Development of a multi-criteria index ranking system for urban runoff best management practices (BMPs) selection

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Abstract Low impact development best management practices (LID-BMPs) are considered to be cost-effective measures for mitigating the water quantity and quality impact of urban runoff. Currently, there are many types of LID-BMPs, and each type has its own intrinsic technical and/or economical characteristics and limitations for implementation. The selection of the most appropriate BMP type(s) for a specific installation site is therefore a very important planning step. In the present study, a multi-criteria selection index system (MCIS) for LID-BMP planning was developed. The selection indexes include 12 first-level indices and 26 second-level indices which reflect the specific installation site characteristics pertaining to site suitability, runoff control performance, and economics of implementation. A mechanism for ranking the BMPs was devised. First, each individual second-level index was assigned a numeric value that was based on site characteristics and information on LID-BMPs. The quantified indices were normalized and then integrated to obtain the score for each of the first-level index. The final evaluation scores of each LID-BMP were then calculated based on the scores for the first-level indices. Finally, the appropriate BMP types for a specific installation site were determined according to the rank of the final evaluation scores. In order to facilitate the application of the MCIS BMP ranking system, the computational process has been coded into a software program, BMPSELEC. A case study demonstrating the MCIS methodology, using an LID-BMP implementation planning at a college campus in Foshan, Guangdong Province, is presented.

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Introduction

Excessive runoff caused by dramatic increase of impervious area is causing flooding in urban areas, and water quality deterioration in receiving water bodies. Best management practices (BMPs) are a means for mitigating the deleterious impact of excessive runoff. However, there are many types of BMPs and potential installation sites available, and the selection process of suitable BMP types is

complex in nature given the variability in site conditions, performance, and cost of BMPs. It is therefore very helpful to stormwater management practitioners to have a BMP selection and placement tool, or decision support aid, in the BMP planning and design process so that the most cost-effective BMP installation plan can be obtained (Zhen and Yu 2004; Gitau et al. 2004).

A number of BMP planning/design decision support systems have been developed in recent years. Most notably are the GIS-based Best Management Practice Decision Support System (BMPDSS) (Cheng et al. 2009; Jia et al. 2012) and the System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) systems (Shoemaker et al. 2009). Both BMPDSS and SUSTAIN provide multiple-scale (site, region, and watershed) applications, detailed BMP process simulations, and cost optimization analyses. More recently, Viavattene et al. (2010) presented a front-end BMP tool that is includes process-based BMP assessment and a multi-criteria analysis for BMP selection. Such comprehensive and highly technical analysis tools would be very helpful to decision makers in selecting the final BMP planning strategy prior to design and implementation. However, in some situations, it could also be adequate to use a simpler tool for BMP selection, much like the use of a one-dimensional as opposed to a two- or three-dimensional model. A simpler analysis can also be used as a preliminary or "screening" tool that would facilitate the complex modeling process involved with the use of BMPDSS, etc. For example, Young et al. (2010) introduced the analytical hierarchal process (AHP) as an analytical framework for BMP selection, through priority ranking of stormwater control objectives and BMP performance metrics. Using the AHP, a BMP priority ranking is accomplished through the construction of pairwise relative rankings of the selection criteria and then of the BMPs themselves against the respective selection criteria.

This paper describes the development of a multi-criteria index ranking system to facilitate BMP selection. The ranking system established a framework that integrates all aspects of the BMP evaluation processes for a comprehensive screening level analysis that assist the decision making in selecting BMPs (USEPA 2004b; Zhen and Yu 2004; Young et al. 2010).

Development of the multi-criteria index system for BMP ranking

Development of the multi-criteria index system (MCIS) involves four steps. The first step was to establish the basic or key criteria categories that the selection system was based upon. In this study, BMP site suitability, runoff control benefits, and cost and maintenance are the three basic categories considered in formulating the MCIS. The suitable BMPs are first selected according to the site suitability criteria, and then these selected BMPs are further evaluated and ranked according to the indices in runoff control benefits category and cost and maintenance category. The technical route map of MCIS for BMPs ranking is illustrated in Fig 1.
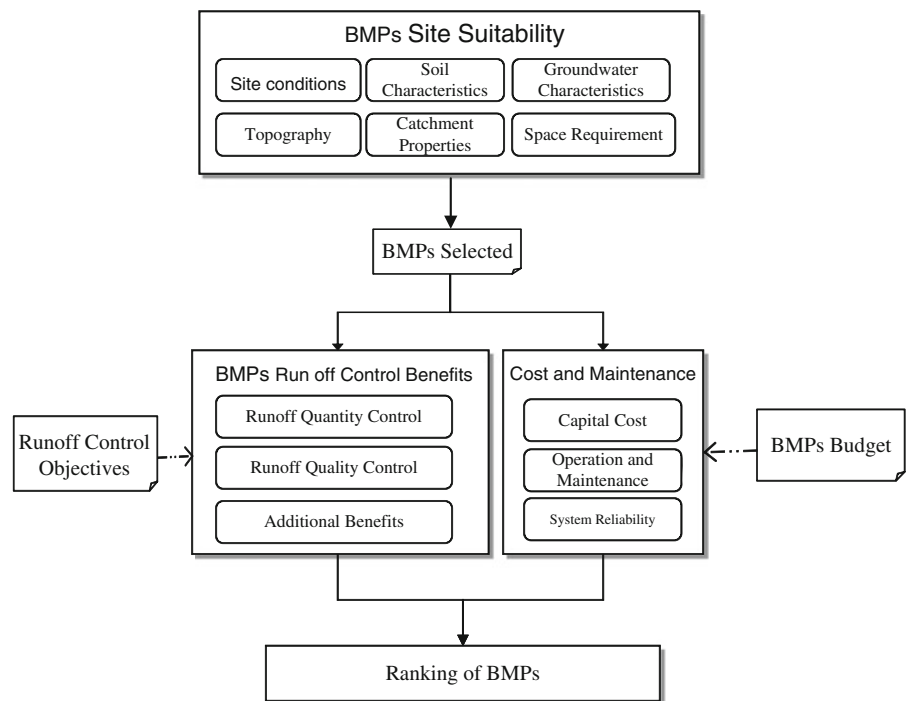
The second step was to select a level of index factors within each criteria category. Each of the selected index factors was further broken down into several second-level index factors. The third step was to establish the benchmark of each index, and the fourth step was to develop a ranking mechanism that integrates every index factor. Details of each of the four steps are described in the following sections.

Determine criteria categories

The main intent of the MCIS development is to provide a simple, yet comprehensive tool for selecting BMPs. MCIS can be used as a screening tool for a preliminary siting and BMP implementation plan. The results can then be incorporated into a more rigorous and complete decision support tool such as SUSTAIN for final BMP selection and design. On the other hand, for circumstances under which a simpler approach is acceptable or even preferred, the MCIS can be used as a convenient tool for BMP planning and implementation. It is with the latter objective in mind that the three key criteria categories were determined, i.e., site suitability, runoff control performance, and cost considerations. With these basic considerations, the MCIS could be used as a stand-alone tool for selecting the most cost-effective BMPs.

Of the three key criteria categories, the site suitability criterion is aimed at screening the various BMPs for appropriateness at the site, while the runoff control and the cost criteria categories are assessment tools for comparing the appropriate BMPs so that one or more cost-effective BMPs could be determined.

Select first- and second-level indexes for each criteria category

Site suitability category

In the site suitability category, a total of six first-level and nine second-level index factors were established for the screening of available BMPs. The hierarchal structure of the index factors is described below and is illustrated in Fig. 2.

