

# Comprehensive Benefit Evaluation System for Low-Impact Development of Urban Stormwater Management Measures

Jiake Li<sup>1</sup> · Chenning Deng<sup>1</sup> · Ya Li<sup>2</sup> · Yajiao Li<sup>3</sup> · Jinxi Song<sup>4</sup>

Received: 6 August 2016 / Accepted: 19 July 2017 /  
Published online: 25 July 2017  
© Springer Science+Business Media B.V. 2017

**Abstract** In recent years, plenty of simulation research about the low impact development(LID) control effect has emerged, but studies on scheme comparison and evaluation are lacking. In this study, a comprehensive benefit evaluation system for LID, including environmental, economic, and social benefits, was established on the basis of Analytic Hierarchy Process(AHP) and urban storm water model. Above all, benefit identification, quantitative evaluation and scheme comparison of single LID measures were obtained according to site investigation, simulated calculation and theoretical analysis. Whereafter, LID combination plans were designed based on single LID measures with high comprehensive benefit values, and their comprehensive benefits were evaluated to obtain the optimal plan. Then, based on well-founded system combined with Storm Water Management Model (SWMM), the design and optimization of LID were conducted, with a case in Xi'an, China. It turned out that the preferential order of the LID single measures according to the comprehensive benefit was: bio-retention > rain barrels > low-elevation greenbelt > green roofs > permeable pavement. Five LID combination plans were designed based on bio-retention, rain barrels, low-elevation greenbelt, and green roofs. Evaluation results showed that plan I (bio-retention and green roofs) was the optimal LID combination plan.

**Keywords** LID · Comprehensive benefit · Analytic hierarchy process · SWMM

---

✉ Jiake Li  
xaut\_ljk@163.com

<sup>1</sup> State Key Laboratory Base of Eco-Hydraulic Engineering in Arid Area, Xi'an University of Technology, Xi'an 710048, China

<sup>2</sup> Urban Planning and Design Institute of Shenzhen, Shenzhen 518028, China

<sup>3</sup> School of Architecture and Civil Engineering, Xi'an University of Science and Technology, Xi'an 710054, China

<sup>4</sup> College of Urban and Environmental Sciences, Northwest University, Xi'an 710027, China

## 1 Introduction

In recent years, global climate change and urbanization development has prompted great changes in hydrology environment. And, flood control, non-point source pollution control and comprehensive utilization of water resources are facing new challenges. Low impact development(LID) has been used in many countries as a new strategy for urban water environmental protection and sustainable storm water management which was proposed by Prince George's County in the 1990s (Davis et al. 2012; Winston et al. 2016). LID is an effective tool used to manage stormwater at the source with decentralized micro-scale control measures (Liu et al. 2016). Currently, bio-retention, rain gardens, green roofs, vegetation swales, permeable pavements, low-elevation greenbelts, and rain barrels are considered main LID measures. The control effect of LID measures were compared through Storm Water Management Model(SWMM) simulation (Baek et al. 2015; Villarreal and Annette 2004; Katherine et al. 2010). Moreover, the LIDs' areas and locations were determined on the basis of simulation results (Ghodsi et al. 2016).

However, there are plenty of studies about LID effect simulation except LID plan comparison and benefit evaluation. **Optimal selection** of LID combination plans is of great importance in the design and construction of a new city (Jia et al. 2015). The lack of studies in this field has done lots of problems which resulted in a slower adoption rate for LID. Therefore, it is a task that brooks no delay to creatively establish a comprehensive benefit evaluation system for LID on the basis of site investigation, theoretical analysis and simulated calculation. The system should take LID measure design as the principal thing combining with environmental benefit, economic benefit, social benefit and other controls, and provides optimal selection of LID plan in design philosophy, evaluation system and plan optimization. Through these the design manager is able to fully comprehend the comprehensive benefit of LID, and change the thought of storm water Management. And then, the difficulty of LID popularization will be overcome.

This study aims to: (1) establish an evaluation system for comprehensive benefit of LID single measures and LID combination plans based on analytic hierarchy process (AHP); (2) apply a paradigm of the Chan River in Xi'an city as the study area and obtain the preferential order of LID single measures and LID combination plans according to comprehensive benefits based on the well-founded evaluation system; (3) determine the optimal LID combination plans suitable for local situation and provide a basis for project planning and design of LID combination plans.

## 2 Establishment of an Evaluation System

Based on urban stormwater simulation software (SWMM, InfoWorks-ICM, Mike-Urban.), the comprehensive benefit of LID measures were evaluated combining with AHP. Then, an evaluation system for comprehensive benefit of LID was established.

### 2.1 Regional Assessments of the Study Area

The regional assessments of the study area should be performed before the preliminary design of LID. The corresponding factors of basic situation about the study area should be effectively evaluated according to site investigation; these factors include site condition (the boundary of

site, land use type and Setback Line), terrain topography (slope and exposure), edaphic conditions (soil type and soil infiltration), and hydrological regime (groundwater condition and water distance).

## 2.2 Appropriate LID Measures

Appropriate LID measures were initially set up based on data gathered, which included a covering feasibility, types of measures, and adoptable area for construction after site investigation. Then, an urban stormwater model of the study area was built.

