Development of a practical best management practice decision support model for engineers and planners in Nordic countries

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Received 7 October 2005; accepted in revised form 7 December 2006

Nordic Hydrology **Vol 38 No 2 pp 107–123** © IWA Publishing 2007

Abstract Seventy-nine and 103 sites within Glasgow and Edinburgh, respectively, were identified to assess if best management practice (BMP) can be integrated into future development, regeneration and retrofitting plans. A practical BMP Decision Support Model based on a matrix and weighting system, incorporating the Prevalence Rating Approach for BMP Techniques (PRABT), has been developed. The findings indicate that ponds (or lined ponds) and permeable pavements are the most likely individual BMP techniques, and ponds combined with swales (or shallow swales) are the most recommended dual BMP combination. A separate case-based reasoning model compared to the 'linear' BMP Decision Support Model has also been developed. The output was similar to the 'linear' model.

Keywords Best management practice; drainage systems; optimization models; regeneration; retrofitting; statistical models

Introduction

Best management practice

Prevention of flooding in urban areas caused by inadequate drainage systems has become a significant problem. With increased development of greenfield and urban regeneration, potential damage due to prolonged flooding could easily lead to substantive financial losses (Schmitt *et al.* 2004). The concept of 'source control' for the treatment of stormwater runoff from impermeable surfaces has become widely accepted amongst drainage engineers in both the United States and Europe (Ellis *et al.* 2004; Villarreal *et al.* 2004; Scholz 2006).

Over the past 20 years, the use of best management practice (BMP) in the United States and sustainable urban drainage systems (SUDS) in the United Kingdom have been instrumental in reducing both the detrimental impact of polluted runoff to the water quality of receiving watercourses, and flooding caused by increased urbanization and traditional stormwater drainage systems. Both BMP and SUDS attempt to mimic the drainage patterns of the natural watershed and can also provide the substantial treatment needed to improve the quality of the water discharged to an acceptable standard (Scholz 2006).

Impact of BMP on water quantity and quality

Rapid urbanization and its consequent increase in impermeable surface areas and changes in land use generally results in problems of flooding and heavy pollution of urban streams and other receiving watercourses. This is frequently coupled with groundwater depletion and a threat to natural water resources (Andoh and Declerck 1997). Traditional drainage systems are no longer adequate in many areas, especially in high density housing estates.

doi: 10.2166/nh.2007.001

The subsequent effects can be life threatening and may lead to damage to buildings and other infrastructure assets, and disrupt the functioning of business and society (Mark *et al.* 2004; Schmitt *et al.* 2004). Through BMP techniques, water is either infiltrated or conveyed more slowly to watercourses or sewer systems *via* ponds, swales, filter strips or other sustainable installations, which could reduce the peak flow during heavy storms (Pettersson 1997).

Stormwater in open systems forms the basis for recreation and the development of ecosystems with a diverse animal and plant life. In many ways, the principles of alternative stormwater management should adopt the natural processes in the environment and adapt them to urban conditions and requirements (Scholz 2006). At the same time, the effects of pollution should be taken into account (Astebøla *et al.* 2004). Butler and Parkinson (1997) mentioned that 'Sustainable urban drainage should maintain a good public health barrier, and avoid local or distant pollution of the environment'. Non-point sources of pollution are difficult to identify and control, and are one of the main reasons that urban rivers fail to reach the water quality objectives set for them, whilst BMP techniques are available to help combat this diffuse pollution (Mitchell 2005). For instance, the runoff from roofs and streets contributes between 50% and 80% of heavy metals to the total mass flow in domestic sewage (Butler and Parkinson 1997).

Development and regeneration in Glasgow

Glasgow is associated with many areas in which the need for BMP is becoming apparent. In 2003, the new 'City Plan' was adopted, outlining a large number of urban areas known as 'New Neighbourhoods' in which redevelopment should occur. The main urban drainage concern for Scottish Water and Glasgow City Council is the lack of sewer system capacity for additional surface water runoff. With future development and regeneration activities, this situation is likely to become worse and the need for BMP implementation becomes vital to Glasgow's continuing expansion (Scholz 2006). New guidelines incorporating a decision-making tool that identifies BMP techniques, which are feasible for a particular site over a range of boundary and environmental conditions, are required.

Furthermore, a previous (unpublished) project undertaken by Hyder Consulting for the East End of Glasgow did not show how BMP implementation could lead to a significant reduction of potential combined sewer overflow spills. However, the desk study failed to incorporate actual site conditions such as the percentage of built-up areas and the local topography of the landscape including watercourses and hills.

Best management practice in Edinburgh

Construction projects in Edinburgh's outskirts are dominated by greenfield development activities. City regeneration projects are predominantly restricted to brownfield sites. Current and proposed building projects within the city boundary are the City Centre, the Granton Waterfront, Edinburgh Park, South Gyle and Sighthill. These areas are likely to become commercial or high density residential developments. Within the City, there are designated recreational areas, which can be used to drain urban runoff after BMP implementation. This process of utilising recreational space is a less controversial form of BMP retrofitting (Scholz 2006).