1. Site conditions

   (a) Land use type

   Some BMPs are appropriate for certain land use types. Examples include porous pavements for parking lots; underground biofilter boxes for highly impervious downtown commercial districts, etc. Land use types considered in the present study and their assigned codes are listed in Table 1 (The Ministry of Construction, PRC 1991).

   (b) Pollutant loading

   Pollutant type and loading intensity in development site are important factors in BMP selection.

   (c) Special requirements

   These refer to recommendations or requirements set forth by authorities regarding BMP implementation. Examples include buffer distance from buildings; proximity from water bodies and alongside of highways, roads, etc.

2. Soil characteristics

   Soil characteristics are classified in accordance to the USDA SCS Hydrologic Soil Group definitions, namely the A, B, C, and D soil groups. The soil classifications and the corresponding soil characteristics are listed in Table 2 (USDA NRCS 1986).

3. Groundwater characteristics

   The depth of the groundwater table is used to characterize groundwater characteristics, which would present limitations of some BMPs use due to pollution concerns.
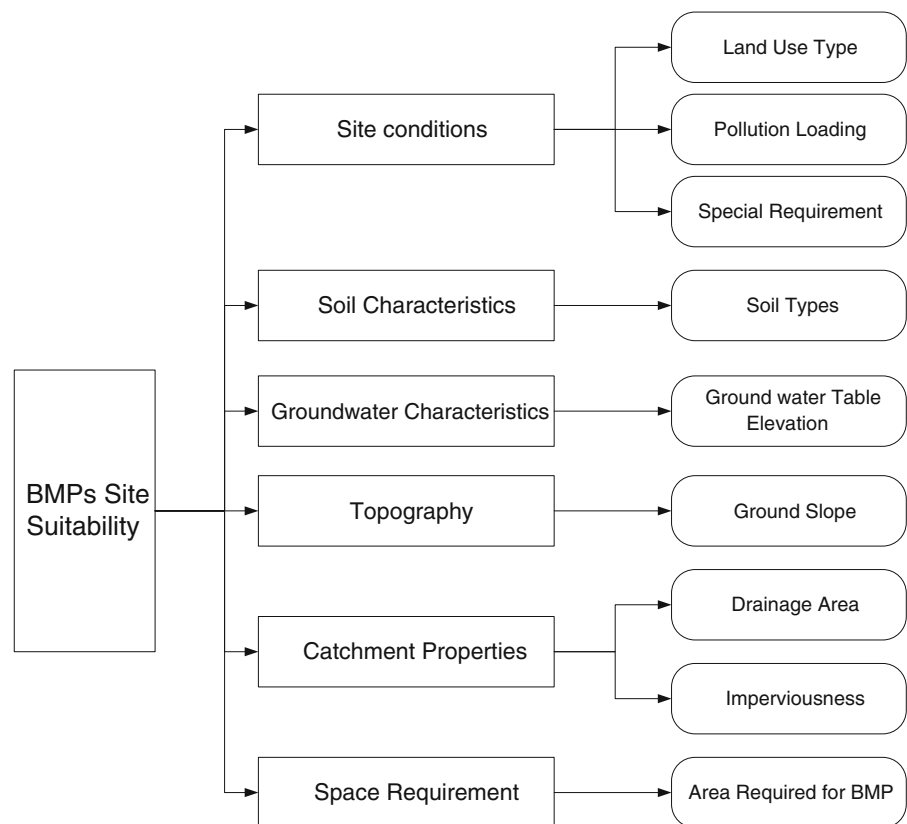
4. Topography

   Ground slope is the most important factor in BMP selection. It is used as the index factor in the study.

5. Catchment properties

   The main catchment properties considered are drainage area and the imperviousness area in the

Fig. 2 Indicators of BMP
site suitability

catchment. Drainage area is a key factor in sizing a
BMP. And the ratio of imperviousness area is the
main consideration factor for BMP selection.
Some BMPs are more suited than others for highly
impervious or ultra-urban areas.

6. Space requirement

   The sizes of surface areas required by each type
   of BMPs are different, such as constructed wet-
   lands require a relatively larger surface area in
   order to achieve the desired performance goals.
   So, the area required for BMP is used as the
   index factor.

Runoff control benefits category

Runoff control performance refers to the mitigating
effects of BMPs on runoff water quantity and quality.
There are three first-level performance indicators,
namely, runoff quantity control, runoff quality control,
and additional benefits. The first-level indicators are
further divided into 12 second-level indicators as
shown in Fig. 3.

1. Runoff quantity control

   The second-level indicators include runoff vol-
   ume reduction, peak flow delay, and flow rate re-
   duction. Different types of BMPs have different
   performances on runoff volume reduction, peak
   flow delay, and flow rate reduction because of the
   different detention storage characteristics. These
   data were summarized in Tables 3 and 4 which were
   obtained by synthesizing information available in
   the literature (USEPA 1999; Baptista et al. 2001; Li
   and Huang 2002; Revitt et al. 2003; Scholes et al.
   2005). Table 3 lists control effectiveness associated
   with various BMP processes, or mechanisms.
   Table 4 was derived from Table 3 based on the
   processes that occurred in various BMP.

2. Runoff quality control

   The second-level indicators include suspended
   sediments removal, oxygen-depletion materials
   removal, bacteria and viruses removal, nutrients
   removal, heavy metal removal, and toxic organic
   compounds removal. These indicators all are the
   pollutants that contained in urban runoff. As

Table 1 Land use types

Code	Category	Contents
R	Residential	Single and multiple family housing developments, residential districts, and neighborhoods
C	Commercial and public facilities	Administrative offices, commercial, financial districts, cultural and recreational areas, sports and medical facilities, nursing homes, schools, research and design institutions
M	Industrial, manufacturing	All forms of industrial, manufacturing and ancillary facilities including plants, warehouses, transport systems, etc.
T	Transportation	Urban transportation systems including railway, highway, pipeline transport, port, airport and their ancillary facilities
S	Road, street public square	Municipal and connecting roads, squares and parking lots
G	Green spaces	Municipal, regional, residential public and protective green space, not including special green space, garden, and woodlands

Table 2 Soil types

Code	Soil type	Characteristics
A	Sandy clay, loamy sand, sandy loam	Soils have low runoff coefficient and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sands or gravels
B	Silty loam, loam	Soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures
C	Sandy clay loam	Soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture
D	Clay loam, sandy clay, silty clay, clay	Soils have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material

shown in Table 3 and 4, different types of BMPs have different performances on these pollutants removal because of the different processes that occurred. These processes include sedimentation, adsorption, infiltration, filtration, plant uptake, evapotranspiration and volatilization, and microbial degradation. And some of the processes which occurred in various BMPs are interlinked when different target pollutants are removed in different types of BMPs.

3. Additional benefits

The second-level indicators include rainwater capture and reuse, ecological benefits, and aesthetic benefits. Different types of BMPs have different performances on these additional benefits, such as rain barrel has the high benefit of rainwater capture and reuse, and bioretention cells and constructed wetlands also bring about ecological and aesthetic benefits.

BMP cost and maintenance category

In this category, BMP cost includes capital investment cost and operational/maintenance costs. Another first-

level indicator is "system reliability," defined as the robustness in BMP design, reliability of the system in meeting design goals and the risks of system failure, etc. There are three first-level indicators, which are divided into five second-level indicators, as listed below and shown in Fig. 4.

