Research on the schemes formulation and optimization method of sponge reconstruction in a highway service area

Yu-hua Peng, Zhuang Li and Yong-shuai Ding

ABSTRACT

This study proposed a method for constructing a low impact development (LID) plan to improve the utilization rate of rainwater in a highway service area and solve the problem of waterlogging. Firstly, based on the theory of LID, taking the total runoff as the control goal, and combining it with the functional zoning of the highway service area and the characteristics of LID facilities, several LID schemes were proposed. Then, the evaluation system of the LID scheme in service area was established by the analytic hierarchy process (AHP). These preliminary construction schemes were compared from three aspects (runoff control efficiency, economic efficiency and social efficiency) to determine the best LID plan. Finally, taking the Pu'er tunnel service area as an example, the construction scheme of the sponge city service area was optimized.

Key words | analytic hierarchy process, highway service area, LID facilities, low impact development, traffic engineering

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HIGHLIGHTS

- The concept of sponge city construction is integrated with traditional highway service areas.
- The proposed construction method of highway sponge service areas can realize the selection of LID facilities and the optimization of construction schemes, which enriches the connotation of design and management of highway service areas.

INTRODUCTION

At present, the drainage design of highway service areas in China follows the concept of fast discharge, which changes the hydrological conditions of the original site greatly, neglects the ecological role and utilization value of rainwater, and the utilization rate of rainwater resources is low. Sponge cities, a new generation of urban rainwater management concept, means the city can be like a sponge, adapting well to environmental changes and disasters caused by rain. The construction of a sponge city is an effective approach to solving urban water issues, particularly waterlogging. How to use the concept of a sponge city to design or transform the highway service area to improve the utilization rate of rainwater has become a focus of exploration in the industry.

The idea of low impact development (LID), in this case used to mean design and engineering to manage stormwater runoff, is an effective way to reduce the negative impact of rainwater runoff on regional environments by managing rainwater sources with scattered small and medium-sized technical facilities (Rodak *et al.* 2019). The construction, location and combination plans of LID facilities need to be determined in combination with LID facility structure and regional characteristics (Shafique & Kim 2017). Mathematical models can be built to optimize the type, location and allocation ratio of LID facilities from the perspectives of goal realization and cost reduction (Seo *et al.* 2017). Based on the LID concept, a test site in Cheongju, South Korea was divided and transformed, which effectively reduced the pollutant emissions and rainfall runoff (Son *et al.* 2017). Taking an area in Virginia, USA as an example, using storm water management model (SWMM) and

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hydrological simulation program – FORTRAN (HSPF) to simulate the hydrological environment at the same time, the results show that SWMM is more accurate for peak flow simulation and easier to use to calibrate parameters (Yazdi *et al.* 2019). In 2014, the Ministry of Housing and Urban-Rural Development of the People's Republic of China (2014) issued *The Construction Guideline of Sponge Cities in China – Low Impact Development of Stormwater Systems (trial)*. '(hereinafter referred to as 'the Guideline'), which guides the construction of a sponge city in terms of planning, design, engineering, construction, management and maintenance. Compared with a traditional plan, the waterlogging removal project based on the concept of a sponge city has a significant effect on waterlogging control (Guo 2017). According to the functions and characteristics of LID facilities, a sponge city transformation was carried out in a residential district in Beijing, and the annual runoff control rate reached 65% after the transformation (Zhang *et al.* 2018). Using the runoff control effect and economic cost as the control targets, a multi-objective optimization mathematical model was constructed to realize the optimization of the sponge city LID programs (Tao *et al.* 2019). The process of SWMM model runoff information processing determines that it can simulate the hydrological conditions of small-scale regions more accurately, and it is a small-scale regional hydrological simulation software with high accuracy and most widely used at this stage (Wang *et al.* 2019).

The scale of land use for highway service areas is similar to that of building compound areas. The study the layout and application of LID facilities in the service area by using the construction concept and method of sponge city is still in the exploratory stage, and the construction of LID scheme lacks effective theoretical and empirical support. In this paper, based on the idea of sponge city construction, combined with the functional zoning of service areas and the performance of LID facilities, several preliminary LID schemes for a service area are proposed. Then, the sponge service area is evaluated by AHP to optimize these preliminary schemes from three aspects: runoff control efficiency, economic efficiency and social efficiency.

LITERATURE REVIEW

According to the Guideline, there are five common kinds of LID facility: infiltration, adjustment, transfer, pollution interception and purification. Site conditions and space requirements are important factors for LID facility selection, and include the geological and hydrological conditions of the service area and the characteristics of the underlying surface. According to the regional characteristics and runoff direction, the service area can be divided into four catchment sections: parking and lane section, sidewalk and pedestrian square section, building section and green section. Combined with site conditions and underlying surface characteristics, LID facilities suitable for the highway service area mainly include: permeable asphalt pavement, permeable cement concrete pavement, permeable brick pavement, green roof, sunken greenbelt, rain garden and grass swale.

Permeable asphalt pavement

The design needs to consider the influence of permeable water storage and drainage functions on the pavement stability. It is generally used in parking lots or traffic lanes with small loads in the service area, and can be divided into the following three types:

(1) Type I: Only the upper layer of asphalt pavement is permeable, and the sealing layer is at the bottom of the upper layer. After entering the upper layer, rainwater is discharged into the adjacent drainage facilities transversely. This type can effectively reduce road surface runoff and eliminate surface water, but there is almost no reduction in total runoff.
(2) Type II: Both the pavement surface layer and the base layer are permeable, and the sealing layer is at the bottom of the base layer. After the rainwater enters the base layer, it flows to the drainage edge ditch by transverse infiltration. This type can not only reduce the total surface runoff, but also alleviate the pressure of the pavement runoff on the drainage system during rainstorm. However, it will have a slight impact on the stability of the roadbed.
(3) Type III: The whole pavement structure layer has a good level of permeability, so rainwater can infiltrate into the subgrade through the pavement. In addition to reducing the pavement runoff and the total runoff, this type can also supplement the groundwater resources in the area, improve the water environment and ecology around the road. However, it has higher requirements for subgrade soil and the road load should not be too large.

