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ScorePP

Priority pollutant behaviour in stormwater Best Management Practices (BMPs)

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Source Control Options for Reducing Emissions of Priority Pollutants (ScorePP)

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Abstract (max. 200 words)

Limited, if any, field monitoring data exists on the behaviour of WFD priority pollutants (PPs) in stormwater Best Management Practices (BMPs). However, stormwater managers currently need to make decisions on the adoption of urban drainage schemes which can address both water quantity and water quality objectives, a need increasingly prioritised by the EU WFD. To address this identified knowledge gap, a theoretical approach to predicting the behaviour of PPs within BMPs, and hence the provision of an assessment of their removal potentials, has been developed. This methodology involves identifying the primary removal processes within 15 BMPs and categorising their relative importance. Physico-chemical data and, where this is missing, expert judgement are used to assess the potential for 52 WFD PPs (an extended list including a range of representative group members) to be removed by the identified processes. These two sets of information are then combined to generate a single overall unit value representing the potential for each BMP to remove a particular pollutant. Ranking these values in descending order enables a pollutant-specific BMP treatment 'order of preference' to be established. This report describes the methodology and presents the results of its application to the extended list of WFD PPs.

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1 Structural Stormwater Best Management Practices

The term Stormwater Best Management Practices (BMPs) refers to a wide range of stormwater control systems which enable the planning, design and management of stormwater to be tackled equally from hydrological, environmental and public amenity perspectives (CIRIA, 2001). These systems can be used individually or in combination with each other (as a treatment train) and both as an alternative to or in combination with conventional piped stormwater drainage systems.

The following sections provide a brief description of the main types of BMPs which are referred to within this report.

1.1 Storage Facilities

1.1.1 Surface flow constructed wetlands

Constructed wetlands are artificial, designed complex vegetative water bodies that can provide treatment (and re-cycling) of both wastewater effluent and stormwater runoff. Surface flow systems (also known as free water systems) are wetlands in which water primarily flows above the ground surface and through the litter layer (Ellis *et al.*, 2003). They simulate natural marshes, employing shallow channels and basins planted with emergent, submergent and/or floating vegetation through which water flows at shallow depths and low velocities.

1.1.2 Sub-surface flow constructed wetlands

A constructed sub-surface flow system is a wetland in which wastewater flows through a lined basin or channel which is filed with a permeable substrate (Ellis *et al.*, 2003). This is planted with wetland plants and flow remains below the media surface.

1.1.3 Detention ponds/basins (dry ponds):

Depressed basins which are normally dry but which temporarily store and attenuate a portion of stormwater runoff following a storm event (CIRIA, 2001). Water is controlled by means of a hydraulic control structure to restrict outlet discharge according to the required detention time. Such dry basins offer public open space for recreational uses but are of limited habitat value.

1.1.4 Extended detention basin (EDB)

Typically consist of two-stage design providing a dry upper level and a smaller lower stage containing permanent water and/or a shallow marsh. To serve as an effective BMP, EDBs need to hold stormwater in the lower stage basin for relatively long periods. For example, Stahre and Urbonas (1990) reported removal rates of 50-70% for total suspended solids with a detention period of 48 hours.

1.1.5 Lagoons

Small, permanent water bodies which are constructed by excavating natural earth basins. They may be lined to prevent infiltration and for safety reasons a fencing surround is often provided. Vegetation may be introduced to assist with the pollutant removal process.

1.1.6 Retention ponds/basins (wet ponds)

Possess a permanent pool of water incorporated into the design and are also known as balancing ponds or flood storage basins. Principally function as sedimentation facilities with soluble pollutants being removed by biological processes which can be enhanced by marginal planting. Such wet ponds/basins can have substantial aesthetic, amenity and ecological benefits in addition to their flood and water quality control benefits.

1.1.7 Sedimentation tank

These structures are intended to intercept and retain coarse sediment and litter carried in stormwater runoff by means of a bed load mechanism and are often located at the front end of a treatment train system.

1.2 Filter strips and swales

1.2.1 Swales

Shallow vegetated channels used to convey stormwater runoff. Pollutants are removed by settling, filtration through the grass sward and by infiltration into the underlying soil. Removal rates exceeding 80% of total suspended solids are quoted for swales having flow velocities less than 0.15 m/s and with high soil infiltration rates (Scholes *et al.,* 2003). Runoff volume may also be reduced through infiltration. Ideally, swales require shallow slopes and soils that drain well and are often used as a pre-treatment measure for downstream BMPs. They can utilise check dams to increase storage, settling and infiltration and to reduce the channel gradient.

1.2.2 Filter (buffer) strips

Vegetative buffer strips are similar to grass swales except they are essentially flat with very low slopes and are designed to promote sheet flow of the incoming stormwater runoff (CIRIA, 2001). The grassed strip intercepts suspended solids and associated pollutants using lateral runoff from land adjacent to streams, drains and basins and may be located along streets and highways. Buffer strips can remove coarse particulates effectively provided the flow is kept shallow and slow. As for grass swale channels, they are commonly used as a pre-treatment device to protect downstream BMPs.

1.2.3 Filter (French) drain

A perforated or slotted drain pipe placed in a backfill aggregate material which is normally wrapped with a geotextile or fabric filter although some French drains may consist solely of aggregate materials. Such drains are primarily used to lower the water table and drain stormwater runoff from a highway surface.

1.3 Infiltration systems

1.3.1 Infiltration trench:

An excavated trench lined with a filter fabric and backfilled with stone. Runoff is diverted to the trench and either exfiltrates into the soil (a complete trench) or enters a perforated under-drain pipe (partial trench) with any excess flow being routed to an outflow.

1.3.2 Soakaway

A stone or rubble-filled pit covered by soil into which a storm drain discharges runoff from roofs and paved areas (Ellis et al, 2004). Although soakaways (or infiltration pits) may be some tens of square metres in plan area where they receive stormwater from a large impermeable catchment, they are frequently much smaller in area (<4 m^2 in plan area), serving only one household and being constructed in the private grounds surrounding the property. Often constructed no more than 2 m deep and with the storm drain discharging to the pit around 1m below ground surface, the resulting volume of water storage in the pit is only some 1 m^3 (assuming 30% void space in the stone or rubble fill). Recent design recommendations suggest that the pit should be lined with a geotextile fabric in order to separate the surrounding soil from the fill material and prevent the loss of storage volume due to soil migration and slippage into the pit.

1.3.3 Infiltration basin

Similar, in principle, to infiltration trenches, except that they are generally used for larger drainage areas and water is temporarily stored in a visible pond. A normal design would involve capturing, at least, the "first-flush" volume. As for detention basins, infiltration basins are frequently dual-purpose areas being used for stormwater runoff control and disposal under wet weather conditions, and recreational amenity use during dry weather (CIRIA, 2001).

1.4 Alternative road and paving structures

1.4.1 Porous paving

A paving material that allows stormwater to rapidly infiltrate the surface pavement layer and enter into a high-void aggregate sub-base reservoir composed of gravel, crushed stone/rock or natural soil (Scholes *et al.*, 2003). Examples of such surfacing are porous macadam and no-fines concrete block paving or pavoirs. Some forms of permeable pavement use grass-concrete blocks, a type of modular pavement well suited to overflow car parks which require a grass surface that must be sufficiently hard wearing to withstand regular vehicle use. The captured runoff is stored in this reservoir until it either infiltrates into the underlying soil, or excess flow is routed through a perforated underdrain system to a conventional outfall.

1.4.2 Porous asphalt

Porous surfacing material only (no sub-base reservoir structure) which encourages direct infiltration of stormwater within the surface material layer, reducing the volume of runoff generated and impacts such as surface ponding. Stormwater is subsequently directed to the edge-of-road, where it may enter a further BMP e.g. swale or piped system.

2 Need for a theoretical approach

Recent reviews of the literature have reported that field monitoring data on the behaviour of many of the Water Framework Directive priority pollutants (PPs) within in BMPs is not available (e.g. Scholes *et al.,* 2005). Even for the more routinely monitored general water quality parameters, such as total suspended soils (TSS), it is difficult to source sufficient monitoring data across a range of BMPs to enable their removal potentials to be confidently compared (Scholes *et al.*, 2007). Further investigation of the relative contributions of the pertinent biological, chemical and physical processes is therefore urgently required, a research need particularly highlighted by the increasing importance being placed on pollution reduction accountability within the context of River Basin Management Plans (EU WFD, 2000). Extensive monitoring data relating to the differential pollutant removal capabilities of many BMPs will only become available as further field work is carried out over the coming years whereas stormwater managers and urban planners need to make decisions now on which urban drainage schemes to adopt. This need to make decisions now on the absence of data is recognised as an increasingly common situation, driven by factors such as increasingly stringent legislation and the use of the precautionary principle.

The ‘gap’ between the needs of practitioners and the availability of empirical data to scientists is acknowledged, however, it is also recognized that a considerable body of scientific knowledge and expertise is available. It was therefore considered appropriate to determine whether this information could be used to support stormwater managers in their on-going work. This question was initially evaluated within the EU funded DayWater stormwater management project (Thévenot and Förster, 2005) and, following a review of existing scientific data, technical information and informed peer discussions, led to the development of an initial framework within which both scientific data and professional judgement could be combined to support a comparative evaluation of BMP pollutant removal performances.

3 Refinement of the ScorePP BMP pollutant removal methodology

Within the ScorePP project, an initial framework developed within the EU stormwater management project DayWater (Scholes *et al.*, 2007) has been further developed and refined, building on the use of fundamental unit operating processes (UOPs) to provide a more structured and systematic approach. A flow chart of the updated approach is presented in Figure 1 and described in the following sections.

3.1 Primary removal processes which take place within BMPs

The primary biological, chemical and physical pollutant removal mechanisms which occur 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; see Table 1) or whether they contribute indirectly to a pollutant removal process (e.g. precipitation and adsorption to suspended solids) (Table 2). Both these latter process are considered to be contributory to, as opposed to directly resulting in removal, as a further process, such as settling and/or filtration, must additionally occur to result in a pollutants' complete removal from the water column.

Table 1 Direct removal processes in BMPs

Removal Processes	Relevant Measurements and units
Settling	Settling velocity (m/s)
Adsorption to substrate	K_{oc} (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_{oc} = organic carbon-water partitioning coefficient = partitioning of a substance between the organic carbon and dissolved phases at equilibrium = ratio of the concentration of a pollutant associated with the organic 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

Table 2 Indirect/contributory removal processes in BMPs

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

Key: K_{oc} = organic carbon-water partitioning coefficient = partitioning of a substance between the organic carbon and dissolved phases at equilibrium = ratio of the concentration of a pollutant associated with the organic phase to its concentration in the dissolved phase at equilibrium

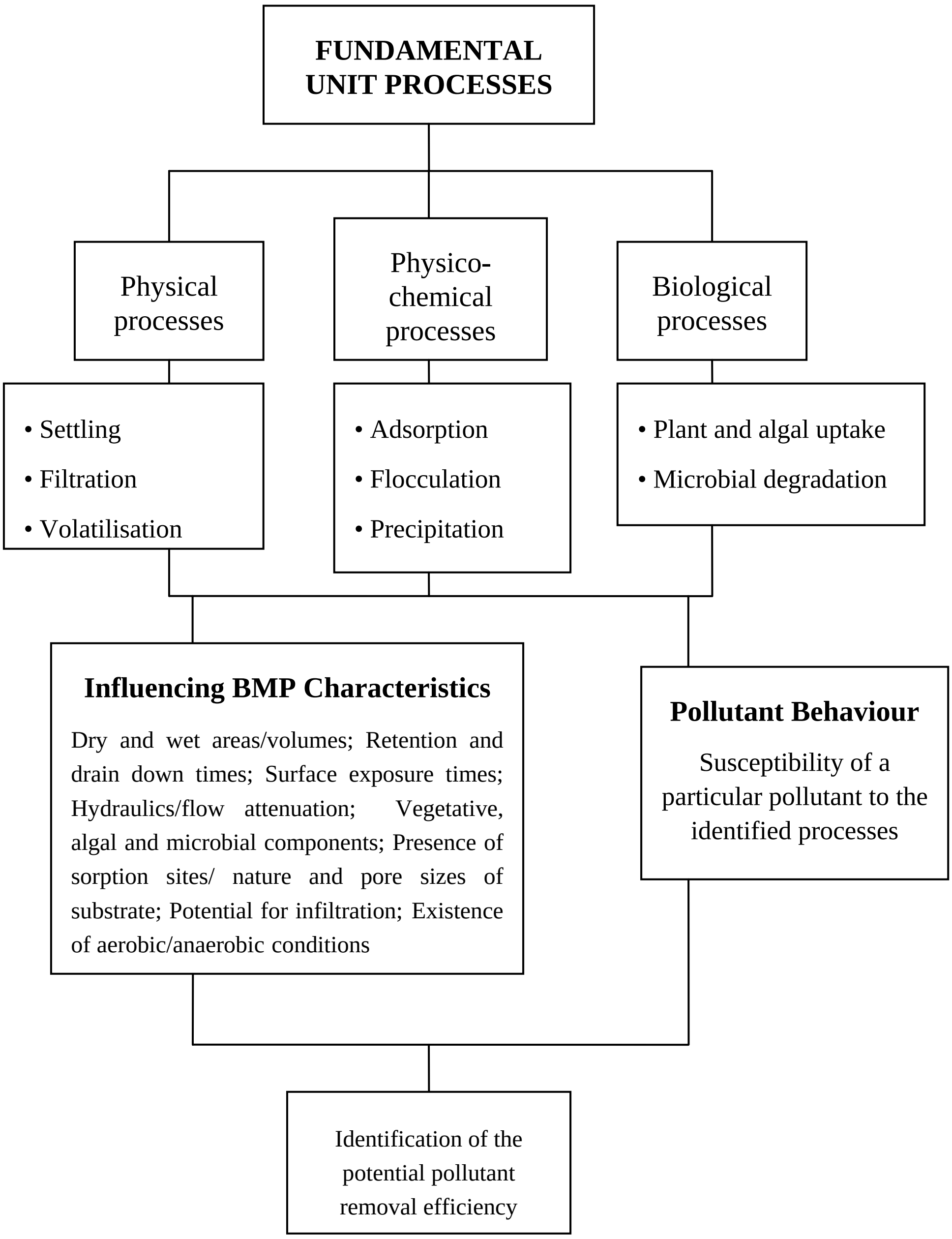

Figure 1. Fundamental unit processes in relation to BMP characteristics and pollutant behaviour.

3.1.1 Potential for removal processes to occur within BMPs

The relative importances of each of the removal mechanisms identified in Figure 1 with regard to occurrence within each of the 15 BMPs identified in Section 1 have been considered and designated as being of high, medium or low importance. Where a removal process is not relevant to a particular BMP, it is designated as being not applicable (NA). The relative importance of the processes both within each BMPs and relative to other BMPs have been assessed in relation to generic BMP 'characteristics' such as presence of vegetation, microbial components, sorption sites the nature and pore sizes of substrates. For example, although settlement of suspended particulate matter will occur within a swale, it is normally a much more important process in retention basins due to the typical presence of a large quiescent volume of water as a component of the latter system. Full explanations of how the potentials for each of the removal processes to occur within each of the BMPs were assessed can be found in (Revitt *et al.*, 2005) with an overview of this classification procedure presented in Tables 3 – 9.

Table 3 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)	Medium/High
Constructed wetlands (SF)	Medium

Table 4 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

Table 5 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)	High
Constructed wetlands (SF)	Medium

Table 6 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)	Medium/High
Constructed wetlands (SF)	Medium

Table 7 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)	Low/Medium
Constructed wetlands (SF)	Medium

Table 8 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)	Low
Constructed wetlands (SF)	Low

Table 9 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)	Medium/High
Constructed wetlands (SF)	Medium

3.1.2 Removal potentials for priority pollutants

Having identified the primary direct and indirect pollutant removal mechanisms within BMPs and considered their potential to occur within 15 types of BMPs (Tables 3 – 9), the propensity for each of the WFD priority pollutants (PPs) to be removed by each of the identified mechanisms were evaluated. Although Annex 10 of the WFD lists 33 PPs, with a further 8 'additional substances subsequently identified, some of the PPs listed refer to groups of substances with recommendations given for 'model compounds' as representatives of the behaviour of the wider group. Taking these extra chemicals into account, Deliverable 3.1 has identified 68 CAS numbers as presented Table 10.

The process of assessing the comparative potential for each PP to be removed by each BMP process has involved the use of the collected physico-chemical data for each of the PPs (provided by DTU and further supplemented by MU; see Holten Lützhøft *et al.,* 2007) in combination with the use of expert judgement where data availability was limited or not available.

The collected data are presented in Tables 11 - 17, together with an assignment of the comparative potential for a PP to be removed by the identified removal process within the categories of high, medium-high, medium, medium-low, or low importance. 'NA' is allocated when a process is not thought be relevant. The quality of the available data did not support further resolution of the categories.

Table 10 List of priority pollutants with associated CAS numbers as identified in Task 3.1.