1. Capital cost

Construction cost is used as the index factor. It should be noted that in many situations, land costs can be an important factor, especially in highly urbanized areas.

2. Operation and maintenance

It includes operation costs and maintenance costs. Operation costs refer to the personnel as well as material costs required in the operation of the BMPs. And maintenance costs refer to personnel, material and replacement part costs required for maintaining BMP performance.
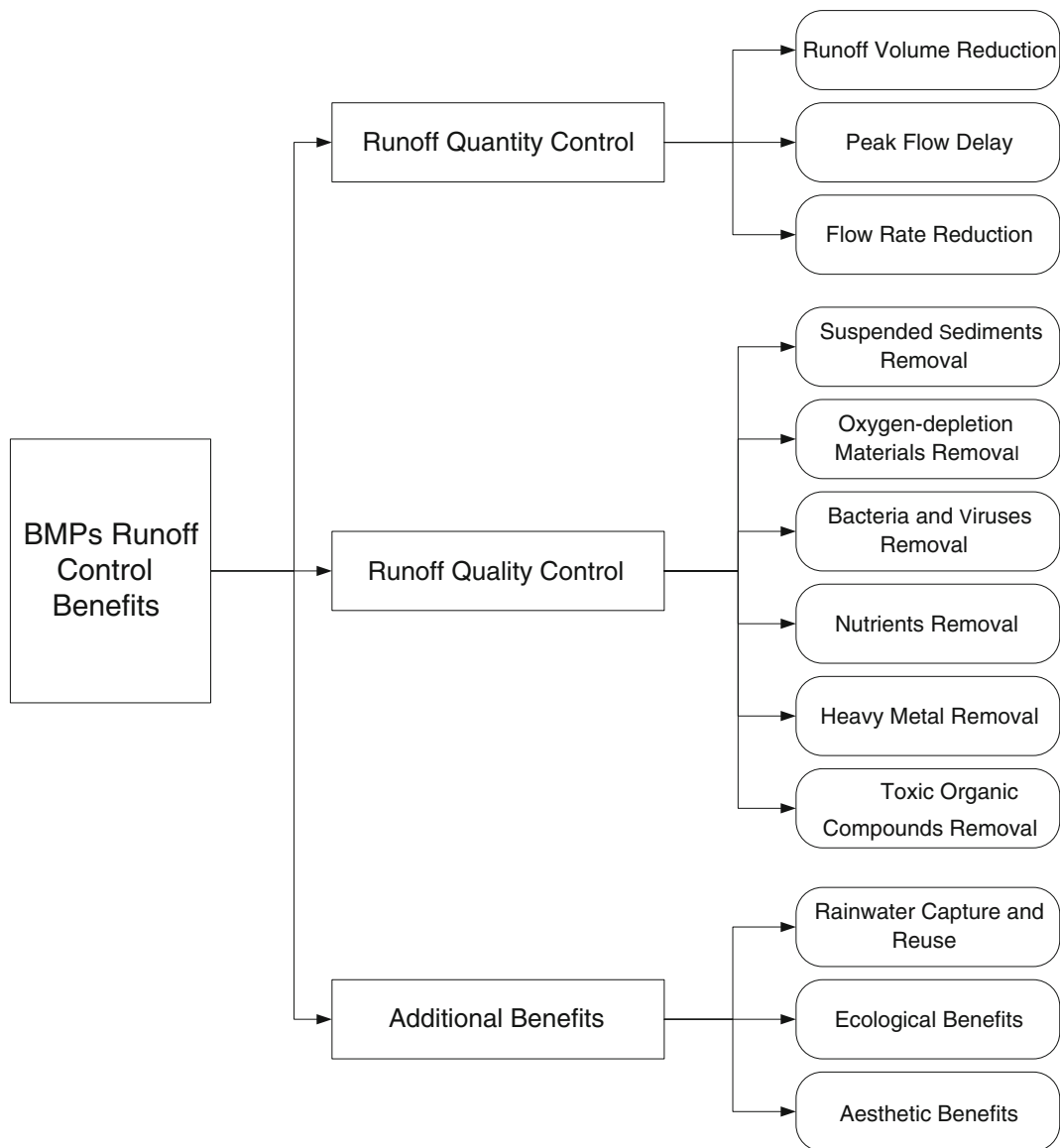
Fig. 3 Indicators of BMP runoff control benefit

3. System reliability

Two second-level indicators are meeting design goals and operational stability and risks. Meeting design goals refer to the robustness in the design approach for various BMPs. It is an indicator whether the BMP will likely fulfill the expectation in its performance. Operational stability and risks indicate the reliability of the BMP in terms of expected performance. For example, a filtration BMP may lose its efficiency due to clogging, etc.

Methodology to establishing benchmarks for each index

The establishment of benchmarks for the BMP assessment indices is based on an extensive search of literature regarding BMP design approaches, implementation case study results, and reported comments and opinions from professionals in the field. Each assessment index needs to be quantified by assigning appropriate numerical values to all the comparative index factors as described in the previous section. The quantified indices are then

Table 3 Control effectiveness of urban stormwater BMP processes

Control target	Detention storage	Sedimentation	Adsorption	Infiltration	Microbial degradation[a]	Filtration	Plant uptake	Evapotranspiration volatilization
Runoff volume	High	None	Low	Medium/high	None	None	Low	Low
Peak flow	High	None	Low	Medium/high	None	Low	Low	Low
Flow rate	Medium/high	None	Low	Low	None	Low	Low	Low
BOD$_5$	Low	Medium	Medium	Medium	Medium	Medium	Medium	Low
COD	Low	Medium	Low/medium	Low/medium	Low/medium	Medium	Low/Medium	Low
SS	Low/medium	High	Medium	Medium/high	Low	High	None	None
E. coli	Low	High	Medium	Medium/high	Low/medium	High	None	None
N	Low/medium	High	High	High	Low	High	High	None
P	Low	Low	Low	Low	Low	Low	High	None
Cd	None	Low	Low	Low	Low	Low	Low	None
Cu	None	Medium	Medium	Low/medium	Low	Medium	Low	None
Ni	None	Low/medium	Medium	Low/medium	Low	Low/medium	Low	None
Pb	None	Medium/high	High	Medium/high	Low	Medium/high	Low	None
Zn	None	Low	Low	Low	Low	Low	Low	None
Cr	None	Low/medium	Low	Low	Low	Low/medium	Low	None
Pt	None	Medium/high	Medium	Medium	Low	Medium/high	Low	None
PAHs	Medium	Medium/high	Medium/high	Medium/high	Low	Medium/high	Medium/high	Medium
PCB	Medium	High	High	High	Low	High	High	Medium

[a] Considering the possibilities of microbial degradation of pollutants by both aerobic and anaerobic decomposition

integrated into a single benchmark number by applying "weighting" factors. The appropriate weights are determined by considering a combination of literature information and expert opinions.

## Quantification of assessment index factors

The most important assessment index for evaluating BMPs is the BMP performance in runoff quantity and quality control. Therefore in this study, BMP performance was used as the primary index category for a quantitative assessment that would lead to the ranking of BMP choices and the eventual selection decisions.

Data presented in Tables 3 and 4 show the control effectiveness associated with various processes and the control effectiveness of common structural BMPs with respect to targets of runoff quantity and quality.

