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A systematic approach for the comparative assessment of stormwater pollutant removal potentials

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Abstract

This paper describes the development of a methodology to theoretically assess the stormwater pollutant removal performances of structural best management practices (BMPs). The method combines the categorisation of the relative importance of the primary removal processes within 15 different BMPs with an evaluation of the ability of each process to remove a pollutant in order to generate a value representing the pollutant removal potential for each BMP. The methodology is demonstrated by applying it separately to a set of general water quality indicators (total suspended solids, biochemical and chemical oxygen demand, nitrates, phosphates and faecal coliforms) to produce a ranked list of BMP pollutant removal efficiencies. Given the limited amount of available monitoring data relating to the differential pollutant removal capabilities of BMPs, the resulting prioritisation will support stakeholders in making urban drainage decisions from the perspective of pollutant removal. It can also provide inputs to existing urban hydrology models, which aim to predict the treatment performances of BMPs. The level of resilience of the proposed approach is tested using a sensitivity analysis and the limitations in terms of BMP design and application are discussed.

Keywords: Best management practices (BMPs); Pollutant removal potentials; Unit operating processes; Stormwater

1. Introduction

The EU Water Framework Directive (WFD) (EU, 2000) identifies the control of diffuse pollution as a key factor in enabling good ecological status to be achieved in aquatic systems and therefore represents a clear driver for the review of current stormwater management practices. The conventional drainage approach to managing stormwater flows involves the direct removal of surface water through a series of pipes to the nearest watercourse to prevent local flooding, with little attention being paid to stormwater quality or its impact on receiving waters. However, the issue of urban water quality is increasingly taking centre stage and associated with this is a greater interest in the use of stormwater best management practices (BMPs). These represent a diverse range of source control procedures, which integrate stormwater quality and quantity control as well as enabling social and amenity perspectives to be incorporated into stormwater management approaches. The term 'BMPs' covers a wide range of structural systems, all of which have the ability to improve stormwater quality and attenuate flow volumes through a combination of biological, physical and chemical processes.

1.1. Selection of BMPs

There are a variety of approaches and guidelines available for selecting the most appropriate type of BMP for a particular site with, for example, many states/counties in the USA having their own stormwater design manuals (e.g. Maryland Department of the Environment, 2000). Typically, these make recommendations in relation to catchment-specific factors such as soil type, available space, capacity to store a design storm event, operation and maintenance requirements and cost (CIRIA, 2000, 2001). In contrast, the potential for specific types of BMPs to remove a particular pollutant of concern, or even the treatment efficiency of BMPs in general, is rarely, if ever, used as a discriminatory criterion. However, as a result of

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the implementation of the EU WFD, and the increasing importance of pollution reduction accountability in the context of River Basin Management Plans, knowledge relating to the ability of different BMP systems to remove a particular pollutant is becoming a prime requirement.

A range of urban hydrology models are available which incorporate assessment of the performance of BMPs as part of the drainage network, although these simulations are primarily based on an evaluation of their hydraulic behaviour. An appropriate example is InfoWorks CS, which models the hydraulic behaviour of BMPs such as soakaways, infiltration trenches, swales and permeable pavements. Additionally, it contains a water quality module which can feedback into the hydraulic simulation, but this relates primarily to the modelling of physical processes, such as sediment build-up, to support pollution control through the identification of CSO problems rather than contributing to the prediction of pollutant removal treatment efficiencies in different BMPs (Wallingford Software, 2006). The Storm Water Management Model (SWMM) integrates BMP hydrological modelling with a consideration of the associated treatment performance (EPA, 2006). However, this requires operators to input their own BMP removal efficiencies, which in the absence of field data would need to be estimated.

A model which more specifically addresses the role of BMPs by incorporating ponds, bioretention systems, infiltration buffer strips, sedimentation basins, pollutant traps, wetlands and swales into stormwater management strategies is the decision-support model MUSIC, Model for Urban Stormwater Improvement Conceptualisation (CRC, 2006). MUSIC models BMP performances using algorithms originally developed for Continuously Stirred Tank Reactors (CSTRs) with different numbers of CSTRs being used to mimic different types of BMPs. Pollutant removal is evaluated using the $k-C^*$ model modification of the first-order kinetic uptake model developed by Kadlec and Knight (1996) to predict the removal of BOD in wetlands. The selection of appropriate values for the first-order rate constant (k) and the background pollutant concentration (C^*) are therefore of critical importance in robustly predicting pollutant removal. However, because the removal processes which occur in BMPs are highly heterogeneous in terms of both space and time (for example, physical processes may dominate during storm events with biological and chemical processes being of greater importance in the longer term), choosing a single 'k' value which covers all these variables is extremely complex. The selection of C^* is also problematic as it may vary greatly in relation to factors such as variations in the time-period between storm events and rainfall intensity. A range of default 'k' and C^* values, based on considerations of the relevant physical processes, are provided within the model for total suspended solids (TSS), total phosphorous and total nitrogen for seven different BMPs. Users are recommended to select from a range of values (e.g. 'k' values from 500 to 5000 m year^{-1} for TSS removal within a wetland) based on factors relating to the specific BMP characteristics and a sensitivity analysis to determine the impact of varying 'k' and 'C^*' values on overall treatment performance. Such a pragmatic approach is necessitated by the current lack of comparable data on pollutant removals across the many different types of BMPs and indicates the need for a fuller investigation into the relative contributions of the pertinent biological, chemical and physical processes.