First, feasibility analysis was implemented for the selected LID single measures. The destruction of the study area and the influence of construction on immediate surroundings were synthetically considered. Second, appropriate LID measures were initially set up according to stormwater management targets. Subsequently, the adoptable area was analyzed based on regional assessment results. The structural features and limiting factors of appropriate LID measures were considered. Finally, the control effects of LID measures for runoff volume, peak runoff, and runoff pollution were simulated by building a proper urban stormwater model (Duan et al. 2016).

## 2.3 Comprehensive Benefit of the Selected LID Measures

Based on the above parameters, the comprehensive benefits to select LID measures were evaluated; these benefits include environmental, economic, and social benefits.

### 2.3.1 Environmental Benefit

The bearing pressure of the urban drainage network could be relieved, and the probability of urban waterlogging could be decreased (Cipolla et al. 2016). Simultaneously, the receiving water could be kept away from contamination, and urban non-point pollution would be effectively controlled. In this section, control effects of a single LID measure were quantitatively evaluated based on the urban stormwater model. The main estimation indexes of environmental benefits include runoff volume reduction, peak discharge reduction, flood peak retardation time, and reduction of principal pollutants including suspended solids(SS), chemical oxygen demand(COD), total nitrogen(TN) and total phosphorus(TP).

### 2.3.2 Economic Benefit

Economic benefit was mainly reflected in the following aspects. First, the construction cost of public infrastructure, the public service industry, and site development were decreased. Second, the control cost of combined sewerage overflow and deluge was reduced. Third, the license fees of stormwater discharge were reduced. Finally, the comfort level and land value were promoted. The costs, operating charges, and maintenance fees of civil construction were mainly considered in this study because of lacking relevant information (Chui et al. 2016). Intuitively, the reduction of these three expenses could represent economic benefit. The civil construction cost covers the initial investment (land cost, construction cost, and installation cost), design expenses, and additional charges (cost of site investigation, programs, and design). Operating charges and maintenance fees included the cost of labor, materials, energy, equipment, and cleaning.

### 2.3.3 Social Benefit

Several advantages of LID measures contribute to social benefit. Not only municipal sewage reuse but also rainfall exploitation and utilization are a great way to save high-quality water resources, ease imbalance between water supply and demand, and provide abundant water for the townscape (Aryal et al. 2016). However, the comprehensive utilization of water can maintain the natural hydrological cycle, increase the underwater recharge, regulate climate, alleviate the island effect of urban heat, and provide some habitats for birds and insects. From the public perspective, improved water management could not improve their quality of life and enhance the publicity and awareness of environment protection. In summary, the social benefits of LID measures depend on the utilization of rainwater, the value of the townscape, and its ecological functions in this study.

### 2.3.4 Evaluation Methodology

Given the complexity of evaluation and the lack of quantitative data, multi-objective decisions of environmental, economic, and social benefits were evaluated based on AHP by the software yaahp (Calabrese et al. 2016). The main procedures are presented.

#### (1) Construction of the hierarchical structure model

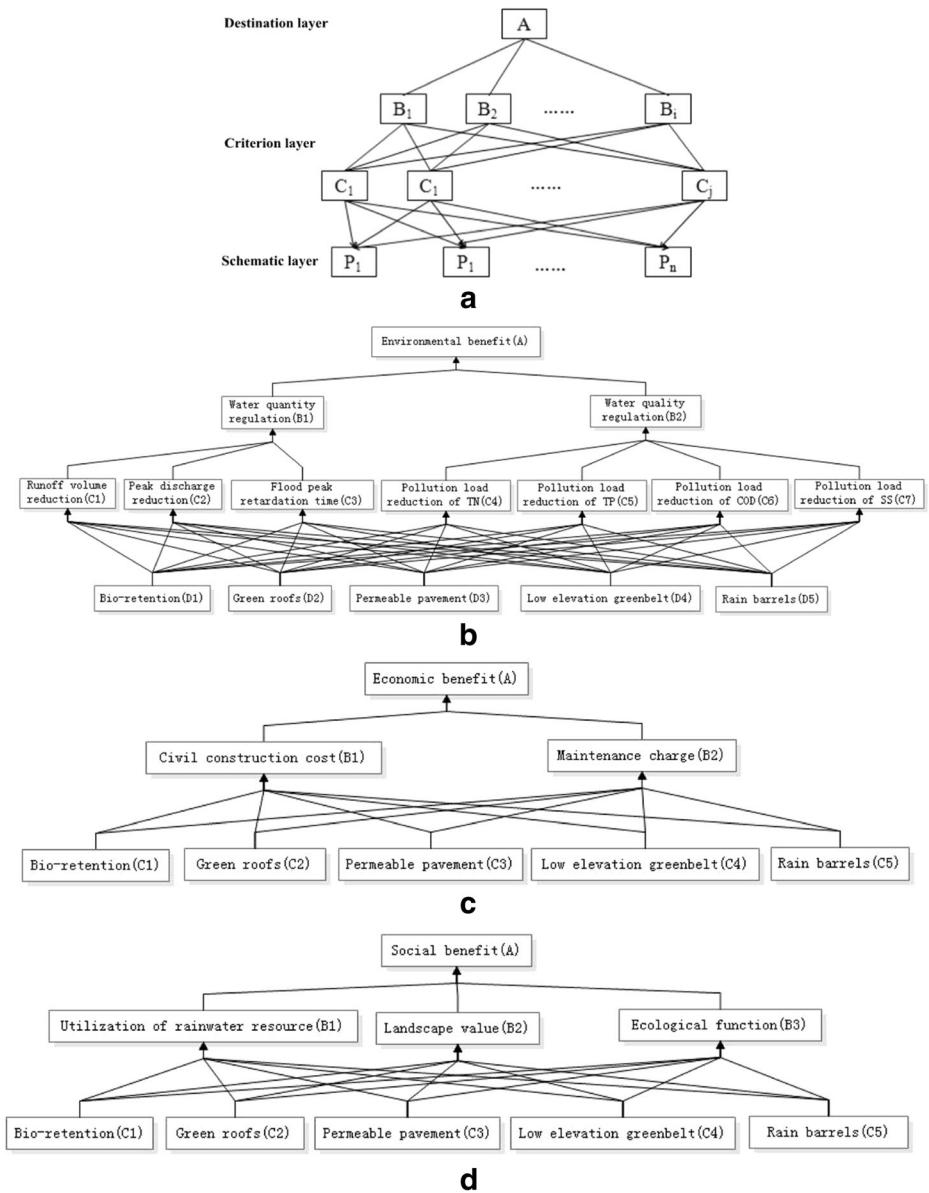
The elements contained in unsolved decision problems were analyzed and aggregated together according to different layers based on their associated impacts and administrative relationship. The hierarchical structure model including a destination layer, several criterion layers, and a schematic layer was constructed (Fig. 1a). The destination layer was the intended target of problem analysis or the ideal result. The criterion layer was composed of various elements, which covered the intermediate steps for achieving the goal. The schematic layer provided various measures or plans to achieve the goal.

