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Adaptive **D**ecision **S**upport **S**ystem (**ADSS**) for the Integration of Stormwater Source Control into Sustainable Urban Water Management Strategies

Determination of numerical values for the assessment of BMPs

prepared by L Scholes, DM Revitt and JB Ellis
Middlesex University

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EXECUTIVE SUMMARY

This report describes the development of a methodology to theoretically assess the effectiveness of structural BMPs with regard to their treatment of 25 selected stormwater priority pollutants (SSPPs). The result is a prioritisation, in terms of pollutant removal efficiency, of 15 different BMPs which can inform end-users and other stakeholders of the best available options for the treatment of urban runoff pollutants of particular environmental concern. The limitations of this approach in terms of the variabilities in BMP designs and applications are also fully described.

The biological, chemical and physical processes which can contribute to the removal of pollutants within structural BMPs have been identified and are divided into direct and indirect mechanisms. The former are defined as those which clearly participate in the direct removal of pollutants whereas the second category incorporates those processes which occur as precursors to direct removal and includes adsorption to suspended solids and precipitation. The direct removal processes include adsorption (to substrate), biodegradation, filtration, volatilisation, photolysis and plant uptake. Volatilisation and photolysis are considered to have lower importance regarding the removal of pollutants compared to the other direct removal processes operating within BMPs and they have therefore been allocated a 0.5 relative weighting in the applied calculation procedure. All processes have been categorised as high, medium, low and not applicable based on an understanding of their relevance to each BMP. It is acknowledged that there is an element of subjectivity to this and therefore a wide consultation has been carried out and all received comments taken into consideration.

The behaviours of each of the 25 SSPPs with respect to both the direct and indirect removal processes have also been categorised using a combination of reference to the appropriate scientific data and scientific knowledge where specific data are not available. A single value representing the potential of each BMP to remove each identified SSPP has been generated by combining the two sets of data relating the removal processes to the BMPs and to the SSPPs, respectively. The resulting orders of preference for the use of BMPs for pollutant removal are discussed in terms of the full range of 25 SSPPs as well as for representative particulate associated pollutants (suspended solids) and soluble pollutants (nitrates). There are clear differences with respect to how the BMPs respond to these different pollutant types but in both cases, infiltration basins and sub-surface flow constructed wetlands are predicted to have the highest removal effectiveness. At the other end of the scale, settlement tanks consistently perform least well.

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1 Introduction

The aim of this document is to describe a methodology which will enable end-users and other stakeholders to assess the treatment potential of BMPs with regard to the removal of urban runoff pollutants of particular environmental concern. In doing this, it further develops the work initiated in DayWater Deliverable 5.3. The initial objective of the current Deliverable 5.4 was to define the orders of preference for the use of BMPs to treat the stormwater priority pollutants (SSPPs) identified by WP4 (Eriksson *et al.,* 2004). However, field monitoring data on the behaviour of many of the SSPPs in BMPs is not available, and therefore a theoretical approach for predicting the fate of SSPPs in BMPs has been developed. This method involves combining the physico-chemical characteristics of a specific pollutant with the relative importance of the major direct and indirect removal processes within each of the structural BMPs (identified in D5.1) to generate an overall single index value which reflects the potential of each BMP to remove each identified SSPP. The overall values are then ranked, in descending order, to generate an order of preference for the use of BMPs for each SSPP. The overall result is an information source which end-users may use to inform the decision-making process for selecting BMPs, with specific regard to stormwater priority pollutant removal. This work will also contribute to the development of the multi-criteria analysis (MCA) approach for BMP selection (Deliverable 5.5), particularly through assisting in the establishment of utility score values representative of BMP pollutant removal capacities. At this stage, only structural BMPs are being addressed but future work will extend the approach to non-structural BMPs.

There will obviously be variations between the performances of individual BMPs from site to site according to a number of variable factors including specific design details, age of the system, and the local environmental and climatic conditions within which the treatment system has to operate. For the purposes of the development of the methodology described in this report, it has been assumed that each BMP is operating at full efficiency in terms of the design potential and that each device is functioning on a 'stand-alone' basis. The general BMP design characteristics used in this report are those previously described in Deliverable 5.1. It is intended at a later stage to investigate how the methodology might be adapted and applied for multi-treatment systems using BMP devices in combination i.e. treatment-train mode. It is also envisaged that later versions of the overall approach will allow stakeholders, using the guidance offered by this report, to enter their own classification values relating to the potential for the different identified removal processes to be ranked for a specific BMP. This may be necessary because the basic designs of BMPs may vary slightly both within (site specific variations) and between different European countries and as expertise increases beneficial modifications will be introduced. The 'basic' model also needs to be able to be adapted as knowledge of the performances of BMPs increases such as in the data provided by the US EPA national BMP stormwater database (www.bmpdatabase.org) which has indicated that some swales demonstrate increases in total coliforms over time.

Infiltration basins represent an example of a BMP where the design characteristics may vary in that they may or may not be planted, particularly around the pond edges, which would influence the potential for plant uptake. Constructed wetlands can be built as either surface flow or sub-surface flow systems depending upon the flow retention required and the pollutant problem needing treatment. The sub-surface flow system will provide enhanced removal by adsorption and filtration as the water passes through the substrate and because of the inherent differences both designs have been considered separately in this report. There are different conventions within Europe relating to the designs associated with porous asphalt. In France, this surface treatment is normally associated with an underground reservoir structure whereas it is used as a stand-alone BMP in the UK. In this report, porous asphalt and porous paving are differentiated in terms of treatment potentials by considering that only the latter is designed with a reservoir structure below the surface material. Where porous asphalt exists in combination with a reservoir structure, the pollutant removal effectiveness will be represented in the adopted approach by the results derived for porous paving. Porous paving illustrates how BMP treatment potential can be improved through the ‘seeding’ of the reservoir structure with micro-organisms to enhance hydrocarbon removal. In such circumstances it would be necessary to increase the classification of microbial degradation as a removal process for this BMP.

2 Classification procedures

2.1 Identification of stormwater priority pollutants

A list of selected stormwater priority pollutants (SSPPs) has been identified within WP4 of the DayWater project using a tool called 'Chemical Hazard Identification and Assessment Tool' (CHIAT). The selection of priority pollutants is mainly based on a decision tree approach in which questions and answers relate to a series of environmental and toxicity criteria. A range of physico-chemical properties have been referred to including, volatilisation, persistence, toxicity, bioaccumulation and sorption, for both the sediment and aquatic phases. In addition, data relating to toxicity, effects on reproducibility, carcinogenic and mutagenic effects and the ability to cause allergic reactions have been utilised (see DayWater Deliverable 4.3). The decision tree based tool was initially applied to a list of over 600 substances identified from the literature as being potentially present in stormwater. It is important to note that substances, which are classified as volatile will be excluded, as these are expected to be evaporated to air before the stormwater reaches the BMP. A final list of selected stormwater priority pollutants was generated and from this 'concern list', 19 substances have been identified for further work. The final list, contains representative pollutants which are either illustrative of the behaviours of a group of pollutants (e.g. pyrene for 4 ring PAH compounds) or, because of similarities in properties, are able to act as indicators for other substances of concern. The more general water quality parameters (suspended solids, BOD, COD, bacteria, nitrate and phosphate) have also been included producing a list of 25 priority stormwater pollutants. These are fully identified in Table 1 together with a brief justification for their inclusion in the list. A key is provided to highlight some of the important characteristics of each pollutant and the indicated reference numbers can be matched to the reference list (Section 7).

2.2 Direct and indirect BMP removal mechanisms

The removal of pollutants by BMPs occurs due to a complex combination of biological, chemical and physical processes. Detailed descriptions of all the BMP removal processes are given in Daywater Deliverable 5.3. The primary removal mechanisms which participate in the removal of pollutants within BMPs have been identified and divided into two categories depending on whether they result in the direct removal of a pollutant from the water column (e.g. settling) or whether they contribute indirectly to a pollutant removal process (e.g. precipitation and adsorption to suspended solids). Both these process are considered to be contributory to, as opposed to not being directly involved in, the overall removal because they will be followed by further processes such as settling and/or filtration.

The two categories of removal mechanisms (direct and indirect), together with the appropriate measures by which they can be quantified, are presented in Tables 2 and 3.

Table 1. Selected stormwater priority pollutants and justification for their selection

Type	Constituent	Chemical Abstracts Service (CAS) registry numbers (where relevant)	Justification
Common water quality parameters	BOD		General water quality parameter
	COD		General water quality parameter
	Suspended solids		General water quality parameter
	Nitrate		General water quality parameter
	Phosphate		General water quality parameter
	Faecal coliforms/pathogens		Indicator water quality parameter
Metals	Cadmium	7440-43-9	P, CMR
	Copper	7440-50-8	P, T
	Nickel	7440-02-0	P, CMR
	Lead	7439-92-1	P, CMR
	Platinum	7440-06-4	P, CMR
	Chromium	7440-47-3	P, CMR*
	Zinc	7440-66-6	P
PAH	Naphthalene	91-20-3	Representative indicator of PAH (2 ring compound), PB, CMR
	Pyrene	129-00-0	Representative indicator of PAH (4 ring compound), PB
	Benzo [a] pyrene	50-32-8	Representative indicator of PAH (5 ring compound), PB, CMR
Herbicides	Pendimethalin	40487-42-1	PB
	Phenmedipham	13684-63-4	PB, CMR
	Terbutylazine	5915-41-3	Representative indicator of triazines, PB, CMR
	Glyphosate	1071-83-6	Widely used urban herbicide
Miscellaneous	Nonylphenolethoxylates (NPEO)	e.g. Tergitol NP-33; 9016-45-9	CMR
	2,4,4'-PCB (PCB 28)	7012-37-5	PB, T, CMR; indicator of chlorinated compounds
	Pentachlorophenol (PCP)	87-86-5	PB, CMR
	Di (2-ethylhexyl) phthalate (DEHP)	117-81-7	PB, CMR
	Methyl tert-butyl ether (MTBE)	1634-04-4	Technical problems (odour).

