Program (WASP) model and CE-QUAL-ICM model enable a dynamic simulation of river flow. In this study, it is supposed that discharges into the river only include the non-point source pollutants from rainfall runoff, models are coupled by using the output pollutants data of rainfall runoff model as the input pollutants data of the river system model. Rainfall runoff model (e.g. SWMM) provides the water flow through the drains into the water body. River system model (e.g. EFDC) simulates water flow and dispersion within the water body.

Model selection is driven by the problem that needs to be solved and data availability (Engel et al., 2007). Before model developed, suitable LID facilities were selected based on regional characteristics.

Alternatives have been formulated as varying percentages (degree of adoption) of these suitable facilities. To evaluate the environmental benefits, the performance of water quantity and quality control was simulated for each LID alternatives. The indicator values of environment benefits were obtained using the coupled model.

2.1.3. Decision making

Multi-Criteria Decision Making (MCDM) methodology-based Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) have been adopted to rank the alternatives and identify the optimal alternative for Sponge City construction. MCDM methodology is widely deployed either to rank alternatives or to select the optimal one as it considers several attributes (Behzadian et al., 2012; Zhou et al., 2006). It is available for generating hierarchy of options in management decisions which have been applied extensively for environmental decision-making (Huang et al., 2011). Given to the complexity of stormwater management decision problems, the MCDM method is an efficient, reliable and consistent solution. Many researchers have developed decision making tools based on MCDM procedure for stormwater management (Chow et al., 2014; Gogate et al., 2017; Jato-Espino et al., 2014; Luan et al., 2019). Among various MCDM methods available, the most preferred approach for environmental decision making problems is TOPSIS (Kalbar et al., 2012; Opricovic and Tzeng, 2004). TOPSIS is based on distance based approach to quantify and compare the preferences of the alternatives over the set of attributes and considers the positive and negative ideal solutions simultaneously (Shih et al., 2007). Compared with other approaches, TOPSIS makes full use of attribute information, provides a cardinal ranking of alternatives, and performs good robustness, easy to compute and easy-to-use for decision analysis (Behzadian et al., 2012; Gogate et al., 2017; Zhou et al., 2006). Therefore, TOPSIS is selected for ranking varies alternatives in this study. The detailed step by step procedure of the TOPSIS methodology is presented in Kalbar et al. (2012).

The selection of appropriate solutions for Sponge City often involves multiple criteria. Two main criteria (water quantity, water quality) comprising four indicators have been used for evaluating several alternatives. The criteria and indicators were chosen in the light of data availability and control objectives usually used in Sponge City guideline (Section 2.1.2). Multiple performance indicators are taken account into the environment benefits provided by LID practices. Although individual indicators can provide meaningful information on environmental impacts, their values need to be integrated to consider for the effectiveness evaluation and alternatives selection. In this study, rainfall runoff model coupled with river system model is utilized to quantify the indicator values for various alternatives. The land-based indicators are gained from the rainfall runoff model. Taking river as blue system, the hydrological and water quality indicators of the receiving water bodies are valued by river system model. Then, a combined indicator score matrix was formulated for four indicators. Based on the procedure of the TOPSIS methodology, the score of each alternative can be obtained.

As described earlier, the integrated assessment framework was used to rank the possible alternatives and evaluate the effectiveness of Sponge City construction for decision-makers. To find best solutions for urban water management, the benefits of Sponge City construction scheme can be discussed by the evaluation results. The performance indicators mentioned above not only provide a quantitative reference for strategic planning but also measure the effectiveness of Sponge City construction That is to say, after optimal alternative was selected based on MCDM method, if the indicator values of the alternative meet the local requirement, it can be used to construct otherwise new alternatives will be proposed. The results allow the decision makers to have a more complete knowledge of the control effect as well as offer significant rational information for decision makers when choosing among different solutions.

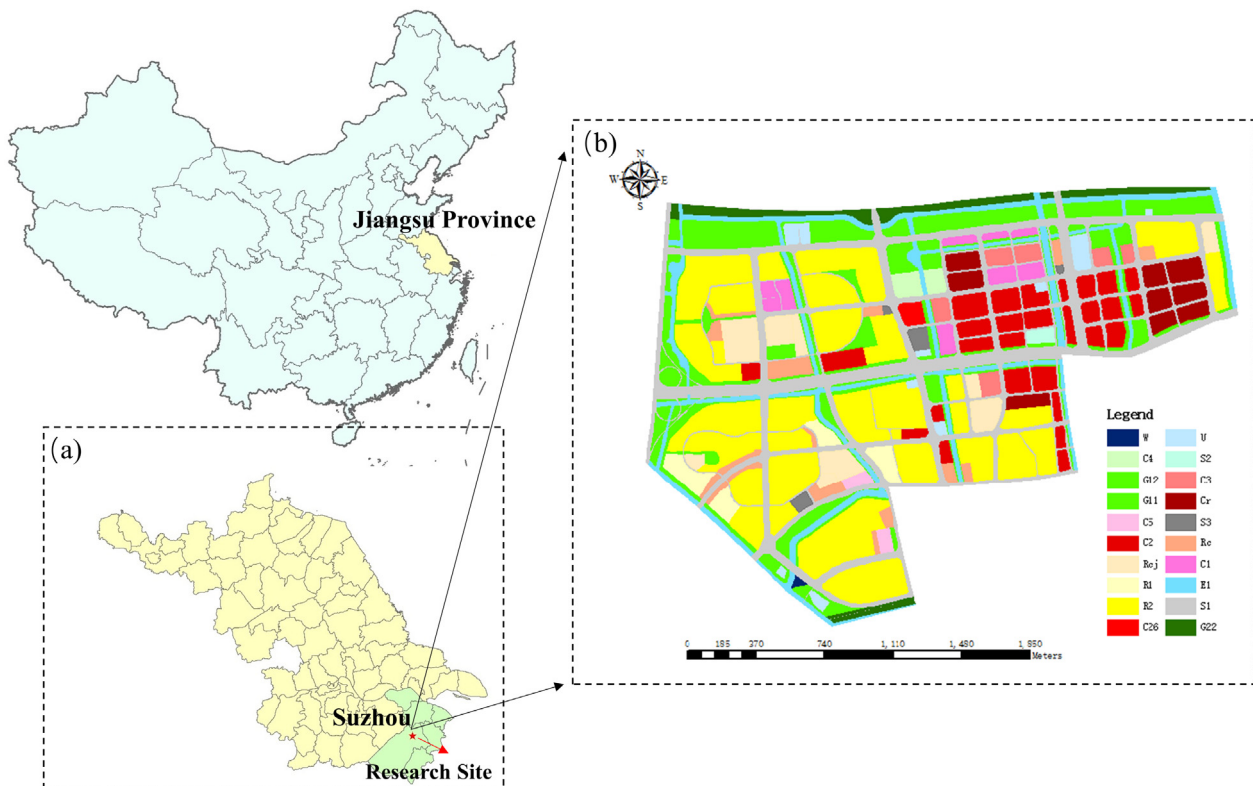


Fig. 2. Location of the study area and associated land uses.

## 2.2. Case study

### 2.2.1. Study watershed and control objectives

In this paper, we adopted the Ping jiang New City in Suzhou (31°18' N, 120°36'), Jiangsu Province, as the case study. The region is a plain river network area in China (Fig. 2(a)). With a total area of 465 ha, Ping jiang New City is highly urbanized, as shown in Fig. 2(b), with over 70% of its area developed for residential land uses. The average annual rainfall is around 1100 mm, most of which falls from April to September during monsoon season.