As development and regeneration activities increase, the amount of impermeable surfaces also increases. It follows that there is a pressing need to use BMP techniques to control runoff by ground infiltration or storage, which has beneficial impacts on downstream catchments (City of Edinburgh Council 1999).

Flooding within the City of Edinburgh is mostly caused by rainfall in the upper river catchment areas which lie outside the boundaries of the city. Recent flooding has occurred predominantly in the following catchments and localities: River Almond and Gogar Burn;

Ferry Burn; South Queensferry; Linn Mill Burn; Braid Burn and Figgate Burn; Burdiehouse, Niddrie and Brunstane Burn (City of Edinburgh Council 1999).

Aims and objectives

The main aims are to establish new BMP option decision-making tools for planners, and to compare the outcomes for Edinburgh and Glasgow with each other. The detailed objectives include the following:

- to identify suitable BMP sites within Glasgow and Edinburgh;
- to classify qualitatively and quantitatively sites suitable for different BMP technologies;
- to outline a BMP Decision Support Model for development, regeneration and site retrofitting purposes;
- to publish the model on the World Wide Web and to evaluate feedback from users;
- to compare the 'linear' with the case-based reasoning modelling concept to assess the usefulness of the BMP database for decision-making; and
- to identify representative BMP technologies for representative construction sites that could be used for demonstration purposes.

Methods

Overview of sites in Glasgow and Edinburgh

Figure 1(a) shows a map of Glasgow highlighting the spatial distribution of 79 sites that were identified during an initial desk study as potentially suitable for the implementation of BMP. In comparison, Figure 1(b) shows a map of Edinburgh highlighting 103 sites that were identified. All the sites were classified into four groups (development, regeneration, retrofitting and recreation) used for planning purposes (Table 1).

BMP decision support matrix and weighting system

The BMP Decision Support Matrix comprises dominant and supplementary criteria, whose aim is to identify the level of BMP implementation feasibility. Dominant criteria (Table 2) specify the technical conditions which must be adhered to for corresponding BMP implementation. Dominant criteria may either be 'hard' or 'soft' such as 'Area for BMP and 'Land Value'. Concerning 'soft' variables, the decision support system user needs to be educated by local experts to appreciate, for example, what a low, medium or high land value is in terms of 'hard' figures (i.e. £*x* per square metre) for his town at a particular moment in time. It would be beyond the scope of this paper to suggest any specific values. This paper just demonstrates the general working principles of the proposed methodology.

Supplementary criteria (Table 2) should be satisfied, but play a less crucial role in identifying the most suitable BMP. Nevertheless, they could be used to decide on the most appropriate BMP technique, because their relative importance is a function of the weighting system outlined in Table 3. The corresponding proportions of weightings for each BMP technique are shown in Table 4.

Supplementary criteria were weighted by the author and his team according to their relative importance for each BMP technique. The corresponding variables for each BMP technique were weighted between 0 (unimportant or not applicable) and 3 (very important) according to their relative importance to each other, and with regard to the constraints identified for each BMP technique. Expert opinions based on the experiences of the author, his Urban Water Research Group and collaborating planners in Glasgow and Edinburgh form the basis of the weightings of the supplementary criteria. These weightings should be seen as examples, and it is possible that there might be a good reason to change them if this decision support system would be applied elsewhere.

