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Optimal spatial layout of low-impact development practices based on SUSTAIN and NSGA-II

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ABSTRACT

The optimal spatial layout of low-impact development (LID) practices is the foundation and core of sponge city construction. Suitable LID facilities are selected in accordance with evaluation indices, such as runoff control, ecological benefit, stability, and cost. In this work, a system for urban stormwater treatment and analysis integration model is designed using a geographic information system. This model is solved using the non-dominated sorting genetic algorithm II to obtain a cost-effectiveness curve and an optimal spatial layout scheme. Results show that the reduction rates of rainwater runoff from LID facilities are 95% and 91% in the southern and northern watersheds, respectively, of the Huaiyuan campus of Ningxia University, Yinchuan, China. The construction costs are US$ 2.8 million and US$ 10.9 million in the southern and northern watersheds, respectively. This study is significant for reducing the risk of urban waterlogging, constructing urban ecological security patterns, and optimally allocating LID facilities.

Keywords: SUSTAIN; Low-impact development; Optimal spatial layout; NSGA-II; Geographic information system

1. Introduction

The rapid expansion of cities considerably increases impermeable areas and this phenomenon disturbs the original hydrological cycle processes and increases the risks of urban waterlogging and non-point source pollution. These problems seriously threaten human health, social stability, and economic development [1]. Therefore, sponge cities have been proposed and popularized to solve such urban problems. Sponge cities can infiltrate, store, absorb, and purify rainwater during rainy season and then release and utilize the stored rainwater during dry season using a construction model of low-impact development (LID) [2].

LID is an effective measure to control runoff and pollutants in sponge cities [3–5]. The hydrological processes of LID facilities can be simulated in accordance with the urban rainstorm management model (SWMM) and the hydrological simulation model [6,7]. These models play active roles in urban rainstorm runoff and LID simulation. However, they have limited functions and factors for spatially allocating LID facilities. Determining how to optimize the spatial layout of LID facilities is, therefore, an important issue for the construction of sponge cities [8,9]. The system for urban stormwater treatment and analysis integration (SUSTAIN) model can solve this problem. SUSTAIN is a decision support system developed by the American Environmental Research Institute for site selection, layout, simulation, and optimization of LID facilities. This model can comprehensively manage and analyze rainwater in watersheds at multiple scales in accordance with climate, meteorology, hydrology, soil, and land use on the ArcGIS 9.3 platform [10]. A visual

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cost–benefit curve can be produced in the SUSTAIN model on the basis of the economic efficiency of LID practices and the control objectives of water quality and quantity to provide various optimal alternative layout schemes.

The spatial layout of LID facilities involves not only meteorological, hydrological, geomorphological, and socioeconomic data but also multiple LID facilities, objectives, constraints, and schemes [11]. Many studies on LID layouts have been conducted to control runoff and pollution [12]. For example, Damodaram and Zechman [13] of A&M University in Texas analyzed the relationship between cost and peak flow using hydrological, hydraulic, and LID technical models and a genetic algorithm. Xu et al. [14] developed a marginal-cost-based greedy strategy to optimize the layout of LID facilities in the urban area of Suzhou and the new district of Xian, China, using the growth and gradual minimization of marginal costs. De Paola et al. [15] optimized LIDs using a harmony search approach to obtain cost-effective solutions with a reduction in the flooded and conveyed volumes. Liu et al. [16] selected and placed optimal best management practice and LID practices using the L-THIA-LID 2.1 model and optimization algorithms with decreases of 3.9–7.7 times of runoff/pollutant load and 4.2–14.5 times of practice cost compared with those under random placement of practices.

Geographic information system (GIS) has also been applied to control urban rainfall runoff [17]. Elliott and Trowsdale [18] embedded spatial modules of GIS, such as attribute, land use, and watershed, in the MOUSE model, which was developed by the Danish Hydraulic Research Center to accurately simulate urban drainage systems. Jia et al. [19] embedded GIS functions, such as data processing, spatial analysis, and thematic mapping, into the SWMM and SUSTAIN models to manage stormwater. Stephanie et al. [20] used Monte Carlo analysis and spatial patterns of GIS to predict that the LID facilities in Chesapeake Bay watershed can remove approximately 1,592 kg sediment, 3 kg phosphorus, and 78 kg nitrogen per km^2 on an annual basis. In summary, GIS can realize optimal spatial LID layouts through the former's spatial expression to compromise the construction cost and hydro-hydraulic objectives of LID practices [21].

