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Multi-objective Optimization Design of Low Impact Development Combining SWMM Model and NSGA-Ⅱ Method - Take a neighborhood in Beijing as an example

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ABSTRACT

Urbanization is increasing the proportion of surface imperviousness, resulting in frequent urban waterlogging and in turn, triggers water pollution and ecological degradation. The establishment of low impact development (LID) facilities can effectively mitigate the impacts while generating multiple ecosystem service benefits, which is important in the context of climate change and dual carbon. This study proposes a many-objective optimization framework to optimize the layout of LID facilities. Firstly, the costs and ecosystem service benefits of different LID facilities are monetized to obtain the net cost. Secondly, runoff and water quality pollution are simulated to obtain the corresponding reduction and removal rates via the SWMM model. The total runoff control rate is combined with the net cost to form a dual-objective function. The optimal paving ratio layout of LID is acquired using the elite non-dominated sorted genetic algorithm (NSGA-II). Deterministic scenario simulation and optimization are carried out in Beijing Zijing Yayuan neighborhood as an example. The results show that the excess carbon released during construction of the permeable paving scenario increases net cost pressure, but its runoff reduction rates and water quality pollution removal rates perform well. The final optimization scenario can realize conflicting trade-offs between objectives, which can reduce direct cost inputs by up to 3.2*105 RMB and ecological compensation inputs by 1.5*105 RMB when the minimum total runoff control rate and pollutant removal rate are achieved. This study contributes to supporting decision-making stormwater management scenarios and highlights the effectiveness of permeability for flooding mitigation.

Keywords: SWMM model, NSGA-II algorithm, Ecosystem service value, Low impact development, Multi-objective optimization

1. INTRODUCTION

Climate change has led to the frequency and quantity of stormwater. The waterlogging which is triggered poses a great threat to human lives and economic assets [1]. With the development of urbanization, the underlying surface ratio increases, and the initial land coverage is gradually replaced by impervious surface [2,3]. The enhancement of rainfall runoff makes the city susceptible to urban flooding during the rainy season. The growth of runoff rates results in ecological degradation. Besides, substantial amounts of pollutants are carried into urban water bodies, triggering environmental problems such as pollution of water-decent sources [4,5].

Low impact development (LID) concept is mainly concentrated on the control of stormwater runoff and surface pollution sources, which aims at reducing runoff from the source while avoiding the impact of the construction process on nature [6].

To rationally model the quantity and quality of water in urban watersheds, the SWMM model can be used as an event-based continuous runoff simulation [7,8]. In particular, the current version of SWMM allows the modeling of hydrological performance for typical LID control [9]. Moreover, the data entry is simpler than other simulation models for non-powered pollution loads, making it a more consolidated urban stormwater simulation model. Embedding the SWMM model into an optimization algorithm is a commonly used way to achieve the optimal layout of LID facilities. Scholars at home and abroad mainly evaluate the optimal setting of

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LID in the multi-objective case by employing the annealing algorithm, PSO particle swarm algorithm, non-dominated sorted genetic (NSGA-II) algorithm, genetic algorithm (GA), combinatorial algorithm models, etc. [10-12]. Nonetheless, the shortcomings of some algorithms are notable, for instance, the PSO algorithm is prone to local optimality in the end due to the initial setting of fewer population parameters, which leads to a very fast convergence rate [13]. The NSGA-II algorithm, instead, improves the NSGA algorithm and shows many advantages. For example, the non-inferiority sorting genetic algorithm is no longer overly complex, and the sampling space is enlarged to avoid losing the best individuals.

There is already much research on simulating and optimizing the layout of LID using stormwater management models coupled with optimization algorithms, however, little consideration has been given to the synergistic realization of environmental benefits and other objectives. Since the identification of ecosystem service benefits of LID facilities is of great significance in their application, it is urgent to seek a more integrated simulation and optimization framework for LID facilities.