As a contribution to meeting these identified needs, this paper describes the development of a systematic approach, based on fundamental scientific principles, for the prediction of the comparative pollutant removal potentials operating within a range of BMPs. The results can be utilised to inform the selection of k values which integrate biological, chemical and physical processes within modelling routines, such as MUSIC, as well as contributing to the wider decision-making framework which typically involves the consideration of a diversity of factors ranging from catchment size to rainfall-runoff coefficients and costings. Hence, the approach described in this paper is not meant to be used as a stand-alone procedure, but one which can contribute to stormwater management decision-making processes with respect to the control of the discharge of specific substances to receiving water bodies until further field data becomes available. Full details on the development of this novel approach are presented, together with its application to TSS, BOD, COD, nitrates, phosphates and faecal coliforms. Results of this procedure are critically discussed and compared, where possible, to observed field data and the validity tested through a sensitivity analysis.

2. Unit removal processes in BMPs

2.1. Identification and controlling factors

The performances of individual stormwater BMPs may vary from site to site in relation to variables such as design specifications, local hydrologic and climatic conditions, and system age (e.g. Ellis et al., 2003). In developing the described methodology, the BMP-type descriptions are as outlined in Table 1. In addition, the individual BMP devices are assumed to be operating at their design efficiency and to be functioning on a 'stand-alone' basis, i.e. not part of a hybrid treatment train. The vulnerability of the treatment potential to variable hydraulic conditions has been taken into account by incorporating the impact of extreme events into the predicted efficiencies of the identified removal processes within different BMPs. The possible impacts of variables, such as system ageing, are partially incorporated through the inclusion of how the different removal processes are likely to be maintained throughout the lifetime of a BMP.

The primary biological, chemical and physical processes associated with pollutant removal in structural BMPs are identified in Fig. 1 and reflect the fundamental unit

Table 1
Descriptions of different structural BMPs

System type	Description
Filter drains	Gravelled trench systems where stormwater can drain through the gravel to be collected in a pipe; unplanted but host to algal growth
Porous asphalt	Open graded powdered/crushed stone with binder: high void ratio; no geotextile liner present
Porous paving	Continuous surface with high void content, porous blocks or solid blocks with adjoining infiltration spaces; an associated reservoir structure provides storage; no geotextile liner present; host to algal growth
Sedimentation tank	Symmetrical concrete structure containing appropriate depth of water to assist the settling of suspended solids under quiescent conditions
Filter strip	Grassed or vegetated strip of ground that stormwater flows across
Swales	Vegetated broad shallow channels for transporting stormwater
Soakaways	Underground chamber or rock-filled volume: stormwater soaks into the ground via the base and sides; unplanted but host to algal growth
Infiltration trench	A long thin soakaway; unplanted but host to algal growth
Infiltration basin	Detains stormwater above ground which then soaks away into the ground through a vegetated or rock base
Retention ponds	Contain some water at all times and retains incoming stormwater; frequently with vegetated margins
Detention basins	Dry most of the time and able to store rainwater during wet conditions; often possess a grassed surface
Extended detention basin	Dry most of the time and able to store rainwater during wet conditions for up to 24 h; grassed surface and may have a low basal marsh
Lagoons	Pond designed for the settlement of suspended solids; fringing vegetation can sometimes occur
Constructed wetlands	Vegetated system with extended retention time
• Sub-surface flow	Typically contain a gravel substrate, planted with reeds, through which the water flows
• Surface flow	Typically contain a soil substrate, planted with reeds, over which the water flows

operating processes (UOPs) familiar to traditional water and wastewater engineers. This UOP approach provides an alternative, and more radical, methodological basis for the selection of BMPs, but one which is being more widely considered within stormwater engineering (Quigley et al., 2005; Scholes et al., 2005). Fig. 1 shows how these fundamental UOP behavioural properties can be integrated with pollutant-specific characteristics to develop a combined value, which represents the potential for a specific pollutant to be removed within a particular BMP system. Repetition of this procedure for each BMP enables a combined value to be developed which represents the relative potential for each BMP to remove the pollutant under consideration. These combined values can then be ranked in a descending order to generate a hierarchy of BMPs with regard to removal of the specific pollutant of concern, which can also be used to support the relative selection of '*k*' values for use in stormwater management modelling.

The primary pollutant removal mechanisms found in BMPs can be divided into two categories depending on whether they result (i) in the direct removal of a pollutant from the water column (e.g. settling; adsorption to substrate; microbial degradation; filtration; plant uptake; volatilisation and photolysis) or (ii) whether they contribute indirectly to the removal of a pollutant (e.g. precipitation; adsorption to suspended solids). The indirect processes contribute to the overall removal of pollutants by occurring before processes such as settling or filtration. Adsorption to suspended solids will be controlled by factors such as the particulate surface area and surface composition. The latter influences the extent of physical adhesion and/or chemi-sorption with the presence of coatings of organic matter particularly affecting the adsorption of organic pollutants. In contrast, precipitation is mainly controlled by variations in the temperature and/or the chemical composition of the water although both processes are assisted by the existence of still as opposed to turbulent conditions.

2.2. Relative importance of the different BMP removal processes

Currently, there is only limited field data available to describe the differential pollutant removal capabilities of BMPs and in the absence of experimental results, it is appropriate to consider a theoretical approach as a pragmatic contribution to managing the uncertainties associated with this acknowledged data gap. This can be achieved by utilising existing knowledge at the UOP level to predict the primary removal mechanisms which occur in each type of treatment system and making informed judgements about the comparative importance of each removal process on both intra- and inter-BMP system bases. The adoption of such a prioritisation approach is commonly applied as part of risk management procedures and has been initiated in this study by designating the relative importance of each removal mechanism within specific BMPs as being of either:

- high importance, i.e. considered to be a dominant removal process within the BMP;
- medium importance, i.e. a process which contributes significantly to the overall BMP pollutant removal capability;
- low importance, i.e. a process which makes only a small contribution to pollutant removal or
- not applicable (NA) where it is not relevant to a particular BMP option.