#### (2) Construction of the comparison and judgment matrix

At each layer, pairwise comparison of elements was performed with scale quantization. The comparison and judgment matrix was subsequently constructed. Generally, the importance between both elements at the same layer was determined under these guidelines. The degrees of importance are commonly evaluated from 1 to 9 (1 represents that the importance of two elements was equal; 3, 5, 7 and 9 represents that the former is slightly, obviously, strongly and extremely more important than the latter respectively; 2, 4, 6 and 8 are the medians of the above-mentioned adjacent judgments. Of course, if the ratio of the importance between  $i$  and  $j$  was  $a_{ij}$ , then the importance between  $i$  and  $j$  was  $a_{ji} = 1/a_{ij}$ ).

#### (3) Single hierarchical arrangement and consistency check

The single hierarchical arrangement was used to calculate the eigenvector and eigenvalue of the related judgment matrix. That is, the order of weighted values and the vector of relative importance were determined, such that elements at the same layer were affected in some elements at the upper layer. Currently, the proper values with its eigenvector were estimated using [eigenvalue method \(EM\)](#), [square root method](#), sum



**Fig. 1** (a) Hierarchical structure model. Hierarchical model of (b) environmental benefit, (c) economic benefit and (d) social benefit in the study area

and product method (ANC), and **least squares method** (LSM). ANC was used in the present research.

In addition, the logical sense of single hierarchical arrangement could only be proved after the consistency check. The calculation steps were as follows.

First, the consistency index (*CI*) was calculated with the following formula.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (1)$$

Where,  $CI$  is the consistency index (if  $CI = 0$ , the established matrix was a completely consistent matrix; if  $CI$  is close to 0, the consistency of the judging matrix was satisfactory; if the value of  $CI$  is high, the consistency of the judging matrix was worse);  $n$  is the only nonzero characteristic root;  $\lambda_{\max}$  is the maximal eigenvalue of the matrix (the higher is  $\lambda_{\max}$  than  $n$ , the worse is the consistency of the judging matrix).

Second, the random index ( $RI$ ) was determined as shown in follows: when the matrix order are from 1 to 9,  $RI$  are 0, 0, 0.52, 0.89, 1.12, 1.24, 1.32, 1.41 and 1.45 respectively.

Third, the consistency ratio ( $CR$ ) was calculated with the following formula.

$$CR = \frac{CI}{RI} \quad (2)$$

Where,  $CR$  is the consistency ratio;  $CI$  is the consistency index;  $RI$  is the random index.

The consistency check was usually determined by the consistency ratio. When  $CR > 0.1$ , the comparison and judgment matrix did not meet the requirements for consistency. Therefore, the comparison and judgment matrix would be reconstructed. When  $CR < 0.1$ , the preferred consistency of the comparison and judgment matrix was obtained.

#### (4) Hierarchical total ranking and consistency check

The order of weight values was finally determined for the relative importance by which elements at a schematic layer affected some element at the destination layer. The optimal LID combination plan was selected by considering the merits or defects of each plan in terms of various elements. Hierarchical total ranking was conducted by calculating the combination of weigh vectors of each hierarchical element and the objectives, arranging the calculations from top to bottom, and synthesizing them step by step. Consequently, the large weight of the total sorts is considered to be the optimal plan. Finally, checking was performed after hierarchical total ranking in a similar manner as the previous step.