Table 4 Runoff control mechanisms and effectiveness for common structural BMPs

Structural BMPs	Detention storage	Sedimentation	Adsorption	Infiltration	Microbial degradation	Filtration	Plant uptake	Evapotranspiration volatilization
Infiltration trench	Low/medium	Low/medium	Medium/high	High	Medium	Medium/high	Low	Low
Infiltration basin	Medium	High	High	High	Medium	Medium/high	Low/medium	Medium
Dry detention pond	High	Medium/high	Medium	Low	Low/medium	Low	Low	Medium
Wet detention pond	High	High	Medium	Low/medium	Medium	Low	Medium	Medium
Vegetated filter strip	Low/medium	Low	Medium	Medium	Low/medium	Medium	Medium	Low/medium
Grassed swale	Medium	Low/medium	Medium	Medium	Low/medium	Medium	Medium	Low/medium
Constructed wetlands	High	Medium	Medium/high	Low/medium	High	Medium/high	High	Medium
Sand filter	Low/medium	Low/medium	Medium/high	Medium	Medium	High	Low	Low
Green roof	Medium/high	Low/medium	Medium	Low	Medium	Medium	Medium	Low/medium
Rain barrel	High	Medium	Low	None	Low	Low/medium	None	Low
Porous pavement	Low/medium	Low/medium	Medium/high	High	Low/medium	Medium/high	Low	Low
Bioretention	Medium	Medium	Medium	Medium	Medium/high	Medium	Medium/high	Low/medium

Fig. 4 Indicators of BMPs cost and maintenance
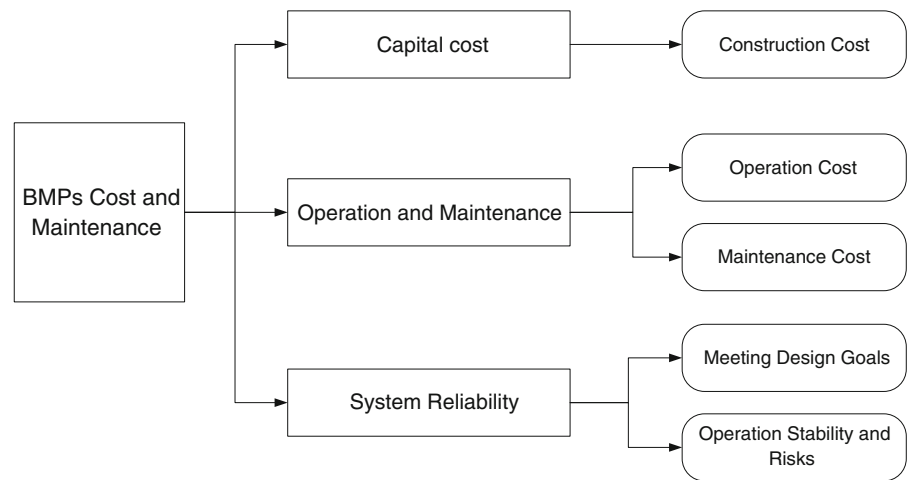
However, only qualitative descriptions, i.e., high, medium, and low, were used to describe BMP effectiveness in both Tables 3 and 4. It should be noted that, in terms of microbial degradation of pollutants, both aerobic and

Table 5 Benchmark selection for BMP site suitability analysis

Structural BMPs	Site conditions			Soil	Groundwater	Topography	Catchment	Space	
	Land use types	Pollution loading	Special requirement	Soil types	Distance between highest ground water level and the bottom of BMP(m)	Ground slope(%)	Drainage area(ha)	Imperviousness (%)	Area required for BMP (ha)
Infiltration trench	R, C, S, T, G	Medium	Buffer distance to building >3 m Buffer distance to stream >30 m	A–B	>3	<15	<2	>0	Medium
Infiltration basin	R, C, S, G	Medium	Buffer distance to stream >30 m	A–B	>3	<15	1–4	>0	Large
Dry detention pond	R, C, S, G	Medium	Higher elevation Buffer distance to stream >30 m	A–D	>1.5	<10	>4	>0	Large
Wet detention pond	R, C, S, G	Medium	Buffer distance to stream >30 m	A–D	>1.5	<10	>6	>0	Large
Vegetated filter strip	R, C, S, M, T, G	High	Adjacent to impervious surface Buffer distance to road <30 m	A–D	>0.60	<5	–	>0	Medium
Grassed swale	R, C, S, T, G	Medium	Adjacent to impervious surface Buffer distance to roads <30 m	A–D	>0.60	0.5–5	<2	>0	Medium
Constructed wetlands	R, C, G	Medium	Buffer distance to stream >30 m	B–D	>1.5	4–15	>10	>0	Large
Sand filter	R, C, M, T	Medium	Buffer distance to stream >30 m	A–D	>0.60	<10	<40	0–50	Small
Green roof	R, C, M	Low	Flat roof; pitched roof with small slope	–	–	<4	–	–	–
Rain barrel	R, C	Low	Buffer distance to building <10 m	–	–	–	–	–	Small
Porous pavement	R, S, C	Low	–	A–B	>0.60	<1	<1.2	>0	–
Bioretention	R, C, S, G	Low	Buffer distance to roads <30 m Buffer distance to stream >30 m Buffer distance to building >3 m	A–D	>0.60	<15	<1	0–80	Small

Table 6 Results on quantity/quality control effectiveness of various BMP processes

Control target	Detention storage	Sedimentation	Adsorption	Infiltration	Microbial degradation	Filtration	Plant uptake	Evapotranspiration volatilization
Runoff volume	3	0	1	2.5	0	0	1	1
Peak flow	3	0	1	2.5	0	1	1	1
Flow rate	2.5	0	1	1	0	1	1	1
COD, BOD$_5$	1	2	1.75	1.75	1.75	2	1.75	1
SS	1.5	3	2	2.5	1	3	0	0
E. coli	1	3	2	2.5	1.5	3	0	0
N, P	1.25	2	2	2	1	2	3	0
Heavy metal	0	1.7	1.7	1.5	1	1.7	1	0
PAHs, PCB	2	2.75	2.75	2.75	1	2.75	2.75	2

anaerobic decomposition were considered. For example, generally BOD$_5$ can be effectively reduced under aerobic conditions. However, under anaerobic conditions, the control effectiveness BOD$_5$ is considered as "medium" to "low."

To quantify BMP effectiveness, a numbering system was devised. The system assigns numbers from 0 to 5 to represent effectiveness, i.e., 0=not suitable, 1=low, 2=medium low, 3=medium, 4=medium high, and 5=high. The following equation was then used to calculate the overall score for BMP performance:

$$X_{ij} = \sum_{i=1}^{m} \sum_{i=1}^{n} e_{ik} \times f_{jk} , k = 1, 2, \cdots 8 \qquad (1)$$

Where,

x_{ij} the effectiveness of the ith BMP in controlling the jth target pollutant.

e_{ik} the function of the kth process or mechanism associated with the ith BMP. These processes are presented in Table 3. A total of eight BMP processes were considered.

f_{jk} the effectiveness of the kth process or mechanism in controlling the jth target pollutant as shown in Table 3.

