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Planning of LID–BMPs for urban runoff control: The case of Beijing Olympic Village

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ABSTRACT

In this paper, a planning analysis of implementing low impact development (LID) type of stormwater best management practices (BMPs) for urban runoff control is presented. The Beijing Olympic Village (BOV) residential area in China was used as a case study. The original BOV stormwater system incorporated some LID BMPs such as porous pavements, green roofs and rainwater cisterns. After the 2008 Olympics, the BOV was converted to a residential complex and some stormwater facilities were modified for landscaping purposes. The performance of the original stormwater management system at the BOV residential area was first evaluated by using the model BMPDSS. BMPDSS is a best management practice (BMP) planning and analysis tool, which is capable of simulating BMP performance and optimizing BMP placement and design. The Storm Water Management Model (SWMM) was used to simulate pipe network hydraulics for the BOV. The present study then examined the performance associated with the BMP modifications for landscaping purposes, and then further BMP modifications designed for enhancing runoff control capabilities of the system. Using the 2008 rainfall data for Beijing, peak flow rate and runoff volume reductions under the three scenarios were calculated by using the coupled SWMM–BMPDSS framework and compared. Optimization analysis for BMP design aimed at achieving either maximum runoff control or total minimum system cost was then conducted. The results were used to form recommendations to the Beijing authorities for modifying the present stormwater management system in order to achieve more runoff control benefits.

1. Introduction

Presently, China is experiencing a very rapid process of urbanization, which brings adverse impact on the water environment. As a result, urban runoff quantity and quality control has emerged as a key concern for municipal officials [1,2]. One of the strategies for mitigating the impact of urbanization is the use of LID–BMPs for urban stormwater runoff quality and quantity control [3,4]. Before implementing the various BMPs, however, it is important, and necessary, to find the most cost-effective selection, design and placement of BMPs [5,6].

In the present study, a BMP implementation planning analysis was conducted using the Beijing Olympic Village (BOV) residential area as a case study. The BOV was used to house athletics from around the world during the 2008 Beijing Summer Olympic Games and has since been converted to a residential complex. Some stormwater management practices were already in place, such as porous pavements, green roofs and rainwater cisterns. In the present study, various types of BMPs were first assessed to determine their suitability for use under local conditions in terms of both technical and economic considerations. The coupled SWMM–BMPDSS model was then used to calculate runoff peak rate and volume reductions under the three aforementioned planning scenarios. Using the local 2008 rainfall data, quantitative estimates of runoff volume and peak reduction rates under the three planning scenarios were obtained. Comparative reduction rates for selected types of LID–BMPs were then calculated. Finally, a BMP optimization analysis was made to find the type and design specifications of BMPs that would provide the most cost-effective, the best reduction rate for runoff control at the BOV. Results of this study would be very useful to the authorities in their planning process for improving the runoff control capabilities of the BOV stormwater management system.

2. Description of the Olympic Village site

The Beijing Olympic Village is located at the north fringe of the main Olympic Stadium, or “Bird Nest” complex (see Fig. 1), which lies in the north central part of Beijing City. The BOV occupies an area of 36 ha, which includes residential, apartments and auxiliary facilities. Land uses in the BOV include 40% of the area for green spaces. There are 42 high-rise residential buildings; five public buildings; and a few leisure clubs. Fig. 2 shows the land use

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Fig. 1. Location of the Beijing Olympic Village (BOV) (below the lower left corner of the Olympic Forest Park).