Key: CMR = Carcinogenic/mutagenic/hazardous to reproduction and/ or endocrine-disrupting; P = Persistent; PB = Persistent and bioaccumulating; T = High acute aquatic toxicity; *= Cr (VI).

References: 14, 16.

Table 2. Indirect/contributory removal processes in BMPs

Removal Process	Relevant measurements and units
Adsorption to suspended solids	K_d (L/g); chemical fraction with which the pollutant is mainly associated.
Precipitation	Water solubility (mg/l)

Key: K_d = adsorption coefficient = partitioning of a substance between the solid and dissolved phases at equilibrium = ratio of the concentration of a pollutant in the solid phase to its concentration in the dissolved phase at equilibrium

Table 3. Direct Removal Processes in BMPs

Removal Processes	Relevant Measurements and units
Settling	Settling velocity (m/s)
Adsorption to substrate	K_d (L/g);associated chemical fraction
Microbial degradation	Rate of biodegradation ($^1/_2$ life in days)
Filtration	Function of K_d (L/g) and precipitation (mg/l)
Volatilisation	K_h (atm-m^3/mole)
Photolysis	Rate of photodegradation ($^1/_2$ life in days)
Plant uptake	Bioaccumulation (K_{ow})

Key: K_d = adsorption coefficient = partitioning of a substance between the solid and dissolved phases at equilibrium = ratio of the concentration of a pollutant in the solid phase to its concentration in the dissolved phase at equilibrium

K_h = Henry's Law constant (based on the relationship that at a constant temperature the mass of gas dissolved in a liquid at equilibrium is proportional to the partial pressure of the gas)

K_{ow} = octanol-water partition coefficient = a measure of the potential for organic compounds to accumulate in lipids = ratio of the concentration of a pollutant in octanol to that in water at equilibrium

3 Removal potentials for stormwater priority pollutants

Following identification of the primary direct and indirect pollutant removal mechanisms within BMPs, the propensity for each of the SSPPs to be removed by each of the identified mechanisms has been identified. This was achieved using the physico-chemical data for each of the SSPPs (taken from DayWater Deliverable 4.3 and from the literature) in combination with the CHIAT approach (developed within WP4) and the use of expert judgement where data availability is limited. The relevant references to the sources of the physico-chemical data are given at the bottom of each of the Tables describing the individual parameters. The result is the designation of the potential for removal of each SSPP by each removal process into categories of high, medium, low or not applicable. The latter classification indicates that a process is not thought to be relevant. Where appropriate the three functional categories have been sub-divided into medium/high and low/medium categories but the quality of the available data upon which the scaling is based is not considered sufficiently precise to support further resolution of the categories. The derived classifications are presented in Sections 3.1.1 and 3.1.2.

3.1 Potential for removal of stormwater priority pollutants by indirect processes

The indirect processes which contribute to pollutant removal in BMPs have been identified as adsorption (to suspended solids) and precipitation.

3.1.1 Adsorption

As described in Section 2.2, the process of adsorption has been sub-divided into the two separate categories of direct and indirect removal processes, as follows:

- Adsorption to substrate is considered to be a direct removal process whereby a pollutant physically or chemically sorbs to the surface of a BMP structure component (e.g. porous paving material) or basal sediment (e.g. within a retention pond) and is hence directly removed from the water column.
- Adsorption to suspended solids is considered to be an indirect or contributory removal process as, once adsorbed to a suspended particle, a further process such as settling or filtration is required to remove the pollutant from the water column.

The potential for an SSPP to be removed by adsorption, either to substrate or suspended solids, is categorised using the same sources of physico-chemical data but relating specifically to adsorption coefficients (for organic pollutants), associated chemical fractions (for metals) and the use of expert judgement (for the basic water quality parameters). The resulting quantitative and qualitative information is presented in Table 4. The metal data is based on the affinity with which individual metals are associated with sediment fractions ranging from the exchangeable fraction (loosely bound; low adsorption potential) through the oxide/organic fractions (medium adsorption potential) to the residual fractions (essentially environmentally immobile; high adsorption potential). With regard to Cr, classification is based on information for the chromate ion (Cr (VI)) to give an indication of the potential for removal of anionic metal ions.

Judgements on the general potential for the basic water quality parameters and the nutrients to adsorb have been derived from their characteristic properties in the urban water environment and knowledge of their known physical and chemical behaviours. The adsorption of fine suspended solids is considered to equate to their flocculation ability which can vary widely depending on factors such as the availability of quiescent conditions and the relative sizes of the particulates involved. The same behaviour can be predicted for faecal coliforms with regard to adsorption/flocculation and because of this variability combined with the known occurrence of these processes, a medium potential for removal has been assigned. Both BOD and COD parameters are representative of a wide range of waterborne organic substances which may vary according to the source of the stormwater. Therefore, a medium removal potential by adsorption is allocated to BOD with this being reduced slightly to 'low/medium' for COD due to the possible contribution of more complex and intractable components to this parameter. Phosphates and nitrate have widely different solubility characteristics which significantly influence the diverse adsorption and precipitation potentials, for these different anions, as identified in Tables 4 and 5.

Where quantitative data, in the form of K_d values, is available for discrete organic pollutants, these values have been compared with the parameter ranges developed by Eriksson *et al.,* (2004) to derive the high, medium or low removal potentials shown in Table 4. In cases where there are discrepancies in predictions from the available adsorption coefficient values either a intermediate removal potential is allocated (e.g. for terbutylazine) or an overall average adsorption ability is assumed (e.g. pendimethalin).

The derived SSPP adsorption potentials will subsequently be used to predict their potential for removal by this process either to suspended solids (indirect removal process) or adsorption to BMP substrate (direct removal process).

3.1.2 Precipitation

The characteristics which influence the potential of a pollutant to precipitate are described in Table 5. The formation of insoluble precipitates is considered to be an indirect process as, once precipitated, further processes of settlement or filtration are then required to remove the SSPP from the water column. Precipitation processes are classified as high, medium or low through a consideration of the solubility of each of the SSPPs in water at 20^0C (see DayWater Deliverable 5.3). Precipitation of metals can result in the formation of both insoluble salts and organic complexes and the solubility will be influenced by factors such as water hardness due to the dependency of this property on the anionic association which will also be affected by the stormwater source and quality. Chloride salts have been selected as being representative of soluble metal compounds against which the solubility of the other SSPPs are benchmarked and the values are given in Table 5 together with the deduced precipitation potentials. An exception to this is Cr, as it is the behaviour of the chromate anion which is being considered. Therefore, the solubility of calcium chromate was selected for use and compared to the developed solubility scale, with calcium being selected as the cation due its typically high abundance in most waters.

The high variability in water solubility values (expressed as mg/l in Table 5) relates to the widely differing solubilities of inorganic and organic pollutants. The cut-off points into low, medium and high classifications have been chosen to represent a realistic differentiation across this wide range. The quantitative data available for the discrete organic pollutants predict high precipitation potentials, based on low solubilities, except for glyphosate and methyl tertiary butyl ether (MTBE) where medium solubilities and hence precipitation potentials exist. Both the BOD and COD parameters are considered to be representative of a wide range of organic pollutants, the majority of which will have a low solubility but with also some more soluble components. COD will also include small amounts of oxidisable inorganic components which will have similar solubility characteristics. Therefore, for both parameters, a medium/high precipitation potential has been allocated. Suspended solids and faecal coliforms are already present in the solid form and therefore are considered to have high removal potentials by this process.

The collected information on both indirect processes (adsorption to suspended solids and precipitation) has been combined in Table 6 to derive the potentials for removal of SSPPs through settling and through filtration. Further information on these processes is given in Section 3.2.