The area consists of 13 rivers with a large numbers of hydraulic engineering facilities such as sluice gates and pumping stations to control river water level and discharge surface water, respectively. A separate drainage system is constructed in the area such that the storm water runoff is drained directly into the rivers. The monitoring pollutant data of 2016 indicates that ammonia nitrogen (NH<sub>3</sub>-N) is the main contaminant of concern in the area as its concentration exceeded the standard most times (Fig. 3). Therefore, controlling NH<sub>3</sub>-N is the key to improve river water quality.

As Ping jiang New City was selected as the pilot of Sponge City in Suzhou, the Ad hoc Plan of Sponge City construction (Government, 2017) is proposed. The plan elaborates the implementation guidelines for Sponge City in 2017–2018, including the required percentage of different types of LID projects on various land use as well as the control objectives target value. Considering the guideline of Sponge City construction, control objectives were listed in Table 1. Based on the local Sponge City construction guide, different control objectives are considered for various rainfall conditions.

- (1) Annual rainfall time series: A 65% VCR<sub>3</sub> was set to meet the minimum requirement of the whole study area. Due to the correlation between SS and other pollutants, the pollutant load reduction of SS is generally used as a control objective for water quality evaluation. SS load should be reduced by 45% after Sponge City construction.
- (2) 2hr design rainfall: River storage depth is selected as the river water quantity indicator for short duration rainfall evaluation because it is the main factor that affects river water quantity control. When storm water events occur, the increase of water level should <35 cm to meet the river storage target value. For river water quality, the main pollutant in study area is NH<sub>3</sub>-N. A Class IV water quality designation, based on the Chinese Surface Water Environmental Quality Standards (GB3838-2002) was chosen for the water quality standard for the blue system.

### 2.2.2. Model development

SWMM is one of the most advanced models for hydrodynamic and water quality simulations in sewer systems. It is widely used to evaluate different storm water control strategies, and provide optimal storm water control solutions (Chui et al., 2016; Kong et al., 2017; Lucas and Sample, 2015; Montalto et al., 2007; Palla and Gnecco, 2015). In particular, SWMM is one of the most preferred models to evaluate the performance of LID practices in storm water management, where it includes a functionality to analysis the performance of LID practices. The LID function allows for the simulation of the physical processes (i.e. storage, infiltration, evapotranspiration, and overflow) occurring in various LID facilities (e.g. rain gardens, porous pavement, green roofs) (Lee et al., 2012). In addition, SWMM is often used in urban areas because it is capable of simulating conveyance systems (Nayeb Yazdi et al., 2019). Based on these considerations, SWMM has been considered the most suitable rainfall runoff model for this work.

The study area was divided into 150 sub-catchments based on the current land use and storm water pipe networks, where each sub-catchment corresponds to an outfall. Then, required data and corresponding sources for the SWMM application were provided in the Supplementary material (Section 1.1).

Based on the statistics of historical rainfall events during 2015–2017 in Suzhou, annual rainfall time series were used as one of the inputs for the model to evaluate the VCRA and pollutants load reduction in land-based area. Also, a range of independent 2hr designed rainfall events of different return periods are considered for evaluation of river indicators. The storm events can be designed according to the relationship of rainfall intensity-duration-frequency in Suzhou, which is described as below:

$$q = \frac{3306.63(1 + 0.8201 \lg P)}{(t + 18.99)^{0.7735}} \quad (2)$$

where  $q$  is rainfall intensity (L/s·ha);  $P$  is return period (yr);  $t$  is rainfall duration (min); The Chicago storm profile is adopted in this study to generate rainfall hydrographs. The rainfall hydrographs of four groups rainfall events of different return periods (1-, 3-, 5-, 10-yr) which have same rainfall duration (2 h) and the location of rainfall intensity ( $r = 0.4$ ).

As for sub-catchment properties, study area underlying surface were classified into greenspace, building and road. Then greenspace is pervious surface, building and road are impervious surface. So the

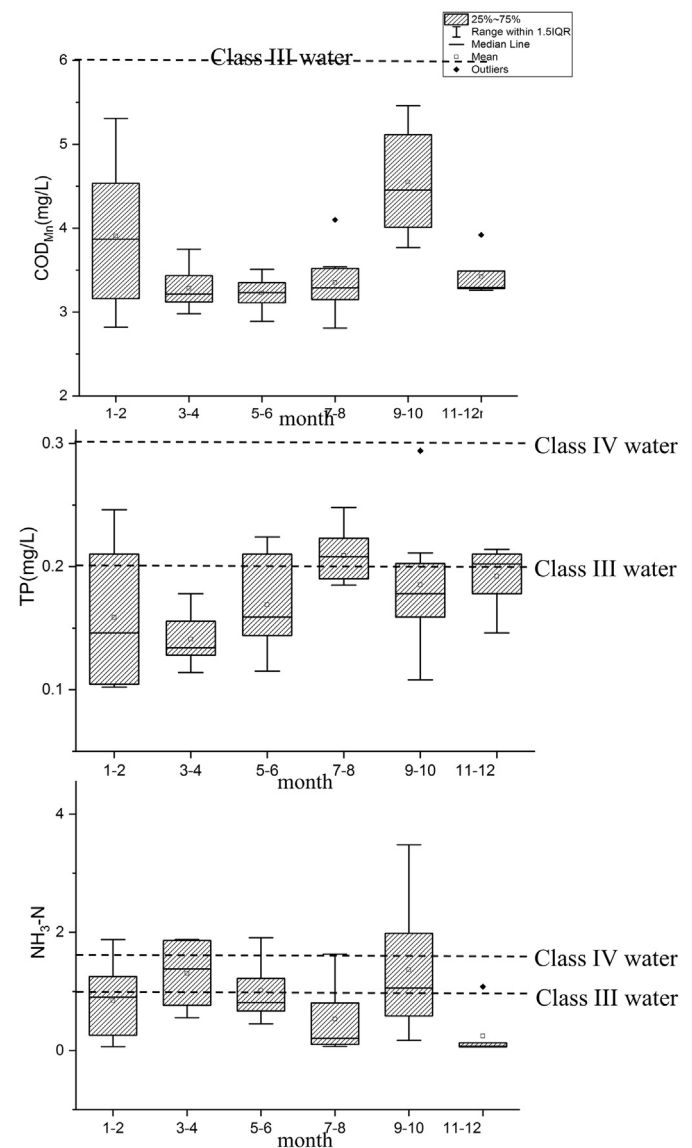


Fig. 3. Box-plots of monitoring pollutant data in 2016 (Class III and Class IV are based on the Chinese Surface Water Environmental Quality Standards (GB3838-2002)).

**Table 1**  
Local control objectives.

Rainfall conditions	Control objectives	Target	
Annual rainfall time series	Water quantity	VCR <sub>a</sub>	65%
	Water quality	Annual pollutant reduction (SS)	45%
	Hydrological	River storage depth	35 cm
2 h design rainfall	Water quality	Pollutant concentration (NH <sub>3</sub> -N)	Class IV water quality designation (<1.5 mg/L)

imperviousness of each sub-catchment is the percentage of building and road areas:

$$\text{Imperviousness} = \text{Building\%} + \text{Road\%} = 100\% - \text{Greenspace\%} \quad (3)$$

Based on the Urban Jiangsu Province Government (2011) and Suzhou Municipal Government (2016), the greenspace rate of different kinds of land use types was determined. Details are provided in the Supplementary material (Section 1.2). Spatial Analysis of GIS was used to process the greenspace rate and building rate of each sub-catchment, then the road rate and impervious rate were also obtained.