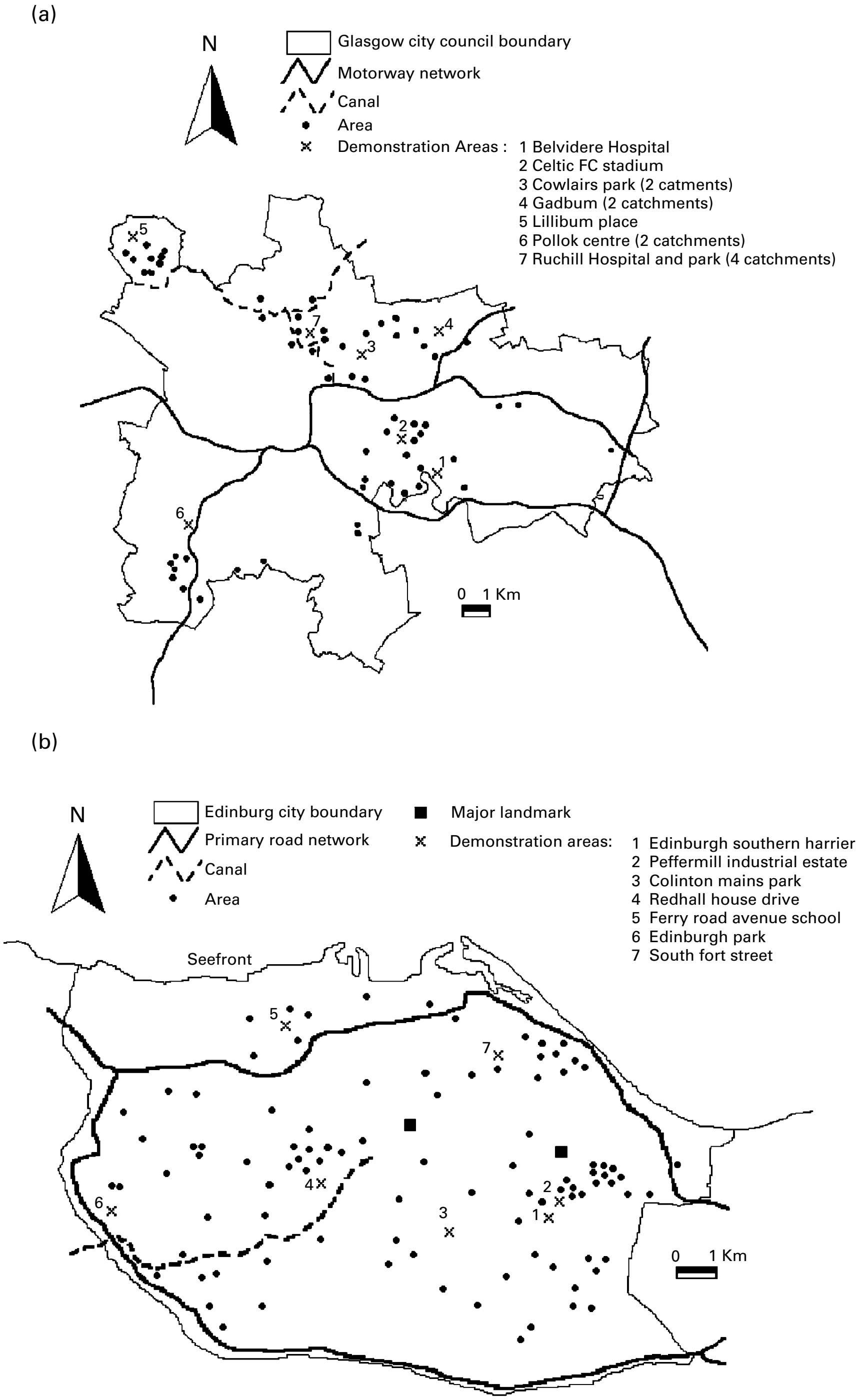

Figure 1 Best management practice sites in (a) Glasgow and (b) Edinburgh

BMP decision support model

The optimization model for BMP implementation in Glasgow and Edinburgh utilised the site classification data to suggest a suitable BMP solution either as an individual BMP technique or as a combination of at least two techniques in the form of a 'BMP management train'. The calculations are performed by a Microsoft Excel steady-state spreadsheet model.

Table 1 Best management practice (BMP) database summary for Glasgow (79 sites) and Edinburgh (103 sites) representing the current situation but taking into account already planned construction work. Proportions for Glasgow (first value) and Edinburgh (second value) are expressed in %

Contamination	Yes: 9 / 0	No: 91 / 100			
Possible BMP area (%)	<20: 1 / 8	$20 < x < 60$: 23 / 4	$60 < x < 80$: 23 / 1	>80: 53 / 87	
Land values	Low: 19/33	Low–Medium: 30/19	Medium: 39/35	Medium–High: 9/9	High: 3/4
Runoff quantity	1: 27/46	2: 24/22	3: 42/25	4: 5/6	5: 3/1
Runoff quality	Poor: 5/0	Average: 52/39	Good: 43/61		
Roof runoff (%)	≤ 50: 63/6	>50: 37/94			
Car park runoff (%)	≤ 50: 85/88	>50: 15/12			
Road runoff (%)	≤ 50: 65/88	>50: 35/12			
Roads[a]	Motorways: 9/0	Primary road: 15/12	A roads: 27/18	B roads: 14/3	Others: 35/67
Drainage type	Sewer only: 60/58	Watercourse: 39/40	Not currently detected: 1/2		
Groundwater	High: 22/15	Low: 62/68	Currently not determined: 16/17		
Soil infiltration	High: 62/68	Low: 22/15	Currently not determined: 16/17		
Impermeable surface (%)	<20: 3/53	$20 < x < 40$: 52/14	$40 < x < 60$: 16/7	$60 < x \leq 80$: 19/8	>80: 10/18
Catchment size (m^2)	$<50\,000$: 30/46	$50\,000 < x > 100\,000$: 28/30	$100\,000 < x \leq 200\,000$: 32/13	$x > 200\,000$: 10/11	
Slope (x in 100 m)	<1: 19/21	$1 < x < 5$: 49/53	$5 < x \leq 10$: 16/19	$x > 10$: 16/7	
Ownership	Council: 62/39	Private: 19/35	Council and private: 19/26		
Ecological impact	Yes: 24/26	No: 76/74			
Acceptance warning	Green Flag: 82/81	Orange Flag: 18/17	Red Flag: 0/2		
Site classification	Development: 35/21	Regeneration: 35/38	Retrofitting: 11/17	Retrofit with parks: 19/24	

[a] Higher classified roads take precedence over any lower classified roads

Table 2 Dominant (d) and supplementary (s) best management practice (BMP) decision support criteria