Therefore, this study constructs a comprehensive objective optimization system from the perspective of the ecosystem service benefits of LID. Combined with the SWMM model stormwater design, the integrated benefits under various scenarios are compared. Ultimately, by embedding the NSGA-II optimization algorithm, the optimization scenarios with different objective orientations are obtained to achieve the scientific layout configuration of LID facilities in the study area.

2. METHODS

2.1 Study area

Zijing Yayuan is located in Tongzhou District, Beijing, completed in 2001, covering an area of 11.80 hectares. The overall terrain is relatively gentle, with slopes in the northern, southern, and central parts of the district, and an average slope of 1.39%. The original area has no recessed green space, permeable paving, and other facilities, which can be roughly divided into road, roof, and green space underlay.

2.2 Stormwater management model

The Storm Water Management Model (SWMM) is a model that can dynamically characterize the simulations of rainfall runoff. According to the topography and drainage pipeline data, the study area can be generalized into 930 sub-catchments.

The design of rainfall is based on the Beijing storm intensity formula, for simulating rainfall events under different return periods. On the basic Chicago rainfall rain pattern design, the value of 0.4 is taken as the rain peak coefficient to design the return period P. In this study, the 2-hour short-calendar time design rainfall pattern is used to construct the rainfall time series of 1-in-1-year, 1-in-5-year, and 1-in-10-year, which also serves as the input of rainfall for the various design scenarios.

2.3 LID laying scenarios

Table 1 LID laying program options

Option	Type and area of LID
A	No LID facilities
B	Recessed green space (13336.22 m^2)
C	Permeable paving (89300.09 m^2)
D	Green roof (7055.46 m^2)
E	Rain garden (13336.22 m^2)
F	Recessed green space (11341.28m^2) + Permeable paving (89300.09 m^2) + Green roof (7055.46 m^2) + Rain garden (1994.94m^2)

Depending on the distribution of buildings in the study area and the applicability of LID facilities, four types of LID facilities are adopted in this study: permeable paving, recessed green space, rain garden, and green roof. Pervious paving can be installed on road surfaces. Recessed green spaces and rain gardens can be set in green spaces. Green roofs can be installed on rooftops. Only one type of LID facility will be placed in each sub-catchment to ensure the effectiveness and continuity of the facilities.

2.4 Optimization module

2.4.1 Optimization variables and constraints

The optimization variable is the percentage of area in the sub-catchment where LID facilities are laid. The construction area of each LID facility in the study area should fluctuate within the maximum value of the corresponding underlying surfaces.

2.4.2 Optimization objectives

2.4.2.1 Runoff reduction

Runoff reductions are obtained by comparing runoff volumes under different LID scenarios and base scenarios.

2.4.2.2 Water quality pollution control

Water quality pollution control ability is obtained by the difference in COD, TN, and TP removal for different LID scenarios compared to the base scenario.

2.4.2.3 Ecosystem service benefits

The value of ecosystem services includes carbon benefits, urban heat island mitigation, air pollution control, and noise reduction, which are calculated utilizing the corresponding empirical formulas.

2.4.2.4 Cost

In the process of investment and construction of LID facilities, there are two main parts of the cost, which are the one-time input cost of the construction process, and the management and maintenance cost of the subsequent maintenance process. This study compiles a list of costs with reference to the manuals and the literature, assuming that the maintenance life is 30 years.

2.4.3 Solution process

The NSGA-II algorithm is invoked in MATLAB, then the objective is set with the custom function and cost function as the variables. The number of iterations is 40. The population size is 80. The decision variable takes values ranging from 0 to 1.

3. RESULTS AND DISSCUSSION

3.1 Deterministic scenario analysis

Errors for all scenarios in terms of surface runoff, flow algorithms, and water quality algorithms are within manageable limits.

2.4.1 Runoff reduction

The rank of magnitude for the runoff reduction rates of the five LID laying scenarios remained constant throughout the three rainfall return periods, with the optimal to least optimal scenarios being the Integrated Adjustment Scenario, the Permeable Paving Scenario, the Undercroft Scenario, the Rain Garden Scenario, and the Green Roof Scenario. As the return period of the storm increases, the difference in the effects of the respective LID facilities decreases.