In the present study, the Huaiyuan campus of Ningxia University, China, is selected to construct a SUSTAIN model. In this model, the decision variable is the scale of LID facilities, evaluation sites are regional outlets, and the evaluation factor is the annual runoff. Spatial simulation and optimization are conducted using a GIS and the non-dominated sorting and sharing genetic algorithm II (NSGA-II). An optimal cost–benefit scheme is obtained with the maximum reduction rate of rainwater runoff and minimum construction cost of LID facilities. This scheme can reduce the risk of urban waterlogging and provide decision-making for the optimal allocation of LID facilities and the spatial pattern of ecological security.

2. Materials and methods

2.1. Study area

The Huaiyuan campus of Ningxia University is located in Xixia District, Yinchuan, China, and has an area of 649,570 m^2. It has a temperate continental climate, and its annual average temperature, precipitation, and sunshine hours are 8.5°C, 200 mm and 2,800–3,000 h, respectively. Rainwater runoff in the campus is discharged into two rainwater pipe networks located in the northern and southern watersheds and drained away from the outlets. The land-use types include building, road, green land, water body, playground, and plaza, which account for 12.5%, 9.9%, 33.5%, 17.1%, 5.5%, and 21.5%, respectively, of the total area of the campus (Fig. 1). The impermeable region accounts for nearly 50% of the total campus area and results in increased total runoff, flow rate, flood peak, and pollutant load [22]. Therefore, a sponge campus should be constructed to maximize runoff reduction and enhance landscape aesthetics.

2.2. Determination of suitable positions of LID facilities

Basic data of the study area, such as meteorological data, land-use types, DEM, soil types, catchments, and rainwater pipe network, are collected and preprocessed for the construction of the SUSTAIN model (Table 1).

Evaluation indices of LID facilities are established to determine the suitable positions of each LID facility in accordance with the runoff control objective, relevant case studies, and characteristics of the LID facilities and the study area [23]. Seven indices, namely, location, soil, groundwater, terrain, watershed, and spatial and special requirements, are determined (Table 2). In the table, S_a includes sandy soil,

Fig. 1. Land-use types in the Huaiyuan campus of Ningxia University, China.

Table 1
Data sources for the SUSTAIN model

Data	Data description	Data source
DEM	Raster data(edem.tif)	Field investigation and spatial interpolation
Land-use type	Raster data(landu.tif)	Vectorization of remote sensing image
Land-use type table	Attribute table(LU-lookup.dbf)	Processing of basic data
Soil type	Shapefile data(soil.shp)	Field investigation
Soil-type table	Attribute table(soil.dbf)	Processing of basic data
Watersheds	Shapefile data(qu.shp)	Vectorization
Rainwater pipe network	Shapefile data(yushuijing.shp)	Field investigation
Rainfall per hour in 2016	Text(rain.dat)	Meteorological station
Meteorological data in 2016	Text(climate.swm)	Meteorological station
Groundwater level	Shapefile data(di_water.shp)	Collection and processing of basic data
Impervious layout	Raster data(imp.tif)	Collection and processing of basic data
LID cost database	Database(LIDCost.mdb)	Field investigation and literature collection

Table 2
Evaluation indices used to determine the suitable LID positions: soil type, slope, special requirement (Sr1), groundwater level (Gl), service area (S), impervious rate (Ir), and spatial requirement (Sr2)

LID	Soil	Slope \%	Sr1	Gl \m	S \ha	Ir	Sr2
Vegetation filter stripe	S_a, S_b, S_c, S_d	<5	Buffer of road and impervious surface <30 m	>0.61	–	>0	Middle
Grassed swale	S_a, S_b, S_c, S_d	0.5–5	Buffer of road and impervious surface <30 m	>0.61	<2	>0	Middle
Sand filtration	S_a, S_b, S_c, S_d	<10	Buffer of river >30 m	>0.61	<40	<0.5	Small
Green roof	–	<4	Flat roof	–	–	–	–
Rain barrel	–	–	Buffer of building <10 m	–	–	–	Small
Porous pavement	S_a, S_b	<1	–	>0.61	<1.2	>0	–
Bio-retention	S_a, S_b, S_c, S_d	<15	Buffers <3 m for building, <30 m for road and >30 m for river	>0.61	<1	<0.8	Small

loamy sand, and sandy loam; S_b includes silty loam and loam; S_c includes sandy clay loam and clay loam; and S_d includes sandy clay, silty clay, and clay. The spatial requirements are determined by the sizes of the actual watersheds. The candidate LID facilities, including vegetation filter stripe, grassed swale, sand filtration, rain barrel, green roof, porous pavement, and bioretention, are selected in accordance with the criteria in Table 2.