BMP technique(s)	Catchment size (m^2)	Area for BMP (m^2)	Future runoff[a] (1–5)	Runoff quality[b]	Land contamination	Land value[c]	Ownership fragmented	Groundwater level
Wetland	>50 000 (s)	>5000 (d)	>2 (d)	Average (d)	No (d)	<4 (d)	No (s)	–
Pond	>15 000 (s)	>50 (d)	–	Average (d)	No (d)	<4 (s)	–	–
Lined pond	>15 000 (s)	>50 (d)	–	–	–	<4 (s)	–	–
Infiltration basin	>15 000 (s)	>50 (d)	<4 (s)	Average (d)	No (d)	<4 (s)	–	Low (d)
Swale	–	>200 (s)	<4 (s)	Average (s)	No (d)	<4 (s)	No (s)	Low (s)
Shallow swale	–	>200 (s)	<3 (s)	Average (s)	No (s)	<4 (s)	No (s)	–
Filter strip	>15 000 (s)	>500 (d)	<4 (s)	Average (d)	No (d)	<4 (d)	No (d)	Low (d)
Soakaway	>3000 (s)	>200 (s)	<3 (s)	Average (s)	No (d)	<5 (s)	–	Low (d)
Infiltration trench	>3000 (s)	>50 (s)	<4 (d)	Average (s)	No (d)	–	No (s)	Low (d)
Permeable pavement	–	–	<4 (s)	Average (s)	No (d)	–	–	–
Underground storage	>5000 (s)	>50 (d)	<5 (s)	–	–	–	–	Low (d)
Water playground	>3000 (s)	>10 (s)	<3 (s)	Good (d)	No (d)	–	–	–
Green roof	–	>20 (s)	<4 (s)	Good (s)	–	–	No (s)	–
Swale + pond	>20 000 (s)	>300 (d)	–	Average (d)	No (d)	<4 (s)	No (s)	Low (s)
Shallow swale + pond	>20 000 (s)	>250 (d)	<4 (s)	Average (d)	No (d)	<4 (s)	No (s)	–
Infiltration trench + underground storage	>8000 (s)	>150 (d)	<5 (s)	Average (s)	No (d)	–	No (s)	Low (s)

BMP technique(s)	Slope (*x* m in 100 m)	Maximum slope	Soil infiltration	Ecological impact	Impermeable area < (%)	Impermeable area > (%)	Drainage to watercourse or sewer
Wetland	–	15 (s)	–	Yes (s)	40 (s)	–	Yes (d)
Pond	–	20 (s)	–	–	65 (s)	–	Yes (d)
Lined pond	–	20 (s)	–	–	65 (s)	–	Yes (d)
Infiltration basin	–	30 (s)	High (d)	–	60 (s)	–	–
Swale	>1 (s)	10 (s)	–	–	85 (s)	–	Yes (s)
Shallow swale	>1 (s)	15 (s)	–	–	90 (s)	–	–
Filter strip	>2 (s)	40 (s)	High (s)	–	50 (s)	–	–
Soakaway	>1 (s)	25 (s)	High (d)	–	90 (s)	–	–

Table 2 – *continued*

BMP technique(s)	Slope (*x* m in 100 m)	Maximum slope	Soil infiltration	Ecological impact	Impermeable area < (%)	Impermeable area > (%)	Drainage to watercourse or sewer
Infiltration trench	>1 (s)	15 (s)	High (d)	–	–	30 (s)	–
Permeable pavement	–	20 (s)	–	–	–	30 (s)	–
Underground storage	–	15 (s)	–	–	–	40 (s)	Yes (d)
Water playground	–	20 (s)	–	–	–	–	–
Green roof	–	20 (s)	–	–	–	–	Yes (d)
Swale + pond	>1 (s)	10 (s)	–	–	55 (s)	–	Yes (d)
Shallow swale + pond	>1 (s)	15 (s)	–	–	60 (s)	–	Yes (d)
Infiltration trench + underground storage	>1 (s)	15 (s)	–	–	–	40 (s)	Yes (d)

[a] Future runoff indicates the estimated quantity of runoff after the BMP has been constructed

[b] Runoff quality indicates the likely water quality determined by key variables such as biochemical oxygen demand, suspended solids, nutrients, hydrocarbons and heavy metals

[c] Land value indicates the current value of the land, but may also reflect expected changes after BMP construction

– = not applicable

Table 3 Weightings for the best management practice (BMP) Decision Support Matrix (corresponding to supplementary criteria, Table 2)

BMP technique(s)	Catchment size (m^2)	Area for BMP (m^2)	Future runoff (1–5)	Runoff quality	Land contamination	Land value	Ownership fragmented	Groundwater level
Wetland	2	0	0	0	0	0	2	0
Pond	1	0	0	0	0	2	0	0
Lined pond	1	0	0	0	0	2	0	0
Infiltration basin	2	0	2	0	0	2	0	0
Swale	0	1	3	2	0	1	3	2
Shallow swale	0	1	2	2	1	1	2	0
Filter strip	2	0	3	0	0	0	0	0
Soakaway	2	2	3	2	0	2	0	0
Infiltration trench	1	1	0	2	0	0	2	0
Permeable pavement	0	0	2	2	0	0	0	0
Underground storage	1	0	2	0	0	0	0	0
Water playground	1	1	2	0	0	0	0	0
Green roof	0	1	3	2	0	0	2	0
Swale + pond	2	0	0	0	0	2	2	2
Shallow swale + pond	2	0	3	0	0	2	2	0
Infiltration trench + underground storage	1	0	3	3	0	0	2	2