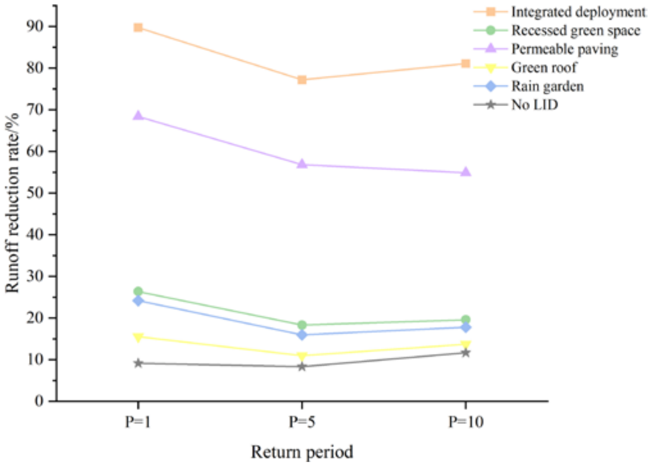

Fig. 1 Runoff reduction of LID scenarios under different return periods

2.4.2 Water Quality Pollution Control

The stronger the storm, the worse the removal of each pollutant by the permeable pavers. The other scenarios performed best at P=1 return period, followed by P=10. Overall it is still Scenario F and Scenario C that have better pollutant removal. In terms of the difference in removal rates for each pollutant, the percentage difference between Scenario F and Scenario C is as high as 31.07% (P=10). The three scenarios B, D, and E remained ineffective in the removal of pollutants.

2.4.3 Ecosystem service benefits

Carbon benefits (Fig. 2) from rain gardens are highest when a mono-LID facility is paved. Carbon emissions are much higher than carbon sinks in the permeable paving scenario, requiring additional expenditure on carbon treatment.

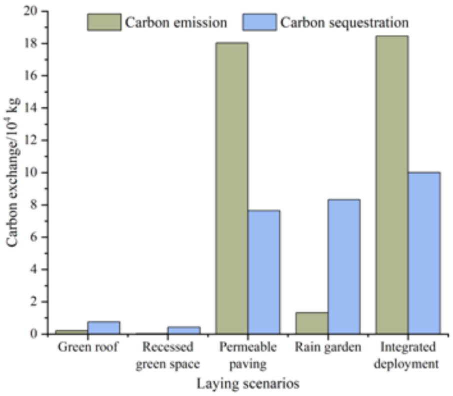

Fig. 2 Carbon exchange under different scenarios

Constructed green roofs and retrofitted permeable pavements reduce architectural energy consumption and cool ambient air, therefore ameliorating the urban heat island effect. The benefits of mitigating the urban heat island are 18.54 RMB, 234.681 RMB, and 253.22 RMB per year for the green roof scenario, the permeable pavement scenario, and the integrated adjustment scenario, respectively.

The value of air pollution reduction per year for the green roof scenario, the recessed green space scenario, the rain garden scenario, and the integrated adjustment scenario in the study area is 630.48 RMB, 1,191.72 RMB, 1,191.72 RMB, and 1,822.20 RMB per year, respectively, based on the added pollution-absorbing function of green spaces in the study area according to the different scenarios of the laying of LID facilities.

The ability to reduce noise exists only when there is a certain height of vegetation covering the ground surface, as accounted for by the rain garden scenario and the comprehensive adjustment scenario with annual benefits of 221.08 RMB and 137.76 RMB.

Taking one year as a time cycle, the capital required to be invested in different LID facilities is calculated with reference to their cost lists, and the ecosystem service value is made to add or subtract the capital in the form of compensation (Fig. 3). The monetized ecosystem service value of the permeable paving scenario is negative, while the ecosystem service value of the rain garden is significant, reaching a maximum cost improvement ratio of 0.55.