Permeable cement concrete pavement

This is a kind of porous lightweight concrete made of coarse aggregate, cement, reinforcement and water. When the permeable capacity of subgrade soil is limited, drainage pipes or plates should be placed in the permeable base. It is mainly used in areas with small load, and to certain degree it will have peak flow reduction and rainwater purification effects.

Permeable brick pavement

The permeability effect of this kind pavement mainly depends on permeability coefficient of the permeable bricks used. According to the Technical Regulations of Permeable Brick Pavement (CJJT188-2012), the permeability coefficient of permeable brick should be greater than 0.1 mm/s. This is mainly used in pedestrian areas with small loads, and can increase rainwater infiltration and reduce surface water.

Green roof

This special roof with sustainable functions is usually composed of a vegetation layer, planting matrix, isolation filter pad, water storage and drainage layer, moisturizing layer, root resistance layer, waterproof layer and the structural layer of the building roof. It can be used on impervious areas, such as building roofs. It can effectively play the role of retention and absorption, reducing the total runoff, and also have a better visual effect.

Sunken greenbelt

The sunken greenbelt refers to the space within about 200 mm below the surface of the surrounding ground or the road and is, mainly composed of herbaceous plants. Through infiltration, the rainwater conservation level in the service area can be effectively improved, and the rainwater runoff can be stored in a short period of time. It has the functions of peak clipping, peak extension and preliminary rainwater purification, and is the main contributor to the ecological effect of the service area.

Rain garden

The rain garden is usually set in the lower elevations of the service area, and varied vegetation can be used. It is mainly used in the green space around the impervious underlying surface of buildings, parking lots, etc., and plays an important role in reducing runoff and purifying water, at low cost and with easy maintenance.

Grass swale

The grass swale is a planted surface ditch that is used to connect other single facilities, rainwater pipes and canal systems in a service area. It can also be used as a pretreatment facility for sunken greenbelts, rain gardens and other facilities. It can collect, transport and discharge runoff rainwater, and will reduce the total amount of runoff and improve the effect of runoff pollution control.

METHODOLOGY AND RESULTS

Preliminary LID plans in a sponge service area

Selecting control objectives

According to the Guideline, the control objectives of sponge city development are peak runoff, total runoff, pollution control and rainwater resource utilization, and one or more objectives should be selected reasonably according to the individual city conditions. The main purpose of constructing a sponge service area is to solve the problem of waterlogging and improve the utilization rate of rainwater resources. In the preliminary determination of LID schemes, total runoff control should be the main control objective. During the evaluation of the schemes, both peak runoff control and rainwater resource utilization should be considered.

The Guideline divides China into five regions and gives the recommended range of control rates of annual total runoff for each region (Figure 1): Area I (85%–90%), Area II (80%–85%), Area III (75%–85%), Area IV (70%–85%), and Area V (60%–85%). The total annual runoff control

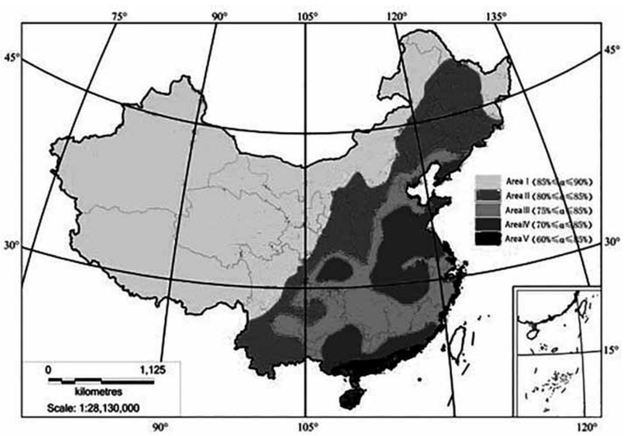

Figure 1 | Regional map of total annual runoff control rate in China.

target of the highway sponge service area can be determined by referring to this range.

Define LID facilities' sizes

The test algorithm in the Guideline was adopted to determine the size of LID facilities. Firstly, several preliminary LID construction schemes were proposed according to the selection principle of LID facilities. Then, the design storage volume was calculated according to the control rate of annual runoff amount. After that, the actual storage volume of the preliminary scheme was calculated according to the sizes and types of LID facilities. When actual storage volume is larger than design storage volume, the design requirements are satisfied. If actual storage volume is less than design storage volume, the sizes of LID facilities should be adjusted until the total runoff control requirements are met.

Design storage volume. According to the Guideline, the design storage volume is determined by the design rainfall, regional area and regional type. There is a corresponding relationship between the design rainfall and the annual total runoff control rate: select the daily rainfall data for many years, deduct the rainfall ≤2 mm (generally no runoff is generated), then sort the daily rainfall from small to large, and count the ratio of total rainfall of less than a certain amount of rainfall to the sum of all the rainfall in the series, which is the annual total runoff control rate, and the corresponding rainfall is the design rainfall. According to the control rate of annual runoff amount and the rainfall data of the service area, the design rainfall corresponding to the control target can be determined. Then the value of the design storage volume is calculated as shown in Equation (1).

$$V_d = 10H\varphi F \quad (1)$$

where V_d is the design storage volume (m^3)
H is the design rainfall (mm)
φ is the comprehensive rain-runoff coefficient
F is the catchment area (ha)

In this equation, comprehensive rain-runoff coefficient can be calculated by the weighted average algorithm $\varphi = \frac{\sum \varphi_i A_i}{\sum A_i}$, where φ_i represents each catchment rain-runoff coefficient (Table 1) while A_i stands for each catchment area.