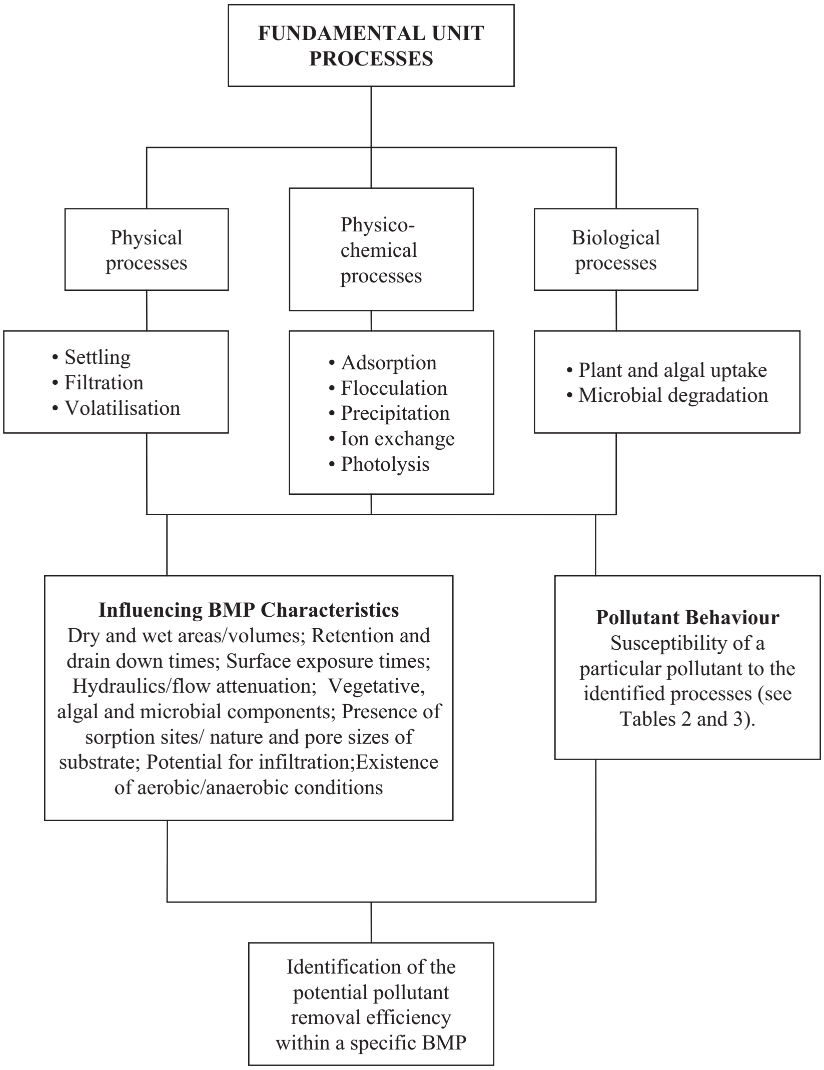

Fig. 1. Fundamental unit processes in relation to BMP characteristics and pollutant behaviour.

Where appropriate, these functional categories are further sub-divided into medium/high and low/medium but it is not considered justifiable to introduce additional sub-classifications. Developing such a systematic approach to support decision-making in the absence of existing data requires the use of expert judgement as a basis for assigning rankings and is therefore a subjective process although experience gained in the wastewater-engineering field provides a sound basis for UOP characterisation. There are also many areas of professional practice such as occupational risk management, where a combined data/professional judgement approach to decision-making is necessary due to operational demands. Embedded within the use of this approach is the understanding that, where expert judgement forms a significant part of the ranking procedure, it is recommended that wider participation should be considered (CERM, Risk Ranking, 1997). The rankings identified and assigned to the various removal processes presented in this paper reflect both the opinions of the authors and collaborative partners and end-users associated with the completed DayWater project (DayWater, 2002). The premises on which the rankings have been assigned are clearly stated to facilitate further discussion and consultation and to assist the development of a more refined and explicit framework, where this is required.

2.3. Descriptions of the identified unit operating processes

2.3.1. Adsorption to substrate

Adsorption to substrate refers to the physico-chemical adherence of pollutants to an artificial substrate (e.g. the gravel matrix of a filter drain), a natural substrate (e.g. vegetation within a swale) or an introduced substrate (e.g. the deposited benthal sediment within a detention pond) and is influenced by those factors previously described for adsorption to suspended solids. It is an important potential removal process in filter drains, porous paving (with underground reservoir) (Legret and Colandini, 1999), sub-surface flow (SSF) constructed wetlands, infiltration basins, soakaways and infiltration trenches due to the close contact achieved between stormwater and substrate surface during the infiltration of an effluent through the relevant permeable material (Table 2). The hydraulic pathways taken by stormwater within swales, filter strips, surface flow (SF) constructed wetlands, detention basins and extended detention basins will result in lower direct contact times with the available substrate and therefore less potential for adsorption. The regular draining down of detention basins following a storm event will encourage adsorption in comparison to retention ponds and lagoons where a permanent water body exists.