Two approaches were used to determinate the parameters: (1) A few parameters were set following the previous research on the Suzhou study area (Chen, 2017; Cheng, 2014; Zhang, 2015). (2) Others were set according to the recommendations presented by SWMM model. Details of SWMM model parameters are provided in the Supplementary material (Section 1.3).

EFDC is a three-dimensional and hydrodynamic water quality model which can simulate hydrodynamics, eutrophication dynamics and the fate and transport of toxic materials. It is widely used in rivers, lakes, reservoirs, estuaries, bays, and coastal zones for environmental assessment and management (Huang et al., 2017; Jeong et al., 2010; Wu and Xu, 2011; Zhou et al., 2014). The EFDC model can predict the water level distributions as well as transport and fate of contaminants in the water body. At the same time, EFDC is often used for model coupling, scenario analysis and strategies optimization (Kim et al., 2017; Luo and Li, 2018; Shin et al., 2019; Zhu et al., 2016). Therefore, EFDC is selected as the river system model for this study.

EFDC is a finite difference-based numerical method for solving the governing equations such that the river networks were discretized as multiple computational grids. The number of grids determines the calculation time of the model, so it should be set carefully. The orthogonality of the grid affected the speed and precision of the model operation, so the deviation of orthogonality of the grid is <3°. Based on the river

planning, the regional river was manually divided into 199 grids. The length grids were generally 70–150 m and the width was 15–30 m.

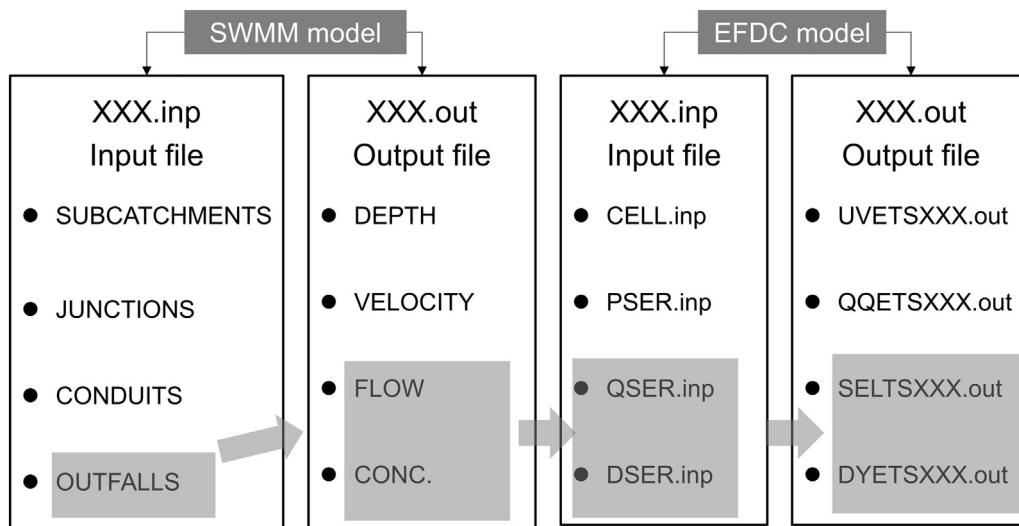
EFDC can simulate hydrodynamic, water quality and sediment transport. In this study, hydrodynamic module was used only, as for water quality, i.e., NH<sub>3</sub>-N, primary degradation reaction of dye tracer was used to simulate the changes of NH<sub>3</sub>-N in Water. Parameters were set according to the relative research (Guo et al., 2008; Ou, 2014; Tian et al., 2014; Wang et al., 2016). Details are provided in the Supplementary material (Section 1.4).

Boundary conditions need to be set in EFDC. Meteorological boundary including atmospheric pressure, air temperature, relative humidity, precipitation, evaporation, solar radiation, cloud cover, wind speed, and wind direction are represented by time variable data from local monitoring stations. As shown in Fig. 4, the flow and pollutants concentration of each outfall can be obtained from the SWMM output file ('FLOW' and 'CONC'). According to the corresponding discharge grid of each outfall in the river. The output data of SWMM can be used as the input data of EFDC where 'FLOW' corresponding 'QSER.inp' and 'CONC' corresponding 'DSER.inp'. Then, boundary conditions for flow and dye tracer were configured.

2.2.3. Model validation

The quantitative evaluation undertaken here was derived from our previously developed SWMM model. Therefore, the validation of model is focus on the three-dimensional and hydrodynamic water quality model.

The aim of validation is to verify the model's ability to realistically represent the river. In the hydrodynamic module, the water level was verified at three monitoring stations in the watershed. Details see Supplementary material (Section 2). The observed water level in November 2016 during rainfall days were used to validate the model. Even though the observed data were discontinuous, the river indicators we obtained were often under short duration rainfall so it has little effect on the evaluation of the accuracy of the model. Results of the validation indicate



**Fig. 4.** Schematic figure of coupled quantitative models.

that the mean error of each monitoring station is <10% and the Nash-Sutcliffe Efficiency (NSE) of each monitoring station is greater than which proved that this model can be served as a computational platform for the further study (Nash and Sutcliffe, 1970).

2.2.4. *Sponge City alternatives*

To formulate different alternatives, the suitable measures including permeable pavement and sunken greenbelt are identified based on local Sponge City planning guideline. The following alternatives are formulated for further evaluation with respect to various criteria and sub criteria to select the optimal alternative.

- (1) Alternative 1: Base/status quo

The alternative 1 represents the condition of the case study before Sponge City implementation. Under this condition, the buildings and roads were all built completely so it was highly urbanized just as the land use map showed. We assume that the drainage structure remains the same for all scenarios apart from the Sponge City implementation.

- (2) Alternatives 2: pilot projects planning

Under this alternative, the LID facilities were implemented based on the design standards of LID projects settled down in the Ad hoc Plan of Sponge City Construction (Suzhou Municipal Government, 2017). There are 13 pilot projects in study area. Permeable pavement and sunken greenbelt are built in road and green space area, respectively. The required percentage of permeable pavement and sunken greenbelt on various land uses were provided in the Supplementary material (Section 3).

Permeable pavement ratio corresponds to permeable pavement. Bio-retention cell was used to represent sunken greenbelt. Based on the requirements of permeable pavement ratio and sunken greenbelt ratio of study area, the construction area of permeable pavement and sunken greenbelt were calculated:

$$A_{bioretention\ cell} = A_{catchment\ area} \times R_{green} \times R_{sunken\ greenbelt} \tag{4}$$

$$A_{permeable\ pavement} = A_{catchment\ area} \times R_{road} \times R_{permeable\ pavement} \tag{5}$$

where  $A_{catchment\ area}$ ,  $A_{bioretention\ cell}$ , and  $A_{permeable\ pavement}$  represent the area of sub-catchment area, bioretention cell and permeable pavement implement.  $R_{green}$ ,  $R_{road}$ ,  $R_{sunken\ greenbelt}$  and  $R_{permeable\ pavement}$  are equal to the green space ratio, road ratio, sunken greenbelt ratio and permeable pavement ratio of each sub-catchment area.