Group name	Priority pollutants	CAS number
Benzene and PAHs	benzene	71-43-2
	naphthalene	91-20-3
	anthracene	120-12-7
	fluoranthene	206-44-0
	benzo(a)pyrene	50-32-8
	benzo(g,h,i)perylene	191-24-2
	indeno(1,2,3-cd)pyrene	193-39-5
	benzo(k)fluoranthene	207-08-9
	benzo(b)fluoranthene	205-99-2
Chlorinated aliphatics	methylene chloride	75-09-2
	chloroform	67-66-3
	carbon tetrachloride	56-23-5
	ethylene chloride	107-06-2
	C10-C13 chloroalkane	85535-84-8
Chlorinated alkenes	trichloroethylene	79-01-6
	tetrachloroethylene	127-18-4
Chlorobenzenes	1,2,4-trichlorobenzene	120-82-1
	trichlorobenzenes	12002-48-1
	pentachlorobenzene	608-93-5
	hexachlorobenzene	118-74-1
Chlorophenols	pentachlorophenol	608-93-5
Hexachlorocyclohexanes	hexachlorocyclohexane	608-73-1
	lindane	58-89-9
DDT and metabolites	para-para-DDT	50-29-3
	ortho-para-DDT	789-02-6
	DDD	72-54-8
	DDE	72-55-9
Phenyl-urea herbicides	diuron	330-54-1
	isoproturon	34123-59-6
Anilides	alachlor	15972-60-8
Triazines	simazine	122-34-9
	atrazine	1912-24-9
Organophosphate esters	chlorfenvinphos	470-90-6
	chlorpyrifos	2921-88-2
Other pesticides	alpha-endosulphan	959-98-8

Table 10 continued

	endosulphan	115-29-7
	hexachlorobutadiene	87-68-3
	trifluralin	1582-09-8
	endrin	72-20-8
	dieldrin	60-57-1
	isodrin	465-73-6
	aldrin	309-00-2
Endocrine disrupters	octylphenols	1806-26-4
	para-tert-octylphenol	140-66-9
	nonylphenols	25154-52-3
	4-para-nonylphenol	104-40-5
	DEHP	117-81-7
	pentabromodiphenylether	32534-81-9
Organometallic compounds	tributyltin cation	36642-28-4
	tributyltin compounds	688-73-3
	tributyltin chloride	1461-22-9
	tributyltin methacrylate	2155-70-6
	bis(tributyltin) oxide	56-35-9
	tetra-N-Butyltin	1461-25-2
	tetramethyl lead	75-74-1
	ethyltrimethyllead	1762-26-1
	diethyldimethyllead	1762-27-2
	methyltriethyllead	1762-28-3
	tetraethyl lead	78-00-2
	methylmercury	22967-92-6
	dimethylmercury	593-74-8
	diethylmercury	627-44-1
	phenylmercuric acetate	62-38-4
Metals and salts	cadmium compounds	7440-43-9
	lead compounds	7439-92-1
	lead acetate	301-04-02
	mercury compounds	7439-97-6
	nickel compounds	7440-02-0

Table 11 Potential for PPs to be removed by adsorption to substrate material (direct process) or suspended solids (indirect process)

Group name	Priority pollutants	Reported range of K_{oc} values (L/g)	Number of values	Mean K_{oc} (L/g)	SD (L/g)	Predicted adsorption level
Benzene and PAHs	benzene	26-370	18	103	106	L/M
	naphthalene	440-2000	6	1,239	647	M
	anthracene	13,100- 130,000	11	36,582	34,630	M/H
	fluoranthene	32,359-295,121	23	80,947	66,231	M/H
	benzo(a)pyrene	151,356-6,309,573	19	1,733,263	1,799,335	H
	benzo(g,h,i)perylene	90,000-10,000,000	9	3,081,100	4,030,033	H
	indeno(1,2,3-cd)pyrene	1,584,893-8,500,000	7	5,138,429	2,879,850	H
	benzo(k)fluoranthene	120,000-1,300,000	9	660,667	377,161	H
	benzo(b)fluoranthene	550,000-3,981,071	6	2,069,450	1,380,332	H
Chlorinated aliphatics	methylene chloride	9-48	6	25.6	14.7	L
	chloroform	34-196	9	75.3	61.3	L
	carbon tetrachloride	47-160	7	79.4	39.9	L
	ethylene chloride	14-44	6	30.6	12.4	L
	C10-C13 chloroalkane	91,200-239,883	5	180,874	59,584	H
Chlorinated alkenes	trichloroethylene	58-920	39	184.3	182.9	L/M
	tetrachloroethylene	139-437	12	256.1	86.2	L/M
Chloro-benzenes	1,2,4-trichlorobenzene	780-27,000	21	5,356	6,853	M
	trichlorobenzenes	631-7,943	12	2,951	2,191	M
	pentachlorobenzene	3,160-79,433	7	16,076	16,810	M/H
	hexachlorobenzene	3,900-920,000	28	154,409	229,837	H
Chlorophenols	pentachlorophenol	300-19,675	35	3,353	3,907	M
Hexachloro-cyclo-hexanes	hexachlorocyclohexane	955-6,600	7	2,900	2,002	M
	lindane	430-7,000	44	2,006	1,521	M
DDT and metabolites	para-para-DDT	113,000-890,000	16	354,020	244,747	H
	ortho-para-DDT	113,000-890,000	16	354,020	244,747	H
	DDD	37,154-131,800	3	99,851	54,300	H
	DDE	26,300-4,470,000	4	Too much variability		
Phenyl-urea herbicides	diuron	224-682	6	416	154	L/M
	isoproturon	124-182	3	193	81	L/M
Anilides	alachlor	120-192	5	164	35	L/M
Triazines	simazine	78-1,690	16	508	530	L/M
	atrazine	54-936	20	244	271	L/M
Organophosphate esters	chlorfenvinphos	93-1318	6	617	444	L/M
	chlorpyrifos	4381-13,600	5	7,327	3,599	M
Other pesticides	alpha-endosulphan					
	endosulphan	1,096-10,038	6	5,552	3,689	M
	hexachlorobutadiene	4,677-11,749	6	6,053	2,798	M
	trifluralin	397-19,500	9	8,784	6,527	M
	endrin	11,000-34,000	3	18,807	13,159	M/H
	dieldrin	1,700-13,700	15	8,694	3,783	M
	isodrin	400-28,000	2	Only two extreme values		M*
	aldrin	400-96,000	6	Too much variability		M*

Table 11 continued

Endocrine disrupters	octylphenols	2,512-18,500	5	9,573	7,988	M
	para-tert-octylphenol	2,512-18,500	5	9,573	7,988	M
	nonylphenols	5,012-31,622	6	15,216	12,595	M/H
	4-para-nonylphenol	5,012-32,400	5	12,215	11,458	M/H
	DEHP	22,000-890,000	13	310,497	270,270	H
	pentabromodiphenylether	147,000-556,801	4	329,245	185,085	H
Organo-metallic compounds	tributyltin cation	316-1,584,893	5	Extreme variability		
	tributyltin compounds	316-1,584,893	5	Extreme variability		
	tributyltin chloride					
	tributyltin methacrylate					
	bis(tributyltin) oxide					
	tetra-N-Butyltin					
	tetramethyl lead					
	ethyltrimethyllead					
	diethyldimethyllead					
	methyltriethyllead					
	tetraethyl lead	4,310	1	4,310		
	methylmercury					
	dimethylmercury					
	diethylmercury					
	phenylmercuric acetate					
Inorganic metal compounds	cadmium compounds					L
	lead compounds					H
	mercury compounds					
	nickel compounds					M

Key: Koc range classification: Low (L) <100; Low/Medium (L/M) 100-1,000; Medium (M) 1,000-10,000; Medium/High (M/H) 10,000-100,000; High (H) >100,000.* = prediction based on the behaviour of other group members; Empty cells in the third column indicate no data available; references listed in section 6.1.

Table 12 Potential for pollutants to be removed by precipitation (indirect process)

Group name	Priority pollutants	Reported range of water solubility (mg/l)	Number of values	Mean solubility (mg/l)	SD (mg/l)	Potential for removal
Benzene and PAHs	benzene	1,790-1,880	2	1,835	63.6	M
	naphthalene	31	1	31		H
	anthracene	0.0434	1	0.0434		H
	fluoranthene	0.26	1	0.26		H
	benzo(a)pyrene	0.0016	1	0.0016		H
	benzo(g,h,i)perylene	0.00026	1	0.00026		H
	indeno(1,2,3-cd)pyrene	0.00019	1	0.00019		H
	benzo(k)fluoranthene	0.0008	1	0.0008		H
	benzo(b)fluoranthene	0.0015	1	0.0015		H
Chlorinated aliphatics	methylene chloride	13,000-28,488	2	20,774.0	10,952	L/M
	chloroform	3,810-7,950	3	6,393.0	2,253.0	M
	carbon tetrachloride	760.4-793	2	776.7	23.1	M/H
	ethylene chloride	8,600-12,035	2	10,318.0	2,429	L/M
	C10-C13 chloroalkane	0.15-0.47	2	0.31	0.23	H
Chlorinated alkenes	trichloroethylene	1,100-1,280	2	1,190	127.3	M
	tetrachloroethylene	150.6-206	2	178.3	39.2	M/H
Chlorobenzenes	1,2,4-trichlorobenzene	49	1	49		H
	trichlorobenzenes	30	1	30		H
	pentachlorobenzene	0.831	1	0.831		H
	hexachlorobenzene	0.0062	1	0.0062		H
Chlorophenols	pentachlorophenol	14-80	2	47	46.7	H
Hexachlorocyclo-hexanes	hexachlorocyclohexane	8	1	8		H
	lindane	7.3	1	7.3		H
DDT and metabolites	para-para-DDT	0.0017-0.0055	2	0.0036	0.0027	H
	ortho-para-DDT	0.085	1	0.085		H
	DDD	0.09-0.16	2	0.1250	0.049	H
	DDE	0.04	1	0.04		H
Phenyl-urea herbicides	diuron	42	2	42.0		H
	isoproturon	65-70	2	67.5	3.5	H
Anilides	alachlor	140-240	2	190	70.7	M/H
Triazines	simazine	6.2	1	6.2		H
	atrazine	34.7-70	2	52.4	25.0	H
Organophosphate esters	chlorfenvinphos	124-145	2	134.5	14.8	M/H
	chlorpyrifos	1.12-2.0	2	1.56	0.62	H
Other pesticides	alpha-endosulphan	0.325-0.51	2	0.42	0.13	H
	endosulphan	0.325-0.51	2	0.42	0.13	H
	hexachlorobutadiene	3.2-50	2	26.6	33.1	H
	trifluralin	0.184-24	2	12.09	16.84	H
	endrin	0.25	1	0.25		H
	dieldrin	0.195	1	0.195		H
	isodrin	0.0142	1	0.0142		H
	aldrin	0.017	1	0.017		H

Table 12 continued

Endocrine disrupters	octylphenols	12.6	1	12.6		H
	para-tert-octylphenol	5-12.6	2	8.80	5.4	H
	nonylphenols	6.35	1	6.35		H
	4-para-nonylphenol	6.35-7	2	6.68		H
	DEHP	0.27-0.285	2	0.278	0.011	H
	pentabromodiphenylether	0.0000009	1	0.0000009		H
Organometallic compound	tributyltin cation					
	tributyltin compounds	0.0073	1	0.0073		H
	tributyltin chloride	1.27-17	2	9	11	H
	tributyltin methacrylate	1.27	1	1.27		H
	bis(tributyltin) oxide	0.75-100	17	30.0	28.1	H
	tetra-N-Butyltin	0.000064	1	0.000064		H
	tetramethyl lead	15-28.38	4	20.5	5.63	H
	ethyltrimethyllead	7.65	1	7.65		H
	diethyldimethyllead	4.62	1	4.62		H
	methyltriethyllead	1.92	1	1.92		H
	tetraethyl lead	0.156-2.34	6	0.76	0.88	H
	methylmercury	100	1	100		M/H
	dimethylmercury	1000-8,860	2	4,930	5,558	M
	diethylmercury	5,650	1	5,650		M
	phenylmercuric acetate	4,370	1	4,370		M
Inorganic metal compounds	cadmium compounds	1.3 - 1,680,000	*	low-high		M
	lead compounds	insol - 597,000	*	low-high		M/H
	lead acetate	1,600	1	1,600		M
	mercury compounds	insol - 73,100	*	low-med/high		M/H
	nickel compounds	1.5 - 1,310,000	*	low-high		M

Key: solubility (mg/l) range classification: Low (L) >100,000; Low/Medium (L/M) 10,000-100,000; Medium (M) 1,000-10,000; Medium/High (M/H) 100-1,000; High (H) <100
* = compound dependent; empty cells in 3rd column indicate no data available; references listed in section 6.1.

Table 13 Potential for pollutants to be removed by settling and filtration (direct processes) due to the combined effects of adsorption to suspended solids and precipitation (indirect processes)

Group name	Priority pollutants	Tendency to adsorb	Tendency to precipitate	Potential for removal
Benzene and PAHs	benzene	L/M	M	M
	naphthalene	M	H	M/H
	anthracene	M/H	H	H
	fluoranthene	M/H	H	H
	benzo(a)pyrene	H	H	H
	benzo(g,h,i)perylene	H	H	H
	indeno(1,2,3-cd)pyrene	H	H	H
	benzo(k)fluoranthene	H	H	H
	benzo(b)fluoranthene	H	H	H
Chlorinated aliphatics	methylene chloride	L	L/M	L
	chloroform	L	M	L/M
	carbon tetrachloride	L	M/H	M
	ethylene chloride	L	L/M	L
	C10-C13 chloroalkane	H	H	H
Chlorinated alkenes	trichloroethylene	L/M	M	M
	tetrachloroethylene	L/M	M/H	M
Chlorobenzenes	1,2,4-trichlorobenzene	M	H	M/H
	trichlorobenzenes	M	H	M/H
	pentachlorobenzene	M/H	H	H
	hexachlorobenzene	H	H	H
Chlorophenols	pentachlorophenol	M	H	M/H
Hexachlorocyclo -hexanes	hexachlorocyclohexane	M	H	M/H
	lindane	M	H	M/H
DDT and metabolites	para-para-DDT	H	H	H
	ortho-para-DDT	H	H	H
	DDD	H	H	H
	DDE	H*	H	H*
Phenyl-urea herbicides	diuron	L/M	H	M
	isoproturon	L/M	H	M
Anilides	alachlor	L/M	M/H	M
Triazines	simazine	L/M	H	M
	atrazine	L/M	H	M
Organophosphate esters	chlorfenvinphos	L/M	M/H	M
	chlorpyrifos	M	H	M/H
Other pesticides	alpha-endosulphan	M*	H	M/H*
	endosulphan	M	H	M/H
	hexachlorobutadiene	M	H	M/H
	trifluralin	M	H	M/H
	endrin	M/H	H	H
	dieldrin	M	H	M/H
	isodrin	M*	H	M/H*

Table 13 continued

	aldrin	M*	H	M/H*
Endocrine disrupters	octylphenols	M	H	M/H
	para-tert-octylphenol	M	H	M/H
	nonylphenols	M/H	H	H
	4-para-nonylphenol	M/H	H	H
	DEHP	H	H	H
	pentabromodiphenylether	H	H	H
Organometallic compounds	tributyltin cation			
	tributyltin compounds		H	
	tributyltin chloride		H	
	tributyltin methacrylate		H	
	bis(tributyltin) oxide		H	
	tetra-N-Butyltin		H	
	tetramethyl lead		H	
	ethyltrimethyllead		H	
	diethyldimethyllead		H	
	methyltriethyllead		H	
	tetraethyl lead		H	
	methylmercury		M/H	
	dimethylmercury		M	
	diethylmercury		M	
	phenylmercuric acetate		M	
Inorganic metal compounds	cadmium compounds	L	M	L
	lead compounds	H	M/H	H
	mercury compounds		M/H	
	nickel compounds	M	M	M