Table 4. Potential for SSPP removal to BMP substrate material (direct) or suspended solids (indirect) due to adsorption

Stormwater Priority Pollutant		Characteristic behaviour/ quantifiable parameters	Potential for removal
Basic parameters	BOD	Representative of a wide range of organic substances, some of which will have an adsorption capability.	Medium
	COD	Representative of a wide range of organic and inorganic substances, some of which will have an adsorption capability.	Low/Medium
	Fine suspended solids	Tendency to flocculate will vary according to existing hydrochemical conditions	Medium
	Faecal coliforms	Tendency to adsorb/flocculate will vary according to existing conditions	Medium
Nutrients	Phosphates	High adsorption potential	High
	Nitrates	Low tendency to adsorb	Low
Metals		**Associated chemical fraction**	
	Cd	Predominantly associated with the exchangeable fraction	Low
	Cu	Predominantly associated with the organic fraction	Medium
	Ni	Predominantly associated with the oxide/organic fractions	Medium
	Pb	Predominantly associated with the oxide/organic/residual fractions	High
	Zn	Predominantly associated with the exchangeable fraction	Low
	Pt	Predominantly associated with the oxide/organic fractions	Medium
	Cr	Cr(VI) predominantly associated with the exchangeable fraction although this decreases with increasing pH	Low
PAHs		**K_d values (or range)**	
	Naphthalene	367	Medium
	Pyrene	13060	High
	Benzo (a) pyrene	$4.5x10^6$	High
Pesticides	Pendimethalin	524; 30-800	Medium
	Phenmedipham	604	Medium
	Terbutylazine	103; 2.2-20	Low/Medium
	Glyphosate	24000	High
Miscellaneous	NPEO	450-1460	Medium
	PCB 28	High tendency to absorb; strong affinity for organic carbon.	High
	Pentachlorophenol	30	Low
	DEHP	3710	High
	MTBE	Low tendency to adsorb	Low

Key: K_d scale: K_d<100 =low potential for adsorption **References: 1, 3, 7, 8, 9, 11, 16, 17, 18, 21, 22, 30, 35.**

K_d 100-1000 = medium potential for adsorption

K_d >1000 = high potential for adsorption

Table 5. Potential for SSPP removal by precipitation (indirect process)

Stormwater Priority Pollutant		Characteristic behaviour/ quantifiable parameter		Potential for removal
Basic parameters	BOD	Representative of a wide range of organic substances, some of which may have a tendency to precipitate (eg fulvic and humic acids).		Medium/High
	COD	Representative of a wide range of organic and inorganic substances, some of which may have a tendency to precipitate.		Medium/High
	Suspended solids	Already in solid form		High
	Faecal coliforms	Already in solid form		High
Nutrients	Phosphates	High tendency to precipitate		High
	Nitrates	Low tendency to precipitate		Low
Metals		Metal chloride solubility (mg/l)	Solubility	
	Cd	1,400,000	High	Low
	Cu	70,600	Medium	Medium
	Ni	642,000	High	Low
	Pb	6,730	Medium	Medium
	Zn	4,320,000	High	Low
	Cr	23,000	Medium	Medium
	Pt	insoluble	Low	High
PAHs				
	Naphthalene	31.7	Low	High
	Pyrene	0.077	Low	High
	Benzo (a) pyrene	0.0023-0.0038	Low	High
Pesticides	Pendimethalin	0.3	Low	High
	Phenmedipham	4.7	Low	High
	Terbutylazine	8.5	Low	High
	Glyphosate	12000	Medium	Medium
Miscellaneous	NPEO	3-9	Low	High
	PCB 28	0.27-0.42	Low	High
	Pentachlorophenol	14-80	Low	High
	DEHP	0.041	Low	High
	MTBE	42,000	Medium	Medium

Key: <100mg/l = low solubility

100 – 100 000mg/l = medium solubility

>100 000mg/l = high solubility

References: 4, 5, 6, 8, 9, 10, 17, 18, 19, 26, 29.

3.2 Potential for removal of stormwater priority pollutants by direct processes

3.2.1 Settling

Table 6 sets out the potential for removal of SSPPs by settling. In this report, settling is taken to be dependent on both a pollutant's propensity to adsorb to suspended particulates (Table 4) and to the potential to precipitate within the water column (Table 5). These two processes are particularly important for soluble pollutants as they influence solid association and hence the potential to sediment-out. Where the pollutants are already predominantly in the solid form (eg. suspended solids and faecal coliforms) the predictions are less uncertain but it is still important to define appropriate classifications in order to achieve a representative comparability across the different types of SSPPs. The overall potential for an SSPP to sediment-out is determined by combining the information developed in Table 4 on the potential for an SSPP to adsorb with data on the tendency of SSPPs to precipitate (Table 5) to give an overall potential for removal by settling.

Table 6. Potential for SSPP removal by settling and filtration (direct processes) due to the combined effects of adsorption to suspended solids and precipitation (indirect processes)

Stormwater Priority Pollutant		**Characteristic behaviour/ quantifiable parameter**		**Potential for removal**
Basic parameters		**Tendency to adsorb**	**Tendency to precipitate**	
	BOD	Medium	Medium/High	Medium
	COD	Low/Medium	Medium/High	Medium
	Suspended solids	Medium	High	High
	Faecal coliforms	Medium	High	High
Nutrients	Phosphates	High	High	High
	Nitrates	Low	Low	Low
Metals	Cd	Low	Low	Low
	Cu	Medium	Medium	Medium
	Ni	Medium	Low	Low/Medium
	Pb	High	Medium	Medium/High
	Zn	Low	Low	Low
	Cr	Low	Medium	Low/Medium
	Pt	Medium	High	Medium/High
PAHs	Naphthalene	Medium	High	Medium/High
	Pyrene	High	High	High
	Benzo (a) pyrene	High	High	High
Pesticides	Pendimethalin	Medium	High	Medium/High
	Phenmedipham	Medium	High	Medium/High
	Terbutylazine	Low/Medium	High	Medium
	Glyphosate	High	Medium	Medium/High
Miscellaneous	NPEO	Medium	High	Medium/High
	PCB 28	High	High	High
	PCP	Low	High	Medium
	DEHP	High	High	High
	MTBE	Low	Medium	Low/Medium

3.2.2 Biodegradation

The potentials for SSPPs to be degraded by microbially-mediated processes are presented in Table 7. The classifications have been derived by consideration of the susceptibilities of the pollutants to both aerobic and anaerobic biodegradation using quantitative (for the discrete organic pollutants where available) and descriptive data obtained from Eriksson *et al.,* (2004) and from the literature. The quantitative values for organic pollutants (biodegradation half-lives) provided in Table 7 relate to field measurements. Where necessary these have been supplemented by laboratory determinations of the degree of biodegradation. The metals are all allocated overall low biodegradation removal potentials based on their generally low susceptibilities to immobilisation by sulphate-reducing bacteria in anaerobic conditions. Similarly, phosphates and nitrates are only microbially reduced in anaerobic conditions with denitrification being a slightly more important process. The BOD parameter, by definition, is highly susceptible to aerobic biodegradation whereas COD, which is representative of more intractable components, will therefore be less readily biodegraded. They are both considered to have low potentials with respect to anaerobic breakdown. The role of suspended solids to both aerobic and anaerobic processes will depend on the nature of the surface organic material and in most cases this is expected to exhibit low biodegradation potentials. A similar behaviour is expected for faecal coliforms under anaerobic conditions but these will be more highly degraded under aerobic conditions.

The aerobic and anaerobic characteristics have been combined to give an overall indication of the tendency of each SSPP to be microbially degraded.

3.2.3 Filtration

The potentials for SSPPs to be removed by filtration-related processes are presented in Table 6. As in the case of settling, removal through filtration is thought to be a function of a pollutant's ability to adsorb (Table 4) to particulate matter in combination with it's susceptibility to undergo precipitation (Table 5). However, although dependent on similar precursor mechanisms, filtration and settling are clearly separate removal processes within a structural BMP. Filtration is the removal of particulate pollutants by the physical sieving of an effluent on passage through a porous substrate or reedbed, whereas settling is the vertical movement of discrete or agglomerated suspended sediment particles to the base of a water column (Ellis *et al.,* 2004). Therefore, although the same indirect processes contribute towards them, they are discrete removal processes and there is no element of 'double counting' towards the overall removal potential.

3.2.4 Volatilisation

Table 8 presents quantitative data on the potential for removal of the organically based SSPPs by volatilisation. Volatilisation is quantified using Henry's Law to calculate the K_h value of a pollutant. This is a partition coefficient representing the ratio of the pollutant concentrations in air and in solution at equilibrium. Where available, K_h values for the SSPPs have been compared to the ranges developed by Eriksson *et al* (2004), and the removal potentials classified as medium or low, respectively. There are no predictions of high removal potentials for any of the discrete organic pollutants, which is expected since volatile compounds will not be selected as SSPPs (see Section 2.1). For BOD and COD, where K_h values were not available, knowledge of the generally complex variety of organics which may contribute to both parameters was used to assign their potential for removal through volatilisation as 'low'. Volatilisation is not considered to be a realistic option for the inorganic SSPPs, which includes the metals and the nitrate/phosphate nutrients, and these have been allocated a 'not applicable' status.

3.2.5 Photolysis

Data on the potentials of the SSPPs to be removed by photolysis are presented in Table 9. Removal potentials were classified using environmental values of the photodegradation half-lives sourced from the literature, or where data were not available, by the use of expert judgement of the SSPP composition and expected behaviour when exposed to sunlight. The cut-off values were selected based on both the overall range of values and taking into account the typical maximum BMP retention times. These are of the order of 24 hours and therefore pollutants with photolysis half-lives within this time period are considered to have high potentials for degradation by this process. Photolysis is not considered to be a relevant process for suspended solids, nutrients (nitrates and phosphates) or the metals. For COD and BOD, a low photolytic potential is assigned based on the increased complexity of the organic material responsible for these parameters relative to the discrete organic pollutants, some of which are allocated high removals for photolysis as a result of the available quantitative data. Faecal coliforms are susceptible to UV light and therefore are allocated a low/medium potential for removal by this process.