Another evaluation index system is established to select the most suitable LID types from the seven abovementioned LID facilities. The indices include efficacy of runoff control (runoff reduction and rainwater utilization), ecological benefit (ecological service and landscape aesthetics), stability (operational stability and design robustness), and cost (construction, maintenance, and management).

The green roof is removed from the candidate LID facilities because of the high maintenance and management costs it will entail in arid areas. The score of each evaluation index is determined in accordance with the LID functions, expertise, and actual situation of the study area. The scores of runoff reduction are between 0 and 24, whereas those of the other indices are between 0 and 5. Each index is graded and normalized to the interval of (0, 1) to eliminate the effects of different dimensions and order of magnitude as follows:

$$X_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

where X_{ij} is the normalized value of the jth factor in the ith index; $i = 1, 2, \dots m$; $j = 1, 2, \dots n$; x_{ij} is the initial score of the jth factor in the ith index; $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of each index, respectively.

The weights of runoff, rainwater utilization, and maintenance cost are set as 1.5, and the other indices are set as 1 in accordance with the expected objectives of the normalized indices. Finally, the total score of each LID facility is calculated using the weighted summation method. For example, the total score of porous pavement is calculated as follows: Score = 0.63 × 1.5 + 0.25 × 1.5 + 0.2 + 0.25 + 0.25 + 0.75 + 0.5 × 1.5 + 0.33 + 0.5 = 4.35.

The most suitable LID types are then determined on the basis of the high scores in Table 3. These types include vegetation filter stripe, grassed swale, rain barrel, porous pavement, and bioretention.

The suitable positions and types of LID facilities are visualized in the ArcGIS platform, as shown in Fig. 2. Bioretention is primarily distributed in the open green land with the largest area of the LID facilities. Grassed swales and vegetation filter stripes are primarily located on both sides of the roads and around plazas. Porous pavements are primarily constructed on the paths within communities, and sidewalks and parts of main roads. Rain barrels are installed within a 10-m-wide buffer of buildings.

Table 3
Total score of each LID facility

LID	Score
Vegetation filter stripe	6.04
Grassed swale	5.55
Sand filtration	1.35
Rain barrel	6.05
Porous pavement	4.35
Bio-retention	6.41

2.3. Construction of the SUSTAIN model

Two watersheds, namely, the southern living district and the northern teaching district, are divided using an artificial division method in accordance with the distributions of pipe networks and regional functions in the study area in constructing the SUSTAIN model. Twenty subcatchments in the southern watershed and 16 subcatchments in the northern watershed are further divided in accordance with land-use types (Fig. 3).

The rainwater networks of the watersheds are a separated drainage system. Inspection wells are located at turning points of pipelines, change points of different pipe diameters, access points of branch pipes, and intersection points of pipelines. The specific flow rates in the northern and southern watersheds are 0.875 and 0.926 L/(s ha), respectively. The average runoff coefficient is 0.6215, and the peak flow rates are between 1.021 and 2.277 m/s. The main pipe comprises reinforced concrete circular pipes with diameters of 700 and 800 mm.

Fig. 2. Suitable positions and types of LID facilities.