2.3.2. Settling

Settling is the vertical movement of discrete or agglomerating suspended sediment particles to the base of a water column (Ellis et al., 2004) and is highly dependent on the retention of a quiescent water volume within the BMP system. It basically represents the Type I and Type II settling processes which occur in conventional wastewater primary settlement tanks (Tchobanoglous et al., 2003). Hence, it will be a predominant mechanism in retention ponds (Pettersson et al., 1999), infiltration basins (Barbosa and Hvitved-Jacobsen, 2001) and extended detention basins (Revitt, 2004), but slightly less important in detention ponds (reduced retention time) and lagoons and sedimentation tanks (comparatively lower volumes and surface areas) (Table 2). Although, the presence of macrophytes in both types of constructed wetland contributes to the formation of quiescent conditions, the presence of dense stands of vegetation also effectively lowers the stationary water column volume, through which settling can occur, leading to the allocation of a comparatively lower potential for settling in these systems. The other types of BMP are assigned 'low/medium' or 'low' removal potentials for settling processes due to the absence of a persistently still water body, which would facilitate particle deposition.

Table 2
Relative importance of substrate adsorption, settling and microbial degradation in BMPs

BMPs	Adsorption to substrate	Settling	Microbial degradation
Filter drain	Medium/high	Low/medium	Medium
Porous asphalt	Low/medium	Low	Low
Porous paving	High	Low/medium	Medium
Filter strip	Medium	Low	Low/medium
Swales	Medium	Low/medium	Low/medium
Soakaways	Medium/high	Low/medium	Medium
Infiltration trench	Medium/high	Low/medium	Medium
Infiltration basin	High	High	High
Sedimentation tank	Low	Medium/high	Low
Retention ponds	Low/medium	High	Medium
Detention basins	Medium	Medium/high	Low/medium
Extended detention basin	Medium	High	Medium
Lagoons	Low/medium	Medium/high	Low
Constructed wetlands (SSF)	Medium/high	Medium	High
Constructed wetlands (SF)	Medium	Medium	Medium

2.3.3. Microbial degradation

Microbial degradation is facilitated by the availability of attachment sites and nutrients within a BMP and both aerobic and anaerobic processes are enhanced by the occurrence of high contact ratios between stormwater and substrate material. Microbial degradation is therefore strongly encouraged within SSF constructed wetlands (Ellis et al., 2003) and infiltration basins (Table 2). Filter drains, porous paving, soakaways, infiltration trenches, retention ponds, extended detention basins and SF constructed wetlands do not typically provide the same diversity of microbial attachment sites and are consequently assigned a medium significance for this process. The prolonged contact of stormwater with an established microbial population is less feasible for detention basins (non-permanent water body), filter strips and swales (low retention times) resulting in the allocation of 'low/medium' removal potentials for these BMPs. The remaining treatment systems (porous asphalt, sedimentation tanks and lagoons) are assigned the lowest importance for this removal process due to the comparatively lower potentials for stormwater to interact with substrates acting as hosts to diverse microbial communities.

2.3.4. Filtration

This UOP in BMPs occurs by the same mechanisms as those present in conventional water treatment plant sand filtration units where physical sieving removes particulate pollutants as they pass through a porous substrate or hydraulic barrier (Ellis et al., 2004). Hence, the potential for filtration to occur is considered to be most effective in porous paving and porous asphalt due to surface filtration (Revitt, 2004), particularly in porous asphalt due to the low pore size of the crushed construction material (Table 3). Infiltration trenches, infiltration basins, soakaways and SSF constructed wetlands involve the passage of stormwater through a sub-surface substrate but filtration is less efficient due to the greater void sizes within gravel, which is typically used as the substrate. Filter drains possess similar substrate structures but do not provide the opportunity for further infiltration to ground. The allocated medium removal potential also applies to SF constructed wetlands and swales, where the filtering function of surface vegetation combines with possible soil infiltration to remove pollutants (Bäckström, 2003). Similar processes are possible in filter strips but shorter contact times between stormwater and the grassed surface result in a lower filtration potential. The remaining BMPs are considered to

Table 3
Relative importance of filtration, volatilisation, photolysis and plant uptake in BMPs

BMPs	Filtration	Plant uptake	Volatilisation	Photolysis
Filter drain	Medium	Low	Low	NA
Porous asphalt	High	NA	Low	Low
Porous paving	High	Low	Low	NA
Filter strip	Low/medium	Medium	Low/medium	Low/medium
Swales	Medium	Medium	Medium	Low/medium
Soakaways	Medium/high	Low	Low	NA
Infiltration trench	Medium/high	Low	Low	NA
Infiltration basin	Medium/high	Low/medium	Medium	Low/medium
Sedimentation tank	NA	NA	Low	Low
Retention ponds	Low	Low	Medium	Low/medium
Detention basins	Low	Low	Medium	Low/medium
Extended detention basin	Low	Low	Medium	Low/medium
Lagoons	Low	Low	Low/medium	Low
Constructed wetlands (SSF)	Medium/high	Medium/high	Low/medium	Low
Constructed wetlands (SF)	Medium	Medium	Medium	Low

have low filtration potentials because of limited contact between stormwater and the basal sediments/substrates.

2.3.5. Plant uptake

The presence of terrestrial or aquatic vegetation provides the potential for plant uptake to occur and therefore this is not an applicable process in non-vegetated BMPs such as porous asphalt and sedimentation tanks. Retention ponds with fringing macrophytes present are allocated a 'low' classification for plant uptake because of the limited contact between aquatic vegetation and the bulk of the pollutants (Table 3). Similarly in detention basins and extended detention basins, surface grass coverage can participate in pollutant removal when stormwater is present. Pollutant bioaccumulation by cell tissue at a low level is also possible in porous paving, filter drains, soakaways and infiltration trenches due to algal growth on the sub-surface gravel or other filler material. A slightly increased plant uptake is envisaged for infiltration basins due to a combination of a naturally grassed surface with an algal-coated gravel substrate. Swales and filter strips are permanently grassed structures, which are allocated medium removal potentials because of efficient contact ratios between stormwater and vegetation. Similar contact efficiencies between stormwater and vegetation are expected in SF constructed wetlands. However, the potential for plant uptake will be highest in SSF constructed wetlands due to the increased contact between stormwater and the elaborate root systems of aquatic macrophytes.