#### 2.3.5 Comprehensive Benefit

Comprehensive benefit was evaluated using weighted sum method based on the evaluation of environmental, economic, and social benefits. The formula of weighted sum method was:

$$Y_i = \sum_{j=1}^n Y_{ij} \quad (3)$$

Where,  $Y_i$  is the comprehensive benefit of the  $i$ th LID measure; and  $Y_{ij}$  is the  $j$ th quantized value of the  $i$ th LID measure.

High calculated value of the comprehensive benefit led to improved performance of the LID measure. Finally, the LID measure with a higher comprehensive benefit was obtained.

## 2.4 Comprehensive Benefit of LID Combination Plans

Various LID combination plans were set in practical projects to prevent the fewness of stormwater management measures (Qin et al. 2013). Therefore, LID single measures with high benefit value were combined into plans. These plans were then evaluated. The evaluation method of the comprehensive benefit was similar between LID single measures and combination plans. The key point was the comprehensive assessment of environmental, economic, and social benefits. Finally, the optimal LID measure for the study area was obtained when combined with the calculated results of the comprehensive benefit. A comprehensive benefit evaluation system for LID of urban stormwater management measures was established based on the above mentioned method (Fig. 2).

## 3 Case Study

### 3.1 Site Description

The area of *Xiyiing Road-Chan River* in Xi'an City was selected as study area. The study area is characterized by East Asian warm temperate continental monsoon climate with four distinctive seasons. Winter and spring are cold and dry by the influence of northwest airflow. Meanwhile, summer and autumn are hot and rainy by the influence of southeast airflow. The extent of the study area is east from *Changtian Road* and *Wanshou Road*, west to *East Second Ring Road*, south from *Xiyiing Road* and *Xianning East Road*, and north to *Changle Road*, with a total catchment area of approximately 802 ha.

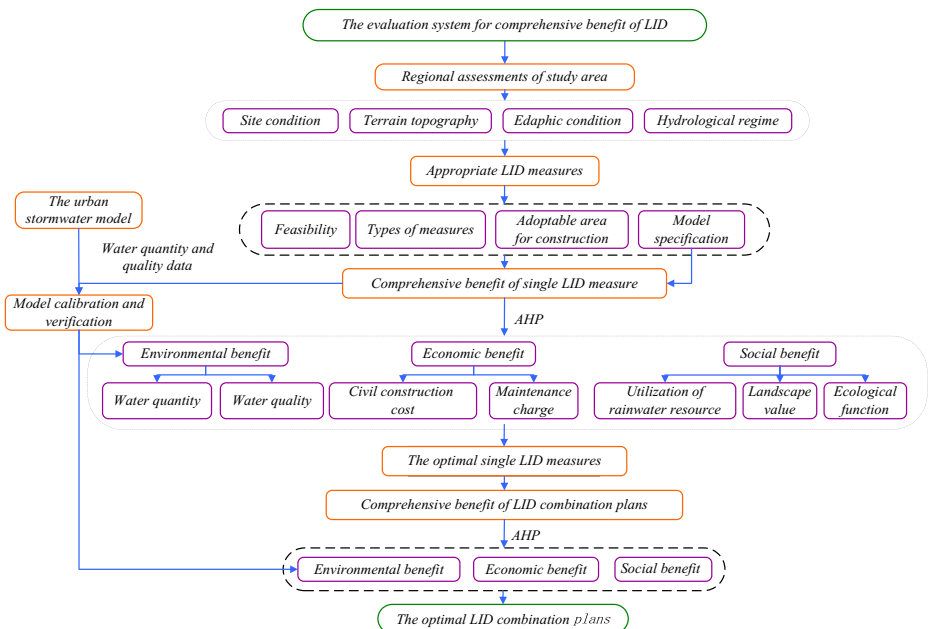


Fig. 2 Comprehensive performance evaluation system of LID measures

## 3.2 Appropriate LID Measures

### 3.2.1 SWMM Model of the Study Area

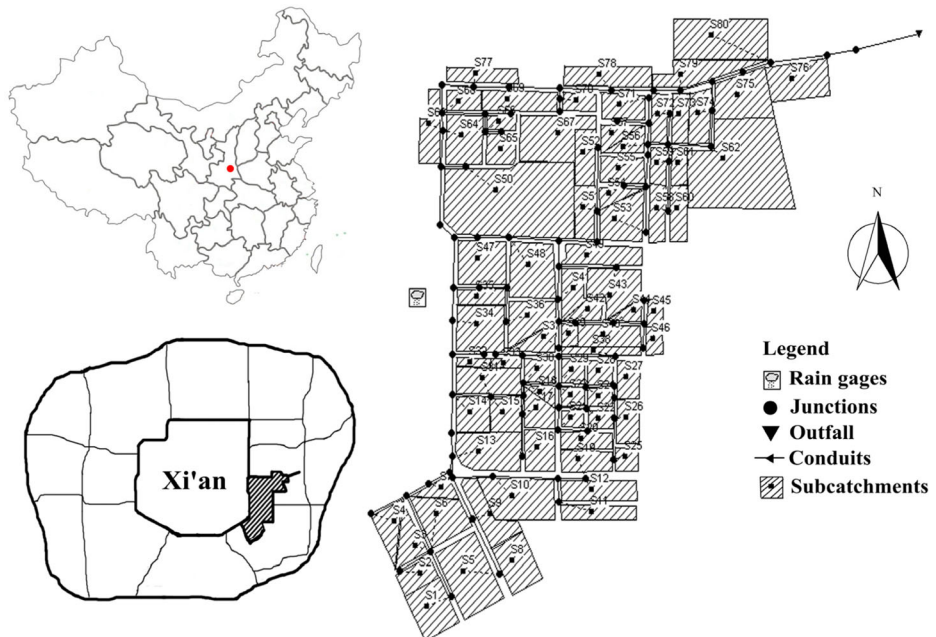
SWMM was selected as the urban stormwater management model in this study because the hydrologic effect, hydraulic characteristics, and water purification could be efficiently simulated in different cases of land utilization (Gironás et al. 2010).