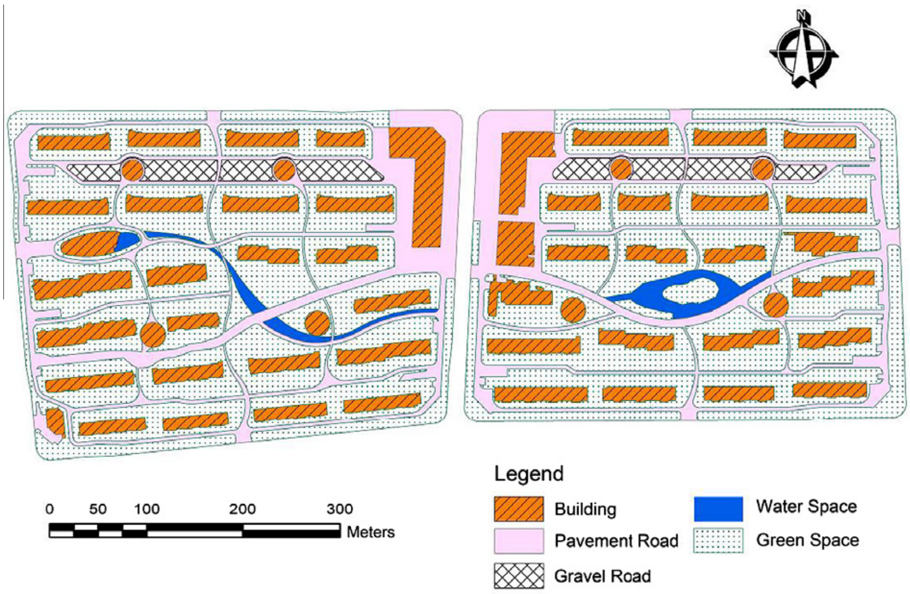

Fig. 2. Beijing Olympic Village land use map.

characteristics of the BOV area. A separate sewer system was built, with runoff generated from the BOV discharged into the City's drainage network via 10 outlet points (see Fig. 3).

The BOV was designed and built as a demonstration of the "green community" concept. However, the thrust of the original "green" design was more on landscaping beauty and rainwater

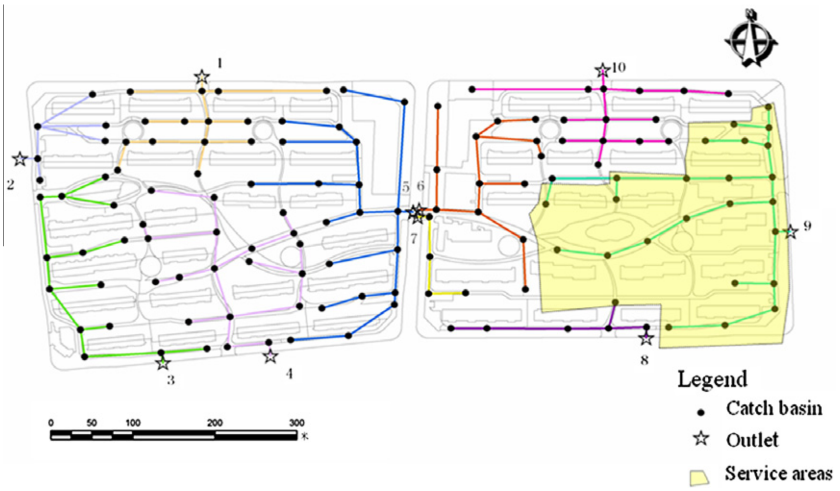

Fig. 3. The layout of BOV's drainage network outlets.