2.3.6. Volatilisation and photolysis

Both processes are strongly dependent on surface exposure but whereas photolysis requires direct exposure to sunlight, volatilisation can occur from the open spaces within a BMP structure. Photolytic degradation will be negligible in filter drains, porous paving, soakaways and infiltration trenches due to the rapid incorporation of stormwater into the BMP structure. A low effectiveness is predicted in sedimentation tanks and lagoons (normally low surface areas and associated retention times), in both types of constructed wetland (restricted exposure of stormwater to sunlight due to the presence of dense stands of vegetation) and in porous asphalt (rapid infiltration into the surfacing material where interaction with UV/visible radiation is still possible). The level of photolysis will be highest (low/medium potential) in filter strips, swales, infiltration basins, retention ponds, detention basins and extended detention basins due to a combination of enhanced surface areas and exposure times (Table 3).

The degree of volatilisation is highest (medium removal potential) in extended detention basins, detention basins, retention ponds, infiltration basins, SF constructed wetlands and swales, where stormwater exposure times and surface area exposure to wind/ambient pressure differentials are optimised, relative to SSF constructed wetlands, lagoons and filter strips (low/medium potentials). Sedimentation tanks, infiltration trenches, soakaways, porous paving, porous asphalt and filter drains are all allocated 'low' removal potentials due to the lower surface exposures associated with these systems (Table 3).

2.4. Susceptibilities of TSS, BOD, COD, nitrates, phosphates and faecal coliforms to the identified primary BMP removal processes

The abilities of the general water quality indicators (TSS, BOD, COD, nitrates, phosphates and faecal coliforms) to be removed by each of the identified mechanisms are described in Table 4. These classifications for the pollutant removal potentials have been derived by consideration of the relevant physico-chemical data, when available, as well as the existing scientific knowledge of the environmental behaviours of the pollutants. Thus, the nutrients (nitrates and phosphates) are both assigned 'high' removal potentials for plant uptake but they differ markedly for adsorption, settling and filtration because of their vastly different water solubilities. Both nutrients are resistant to aerobic biodegradation but can be assigned 'low' and 'low/medium' potentials for removal under anaerobic conditions. The classifications quoted in Table 4 represent the combined impacts of both biodegradation processes. BOD and COD demonstrate similar susceptibilities to the range of removal processes with the slightly higher composition of intractable organics in COD resulting in marginally

Table 4
Potential for direct BMP processes to remove TSS, BOD, COD, nitrates, phosphates and faecal coliforms

	TSS	BOD	COD	Nitrates	Phosphates	Faecal coliforms
Adsorption	Medium	Medium	Low/medium	Low	High	Medium
Settling	High	Medium	Medium	Low	High	High
Microbial degradation[a]	Low	Medium	Low/medium	Low	Low	Low/medium
Filtration	High	Medium	Medium	Low	High	High
Volatilisation	NA	Low	Low	NA	NA	NA
Photolysis	NA	Low	Low	NA	NA	Low/medium
Plant uptake	NA	Medium	Low/medium	High	High	NA

NA = not applicable.

[a] Based on a consideration of aerobic and anaerobic processes.

reduced tendencies to undergo adsorption, plant uptake and microbial degradation. In the latter process, anaerobic degradation is considered to represent a low potential for removal for both oxygen demanding parameters but the corresponding aerobic process can produce 'high' and 'medium' removals respectively for BOD and COD resulting in the combined classifications shown in Table 4. Faecal coliforms and TSS are expected to show similar removal capabilities with the only known exception being the susceptibility of the former to photolysis (van der Steen et al., 2000). The potentials of the selected pollutants to undergo both settling and filtration have been based on their abilities to adsorb to suspended solids and to precipitate, which have been identified as relevant indirect processes. Although they are dependent on similar precursor mechanisms, filtration and settling are clearly separate removal processes within a structural BMP.

3. Development and testing of an approach for the prediction of removal potentials

3.1. Aggregation of data on the relative importance of removal processes within BMPs with the potential for the selected parameters to be removed by the same processes

The potential for a pollutant to be removed within a BMP can be considered to be a function of the type and magnitude of the removal processes which occur within a BMP in combination with the susceptibility of the pollutant to be removed by these removal processes. The developed methodology enables these two data sets to be combined by adopting the risk-rating approach of converting the classifications of high, medium, low and 'not applicable' to the numeric values 3, 2, 1 and 0, respectively (Boyle, 2000). Intermediate values of 1.5 and 2.5 were allocated to low/medium and medium/high classifications as appropriate. The potential of a particular pollutant (e.g. TSS) to removal by settling can be represented by the combination of the derived numeric value representing this process with the corresponding value representing the importance of settling within a particular BMP (e.g. infiltration trench) (Tables 2, 4 and 5). A multiplicative approach has been used to produce the combined values to highlight the 'extremes' (i.e. the best and worst values) and provide greater discriminatory power than would be achieved by addition. An additional factor in the calculation is that photolysis and volatilisation are both assigned weightings of 0.5 relative to the other removal processes to signify their typically lower contributions to the overall pollutant removal capability of BMPs. The separate values calculated for each removal process can then be summed to give a single overall value representing the removal potential of TSS in an infiltration trench, as displayed in Table 5.

Table 5
Potential for removal of TSS by an infiltration trench

	Significance of process to the pollutant	Significance of process to BMP	Combined value
Adsorption	2	2.5	5
Settling	3	1.5	4.5
Microbial degradation	1	2	2
Filtration	3	2.5	7.5
Volatilisation[a]	0	1	0
Photolysis[a]	0	0	0
Plant uptake	0	1	0
		Overall value	19

[a] Assigned a weighting of 0.5.