- (3) Alternative 3: pilot projects + sunken greenbelt provided for 5% green space in the sub-catchments remained
- (4) Alternative 4: pilot projects + permeable pavement provided for 5% road area in the sub-catchments remained
- (5) Alternative 5: pilot projects + permeable pavement provided for 5% road area and sunken greenbelt provided for 5% green space in the sub-catchments remained
- (6) Alternative 6: pilot projects + permeable pavement provided for 10% road area and sunken greenbelt provided for 5% green space

in the sub-catchments remained

- (7) Alternative 7: pilot projects + permeable pavement provided for 5% road area and sunken greenbelt provided for 10% green space in the sub-catchments remained
- (8) Alternative 8: pilot projects + permeable pavement provided for 10% road area and sunken greenbelt provided for 10% green space in the sub-catchments remained (Table 2)

3. Results and discussion

3.1. Results of the TOPSIS assessment

Based on the proposed integrated assessment framework, the Sponge City alternatives were ranked using TOPSIS. Given to the design requirement of local drainage systems, 2 h design rainfall event under the 3-year return period was used to assess the river storage depth and pollutant concentration. We supposed that four indicators have equal weight. The results in Table 3 show that alternative 8 (with a score of 1) is selected as the optimal solution. It can be concluded that the performance of Sponge City facilities increases with a larger implement scale. Under alternative 8, by implementing a large number of LID practices in series at a watershed scale, the effectiveness of LID practices on hydrology and water quality became discernible. The indicator score of the non-LID alternative was 0, which suggests that all LID alternatives produce positive effects on the considered impact categories. This result is in accordance with the literature that permeable pavement and sunken greenbelt were effective in reducing runoff and nutrients (Liu et al., 2019; Mahmoud et al., 2019; Razzaghamanesh and Borst, 2019; Xiong et al., 2019). By comparing the alternative 3 (with a score of 0.5518) and alternative 4 (with a score of 0.5646) (or alternative 6 and alternative 7), which added the conversion of 5% of road areas to permeable pavement and 5% of green areas to sunken greenbelt, respectively, it indicates that permeable pavement performs better than sunken greenbelt with same added proportion. This was likely due to the runoff and pollutant control efficiency of the permeable pavement being greater than that of the sunken greenbelt in this study area. The effects of LID facilities may vary under different region features including land uses and soil properties of implement area, which is in accordance with the literature (Liu et al., 2016). It also suggests that design guidelines for different catchments should be tailored to their natural and drainage characteristics. For further analysis, alternative-1, -2, -8 were selected as the typical alternatives due to they represent non-LID, pilot project and whole area implement.

3.2. Annual rainfall time series simulation results

According to the indicators definition of  $VCR_a$  and annual pollutant reduction, annual rainfall time series are used to simulate the cumulative effects of successive storm (Thorkild Hvitved-Jacobsen, 1988). Rainfall data from 2015 to 2017 were used to conduct the long-term effect of runoff quantity and quality control in this study. The land-based water quantity and quality indicators were obtained to explore how much difference does the construction of LID facilities have for the environmental benefits in the study area.

Table 2 Alternatives for comparison.

Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8
Base status	Pilot projects	Pilot projects +5% sunken greenbelt	Pilot projects +5% permeable pavement	Pilot projects +5% permeable pavement+5% sunken greenbelt	Pilot projects +10% permeable pavement+5% sunken greenbelt	Pilot projects +5% permeable pavement +10% sunken greenbelt	Pilot projects +10% permeable pavement+10% sunken greenbelt

**Table 3**  
Results of ranking after applying TOPSIS method.

Alternatives	Score	Rank
A1	0	8
A2	0.2462	7
A3	0.5518	6
A4	0.5646	5
A5	0.8462	4
A6	0.9095	2
A7	0.9001	3
A8	1.0000	1

### 3.2.1. $VCR_a$

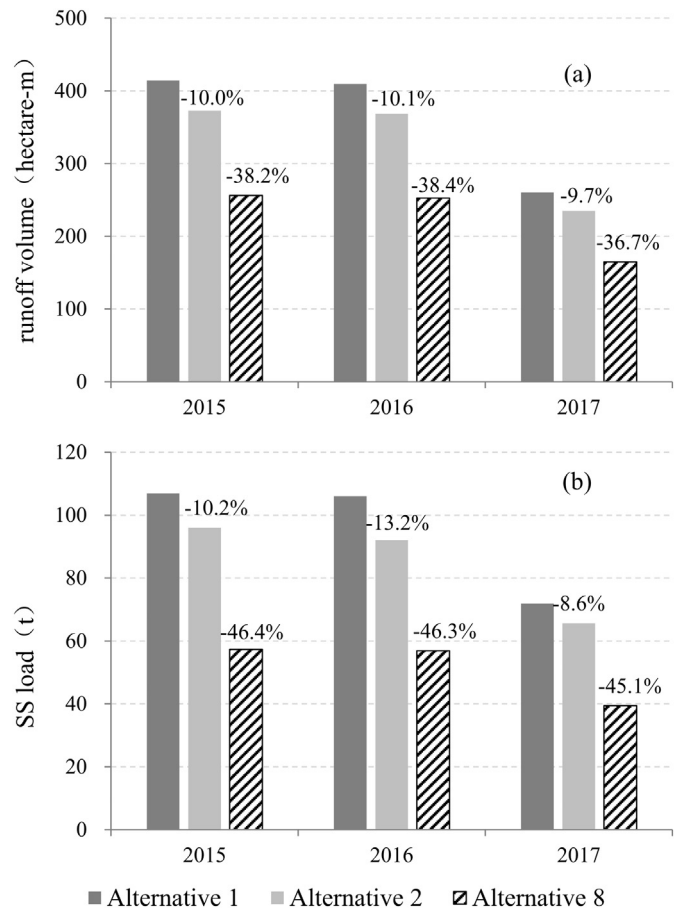
The annual rainfall volume, annual flow volume and the calculation results of  $VCR_a$  from 2015 to 2017 under different alternatives are shown in Table 4. Model results indicate that without any additional LID interventions, only an average 43.8% rainfall runoff is retained in the catchments. This is a rather low  $VCR_a$  due to highly urbanization of the study area. Under alternative 2, the  $VCR_a$  had an average value of 49.4% while 65% under alternative 8. With LID implementation according to pilot project planning, an average of 49.4% of rainfall is retained and the value is 65% with permeable pavement provided for 10% roads and sunken greenbelt provided for 10% green areas in other catchments. Although all levels of LID implementation increased the  $VCR_a$ , the relative largest increase occurs from the alternative 2 to alternative 8 (15.6% more than alternative 2). The LID coverage from alternative 1 to alternative 2 increases the  $VCR_a$  from 43.8% to 49.4% which is relatively mild. Firstly, these results indicate that as the amount of LID is increased there are increasing returns (at least in terms of  $VCR_a$ ). The results also highlight that enlarging the LID scale to whole area can provide a significant amount of annual rainfall retention within the catchment.

The runoff control performance of different LID alternatives under annual rainfall simulation is compared in Fig. 5(a). The percentage value above each bar represents the reduction percentage of the corresponding alternative compared to alternative 1 (base status). The higher percentage (the shorter bar), the better performance. Under alternative 2, compared to those under alternative 1, runoff volume was reduced by 9.7%–10.0%, respectively. Under alternative 8, runoff volume was reduced by 36.7%–38.4%, significantly superior to other alternatives. The results in Fig. 5(a) demonstrate that the reduction of runoff volume will be increased with larger scale of LID facilities.

The results of  $VCR_a$  and runoff volume reduction convey that the performance of LID facilities depend on their amount and scale. Randall et al. (2019) investigated the effect of different place proportion for LID facilities on runoff control performance. They found that the 'High-LID' scenario which had the conversion of 60% of roof area to green roof, 70% of road areas to permeable pavement and 20% of green areas to rain garden could increase the baseline volume capture ratio from 59.9% to 88.7%, which supported that the performance of LID facilities increases with larger LID amount. However, the performance discrepancy comes from the spatial distribution of LID were not fully explored. Therefore, the findings in this research are instructive to LID planning for the reason that the scale of LID facilities could exert

**Table 4**  
Water quantity simulation results under alternative 1, 2, 8.

Indicators	Rainfall volume (hectare-m)			Annual flow volume (hectare-m)			$VCR_a$ (%)
	2015	2016	2017	2015	2016	2017	
Alternative 1	736.6	716.9	471.8	414.4	409.7	260.3	43.8
Alternative 2	736.6	716.9	471.8	372.8	368.5	235.1	49.4
Alternative 8	736.6	716.9	471.8	256.2	252.5	164.8	65.0



**Fig. 5.** The runoff volume and SS load simulation results during 2015–2017.

profound influence on the system running apart from the amount in actual practice.