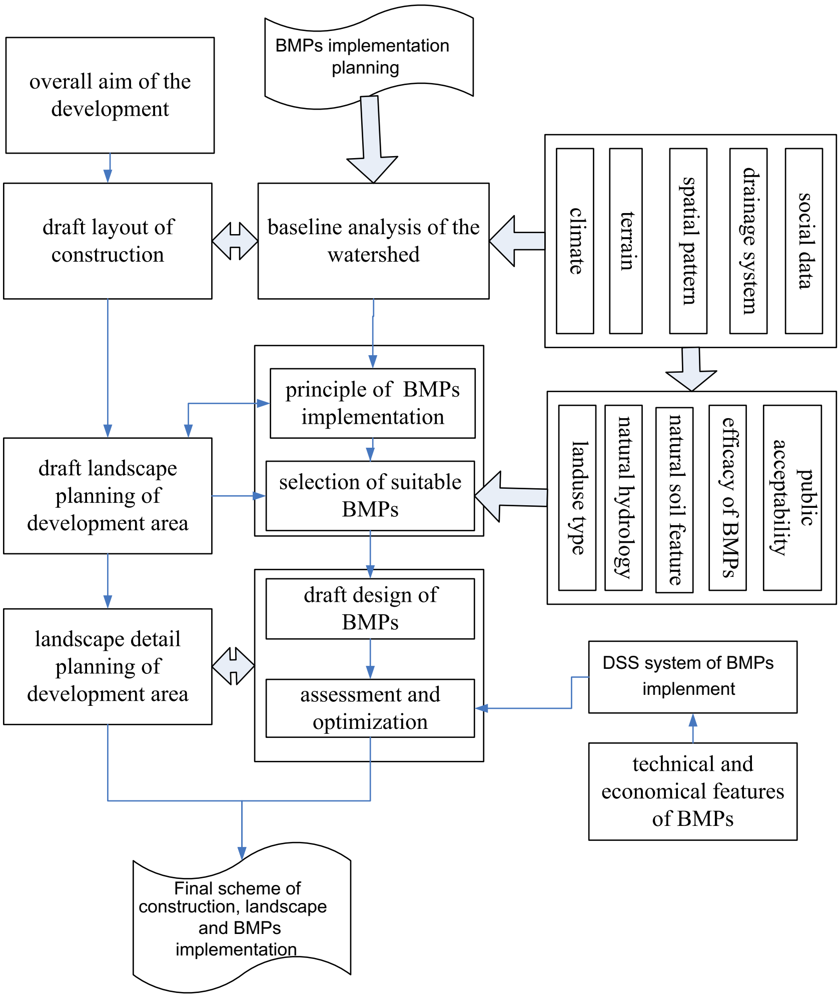

Fig. 4. The framework of BMPs implementation planning.

storage than urban flood control and water quality benefits. The exiting rainwater management system did include some "LID-type" BMPs such as green roofs and porous pavements. However, each facility was designed individually according to local runoff control guidelines and no "system-wide" or synergetic performance was considered. Also, no system-wide assessment of runoff control performance was implemented thus far, as research on stormwater management practices and the collection of necessary

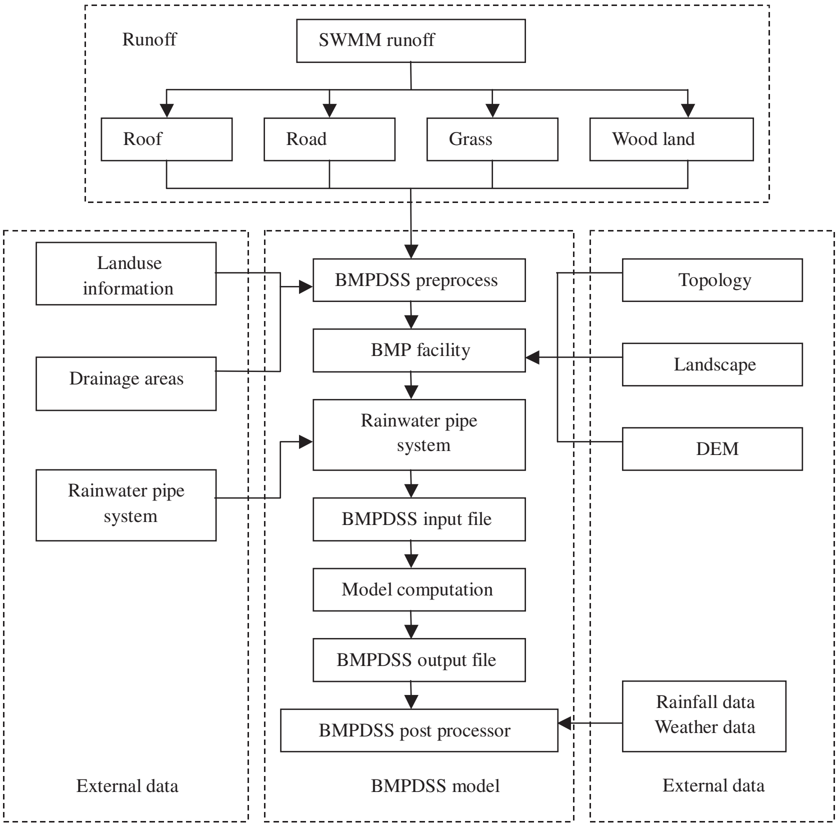

Fig. 5. The SWMM–BMPDSS modeling structure.

Fig. 6. Layout of stormwater practices at the Beijing Olympic Village.

urban runoff data are just beginning to receive general attention in China [7–9]. Consequently, there lies an opportunity to use the BOV study to demonstrate the use of modeling techniques for the evaluation of urban runoff systems for retrofit and/or expansion opportunities in order to gain enhanced runoff control benefits.