Actual storage volume. Among LID facilities, permeable brick pavements, permeable asphalt pavements, permeable cement concrete pavements, grass swales and green roof structures have a small internal void volume, which is not included in the calculation of the total storage volume. The sunken greenbelt with a large area is restricted by slope and the vertical conditions of catchment surface, and its storage volume is far less than its design storage volume, so it is not included in the calculation.

For the sunken greenbelt and rain garden with small areas, the sunken depth is involved in the calculation of the storage volume. The calculation method is shown in Equation (2) (Guide to the Design of Sponge City Construction Project in Kunming 2016).

$$V_a = \sum_{i}^{n} h_i \cdot F_i \quad (2)$$

where V_a is the actual storage volume (m^3)
h_i is the effective storage depth of facility i (m)
F_i is the area of facility i (m^2)

Table 1 | Common rain-runoff coefficients

Catchment type	Rain-runoff coefficient φ
Green roof	0.3–0.4
Concrete roof, flat roof without gravel, asphalt roof	0.8–0.9
Concrete, asphalt pavement and square	0.8–0.9
Large stones pavement and square	0.5–0.6
Asphalt surface treatment of gravel and square	0.45–0.55
Graded gravel road and square	0.4
Dry masonry or gravel pavement and square	0.4
Unpaved earth pavement	0.3
Greenbelt	0.15
Permeable pavement (permeable asphalt pavement, permeable cement concrete pavement, permeable brick pavement)	0.08–0.45

Evaluation system of LID schemes in sponge service area

There may be several preliminary LID schemes to meet the total runoff control objectives of the sponge service area. However, the construction cost, maintenance cost and social efficiency should also be taken into comprehensive consideration when determining the construction scheme, to transform the decision-making about multi-objectives, multi-criteria and difficulties into multi-level and single objective problems. It is therefore necessary to build an evaluation system for LID schemes. Through the evaluation system, the comprehensive benefits of combinations of different LID facilities are compared to determine the optimal LID construction scheme.

Evaluation indexes

Runoff control efficiency. The main goal of sponge function enhancement in a service area is to improve the utilization rate of rainwater. The runoff control effect of LID facility combination is the key for a sponge service area construction scheme. Compared with the traditional development situation, LID facilities reduce surface runoff and peak runoff through infiltration, detention and other measures. The runoff control efficiency can be evaluated by two indexes: total runoff control and peak runoff control.

Building a simulation model of surface runoff is one of the main ways to quantify the reduction effect of total runoff and peak runoff in a sponge service area. Combined with the pipeline network, catchment area division, LID facility size and other aspects of the service area, an SWMM surface runoff simulation model can be constructed to obtain the total runoff and peak runoff reduction in the service area, so as to evaluate the runoff control effect of each scheme.

Economic efficiency. The economic efficiency of LID facilities includes the one-time construction cost and subsequent annual management and maintenance costs. In order to compare various schemes, the unit area construction cost of LID is used as the construction cost, and the annual average management and maintenance costs per unit area are used as the management and maintenance costs.

Social efficiency. LID facilities such as sunken green space, rain gardens and permeable pavements improve the utilization rate of rainwater in the service area. These facilities can play an important role in plant growth and the reduction of maintenance costs, making a better ecological landscape, and contributing to beautifying the service area, and therefore having a good social efficiency.

Determine the weight of evaluation index

The evaluation of LID schemes is a typical problem with multi-objectives, multi-criteria, and difficulties to quantify. Analytic hierarchy process (AHP) can be used to determine the weight of the evaluation index. The general steps are as follows: (1) establish the target hierarchical structure model; (2) construct the judgement matrix; (3) calculate the weight value and check the consistency.

Establish the target hierarchical structure model. According to the principle of the LID scheme evaluation index and AHP, taking the LID scheme of the service area as the target layer, runoff control efficiency, economic efficiency and social efficiency as the criterion layer, runoff total amount and peak reduction, construction cost, management and maintenance cost as the index layer, the established hierarchical structure model is shown in Figure 2.

Construct the judgement matrix. The judgement matrix is constructed by comparing the importance of the two indexes of the same layer to the index of the upper layer. The importance of the index C_i relative to C_j to the B_k is represented by a_{ij}. The value of a_{ij} ranges from 1 to 9 (Table 2). Experts are invited to assign values to a_{ij}, and the average value of the experts' assignment values is calculated as the final assignment of the matrix, forming the judgement matrix $A = (a_{ij})_{n\times n}$ (Table 3).

Calculate the weight value and test the consistency. According to judgement matrix A, the relative weight of each index

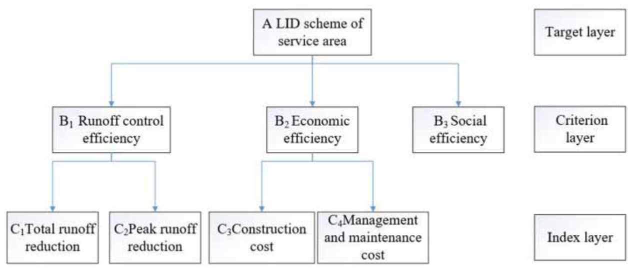

Figure 2 | Target hierarchical structure model.