The same scoring system as described above was used to quantify the other BMP benefits and also the cost category indicators. It should be noted that the numbers generated in this study do not actually represent an "absolute" quantification. Rather, the numbers only represent the relative scores of various BMPs

Table 7 Quantitative results of the roles of control mechanisms in different BMPs

Structural BMPs	Detention storage	Sedimentation	Adsorption	Infiltration	Microbial degradation	Filtration	Plant uptake	Evapotranspiration volatilization
Infiltration trench	1.5	1.5	2.5	3	2	2.5	1	1
Infiltration basin	2	3	3	3	2	2.5	1.5	2
Dry detention pond	3	2.5	2	1	1.5	1	1	2
Wet detention pond	3	3	2	1.5	2	1	2	2
Vegetated filter strip	1.5	1	2	2	1.5	2	2	1.5
Grassed swale	2	1.5	2	2	1.5	2	2	1.5
Constructed wetlands	3	2	2.5	1.5	3	2.5	3	2
Sand filter	1.5	1.5	2.5	2	2	3	1	1
Green Roof	2.5	1.5	2	1	2	2	2	1.5
Rain barrel	3	2	1	0	1	1.5	0	1
Porous pavement	1.5	1.5	2.5	3	1.5	2.5	1	1
Bioretention	2	2	2	2	2.5	2	2.5	1.5

Table 8 Composite scores of structural BMPs control effectiveness

Structural BMPs	Runoff quantity control				Runoff quality control						
	Runoff volume	Peak flow	Flow rate	Total	COD, BOD$_5$	SS	E. coli	N,P	Heavy metals	PAHs, PCB	Total
Infiltration trench	16	18.5	13.3	47.75	24.88	28.75	29	25.88	18.55	34.88	161.93
Infiltration basin	19	21.5	16	56.5	30.63	35	35	32	22.45	43.75	198.83
Dry detention pond	15.5	16.5	13.5	45.5	20.63	23	22.25	21.25	13.35	30.13	130.6
Wet detention pond	17.75	18.8	15	51.5	25.13	26.25	25.75	26.75	16.45	36.13	156.45
Vegetated filter strip	14.25	16.3	12.5	43	21.38	21.75	21.75	23.38	15	30.75	134
Grassed swale	15.75	17.8	13.8	47.25	22.88	24	23.75	25	15.85	33.13	144.6
Constructed wetlands	19.25	21.8	18	59	30.5	29.75	29.75	32.75	20.15	42.63	185.53
Sand filter	13.5	16.5	12.8	42.75	24.13	27.75	28	24.88	17.9	33.5	156.15
Green roof	14.75	16.8	14	45.5	22.5	22.75	22.5	24.13	14.85	31.88	138.6
Rain barrel	10.5	12	10.5	33	14	18	17	13.75	8.65	20.38	91.78
Porous pavement	16	18.5	13.3	47.75	24	28.25	28.25	25.38	18.05	34.38	158.3
Bioretention	16.25	18.3	14.3	48.75	26.5	26.5	26.75	28.5	18.2	36.88	163.33

when they can be compared on the basis of their performance and the required capital and maintenance costs.

Normalizing the numerical indicators

In order to compare the various BMPs under a unified scale, the results from the quantified index factor analysis are normalized to give an assessment index value between 0 and 1. The normalization is made by using the following equation:

$$r_{ij} = \frac{x_{ij} - \mathrm{Min}(x_{ij})}{\mathrm{Max}(x_{ij}) - \mathrm{Min}(x_{ij})}, i = 1, 2, \ldots 12 \qquad (2)$$

In which:

r_{ij} normalized assessment index factor for BMP i and indicator j. Here, the indicator j refers to the second-level index of runoff control benefits category and BMP cost and maintenance category. j $k=1,2,\ldots.17$.

i BMP type, a total of 12 LID-type BMPs are evaluated.

The total assessment score for BMP i is then obtained by calculating the sum of the weighted normalized indices for all indicators:

$$I_i = \sum_{j=1}^{17} f_{ij} \times r_{ij}, i = 1, 2, \ldots 12 \qquad (3)$$

Where

I_i total weighted assessment score for BMP i.
f_{ij} weighting factor.

The weighting factors are to be determined by professionals in accordance with site conditions, local

Table 9 Evaluation of additional BMPs benefits

Structural BMPs	Rainwater capture and reuse	Ecological benefits	Aesthetic benefits
Infiltration trench	2	1	1
Infiltration basin	3	1	1
Dry detention pond	4	1	1
Wet detention pond	5	3	3
Vegetated filter strip	1	2	3
Grassed swale	1	2	2
Constructed wetlands	5	5	5
Sand filter	1	0	1
Green roof	1	4	4
Rain barrel	5	0	1
Porous pavement	2	1	2
Bioretention	3	4	5

Table 10 Capital, operational, and maintenance cost of structural BMPs

Structural BMPs	Construction cost (Euro/m^3, 1999)	Operational cost	Maintenance cost (Euro/m^3, 1999)
Infiltration trench	30–70	Regular inspection, dredging Requires infill replacement every 5–10 years	1.5–5
Infiltration basin	30–70	Regular inspection, dredging Requires infill replacement every 5–10 years	1.5–5
Dry detention pond	9–91	Requires dredging every 5–10 years	0.3–1.52
Wet detention pond	9–136	Requires grass cuttings twice every year Requires equipment checked every year Requires dredging and sediment cleaning every 5–10 years	0.83–1.61
Vegetated filter strip	30.5–38	Regular inspection; sediment cleaning Requires replacement after 10–12 years	0.3–0.45
Grassed swale	7.6–60	Regular cuttings; dredging Requires dredging every 10 years	0.5–1.05
Constructed wetlands	20–230	Annual maintenance for first 5 years Pruning, harvesting and replanting for wetland plants Regular inspection or infill replacement	1.2–20 Maintenance costs can be reduced by 50 % after 3 years
Sand filter	–	Regular maintenance: dredging	–
Green roof	–	Regular inspection and maintenance: the same as common roof	–
Rain barrel	–	Regular inspection, prevent sludge	–
Porous pavement	33.5–228	Regular cleaning road blockages and sludge of gaps Depreciation life of permeable asphalt is 10–15 years	0.3–1.52
Bioretention	70–140	Regular pruning, weeding, adding plants, soil Irrigation when rainless	3.5–9.8

Table 11 Evaluation of BMPs operational and maintenance cost

Structural BMPs	Construction cost	Operational cost	Maintenance cost	Meeting design goals	Operational stability and risks
Infiltration trench	4	3	2	3	1
Infiltration basin	4	3	2	3	1
Dry detention pond	4	5	5	4	4
Wet detention pond	3	2	2	5	3
Vegetated filter strip	5	5	5	2	5
Grassed swale	5	2	3	5	5
Constructed wetlands	1	1	2	4	3
Sand filter	1	1	1	3	3
Green roof	3	5	4	4	4
Rain barrel	4	4	5	5	5
Porous pavement	2	4	3	3	3
Bioretention	2	2	2	5	5