3.2.6 Plant uptake

Table 10 presents data on the potential of the SSPPs to be removed from the water column by plant uptake. For the discrete organic pollutants, this behaviour was assessed using K_{ow}, the octanol-water partition coefficient. The majority of these organic pollutants are predicted to have high or medium tendencies to bioaccumulate with methyl tertiary butyl ether and glyphosate being exceptions. The negative K_{ow} value for glyphosate is a function of its high water solubility and so there is only a low potential to bioaccumulate for this pollutant. Where K_{ow} values cannot be developed (e.g. particulate associated pollutants; metals) or are not available (e.g. nutrients), knowledge of their typical environmental behaviours has been used to determine their potential for uptake. The nutrient properties of phosphates and nitrates suggest high plant uptake potentials whereas the relative low affinities of the metals for plant tissue indicate that the opposite situation exists. It is known that copper has a higher tendency to be associated with organic matter than most of the other metals but this was not considered to be sufficiently distinctive to influence the relative level of plant uptake. This process is not applicable for either suspended solids or coliforms but will be possible for the organic material represented by the BOD and COD parameters. A medium plant uptake potential has been assigned to BOD with this decreased to 'low/medium' for COD due to the higher composition of more intractable material in the latter.

Table 7. Potential for SSPP removal by microbially-mediated processes (aerobic and anaerobic)

Stormwater Priority Pollutant		Characteristic behaviour/ quantifiable parameter		Potential for removal		
Basic parameters		Susceptibility to aerobic degradation	Susceptibility to anaerobic degradation	Aerobic	Anaerobic	Overall removal
	BOD	High	Low	High	Low	Medium
	COD	Medium	Low	Medium	Low	Low/Medium
	Suspended solids	Low	Low	Low	Low	Low
	Faecal coliforms	Medium	Low	Medium	Low	Low/Medium
Nutrients	Phosphates	NA	Low	NA	Low	Low
	Nitrates	NA	Denitrifying bacteria	NA	Low/Medium	Low
Metals	Cd	NA	Immobilised by sulphate-reducing bacteria		Low	Low
	Cu	NA	Immobilised by sulphate-reducing bacteria		Low	Low
	Ni	NA	Immobilised by sulphate-reducing bacteria		Low	Low
	Pb	NA	Immobilised by sulphate-reducing bacteria		Low	Low
	Zn	NA	Immobilised by sulphate-reducing bacteria		Low	Low
	Cr	NA	Immobilised by sulphate-reducing bacteria		Low	Low
	Pt	NA	Immobilised by sulphate-reducing bacteria		Low	Low
PAHs	Naphthalene	<1->80days sediment	Negligible degradation	Medium*	Negligible	Low
	Pyrene	199-260 days in soil	**	Low	Low	Low
	Benzo (a) pyrene	229-309 days in soil	**	Low	Low	Low
Pesticides	Pendimethalin	1300 days in soil	60 days in soil	Low	Medium	Low/Medium
	Phenmedipham	20 days in soil	120 days in soil	High	Medium	Medium/High
	Terbutylazine	30-60 days	No data	High	No data	Medium
	Glyphosate	Avg. 44 days in soil	High	High	High	High
Miscell-aneous	NPEO	42 days	>60 years	High	Low	Medium
	PCB 28	5-17 months in soil	Low by reductive dechlorination	Low	Low	Low
	Pentachlorophenol	20-120 days in soil;	10-70days in flooded soil	Medium/High	High	Medium/High
	DEHP	1 month in river water; slower in sediment due to adsorption	Much slower than in aerobic sediments	Medium	Low	Low/Medium
	MTBE	Low	Low	Low	Low	Low

Key: low persistence T1/2 <60days; inherent persistence T1/2 60-180; persistent T1/2>180d;

* Medium value allocated because although field data predicts a high biodegradability, laboratory data indicates limited degradation.

** No field data available but laboratory data indicates low biodegradability.

References: 4, 5, 9, 10, 16, 17, 25, 26, 29, 30, 31.

Table 8. Potential for SSPP removal by volatilisation

Stormwater Priority Pollutant		**Characteristic behaviour/ quantifiable parameter**	**Potential for removal**
Basic parameters	BOD	Representative of a wide range of organic substances, some of which may be volatile	Low
	COD	Representative of a wide range of organic and inorganic substances, some of which may be volatile.	Low
	Suspended solids	NA	NA
	Faecal coliforms	NA	NA
Nutrients	Phosphates	NA	NA
	Nitrates	NA	NA
Metals	Cd	NA*	NA
	Cu	NA	NA
	Ni	NA	NA
	Pb	NA	NA
	Zn	NA	NA
	Cr	NA	NA
	Pt	NA	NA
PAHs		**K_h value**	
	Naphthalene	$4.4x10^{-4}$	Medium
	Pyrene	$1.19x10^{-5}$	Medium
	Benzo (a) pyrene	$4.57x10^{-7}$	Medium
Pesticides	Pendimethalin	$8.6x10^{-7}$	Medium
	Phenmedipham	$2.5x10^{-8}$	Low
	Terbutylazine	$3.72x10^{-8}$	Low
	Glyphosate	$4.08x10^{-19}$	Low
Miscellaneous	NPEO	$1.1x10^{-6}$	Medium
	PCB 28	$2.0x10^{-4}$	Medium
	Pentachlorophenol	$2.45x10^{-8}$ - $2.75x10^{-6}$	Low*
	DEHP	$1.3x10^{-7}$– $1.71x10^{-5}$	Medium
	MTBE	$5.87x10^{-4}$	Medium

Key: K_h range classification: low <10^{-7}atm.m^3/mol; medium 10^{-7}-10^{-3} atm.m^3/mol; high >10^{-3} atm.m^3/mol; NA = not applicable.

Pentachlorophenol has a pK_a of 4.7 and at pH values above this will exist mainly in the ionic form ensuring resistance to evaporation; hence a low potential for volatilisation is assigned.

References: E. Eriksson *personal communication*, 5, 6, 16, 26.

Table 9. Potentials for SSPP removal by photolysis

Stormwater Priority Pollutant		Characteristic behaviour/ quantifiable parameter	Potential for removal
Basic parameters	BOD	Representative of a wide range of organic substances, some of which may have be photodegradable.	Low
	COD	Representative of a wide range of organic and inorganic substances, some of which may be photodegradable.	Low
	Suspended solids	NA	NA
	Faecal coliform	Photodegradable	Low/Medium
Nutrients	Phosphates	NA	NA
	Nitrates	NA	NA
Metals	Cd	NA	NA
	Cu	NA	NA
	Ni	NA	NA
	Pb	NA	NA
	Zn	NA	NA
	Cr	NA	NA
	Pt	NA	NA
PAHs		Half-life	
	Naphthalene	71 hours	Medium
	Pyrene	0.68 hours	High
	Benzo (a) pyrene	1.4-8.4 hours	High
Pesticides	Pendimethalin	Low susceptibility	Low
	Phenmedipham	23 hours	High
	Terbutylazine	>40 days	Low
	Glyphosate	Negligible	NA
Miscellaneous	NPEO	10-15 hours	High
	PCB 28	17-210 days	Low
	Pentachlorophenol	20 minutes – 48 hours	Medium/High
	DEHP	Not considered to be important	NA
	MTBE	Does not absorb light >210nm	NA

Key: High = referenced as major process with $t_{½}$ <24 hours; Medium, $t_{½}$ = 1-5 days; Low = referenced as slow process with $t_{½}$ >5 days;

NA = not applicable

References: 4, 5, 6, 8, 9, 12, 20, 24, 25, 26, 29, 32, 34.

Table 10. Potential for SSPP removal plant uptake

Stormwater Priority Pollutant		Characteristic behaviour/ quantifiable parameter	Potential for removal
Basic parameters	BOD	Representative of a wide range of organic substances, some of which may bioaccumulate.	Medium
	COD	Representative of a wide range of organic and inorganic substances, some of which may bioaccumulate.	Low/Medium
	Suspended solids	NA	NA
	Faecal coliforms	NA	NA
Nutrients	Phosphates	Highly bioaccumulative	High
	Nitrates	Highly bioaccumulative	High
Metals	Cd	Low level of bioaccumulation	Low
	Cu	Low level of bioaccumulation	Low
	Ni	Low level of bioaccumulation	Low
	Pb	Low level of bioaccumulation	Low
	Zn	Low level of bioaccumulation	Low
	Cr	Low level of bioaccumulation	Low
	Pt	Low level of bioaccumulation	Low
PAHs		Log K_{ow}	
	Naphthalene	3.3	Medium
	Pyrene	5.1	High
	Benzo (a) pyrene	6.13	High
Pesticides	Pendimethalin	5.18	High
	Phenmedipham	3.49	Medium
	Terbutylazine	3.1	Medium
	Glyphosate	-4.47	Low
Miscellaneous	NPEO	4.2	Medium
	PCB 28	5.62	High
	Pentachlorophenol	3.32-5.86	Medium*
	DEHP	7.5	High
	MTBE	1.24	Low

Key: K_{ow} scale: low bioaccumulation, log K_{ow} <3; medium bioaccumulation, log K_{ow} = 3-4.5; high bioaccumulation, log K_{ow} >4.5; NA = not applicable.

The range of K_{ow} values for pentachlorophenol cover the medium and high bioaccumulation categories; a medium classification is assigned based on the pK_a related properties of this pollutant (see also Table 8).

References: E. Eriksson *personal communication*, 2, 3, 5, 7, 9, 16, 23, 26, 31.