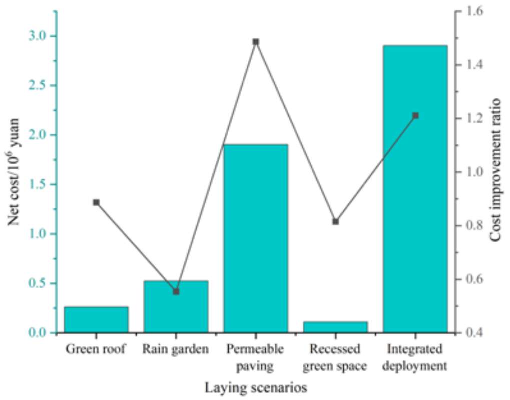

Fig. 3 Net cost and cost improvement ratio under different scenarios

3.2 Optimization module analysis

Based on the overall results of the scenario simulations, the permeable paving scenario is selected for optimization in this study. The decision variable is the percentage of permeable paving laid in each sub-catchment, and the NSGA-II algorithm is used to optimize the gross runoff control rate and net cost. Taking 30 years as the operation cycle, the figure below (Fig. 4) represents the scatter points corresponding to the gross runoff control rate and net cost of the non-dominated individuals after 40 iterations and constitutes a Pareto-optimal curve.

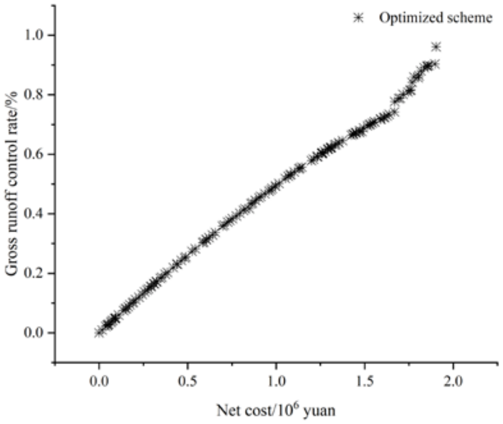

Fig. 4 Pareto-optimal curve

As shown in Table 2, the recommended scenarios resulting from the objective optimization tend to achieve relatively higher gross runoff control and lower net cost inputs than the deterministic paving scenarios, while satisfying different goal-oriented choices and providing options for trade-offs among conflicting relationships of the objectives. After optimizing the proportions, the maximum reduction in direct cost inputs of $3.2*10^5$ RMB and ecological compensation inputs of $1.5*10^5$ RMB can be achieved when the minimum gross runoff control rate and water quality pollution removal rate are met. Therefore, the optimization scenario is more effective for the deterministic scenario in the actual layout.

Table 2 Optimized deployment scheme for permeable paving

Scheme	Laying ratio/%	Total runoff control rate /%	pollutants removal rate /%
1	66.08	66.47	41.42
2	80.51	70.13	44.50
3	90.18	80.16	49.09
4	99.67	90.35	50.15

Scheme	Ecosystem compensation /10^6 RMB	Cost/10^6 RMB	Net Cost/10^6 RMB
1	0.47	0.96	0.49
2	0.50	1.03	0.53
3	0.56	1.15	0.59
4	0.62	1.28	0.66

4. CONCLUSIONS

In this study, different LID facility deployment scenarios are first established based on the SWMM model to compare the differences in runoff, water quality, ecosystem service benefits, and costs under different storm return periods. After selecting the most appropriate scenario, the NSGA-II algorithm is used to invoke the SWMM model to obtain the optimal LID facility laying ratio under the selected scenario, with gross runoff control rate and net cost as the bi-objective function. In terms of runoff reduction, each LID facility paving scenario has the highest reduction rate at P=1, and an increase in the return period will reduce the extent of runoff reduction by LID facilities. For the control of water quality pollutants COD, TN, and TP, the paving scenarios for each LID facility had lower removal rates at P=5 relative to other return periods. In addition, the scenarios have different preferences for removal rates of different types of contaminants. Optimization of the permeable paving scenario in the scenario simulation can reduce direct cost inputs by up to $3.2*10^5$ RMB and ecological compensation inputs by up to $1.5*10^5$ RMB when the minimum gross runoff control rate and pollutant removal rate are met.

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DECLARATION OF INTEREST STATEMENT

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

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