Table 12 Normalized and integrated BMP selection indicators

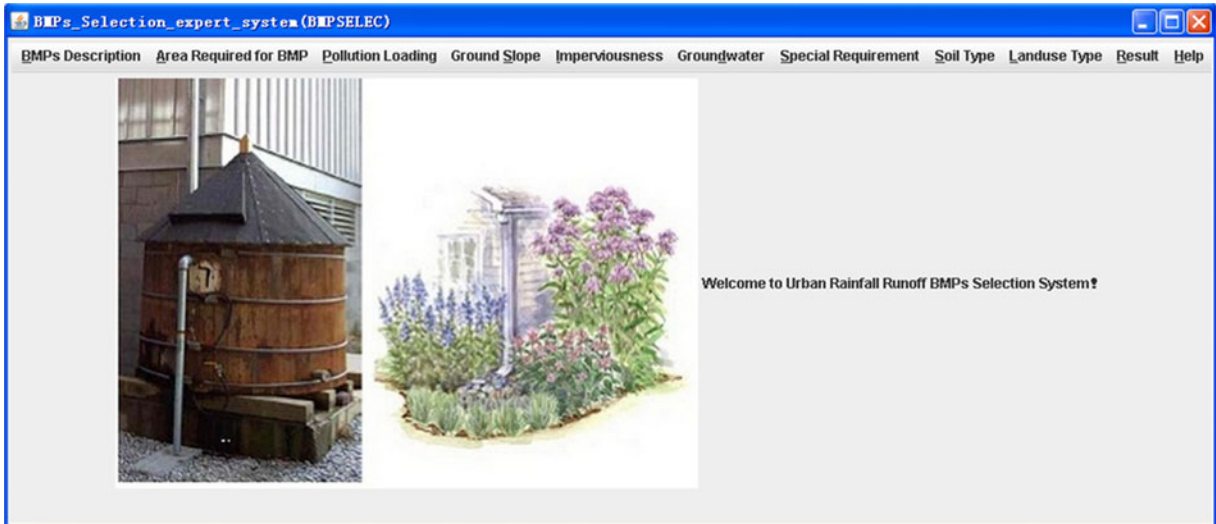| Evaluation indicator		Infiltration trench	Infiltration basin	Dry detention pond	Wet detention pond	Vegetated filter strip	Grassed swale	Constructed wetlands	Sand filter	Green roof	Rain barrel	Porous pavement	Bioretention
Runoff quantity control	Runoff volume	0.63	0.97	0.57	0.83	0.43	0.6	1	0.34	0.49	0	0.63	0.66
	Peak flow	0.67	0.97	0.46	0.69	0.44	0.59	1	0.46	0.49	0	0.67	0.64
	Flow rate	0.37	0.73	0.4	0.6	0.27	0.43	1	0.3	0.47	0	0.37	0.5
Runoff quality control	Suspended sediments	0.63	1	0.29	0.49	0.22	0.35	0.69	0.57	0.28	0	0.60	0.5
	Oxygen-depletion materials	0.65	1	0.40	0.67	0.44	0.53	0.99	0.61	0.51	0	0.60	0.75
	Bacteria, viruses	0.67	1	0.29	0.49	0.26	0.38	0.71	0.61	0.31	0	0.63	0.54
	Nutrients	0.64	0.96	0.39	0.68	0.51	0.59	1	0.59	0.55	0	0.61	0.78
	Heavy metal	0.72	1	0.34	0.57	0.46	0.52	0.83	0.67	0.45	0	0.68	0.69
	Toxic organic compounds	0.62	1	0.42	0.67	0.44	0.55	0.95	0.56	0.49	0	0.60	0.71
Additional benefits	Rainwater reuse	0.25	0.5	0.75	1	0	0	1	0	0	1	0.25	0.5
	Ecological benefits	0.20	0.2	0.2	0.6	0.4	0.4	1	0	0.8	0	0.2	0.8
	Aesthetic benefits	0	0	0	0.5	0.5	0.25	1	0	0.75	0	0.25	1
Capital cost	Construction cost	0.75	0.75	0.75	0.5	1	1	0	0	0.5	0.75	0.25	0.25
Operation & maintenance	Operational cost	0.5	0.5	1	0.25	1	0.25	0	0	1	0.75	0.75	0.25
	Maintenance cost	0.25	0.25	1	0.25	1	0.5	0.25	0	0.75	1	0.5	0.25
System reliability	Meeting design goals	0.33	0.33	0.67	1	0	1	0.67	0.33	0.67	1	0.33	1
	Operation stability and risks	0	0	0.75	0.5	1	1	0.5	0.5	0.75	1	0.5	1
Total		7.87	11.17	8.69	10.28	8.94	12.59	5.55	9.24	5.5	8.42	10.82	

Fig. 5 *BMPSELEC* interface I

regulatory requirements, social and economic considerations, and other pertinent factors. The final ranking of the BMPs can then be obtained and the selection be made.

Developing a BMP ranking mechanism

To develop the ranking mechanism for the MCIS, the first step was to establish the basis for quantitative ranking of the 12 LID-type BMPs considered in the present study. The basis was derived by synthesizing a large amount of literature information on BMP site suitability, runoff control effectiveness, and costs. The basis sets quantitative benchmarks for the 12 BMPs so that a ranking of the BMPs can be obtained by calculating the total assessment score for each BMP.

BMP site suitability analysis benchmarks

Based on an extensive review and of pervious literature (e.g., USEPA 1999, 2004a, b; Revitt et al. 2003; Hunt and Lord 2006; Scholes et al. 2005), benchmarks
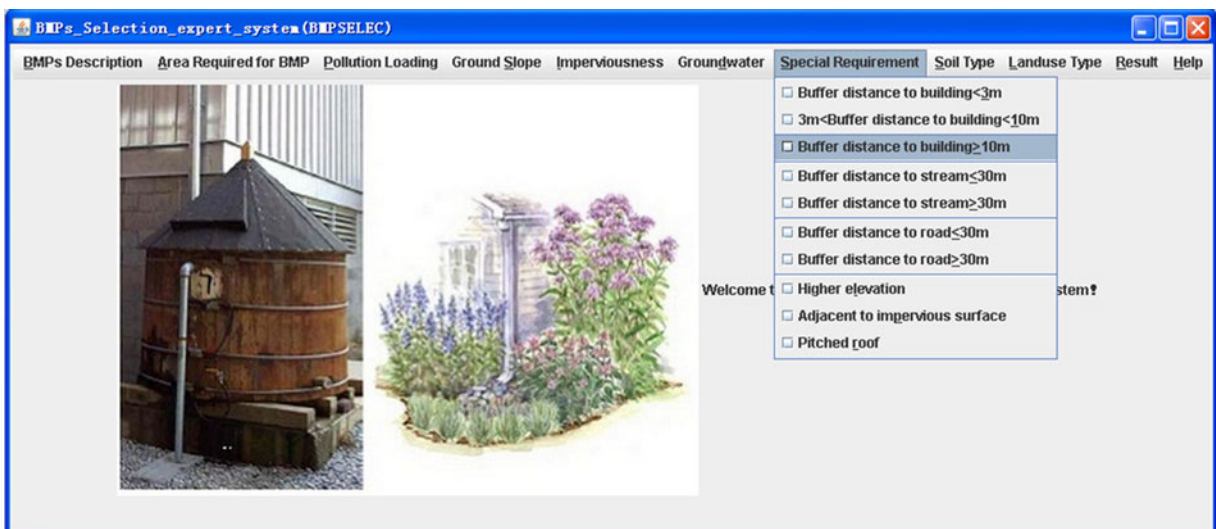
Fig. 6 *BMPSELEC* interface II
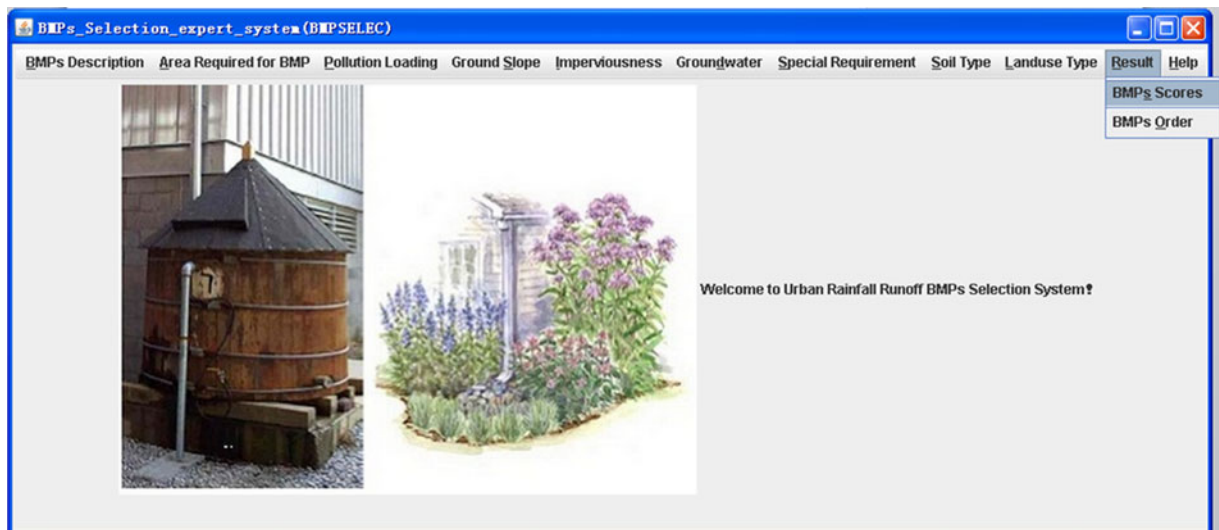
Fig. 7 *BMPSELEC* interface III