Note: empty cells indicate no data available; references listed in section 6.1

Table 14 Potential for PPs to be removed by volatilisation

Group name	Priority pollutants	Reported range of Henry's constant values (atm-m^3/mol)	Number of values	Mean K_h values (atm-m^3/mol)	SD (atm-m^3/mol)	Predicted Volatility level
Benzene and PAHs	benzene	4.48E-03 / 5.72E-03	5	5.35E-03	5.09E-04	H
	naphthalene	4.27E-04 / 7.99E-04	5	5.26E-04	1.55E-04	M/H
	anthracene	1.80E-06 / 6.5E-05	7	4.14E-05	2.31E-05	M
	fluoranthene	6.48E-06 / 1.61E-05	6	1.03E-05	4.08E-06	M
	benzo(a)pyrene	4.57E-07 / 1.13E-06	5	6.24E-07	2.85E-07	L/M
	benzo(g,h,i)perylene	5.30E-08 / 3.31E-07	4	2.00E-07	1.26E-07	L/M
	indeno(1,2,3-cd)pyrene	6.95E-08 / 1.6E-06	4	5.22E-07	7.31E-07	L/M
	benzo(k)fluoranthene	4.36E-07 / 8.29E-07	4	6.49E-07	1.75E-07	L/M
	benzo(b)fluoranthene	5.17E-07 / 1.1E-04	4	3.10E-05	5.36E-05	M
Chlorinated aliphatics	methylene chloride	1.12E-03 / 3.25E-03	4	1.96E-03	9.73E-04	H
	chloroform	1.72E-03 / 4.84E-03	4	3.41E-03	1.05E-03	H
	carbon tetrachloride	2.2E-02 / 3.04E-02	4	2.79E-02	3.51E-03	H
	ethylene chloride	8.85E-04 / 1.0E-03	4	9.96E-04	1.12E-04	M/H
	C10-C13 chloroalkane	1.2E-07 / 7.53E-04	4	1.90E-04	3.75E-04	M/H
Chlorinated alkenes	trichloroethylene	9.85E-03 / 1.09E-02	5	1.04E-02	3.94E-04	H
	tetrachloroethylene	1.51E-02 / 2.14E-02	5	1.81E-02	2.27E-03	H
Chlorobenzenes	1,2,4-trichlorobenzene	1.83E-03 / 1.42E-02	5	1.73E-03	7.35E-04	H
	trichlorobenzenes	1.36E-03 / 3.71E-03	6	2.30E-03	1.09E-03	H
	pentachlorobenzene	7.03E-04 / 9.96E-02	4	3.48E-03	3.60E-03	H
	hexachlorobenzene	4.96E-04 / 1.70E-03	5	1.08E-03	5.23E-04	H
Chlorophenols	pentachlorophenol	2.44E-08 / 3.4E-06	5	1.45E-06	1.57E-06	M
Hexachlorocyclo -hexanes	hexachlorocyclohexane	2.8E-07 / 6.89E-06	4	2.10E-06	3.20E-06	M
	lindane	1.82E-06 / 7.42E-05	6	1.66E-05	2.86E-05	M
DDT and metabolites	para-para-DDT	1.94E-06 / 3.80E-05	5	1.29E-05	1.43E-05	M
	ortho-para-DDT	8.30E-06 / 3.89E-05	4	1.96E-05	1.49E-05	M
	DDD	4E-06 / 4E-05	6	1.30E-05	1.52E-05	M
	DDE	2.1E-05 / 8.05E-05	5	3.64E-05	2.64E-05	M
Phenyl-urea herbicides	diuron	5.04E-04 / 5.1E-05	5	1.07E-05	2.25E-05	M
	isoproturon	1.48E-10 / 4.70E-09	4	1.71E-09	2.16E-09	L
Anilides	alachlor	8.32E-09 / 3.2E-08	6	2.29E-08	8.90E-09	L
Triazines	simazine	9.42E-10 / 3.51E-09	4	1.12E-08	1.90E-08	L
	atrazine	15.2E-09 / 5E-08	5	1.20E-08	2.13E-08	L
Organophosphat e esters	chlorfenvinphos	2.4E-05 / 2.5E-03	4	1.09E-03	1.15E-03	H
	chlorpyrifos	2.31E-08 / 1.1E-05	4	5.80E-06	5.19E-06	M
Other pesticides	alpha-endosulphan	5.47E-06 / 6.08E-05	5	1.89E-05	2.35E-05	M
	endosulphan	1E-05 / 6.5E-05	4	2.45E-05	2.70E-05	M
	hexachlorobutadiene	8.15E-03 / 5.41E-02	5	2.28E-02	1.87E-02	H
	trifluralin	1.03E-04 / 6.21E-03	5	1.34E-03	2.72E-03	H
	endrin	2.84E-07 /7.51E-06	5	5.27E-06	3.01E-06	M
	dieldrin	1E-05 / 3.24E-05	5	1.60E-05	9.38E-06	M
	isodrin	5E-05 / 9.13E-03	4	2.52E-03	4.41E-03	H

Table 14 continued

	aldrin	4.4E-05 / 4.93E-04	5	2.53E-04	1.66E-04	M/H
Endocrine disrupters	octylphenols	7.09E-06 / 8.68E-06	4	7.66E-06	7.56E-07	M
	para-tert-octylphenol	3.33E-07 / 3.49E-05	5	1.02E-05	1.41E-05	M
	nonylphenols	2.45E-09 / 3.7E-05	7	1.35E-05	1.52E-05	M
	4-para-nonylphenol	7.09E-06 / 3.40E-05	2	2.05E-05	1.90E-05	M
	DEHP	1.6E-08 / 1.71E-05	5	3.52E-06	7.59E-06	M
	pentabromodiphenylether	6.08E-07 / 8.71E-06	5	3.54E-06	3.69E-06	M
Organometallic compounds	tributyltin cation					H
	tributyltin compounds	1.52E+00	1	1.52E+00		H
	tributyltin chloride	7.62E-02	1	7.62E-02		H
	tributyltin methacrylate	4.80E-02	1	4.80E-02		H
	bis(tributyltin) oxide	3.02E-07	1	3.02E-07		L/M
	tetra-N-Butyltin	6.04E+00	1	6.04E+00		H
	tetramethyl lead	6.10E-01	1	6.10E-01		H
	ethyltrimethyllead	3.53E-01	1	3.53E-01		H
	diethyldimethyllead	4.68E-01	1	4.68E-01		H
	methyltriethyllead	6.22E-01	1	6.22E-01		H
	tetraethyl lead	5.68E-01 / 6.81E-01	2	6.25E-01	7.99E-02	H
	methylmercury					H
	dimethylmercury	2.13E-03	1	2.13E-03		H
	diethylmercury	3.76E-03	1	3.76E-03		H
	phenylmercuric acetate	5.66E-10	1	5.66E-10		L
Inorganic metal compounds	cadmium compounds	Not applicable				
	lead compounds					
	mercury compounds					
	nickel compounds					

Key: Kh range classification: High (H) > 1E-3; Medium/High (M/H) 1E-4 - 1E-3; Medium (M) 1E-6 - E-4; Low/Medium (L/M) 1E-7 - 1E-6; Low (L) < 1E-7; empty cells indicate no data available; references listed in section 6.1

Table 15 Potential for pollutants to be removed by plant uptake

Group name	Priority pollutants	Reported range of K_{ow} values (L/g)	Number of values	Mean K_{ow} value (L/g)	SD (L/g)	Predicted level of bioaccumulation
Benzene and PAHs	benzene	135-135	8	135		L
	naphthalene	1,023-3,467	6	2,046	658	L/M
	anthracene	28,184-35,481	7	31,572	3,390	M
	fluoranthene	89,125-316,228	6	170,096	77,227	M/H
	benzo(a)pyrene	933,254-1,348,963	5	1,203,200	183,025	H
	benzo(g,h,i)perylene	3,160,000-6,025,596	6	4,250,333	1,109,241	H
	indeno(1,2,3-cd)pyrene	1,995,262-12,589,254	8	4,990,125	3,209,703	H
	benzo(k)fluoranthene	1,000,000-6,918,310	8	2,256,250	2,014,946	H
	benzo(b)fluoranthene	602,560-3,715,352	9	1,731,196	1,075,450	H
Chlorinated aliphatics	methylene chloride	17.8-17.8	5	17.8	0	L
	chloroform	83.2-93.3	5	91.3	4.5	L
	carbon tetrachloride	398-676	6	563.4	132.3	L/M
	ethylene chloride	29.5-30.2	6	30.1	0.3	L
	C10-C13 chloroalkane	24,547-1,000,000	14	451,596.0	406,306	M/H
Chlorinated alkenes	trichloroethylene	162.2-512.9	11	321.7	137.8	L
	tetrachloroethylene	338.8-2,512	10	1,486	1,088	L/M
Chlorobenzenes	1,2,4-trichlorobenzene	7,943-15,849	9	11,793	2,767	M
	trichlorobenzenes	7,943-15,849	9	11,793	2,767	M
	pentachlorobenzene	63,096-181,970	9	134,360	36,371	M/H
	hexachlorobenzene	147,911-776,247	10	401,476	271,970	M/H
Chlorophenols	pentachlorophenol	100,000-141,254	7	125,823	14,345	M/H
Hexachlorocyclo-hexanes	hexachlorocyclohexane	5,012-18,197	9	9,396	4,447	M
	lindane	4,074-6,310	8	5,262	715	M
DDT and metabolites	para-para-DDT	912,011-3,338,442	6	2,112,789	1,093,320	H
	ortho-para-DDT	6,165,950	1	6,165,950		H
	DDD	562,341-1,258,925	6	785,366	486,482	M/H
	DDE	489,779-5,754,339	7	2,816,141	2,362,989	H
Phenyl-urea herbicides	diuron	398-479	4	418.3	41.0	L
	isoproturon	316-741	3	457.7	245.4	L
Anilides	alachlor	427-3,388	10	1,687	1,260	L/M
Triazines	simazine	87.1-182.0	4	143	40	L
	atrazine	218.8-562.3	7	425	109	L
Organophosphate esters	chlorfenvinphos	4,786-14,125	5	7,811	3,634	M
	chlorpyrifos	16,982-128,825	6	76,944	46,642	M
Other pesticides	alpha-endosulphan	3,311-12,589	4	7,243	3,879	M
	endosulphan	3,981-12,589	5	8,018	4,315	M
	hexachlorobutadiene	19,953-79,433	7	56,743	18,188	M
	trifluralin	117,490-218,776	6	168,133	55,477	M/H
	endrin	36,308-398,107	9	144,517	110,069	M/H
	dieldrin	41,687-316,228	7	232,657	92,006	M/H

Table 15 continued

	isodrin	3,162,278-5,623,413	2	4,392,846	1,740,285	H
	aldrin	199,526-3,162,278	9	2,257,279	1,183,207	H
Endocrine disrupters	octylphenols	12,589	1	12,589		M
	para-tert-octylphenol	9,120-199,526	5	88,800	97,402	M
	nonylphenols	15,849-575,440	5	237,178	281,360	M/H
	4-para-nonylphenol	15,849-575,440	5	237,178	281,360	M/H
	DEHP	74,131-39,810,717	7	17,107,756	17,875,918	H
	pentabromodiphenylether	3,715,352-79,432,823	6	32,675,830	35,708,421	H
Organometallic compounds	tributyltin cation	1,549-12,589	5	8,113	4,637	M
	tributyltin compounds	1,549-12,589	5	8,113	4,637	M
	tributyltin chloride	158.4-57,544	2	28,851	40,578	
	tributyltin methacrylate	13,804	1	13,804		M
	bis(tributyltin) oxide	1,585-11,220	5	6,339	3,452	M
	tetra-N-Butyltin	234,422,000	1	234,422,000		H
	tetramethyl lead	933.3-4,920	3	2,426	2,173	L/M
	ethyltrimethyllead	7,586	1	7,586		M
	diethyldimethyllead	10,965	1	10,965		M
	methyltriethyllead	24,547	1	24,547		M
	tetraethyl lead	14,125-20,893	3	18,637	3,908	M
	methylmercury	1.99-346.7	3	132.9	186.7	L
	dimethylmercury	389.0	1	389.0		L
	diethylmercury	40.74	1	40.74		L
	phenylmercuric acetate	5.13	1	5.13		L
Inorganic metal compounds	cadmium compounds					L
	lead compounds					L
	mercury compounds					
	nickel compounds					L

Key: Kow range classification: Low (L) <500; Low/Medium (L/M) 500-5,000; Medium (M) 5,000-100,000; Medium/High (M/H) 100,000-1,000,000; High (H) >1,000,000; empty cells in the 3rd column indicate no data available; references listed in section 6.1

Table 16 Potential for pollutants to be removed by photolysis

Group name	Priority pollutants	Reported range of photodegradation half-life (h)	Number of values	Mean photo-degradation half-life (h)	SD (h)	Potential for removal
Benzene and PAHs	benzene	240 - 410	4	351.2	96.3	L
	naphthalene	25 - 550	5	51.2	30.3	M
	anthracene	0.5 - 5	6	2.4	2.4	H
	fluoranthene	21-200	6	87.0	75.6	M
	benzo(a)pyrene	0.7 - 8.0	5	2.4	3.2	H
	benzo(g,h,i)perylene	3 - 29	3	15.3	12.3	H
	indeno(1,2,3-cd)pyrene	0.8 - 62	7	18.4	24.0	H
	benzo(k)fluoranthene	0.9 - 35	15	11.3	10.9	H
	benzo(b)fluoranthene	0.5 - 21	6	8.2	7.4	H
Chlorinated aliphatics	methylene chloride					L
	chloroform					L
	carbon tetrachloride					L
	ethylene chloride					L
	C10-C13 chloroalkane					L
Chlorinated alkenes	trichloroethylene	2400-7704	2	5052.0	3750.5	L
	tetrachloroethylene					L
Chlorobenzenes	1,2,4-trichlorobenzene					L
	trichlorobenzenes					L
	pentachlorobenzene					L
	hexachlorobenzene	144-1680	2	912.0	1086.1	L
Chlorophenols	pentachlorophenol	0.2 - 1	10	0.5	0.3	H
Hexachlorocyclo -hexanes	hexachlorocyclohexane					
	lindane	169-1791	5	1168	676	L
DDT and metabolites	para-para-DDT					L
	ortho-para-DDT					L
	DDD					L
	DDE	15-72	6	24	19	M/H
Phenyl-urea herbicides	diuron	600 - 1732	5	955	480	L
	isoproturon	1500	1	1500		L
Anilides	alachlor	6 - 360	4	183	204	L
Triazines	simazine	108 - 576	4	411	208	L
	atrazine	7.0 - 346	8	69	96	
Organophosphat e esters	chlorfenvinphos					L
	chlorpyrifos	53-1032	7	621	338	L
Other pesticides	alpha-endosulphan					L
	endosulphan	84 - 804	5	384	290	L
	hexachlorobutadiene	72 - 720	7	206	232	L
	trifluralin	0.5 - 29	6	8	11	H
	endrin					L
	dieldrin					L
	isodrin					L

Table 16 continued

	aldrin	96 - 672	7	267	200	L
Endocrine disrupters	octylphenols					L
	para-tert-octylphenol					L
	nonylphenols	10 - 15	2	13	3	H
	4-para-nonylphenol	10 - 15	0	13	3	H
	DEHP					L
	pentabromodiphenylether	72 - 2160	5	533	911	L
Organometallic compounds	tributyltin cation					
	tributyltin compounds					
	tributyltin chloride	2136	1	2136		
	tributyltin methacrylate					
	bis(tributyltin) oxide	20-432	4	120.1	208	
	tetra-N-Butyltin					
	tetramethyl lead	192	1	192		
	ethyltrimethyllead	192	1	192		
	diethyldimethyllead	192	1	192		
	methyltriethyllead	192	1	192		
	tetraethyl lead	10-456	4	168	210	
	methylmercury					
	dimethylmercury					
	diethylmercury					
	phenylmercuric acetate	16-39	2	27.5	16.3	M/H
Inorganic metal compounds	cadmium compounds	Not applicable				
	lead compounds					
	mercury compounds					
	nickel compounds					

Key: T1/2 life (h) range classification: Low (L) > 120h; Low/Medium (L/M) 96 - 120h Medium (M) 48 - 96h; Medium/High (M/H) 24 - 48h; High (H) < 24 h; empty cells indicate no data available; references listed in section 6.1