4 Primary removal mechanisms within each BMP

The primary direct and indirect removal processes, together with ways in which they could be quantified, have been identified in Section 2.2. In this section, the relative importance of each of the removal mechanisms within each structural BMP will be considered and designated as being of high, medium or low importance, or as being not applicable (NA) where it is not relevant to a particular BMP.

The structural BMPs considered are those identified in DayWater Deliverable 5.1. It is appreciated that, while there are distinct types of BMPs, the actual characteristics of an individual BMP within a recognised 'type' can vary from system to system (see also Section 1). To avoid any confusion over such issues and for reasons of consistency, the removal mechanisms outlined in Section 2.2 will be related to each BMP according to the descriptors provided in Table 11, below.

Table 11. Descriptions of types of 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; geotextile liner may be 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 hours; 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 (SSF)	Typically contain a gravel substrate, planted with reeds, through which the water flows
Surface flow (SF)	Typically contain a soil substrate, planted with reeds, over which the water flows.

The classification of removal processes as being of high, medium or low importance was achieved by considering their relative importance both within each BMP and relative to the other BMPs. For example, although microbial degradation occurs in porous paving, it is normally a much more important process in sub-surface flow constructed wetlands due to the ready supply of nutrients, organics and attachment sites typically associated with wetland substrates. The relative importance of the removal processes relevant to different types of BMPs are presented in Tables 12 -19.

4.1 Adsorption to substrate

Table 12 identifies how adsorption to substrate can be categorised for the different types of BMPs. Adsorption to substrate refers to the adsorption of SSPPs to either 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 sediment in a detention pond). Adsorption to suspended solids is an indirect process and is considered within the settling and filtration processes (Tables 14 and 16, respectively).

Adsorption to substrate is considered to have the highest importance as a potential removal process in filter drains, porous paving, constructed wetlands (sub-surface flow), infiltration basins, soakaways and infiltration trenches due to the close contact achieved between stormwater and substrate surface during the infiltration of an effluent through a permeable material. Adsorption to substrate is considered to be a less important process in porous asphalt in comparison to porous paving as the former is typically a surfacing material only whereas porous paving normally incorporates an underground sub-surface permeable structure to which pollutants may also adsorb. The relative importance of adsorption to substrate is considered to be lower, although of a similar magnitude, in swales, filter strips, constructed wetlands (surface flow), detention basins and extended detention basins, primarily because these systems do not offer such high contact ratios between substrate and stormwater. The potential for adsorption was considered to be slightly lower in retention ponds and lagoons compared to detention basins, as the latter will typically drain down following a storm event, encouraging adsorption to the basin walls and basal substrate, whereas a retention pond does not periodically empty in a similar manner. The potential for adsorption to substrate was assigned the lowest category for a sedimentation tank where the generally smaller construction, provides a comparatively lower surface area on which adsorption processes may occur.

It is appreciated that in specific cases the use of such general assumptions may not always be strictly valid. However, it is felt that the adopted approach is justified when the objective is the development of a ‘basic’ model which can enhance the end-users understanding of pollutant removal by BMPs, hence informing the decision-making process from the point of view of the treatment of specific SSPPs of concern. A further important point is that this model has a highly flexible structure and as such it could readily be modified to reflect site specific variations.

Table 12. Adsorption to substrate

BMP	Relative importance of mechanism
Filter drain	Medium/High
Porous asphalt	Low/Medium
Porous paving	High
Filter strip	Medium
Swales	Medium
Soakaways	Medium/High
Infiltration trench	Medium/High
Infiltration basin	High
Sedimentation tank	Low
Retention ponds	Low/Medium
Detention basins	Medium
Extended detention basin	Medium
Lagoons	Low/Medium
Constructed wetlands (SSF) Constructed wetlands (SF)	Medium/High Medium

4.2 Settling

The potential importance of settling as a removal process in each of the BMPs is presented in Table 13. As previously described (Section 3.2.1), the potential for removal of an SSPP by settling is considered to be dependent on the pollutant's propensity to both adsorb to particulate material and to precipitate. However, the importance of settling as a process within a BMP is also a function of the quiescent water volume within the BMP in combination with the pollutant retention time. Hence, the potential for settling is considered to be highest in extended detention basins, infiltration basins and retention ponds, due to their extensive open water bodies and their potential for the extended retention of pollutants. Again it is recognised that specific wet storage basins can have prolonged hydraulic retention times which may exceed 10-12 days in some cases. Such extended detention times would increase the likelihood of settling for even very fine particulates and the relative removal potentials indicated in Table 13 can be modified by the end-user as appropriate to allow for such site-specific design variation.

Detention ponds, lagoons and sedimentation tanks, are considered to have slightly lower removal potentials. Detention ponds do not provide a settling water volume for the same length of time whereas lagoons and settlement tanks tend to be comparatively smaller constructions which do not facilitate settling to the same extent. The potential for settling is considered to be comparatively lower in constructed wetlands (both sub-surface flow and surface flow), as they typically have a lower stationary water column volumes (through which settling can occur) due both their construction and the presence of dense stands of vegetation. Filter drains, porous paving, swales, soakaways and infiltration trenches are assigned 'low/medium' removal potentials for settling processes due to the absence of a persistently still water body which would facilitate particle deposition. Porous asphalt, due to the presence of a thin surface covering, offers very limited opportunity for settling to occur, and similarly filter strips, due to their surface flow characteristics, offer limited detention of stormwater and therefore only a minor settling potential.

Table 13. Settling

BMP	Relative importance of mechanism
Filter drain	Low/Medium
Porous asphalt	Low
Porous paving	Low/Medium
Filter strip	Low
Swales	Low/Medium
Soakaways	Low/Medium
Infiltration trench	Low/Medium
Infiltration basin	High
Sedimentation tank	Medium/High
Retention ponds	High
Detention basins	Medium/High
Extended detention basin	High
Lagoons	Medium/High
Constructed wetlands (SSF)	Medium
Constructed wetlands (SF)	Medium

4.3 Microbial degradation

Table 14 presents information on the relative importance of microbial degradation as a removal process within BMPs. The potential for this process to occur is considered to be highest in sub-surface flow constructed wetlands and infiltration basins due to the ready availability of microbial attachment sites within both substrate and plant root systems, in combination with the occurrence of high contact ratios between stormwater and substrate material. Filter drains, porous paving, soakaways, infiltration trenches, retention ponds, extended detention basins and surface flow constructed wetlands do not typically provide the same diversity of microbial attachment sites and are consequently assigned a medium significance for this process. It is important to recognise that the performances of certain BMPs can be modified by external actions. This is the case for porous paving which can be 'seeded' with micro-organisms to enhance hydrocarbon removal (Newman *et al.,* 2001). If seeding of the porous paving was an approach being considered by an end-user at a particular site, the relative importance of microbial degradation as a removal process for porous paving could be increased from a classification of 'medium' in the basic model (see Table 14) to a classification of 'high' in a new and adapted model to reflect this site specific adjustment.

Detention ponds, filter strips and swales are allocated 'low/medium' removal efficiencies for microbial degradation. With regard to detention ponds, this is considered to be associated with the non-permanence of the water body prohibiting the development of an established microbial population, whereas for swales and filter strips, it is a function of their typically lower retention times. However, swales and filter strips have the ability for more microbial degradation than sedimentation tanks and lagoons as vegetated/substrate systems have the potential to host higher numbers of micro-organisms than unvegetated or poorly-vegetated systems and due to the fact that such bioretention systems can 'grow' bacterial groups in situ. The importance of microbial degradation is similarly low in porous asphalt, due to its low ability to support a microbial biomass.

Table 14. Microbial degradation

BMP	Relative importance of mechanism
Filter drain	Medium
Porous asphalt	Low
Porous paving	Medium
Filter strip	Low/Medium
Swales	Low/Medium
Soakaways	Medium
Infiltration trench	Medium
Infiltration basin	High
Sedimentation tank	Low
Retention ponds	Medium
Detention basins	Low/Medium
Extended detention basin	Medium
Lagoons	Low
Constructed wetlands (SSF) Constructed wetlands (SF)	High Medium

4.4 Filtration

Information on the relative effectiveness of filtration as a removal mechanism is presented in Table 15. As described in Section 3.2.3, filtration is the removal of particulate pollutants by the process of physical sieving of an effluent on passage through a porous substrate or a hydraulic barrier. Hence the potential for filtration to occur is considered to be most effective in porous paving and porous asphalt due to surface filtration, particularly in porous asphalt due to the low pore size of the crushed construction material, combined with the role of reservoir structures where these are present. Infiltration trenches, infiltration basins, soakaways and constructed wetlands (SSF) can all involve the passage of stormwater through a sub-surface substrate but the greater void sizes within the gravel which is typically used results in slightly less efficient filtration. Filter drains possess similar substrate structures but differ in that stormwater filters through gravel prior to collection in a basal pipe in contrast to the previous BMPs where there is the potential for effluent to further infiltrate. A medium removal potential for filtration is also assigned to swales and surface flow constructed wetlands. In both systems the presence of surface vegetation (grass and/or reeds) provides a hydraulic barrier to flow with the resulting frictional capacity offering a filtration function which combines with possible infiltration into the soil to remove pollutants. In contrast, filter strips are considered to have a lower potential for filtration due to the comparatively shorter contact times with the grassed surface during which filtration may occur. Lagoons, detention basins, extended detention basins and retention ponds are all considered to have a low potential for filtration associated with limited contact between stormwater and the basal sediments/substrates. Filtration is not thought to be a feasible process in sedimentation tanks due to the limited presence of basal sediments and the typically concrete construction which together do not encourage filtration processes.