Table 2 | Standard table of the value of a_{ij} in the judgement matrix

Relative importance	Mean
1	Equally important
3	*i* is a little more important than *j*
5	*i* is clearly more important than *j*
7	*i* is significantly more important than *j*
9	*i* is much more important than *j*
2, 4, 6, 8	The intermediate value of two adjacent values
Reciprocal	$a_{ji} = 1/a_{ij}$

Table 3 | Judgement matrix form

B_k	C_1	C_2	…	C_n
C_1	a_{11}	a_{12}	…	a_{1n}
C_2	a_{21}	a_{22}	…	a_{2n}
⋮	⋮	⋮	⋱	⋮
C_n	a_{n1}	a_{n2}	…	a_{nn}

C_1, C_2, …, C_n in the index layer C to the B_k in the criterion layer is calculated by the characteristic root method. Firstly, the maximum eigenvalue λ_{max} and eigenvector of the judgement matrix A are calculated, and then the eigenvector is normalized to be the weight vector W.

In order to reduce the influence caused by subjective judgment on the evaluation results, it is necessary to test the consistency of the judgement matrix.

Calculate consistency index *CI* using Equation (3).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

where *CI* is the consistency index
n is the judgement matrix's order

Search the average random consistency index *RI*.

According to the order of the judgement matrix, search the corresponding average consistency index *RI* referring to Table 4.

Calculate the consistency ratio *CR* using Equation (4).

$$CR = \frac{CI}{RI} \tag{4}$$

When $CR < 0.1$, the judgement matrix has a better consistency; otherwise, it is necessary to adjust the judgement matrix and re-assign the indexes with large differences of expert values until the constructed judgement matrix passes the consistency test (Li & Dou 2009).

Index scoring criteria

In LID scheme evaluation system, the total runoff control, peak runoff control, construction cost per unit, management and maintenance costs per unit are quantitative indexes, while social efficiency is qualitative index. In order to make the evaluation result more objective, quantitative indexes are measured and scored. The qualitative indexes are obtained from the weighted value of the unit area of single LID facilities by AHP, and the score is calculated by combining the sizes of the facilities.

Runoff control efficiency. The runoff of the target service area is simulated by the SWMM model, and the total runoff and peak runoff can be obtained. According to Equation (5), the total runoff reduction rate and peak runoff reduction rate of each scheme are calculated. The two indicators can directly reflect the runoff control efficiency of each scheme, so they are used as the scoring values of total runoff reduction and peak runoff reduction respectively.

$$L_{zi} = \frac{Z_i - Z}{Z}, \quad L_{Fi} = \frac{F_i - F}{F} \tag{5}$$

where L_{Zi} is the reduction rate of total runoff in scheme *i*;
Z_i is the total runoff in the service area in scheme *i*;
Z is the total runoff in the service area under the traditional situation;
L_{Fi} is the reduction rate of peak runoff in scheme *i;*
F_i is the peak runoff in the service area in scheme *i*;
F is the peak runoff in the service area under the traditional situation.

Economic efficiency. By investigating the materials, management and maintenance costs of LID facilities in the target service area, the construction, annual management and maintenance costs can be calculated for each scheme. The lower the construction, management and maintenance costs, the higher the economic efficiency scores, so the inverse treatment is adopted for the cost as the index score of the construction, management and maintenance costs of each scheme.

Social efficiency. Experts are invited to score the contrasting degree of social efficiency between LID facilities, using the 1–9 scale method (Table 2) to construct a judgement

Table 4 | Average consistency index *RI*

Order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.46	1.46	1.49

matrix. After checking the consistency of the judgement matrix according to Equations (3) and (4), the eigenvector of the judgement matrix is calculated and normalized, and social efficiency weights of each LID facility per unit area can be obtained.

Combined with the size of LID facilities in the preliminary plan, the social efficiency weight of LID facilities per unit area is multiplied by the corresponding facility size, and the results are accumulated as the evaluation value of the social efficiency index for each scheme.

Evaluation method

When using multiple indicators to evaluate the LID schemes in the service area, considering that the index values have different dimensions and orders of magnitude, they cannot be compared directly. The linear normalization method is used to deal with the same index score of different schemes, as shown in Equation (6).

$$Y_{ki} = \frac{X_{ki}}{\sum_{k=1}^{n} X_{ki}} \tag{6}$$

where Y_{ki} is the score of index i in scheme k;
X_{ki} is the evaluation score of index i in scheme k;
n is the number of schemes.

The above equation provides the index scores of each scheme. Combined with the LID target hierarchy model diagram of the service area and the weight of each index, the comprehensive scores of the preliminary scheme are determined. The scheme with the highest score is the optimal scheme, as shown in Equations (7) and (8).

$$Z_{ku} = \sum_{i=1}^{2} Y_{ki} \cdot C_{ui} \tag{7}$$

$$\lambda_k = \sum_{u=1}^{3} Z_{ku} \cdot B_u \tag{8}$$

where Z_{ku} is the score of criterion u in scheme k (The scores of runoff control efficiency and economic efficiency in the criterion layer are calculated according to equation (7). The social efficiency scoring process is detailed in the ‘Social efficiency’ section. It gives the social efficiency score of the scheme after normalization according to Equation (6)).

Y_{ki} is the score of index i in scheme k;
C_{ui} is the weight value of index i to criterion u;
λ_k is the comprehensive score of scheme k;
B_u is the weight value of the criterion u to the target layer.

CASE STUDY

Study area

The reconstruction project of the Pu’er tunnel service area of Yunnan Mosi Expressway (G8511) is located in Pu’er city, which has a subtropical plateau monsoon climate with abundant rainfall: the annual average is 1,476 mm. The service area covers 32,598 m^2, including buildings (3,934 m^2), cement concrete pavement (17,897 m^2), green areas (7,219 m^2) and pedestrian squares (3,548 m^2). The soil is loam sand with good permeability. The overall terrain of the service area is higher in the west and lower in the east. The layout of the service area and the drainage pipe network before the reconstruction is shown in Figure 3.