BMP technique(s)	Slope (x m in 100 m)	Maximum slope	Soil infiltration	Ecological impact	Impermeable area <(%)	Impermeable area > (%)	Drainage to watercourse	Drainage to watercourse or sewer
Wetland	0	1	0	2	1	0	0	0
Pond	0	1	0	0	1	0	0	0
Lined pond	0	1	0	0	1	0	0	0
Infiltration basin	0	1	0	0	1	0	0	0
Swale	2	2	0	0	1	0	0	2
Shallow swale	2	2	0	0	2	0	0	0
Filter strip	2	1	2	0	1	0	0	0
Soakaway	1	1	0	0	2	0	0	0

Table 3 – *continued*

BMP technique(s)	**Slope (*x* m in 100 m)**	**Maximum slope**	**Soil infiltration**	**Ecological impact**	**Impermeable area <(%)**	**Impermeable area > (%)**	**Drainage to watercourse**	**Drainage to watercourse or sewer**
Infiltration trench	2	2	0	0	0	1	0	0
Permeable pavement	0	1	0	0	0	1	0	0
Underground storage	0	2	0	0	0	1	0	0
Water playground	0	1	0	0	0	0	0	0
Green roof	0	1	0	0	0	0	0	0
Swale + pond	1	1	0	0	1	0	0	0
Shallow swale + pond	1	1	0	0	1	0	0	0
Infiltration trench + underground storage	1	2	0	0	0	2	0	0

Table 4 Proportions of weightings for the best management practice (BMP) Decision Support Model and case-based reasoning (CBR) model applied for Glasgow and Edinburgh (%)

	BMP Decision Support Model				CBR Model			
Glasgow (top)/Edinburgh (bottom) sites (%)	**–[a]**	**x**	**xx**	**xxx**	**–**	**x**	**xx**	**xxx**
Wetland	80	8	3	10	82	8	4	6
Pond	13	9	19	59	10	16	30	43
Lined pond	1	11	23	65	3	16	34	47
Infiltration basin	34	19	11	35	33	15	23	29
Swale	8	10	61	22	6	11	48	34
Shallow swale	0	25	53	22	0	25	51	24
Filter strip	54	10	10	25	49	16	19	15
Soakaway	29	10	33	28	28	35	6	30
Infiltration trench	37	10	30	23	35	11	39	14
Permeable pavement	8	13	23	57	5	15	42	38
Underground storage	23	14	30	33	22	20	30	28
Water playground	58	10	4	28	61	11	5	23
Green roof	4	14	47	35	6	48	15	30
Swale + pond	13	24	44	19	13	29	34	24
Shallow swale + pond	13	16	35	35	11	19	34	35
Infiltration trench + underground storage	9	29	54	8	5	29	57	9
Wetland	85	9	4	2	88	7	3	2
Pond	5	11	24	60	2	16	39	44
Lined pond	4	11	24	61	2	15	39	45
Infiltration basin	16	28	9	48	15	19	30	36
Swale	1	13	38	49	0	10	37	53
Shallow swale	0	15	45	41	0	12	47	42
Filter strip	32	17	24	27	29	20	36	15
Soakaway	16	8	35	42	15	23	17	46
Infiltration trench	21	5	39	35	19	4	51	25
Permeable pavement	1	8	20	71	0	6	39	55
Underground storage	17	7	48	29	15	14	53	18
Water playground	40	14	7	40	44	12	15	30
Green roof	4	13	34	50	8	32	16	45
Swale + pond	7	30	34	29	4	30	44	22
Shallow swale + pond	7	31	24	38	2	25	45	28
Infiltration trench + underground storage	6	15	62	17	2	16	64	18

[a] – = non-applicable, x = applicable, xx = recommended option, xxx = best option

The relative feasibility of the selected 16 BMP techniques (including combinations) is specified for each selected BMP demonstration site in terms of a BMP Decision Support Matrix and associated weighting system.

All site classification data for the 182 sites were inputted into the BMP Decision Support Tool database, and the following operations were carried out in Microsoft Excel:

- All raw site information data are transferred into the input data spreadsheet, which corresponds to the BMP Decision Support Matrix.
- If all the dominant criteria for a particular BMP technique are satisfied by the site data, the final BMP technique is determined by a weighting system that is based on supplementary criteria.

- Otherwise, the model would directly indicate that the BMP technique (or a combination of two BMP techniques) is non-applicable, which means it should not be used for the corresponding site because of unfavorable site conditions.

All supplementary BMP variables relevant for the corresponding site are checked to obtain cumulative sums of weightings for each BMP technique. If a site meets all the requirements for a particular BMP technique, the highest possible cumulative sum will be obtained. The actual cumulative sum can be compared with the highest possible cumulative sum to indicate the level of suitability of a particular BMP technique for the corresponding site. The higher the sum, the more suitable the BMP technique is likely to be for the corresponding site.