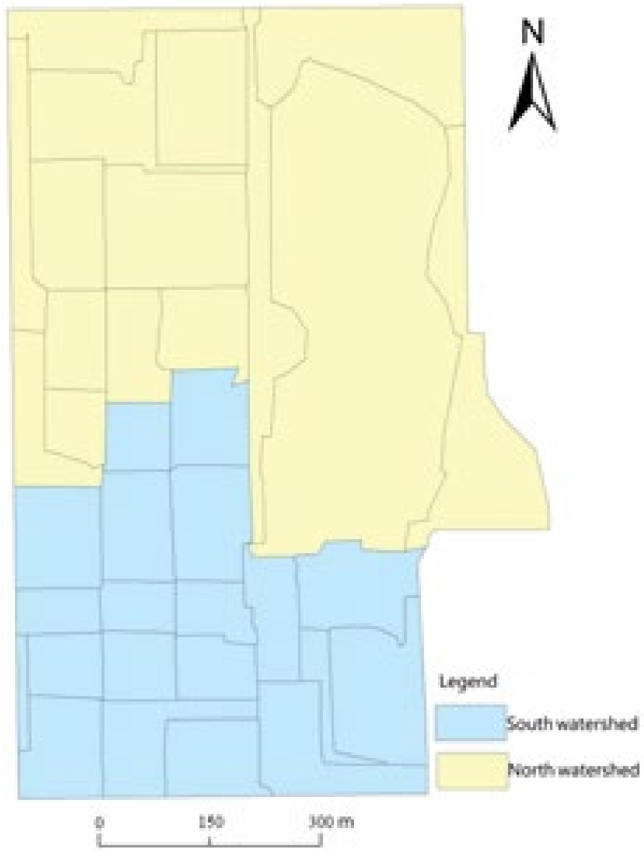

Fig. 3. Watersheds and subcatchments in the study area.

The parameters and cost of each LID facility are set as shown in Table 4. The cost of each LID facility in Table 4 is determined in accordance with the actual situation in Yinchuan, and the construction costs of the various LID facilities in Beijing, China, are obtained from the Technical Guidelines for Sponge City Construction. The decision variable is generally the size of each LID facility; the decision variable of the rain barrel is its number. The relationship between the size and performance of each LID facility is analyzed. The runoff loss in the rainwater pipe network is assumed to be 0 because of the small study area.

The simulation processes and methods of the SUSTAIN model are set as shown in Table 5.

2.4. Construction of a multi-objective model

The multi-objective function includes the minimum total cost and the maximum reduction rate of surface runoff from various LID practices.

The total cost of LID practices from construction, maintenance, and opportunity is calculated as follows:

$$\text{Min}E = \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{n=1}^{N} x_{lmn}E_{lmn}S_{lmn}\left[\left(1+i\right)^{P} + r_{lmn}\sum_{p=1}^{P}\left(1+i\right)^{(p-1)}\right] \tag{2}$$

where E is the total cost of various LID practices; E_{lmn} and S_{lmn} are the cost per unit area and the area of the nth land parcel in the mth LID facility of the lth subcatchment, respectively; $l = 1, 2, \ldots, L$; L is the number of subcatchments; $m = 1, 2, \ldots, M$; M is the number of LID facilities in the lth subcatchment; $n = 1, 2, \ldots, N$; N is the number of land parcels in the mth LID facility; x_{lmn} is a binary variable that indicates whether the mth LID facility is constructed on the nth land parcel of the lth subcatchment or not; r_{lmn} is the ratio of annual maintenance cost to construction cost of the nth land parcel in the mth LID facility of the lth subcatchment; i is the interest rate; $p = 1, 2, \ldots, P$ is the lifespan of each LID practice; and P is the design life of each LID facility.

The average reduction rate of surface runoff after LID practices is the percentage of runoff in the outlet after and before LID practices.

$$\text{Max}U = \frac{100}{L}\sum_{l=1}^{L}\left(1 - \frac{1}{V_l}\sum_{m=1}^{M}\sum_{n=1}^{N} x_{lmn}W_{lmn}\right) \tag{3}$$

where U is the average reduction rate of surface runoff; V_l is the runoff volume in the outlet of the lth subcatchment before LID practices; and W_{lmn} is the increased water storage of the nth land parcel of the mth LID practices on the lth subcatchment after LID practices.

Technical and physical constraints include design runoff, and shape change rate. The design runoff of each LID facility is calculated as follows:

$$D \le \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{n=1}^{N} \delta_{lmn}\mu_{lmn}S_{lmn}x_{lmn} \tag{4}$$

where D is the design runoff, L/s; S_{lmn} is the area of the nth land parcel in the mth LID facility of the lth subcatchment, ha; δ_{lmn} is the design storm intensity, L/(s.ha); and μ_{lmn} is the runoff coefficient.

The shape change rate of LID practices is calculated as follows:

$$-\varepsilon \le \frac{d\left(\sum_{m=1}^{M}\sum_{n=1}^{N} t\left(r\right)_{mn} x_{lmn}\right)}{dr} \le \varepsilon \tag{5}$$

where $\varepsilon > 0$ is the change rate of an LID shape; $t(r)_{mn}$ is the thickness t of the mth LID facility on the nth land parcel, which is a function of radius r, $t_{\min} \le t(r)_{mn} \le t_{\max}$; $t_{\min}$ and $t_{\max}$ are the minimum and maximum thicknesses of an LID facility, respectively.