Definition of control objectives of LID scheme

According to the recommended regional annual total runoff control rate in the Guideline (Figure 1), Pu’er city is located in Area II, which means that the annual total runoff control rate is over 80%. Considering the limited conditions for the transformation of the service area, the annual total runoff control rate of the Pu’er tunnel service area is defined at 80%.

Based on the past few years’ rainfall data for Pu’er, the relationship between the annual total runoff control rate and the design rainfall in the service area of Pu’er tunnel is shown in Table 5.

According to Table 5, the design rainfall corresponding to the annual total runoff control rate ‘80%’ in the service area of Pu’er tunnel is 22.83 mm.

Preliminary schemes of LID

There are many heavy vehicles in the traffic lanes and large-vehicle parking areas of the Pu’er tunnel service area, so it is not suitable for permeable asphalt pavement. The service area soil has good permeability, in the case of similar runoff control efficiency, considering that the permeable cement concrete pavement needs to be set with more joints, while the permeable asphalt pavement construction

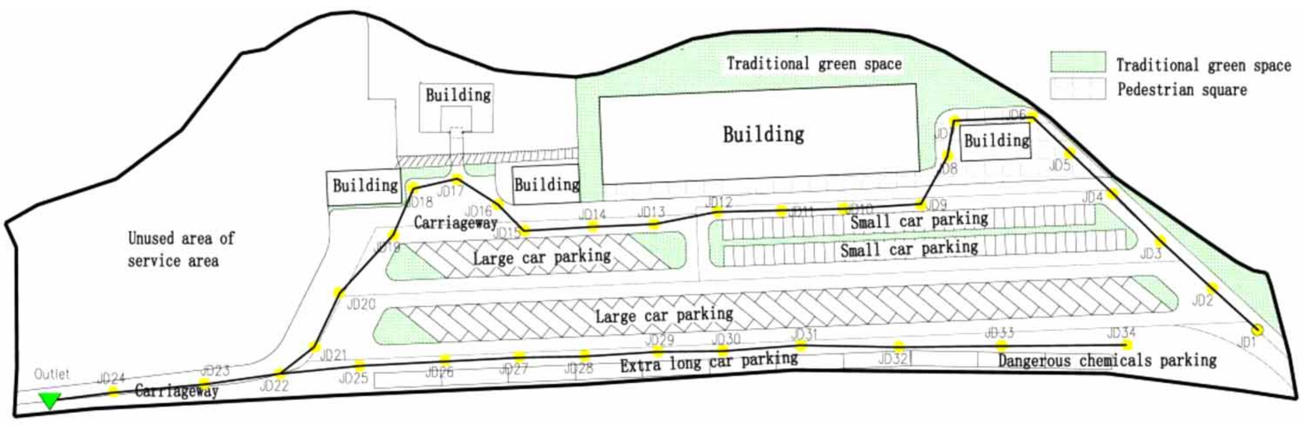

Figure 3 | Schematic diagram of Pu'er tunnel service area.

Table 5 | Design rainfall correspond to annual total runoff control rate in Pu'er

Annual total runoff control rate/%	60	65	70	75	80	85
Design rainfall/mm	12.14	14.10	16.37	19.16	22.83	27.57

is relatively simple, so type III permeable asphalt pavement is used for the car parking section. Permeable brick pavement is not as strong as permeable cement concrete pavement. However, the design of permeable brick pavement is more flexible and changeable, and so easily highlights the characteristics and aesthetic feeling of the service area. The pedestrian flow of the pedestrian square in the service area is relatively small, so after full consideration, permeable brick pavement is selected to transform the pedestrian square. The roof of the building can be transformed into green roof, and the greening area can be transformed into sunken greenbelt and rain garden. Considering that the sanitary management of the Pu'er tunnel service area is properly in place and the demand for pollution control is not high, a grass swale is not used to transform the existing drainage ditch. The LID facilities of permeable brick pavement, permeable asphalt pavement, sunken greenbelt, rain garden and green roof are first selected, and the parameters are set according to the recommended values of the Guideline and the characteristics of Pu'er tunnel service area.

Scheme I

Scheme design. From the perspective of economic and low-density reconstruction, four low-cost LID facilities, permeable brick, permeable asphalt pavement, sunken greenbelt and rain garden, are selected as the LID design scheme of the service area of Pu'er tunnel, as shown in Figure 4.

Inspection of the design storage volume. As for the Pu'er tunnel service area, the space area of each underlying