Repeating this procedure for each BMP and then ranking the overall values in descending order of magnitude effectively enables an order of preference for the relative potential of BMPs to remove TSS to be generated. In addition to TSS, this procedure was also applied to BOD, COD, nitrates, phosphates and faecal coliforms, and the ranked results are presented in Figs. 2 and 3 where a ranking of 1 identifies the BMP possessing the highest removal potential for the identified pollutant. The values upon which the rankings are based are ordinal and not numeric and therefore represent the order of predicted BMP performances relative to each other but do not have any quantitative meaning in terms of actual removal performance.

Figs. 2 and 3 show that settlement tanks are consistently predicted to be the worst performing BMP system followed

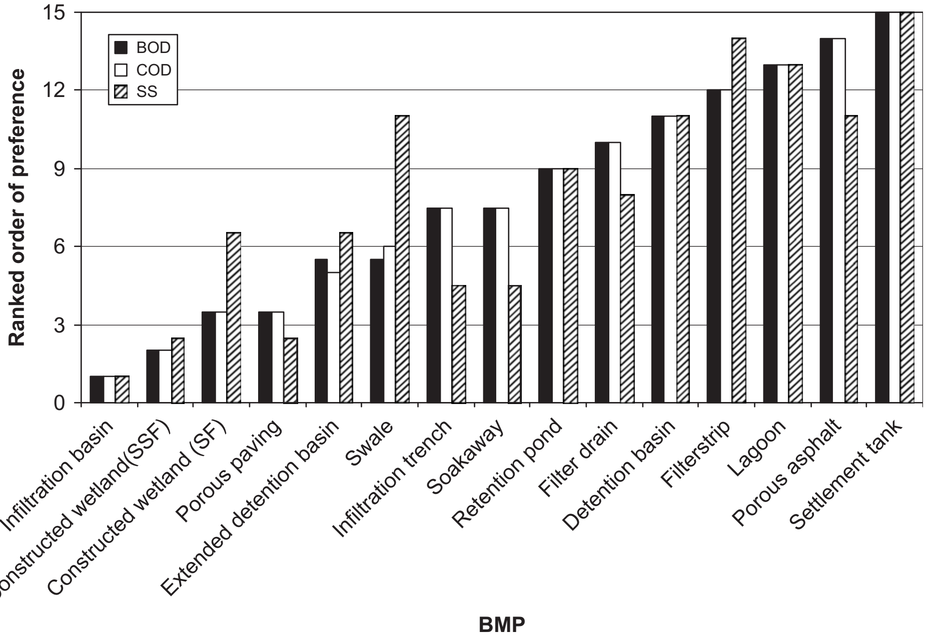

Fig. 2. Predicted order of preference for the use of BMPs to remove BOD, COD and TSS.

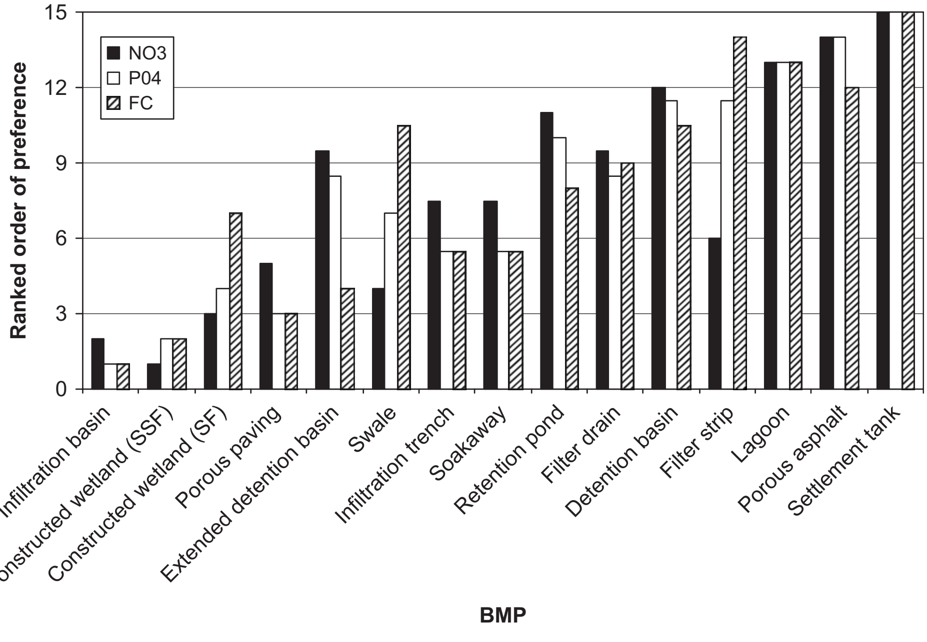

Fig. 3. Predicted order of preference for the use of BMPs to remove nitrates, phosphates and faecal coliforms.

by porous asphalt, although TSS and faecal coliforms have slightly enhanced removals for the latter. In contrast, infiltration basins offer the highest predicted removal efficiencies for five of the six pollutants evaluated. The exception is nitrates where SSF constructed wetlands achieve the highest ranking. This type of constructed wetland is more efficient than the SF type for the range of considered pollutants. Porous paving is predicted to behave equally as well, if not better than SF constructed wetlands, except for nitrates, as the removal of this pollutant is strongly influenced by the importance of plant uptake processes (Table 3). Extended detention basins generally demonstrate the best performances for BMPs relying predominantly on 'stormwater volume capture' as the major pollutant removal process, followed by retention ponds, detention basins and lagoons. Swales exhibit a large variability in the predicted hierarchy for their removal of the different pollutants with TSS and faecal coliforms being the least efficiently retained. Filter strips show a similar variability but with overall lower efficiencies. For

BMPs utilising infiltration as the major pollutant removal process, infiltration trenches and soakaways show identical mid-range removal characteristics and are predicted to consistently out-perform filter drains.