All technical and physical variables are non-negative.

2.5. Design of NSGA-II

The multi-objective function under the SUSTAIN and GIS environments is solved by NSGA-II to obtain the optimal spatial layout scheme of the LID facilities. NSGA-II is a global search algorithm that mimics the evolutionary process of organisms [24]. Offspring is generated from the parent population by selection, crossover, and mutation [25]. The parent and offspring populations are merged and compete

Table 4
Parameters and cost of each LID facility

LID facility	Maximum scale (ft^2)	Increment of scale (ft^2)	Width (ft)	Length (ft)	Height (ft)	Cost ($)
Bio-retention	68,320	80	8	10	1	8.7/(ft^2)
Vegetation filter stripe	144,300	300	15	20	–	7/(ft^2)
Grassed swale	138,300	300	15	20	1	17.3/(ft^2)
Porous pavement	6,000	200	10	20	–	1.34/(ft^2)
Rain barrel	–	–	1.6	–	0.8	4.3/a rain barrel

Table 5
Simulation processes and methods of SUSTAIN model

Simulation process	Simulation method	Simulation process	Simulation method
Precipitation	Meteorological data	Erosion of non-depositional pollutants	Exponential scour curve
Snow melt	Degree-Day equation	Accumulation and erosion of sediments on the permeable surface	SEDMNT method
Evaporation	Constant evaporation rate and average monthly evaporation	Accumulation of sediments on the impervious surface	Exponential function cumulative formula
Surface runoff	Combined continuity equation and Manning equation	Erosion of sediments on the impervious surface	Exponential scour curve
Groundwater runoff	Two-zone groundwater model	Transmission of pollutants	Multistage serial, completely mixed and continuous stirred tank reactor (CSTR)
Overland flow	Nonlinear reservoir model	Elimination of pollutants	First-order degradation equation
Penetration	Green-Ampt method	Flow routing of buffers	Dynamic wave overland flow equation
Accumulation of non-depositional pollutants	Exponential function cumulative formula	Interception of pollutants in the buffers	VFSMOD algorithm

with each other using an elitist strategy to produce the next-generation population [24]. The algorithm can obtain optimal or approximate optimal solutions quickly and accurately. A shared function is used to evenly distribute the solutions for the most cost-effective scenario [26]. The Pareto optimality is approximated after the entire population is continuously updated using NSGA-II.

The pseudocode of NSGA-II is depicted as follows.

- Step 1. A parent population P_0 of size N is initialized randomly as a fitness value for each solution
  Members in P_0 are sorted on the basis of non-domination relationship.
  The offspring population Q_0 of size N is generated using the operators of selection, crossover, and mutation

- Step 2. Non-dominated sorting for population P
  for m in P
  for n in P
  if m dominates n then
  S_m.append(n)
  if m is dominated by n then
  p_m += 1
  if no solution dominates m then
  Current front Frontier$_1$.append(m)
  $i = 1$
  while Frontier$_i$ is a nonempty set and a separate list H is an empty set
  for m in Frontier$_i$
  for n in S_n
  Modify each member from the set S_n
  p_n −= 1
  if $q_n = 0$ then H.append(n)
  i += 1
  Current front Frontier$_i$ is formed with all members of the newly determined front H.
  The population P_{i+1} of size $2N$ is created with a combination of P_i and S_i.
  P_{i+1} is sorted in accordance with non-dominant partial-order relationship

- Step 3. Crowding distance comparison operator
  Number of solutions j = len(J)
  For j in J
  Initialize distance j.distance = 0
  For each objective function(k) in function list

Individual distances for function(k) is calculated and summed
J = sort(J, function(k))
J[0].distance = J[len[J]−1].distance = ∞ to select boundary points on each front
for all other points j = 2 *to* (J−1)
K[j].distance = K[j].distance + (function(J[j + 1]) − function(J[j−1])) /($f_{\max}$[j + 1]) − $f_{\min}$[j + 1]))

- Step 4. Constraints handling
  Two solutions (A and B) are selected randomly using the binary tournament selection method.
  The two solutions are compared with each other to determine that A is better than B according to the following conditions
- A and B are all feasible and A dominates B
- A is feasible and B is infeasible
- A and B are infeasible, however, amount of constraint violation from A is less than that from B