### 3.2.2. Annual pollutant load reduction

The pollutant control performance of different LID alternatives under annual rainfall simulation is compared in Fig. 5(b). These results showed that the two alternatives with LID can effectively control pollutant loads which are similar with the previous research (Ahiablame et al., 2013; Baek et al., 2015; Liu et al., 2016; Roy et al., 2008). Under alternative 2, SS load were reduced by 8.6%–13.2%, respectively, compared to those under alternative 1, while 45.1%–46.3% reduction under alternative 8. For the pollutant control performance, the basic regularities keep nearly the same as the runoff control. The annual SS load reduction under alternative 8 was relatively high compared with alternative 2 because it has larger scale of LID implement. The annual SS load reduction increases from 10.7% to 45.9% when covert 10% of road areas to permeable pavement and 10% of green areas to sunken greenbelt apart from existing pilot project. Therefore, the effectiveness of Sponge City construction can be improved by increase the implement scale within a sufficient budget (Lee et al., 2012; Maringanti et al., 2009; Rodriguez et al., 2011).

### 3.3. 2hr-Design rainfall simulation results

For the analysis of rainfall runoff control and river environment improvement performance of Spongy City construction, alternatives were simulated using coupled model to evaluate the effectiveness under 2hr-design rainfall events. The performance of green-grey-blue system under varieties of rainfall events was significantly different due to different rainfall characteristics. For the purpose of evaluating the system ability when facing climate driven extreme events, it is necessary to



analysis considering different return periods (Fortunato et al., 2014; Qin et al., 2013). In this paper, 1-, 3-, 5-, 10-year were used for simulation. Then indicator values are obtained for later analysis.

### (1) Runoff volume reduction

The runoff control performance of different LID alternatives under different rainfall return periods is compared in Fig. 6(a). Under alternative 2, the runoff volume of 1, 3, 5, 10-year return period were reduced by 8.7%, 7.4%, 6.8%, 6.0%, respectively, compared to those under alternative 1. Under alternative 8, the runoff volume of 1, 3, 5, 10-year return period were reduced by about 31.1%, 24.6%, 22.3%, 19.6%, respectively. By converting 10% of road areas to permeable pavement and 10% of green areas to sunken greenbelt apart from existing pilot project, the runoff volume reduction of 1, 3, 5, 10-year return period were increased by about 257.5%, 232.4%, 227.9%, 226.7%. Firstly, these results demonstrate the runoff control ability of LID facilities under designed rainfall events. These results also suggest that the runoff control effect of LID construction in whole area is better than that of local area which has the similar regularities as the annual rainfall simulation results.

It should be mentioned that runoff volume was reduced by 31.1% for alternative 8 compared to alternative 1 under 1-year return period, which is significantly superior to other return periods. Previous studies have reported that the runoff control effects were greater for relative small and frequent rainfall events (Damodaram et al., 2010, Holman-Dodds et al., 2003, Hood et al., 2007). This regularity can be obtained from Fig. 6(a), which shows that the increase of return periods could result in decrease in LID control effect.

### (2) Pollutant loads reduction

The pollutant control performance of different LID alternatives under different rainfall return periods is compared in Fig. 6(b). Compared to the alternative 1, the SS loads were reduced by about 10%

under alternative 2, while 40% under alternative 8. By converting 10% of road areas to permeable pavement and 10% of green areas to sunken greenbelt apart from existing pilot project, the SS load reduction of 1, 3, 5, 10-year return period were increased by about 313.2%, 308.7%, 310%, 310.4%. This demonstrates that the effect of LID facilities on pollutant control can be improved by increasing their scale.

Even though plenty of researches have been conducted to the LID facilities runoff control performance under different rainfall characteristics by using varieties of models, but studies on water quality improvement were lacking. The SS load of different return periods are shown in Fig. 6(b). It can be seen that 1-year return period takes the best which means the pollutant control performance of LID facilities performs better when rainfall is small. Besides, the results indicate that the total pollutant loads increase as rainfall intensity increases which is the consequence of aggravated runoff scour.

### (3) Water level results

Six grids in Xi Shi Qu river, Pin Men river and Xie He river were selected to analysis the river water level and water quality (Fig. 7), among which the grids 1, 3, 5 were near the rainwater outlet while the grids 2, 4, 6 were >100 m away from rainwater outlet. Therefore, it is possible to observe how the runoff affects the river grids both near the outlet and far away from the outlet.

The water level change curves in analysis grids are shown in Fig. 8, which are basically in the same trend. With the peak rainfall in 45 min, the water level rapidly rises during 40–45 min and become slowly rising after 120 min and finally become stable after 180 min. Under 1-year return period, the peak water level is <3.3 m while it is above 3.4 m under 10-year return period. It indicates that the increase of return period could results in the increase in peak water level. It could be explained that high intensity rainfall results in large amount of runoff which discharge into rivers. The result also suggests that peak water level could be effectively mitigated by implementing LID facilities. Rising height of water level under different return periods are shown in Table 5. Under alternative 1, drainage requirements can be met when return period is 1 year. However, pump station needs to be opened to discharge water under other return periods. Compared to alternative 1, LID facilities can decrease the rising height of water level. Under alternative 2, drainage requirements can be met when return periods are 1 and 3 year. Under alternative 8, drainage requirements can be met when return periods are 1, 3 and 5 year. It can be concluded that the watershed has ability to face more extreme rainfall events when implementing larger scale LID facilities. In addition, the water level change curves at grids near the outlets were coincidence with the grids far from outlets. This indicates that there is no significant spatial difference in water level control effect at different locations.

The water level results obtained by coupled model confirm the LID ability to improve river hydrology environment. However, the current research on river hydrology and water quality improvement is mainly restricted to water projects; few researches have been reached on the impact of green infrastructure on river (Campbell et al., 2001; Karr, 1991; LFG et al., 2003; Lowney, 2000). Flood disaster would happen when rising water level is higher than river storage depth. Therefore, the control of river water level plays an important role in flood control. In fact, the Sponge City facilities control the drained land-based runoff which results in a decrease of river water level. Attentions should be focus on the Sponge City facilities effect on river hydrology.