Table 17 Potential for pollutants to be removed by microbial degradation

Group name	Priority pollutants	Aerobic degradation				Anaerobic degradation				Potential for removal		
		Reported range in bio-degradation half life (d)	Number of values	Mean biodegradation half-life (d)	SD (d)	Reported range in biodegradation half life (d)	Number of values	Mean biodegradation half-life (d)	SD (d)	Aero*	An**	Overall
Benzene and PAHs	benzene	2-28	8	11	9.18	28-720	5	249	275	H	L	M
	naphthalene	1-31	21	12	10.26	96	1	96		H	M	M/H
	anthracene	3.3-210	17	80	62.9					M/H		L/M
	fluoranthene	2-440	18	153	139.4	560-5475	5	2362	1845	M	L	L/M
	benzo(a)pyrene	54-830	11	327	253.8	228-2117	2	1173	1336	L	L	L
	benzo(g,h,i)perylene	173-865	10	522	193.9	590-2600	6	2311	1779	L	L	L
	indeno(1,2,3-cd)pyrene	58-790	15	335	278.1					L		L
	benzo(k)fluoranthene	65-1400	15	451	409	1140-8560	6	3958	2659	L	L	L
	benzo(b)fluoranthene	87-610	7	286	174.6	2190-5860	4	4291	1703	L	L	L
Chlorinated aliphatics	methylene chloride	1-704	6	333	306	11-108	5	50.8	52.3	L	M/H	M
	chloroform	2-180	4	92	102.2	2-37	11	15	11	M	H	M/H
	carbon tetrachloride	5-365	3	184	180	3-28	6	10.8	9.6	L	H	M
	ethylene chloride	9-365	4	132	160	52-460	8	242	167	M	L	L/M
	C10-C13 chloroalkane											
Chlorinated alkenes	trichloroethylene	31-730	10	261	213.1	58-1099	19	412	327	L	L	L
	tetrachloroethylene	31-180	3	81	85.7	87-3647	7	1167	1420	M	L	L/M
Chlorobenzenes	1,2,4-trichlorobenzene	2.1-150	5	52	57.6	110-200	2	155	64	M/H	L/M	M
	trichlorobenzenes	194-1380	10	723	513	17-776	4	333	324	L	L	L
	pentachlorobenzene	2.1-150	10	43	40.2	23-200	4	93.5	80.3	M/H	M	M
	hexachlorobenzene	41-4161	11	1676	1412	21-3869	6	2296	1818	L	L	L
Chlorophenols	pentachlorophenol	10-48	8	24	13.23	17.5 - 80	3	43.8	32.4	H	M/H	M/H
Hexachlorocyclo-hexanes	hexachlorocyclohexane	23.4-184	10	84	49.3	48	1	48		M	M/H	M
	lindane	4-365	12	126	131.6	0.3-31	6	11.9	11.4	M	H	M/H
DDT and metabolites	para-para-DDT	730-10950	13	4592	3028					L		L
	ortho-para-DDT	986	1	986						L		L
	DDD	548-8030	5	2730	3007	31-160	2	95.5	91.2	L	M	L/M
	DDE	536-5800	5	2761	2783					L		
Phenyl-urea herbicides	diuron	70-372	4	236	140.1	17-995	3	356	554	L	L	L
	isoproturon	6.5-61	8	30	19.24	4-15	2	9.8	7.8	H	H	H
Anilides	alachlor	7-808	6	224	339	5-100	2	52.5	67.2	L	M/H	M
Triazines	simazine	30-110	7	69	30.2	58-77	4	69	8	M/H	M/H	M/H
	atrazine	30-231	8	102	69.4	77-289	4	172	76	M	L/M	M
Organophosphate esters	chlorfenvinphos	4-161	16	62	54.7	15-135.5	3	69.5	61.1	M/H	M/H	M/H
	chlorpyrifos	1.2-34	13	16	11.6					H		
Other pesticides	alpha-endosulphan	8-60	5	31	26.4	8-150	2	79	100	H	M/H	M/H
	endosulphan	2-42	9	23	13.94	8-150	3	102	81	H	M	M/H

Table 17 continued

	hexachlorobutadiene	28-300	4	97	135.3					M		M
	trifluralin	21-405	10	152	113.7	22-211	4	82.3	87.1	L/M	M	M
	endrin	1460-5110	6	2968	1489					L		
	dieldrin	870-7300	6	2306	2526					L		
	isodrin	183-2190	3	913	1110					L		
	aldrin	20-110	7	54	36.6					M/H		
Endocrine disrupters	octylphenols	5-50	3	21	25.4					H		
	para-tert-octylphenol	5	1	5						H		
	nonylphenols	5-20	8	11	5.66	46-63	2	54.5	12	H	M/H	M/H
	4-para-nonylphenol											
	DEHP	3-54	14	22	13.94	21-389	6	175	169	H	L/M	M
	pentabromodiphenylether	150-600	3	300	260					L		L
Organometallic compounds	tributyltin cation											
	tributyltin compounds	6-183	12	92	62.7	46- 1095	4	650	438	M	L	L/M
	tributyltin chloride											
	tributyltin methacrylate											
	bis(tributyltin) oxide											
	tetra-N-Butyltin											
	tetramethyl lead											
	ethyltrimethyllead											NA
	diethyldimethyllead											
	methyltriethyllead											
	tetraethyl lead											
	methylmercury											
	dimethylmercury											
	diethylmercury											
	phenylmercuric acetate											
Inorganic metal compounds	cadmium compounds									NA	L	L
	lead compounds									NA	L	L
	mercury compounds											
	nickel compounds									NA	L	L

Key: $T^{1}/_{2}$ (days) range classification: Low (L) >180 days; L/M = 130-180 days; M = 80-130 days; M/H = 30-80 days; H = <30 days; * = aerobic degradation; ** = anaerobic degradation; empty cells indicate no data available

The data presented in Tables 11-17 includes field, laboratory and theoretical data sourced from a wide range of on-line databases, peer-reviewed publications and reports. The aim was to collect a minimum of 6 values per pollutant per characteristic, however this was not always possible. Data relating to the behaviour of PPs in sewage or sewage treatment plants were not included, as, due to the different characteristics of wastewater, these values were considered not to be applicable to urban stormwater runoff. In some instances, where data were not available, a decision on the comparative removal potential of a specific pollutant by a particular process was made based on the characteristics of other group members, if appropriate (i.e. the use of expert judgement).

It was possible to compile complete data sets for 52 of the 68 pollutants identified in Table 10. These 52 pollutants include 32 of the 33 priority substances (the exception being C10-C13 chloroalkanes for which it was not possible to source any biodegradation data) and all 8 of ‘other’ pollutants. The remaining substances are various tributyltin, lead compounds and mercury compounds.

3.1.3 Development of the pollutant removal potentials

Completion of the procedures outlined in Sections 3.1.1. and 3.1.2 results in the generation of two sets of data; the first relating to the relative importance of identified removal processes occurring within a BMP and the second relating to the relative susceptibility of a range of pollutants to be removed by these processes. These two data sets have been combined through the adoption of a risk-rating approach, involving the conversion of the allocated 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 are allocated to low/medium and medium/high classifications as appropriate. The potential of a particular pollutant (e.g. benzene) to be removed by a particular process (e.g. settling) can then be represented by the combination of the derived numeric values representing its ability to be removed by this process with the corresponding value representing the importance of settling within the chosen BMP (e.g. infiltration trench) (Tables 4, 13 and 18) using either addition or multiplication. In the development of this approach, multiplication is used to combine values as this method highlights the 'extremes' (i.e. the best and worst values) providing a 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, for example, the removal potential of benzene in an infiltration trench, as displayed in Table 18. 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 benzene to be generated (see Table 19).

Table 18 Potential for the removal of benzene by an infiltration trench

Removal process	Significance of process to BMP	Significance of process to pollutant	Combined value
Adsorption to substrate	2.5	1.5	3.75
Settling	1.5	2	3
Microbial degradation	2	2	4
Filtration	2.5	2	5
Volatilisation	0.5*	3	1.5
Photolysis	NA	1	0
Plant uptake	1	1	1
		Overall value	**18.25**

- incorporates a weighting of 0.5 (see Section 3.1.3 for further information)

Table 19 BMP order of preference for the removal of benzene in different BMPs

	Overall values	Ranked position
Infiltration basin	26.75	1
Constructed wetland (SSF)	24	2
Constructed wetland (SF)	20.5	3
Porous paving	20	4
Extended detention basin	19.75	5
Retention pond	19	6
Swale	18.75	7
Infiltration trench	18.25	8.5
Soakaway	18.25	8.5
Detention basin	17.75	10
Filter drain	17.25	11
Filter strip	16	12
Lagoon	15	13
Porous asphalt	14.25	14
Settlement tank	10.5	15

4 Results of the application of the ScorePP BMP pollutant removal methodology

4.1 BMP orders of preference by pollutant group

This procedure has been applied to all 52 pollutants, and an overview of the ranked results by pollutant group (as set out in Table 10) is presented in Figure 2 (for full results see the Appendix). In Figure 2, a ranked position of 1 identifies the BMP possessing the highest removal potential for the identified pollutant or pollutant group from the water phase, with BMPs offering a comparatively lower potential for removal from the water phase listed sequentially. A key point in considering this pollutant specific 'order of preference' is that the values upon which the rankings are based are ordinal and not numeric; i.e. they are used purely to order the BMPs relative to one another and do not have any quantitative meaning in terms of actual removal performance.

Data presented in Figure 2 indicates that, irrespective of pollutant group, infiltration basins and sub-surface flow (SSF) constructed wetlands offer the greatest potential for removal for all the pollutants evaluated. These two systems also consistently ranked most highly for the removal the stormwater priority pollutants identified and assessed during the EU FP5 funded DayWater project (e.g. Scholes *et al.*, 2007), clearly supporting their use for the improvement of water quality. This consistently high potential for removal is understood to be associated with the fact that, unlike the other BMP systems evaluated, both infiltration basins and SSF constructed wetlands offer considerable potential for all the direct and indirect processes to occur. However, through the orders of preference generated, variations in the comparative potentials for different BMPs to remove various pollutant groups can be seen. For example, the data for porous paving indicates that this BMP offers a comparatively greater potential for the removal of triazines and phenyl urea herbicides than for chlorinated aliphatics or metals. This greater potential for the removal of the former compounds is understood to be related to the fact that porous paving offers relatively high potentials for processes such as adsorption and filtration to occur. At the lower end of the derived BMP order of preference, porous asphalt and settlement tanks consistently offer the lowest potential for the removal of all the pollutant groups evaluated. Key factors in this are that both systems do not offer the potential for all of the biological, chemical and physical removal processes to occur, and where a process does occur, it is comparatively less important. For example, settlement tanks offer no potential for processes such as plant uptake and filtration to occur, with their generally smaller size (in comparison to BMPs such as retention ponds and detention basins) offering a relatively lower potential for processes such as volatilisation and photolysis to occur. In contrast, although porous paving offers a high potential for filtration to occur (involving the passage of stormwater through a substrate with a characteristically small pore size), as a surfacing material it does not detain stormwater for any extended period of time and therefore offers only low potential for further processes such as settling and volatilisation to occur.

4.2 BMP orders of preference for selected metals

To illustrate the use of the methodology in relation to metals, the BMP orders of preference for the removal of 3 organometallic compounds (tributyltin, tetramethyl lead and methylmercury) and 2 inorganic pollutants (Ni and Cd) are presented in Figure 3. There are some clear variations within the BMP orders of preference generated for different metals, and this is understood to be a function of the differing biological and physico-chemical characteristics of the various metals being assessed. For example, the 3 organometallic compounds, which are susceptible to processes such as volatilization and photolysis, show a greater potential for removal in systems which facilitate these processes (e.g. extended detention basins) in comparison to the potential for these same systems to remove inorganic Ni and Cd compounds which are not found in the environment in a methylated form.

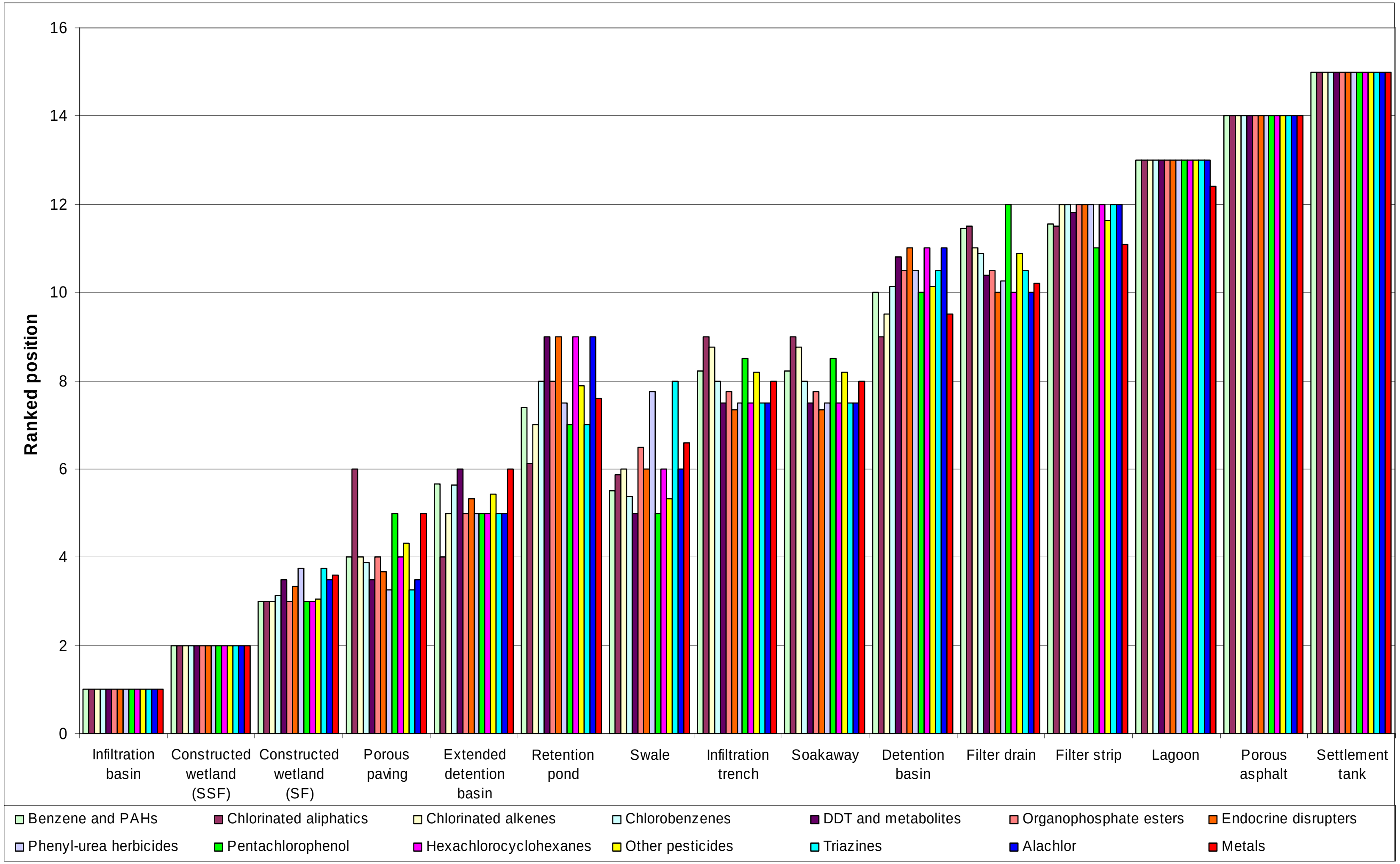

Figure 2 Overview of the BMP orders of preference for the removal of identified pollutants (by group)

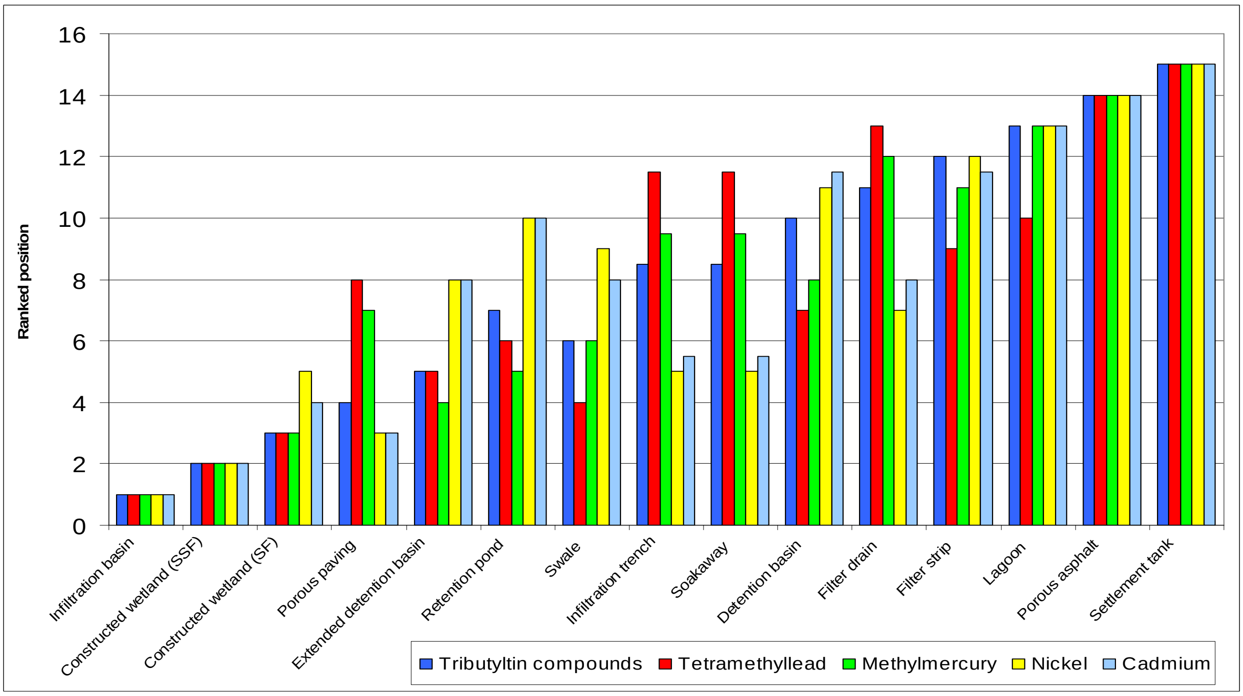

Figure 3 BMP order of preference for the removal of various metals

4.3 BMP orders of preference for the removal of selected organics

Figure 4 presents the BMP orders of preference for benzene and 8 PAHs (naphthalene, anthracene, fluoranthene, benzo(a)pyrene, benzo(g,h,i)perylene, indeno(1,2,3-cd)pyrene, benzo(k)fluoranthene, benzo(b)fluoranthene). Unlike the data for metals presented in Figure 3, it is interesting to note that there appears to be little variation between pollutants in relation to their potential to be removed by a particular BMP, despite the fact that many of the pollutants are known to have differing physico-chemical characteristics.