3.2. *Comparison of predicted pollutant removal efficiencies with monitored values*

The predicted ranked order of BMPs with respect to their pollutant removal potentials can only be confidently compared with existing monitoring data for TSS as this is the only pollutant for which 5 independent data sets exist for a realistic number of BMPs throughout Europe and N. America (ASCE/USEPA, 2006; Ellis et al., 2003; Scholes et al., 2005; Schueler, 1997; USEPA, 2006; Winer, 2000; Yu et al., 1993). The mean values are plotted in Fig. 4, together with the standard deviations which demonstrate the variabilities in this field data resulting from the use of different monitoring strategies and associated evaluation methods and the dependence, in some cases, of the BMP performance on the magnitude of influent concentrations and loadings. There is a tendency for monitored pollutant capture rates to decrease and be more variable as influent concentrations fall. In this initial stage of the model development, the theoretical considerations are based on all BMPs operating at their design potential. However, the monitored systems will be at different stages of their operational lives and hence subject to factors such as ageing, which are not yet fully incorporated in the developed approach. However, in spite of these differences, there is a good agreement between the systematically predicted hierarchy for suspended solids removal efficiencies (Fig. 2) and those determined for the monitored data (Fig. 4) with, for example, 4 of the top 5 BMPs predicted using the theoretical approach also appearing in the top 5 BMPs identified using field data. The major discrepancy appears to be for swales, which perform considerably better in practice than is predicted theoretically. It may be that the theoretical interpretations of swale performance have under-estimated the potential for particulate removal by filtering (by the grass sward) and settling (due to vegetative interactions reducing the rate of flow). This has been tested by increasing the relative importances of settling and filtration in swales from low/medium to medium and from medium to medium/high classifications, respectively. The impact is an expected improved TSS removal behaviour in swales, which is now similar to that predicted for infiltration trenches and SSF constructed wetlands.

In contrast, constructed wetlands (particularly SSF systems) and extended detention basins appear to under-perform relative to their predicted removal performances for TSS. For extended detention basins, only the minimum data requirement (5 independent values) was available and therefore it is possible that the calculated mean values are not truly representative of the optimum performance. The monitored value for SSF constructed wetlands was 81.0 ± 11.1%, which is consistent with the predicted high hierarchical position. The most reliable monitored data (based on 43 independent measurements) is for retention ponds (73.8 ± 15.9%) and this suggests a TSS removal potential which is entirely consistent with the predicted performance which is indicated to be less efficient than a SSF wetland. Monitoring results, above the minimum 5 data sets, are also available for retention ponds for the other pollutants (except phosphates), and hence it is possible to observe if there are any comparable trends between the different pollutants for this particular BMP.

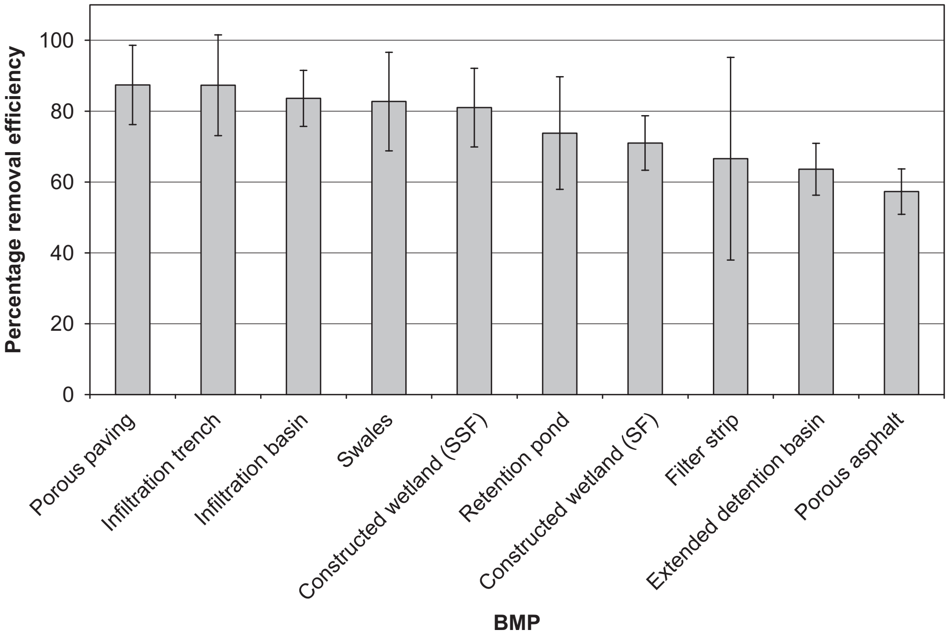

Fig. 4. Average monitored TSS percentage removal efficiencies (±SD) for BMPs.

The measured values for BOD (51.9±25.7%) and COD (55.9±25.6%) are similar and consistent with the relative hierarchical positions predicted theoretically (Fig. 2). The reduced ability of this BMP to remove nitrates (33.6±43.1%) compared to faecal coliforms (71.3±14.0%) is also in agreement with the predicted order of preference indicated in Fig. 3 for these pollutants.