3. The LID–BMPs planning analysis framework

The thrust of a watershed-based BMP planning analysis is the evaluation of the "combined", or synergic, effect of all the BMPs installed in the watershed at a prescribed evaluation point or points. The evaluation point could be the outlet of a watershed or any selected point or points upstream. In general, the planning analysis would include the following main elements:

- Baseline analysis – watershed climate, terrain, development, etc. and their spatial variations; natural and manmade drainage systems, and relevant social/economical information.
- BMP planning – selection and preliminary placement of BMPs. Data on the efficacy of various BMPs; construction and maintenance costs; watershed hydrology, soil characteristics and land uses, and public acceptance information are needed.
- BMP design, assessment and optimization – a preliminary design of BMPs, in terms of the placement, type and size, is assessed by using an analysis tool such as BMPDSS. The optimization analysis will help determine the final BMP design.

The BMP planning framework is depicted in Fig. 4 and some details of the planning process are described in the following sections.

3.1. Baseline analysis of the watershed

For the purpose of implementing LID practices, appropriate BMPs types, sizes and spatial layout should be designed in concert with the overall development site construction and associated landscape planning. Relevant information for the development areas need to be collected and analyzed, such as climate, terrain, spatial distribution pattern and the drainage system of the development area, and social/economic data, etc.

3.2. The principles of LID–BMPs implementation

The LID–BMP implementation should be fully coordinated with the local construction plan and be integrated, if possible, into the site landscaping scheme. The main principles of LID–BMP planning usually include (1) preserve the original terrain, (2) limit the ratio of impervious surface areas, (3) avoid the direct connection of impervious areas, (4) select the most suitable BMP types according to local conditions in terms of both technical and social/economic factors, and (5) set an appropriate goal for the LID–BMP implementation.

3.3. Selections of suitable BMPs

The suitability of each BMP for use at any location should be determined in accordance to local social/economic conditions. Such conditions include land use, natural hydrology and soil feature, areas of sub-watersheds, slope of the development region, and the desired effects of development. Public acceptability is also an important consideration.

3.4. Preliminary design of BMPs

The preliminary design of BMPs in development region could be made based on the suitability of different BMPs, natural conditions of the development site and the landscape planning features.

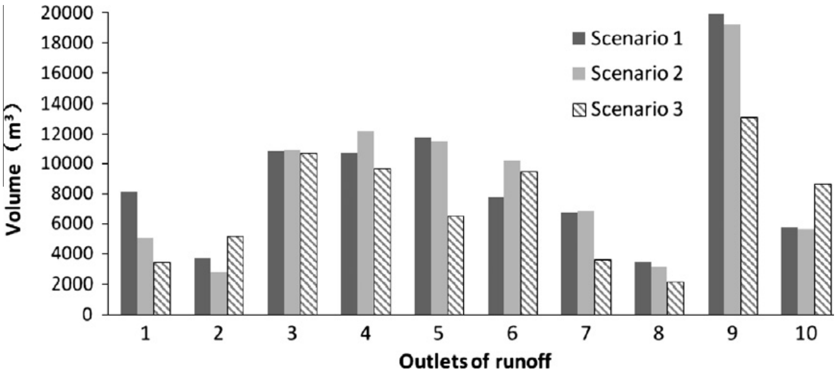

Fig. 7. Runoff volume at BOV outlet points under various scenarios.

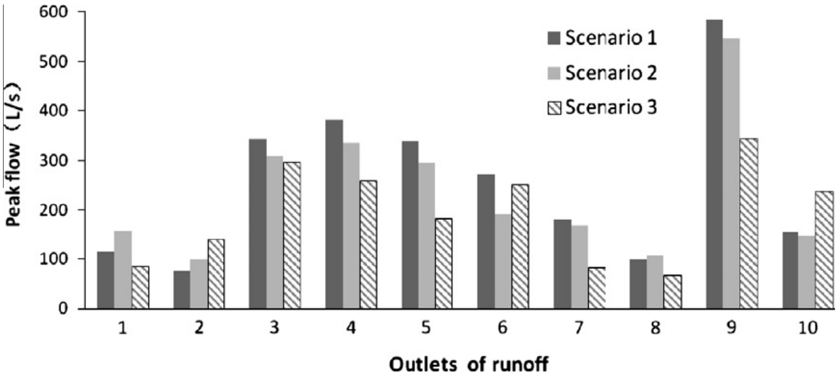

Fig. 8. Peak flow rate at BOV outlet points under various scenarios.

3.5. Assessment and optimization of BMPs

In order to achieve the best benefits, assessment and optimization tools were needed to evaluate the effectiveness of the BMPs. To support the decision making of BMPs planning, the tools should integrate the urban runoff simulation model; economical and technical feature data for various BMPs, GIS database, and the optimization module. In this study, the SWMM model and the BMPDSS tool were coupled and used for the assessment and optimization of different BMP scenarios.