The actual sum was divided by the maximum possible sum to get a BMP suitability index between 0.00 and 1.00. The suitability indices for each BMP technique were classified into four classes suggesting different actions to the decision-maker. The class boundaries were determined empirically, and are based on the BMP expert knowledge and understanding of the corresponding author, his research team and senior planners in Glasgow and Edinburgh. An index below 0.30 would indicate that the BMP technique should not be used for the corresponding site because of unfavorable conditions (non-applicable). An index between 0.30 and 0.75 would indicate satisfactory conditions for the implementation of a particular BMP technique (applicable). Conditions are good for the range between 0.75 and 0.95 (recommended option). If the index is >0.95, BMP implementation is strongly encouraged, because the conditions for implementation are very good (best option); for instance, no harm to the environment, elegant engineering solution and very cost-effective.

Prevalence rating approach for BMP techniques (PRABT) analysis

The majority of potential construction sites will be suitable for the implementation of at least two different BMP techniques. For these sites, more than one individual BMP technique might be possible, or even more than one combination of different BMP techniques might be suitable. Each site should be associated with a recommended BMP option, which is achieved by using a novel scaling method named Prevalence Rating Approach for BMP Techniques (PRABT) for the first time. The PRABT method rates all BMP options on a scale by their attribute of alleviating runoff volume while being environmentally sympathetic.

Table 5 shows that the PRABT scale promotes the most favourable BMP technique. The PRABT scale comprises civil engineering and sustainability ratings. The civil engineering perception rating is influenced by issues such as water management, flood attenuation, and health and safety, but not by ecological issues, for example. In contrast, environmentalists are also concerned with flood control but their main emphasis is on using sustainable materials and methods, and increasing the beneficial impact of BMP on the urban ecology. Environmentalists wish to increase or create natural habitats by using BMP, which are also visually sympathetic to the mature landscape. There is a simple weighting system for these two rating systems to allow the user to compromise different points of view. For example, if the user is a civil engineer, he or she might prefer to increase the weighting given to the civil engineering rating. Alternatively, more weighting might be given to the sustainability rating by environmentalists or ecologists.

The PRAST scale is not weighting weights. In contrast to Table 3, where weights are assigned to different site variables relating to all BMP techniques, Table 5 proposes an optional concept where all BMP techniques are weighted according to their practical engineering and sustainability enhancement functions. These functions do not relate directly to the site assessment variables. Furthermore, the introduction of other variables such as amenity value, social interactions and economical benefit is also possible.

Table 5 Methodology for the Prevalence Rating Approach for best management practice (BMP) Techniques (PRABT) scale: an example

Original PRABT number	BMP technique(s)	Civil engineering rating (weighing value = 4/10)	Sustainability rating (weighing value = 6/10)	Final weighted score	Final PRABT position
14	Swale + pond	90	97	942	1
15	Shallow swale + pond	90	90	900	2
2	Attenuation / detention pond	65	85	770	3
1	Wetland	40	100	760	4
3	Lined attenuation / detention pond	65	80	740	5
4	Infiltration basin / pond	70	75	730	6
5	Swale	55	80	700	7
6	Shallow swale	60	70	660	8
16	Infiltration trench + underground storage	70	60	640	9
13	Green roof	60	50	540	10
10	Permeable pavement	60	35	450	11
7	Filter strip	20	60	440	12
8	Soakaway	70	25	430	13
12	Water playground	15	50	360	14
11	Underground storage	65	10	320	15
9	Infiltration trench	50	15	290	16

Case-based reasoning (CBR) model used for BMP decision-making

Case-based reasoning is a method of problem solving which has arisen out of the field of artificial intelligence, and aims to recreate the robust problem-solving technique often used by humans within the constraints of a computer program (Aamodt and Plaza 1994; Arditi and Tokdemir 1999). When a human encounters a problem, he or she tends to remember similar situations that he or she came across in the past, and the methodology by which solutions were found. By recalling these events, it becomes possible to reuse the previous solution(s) to solve the current problem, perhaps adjusting the methodology and outcome slightly to meet the specific requirements of the new task (Aamodt and Plaza 1994).

Case-based reasoning works very similarly to the human logic of data handling. A data set of past experiences (e.g. allocation of BMP techniques for sites) that may be useful to solve a particular type of query (e.g. BMP planning for a new site) is kept in a database. The difficulty in CBR is the design of a system that is capable of recalling past experiences, which would provide useful information when a new problem is introduced to the system. In CBR terminology, the process of finding a solution to a former problem is referred to as a 'case' and is stored in the system's 'case base'. Each case should be stored within the case base systematically and consistently. The chosen structure is referred to as the 'case representation' (Arditi and Tokdemir 1999).

When a new problem is introduced to the CBR system, it should be represented in the same format as the stored cases, and then the process of deciding which of the past cases may be of use in finding a solution to this problem can begin. The main assumption underlying a CBR methodology is that similar problems will have similar solutions. It follows that the most useful cases in the case base will be those that are most similar to the problem case (Kaster *et al.* 2005).