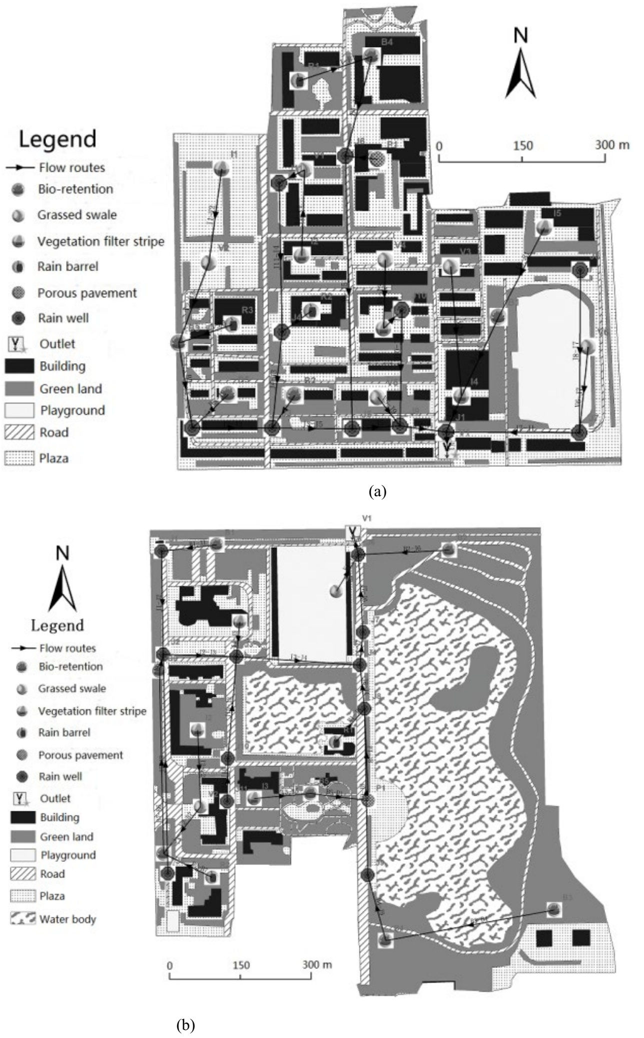

Fig. 4. Optimal spatial LID layout schemes in the southern (a) and northern (b) watersheds.

- Step 5. Sort the population P_{i+1} in descending order
  All points in Frontier$_1$ are selected for the P_{i+1} if the size of Frontier$_1$ is smaller than N
  Choose the first N elements of P_{i+1}
  Choose the remaining members of the P_{i+1} from the next non-dominated front
  P_{i+1} is applied for selection, crossover, and mutation to generate an offspring population S_{i+1}

- Step 6. Repeat until the maximum iterations are reached or the optimal solutions and the Pareto frontier are obtained.

3. Results and discussion

The outlets of the northern and southern watersheds are selected as the evaluation points, and the scale of each LID facility is selected as the decision variable. The annual runoff reduction is selected as the optimization factor. Runoff infiltration is simulated using the Green-Ampt method. The SUSTAIN model is solved using meteorological data and the NSGA-II to generate the optimal spatial LID scenarios.

Fig. 4 shows the optimal layout schemes for the LID facilities in the northern and southern watersheds of the study area. Bioretentions are arranged within large green spaces and between buildings with small building density. Rain barrels are installed around the buildings with large building density. Main roads and sidewalks are retrofitted using porous pavement. Vegetation filter stripes and grassed swales are constructed in the gardens. The areas of vegetation filter stripes, porous pavements, grassed swales, and bioretentions account for 1%, 7%, 11%, and 81% in the southern watershed and for 5%, 36%, 1%, and 58% in the northern watershed, respectively, of the total areas of LID facilities (Table 6).

The cost–benefit curves of the LID facility layouts in the northern and southern catchments are obtained from more than 10,000 simulations (Fig. 5). Each point represents an LID scheme in Fig. 5. The Pareto frontiers of the optimal LID schemes in the southern (Fig. 5a) and northern (Fig. 5b) watersheds are obtained as shown in black points in Fig. 5. The Pareto frontiers have the highest reduction rate of rainwater runoff under the same cost or the lowest cost under the same reduction rate of rainwater runoff [27]. The highlighted black point on the upper left area of Fig. 5a is the best scheme for the southern watershed, with construction costs of US$ 2.8 million and an annual surface runoff reduction rate of 95%, as shown in Fig. 4a. The highlighted black point on the upper left part of Fig. 5b is the best scheme for the northern watershed, with construction costs of US$ 10.9 million and an annual surface runoff reduction rate of 91% (Fig. 4b).