3.6. Final scheme of construction, landscape and BMPs implementation

After the BMP planning assessment and scenario optimization, a "best", in terms of cost-effectiveness; control target, etc., LID–BMPs implementation plan could be proposed to the decision-making entity. The runoff control scheme can then be integrated into the overall construction and landscape design master plan at the development or retrofit site.

4. BMP planning analysis

4.1. Selection of analysis tools

In selecting an appropriate analysis tool for the BOV BMPs evaluation study, consideration was given to models that have the capability of simulating storm sewer networks and also various LID-types of BMPs. The Storm Water Management Model, SWMM, and the BMP Decision Support System, BMPDSS, were eventually selected.

SWMM is a widely used stormwater simulation model developed for USEPA [10]. It can be used for single-event to long-term simulation of the surface runoff/subsurface runoff quantity and quality from primarily urban/suburban areas. SWMM contains a flexible set of hydraulic modeling capabilities used to route runoff and external inflows through the drainage system network of pipes, channels, storage/treatment units and diversion structures.

BMPDSS was jointly developed to support analysis and decision making for stormwater management planning and design at both the site scale and the watershed levels by the USEPA and the Prince George's County [11]. It is a decision-making tool for placing BMPs at strategic locations in urban watersheds on the basis of integrated data collection and hydrologic, hydraulic, and water quality modeling. It has specific functions of BMP facilities control simulation and optimization module for decision support analysis of urban BMPs planning and placement analysis [12].

4.2. Coupling of the SWMM and BMPDSS models

In order to enhance the capabilities of BMPDSS in analyzing complex hydraulic conditions in urban sewer networks, the SWMM model was coupled with BMPDSS to support the LID–BMP simulation and optimization. The coupled SWMM–BMPDSS modeling structure is shown in Fig. 5. The SWMM module was used to generate the time series data of surface runoff from different types of land uses such as roof, road, grass and wooded areas. The runoff time series data were then used as input to the BMPDSS Model for analyzing BMPs placement and optimization.

4.3. Input data preparation

Input to SWMM includes local hydro-meteorological data and surface quantity data such as topography, drainage systems, etc. Using the above data, along with land use, soil and terrain data, time series data of surface runoff from specific land use can be generated. In addition to the runoff time series data, BMPDSS would require data for BMP types and specifications, costs and also available locations for installing various types of BMPs.

The long-term average annual rainfall in Beijing is 603.6 mm, with rainfall mostly occurring during the months of May to September. The Year 2008 had a total rainfall of 602.6 mm and was chosen as a "representative" year for the present analysis. Data on topography; the current drainage system, design details for the existing BMPs and cost were obtained from the Beijing Municipal Government.

5. Analysis scenarios and results

5.1. Analysis scenarios

For the analysis of the BOV stormwater system wide performance, three basic scenarios were set as follows:

Scenario 1: Original scheme – under original conditions, there were several types of rainwater management practices in place, namely, green roofs; porous pavements; infiltration trenches; rain barrels, and green space or lawns. The main design objective for the facilities was flood mitigation and rainwater utilization.

Scenario 2: Landscape Improvement Plan – under the landscaping improvement plan, which was devised for the transformation of the athletic village to a residential complex, was included the increase of green spaces; the reduction of paved roads, and the enhancement of the green roofs and the green spaces. It aimed at improving landscape features.

Scenario 3: Recommended Plan – the plan with additional and/or modified LID BMPs based on consideration of LID design principles, such as re-routing roof runoff through green spaces before entering the rain barrels; increasing the detention times of storage facilities, and the use of properly designed bioretention cells.

Fig. 6 depicts the layout of stormwater facilities under the original conditions.

5.2. Scenarios simulation results

For the present study, the target index for evaluating system performance was runoff quantity, which included total stromwater runoff volume and the peak flow rate. For each scenario, these quantities were calculated at a total of 10 outlet points of the BOV drainage system that are entry points to the Beijing City drainage network. Rainfall data used in the analyses were from Year 2008, which was considered as a 'representative" year for the Beijing area in terms of total rainfall amount and the seasonal distribution of rainfall.