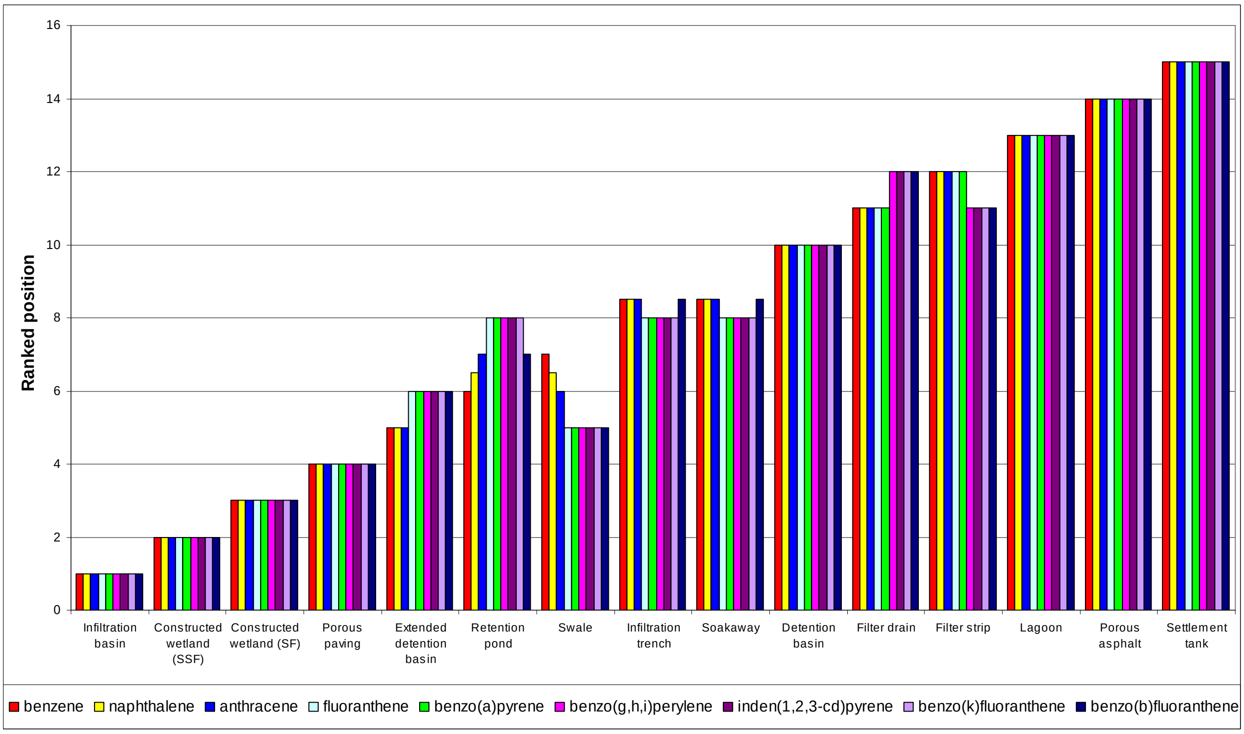

Figure 4 BMP order of preference for the removal of benzene and PAHs

This apparently contradictory behaviour of metals and aromatic hydrocarbons, where differing physico-chemical characteristics of metals appear to result in variations in BMP order of preference but the differing behaviours of organics do not, can be understood through a closer examination of the methodology used to combine the two sets of data generated in the initial stages of the process (see Sections 3.1.1 and 3.1.2), and set out in Tables 20 and 21 in relation to benzene and benzo (b) fluoranthene, respectively, as examples. In both Tables, the 2[nd] column contains data which indicates the susceptibility of each pollutant to the associated removal process listed in the preceding column. Columns 3, 4 and 5 present data indicating the potential for the associated removal process to occur within infiltration basins, swales and settlement tanks (selected to represent the ‘top, middle and bottom’ of BMP orders of preference generated for both pollutants) multiplied by the pollutant susceptibility data (as presented in column 2). The value given in bold at the bottom of columns 3, 4 and 5, are the single overall unit values representing the potential for the pollutant to be removed by infiltration basins, swales and settlement tanks, respectively.

Comparison of the data in columns 1 of Tables 20 and 21, clearly reflect the differences between the susceptibility of 2 pollutants to the removal processes, indicating that benzo (b) fluoranthene generally has a comparatively higher susceptibility to removal by the listed removal processes than benzene (the exceptions being microbial degradation and volatilisation). This comparatively greater susceptibility to removal is also reflected in the higher single overall unit values representing the potential for benzo (b) fluoranthene to be removed by each of the identified systems in comparison to the values associated with the potential for benzene to be removed by the same systems. It hence becomes apparent that in calculating the single overall values representing differing potential for removal of various pollutants by different BMPs, the susceptibility of different pollutants to different processes is assessed. However, it can also be seen that on ranking the data on a per pollutant basis, the BMP orders of preference will be the same for both pollutants. As the aim of this approach is to compare the potential for different BMPs to remove a particular pollutant, rather than compare the potential for different pollutants to be removed by the same BMP, the fact that this information is not initially visible is not an issue.

Table 20 Potentials for the removal of benzene by an infiltration basin, swale and settlement tank

Removal process	Benzene	Infiltration basin	Swale	Settlement tank
Adsorption to substrate	1.5	4.5	3.0	1.5
Settling	2.0	6.0	3.0	5.0
Microbial degradation	2.0	6.0	3.0	2.0
Filtration	2.0	5.0	4.0	0.0
Volatilisation	3.0	3.0	3.0	1.5
Photolysis	1.0	0.5	0.8	0.5
Plant uptake	1.0	1.5	2.0	0.0
Overall values		**26.8**	**18.8**	**10.5**

Table 21 Potentials for the removal of benzo (b) fluoranthene by an infiltration basin, swale and settlement tank

Removal process	Benzo (b) fluoranthene	Infiltration basin	Swale	Settlement tank
Adsorption to substrate	3.0	9.0	6.0	3.0
Settling	3.0	9.0	4.5	7.5
Microbial degradation	1.0	3.0	1.5	1.0
Filtration	3.0	7.5	6.0	0.0
Volatilisation	2.0	2.0	2.0	1.0
Photolysis	3.0	2.3	2.3	1.5
Plant uptake	3.0	4.5	6.0	0.0
Overall values		**37.25**	**26.25**	**14**

4.4 Overview of the ranges in ranked positions of BMPs across all pollutants assessed

Table 22 presents the maximum and minimum ranked position for each BMP across all of the pollutants assessed. This indicates that some BMPs are consistent performers (i.e. no variation in their ranked position) up to a maximum range in ranked position of 6.5 places, indicating that a systems pollutant removal potential varies depending on the bio-physico-chemical properties of the pollutant being assessed.

In relation to the 52 pollutants assessed within ScorePP, 4 of the 15 BMPs are identified as 'consistent performers'; infiltration basins and SSF constructed wetlands consistently appear at the top of the BMP orders of preference generated, supporting their use in removing pollutants from the water column. In contrast, porous asphalt and settlement tanks consistently offer the lowest potential for pollutant removal, irrespective of pollutant type, suggesting these BMPs would make a comparatively lower contribution to meeting water quality objectives.

Table 22 Maximum and minimum ranked position for each BMP across all pollutants assessed

BMP	Range of ranked positions
Infiltration basin	1
Constructed wetland (SSF)	2
Constructed wetland (SF)	3 – 5
Porous paving	3 – 8
Extended detention basin	4 – 8
Retention pond	5 – 10
Swale	4 – 9
Infiltration trench	5 – 11.5
Soakaway	5 – 11.5
Detention basin	7 – 11.5
Filter drain	7 – 13
Filter strip	9 – 12
Lagoon	10 – 13
Porous asphalt	14
Settlement tank	15

Within the orders of preference generated, 11 of the 15 BMPs show variation in their ranked positions suggesting that some BMPs offer a greater potential to remove certain pollutants in comparison to others. For example, the ranked position of extended detention basins ranges from a highest ranked position of 4^{th} in an order of preference (e.g. for the chlorinated aliphatics methylene chloride and carbon tetrachloride) to a lowest ranked position of 8^{th} (for the metals Ni and Cd). This range in ranked position reflects differences in the physico-chemical characteristics of these pollutants (for example, methylene chloride are highly volatile with a relatively low potential to adsorb in contrast to the metals which have a greater potential for removal through adsorption and filtration but are not susceptible to e.g. volatilization (see Tables 13 and 14) together with the design or components of various BMP types which differentially facilitate or negate the potential for identified processes to occur (see Tables 3-10).

4.5 Comparison of the ScorePP methodology with field data

Previous work by Scholes *et al.*, (2007) reported on the difficulties of 'ground-truthing' the theoretically-generated orders of preference with field performance data due to the current lack of monitoring studies, to the extent that TSS was the only pollutant for which 5 independent data sets could be identified for a realistic number of BMPs throughout Europe and North America. Recent attempts to up-date this work have found little, if any data, on the behaviour of many of the WFD priority pollutants within the different types of BMPs. However, an exception to this is a paper by Matamoros *et al.* (2007) who reported on the removal of 8 priority pollutants by a pilot-scale horizontal subsurface flow constructed wetland. Table 23 presents the measured removal efficiencies (% removal) from this study and shows how the data can be ranked to indicate the relative potential for each pollutant to be removed by a sub-surface flow constructed wetland. This is directly compared with the ranjking derived using the ScorePP methodology to predict the relative potential for the selected pollutants to be removed by the same treatment system (final column of Table 23).

Inspection of the two ranking sets (columns 3 and 4 in Table 23) suggests clear similarities between the field and theoretically-derived orders of preference, the notable exception being lindane. Field data reports that the removal of lindane is greater than pentachlorophenol, which is followed by chlorpyrifos, in contrast to the ScorePP methodology which for these three PPs predicts the greatest removal potential for pentachlorophenol followed by chlorpyrifos and then lindane. The theoretical approach involves the use of physico-chemical data sourced from a wide variety of field and laboratory-based studies (see Tables 11-17). Inspection of the physico-chemical data used to assess the susceptibilities of lindane, chlorpyrifos and pentachlorophenol indicates that similar removal potentials exist for most processes but with differences in regard to microbial degradation, photolysis and plant uptake resulting in the relatively lower potential for the removal of lindane in comparison to the other two compounds. It should be noted that the ScorePP methodology incorporates the use of laboratory data which may not be fully representative of field conditions and therefore the urgent need for the collection of further field data is again highlighted.

Table 23 Overview of field and theoretically-derived data on the removal of selected priority pollutants by a sub-surface flow constructed wetland

Priority pollutant	Matamoros et al., (2007)		Score PP methodology
	Removal efficiency (%)	Ranked data	Ranked data
Pentachlorobenzene	>99	2	1
Endosulphan	>99	2	2.5
Lindane	>99	2	5
Pentachlorophenol	94	4	2.5
Chlorpyrifos	83	5	4
Alachlor	80	6	7
Simazine	25	7	6
Diuron	0	8	8

Despite small differences in the generated orders of ranking preference, the strength of the overall correlation between the field and theoretically-derived results can be assessed using Spearman's rank correlation to test the null hypothesis of no correlation between ranked data sets. The null hypothesis is clearly rejected ($r = 0.815$; $p<0.05$) indicating a high level of correlation between the field and theoretically derived data sets and providing support for the robustness of the ScorePP approach and methodology.

5 Conclusions

The development of a systematic approach to comparatively assessing the potential for BMPs to remove the WFD priority pollutants (together with a range of further related compounds and metabolites) is fully described. This methodology is primarily based on an assessment of the primary unit operating processes known to occur within BMPs in relation to both their relative importance within BMPs (based on knowledge of a system's performance) and their potential to remove a particular pollutant (based on a pollutant's biological and physico-chemical properties). It incorporates the use of quantitative and qualitative data, together with the use of expert judgement where data was not available.

The results of the application of this innovative approach indicate that, irrespective of pollutant type, infiltration basins and SSF constructed wetlands offer the greatest potential for the removal for all the pollutants evaluated. This consistently high potential for removal is understood to be associated with the fact that, unlike the other systems, both infiltration basins and SSF constructed wetlands offer considerable potential for all the direct and indirect processes to occur, providing strong support for their use in limiting the release of priority pollutants to receiving waters.

Key to the correct interpretation and use of information generated by this methodology is appreciation of the fact that although this approach indicates one BMP offers greater potential for removal of a particular pollutant in comparison to another, it gives no indication of how important this difference is; the data is ordinal and not quantitative. However, bearing this caveat in mind, the development of pollutant-specific orders of preference for BMPs can provide useful support to urban stormwater managers, who, irrespective of the limited amount of monitoring data available, are currently required to make decisions and adopt urban drainage schemes to achieve compliance with the EU WFD. This support is specifically related to priority pollutant control, and it is suggested that its application could also inform the use of more sophisticated modelling procedures, such as MUSIC (CRC, 2006) and SWMM (US EPA 2006), which require users to partially or entirely express their own judgement in assessing the differential pollutant treatment capabilities of BMPs.

Whilst having been developed to support stormwater practitioners in making decisions in the current circumstances of limited data availability, as further field data becomes available it will be possible to calibrate and refine the described systematic approach using a more robust field dataset, 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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7 Appendix