Table 15. Filtration

BMP	Relative importance of mechanism
Filter drain	Medium
Porous asphalt	High
Porous paving	High
Filter strip	Low/Medium
Swales	Medium
Soakaways	Medium/High
Infiltration trench	Medium/High
Infiltration basin	Medium/High
Sedimentation tank	NA
Retention ponds	Low
Detention basins	Low
Extended detention basin	Low
Lagoons	Low
Constructed wetlands (SSF) Constructed wetlands (SF)	Medium/High Medium

4.5 Volatilisation and photolysis

Tables 16 and 17 present information on the potentials for removal by volatilisation and photolysis in the different structural BMPs. Although both processes are strongly dependent on surface exposure, photolysis requires direct exposure to sunlight, and so benefits from situations where stormwater is retained above ground. In contrast, volatilisation can take place within a BMP structure providing it is not completely filled with stormwater. Photolysis of the compounds contained within urban runoff will be negligible in filter drains, porous paving, soakaways and infiltration trenches due to the rapid incorporation of stormwater into the BMP structure. Photolysis is considered to have a low effectiveness in sedimentation tanks and lagoons, due to their relatively low surface areas and associated retention times, and in constructed wetlands (both sub-surface flow and surface flow), where exposure of stormwater to sunlight can be restricted due to the presence of dense stands of vegetation. A similar removal effectiveness is assigned to porous asphalt as, although stormwater is rapidly infiltrated into the surfacing material, it is typically held only a few millimetres below the surface and the constituents can be subjected to interaction with UV/visible radiation. Photolysis will be slightly enhanced as a removal potential in filter strips, swales, infiltration basins, retention ponds, detention basins and extended detention basins due to the increased surface areas and exposure times.

The potential of volatilisation to reduce pollutant levels is also a function of the size of exposed surface area typically associated with a BMP combined with the surface retention time. Hence, this process is highest (medium removal potentials) in extended detention basins, detention basins, retention ponds, infiltration basins, constructed wetlands (surface flow) and swales, followed by constructed wetlands (sub-surface flow), 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 16. Volatilisation

BMP	Relative importance of mechanism
Filter drain	Low
Porous asphalt	Low
Porous paving	Low
Filter strip	Low/Medium
Swales	Medium
Soakaways	Low
Infiltration trench	Low
Infiltration basin	Medium
Sedimentation tank	Low
Retention ponds	Medium
Detention basins	Medium
Extended detention basin	Medium
Lagoons	Low/Medium
Constructed wetlands (SSF) Constructed wetlands (SF)	Low/Medium Medium

Table 17. Photolysis

BMP	Relative importance of mechanism
Filter drain	NA
Porous asphalt	Low
Porous paving	NA
Filter strip	Low/Medium
Swales	Low/Medium
Soakaways	NA
Infiltration trench	NA
Infiltration basin	Low/Medium
Sedimentation tank	Low
Retention ponds	Low/Medium
Detention basins	Low/Medium
Extended detention basin	Low/Medium
Lagoons	Low
Constructed wetlands (SSF) Constructed wetlands (SF)	Low Low

4.6 Plant uptake

Table 18 presents information on the relative importance of plant uptake. Plant uptake is not an applicable process with regard to porous asphalt and sedimentation tanks as these systems are not vegetated. Marginal aquatic macrophytes, such as *Typha* and *Phragmites*, are frequently present around the edges of retention ponds but because of the limited contact of these aquatic species with the bulk of the pollutants these BMP systems are assigned to the 'low' category. Cell tissue uptake is also possible at a low level in porous paving, filter drains, soakaways and infiltration trenches due to the occurrence of algal growth, typically present on the asphalt or gravel substrate, which has the potential to bioaccumulate pollutants. Plant uptake is also considered to be potentially at a similar level in detention basins, extended detention basins and lagoons. In these systems plant uptake is associated with the possible contact with fringing macrophytes and the existence of surface grass coverage which provides the potential for low vegetative removal when stormwater is present. A slightly increased plant uptake is allocated to infiltration basins as these systems, which are often naturally grassed and hence offer the potential for plant uptake, also incorporate a gravel substrate, providing attachment sites for algae. Swales and filter strips, as permanently grassed structures, provide higher contact ratios between stormwater and vegetation and are allocated medium removal potentials by this process. A similar uptake potential is considered to be present in surface flow constructed wetlands due to the high contact area presented to the stormwater by these fully planted systems. However, the potential for plant uptake is considered to be highest in sub-surface flow constructed wetlands due to the increased contact of the stormwater with elaborate root systems of the densely planted vegetation.

Table 18. Plant uptake

BMP	Relative importance of mechanism
Filter drain	Low
Porous asphalt	NA
Porous paving	Low
Filter strip	Medium
Swales	Medium
Soakaways	Low
Infiltration trench	Low
Infiltration basin	Low/Medium
Sedimentation tank	NA
Retention ponds	Low
Detention basins	Low
Extended detention basin	Low
Lagoons	Low
Constructed wetlands (SSF) Constructed wetlands (SF)	Medium/High Medium

5 Development of removal potentials for SSPPs in BMPs

To achieve the objective of predicting the potential for removal of SSPPs in BMPs, a method has been developed which enables the data sets presented in Section 3 (Potential for removal of stormwater priority pollutants by BMP removal processes) and Section 4 (Relative importance of the primary removal mechanisms within each BMP) to be combined. The approach adopted involves the conversion of the designated high, medium and low classifications to values of 3, 2 and 1, respectively, with no value being assigned to processes considered to be 'not applicable'. Intermediate designations are assigned appropriate values e.g. medium/high is allocated a score of 2.5. The numeric value for the effectiveness of a removal process for a SSPP is then combined with a numeric value for the relevance of that process within a specific BMP, to give a value which represents the potential for a particular SSPP (e.g. pyrene) to be removed by a particular removal process (e.g. microbial degradation) within a particular BMP (e.g. an infiltration trench). An additional factor in the calculation process is that photolysis and volatilisation have both been assigned a weighting of 0.5 relative to the other removal processes to represent their typically lower contributions to the overall removal of pollutants within BMPs. The values calculated for each removal process within a BMP can then be combined to give an overall value for the removal potential of a specific SSPP in a specific BMP. The use of this approach is illustrated in Table 19 for the removal of pyrene by an infiltration trench.

Table 19. Potential for removal of pyrene by an infiltration trench

Removal processes	Significance of process to BMP	Significance of process to SSPP	Value (added)	Value (multiplied)
Adsorption to substrate	2.5	3.0	5.5	7.5
Settling	1.5	3.0	4.5	4.5
Microbial degradation	2.0	1.0	3.0	2.0
Filtration	2.5	3.0	5.5	7.5
Volatilisation	0.5**	2.0	2.5	1.0
Photolysis	NA**	3.0	*	*
Plant uptake	1.0	3.0	4.0	3.0
		Overall value	25.0	25.5

Key: * = value could not be calculated; **0.5 weighting applied

The presence of the 'not applicable' category for the removal process prevents the calculation of a combined value (Table 19). This approach is logical because, as can be seen in the above example, although pyrene is susceptible to photolytic degradation, photolysis is not a prevalent removal process in infiltration trenches and therefore due to its non-relevance it does not receive a combined value. Two approaches for combining the data in columns 2 and 3 of Table 19 have been used - addition and multiplication – and the results of both derivations are shown.

The overall combined values (by addition and multiplication) representing the removal potentials for pyrene by each BMP are shown in Table 20 with the values ranked in descending order to generate a hierarchy of BMPs with regard to the removal of pyrene. The additive approach, although the most simple technique, does not highlight the 'extremes' (i.e. the best and the worst values) to the same extent as multiplication, and therefore this latter approach has been adopted to achieve a higher level of discriminatory power.

Table 20. Order of preference for the use of BMPs to remove pyrene, illustrating the use of additive and multiplicative approaches

BMP	Addition		BMP	Multiplication
Infiltration basin	32.75		Infiltration basin	37.25
Constructed wetland SSF	31.75		Constructed wetland SSF	34.5
Constructed wetland SF	29.5		Constructed wetland SF	29.5
Porous paving	29.0		Porous paving	28.5
Extended detention basin	28.75		Swale	28.25
Swale	28.75		Extended detention basin	27.25
Retention pond	28.25		Retention pond	25.75
Detention basin	27.75		Infiltration trench	25.5
Filter strip	27.5		Soakaway	25.5
Lagoon	26.25		Detention basin	25.25
Infiltration trench	25.0		Filter strip	24.75
Soakaway	25.0		Filter drain	24.0
Filter drain	24.5		Lagoon	22.0
Porous asphalt	22.5		Porous asphalt	20.0
Settlement tank	17.5		Settlement tank	14.0

The results in Table 20 show that the use of infiltration basins is the preferred option for pyrene removal using both additive and multiplicative approaches. Constructed wetlands (sub-surface flow and surface flow) and porous paving are all predicted within the top four choices by both approaches and in the same order of prioritisation. Subsequent BMPs show some variations in the predicted prioritisation depending on the combination approach used but porous asphalt and settlement tanks are clearly anchored at the bottom of the list as the least appropriate treatment systems for the removal of pyrene. It is important to remember that the values calculated are ordinal and NOT numeric i.e. the actual numbers are only important in determining the order of predicted BMP performances relative to each other. Thus the derived results indicate that the use of an infiltration basin is more preferable than a sub-surface flow constructed wetland with regard to the removal of pyrene, but it does not indicate the extent by which an infiltration basin exceeds the performance of a sub-surface flow constructed wetland system.