#### (1) Generalization of the study area

In compliance with the principle of generalization, the study area was divided into 80 sub-catchments, 97 conduits, 97 junctions, and 1 outfall according to the topography and rainwater pipe network distribution map of the study area. The division results are shown in Fig. 3. The area of each sub-catchment was between 2.88 and 62 ha. All drainage pipes in the study area were reinforced concrete circular pipes with a pipe diameter between 500 and 2500 mm.

#### (2) Model parameters

On the basis of available data and model principle, the land-use types of the study area were classified as traffic, industrial, commercial, and residential areas. The Horton model was selected to simulate infiltration, and the maximum and minimum infiltration rates were respectively 76 mm/h and 3 mm/h. The nonlinear reservoir model was selected to simulate convergence. The kinematic wave equation and the completely mixed first-order attenuation



**Fig. 3** Generalized map of the study area



equation were selected to simulate water movement in the pipeline transmission system (Li et al. 2016). SWMM model parameters were calibrated and validated according to the synchronous rainfall, water quality and quantity monitoring data of four rainfall processes (20130828, 20131014, 20140613 and 20140830) in the study area. The calibrated values of average slope, N-Imperv(Manning coefficient of impervious surface), N-Perv(Manning coefficient of pervious surface), Dstore-Imperv(Depression storage of impervious surface), Dstore-Perv(Depression storage of pervious surface) and Zero-Imperv(area percentage of no depression storage) are 0.5%, 0.015, 0.1, 0.01 mm, 3 mm and 25% respectively.

### 3.2.2 LID Measures

The study area was built as a flourishing region; thus, LID measures with large areas could not be constructed. Bio-retention, green roof, permeable pavement, low-elevation greenbelt, and rain barrels were selected as appropriate LID measures in this study.

Guideposts of the sponge city and specific conditions of different blocks were considered in area determination of LID measures. The recommended value of the construction area was determined based on the assessment standards of the sponge city including *Engineering Technical Code for Rain Utilization in Building and Sub-district* (GB 50400–2006), *Evaluation Standard of Green Building* (GB 50378–2006), *Engineering Technical Code for Rain Utilization of Shenzhen City* (SZDB/Z 49–2001), and *the Sino-Singapore Tianjin Eco-city Green Building Evaluation Standard*.

## 3.3 Comprehensive Benefit of Select LID Measures

The comprehensive benefits of LID single measures were evaluated according to their environmental, economic, and social benefits.

### 3.3.1 Environmental Benefit

Given bio-retention as an example, the conditions of outflow volume and contaminant in the study area were simulated before and after the addition of the LID measures.

#### (1) Simulation settings

The bio-retention was projected in the study area based on SWMM. The construction area of bio-retention was 66.45 ha, which was 8.2% of the study area. The design parameters of bio-retention were settled based on the design requirements and recommended values from SWMM. Meanwhile, the rainfall for one hour with a return period of 2 years was designed based on the Xi'an City rainfall intensity formula and the Chicago rainfall pattern.

#### (2) Simulation results

The conditions of the outflow volume and contaminant in the study area were simulated before and after the addition of bio-retentions once every 2 years (Table 1).

The simulation settings of green roofs, permeable pavement, low-elevation greenbelt, and rain barrels were determined using the same method. The construction areas were 71.88, 90.12, 66.45, and 71.88 ha, which accounted for 9.6%, 11.1%, 8.2%, and 9.6% of the study

**Table 1** Environmental benefit of designate LID measures

LID measures	Volume reduction			Pollution reduction			
	Peak flow	Peak flow arrival time	Total runoff amount	COD	SS	TN	TP
Bio-retention	36.46%	9 min	38.79%	28.32%	34.46%	36.10%	33.68%
Green roofs	24.56%	5 min	29.92%	19.06%	22.94%	24.61%	22.61%
Permeable pavement	18.37%	3 min	22.62%	13.31%	16.01%	17.44%	15.85%
Low-elevation greenbelt	26.39%	6 min	30.00%	19.61%	23.74%	25.38%	23.34%
Rain barrels	6.01%	0 min	11.27%	5.34%	6.17%	6.99%	6.24%

area respectively. The design parameters of these LID single measures were settled based on the design requirements and recommended values from SWMM. The construction area of low-elevation greenbelts was set to be the same as that of bio-retention to compare the regulation effects among LID single measures, and the construction area of the rain barrels was the same as that of the green roofs. The conditions of the outflow volume and contaminant in the study area were simulated before and after the addition of LID measures once every 2 years (Table 1).