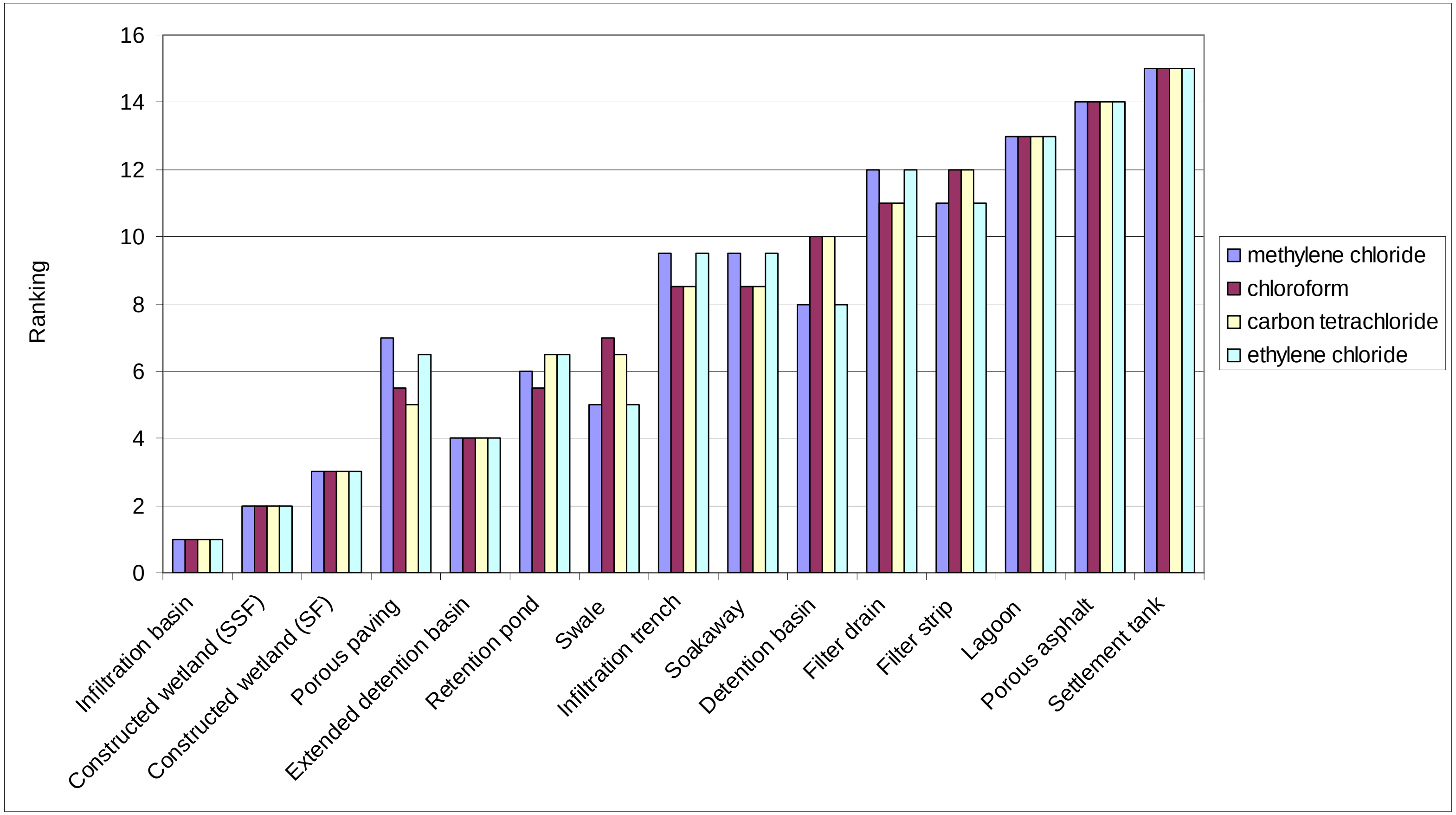

Figure 5 BMP order of preference for the removal of chlorinated aliphatics

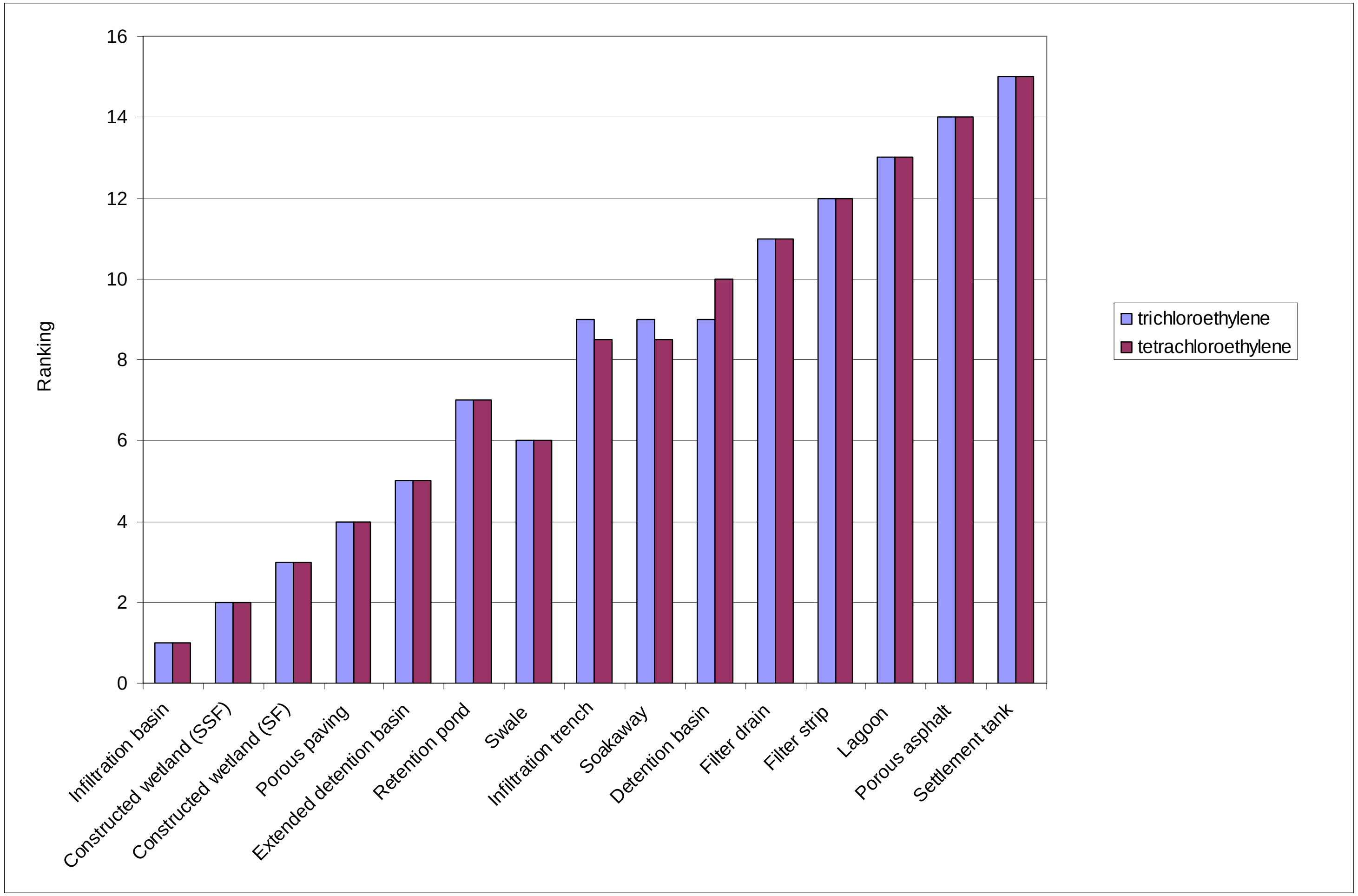

Figure 6 BMP order of preference for the removal of chlorinated alkenes

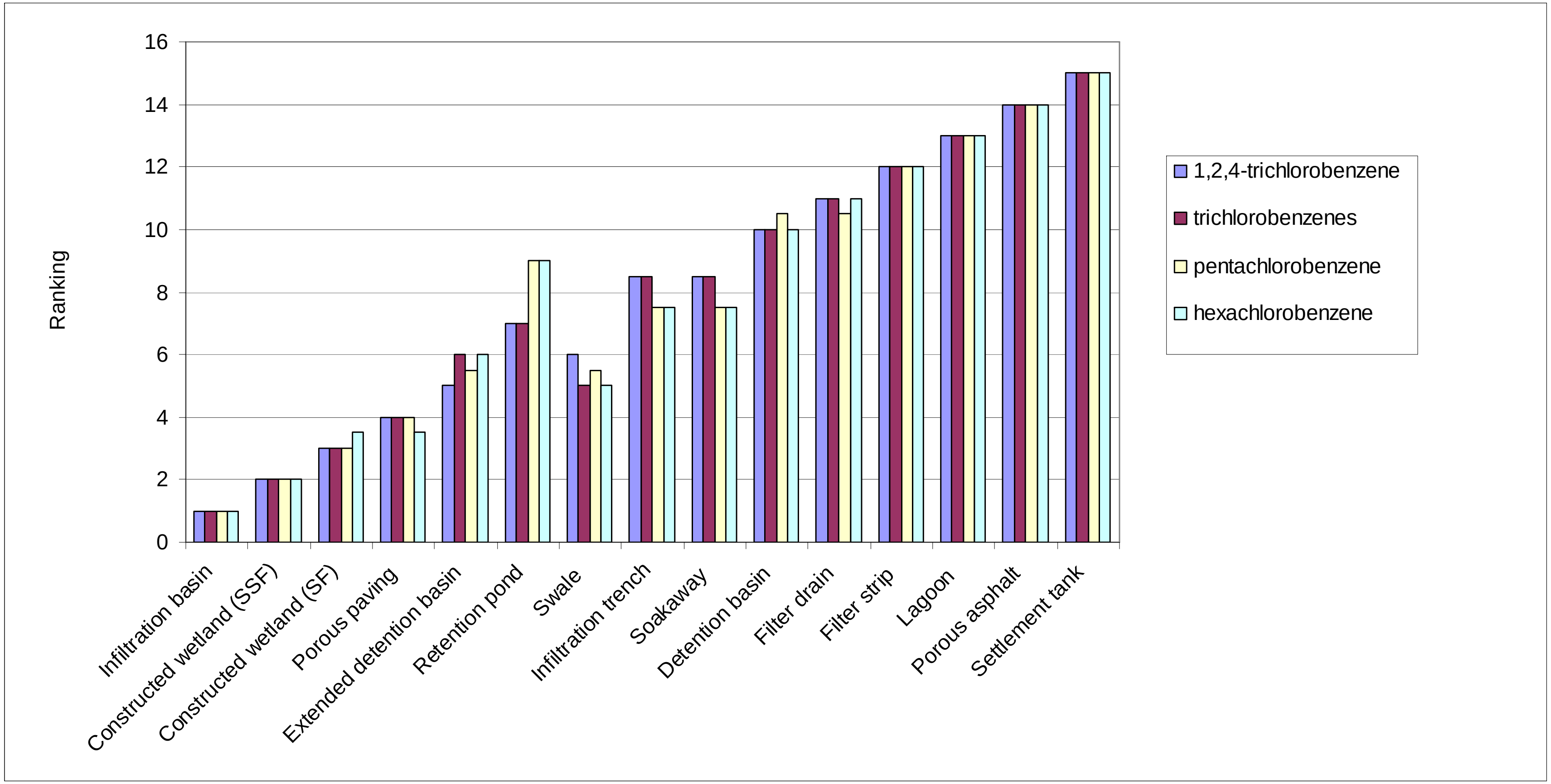

Figure 7 BMP order of preference for the removal of chlorobenzenes

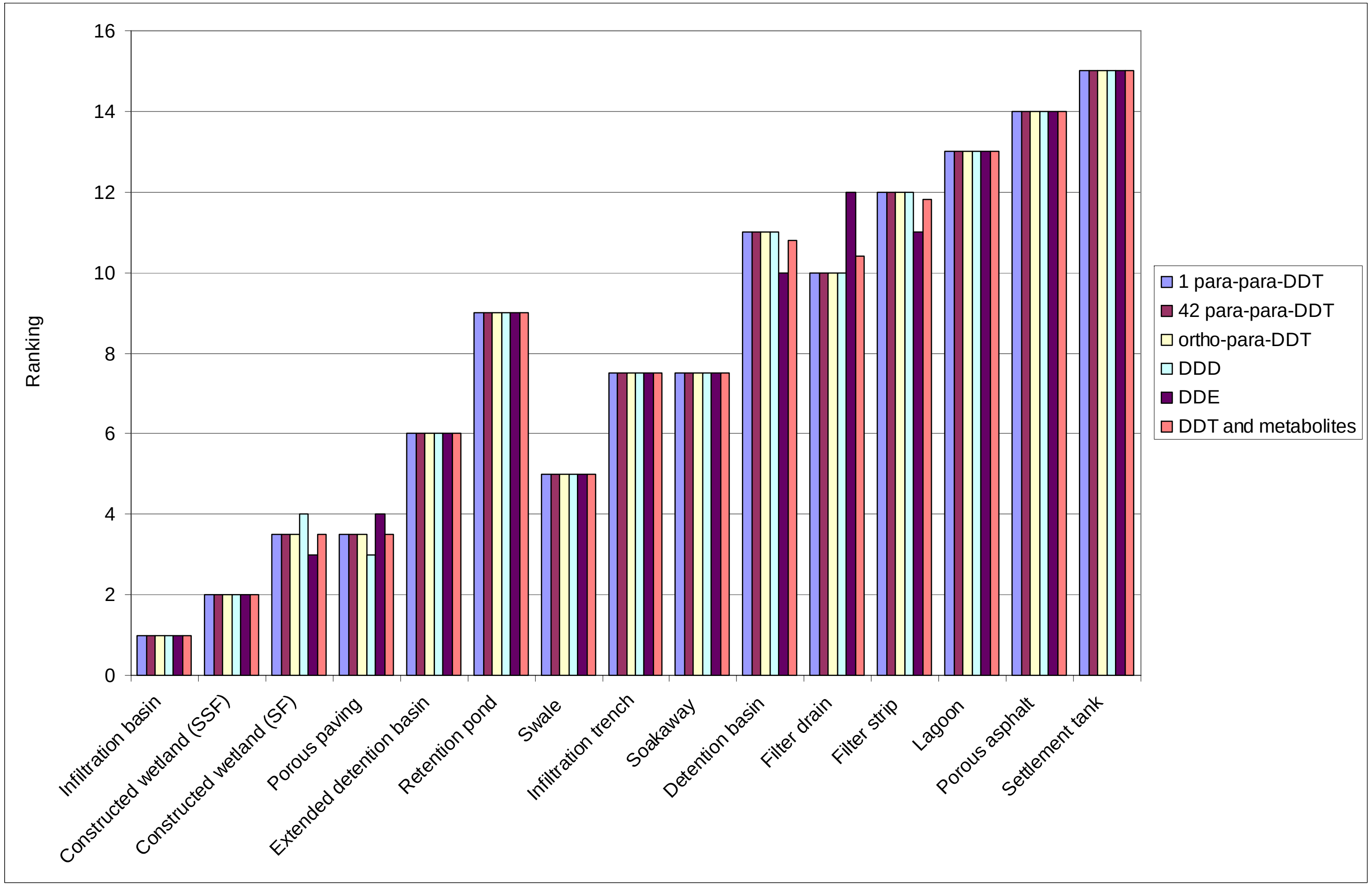

Figure 8 BMP order of preference for the removal of DDT and metabolites

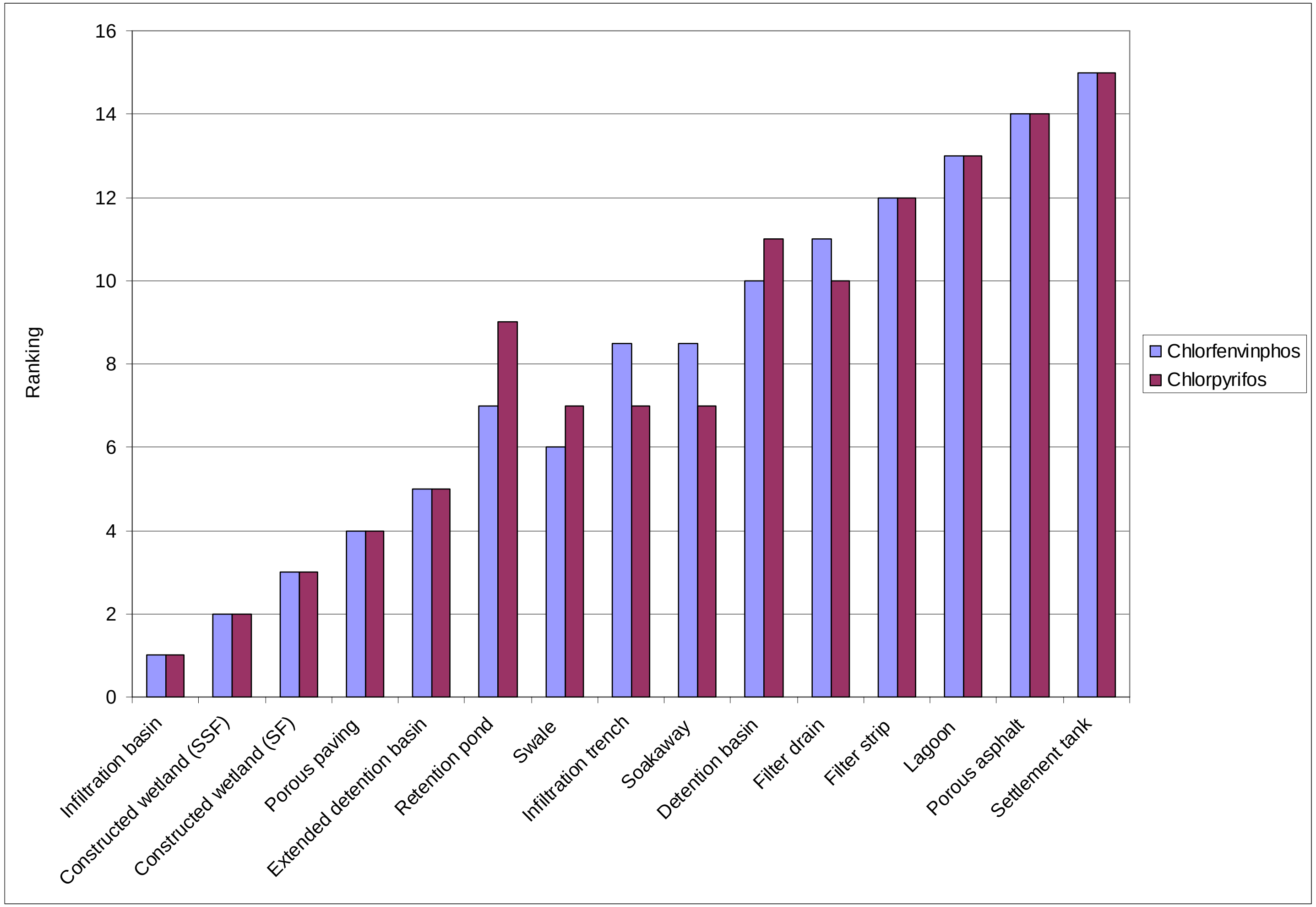