The performance of NSGA-II in obtaining the optimal LID layout is validated using a 64-bit Windows 10 operating system with the following processor specifications: Inter (R) Core (TM) i7-4710MQ, 8G memory and CPU@2.50 GHz 2.50 GB. After 21 run times of the NSGA-II, the average running time is determined to be 423.26 ms with an average iteration number of 10,038.

Table 6
Number and cost (million dollars) of LID facilities for the optimal LID schemes in the southern and northern watersheds, as shown in Fig. 4

LID facility	Southern watershed		Northern watershed	
	Number	Cost	Number	Cost
Bio-retention	3,259	2.27	9,086	6.32
Vegetation filter stripe	133	0.03	519	0.10
Porous pavement	7,314	0.20	20,342	0.55
Grassed swale	59	0.30	756	3.93

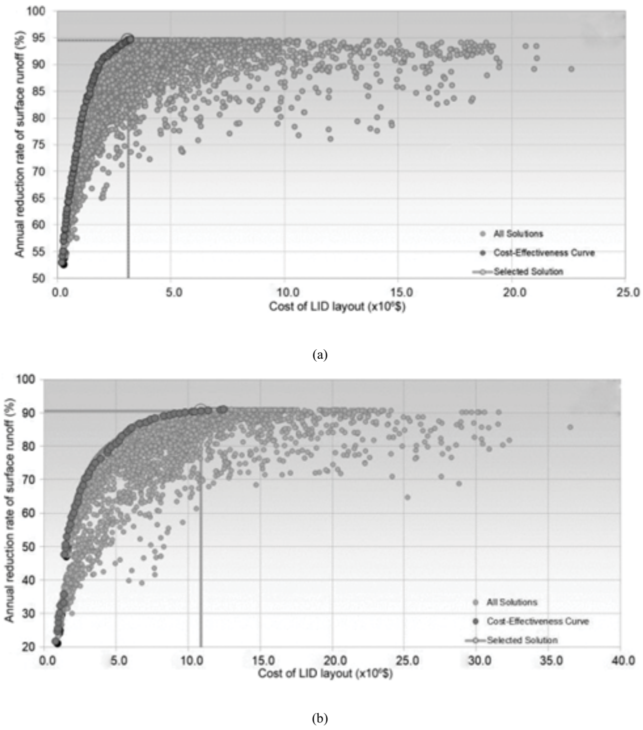

Fig. 5. Cost–benefit curves of the LID layouts in the southern (a) and northern (b) watersheds.

4. Conclusions

Suitable LID facilities are selected on the basis of evaluation indices, such as runoff control, ecological benefit, stability, and cost. A SUSTAIN model is established in a GIS environment. A multi-objective model that includes the minimum total cost and the maximum reduction rate of surface runoff of LID practices is constructed, and NSGA-II is applied to optimize the spatial layout of LID facilities. Visual cost–benefit curves with Pareto frontiers in the southern and northern watersheds of the study area are presented. Optimal spatial layout schemes of the LID facilities are selected on the basis of the expected goal.

The construction costs of the optimal LID schemes are US$ 10.9 million in the northern watershed and US$ 2.8 million in the southern watershed of the Huaiyuan campus of Ningxia University. The reduction rates of rainwater runoff can reach 91% in the northern watershed and 95% in the southern watershed. The optimal spatial layouts of LID facilities can reduce the frequency of waterlogging and the influence of rainfall runoff on these regions to improve the water quality of runoff and protect the ecological environment at minimum cost.

Bioretentions are primarily distributed in large green spaces and between buildings with small building density. Vegetation filter stripes and grassed swales are located in fragmented green lands. Porous pavements are allocated in main roads and sidewalks. Bioretention in the southern watershed occupies 81% of the construction area and consumes US$ 2.27 million in construction cost. Furthermore, bioretention in the northern watershed occupies 58% of the construction area and consumes US$ 6.32 million in construction cost. These results are significant for the selection and layout of LID facilities in arid and semi-arid regions.

This study also has certain deficiencies. The evaluation indices of LID facilities may be incomplete relative to the actual conditions in arid and semi-arid areas because some parameters of the LID facilities in the model are set in accordance with foreign standards. Moreover, the reduction rate of runoff pollutants is disregarded in this study. These problems need to be solved in future works.

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