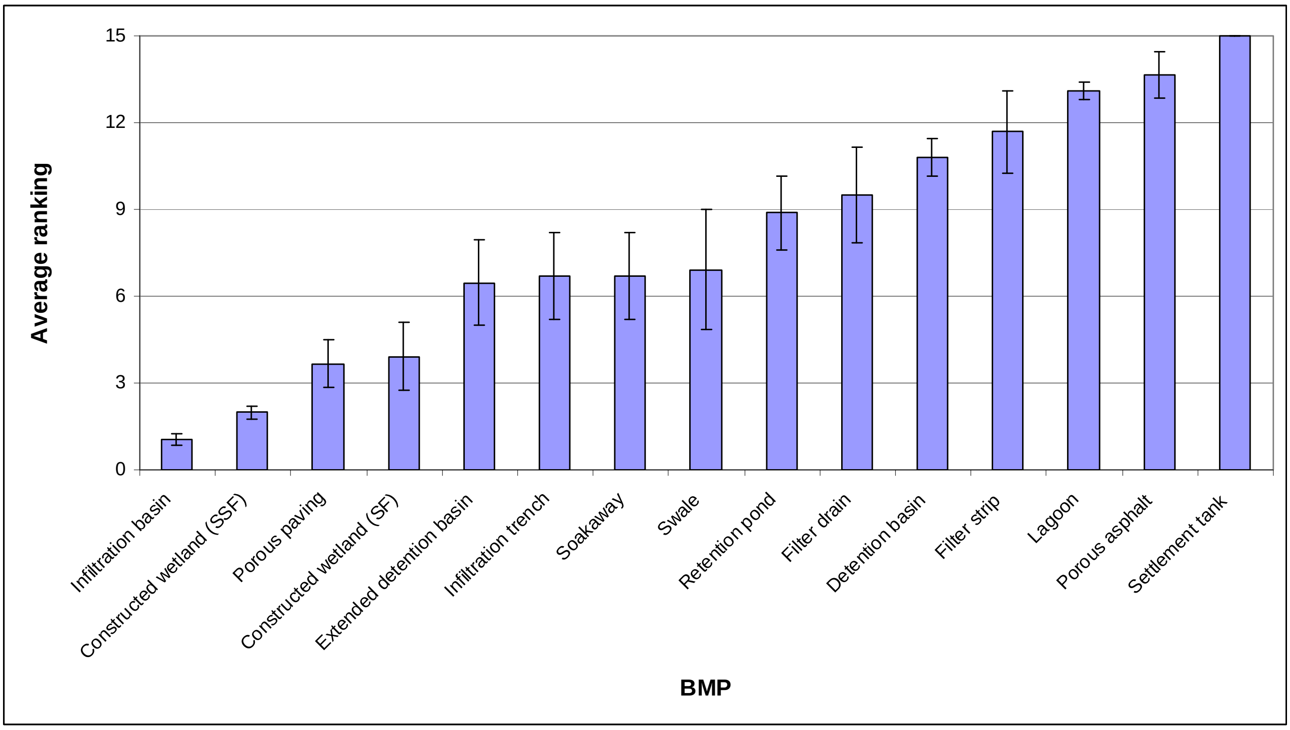
6 Comparison of the predicted performances of different BMPs

In this section the orders of preference for the removal of pollutants by BMPs are presented and discussed using three classifications of SSPPs as examples. To provide an overview of the applicability of the developed approach, the relative rankings of BMPs with respect to the removal of all SSPPS as a combined group are discussed in Section 6.1. In addition, the predicted performances of BMPs with regard to suspended solids (representing particulate associated pollutants) and nitrates (representing soluble pollutants) are described in Sections 6.2 and 6.3 to demonstrate the results obtained for pollutants with markedly different environmental behaviours.

6.1 Average ranked order of preference of BMPs for the removal of all SSPPs (as a combined group).

The data presented in the Figure 1 shows the average ranked order of preference (with standard deviations) for BMPs for the treatment of SSPPs as a combined group. The average ranked position was initially calculated by analysing the potential for removal by each of the BMPs for each of the SSPPs separately (see Table 20). These values were ranked to generate an order of preference for the use of BMPs for each SSPP. The SSPP-specific orders of removal preference were then combined by averaging the ranked data to give an overall indication of the comparative potential of the different BMPs to remove the combined pollutant group of 25 SSPPs. The inclusion of standard deviations illustrates the robustness of the average ranked position.

The two BMPs with the greatest potential for removal of the combined SSPPs are infiltration basins and sub-surface flow constructed wetlands (Figure 1), and the small standard deviations associated with these BMPs suggest that the high average rankings are a valid reflection of their performance across all the SSPPs. The high pollutant removal potentials predicted for



Key: SSF = sub-surface flow, SF = surface flow

Figure 1. Average ranked order of BMPs (±SD) for the removal of 'all SSPPs'

infiltration basins and sub-surface constructed wetlands are associated with the significant occurrence of all of the removal processes outlined in Sections 3.1 and 3.2. For example, both systems involve close contact being maintained between the incoming stormwater and a substrate together with attached microbial populations and/or plant roots enhancing the potential for processes such as adsorption, microbial degradation, plant uptake and filtration.

The second ranking group of BMPs includes surface flow constructed wetlands and porous paving. Although surface flow wetlands are planted systems their design results in less persistent close contact between the stormwater and vegetation/substrate than in sub-surface flow systems producing lower overall removal potentials. Porous paving, involves stormwater passing through a below ground substrate, which may be colonised by algae, but the absence of vegetation produces a reduced potential for both plant uptake and microbial degradation compared to infiltration basins and subsurface-flow wetlands. Additionally the rapid infiltration of stormwater into porous paving structures eliminates the potential for photolytic processes to occur.

The tird tier of BMPs in terms of removal potentials for all SSPPs can be grouped as extended detention basins, swales, infiltration trenches and soakaways (Figure 1). The relatively large standard deviation associated with the average ranked value for swales suggests that the removal potentials associated with this BMP vary according to SSPP-type. A closer examination of the data (not presented here) indicates that the potential for swales to remove PAHs and pesticides tends to be greater than for metals and suspended solids. This different behaviour is believed to be associated with the susceptibility of both PAHs and pesticides to be removed by photolysis and volatilisation and to be taken up by plants compared to metals and suspended solids.

Retention ponds, filter drains, detention basins and filter strips constitute the next grouping of BMPs followed by lagoons, porous asphalt and settlement tanks, which demonstrate the lowest predicted pollutant removal potentials (Figure 1). The relatively low standard deviations associated with this last group of BMPs suggest that their poor predicted pollutant removal potentials are a true reflection of overall performance. This is considered to be associated with the fact that, in comparison to the BMPs discussed earlier, they either lack the components to facilitate the required physical, chemical or biological removal processes or these are present in limited amounts. For example, although lagoons offer the opportunity for all the removal processes to occur, their significance is reduced due to factors such as:

- the typically smaller size of lagoons in comparison to retention ponds and detention basins
- the characteristic presence of only peripheral vegetation (if any)
- limited contact between the stormwater and the substrate materials.

The combination of these factors significantly reduces the potential for a range of removal processes to occur, such as adsorption to substrate, microbial degradation and filtration. Porous asphalt, as described in Section 4, typically consists of only a thin unplanted surfacing layer, and therefore the potential for removal by processes such as sedimentation and microbial degradation is typically low and plant uptake is not possible. However, filtration is a significant process in porous asphalt due to the typically small void size of the material used to construct this type of BMP. Sedimentation tanks exhibit the lowest overall SSPP removal potential which is also consistent across the individual SSPPs. The design of this type of BMP typically consists of a symmetrical, unplanted, concrete storage structure for which all removal processes other than sedimentation are either negligible or of low effectiveness.

6.2 Ranked order of preference of BMPs for the removal of suspended solids

The order of preference for BMPs to remove suspended solids as an individual pollutant (Figure 2) differs from that calculated for the removal of SSPPs as a combined group (Section 6.1). Infiltration basins offer the highest predicted removal potential, followed by sub-surface flow wetlands and porous paving, and then by infiltration trenches and soakaways in order of preference. Suspended solids are most readily removed by processes of sedimentation, filtration, adsorption to substrate and, to a lesser extent and also depending on particle composition, microbial degradation. The potentials for these processes to occur tend to be highest in these BMPs, as they all involve the infiltration of stormwater through a permeable substrate enhancing physical filtration, promoting adsorption to substrate and providing the opportunity for degradation by micro-organisms attached to substrate. Although surface flow wetlands and extended detention basins also support these processes, the stormwater does not have to pass through a substrate and therefore filtration, in particular, is less efficient resulting in a lower ranked position for these BMPs in the order of preference for removal of suspended solids.