were assigned for the 12 level 2 index factors pertinent to site suitability for the 12 commonly used structural BMPs. The results are given in Table 5.

BMP runoff control analysis benchmarks and ranking

Runoff quantity and quality control processes of various BMPs have been described and presented earlier in this paper and summarized in Tables 3 and 4. Combining the qualitative evaluations listed in Tables 3 and 4, and assigning numerical equivalents ranging from 0 to 3, Tables 6 and 7 were obtained. Table 6 presents quantitatively the comparison of scores for BMP processes in controlling runoff. The control targets selected for demonstrating the MCIS formation are described below.

Runoff quantity control targets: runoff volume, peak flow, and flow rate.

Runoff quality control targets: Suspended sediments (SS), oxygen-depletion materials (COD and BOD_5), bacteria and viruses (*Escherichia coli*), nutrients (N and P), heavy metals (Cd, Cu, Ni, Pb, Zn, Cr, and Pt), and toxic organic compounds (PAHs and PCB).

The assigned scores for BMP processes in the summarized runoff quality control targets were the average value of the individual scores for BMP processes in its each runoff control target shown in Table 3. For example, the scores for BMP processes in oxygen-depletion materials targets were the average value of the individual scores for BMP processes in COD and BOD_5.

Table 7 presents the quantitative results of the roles of control mechanisms in different BMPs. For example, storage is not a major process for reducing runoff volume by infiltration trenches. Therefore, a low/medium rating was assigned, and the corresponding numerical score is 1.5 for process "storage." By the same token, a score of 3 was given to process "storage" for BMP "constructed wetland" because of its large storage capacity.

To obtain the composite score of BMP effectiveness for both runoff quantity and quality targets, Eq. (1) was used with data listed in Tables 6 and 7.
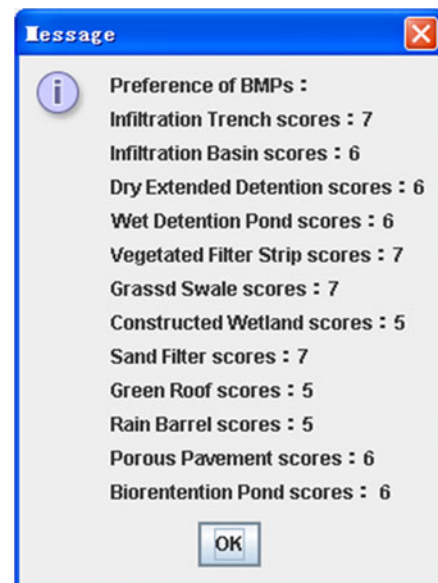

Fig. 8 *BMPSELEC* interface IV

For example, the composite score for infiltration trenches in controlling runoff volume was calculated as:

$$
\begin{aligned}
\text{Composite score} = {} & 1.5 \times 3 + 1.5 \times 0 + 2.5 \times 1 + 3 \\
& \times 2.5 + 2 \times 0 + 2.5 \times 0 + 1 \times 1 \\
& + 0.5 \times 1 \times 1 \\
= {} & 16
\end{aligned}
$$

The results for the composite scores for all BMPs are presented in Table 8. It should be noted that for the above computation, the weighting factors were all taken as 1, except for evapotranspiration volatilization, which was assumed to be 0.5.

It was shown from results listed in Table 8 that constructed wetlands and infiltration basins exhibit the best composite scores in general. Infiltration trenches, wet ponds, porous pavements, and bioretention cells show moderate composite scores. Green roofs, dry ponds, vegetative filters, and rain barrels are less effective than the other BMPs.

Other BMP benefits

As described earlier, there are other benefits of BMPs, especially the LID types that could be realized. These benefits include rainwater utilization, erosion control, protection of habitats and other ecological functions, moderating urban heat-island effects, etc. In addition, certain BMPs such as bioretention cells and constructed wetlands also bring about landscape and recreational benefits.

Using the (0, 1, 2, 3, 4, 5) scoring scheme, an assessment was made of the BMP benefits in terms of rainwater utilization potential, ecological services, and landscape values. The results are listed in Table 9.

BMP cost benchmarks and ranking

Data on the capital, operational, and maintenance costs of BMPs are still relatively scarce. In this study, information presented in a number of European and US experiences (USEPA 1999; Baptista et al. 2001; Revitt and Ellis 2001; Hunt and Lord 2006) were gathered and summarized in Table 10 below. The data include BMP construction (land cost excluded), operational, and maintenance costs.

Quantification of the BMP cost information was made by using the (1, 2, 3, 4, 5) rating scale and giving appropriate numbers to each of the 12 BMPs on the basis of capital costs, management requirement, maintenance cost, meeting design goals, and operational stability, as shown in Table 11.
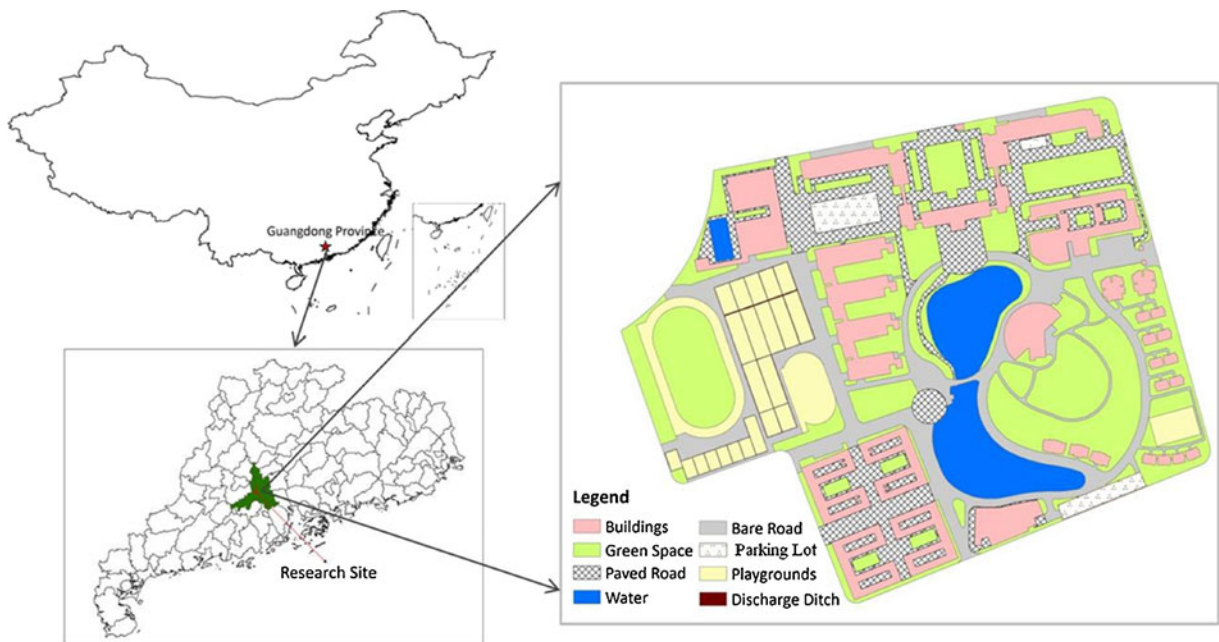