The concept of similarity is fundamental in CBR theory, making inexact matching possible, which is required when previously unseen problems arise. A mechanism is implemented within the system which is capable of recalling past cases that are most closely matched to the problem presented in terms of the variable(s) used to describe the cases. Therefore, the variables used should be carefully chosen, so that the solutions recalled will also be relevant to the problem case. Once the most similar cases have been selected, the predicted solution is found using an adaptation or learning process (Aamodt and Plaza 1994).

Concerning BMP decision-making issues, case-based reasoning could provide a systematic and effective approach to arrive at a more realistic output (if compared to human judgment alone) through establishing a large database, which could include all BMP installation implementations throughout Scotland or even Britain and the United States in the future. For the Glasgow and Edinburgh BMP Management Project, 182 sites were available to build up a database of 'cases' which has a high variety of different sites. A suitable BMP technique for a new site is suggested based on a comparison between the new site information and previous 'cases'. The recommended BMP option and the PRABT output are obtained through the CBR model.

Results and discussion

BMP decision support model output

The BMP Decision Support Model output is based on the raw data of 182 sites (Table 1 and Figure 1). Sites in Edinburgh have more roof runoff in comparison to sites in Glasgow because of the higher housing density. The proportion of properties owned by the Council is higher in Glasgow if compared to Edinburgh, reflecting the high proportion of the population close to the poverty line. Glasgow has considerably more regeneration sites compared to Edinburgh where planners mainly rely on BMP retrofitting due to a lack of affordable open space. The BMP variables ‘land value’ and ‘runoff quantity’ are influenced greatly by property purchasing costs and available storage volumes, respectively. They are the most influential variables for both cities. ‘Land value’ is estimated as a relative variable.

The expected high runoff quantity in Glasgow (i.e. the rainy Scottish West Coast) corresponds with relatively large catchment sizes. This contrasts with the situation in Edinburgh (i.e. the dry Scottish East Coast) where runoff quantity is low for the corresponding relatively small catchment sizes (Table 1). It follows that BMP introduction in Glasgow is likely to have a greater beneficial impact on the urban hydrology and city development.

Table 4 shows the proportions of four BMP Decision Support Model categories (non-applicable, applicable, recommended option and best option) for different BMP techniques applied for sites in Glasgow (G) and Edinburgh (E). Ponds (G: 59%; E: 60%), lined ponds (G: 65%; E: 61%) and permeable pavements (G: 57%; E: 71%) obtained high proportions for best BMP options considering individual BMP techniques for both Glasgow and Edinburgh. Moreover, ponds combined with swales (G: 19%; E: 29%) or shallow swales (G: 35%; E: 38%) are the most likely choices for BMP combinations. This output is reasonable considering general technical judgment. Ponds (or lined ponds) increase the duration of the flow hydrograph with a consequent reduction in peak flow, which is considered to be the most effective BMP technique to control stormwater quantity and quality (Pettersson 1997). Permeable pavements require little additional space and could be applicable in most situations. Swales (or shallow swales) are generally grassed stormwater conveyance channels that use biofiltration and limited ground infiltration to remove pollutants. Swales can also form a network within a BMP development scheme, linking BMP features or conveying runoff to a watercourse or sewer.

Comparing the output from Glasgow and Edinburgh with each other, sites in Edinburgh are more suitable for below-ground BMP techniques such as infiltration trenches, permeable pavements and underground storage facilities. Underground storage is more suitable for retrofitting sites in Edinburgh due to a lack of affordable open space. For both cities, the wetlands option obtained a high proportion of ‘non-applicable’ entries although wetlands are considered to be the most ecological BMP technique by environmentalists. However, wetlands usually require relatively large construction areas, and high ecological impact potentials.

The seven demonstration sites in Glasgow and Edinburgh, respectively, were selected based on the rationale that demonstration sites should represent different geographical areas, types of land usage, site classification types and BMP techniques to be implemented. Moreover, the detailed design of demonstration sites would help people to have a better understanding of BMP.

A free trial version of the BMP Decision Support Model has been published on the internet (http://www.see.ed.ac.uk/research/environ/uw12.html). Users are encouraged to provide the author with feedback.

PRABT analysis

As outlined in the methodology section, both individual and combinations of BMP techniques were rated on the PRABT scale (Table 5). Rating methods based on civil engineering and sustainability perceptions were explored. Concerning Glasgow and Edinburgh, civil engineers are predominantly concerned with reducing the peak flow to alleviate the risk of flooding further downstream, and minimizing the space for BMP implementation to utilize the majority of available land for construction. Correspondingly, environmentalists are predominantly concerned with increasing the ecological impact of BMP to enhance biodiversity. For the purpose of this modelling example, civil engineering rating obtained 4 out of 10, and sustainability rating 6 out of 10 weighting points. The final

Table 6 Results of the decision support and case-based reasoning (CBR) models for the implementation of best management practice (BMP) techniques using the Prevalence Rating Approach for BMP Techniques (PRABT) scale for both Glasgow and Edinburgh sites