(3) Environmental benefit was evaluated by AHP

First, the hierarchical structure model was constructed based on the evaluation methodology of environmental benefit (Fig. 1b). Second, the comparison and judgment matrix was constructed. Comparison as well as judgment matrix and its assignment were constructed based on the environmental benefits of the select LID measures in Tables 1 and 2. Third, the single hierarchical arrangement and consistency were checked while the results of the weight

**Table 2** Comparison and judgment matrix of environmental benefit indexes

A	B1	B2	B1	C1	C2	C3	B2	C4	C5	C6	C7	C1	D1	D2	D3	D4	D5
B1	1	1	C1	1	2	3	C4	1	1	1	1	D1	1	2	3	2	6
B2	1	1	C2	1/2	1	2	C5	1	1	1	1	D2	1/2	1	2	1/2	4
			C3	1/3	1/2	1	C6	1	1	1	1	D3	1/3	1/2	1	1	3
							C7	1	1	1	1	D4	1/2	2	1	1	5
												D5	1/6	1/4	1/3	1/5	1
C2	D1	D2	D3	D4	D5	C3	D1	D2	D3	D4	D5	C4	D1	D2	D3	D4	D5
D1	1	2	3	2	4	D1	1	3	4	3	6	D1	1	2	4	2	6
D2	1/2	1	2	1	3	D2	1/3	1	2	1/2	4	D2	1/2	1	2	1	4
D3	1/3	1/2	1	1/2	2	D3	1/4	1/2	1	1/3	2	D3	1/4	1/2	1	1/2	3
D4	1/2	1	2	1	3	D4	1/3	2	3	1	4	D4	1/2	1	2	1	4
D5	1/4	1/3	1/2	1/3	1	D5	1/6	1/4	1/2	1/4	1	D5	1/6	1/4	1/3	4	1
C5	D1	D2	D3	D4	D5	C6	D1	D2	D3	D4	D5	C7	D1	D2	D3	D4	D5
D1	1	3	4	3	6	D1	1	3	2	1	6	D1	1	3	5	3	7
D2	1/3	1	2	1	3	D2	1/3	1	2	1	4	D2	1/3	1	2	1	4
D3	1/4	1/2	1	1/2	2	D3	1/2	1/2	1	1/2	3	D3	1/5	1/2	1	1/3	3
D4	1/3	1	2	1	4	D4	1	1	2	1	4	D4	1/3	1	3	1	4
D5	1/6	1/3	1/2	1/4	1	D5	1/6	1/4	1/3	1/4	1	D5	1/7	1/4	1/3	1/4	1

A - environmental benefit; B1- water quantity control; B2- water quality control; C1- total runoff amount; C2 - peak runoff reduction; C3 - peak flow arrival time retardation; C4 - reduction rate of TN; C5 - reduction rate of TP; C6 - reduction rate of COD; C7 - Reduction rate of SS; D1 - bio-retention; D2 - green roofs; D3 - permeable pavement; D4 - low-elevation greenbelt; D5 - rain barrels

vector and the inspection were calculated (Table 3). The calculations showed that all consistency ratios(CRs) in Table 3 were less than 0.1. In other words, the results conformed to the requirements of the consistency check. Finally, the hierarchical total ranking and consistency were checked. Hierarchical total ranking was conducted based on the consequences of single hierarchical arrangement. The results are presented in Table 4.

The CR of C layer was 0.0147, and the CR of D layer(Environmental benefit) was 0.0159. The calculations showed that all CRs were less than 0.1. In other words, the results conformed to the requirements of the consistency check. The preferential order of LID single measures based on the environmental benefit was: bio-retention > low-elevation greenbelt > green roofs > permeable pavement > rain barrels.

### 3.3.2 Economic Benefit

The hierarchical structure model of economic benefit was constructed (Fig. 1c). The comparison and judgment matrix were also constructed based on the civil construction cost and maintenance charge of these five LID single measures. Hierarchical total ranking was conducted based on the consequences of single hierarchical arrangement (Table 5).

The CR of C layer(Economic benefit) was 0.0355, which is less than 0.1. Hence, the results conformed to the requirements of consistency checks. The preferential order of LID single measures based on economic benefit was as follows: rain barrels > low-elevation greenbelt > green roofs > permeable pavement > bio-retention.