The SWMM–BMPDSS models were then used to process the hourly rainfall and other necessary data to generate runoff volumes and peak flow rates at the 10 outlet points from the BOV under each of the three scenarios described above. The results can be summarized as follows:

(1) For total runoff volume, under Scenario 3 (Recommended Plan), 27% more volume reduction would be achieved compared to that under Scenario 1 (existing scheme) and 21% more volume reduction compared to that under Scenario 2 (landscaping improvement plan). The results are shown in Fig. 7.

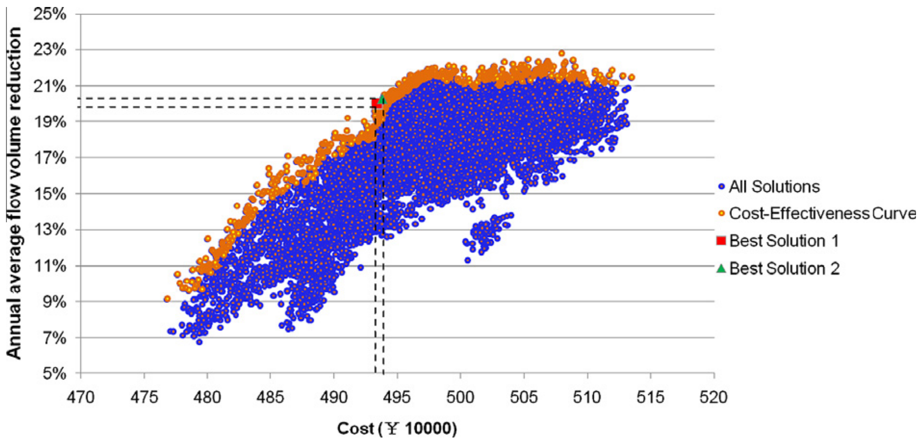

Fig. 9. Optimization result for minimizing cost.

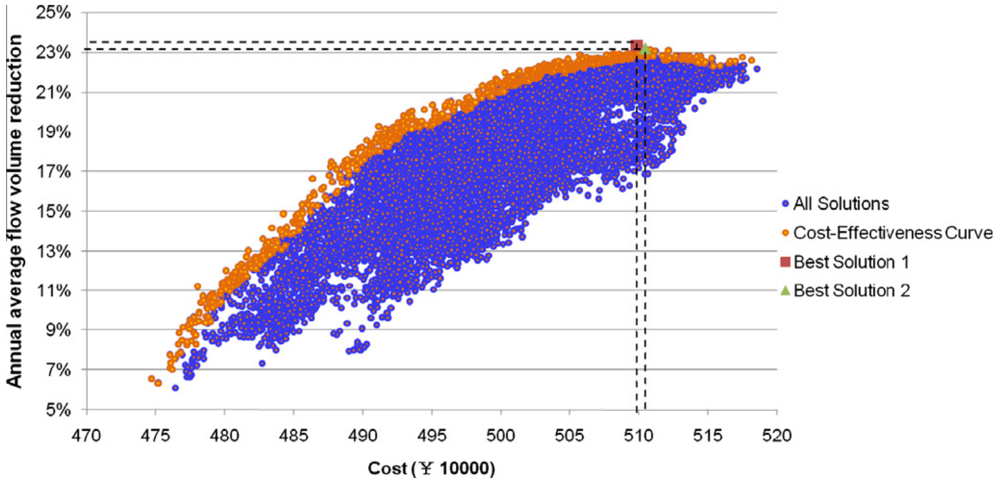

Fig. 10. Optimization result for maximizing benefit.

Table 1
The comparison of BMPs sizes before and after optimization.

BMPs		Scenario 3	Optimal (best solution 1)	
			Maximize benefit	Minimize cost
Green roof	Area	50%	35%	27%
	Soil depth	0.3 m	0.6 m	0.6 m
Bioretention	Area	26%	24%	7%
	Weir height	0.3 m	1.0 m	0.8 m
	Soil depth	0.3 m	0.8 m	0.8 m
Infiltration trench	Area	100%	67%	40%
	Soil depth	0.5 m	0.6 m	0.6 m
Rain barrel	Diameter	1.8 m	1.0 m	0.4 m
	Weir height	1.8 m	1.6 m	0.9 m

(2) For peak flow rate, under Scenario 3 (Recommended Plan), 21% more peak flow rate reduction would be achieved compared to that under Scenario 1, and a 17% more reduction under Scenario 2. The results are shown in Fig. 8.

The results clearly showed that by properly designing and implementing the LID-type of BMPs for the BOV residential complex, significant higher runoff volume and peak flow reductions could be realized.