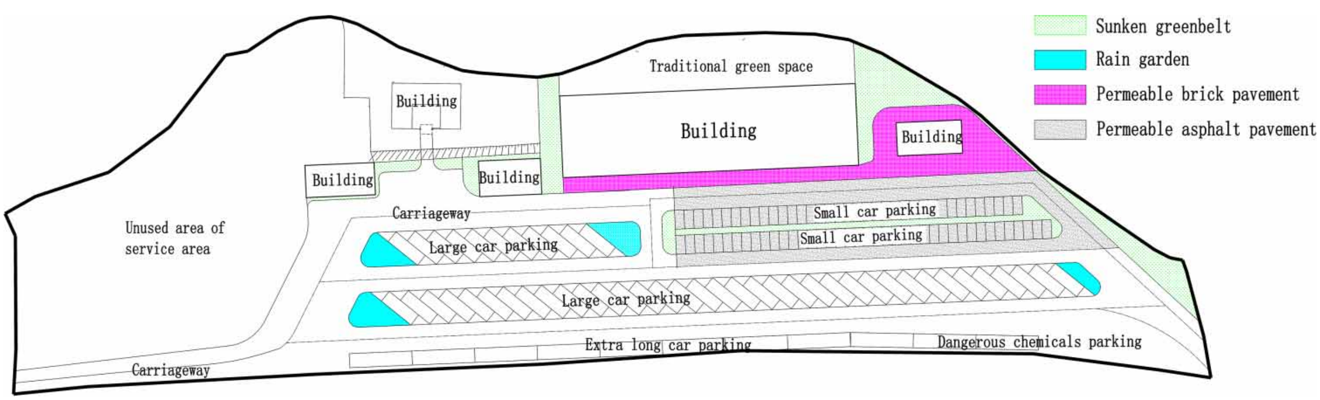

Figure 4 | Scheme I.

surface and the corresponding rainfall runoff coefficient are shown in Table 6.

Calculation of the comprehensive runoff coefficient and design storage volume of the service area according to Equation (1):

$$\varphi = \frac{\sum F_i \cdot \varphi_i}{F} = 0.6276, V = 10H\varphi F = 467.07\ m^3$$

Combined with the recommended values of the Guideline and the characteristics of the service area, the parameters of the sunken greenbelt and rain garden are shown in Table 7. Limited by the vertical conditions of the catchment area, only small-scale sunken greenbelt scattered around the building and parking area are part of the calculation of storage volume, and the area is 2,006 m^2.

According to Equation (2), the total storage volume of LID facilities is calculated as 506.36 m^3, which meets the requirement of 467.07 m^3 for the storage volume with the annual runoff total control rate of 80%.

Scheme II

Scheme design. Compared with Scheme I, Scheme II increases the types and sizes of LID facilities to enhance the control of rainwater runoff in the service area and increases the social efficiency. Permeable brick pavement, permeable asphalt pavement, sunken greenbelt, rain garden and green roof are selected as the LID design scheme for Pu'er tunnel service area, as shown in Figure 5.

Table 6 | Characteristics of underlying surface in Scheme I

Underlying surface	Area F_i/m^2	Rainfall runoff coefficient φ_i
Permeable asphalt pavement	2817	0.30
Cement concrete pavement	15,080	0.90
Permeable brick pavement	3548	0.40
Concrete roof	3934	0.90
Greenbelt	2818	0.15
Sunken greenbelt	3989	0.15
Rain garden	412	0.15

Table 7 | Rain garden and sunken greenbelt's parameters

Type	Area/m^2	Storage depth/m
Rain garden	412	0.45
Sunken greenbelt	2,006	0.16

Inspection of the design storage volume. As for the Pu'er tunnel service area, the space area of each underlying surface and the corresponding rainfall runoff coefficient are shown in Table 8.

According to the total runoff control target of the LID scheme, the corresponding design rainfall is 22.83 mm. According to Equation (1), the comprehensive runoff coefficient and storage volume of the service area are calculated as being:

$$\varphi = \frac{\sum F_i \cdot \varphi_i}{F} = 0.5716, V = 10H\varphi F = 425.39\ m^3$$

Limited by the vertical conditions of the catchment area, only small-scale sunken greenbelt scattered around the building and parking area are part of the calculation of storage volume, and the area is 2,025.19 m^2. According to Equation (2), the total storage volume of LID facilities is calculated as 509.43 m^3, which meets the requirement of 425.39 m^3 for the storage volume with the annual runoff total control rate of 80%.

Optimum scheme

Determination of the evaluation index weight

Ten experts engaged in sponge city construction were invited to determine the importance of three indicators, namely runoff control efficiency, economic efficiency and social efficiency, and then the average value of the judgment results was calculated (see Table 9). Meanwhile the importance of each indicator in the index layer corresponding to the indicator in the upper criterion layer was estimated, and its average value was calculated (Tables 10 and 11).

According to Equations (3) and (4), the consistency of each judgement matrix is tested, and the results meet the requirements of consistency. The weight values of the indicators of the LID scheme are shown in Table 12.

Comprehensive scores of LID schemes in service area

Evaluation of runoff control efficiency. Based on simulating two LID schemes by SWMM, the total runoff and peak runoff data during the design return period of 0.1a, 2a, 5a and 15a are shown in Table 13. In order to reflect the runoff control effect of LID schemes, the SWMM simulation

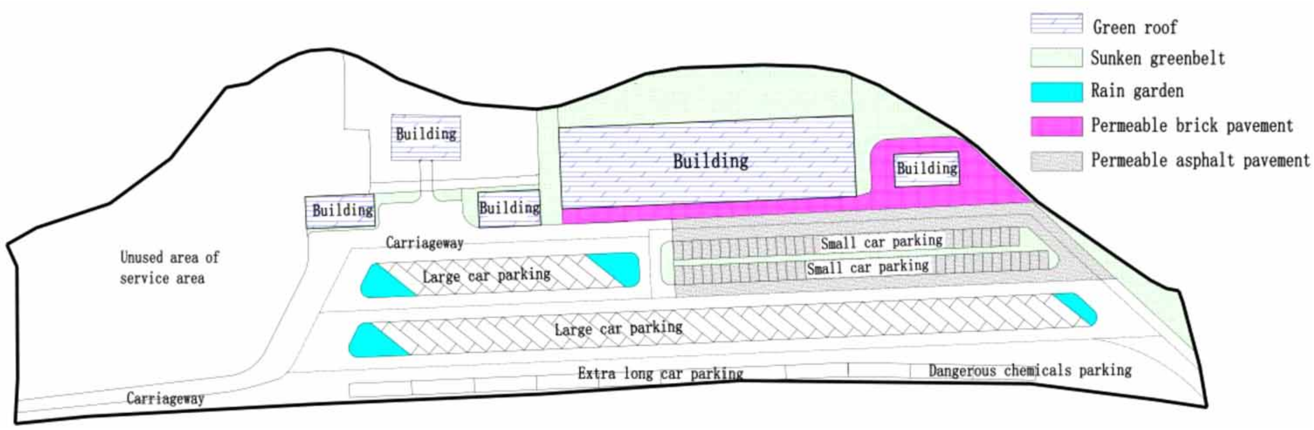

Figure 5 | Scheme II.