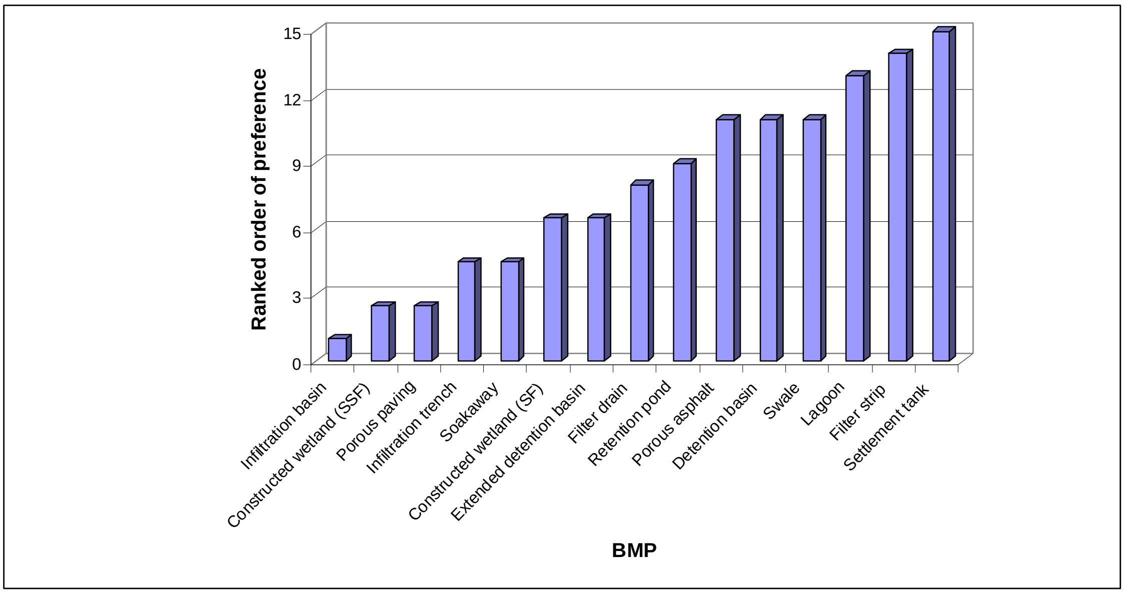


Figure 2. Ranked order of preference of BMPs for the removal of suspended solids

The middle ranking positions with respect to removal of suspended solids are occupied by filter drains, retention ponds, swales, detention basins and porous asphalt. Although filter drains involve the passage of stormwater through a porous substrate, unlike infiltration trenches and soakaways, the partially treated stormwater is subsequently directed into a basal pipe and cannot receive further treatment by infiltrating into the surrounding soil. Retention ponds and, to a slightly lesser extent, detention basins demonstrate relatively high potentials for sedimentation but both adsorption and filtration processes are less well supported and this contributes significantly to their comparatively lower ranking. As previously described, filtration is a significant process in porous asphalt but the typically low bulk volume of this BMP system offers little potential for adsorption to substrate and, in particular, for sedimentation to occur and hence its position towards the lower end of the overall order of BMP preference. Swales occupy an identical position to both porous asphalt and detention ponds but for different reasons with the characteristically lower retention times of swales, in comparison to BMPs such as retention ponds, effectively reducing the potential for processes such as sedimentation and microbial degradation to occur.

As for the order of BMP preference for the removal of all SSPPs, lagoons, filter strips and settlement tanks are again considered to offer low potentials for suspended solids removal.

Although the potential for sedimentation to occur is relatively high within both settlement tanks and lagoons, the potential for adsorption to substrate and filtration is considered to be either low or not to occur at all resulting in their low ranked position. With regard to filter strips, the low suspended solids removal potential is considered to be a function of both the relatively short retention times which limits the sedimentation process as well as the over-grass flow mechanism which reduces the potential for filtration.

6.3 Ranked order of preference of BMPs for the removal of nitrates

The order of ranking preference for BMPs for the removal of a predominantly soluble pollutant, represented by nitrates, (Figure 3) differs quite significantly from that generated for the removal of suspended solids (Figure 2, Section 6.2). Due to the preference of nitrates for the soluble phase, their potential to be removed by processes such as sedimentation, adsorption to substrate and filtration is of low significance. The overall potential for nitrates to be microbially transformed is considered to be low overall as they are only susceptible to microbial degradation under anaerobic conditions. In contrast, nitrates are highly susceptible to plant uptake and this is a factor which plays a key role in influencing the order of BMP preference as five of the top six most highly ranked BMPs are planted systems (sub-surface and surface flow constructed wetlands, infiltration basins, swales and filter strips). The exception is porous paving which is also more highly ranked than filter strips. The factors that compensate for the lack of plant uptake of nitrates in porous paving are considered to be associated with the following:

- the substrate of porous paving may be colonised by algal populations which have the ability to utilise nitrates
- the potentials for adsorption to substrate and microbial degradation to occur in porous paving are all considered to be greater than in filter strips due to typical retention time differences as well as the degree of contact between substrate and stormwater.

Similar reasons can also be put forward for infiltration trenches and soakaways which are equivalent and occupy the next overall ranking position for nitrate removal.

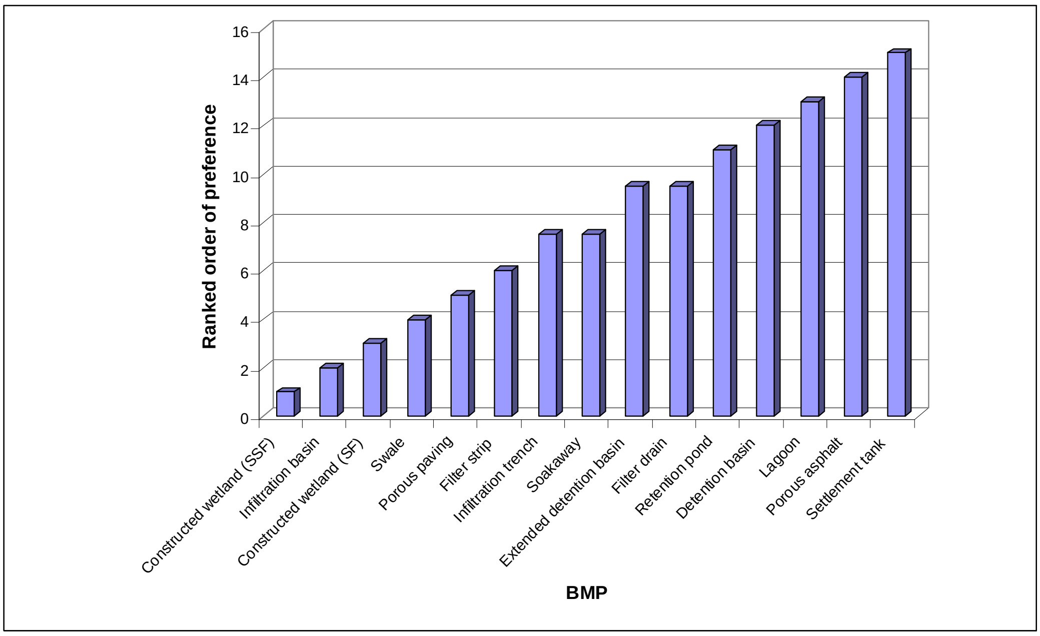


Figure 3. Ranked order of preference for the removal of nitrates by BMPs

For the remaining BMPs, the effectiveness for plant uptake to occur is considered to be equally low and associated with limited stormwater contact with grassed surfaces (extended detention basins and detention basins), the presence of vegetation fringes (retention ponds and swales) or algae growth on BMP substrates (filter drains). The order of preference of these BMPs is therefore largely influenced by differences in the potentials for adsorption to substrate, sedimentation and microbial degradation to occur. However, settlement tanks offer no potential for plant uptake and only low potentials for microbial degradation and adsorption to substrate and consequently are positioned at the bottom of the predicted ranking order of BMPs. This is also consistent with the predicted behaviour of this BMP towards suspended solids.

It is important to stress that the theoretical development described in this report is essentially concerned with the quantification of removal potentials under conditions of unconstrained process operation. Poor BMP design and/or ineffective maintenance are liable to degrade the process potentials over time and thus they may not match the theoretical values developed by the current methodology.

7 Conclusions

This report describes the development of a methodology, based on the input of theoretical data and knowledge, to identify the relative efficiencies with which BMPs are able to remove the pollutants commonly associated with stormwater. End-users will be able to use the generated results to determine which individual BMPs are best suited to the removal of selected pollutants and hence utilise this information as part of the planning procedure for proposed treatment systems. Within the DayWater project the predicted results are being utilised to develop scores for the pollution control indicator within the technical criteria section of the multi-criteria analysis, which assists end-users in the selection of BMPs for particular stormwater control scenarios. The results for three different categories of pollutants (all 25 identified selected stormwater priority pollutants; suspended solids; nitrates) are reported and indicate that infiltration basins and sub-surface flow constructed wetlands are the most efficient treatment systems with regard to their pollutant removal capabilities with settlement tanks consistently demonstrating the worst performances. In all cases, the predicted prioritisation of the BMPs with regard to their pollutant removal potentials can be explained by a careful consideration of the relative strengths of the different removal processes as this is one of the factors which have been built into the developed methodology. The other important factor in the developed approach is the susceptibility of an individual or group of pollutants to each of the identified removal processes (settling, adsorption to substrate, microbial degradation, filtration, plant uptake, volatilisation and photolysis) which are known to occur within BMPs.

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