### (4) River water quality results

The NH<sub>3</sub>-N concentration change curves of six grids under different return periods are shown in Fig. 9. It can be concluded that the peak concentration of NH<sub>3</sub>-N appears in 55–60 min in the

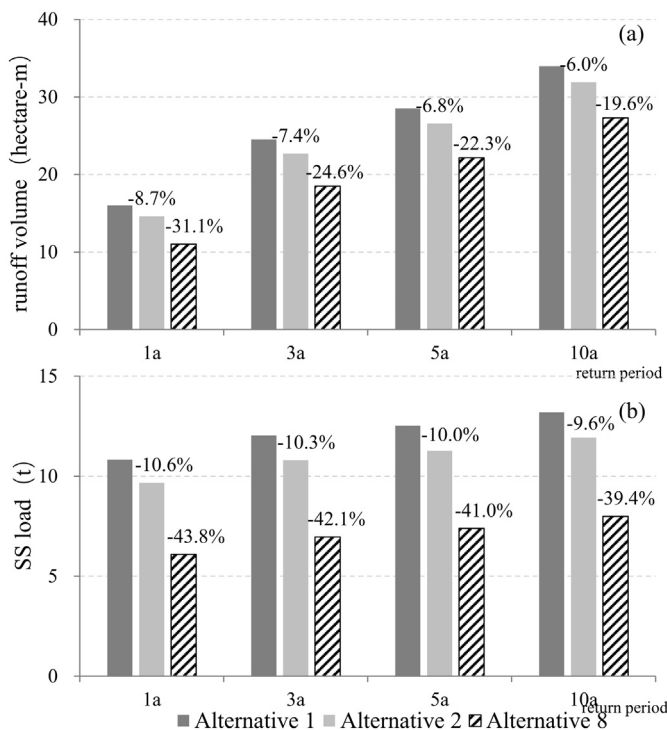


Fig. 6. The runoff volume and SS load simulation results during 2hr designed rainfall under different return periods

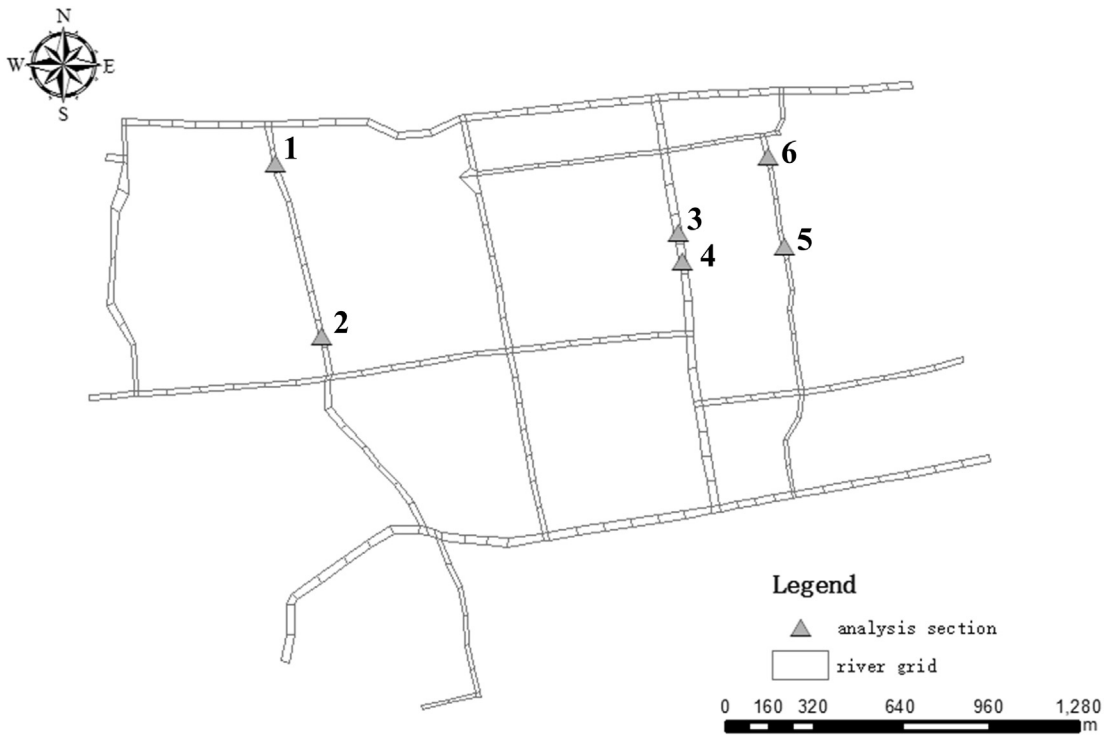


Fig. 7. Analysis grids location.

grids near outlet, then the concentration became stable after 180 min. As for the grids far away from outlet, the  $\text{NH}_3\text{-N}$  peak concentration appeared later. Due to the dilution or mobilization of

contaminants, the  $\text{NH}_3\text{-N}$  peak concentration was much lower than the near one. With the increase of return period, the  $\text{NH}_3\text{-N}$  peak concentration become larger which demonstrates that rainfall

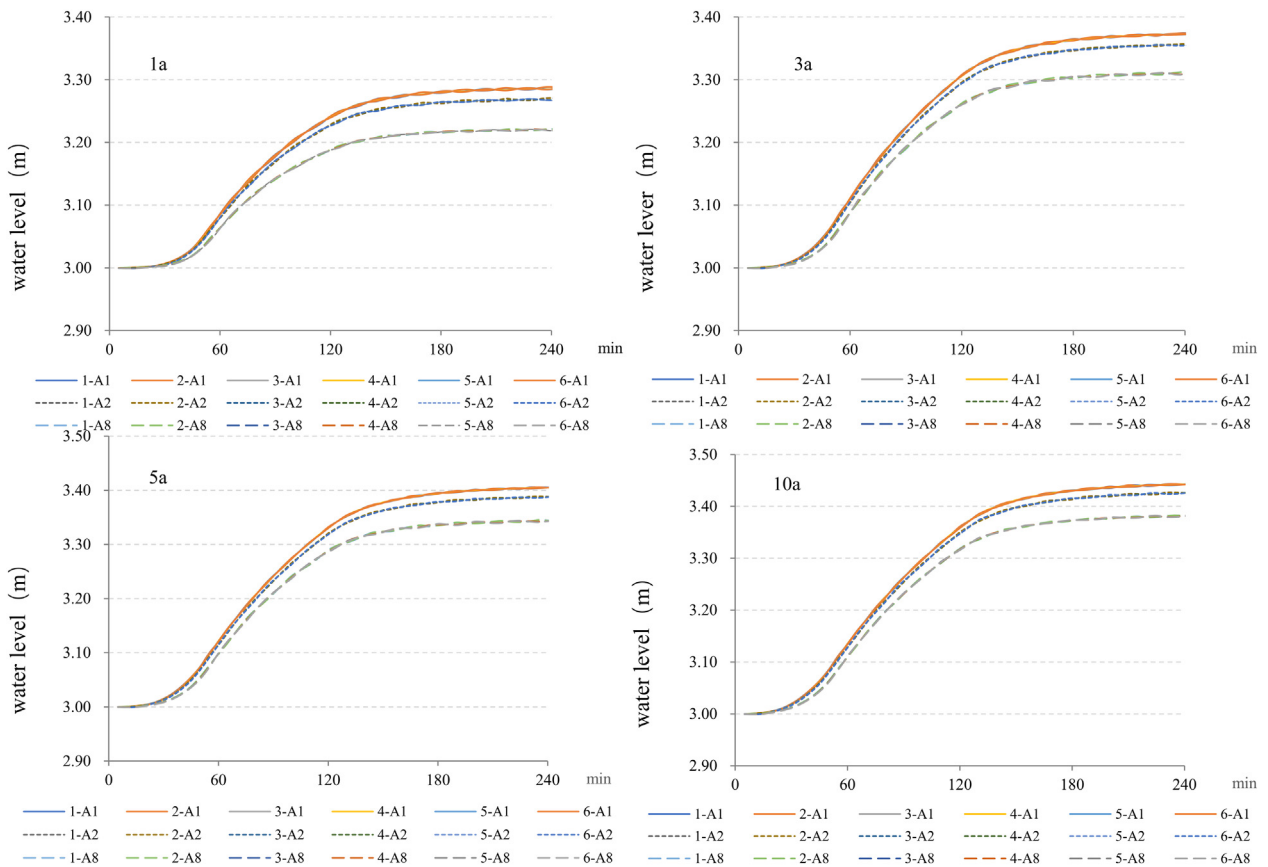


Fig. 8. Water level change curves in analysis grids.