Figure 9 BMP order of preference for the removal of organophosphate esters

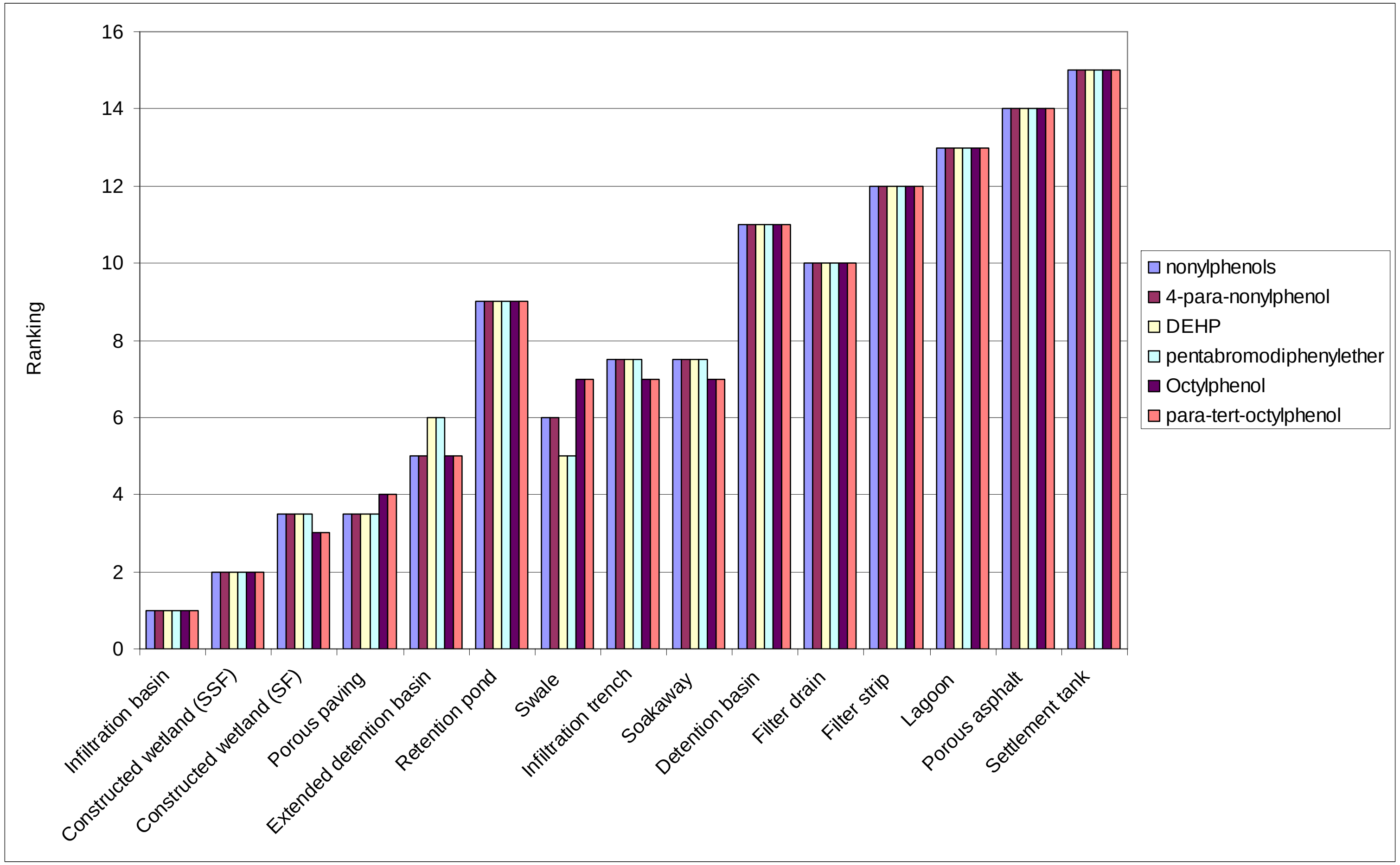

Figure 10 BMP order of preference for the removal of endocrine disruptors

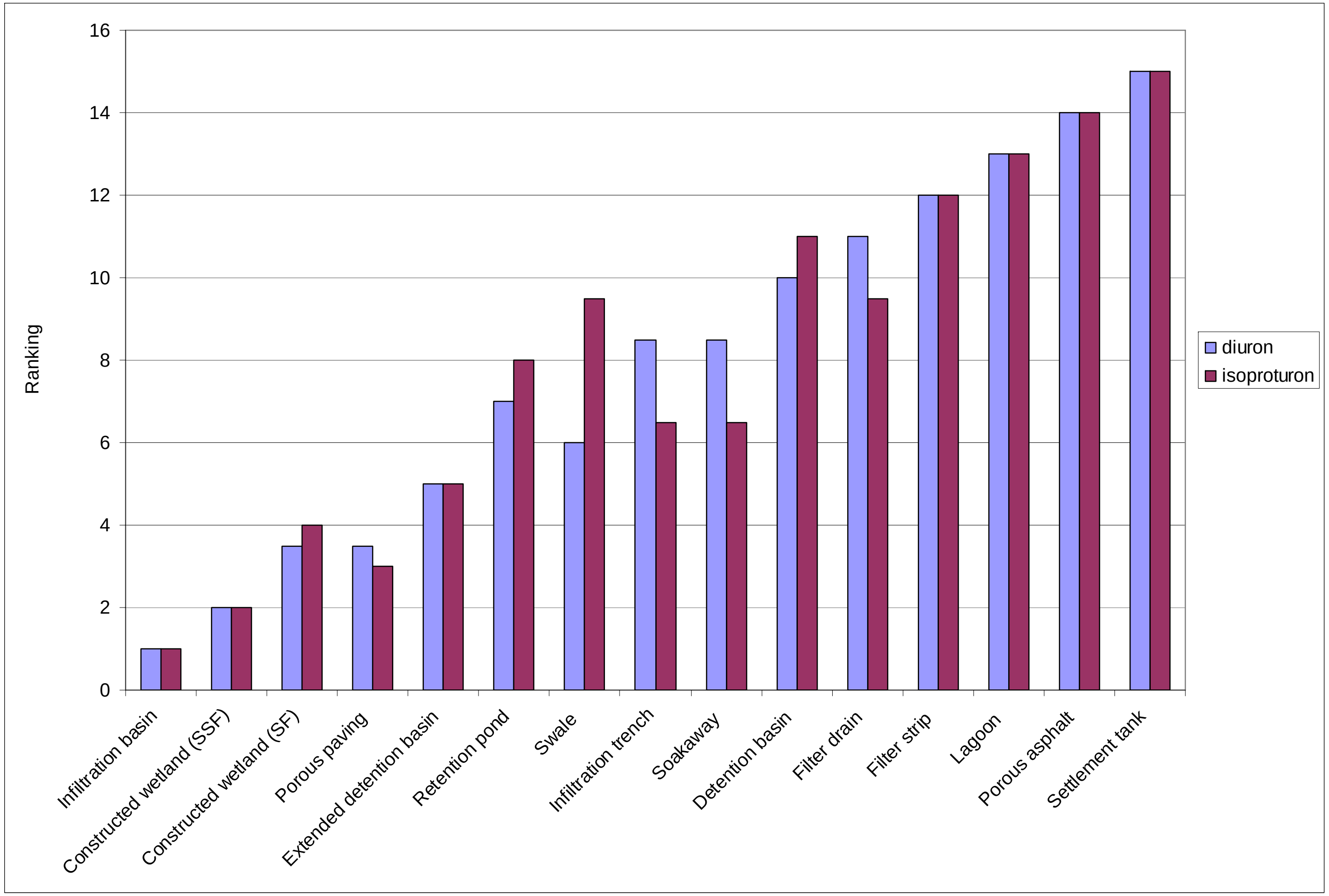

Figure 11 BMP order of preference for the removal of phenyl-urea herbicides

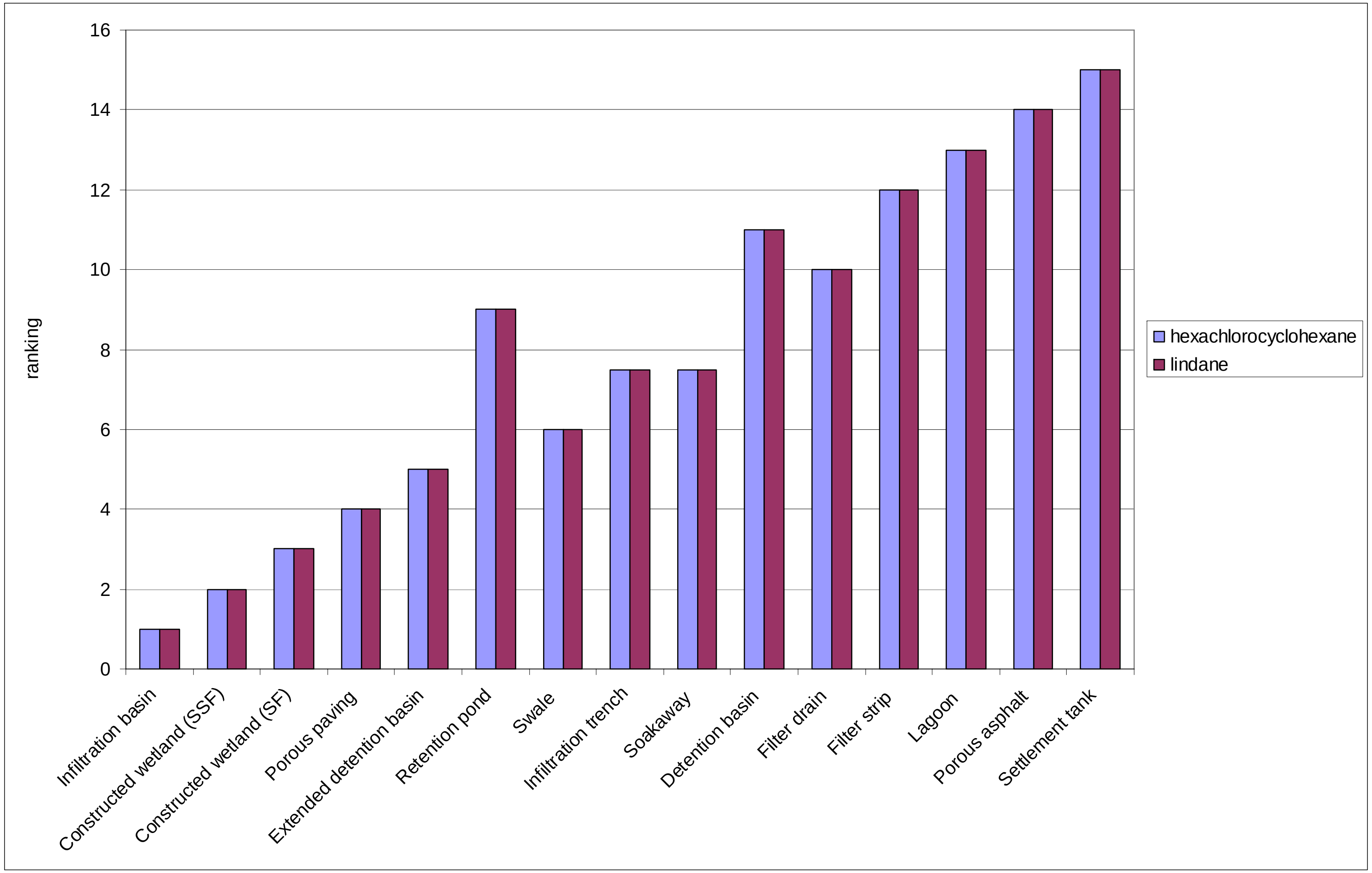

Figure 12 BMP order of preference for the removal of hexachlorocyclohexanes

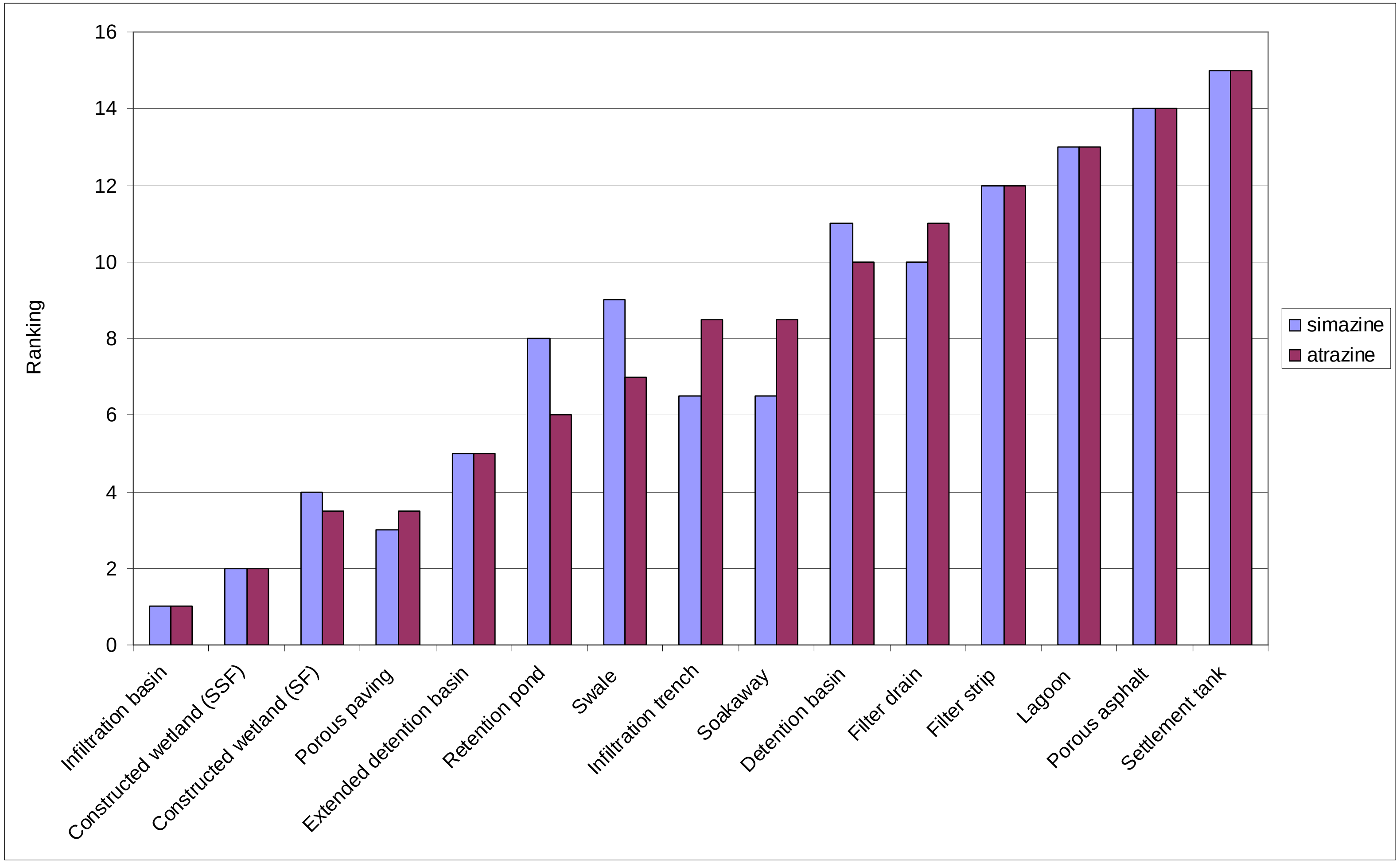

Figure 13 BMP order of preference for the removal of triazines

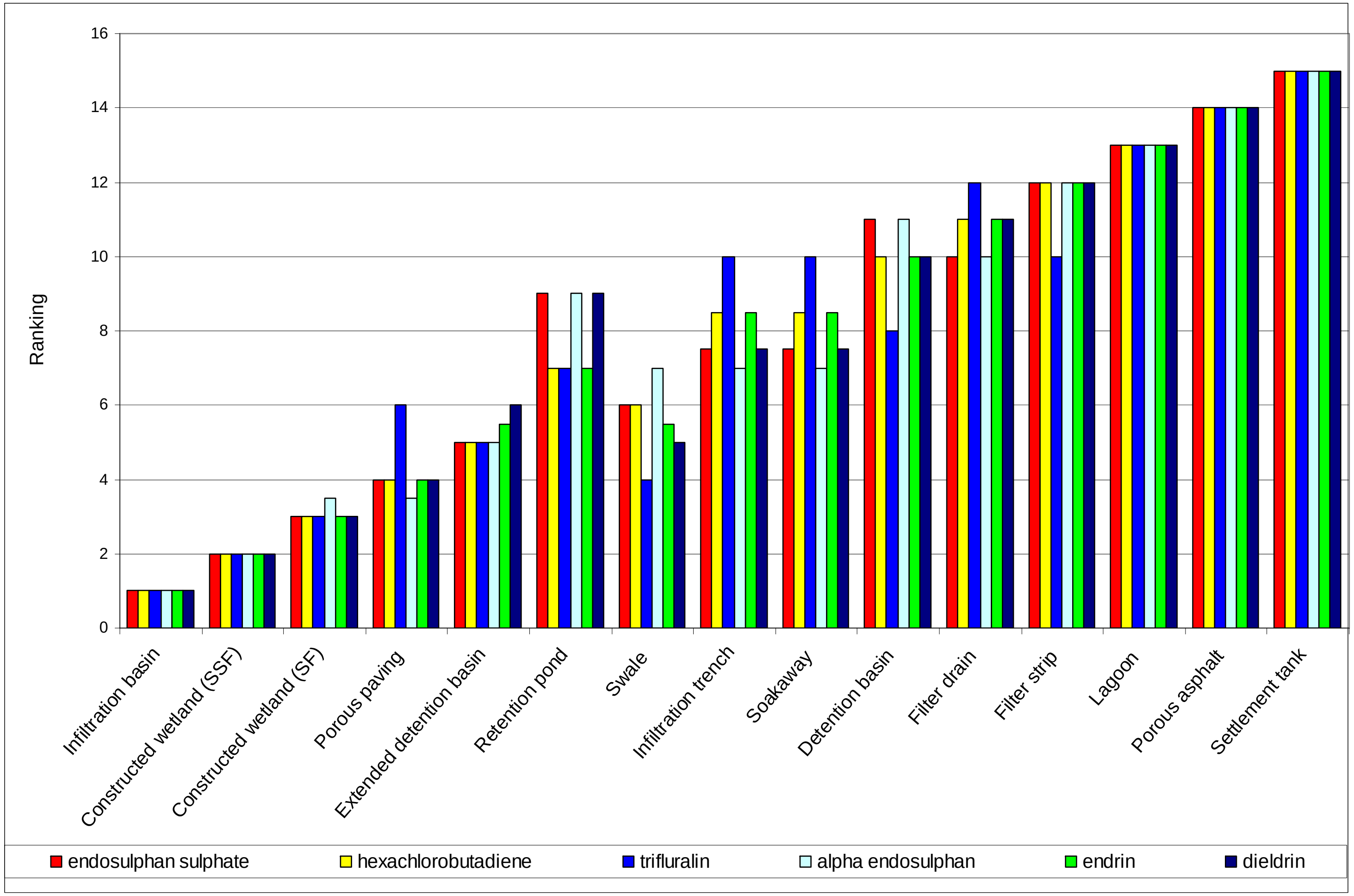