**Table 3** Calculated weight vector and inspection results of environmental benefit evaluation

A	Single ordering weight value	B1	Single ordering weight value	B2	Single ordering weight value	C1	Single ordering weight value	C2	Single ordering weight value
B1	0.5	C1	0.5396	C4	0.25	D1	0.3845	D1	0.375
B2	0.5	C2	0.297	C5	0.25	D2	0.2157	D2	0.2154
$\lambda_{max}$	2	C3	0.1634	C6	0.25	D3	0.1239	D3	0.1208
CI	0	$\lambda_{max}$	3.0092	C7	0.25	D4	0.2255	D4	0.2154
CR	0	CI	0.0046	$\lambda_{max}$	4	D5	0.0504	D5	0.0735
		CR	0.0088	CI	0	$\lambda_{max}$	5.0369	$\lambda_{max}$	5.0331
				CR	0	CI	0.0092	CI	0.0083
						CR	0.0082	CR	0.0074
C3	Single ordering weight value	C4	Single ordering weight value	C5	Single ordering weight value	C6	Single ordering weight value	C7	Single ordering weight value
D1	0.4534	D1	0.4039	D1	0.4632	D1	0.3456	D1	0.4759
D2	0.1639	D2	0.2139	D2	0.1816	D2	0.2054	D2	0.1833
D3	0.0941	D3	0.116	D3	0.1043	D3	0.1387	D3	0.095
D4	0.2345	D4	0.2139	D4	0.1924	D4	0.2559	D4	0.1987
D5	0.0541	D5	0.0522	D5	0.0585	D5	0.0544	D5	0.0471
$\lambda_{max}$	5.1241	$\lambda_{max}$	5.0392	$\lambda_{max}$	5.0491	$\lambda_{max}$	5.1378	$\lambda_{max}$	5.1021
CI	0.0310	CI	0.0098	CI	0.0123	CI	0.0344	CI	0.0255
CR	0.0277	CR	0.0088	CR	0.011	CR	0.0308	CR	0.0228

$\lambda_{max}$  is the maximal eigenvalue of matrix; CI is the consistency index; and CR is the consistency ratio

**Table 4** Results of hierarchical total ranking of environmental benefit evaluation

C layer	General ranking weight value	D layer	General ranking weight value
C1	0.2698	D1	0.4076
C2	0.1485	D2	0.2016
C3	0.0817	D3	0.1158
C4	0.1250	D4	0.2196
C5	0.1250	D5	0.0554
C6	0.1250		
C7	0.1250		

### 3.3.3 Social Benefit

The social benefit of LID measures depends on the utilization of rainwater, the value of the townscape, and its ecological function. The hierarchical structure model for economic benefit was constructed (Fig. 1d). The social benefits of the selected LID measures were divided into the following classes for evaluation: nothing, low, lower, medium, higher, and high. The comparison and judgment matrix and assignment was constructed based on the social benefit of the selected LID measures. Hierarchical total ranking was conducted based on the consequences of single hierarchical arrangement (Table 5).

The CR of C layer(Social benefit) was 0.0149, which is less than 0.1. Hence, the results conformed to the requirements of the consistency check. The preferential order of LID single measures based on social benefit was: rain barrels > bio-retention > green roofs > low-elevation greenbelt > permeable pavement.

### 3.3.4 Comprehensive Benefit

Weighted sum method was adopted to evaluate the comprehensive benefit of these five LID measures. Comprehensive efficiency value was calculated by summation of index weights (Table 5). The preferential order of LID single measures based on the comprehensive benefit was: bio-retention > rain barrels > low-elevation greenbelt > green roofs > permeable pavement.

**Table 5** Comprehensive efficiency value (General ranking weight value) of LID measures

LID measures	Environmental benefit (D layer)	Economic benefit (C layer)	Social benefit (C layer)	Comprehensive benefit
Bio-retention	0.4076	0.0609	0.2968	0.7653
Green roofs	0.2016	0.1443	0.2186	0.5645
Permeable pavement	0.1158	0.087	0.0868	0.2896
Low-elevation greenbelt	0.2196	0.3175	0.0900	0.6271
Rain barrels	0.0554	0.3904	0.3079	0.7537
Plan I	0.3814	0.0435	0.2946	0.7195
Plan II	0.0899	0.0786	0.2989	0.4674
Plan III	0.1644	0.2329	0.1429	0.5402
Plan IV	0.0516	0.4851	0.1389	0.6756
Plan V	0.3137	0.1599	0.1247	0.5983

### 3.4 Comprehensive Benefit of LID Combination Plans

According to the evaluation of LID single measures based on comprehensive benefits, the permeable pavement was eliminated for constructing LID combination plans because its comprehensive benefit was the lowest among the five LID single measures. Therefore, the five LID combination plans were composed of bio-retention, green roof, low-elevation greenbelt, or rain barrels.

- Plan I: Bio-retention + Green roofs
- Plan II: Bio-retention + Rain barrels
- Plan III: Green roofs + Low-elevation greenbelt
- Plan IV: Low-elevation greenbelt + Rain barrels
- Plan V: Green roofs + Low-elevation greenbelt + Rain barrels

Based on the same method for evaluating the comprehensive benefit of LID single measures, the comprehensive benefits of these five LID combination plans were obtained (Table 5). The results showed that the preferential order of LID combination plans was: Plan I > Plan IV > Plan V > Plan III > Plan II. Although the economic benefit of Plan I was relatively low, the environmental and social benefits were high. Overall, Plan I (bio-retention and green roofs) was the optimal LID combination plan. For Plan IV, the environmental benefit was relatively low, but economic and social benefits were high.

## 4 Conclusions and Recommendations

The SWMM model of the Chan River study area was constructed based on the well-founded evaluation system.