Table 8 | Characteristics of underlying surface in Scheme II

Underlying surface	Area F_i/m^2	Rainfall runoff coefficient φ_i
Permeable asphalt pavement	2817	0.30
Cement concrete pavement	15,080	0.90
Permeable brick pavement	3548	0.40
Green roof	3322	0.35
Concrete roof	612	0.90
Greenbelt	1301	0.15
Sunken greenbelt	5506	0.15
Rain garden	412	0.15

Table 9 | Criterion layer judgement matrix

LID scheme comprehensive evaluation	B_1 Runoff control efficiency	B_2 Economy efficiency	B_3 Social efficiency
B_1 Runoff control efficiency	1	5	6
B_2 Economy efficiency	1/5	1	2
B_3 Social efficiency	1/6	1/2	1

Table 10 | B_1-C_i index layer judgement matrix

B_1 Runoff control efficiency	C_1 Total runoff control	C_2 Peak runoff control
C_1 Total runoff control	1	4
C_2 Peak runoff control	1/4	1

Table 11 | B_2-C_i index layer judgement matrix

B_2 Economy efficiency	C_3 Construction cost per unit area	C_4 Maintenance cost per unit area
C_3 Construction cost per unit area	1	5
C_4 Maintenance cost per unit area	1/5	1

model of the service area before transformation is built, and the total runoff and peak runoff are shown in Table 14. Combined with Tables 13 and 14, the runoff reduction rates of LID schemes are calculated according to Equation (5). The average total runoff control rate and peak runoff reduction rate of each scheme are calculated respectively as the schemes' score, and according to Equation (6), the average value is normalized as the score of the runoff control efficiency of the scheme, as shown in Table 15.

Evaluation of the economic efficiency. Through investigating the cost of LID facilities service area in Yunnan province, the unit price of construction and annual maintenance expenses of each LID scheme are shown in Table 16. Combined with the sizes of facilities, the construction and maintenance costs of the service area are calculated. The treatment is carried out in the form of reciprocal processing, and the economic efficiency score of the scheme after normalization is shown in Table 17.

Evaluation of social efficiency. Ten experts engaged in sponge city construction were invited to compare the importance of the social efficiency for LID facilities per unit area. The judgement matrix is constructed to obtain the social

Table 12 | LID scheme indexes weight

Target layer	Weight	Criterion layer	Weight	Index layer	Weight
LID scheme in service area	1	Runoff control efficiency	0.726	Total runoff control	0.80
				Peak runoff control	0.20
		Economy efficiency	0.172	Construction cost per unit area	0.83
				Maintenance cost per unit area	0.17
		Social efficiency	0.102	/	/

Table 13 | Runoff conditions of service areas in different LID schemes

	Peak runoff/CMS		Total runoff/m^3	
Rainfall return period/a	Scheme I	Scheme II	Scheme I	Scheme II
$P = 0.1$	0.1373	0.1023	6.228	3.978
$P = 2$	0.4026	0.3338	18.106	14.12
$P = 5$	0.5142	0.4235	23.054	18.596
$P = 15$	0.5654	0.4889	29.432	24.417

Table 14 | Runoff conditions of pre-reconstruction in service area

Rainfall return period/a	Peak runoff/CMS	Total runoff/m^3
$P = 0.1$a	0.3666	13.498
$P = 2$a	1.0015	35.279
$P = 5$a	1.2226	42.629
$P = 15$a	1.331	51.539

Table 15 | Runoff control efficiency value of each scheme

Scheme	Average reduction rate of total runoff/%	Normalized processing value	Peak runoff reduction rate/%	Normalized processing value
I	47.84	0.44	59.45	0.47
II	59.88	0.56	66.85	0.53

efficiency weight of each LID facility, as shown in Table 18. Combined with the sizes of LID facilities in the schemes, the social efficiency weight of LID facilities per unit area is multiplied by the corresponding facility size, and the results are accumulated as the score value of social efficiency index of each scheme. The social efficiency scores of the scheme (after normalization) are shown in Table 19.

Comprehensive score of each scheme. According to two different LID construction schemes of the Pu'er tunnel service area, combined with Tables 15, 17, 19 and 12, the comprehensive scores of LID schemes, calculated according to Equations (7) and (8), are shown in Table 20.

From the above table, the comprehensive score of Scheme II is higher than that of Scheme I, so Scheme II is chosen as the LID scheme of Pu'er tunnel service area.

DISCUSSION

At present, the sponge transformation scheme of the service area has a large amount of experience, and there is no clear understanding of the application scales of LID facilities, which easily leads to less facilities, an inability to improve the water environment, or too many facilities lead to high economic cost.