**Table 5**

Rising height of water level (cm) under different return periods.

	1a	3a	5a	10a
Alternative 1	29	37	41	44
Alternative 2	27	35	39	42
Alternative 8	22	31	34	38

characteristics have impacts on changes in water quality (Noble et al., 2003; Wang et al., 2019).

The outflows discharged into receiving water bodies would have a significance influence on spatiotemporal dynamics of water quality indicators in the river (Kimmerer, 2002; Sklar and Browder, 1998). The control of surface pollutant load would improve the river water environment. Examining the Sponge City facilities implement responses to river water quality should not be ignored. It can be seen from Fig. 9 that the NH<sub>3</sub>-N peak concentration are decreased under LID alternatives. Taking grid 5 and 6 as example, under alternative 1, the NH<sub>3</sub>-N peak concentration are 1.93 mg/L, 2 mg/L, 2.02 mg/L, 2.01 mg/L under 1, 3, 5, 10 year return period in grid 5 while 1.58 mg/L, 1.57 mg/L, 1.56 mg/L and 1.56 mg/L in grid 6. Under alternative 2, the NH<sub>3</sub>-N peak concentration are decreased by 4.7%, 5.0%, 5.0%, 4.0% under 1, 3, 5, 10-year return period in grid 5 while 1.9%, 1.3%, 1.3%, 1.3% in grid 6. Under alternative 8, the NH<sub>3</sub>-N peak concentration are decreased by 10.9%, 12.5%, 12.9%, 12.4% under 1, 3, 5, 10-year return period in grid 5 while 3.2%, 7.9%, 2.6%, 2.6% in grid 6. The results demonstrate that LID facilities have a positive effect on river water quality. Besides, the pollutant control effect performs well with the increasing of LID implement

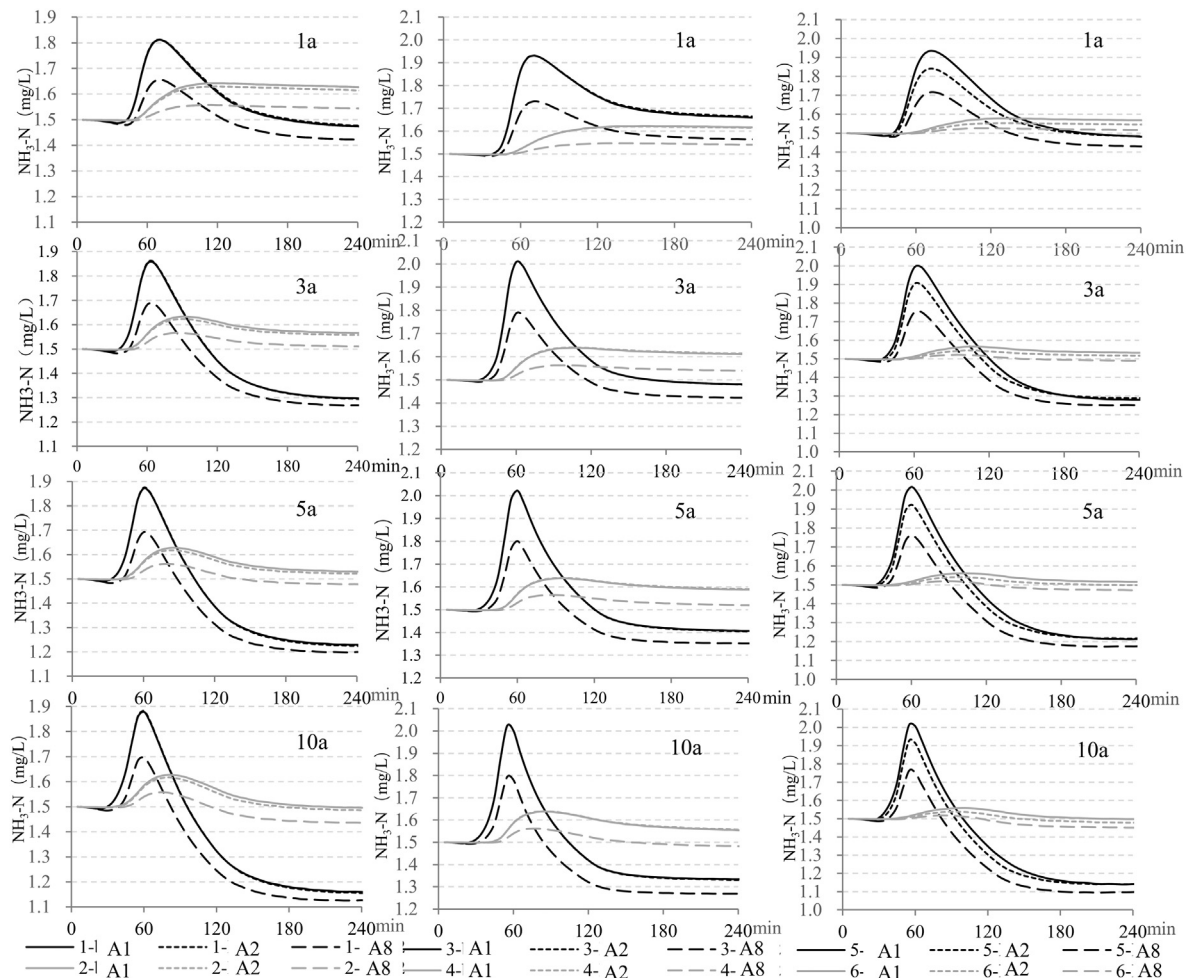
scale. It should be mentioned that besides grid 5 and 6, the alternative 2 cannot improve the water quality which can be inferred that although LID implement for some catchment can improve the water quality of local rivers, it has limited effect on the improvement of the whole river water environment.

3.4. Evaluation of LID effects on rivers

It is of significant that the close quantitative correlations exist between the indicators of green-grey-blue system. It can be known that the LID facilities have positive effect on the surface runoff and pollutants control. Besides the pollutants discharged into river affect the river water quality directly, it is significantly influenced by the runoff discharged from land-based area which dilutes the pollutant concentration (Zhang et al., 2009). To determine the contribution of NH<sub>3</sub>-N load control and runoff volume control to the response of river NH<sub>3</sub>-N concentration, describe different mechanisms and driving factors influencing changes of water quality, a linear regression-based approach was applied in this study. The liner regression model was used to solve the problem like whether the reduction of surface runoff and pollutants is linked to the decrease of the pollutant concentration in the receiving water body.

Given to alternative 8 can improve the water quality of surface runoff in whole study area. This was given as an example in the model simulation. The liner regression model was then constructed as below:

$$Y_j = \alpha_{j1}X_{j1} + \beta_{j2}X_{j2} + \delta_j + \varepsilon_j, \varepsilon_j \sim N(0, \sigma_j^2) \tag{6}$$



**Fig. 9.** NH<sub>3</sub>-N concentration change curve of six sections under different return periods.

**Table 6**  
Linear regression coefficients of different variable.

Response variables			$\delta_j$	$\alpha_{j1}$	$\beta_{j2}$
$j = 1$	Near outfall	Peak NH <sub>3</sub> -N	2.051	-1.632	0.186
$j = 2$		Mean NH <sub>3</sub> -N	1.230	-1.807	0.068
$j = 3$	Remote outfall	Peak NH <sub>3</sub> -N	1.538	-1.044	0.036
$j = 4$		Mean NH <sub>3</sub> -N	1.382	-1.356	0.355

where  $Y_j$  are the response variables, i.e. river NH<sub>3</sub>-N concentration ( $j = 1, 2, 3, 4$ );  $X_{j1}, X_{j2}$  are explanatory variables,  $X_{j1}$  are the reduction of NH<sub>3</sub>-N load,  $X_{j2}$  are the reduction of runoff volume;  $\alpha_{j1}, \beta_{j2}$  are the regression coefficients of each explanatory variable;  $\delta_j$  are the intercepts; and  $\varepsilon_j$  are the random terms of each regression equation, which should be normally distributed with a mean 0 and variance  $\sigma_j$ .