The preferential order of LID single measures based on the comprehensive benefit was: bio-retention > rain barrels > low-elevation greenbelt > green roofs > permeable pavement. Five LID combination plans were designed with bio-retention, rain barrels, low-elevation greenbelt, and green roofs. These combinations are Plan I (Bio-retention + Green roofs), Plan II (Bio-retention + Rain barrels), Plan III (Green roofs + Low-elevation greenbelt), Plan IV (Low-elevation greenbelt + Rain barrels), and Plan V (Green roofs + Low-elevation greenbelt + Rain barrels).

For the environmental benefit of LID combination plans, the preferential order was: Plan I > Plan V > Plan III > Plan II > Plan IV. For the economic benefit of LID combination plans, the preferential order was: Plan IV > Plan III > Plan V > Plan II > Plan I. For the social benefit of LID combination plans, the preferential order was: Plan II > Plan I > Plan III > Plan IV > Plan V. In conclusion, for the comprehensive benefit of LID combination plans, the preferential order was: Plan I > Plan IV > Plan V > Plan III > Plan II. Plan I (bio-retention and green roofs) was the optimal LID combination plan. Although economic benefit of Plan I was relatively low, its environmental and social benefits were high. Overall, Plan I (bio-retention and green roofs) was the optimal LID combination plan. For Plan IV, the environmental benefit was relatively low, but the economic and social benefits were high.

Therefore, future studies should: (1) step up efforts of rainfall synchronous monitoring and data collection and provide a basis for establishment of an urban stormwater management model; (2) improve the evaluation system by considering various factors; (3) quickly build the

database of the engineering economic cost of LID measures for different regions in China and reasonably provide a basis for design cost accounting of LID measures in urban stormwater management.

**Acknowledgments** This research was financially supported by the Natural Science Foundation of Shaanxi Province (Grant No. 2015JZ013), the National Natural Science Foundation of China (Grant No. 51279158), and Program for Key Science and Technology Innovation Team in Shaanxi Province (Grant No. 2014KCT-27).

## References

- Aryal SK, Ashbolt S, McIntosh BS, Petrone KP, Maheepala S, Chowdhury RK, Gardener T, Gardiner R (2016) Assessing and mitigating the hydrological impacts of urbanisation in semi-urban catchments using the storm water management model. *Water Resour Manag* 30(14):1–18
- Baek SS, Choi DH, Jung JW, Lee HJ, Lee H, Yoon KS, Cho KH (2015) Optimizing low impact development (LID) for stormwater runoff treatment in urban area, Korea: experimental and modeling approach. *Water Res* 86:122–131
- Calabrese A, Costa R, Levialdi N, Menichini T (2016) A fuzzy analytic hierarchy process method to support materiality assessment in sustainability reporting. *J Clean Prod* 121:248–264
- Chui TFM, Liu X, Zhan WT (2016) Assessing cost-effectiveness of specific LID practice designs in response to large storm events. *J Hydrol* 533:353–364
- Cipolla SS, Maglionico M, Stojkov I (2016) A long-term hydrological modelling of an extensive green roof by means of SWMM. *Ecol Eng* 95:876–887
- Davis AP, Traver RG, Hunt WF, Lee R, Brown RA, Olszewski JM (2012) Hydrologic performance of bio-retention storm-water control measures. *J Hydrol Eng* 17(5):604–614
- Duan HF, Li F, Yan HX (2016) Multi-objective optimal Design of Detention Tanks in the urban Stormwater drainage system: LID implementation and analysis. *Water Resour Manag* 30(13):4635–4648
- Ghodsi SH, Kerachian R, Zahmatkesh Z (2016) A multi-stakeholder framework for urban runoff quality management: application of social choice and bargaining techniques. *Sci Total Environ* 550:574–585
- Gironás J, Roesner LA, Rossman LA, Davis J (2010) A new applications manual for the storm water management model (SWMM). *Environ Model Softw* 25(6):813–814
- Jia HF, Yao HR, Tang Y, Yu SL, Field R, Tafuri AN (2015) LID-BMPs planning for urban runoff control and the case study in China. *J Environ Manag* 149:65–76
- Katherine A, Franco M, Alisha G (2010) Observed and modeled performances of prototype GreenRoof test plots subjected to simulated low-and high-intensity precipitations in a laboratory experiment. *J Hydrol Eng* 15(6): 448–461
- Li JK, Li Y, Li YJ (2016) SWMM-based evaluation of the effect of rain gardens on urbanized areas. *Environ Earth Sci* 75(1):1–14
- Liu YZ, Cibir R, Bralts VF, Chaubey I, Bowling LC, Enge BA (2016) Optimal selection and placement of BMPs and LID practices with a rainfall-runoff model. *Environ Model Softw* 80:281–296
- Qin HP, Li ZX, Fu G (2013) The effects of low impact development on urban flooding under different rainfall characteristics. *J Environ Manag* 129C(18):577–585
- Villarreal EL, Annette SD (2004) Inner City Stormwater control using a combination of best management practices. *Ecol Eng* 22(4):279–298
- Winston RJ, Dorsey JD, Hunt WF (2016) Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. *Sci Total Environ* 553:83–95