Figure 14 BMP order of preference for the removal of 'other' pesticides

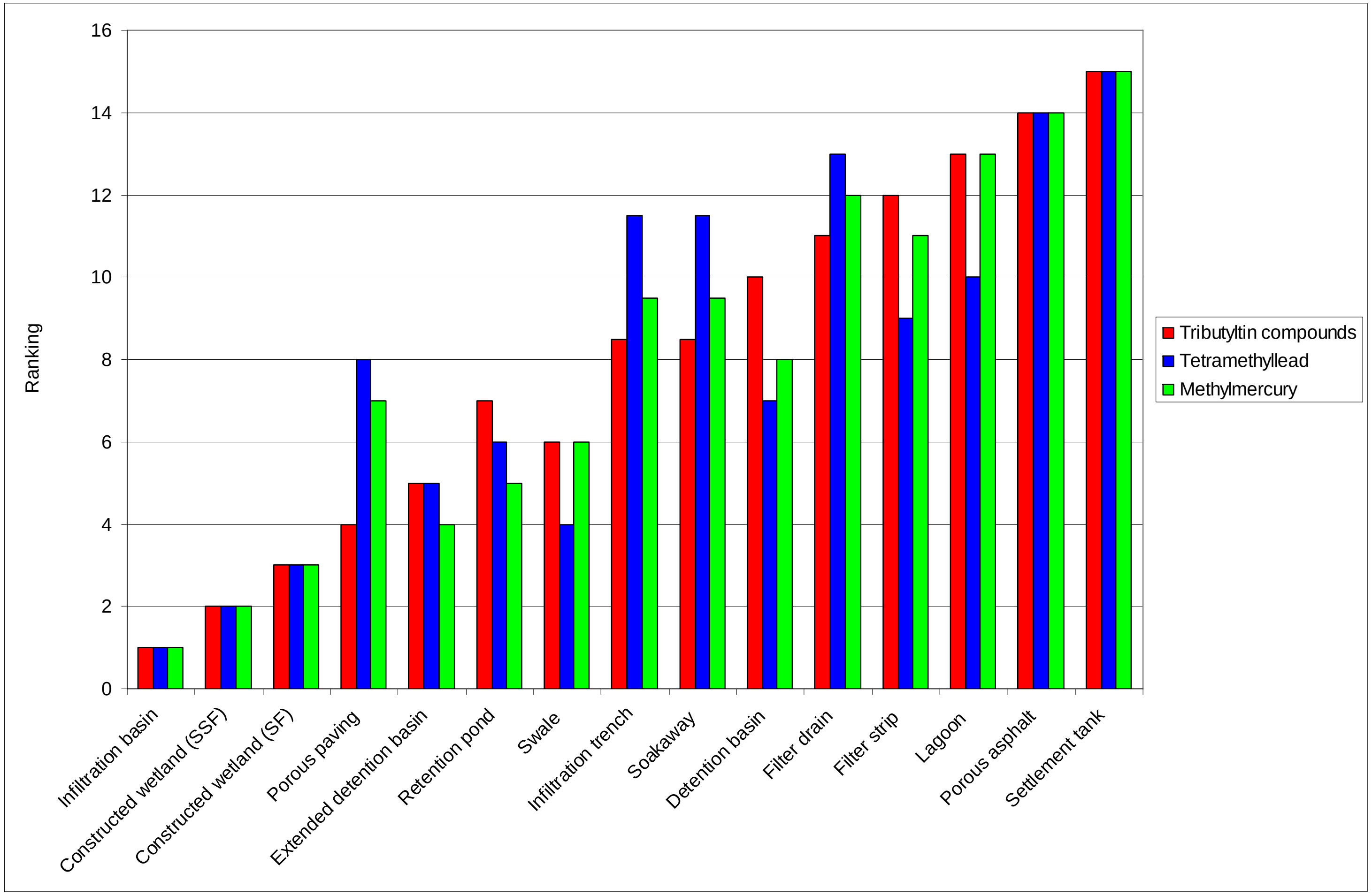

Figure 15 BMP order of preference for the removal of organometallic compounds

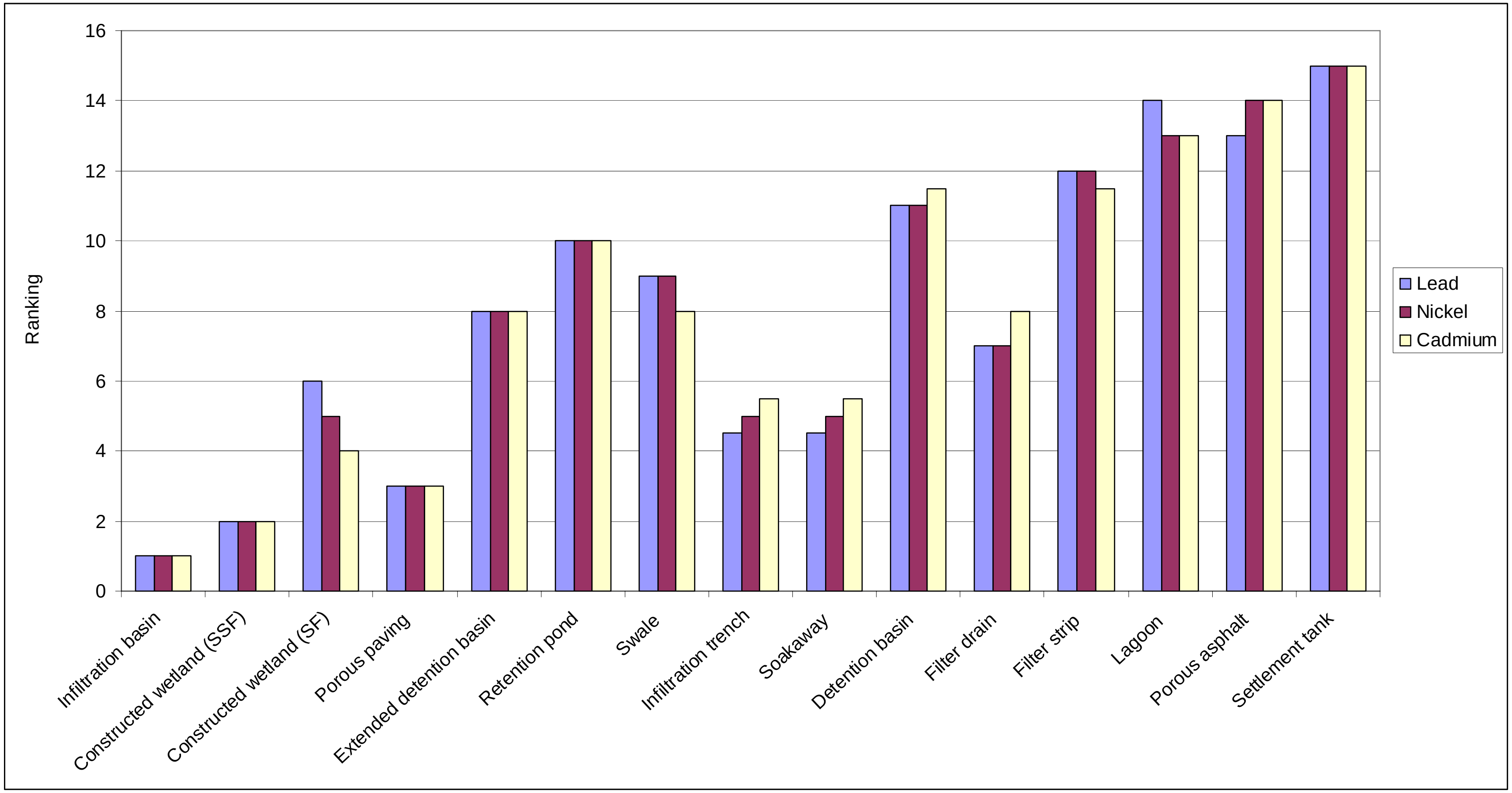

Figure 16 BMP order of preference for the removal of inorganic metal compounds

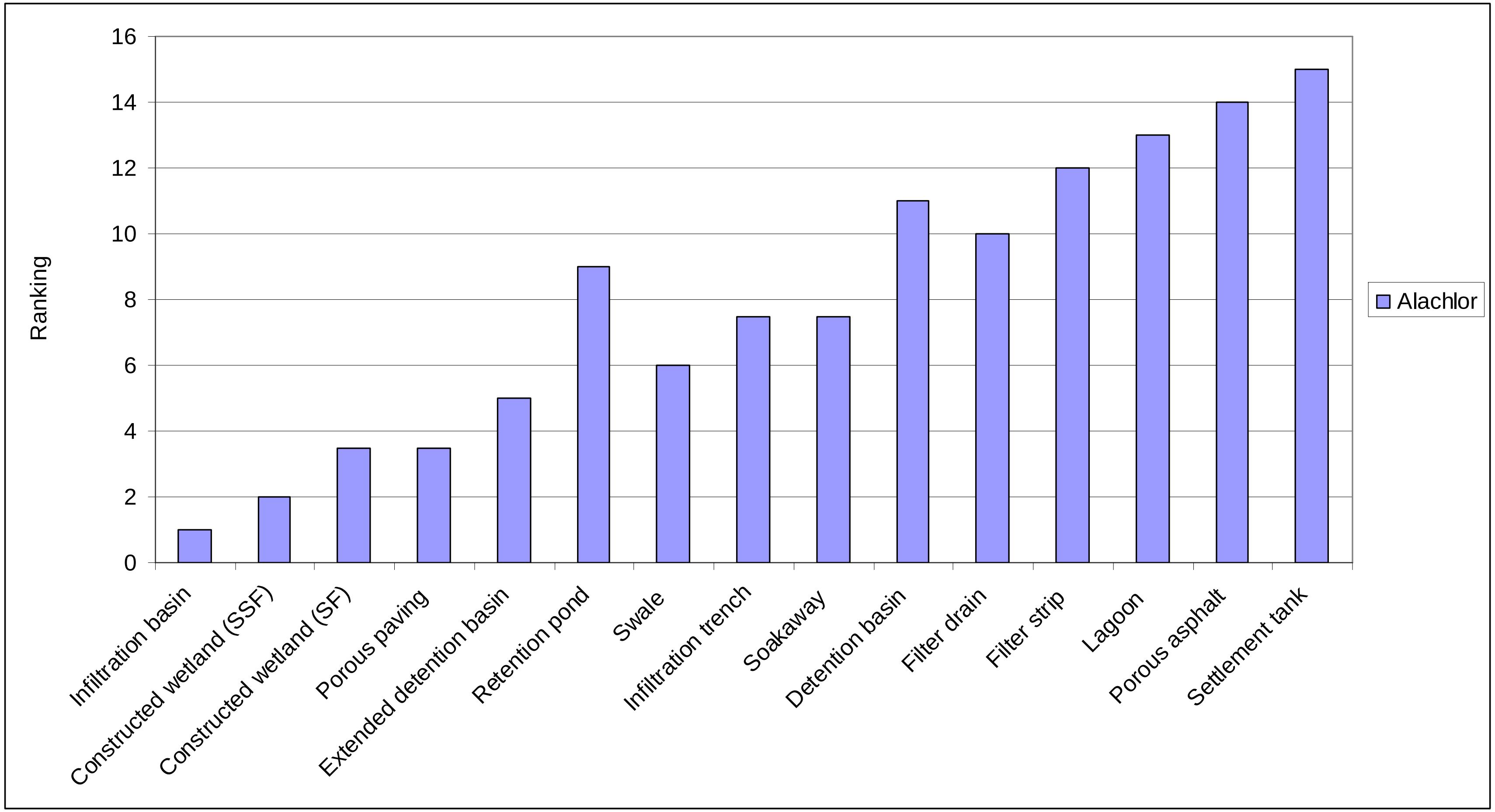

Figure 17 BMP order of preference for alachlor

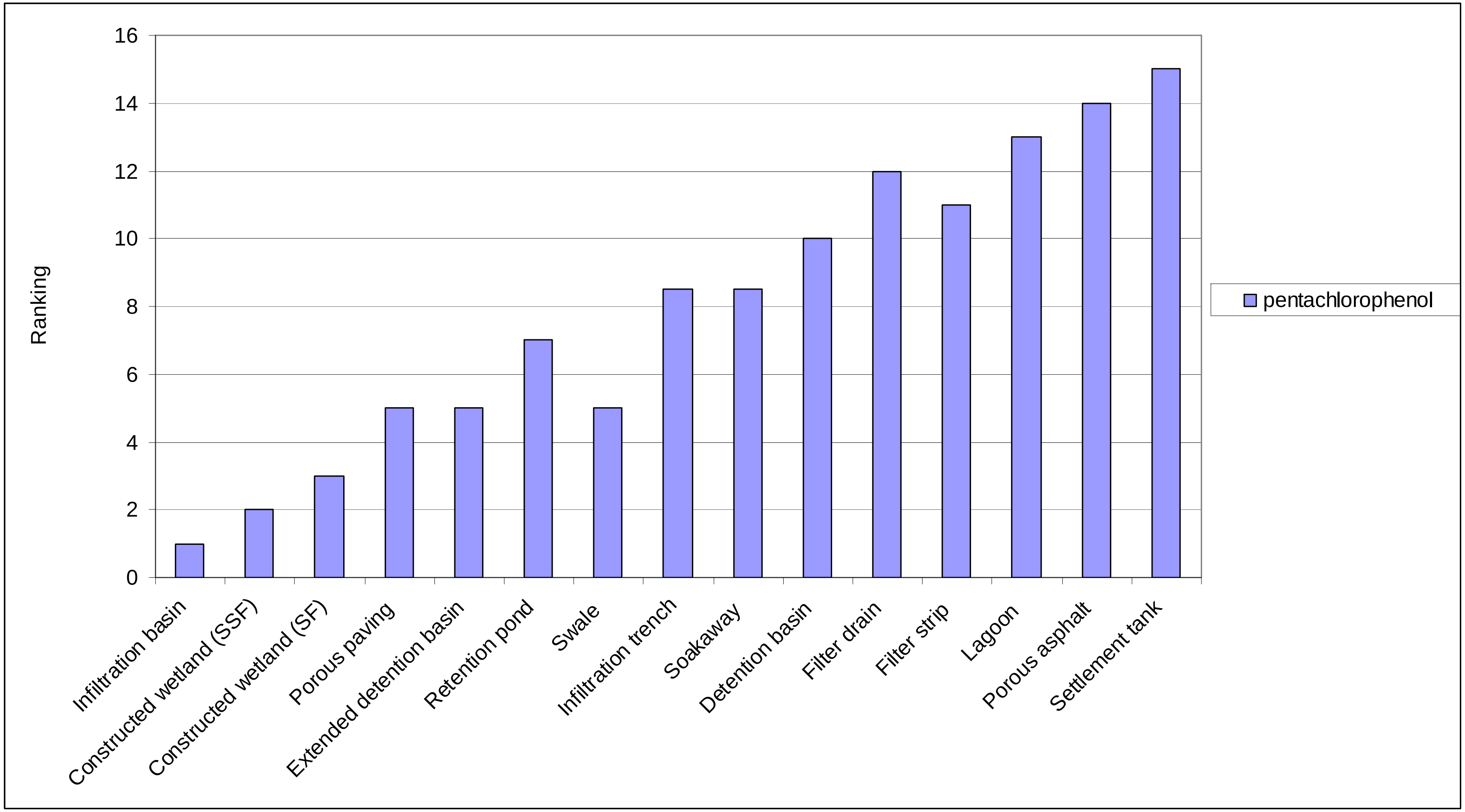

Figure 18 BMP order of preference for the removal of pentachlorophenol