The linear regression analysis results were shown in Table 6. The model results showed that for any  $j$ ,  $|\alpha_{j1}| \gg |\beta_{j2}|$ . The results demonstrate that the control of surface NH<sub>3</sub>-N load has negative effect while the control of runoff volume has positive effect on NH<sub>3</sub>-N concentration in the river. In addition, it can be inferred that the reduction of surface NH<sub>3</sub>-N load had a greater effect on river water quality compared to reduction of surface runoff. From this result, it can be concluded that though the surface runoff dilution effect had effect on the river water quality, the control of surface pollutants can play a more significant role in the river water quality improvement. The construction of Sponge City will improve the river water environment but the key is pollutant control. This conclusion is important to understand the river water environment improvement by Sponge City construction.

3.5. Integrated performance assessment results of green-grey-blue system

According to the framework, it is important to determine whether the assessment indicators value meet the Sponge City goal after ranking varies alternatives (See Table 7). The evaluation of typical alternatives (alternative 1, 2, 8) based on their water quantity and quality indicators corresponding with Table 1. For land-based indicators, the alternative 1 and alternative 2 with VCR<sub>a</sub> of 43.8 and 49.3%, respectively, did not reach the local target of 65%. With the VCR<sub>a</sub> of 65%, only the alternative 8 result lies within the target range. The alternative 2 with annual SS load reduction of 10.9% also did not reach the local target of 45% while alternative 8 result lies within the target range with the annual SS load reduction of 46%. For river storage depth, local requirements of 35 cm can be met when return period is 1 year under alternative 1. Under alternative 2, local requirements can be met when return period are 1 and 3 year. Under alternative 8, local requirements can be met when return period is 1, 3 and 5 year which has ability to face more

extreme rainfall events. These results demonstrate that the system is of much resilience with the increasing scale of LID facilities. Although the river water quality can meet the requirement under each alternative, the water quality is better under alternative 8. It can be concluded that alternative 8 can meet the local Sponge City construction requirement mostly when compared with alternative 2. Overall, in terms of providing maximum environment benefits for whole urban water environment, alternative 8 was considered the desirable Sponge City solutions to be applied to the study area. Firstly, the results indicate that Sponge City goals can be met within the case study area with realistic levels of LID implementation. The results also demonstrate that the larger scale implement of Sponge facilities can meet hydrologic and water quality management objectives better than the local implement. This study provides a decision-making basis for future planning in the study area.

The proposed integrated assessment framework enables a decision maker to select the most appropriate scheme without bias or subjectivity. The framework is original and different from the former relative researches. Most studies have assessed Sponge City performance using only land-based indicators (i.e. VCR<sub>a</sub>, runoff volume reduction, pollutant load reduction) (Casal-Campos et al., 2015; Her et al., 2017; Joyce et al., 2018; Li et al., 2019; Wang et al., 2018; Wang et al., 2017a). Nevertheless, only part of the green-grey-blue performance can be reflected in this case and the potential conflicting relationship among different aspects of system performance may be ignored. Our research expands the assessment boundary of Sponge City construction by considering the receiving water body response. The performance of Sponge City construction is evaluated by various indicators corresponding to different parts of green-grey-blue system. It is confirmed that assessing performance based on only part of the system will inadequately reflect the comprehensive benefit of Sponge City. For example, a major finding of this research is that the construction of Sponge City can achieve respectable comprehensive performance both in rainfall runoff control and river water environment improvement. It is necessary to take a holistic perspective of Sponge City environmental benefits in green-grey-blue system and provides a foundation to achieve the integrated management and sustainability of urban water environment. The approach represents a shift toward such an integrated assessment through an evaluation of different parts of green-grey-blue system, which can be transferred to other regions to conduct similar research.

Previous research related to Sponge City performance assessment focused on evaluation of runoff control effects with and without Sponge City facilities. Here, a coupled model is imperative to obtain the indicators of different parts of green-grey-blue system for an integrated assessment. To the best of our knowledge, this study is the first to assess Sponge City performance with a coupled model which consists of

**Table 7**  
Integrated performance assessment results under different Sponge City scenarios.

Rainfall conditions	Control objectives	Target value	Alternative 1		Alternative 2		Alternative 8			
			Simulation value	Assessment result	Simulation value	Assessment result	Simulation value	Assessment result		
Annual rainfall time series	VCR <sub>a</sub>	65%	43.8%	×	49.3%	×	65.0%	√		
	Pollutants load reduction (SS)	45%			10.9%	×	46.0%	√		
	River storage capacity	1-yr	35 cm	29	√	27	√	22	√	
		3-yr		37	×	35	√	31	√	
		5-yr		41	×	39	×	34	√	
		10-yr		44	×	42	×	48	×	
2 h rainfall under different return periods	Peak pollutants concentration (NH <sub>3</sub> -N)	1-yr	1.48 mg/L	√	1.48 mg/L	√	1.44 mg/L	√		
		3-yr	Grid	1.39 mg/L	√	1.39 mg/L	√	1.36 mg/L	√	
		5-yr	1	1.35 mg/L	√	1.35 mg/L	√	1.32 mg/L	√	
		10-yr	1.5	1.31 mg/L	√	1.31 mg/L	√	1.28 mg/L	√	
			1-yr	mg/L	1.49 mg/L	√	1.48 mg/L	√	1.45 mg/L	√
			3-yr	Grid	1.39 mg/L	√	1.39 mg/L	√	1.36 mg/L	√
			5-yr	5	1.36 mg/L	√	1.35 mg/L	√	1.32 mg/L	√
			10-yr		1.32 mg/L	√	1.31 mg/L	√	1.28 mg/L	√

‘×’ represents the result did not meet the control subjects; ‘√’ represents the result meet the control subjects.

SWMM and EFDC models. In particular, the land-based indicators (i.e.  $VCR_a$ ) can be obtained by the output data of SWMM model. The output data of SWMM is used as the input data of EFDC model which can represent the process that rainfall runoff flow into the river through the outlets. The river-based indicators (i.e. river storage depth) can be obtained by the output data of EFDC model. The rainfall runoff control effect and river water environment improvement of Sponge City can be combined using the coupled model.

#### 4. Conclusions

In this paper, a decision-support integrated framework considering both rainfall runoff control and river environment improvement has been developed to evaluate the effectiveness of different Sponge City planning options. This is an improvement from previous studies in which only urban drainage-based water quantity and quality control effects is investigated. A coupled model was used to quantify the performance of various LID alternatives. Based on that, a case study in China was presented. Paper results suggest that Sponge City can have positive effect on rainfall runoff control and river water environment improvement. In addition, the performance increases with larger scale deployment under small rainfall events. The desirable Sponge City solution obtained from the proposed performance assessment system can be specific to each region due to local-specific project goals and site conditions. The integrated assessment framework can provide insights into ways to take account into the comprehensive benefits of Sponge City constructions and can also be applied to optimal selection and performance effect assessment of LID facilities in other Sponge City projects.

#### 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.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.138608>.

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