		Glasgow sites / Edinburgh sites			
		BMP Decision Support Model		CBR Model	
PRABT position	BMP technique(s)	Number of sites	% of sites (%)	Number of sites	% of sites (%)
1	Swale + ponds	15 / 30	19 / 29	19 / 23	24 / 22
2	Shallow swales + ponds	14 / 9	18 / 9	11 / 6	14 / 6
3	Attenuation / detention ponds	18 / 23	23 / 22	5 / 17	6 / 17
4	Wetlands	0 / 0	0 / 0	0 / 0	0 / 0
5	Lined attenuation / detention ponds	4 / 1	5 / 1	3 / 1	4 / 1
6	Infiltration basin / ponds	1 / 1	1 / 1	0 / 2	0 / 2
7	Swales	3 / 12	4 / 12	9 / 22	11 / 21
8	Shallow swales	1 / 0	1 / 0	2 / 2	3 / 2
9	Infiltration trenches + underground storage	1 / 3	1 / 3	4 / 0	5 / 0
10	Green roof	5 / 9	6 / 9	2 / 9	3 / 9
11	Permeable pavement	10 / 13	13 / 13	11 / 16	14 / 16
12	Filter strips	0 / 0	0 / 0	0 / 0	0 / 0
13	Soakaways	0 / 0	0 / 0	0 / 1	0 / 1
14	Supplementary water playground	0 / 0	0 / 0	0 / 0	0 / 0
15	Underground storage	6 / 0	8 / 0	7 / 1	9 / 1
16	Infiltration trenches	0 / 0	0 / 0	0 / 0	0 / 0
17	No BMP possible	1 / 2	1 / 2	6 / 3	8 / 3

BMP technique positioning after PRABT implementation (example only) is shown in Table 6. Findings indicate that combinations of ponds and swales obtained the highest score (see above). In comparison, the approach rates infiltration trenches as the least favourable BMP technique, because of the frequently insufficient engineering performance and low environmental benefit (Jefferies *et al.* 1999).

The PRABT scale is applied to all the BMP possibilities and recommends the highest ranked BMP technique as the solution. The numbers and proportions of individual and dual BMP techniques derived from the PRABT analysis are shown in Table 6. Noticeably, the combination of swales (or shallow swales) with ponds and ponds alone have the greatest proportion of recommended BMP solutions for both sites in Glasgow and Edinburgh. Wetlands, filter strips and some other BMP features scored 0%. However, these techniques were potentially suitable for some sites, but a different BMP technique, which featured higher on the PRABT scale, was more suitable. Moreover, there is one site in Glasgow and there are two sites in Edinburgh that are not associated with any recommended BMP technique, mainly because of steep slopes on the sites (Table 6).

Case-based reasoning (CBR) model output

The output of the BMP Decision Support Model incorporating PRABT is shown in Tables 4 and 6. The output from the CBR model is similar to the BMP Decision Support Model output. The novel idea is to use CBR in the decision-making process for BMP installations. However, a larger 'case base' would have been an advantage in order to increase the practical relevance of this technique.

Conclusions

- A survey of 182 sites in Glasgow and Edinburgh indicated that it is feasible to implement different BMP techniques and short BMP treatment trains within both cities, which are fundamentally different from each other.
- A general BMP implementation matrix (including dominant and supplementary criteria), which can be adapted for other cities and countries, has been outlined.
- A practical BMP Decision Support Model based on a support matrix (BMP variable specifications for BMP techniques) and an associated weighting system has been developed to give the practitioner a novel tool to assess the suitability of different BMP techniques for a particular site with and without applying his or her own judgement.
- A trial BMP Decision Support Model version has been published on the website to obtain user feedback.
- The modelling outcome indicates that ponds (or lined ponds) and permeable pavements are the most frequently proposed BMP techniques for Glasgow and Edinburgh, and ponds combined with swales (or shallow swales) are the most recommended BMP combinations.
- Fourteen BMP demonstration sites that are representative for both different sustainable drainage techniques and different geographical areas available for development, regeneration or retrofitting within Glasgow and Edinburgh have been identified.
- The Prevalence Rating Approach for BMP Techniques (PRABT), which allows for the application of different proportions of civil engineering and sustainability judgement used in BMP decision-making to be made, was developed. Ponds linked to swales (or shallow swales) were placed at the top (most suitable) after PRABT ranking was undertaken. They were also associated with the highest proportion of recommended BMP solutions for both Glasgow and Edinburgh.
- A separate case-based reasoning (CBR) model was compared to the BMP Decision Support Model. The outputs of both models compared well with each other, indicating that the CBR model works similarly to the human mind.

Acknowledgements

Technical support was provided by Mr. Pi Yin, Mr. N.L. Corrigan, Mr. J.H. Thomas, Mr. O. Birchinger, Ms. M. Wagner, Mr. D.A. Gallagher and Mr. P.E. Byrne. The author wishes to thank the senior planners in Glasgow (particularly Mr. B. Aaen and Mr. S. Gillon) and Edinburgh for their advice and guidance. The research was directly sponsored by The Royal Academy of Engineering (Global Research Award; awarded to M. Scholz in April 2004) and Glasgow City Council.

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