This paper took the reconstruction scheme of service area as the research subject. Firstly, the service area was

Table 16 | Price and size of each LID facility

LID facility	Construction expenses/(yuan/m^2)	Annual maintenance expenses/(yuan/m^2)	Sizes of Scheme I/m^2	Sizes of Scheme II/m^2
Permeable asphalt pavement	480	20	2,817	2,817
Permeable brick pavement	120	4	3,548	3,548
Sunken greenbelt	50	5	3,989	5,506
Rain garden	600	40	412	412
Green roof	380	60	/	3,322

Table 17 | Economy efficiency of each scheme

Scheme	Construction expenses/10 K yuan	Reciprocal and normalization treatment	Annual maintenance expenses/10 K yuan	Reciprocal and normalization treatment
I	222.46	0.62	10.70	0.75
II	356.28	0.38	31.39	0.25

Table 18 | Social efficiency weight and size of each LID facility

LID facility	Social efficiency weight	Size of Scheme I/m^2	Size of Scheme II/m^2
Permeable asphalt pavement	0.06	2,817	2,817
Permeable brick pavement	0.13	3,548	3,548
Sunken greenbelt	0.23	3,989	5,506
Rain garden	0.35	412	412
Green roof	0.23	/	3,322

Table 19 | Social efficiency of each scheme

Scheme	Social efficiency	Normalized processing value
I	1,691.93	0.38
II	2,804.9	0.62

Table 20 | Comprehensive score of each scheme

Scheme	I	II
Comprehensive score	0.49	0.51

divided into four sections according to the type of catchment area: parking and lane section, sidewalk and pedestrian square section, building section and green section, and then analyzed the LID facilities suitable for each area to provide theoretical guidance for the application of LID facilities. Next, taking the control rate of annual total runoff as the control target, the application scale of LID facilities was limited to make the formulation of the service area reconstruction schemes more accurate. Finally, due to the diversities of facilities in the process of scheme formulation, a variety of schemes were produced. Therefore, this paper constructed the evaluation system of service area reconstruction scheme, and selected the best scheme from three aspects of runoff control benefit, economic benefit and social benefit.

When formulating the service area schemes and evaluation system in this article, there are still strong subjective and empirical shortcomings. For example, the initial selection of the LID facility scales needed to be determined by trial algorithms. The weights of the evaluation system indicators based on the AHP were mainly determined by the experience of experts. These issues can be further studied in future work. However, this article has quantified the schemes to a certain extent, and improved the previous way of formulating the transformation plan based solely on experience. For example, the introduction of total runoff control targeted to quantify the overall scale of LID facilities, and the runoff control and construction cost value was used as a score, which truly reflected the control effect and economic benefits of the scheme.

CONCLUSIONS

(1) In this paper, the zoning characteristics of the service area and LID facility construction characteristics were analyzed to provide theoretical guidance for the scientific layout of LID facilities in sponge service area.
(2) In this paper, the annual total runoff control rate was taken as the main control target of sponge transformation in service area to control the scale of LID facilities. This method could replace the use of experience in the process of scheme formulation and avoid the problems of insufficient or excessive layout facilities;
(3) Based on the AHP, a set of evaluation systems of the LID scheme in the service area is established, which can quantify the advantages and disadvantages of the LID preliminary schemes, and provide support for determining the optimal construction scheme of the service area.
(4) Taking the Pu'er tunnel service area as an example, this paper sets out two service area reconstruction schemes. The runoff control effects of the two schemes are up to 80%. By comparing the two schemes through the evaluation system, the second scheme is found to be the

transformation scheme that achieves the best results in terms of runoff control, economic and social benefits.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

CJJ/T188-2012 *Technical Specification for Pavement of Water Permeable Brick*. China Architecture Publishing & Media Co., Ltd, 2012, Beijing.

Guide to the Design of Sponge City Construction Project in Kunming (Trial) 2016 Resource document. http://zfjs.km.gov.cn/c/2017-02-22/1710345.shtml.

Guo, J. 2017 *Research on Sponge City Idea and Its Application in Urban Waterlogging Planning*. Yangzhou University.

Li, L. & Dou, K. 2009 Research on the consistency of the judgement matrix in AHP. *Computer Technology and Development* **19** (10), 131–133.

Ministry of Housing and Urban-Rural Development of the People's Republic of China 2014 *The Construction Guideline of Sponge Cities in China – Low Impact Development of Stormwater Systems (trial)*.

Rodak, C. M., Moore, T. L., David, R., Jayakaran, A. D. & Vogel, J. R. 2019 Urban stormwater characterization, control, and treatment. *Water Environment Research* **91** (10), 1552–1586.

Seo, M., Jaber, F. & Srinivasan, R. 2017 Evaluating various low-impact development scenarios for optimal design criteria development. *Water* **9** (4), 270–288.

Son, C. H., Hyun, K. H., Kim, D., Baek, J. I. & Ban, Y. U. Ban 2017 Development and application of a low impact development (LID)-based district unit planning model. *Sustainability* **9** (1), 145–162.

Shafique, M. & Kim, R. 2017 Retrofitting the Low impact development practices into developed urban areas including barriers and potential solution. *Open Geosciences* **9** (1), 240–254.

Tao, T., Xiao, T., Wang, L. & Yan, H. 2019 Multi-objective optimization design of low impact development plan in sponge city construction. *Journal of Tongji University (Natural Science)* **47** (01), 92–96.

Wang, L., Chen, K., Tan, X. & Si, S. 2019 Application of SWMM model in sponge city planning. *Water & Wastewater Engineering* **55** (S1), 20–22.

Yazdi, M. Y., Ketabchy, M., Sample, D. J., Scott, D. & Liao, H. 2019 An evaluation of HSPF and SWMM for simulating streamflow regimes in an urban watershed. *Environmental Modelling and Software* **118**, 211–225.

Zhang, C.-j., Hu, Q., Zhang, Y., Wei, X., Wu, Y.-l. & Luo, S.-x. 2018 Study on sponge constructions during renovation of old residences. *Architecture Technology* **49** (02), 123–126.

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