3.3. *Support in the selection of k values within urban hydrological modelling*

The development of a BMP order of preference in relation to a particular pollutant of concern not only provides an important contribution to the wider decision-making process but also provides relevant input to the selection of appropriate *k* values within stormwater management models. Currently, the MUSIC model proposes a range of *k* values for TSS removal within ponds, infiltration systems, wetlands, swales and sedimentation basins. A comparison of the descriptions provided within the MUSIC user manual with those in Table 1 identifies these BMPs as corresponding to retention ponds, infiltration basins, constructed wetlands (SSF for the purposes of this example), swales and settlement tanks, respectively as defined in this study. The extensive ranges of *k* values recommended for these BMPs are:

- infiltration basins (200–1000 m year^{-1}),
- constructed wetlands (500–5000 m year^{-1}),
- retention ponds (200–1000 m year^{-1}),
- swales (4000–15 000 m year^{-1}) and
- settlement tanks (4000–15 000 m year $^{-1}$).

The BMP order of preference generated for TSS removal (Fig. 2) would suggest that the *k* values assigned to the above systems decrease in value in the order infiltration basin > constructed wetland (SSF) > retention pond > swale > settlement tank. There is a clear discrepancy for swales and settlement tanks, which have been assigned the highest ranges of proposed *k* values based on physical processes only. The differences resulting from an integrated consideration of biological, chemical and physical processes suggest that revised *k* values may be appropriate for modelling approaches, such as MUSIC, with the current values assigned to infiltration basins, retention ponds and constructed wetlands underestimating their role in TSS removal.

3.4. *Sensitivity analysis on the predicted removal priorities*

Sensitivity analysis identifies the variability in response of the results generated using a particular approach to any assumptions that may have been made about the data or methods used to derive them. It is therefore appropriate to test the sensitivity of the orders of preference generated (i.e. the approach output) to changes in the approach input (i.e. variations in the weightings placed on input parameters). To achieve this, a simple factorial approach was applied to testing the influence of each removal process in turn on the overall pollutant removal capability of each BMP. This involved setting the weighting of a specific removal process to 0% (i.e. effectively assuming a process does not occur) and then recalculating the order of BMP preference to assess the influence of the chosen process on the overall potential of a system to remove a particular pollutant. This approach also provides an opportunity to determine how well the developed approach simulates the systems it sets out to represent by supporting the identification of the most influential removal processes within each BMP.

The results of applying this process to the removal of TSS by BMPs are compared to the default ranked order of preference (i.e. before any alteration of weightings took place) in Table 6. As can be seen from the ranges of values, demonstrated by the highest and lowest ranked positions, the responses of individual BMPs varied considerably. The relative increases and decreases in the ranked positions, reflect the differential responses of BMPs to comparable variations in weightings applied sequentially to each of the removal processes.

Seven of the BMPs are identified in Table 6 as producing overall changes in position of ⩾5 places. These represent the BMPs, which are most vulnerable to changes in the weightings applied to the removal processes. It is interesting to note that for these seven BMPs, the greatest decreases within the order of preference for retention ponds, detention ponds and extended detention basins, in relation to their potential to remove TSS, was instigated by applying a 0% weighting to sedimentation. In contrast, the same allocation to filtration had the greatest impact on the relative TSS removal potential of porous paving,

Table 6
Impact of separately reducing the contributions of individual removal processes on the ranked position of BMPs with respect to TSS removal

BMP	Default ranked order of preference	Highest and lowest ranked positions
Infiltration basin	1	1–2
Constructed wetland (SSF)	2.5	2–3.5
Porous paving	2.5	1–6[a]
Soakaways	4.5	4.5–9.5[a]
Infiltration trench	4.5	4.5–9.5[a]
Constructed wetland (SF)	6.5	6–8
Extended detention basin	6.5	2–11[a]
Filter drain	8	6.5–10
Retention ponds	9	3.5–13[a]
Detention basins	11	5–12[a]
Porous asphalt	11	6.5–15[a]
Swales	11	9–13
Lagoons	13	9.5–14
Filter strip	14	10–14
Sedimentation tank	15	12–15

[a] BMPs which show an overall change in ranked position of ⩾5 places.

soakaways, infiltration trenches and porous asphalt. The differential identification of sedimentation and filtration as being the most influential removal processes within BMPs, which function by stormwater storage and infiltration, respectively, enables confidence to be expressed in the developed approach.

4. Conclusions

This report describes the development of a methodology, based on the input of theoretical data and knowledge, to identify the relative performances of BMPs for the removal of pollutants commonly associated with stormwater. Comparison of the predicted order of preference for the use of BMPs to remove TSS with existing field data shows good agreement for most systems although for swales, there is evidence of an under-prediction of the ability to remove TSS. However, it is demonstrated that the model can easily be refined to more closely simulate the prevalent field conditions. The use of a simple factorial approach to sensitivity analysis identified sedimentation as the most influential TSS removal process in retention ponds, detention ponds and extended detention basins compared to filtration in porous paving, porous asphalt, infiltration trenches and soakaways. This provides initial confidence that the assumptions made in the development of this systematic framework approach are reasonable and credible. The predicted orders of preference for BMPs for the different pollutants can provide important inputs into existing modelling procedures where available data is deficient but the selection of appropriate k values is essential.

A major problem for stormwater managers in decision-making involving water quality is the limitation in the current amount of available and reliable monitoring data relating to the behaviours of different pollutants within BMPs. However, irrespective of this data gap, stormwater managers are required to make decisions and adopt urban drainage schemes to achieve compliance with the EU WFD. As further field data becomes available it will be possible to calibrate and refine the described systematic approach using a more robust field data set, and also to classify removal processes using quantifiable (or at least end-point) values. However, in the interim period the described methodology provides relevant information, which can support and inform discussions related to diffuse pollution control (as prioritised under the EU WFD) as well as feed into the more comprehensive considerations required within an integrated approach to urban stormwater management.

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