5.3. BMP optimization

In the scenario analysis described above, the BMP sizes were kept the same as those of the original installation (Scenario 1). In order to demonstrate whether the BMP designs could be revised for better system performance or lower costs, the optimization module of BMPDSS was used to assess BMP performance in a subarea of the BOV. The subarea selected was the service area of Outlet #9 (See Fig. 3). Several BMP types, i.e., infiltration trenches, green roofs, rain barrels and bioretention cells were placed in this subarea as those under Scenario 3. In the optimization analysis, the sizes of BMPs were allowed to vary in order to provide an optimal solution in terms of system performance and cost.

To formulate an optimization problem, BMPDSS requires the user to specify four sets of information: decision variables, assessment points and evaluation factors, management targets, and the BMP cost functions. The decision variables include length, width, depth of BMPs, e.g., the diameter of a rain barrel, etc. According to information collected for local stormwater facilities, construction costs for on-ground facilities and on-roof ones were estimated to be 500 and 700 Yuan RMB per cubic meter, respectively [13].

Two optimization targets were set for the present analysis:

(1) Minimizing cost target:

The annual average flow volume was selected as the evaluation factor, and the control target was set at 20% reduction of the value under Scenario 3. The stopping criterion was set as a 100 Yuan RMB cost reduction, which means that the search will be stopped if the cost of the next best solutions found does not show a reduction of at least 100 Yuan RMB. The results are shown in Fig. 9. In the figure, the *X*-axis shows the construction cost and the *Y*-axis shows the annual average flow volume reduction percent of the value under Scenario 3.

It can be seen that the annual average flow volume reduction of the best solution 1 (the "knee-of-curve" point) was 20.02%, and the corresponding cost was 4.934 million Yuan RMB. The annual average flow volume reduction of another possible solution, solution 2 was 20.28%, and the corresponding cost was 4.938 million Yuan RMB.

(1) Maximizing benefits as the target:

The annual average flow volume was also selected as the evaluate factor in this run. The stopping criterion was set as a 1% reduction, which means that the search will be stopped if the control benefit of the best solutions found does not show a reduction of at least 1%. The results are shown in Fig. 10.

The annual average flow volume reduction of the best solution 1 (the "knee-of-curve" point) was 23.33%, and the corresponding cost was 5.099 million Yuan RMB. The annual average flow volume reduction of best solution 2 was 23.19%, and the corresponding cost was 5.105 million Yuan RMB.

The results indicate that with an increase of 165 thousand Yuan RMB, the system could generate an increase of roughly 3% more runoff volume reduction. Whether this additional benefit justifies the increase in expenditure should be dependent on a further examination of how much impact would a 1% runoff reduction cause. For example, a recent survey conducted in China [14] showed that a majority of potential home buyers would be willing to pay more for "green" features such as scenery ponds, etc. Since many LID type of BMPs, e.g., bioretention cells, swales, pond/wetland systems, could "double-up" as waterscapes (e.g., bioretention cells as flower beds), there may be a good justification for enhanced BMP installations.

After the optimization analysis, the optimal sizes of all the BMPs were found. A comparison of the sizes of BMPs between those under Scenario 3 and those obtained through the optimization runs is summarized in Table 1. It can be seen from Table 1 that the optimal sizes off BMPs are generally smaller than those under Scenario 3. For example, the green roof size was reduced from covering 50% of the roof area to almost half (27%) under the minimum cost scenario, and the rain barrel diameter was reduced from 1.8 m to 0.4 m, etc.

6. Conclusions

Along with the rapid urbanization in China, urban woes have occurred and have been great concerns of many city officials and the general public. Among these urban problems, the negative impact of urban runoff on hydrology and water quality is among the most serious ones. The present study examined the use of low impact development (LID) practices in mitigating urban runoff impacts. The BOV, which was built as a demonstration of the "green community" concept, was selected as a case study to analyze the benefits of optimized LID BMP implementation on reducing runoff volume and peak rates. The coupled SWMM–BMPDSS model was used for the analysis. The results showed that compared to the existing condition, the recommended BMP plan would cause a 27% and 21% reduction for total runoff volume and the peak flow rate, respectively. Using the optimization module of BMPDSS, the sizes of BMPs could be further reduced and still meet the target of minimizing cost or maximizing benefits. The research results could lead to useful recommendations for modifying the present stormwater management system at the BOV, and also at other urban sites, in order to achieve more runoff control benefits.

Acknowledgments

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