Fig. 9 Location of the case study

Fig. 10 Layout scheme of BMPs

Integrating and normalization of BMP selection index scores

The assessment scores on BMP runoff quantity/quality control effectiveness, other benefits, capital and operational/maintenance costs, and system stability are first normalized by using Eq. (2) and then are added to give an overall score for each of the 12 BMPs using Eq. (3). The results are listed in Table 12. It should be noted that, when adding the scores for the various assessment categories, weights could be given if one or more categories, e.g., runoff quantity and cost, are deemed more important than the others in the evaluation process. Since the objective of the present paper is to just demonstrate the methodology, an equal weight was given to all the categories.

The results indicate, again, that constructed wetlands, infiltration basins, and bioretention cells are good BMPs to consider on the whole. On the other hand, even though green roofs offer only moderate runoff control benefits, higher scores in other categories raised the overall score and therefore become good choices to be considered.

Development of the BMP selection software, BMPSELEC

In order to facilitate the somewhat complicated steps and processes required for the execution of the MCIS BMP ranking system, a computer software package, *BMPSELEC*, was developed in the present study. The development environment is described as follows.

The development platform used was Eclipse3.5, and the development tools were Visual Editor and Swing. The programming language used was JAVA. *BMPSELEC* can be run under Windows XP/7 system.

Table 13 Computation of BMP selection indicators for the study area

Evaluation indicator		Infiltration trench	Wet detention pond	Vegetated filter strip	Grassed swale	Green roof	Rain barrel	Porous pavement	Bioretention
Runoff quantity control	Runoff volume	0.76	1	0.52	0.72	0.59	0	0.76	0.79
	Peak flow	0.96	1	0.63	0.85	0.7	0	0.96	0.93
	Flow rate	0.61	1	0.44	0.72	0.78	0	0.61	0.83
Runoff quality control	Suspended sediments	1	0.77	0.35	0.56	0.44	0	0.95	0.79
	Oxygen-depletion materials	0.87	0.89	0.59	0.71	0.68	0	0.8	1
	Bacteria, viruses	1	0.73	0.4	0.58	0.46	0	0.94	0.81
	Nutrients	0.82	0.88	0.65	0.76	0.7	0	0.79	1
	Heavy metal	1	0.79	0.64	0.73	0.63	0	0.95	0.96
	Toxic organic compounds	0.88	0.95	0.63	0.77	0.7	0	0.85	1
Additional benefits	Rainwater reuse	0.25	1	0	0	0	1	0.25	0.5
	Ecological benefits	0.25	0.75	0.5	0.5	1	0	0.25	1
	Aesthetic benefits	0	0.5	0.5	0.25	0.75	0	0.25	1
Capital cost	Construction cost	0.67	0.33	1	1	0.33	0.67	0	0
Operation and maintenance	Operational cost	0	0	1	0.33	0.67	1	0.33	0
	Maintenance cost	0.33	0	1	0	1	0.67	0.67	0
System reliability	Meeting design goals	0.33	1	0	1	0.67	1	0.33	1
	Operation stability and risks	0	0.5	1	1	0.75	1	0.5	1
Weighted total		10.23	12.26	11.35	11.15	11.85	6.51	10.69	12.61
Ranking		7	2	4	5	3	8	6	1

BMPSELEC was designed with a dropdown menu style and is very easy to use. A user needs to only choose the right item from the dropdown menu based on the local conditions and then the system will generate the results of ranking the various BMPs. The following figures (Figs. 5, 6, 7, and 8) show some interfaces of *BMPSELEC*.

A case study—Foshan, China BMP selection

As a demonstration of the MCIS BMP selection methodology, a case study was conducted on the campus of the Guangdong College of Environment Protection in Foshan City, Guangdong, in Southern China. Figure 9 below depicts the location of the case study.

Foshan City is a metropolis with a population exceeding 6 million. The climate is sub-tropical with an annual rainfall of around 1,600 mm. The college is undergoing an expansion project and is considering the incorporation of a number of LID-BMPs for stormwater management.

According to construction planning of the college campus, the total area of the campus is about 30 ha, and imperviousness ratio is 59 %. The main land use type is commercial and public facilities (Code C), which includes some buildings and roads, a basketball court, and a wet pond. The pollution loading generated at the campus site is considered low. According to onsite survey, the soil types at the site include B, C, and D. The depth of the ground water table ranges between 3.41 and 13.98 m. The ground slope is less than 4 % mostly but increases to15% at the hilly area in the middle. Currently, the overall construction planning for the site has already been approved by the authorities; therefore, BMPs that require large spaces (significant alteration of the site planning) for installation cannot be considered.

Considering the site characteristics and other pertinent information, a preliminary BMP screening analysis was conducted based on Table 5. It was decided that four BMPs, namely, dry ponds, infiltration basins, sand filters, and constructed wetlands were not suitable BMPs for use at the Foshan site. The disqualifying factors were slope and installation space requirements, service area, and imperviousness. Also, the existing artificial lake could be modified as wet pond to enhance its BMP functions.

An MCIS ranking analysis was performed on the remaining eight BMPs. The overall assessment scores after integration and normalization of the initial scores are listed in Table 13 below. It should be noted that because the costs of BMPs are of primary concern to the College, the weighting factors for the cost category were given a value of 1.5, while the other weighting factors were given a value of 1.0.

The results presented in Table 13 indicate that for the Foshan college site, bioretention cells, wet pond, and green roofs are the most preferred LID-type BMPs, while porous pavements, infiltration trenches, and rainwater barrels are the least. Based on the above analysis and the thoughts of the College, the selection and layout of the BMPs for the Foshan college site was determined and is shown in Fig. 10.

Conclusions

A watershed BMP selection tool (MCSI) was developed in the study to assist the selection of the most appropriate BMP type(s) for a specific installation site. The MCSI was based on three basic criteria categories, which are BMP site suitability, runoff control effectiveness, and costs. And the three basic criteria categories consist of a total of 12 level 1 and 26 level 2 index factors.

A methodology was then devised to integrate all index factors and to quantify BMP ranking assessment scores. Also, a software program, *BMPSELEC*, was developed to facilitate the analyses required in the MCIS framework.

The methodology at last was applied to a demonstration site in Foshan City in Southern China. It is shown that the developed MCSI framework is simple, comprehensive, and easy to use. MCSI can be used as a preliminary BMP screening tool, but can also be used as a stand-alone method for BMP selection and planning.

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