

Evidence of traffic-related pollutant control in soil-based Sustainable Urban Drainage Systems (SUDS)

F. Napier^{1*}, C. Jefferies¹, K.V.Heal², P. Fogg³, B.J. D'Arcy⁴ and R. Clarke⁵

1 University of Abertay Dundee, Bell Street, Dundee, DD1 1HG, UK; c.jefferies@abertay.ac.uk; f.napier@abertay.ac.uk

2 University of Edinburgh, School of GeoSciences, Crew Building, West Mains Road, Edinburgh, EH9 3JN, UK; Kate.Heal@ed.ac.uk

3 Cambridge Environmental Assessments, ADAS Gleadthorpe, Medan Vale, Mansfield, Nottinghamshire, NG20 9PF, UK; Paul.Fogg@cea-res.co.uk

4 Central Advisory Unit, Scottish Environment Protection Agency, Perth PH2 0PA, UK; Brian.Darcy@sepa.org.uk

5 Scottish Environment Protection Agency, Clearwater House, Heriot Watt Research Park, Avenue North, Riccarton, Edinburgh, EH14 4AP, UK

**Corresponding author, e-mail f.napier@abertay.ac.uk*

ABSTRACT

SUDS are being increasingly employed to control highway runoff and have the potential to protect groundwater and surface water quality by minimising the risks of both point and diffuse sources of pollution. While these systems are effective at retaining polluted solids by filtration and sedimentation processes, less is known of the detail of pollutant behaviour within SUDS structures. This paper reports on investigations carried out as part of a co-ordinated programme of controlled studies and field measurements at soft-engineered SUDS undertaken in the UK, observing the accumulation and behaviour of traffic-related heavy metals, oil and PAHs. The field data presented were collected from two extended detention basins serving the M74 motorway in the south-west of Scotland. Additional data were supplied from an experimental lysimeter soil core leaching study. Results show that basin design influences pollutant accumulation and behaviour in the basins. Management and/or control strategies are discussed for reducing the impact of traffic-related pollutants on the aqueous environment.

KEYWORDS

Detention basins; metals; oil; soil; soil water, SUDS

INTRODUCTION

As point source emissions of pollutants are increasingly brought under control, diffuse sources have emerged as a serious and continuing threat to the aquatic environment (SEPA, 1999). Highway runoff is a major contributor to diffuse pollution and is the source of many pollutants that can adversely affect the water quality and ecology of receiving waters (Gray, 2004). Levels of traffic-related persistent pollutants such as zinc and copper continue to rise in line with increasing traffic volumes (Napier and Jefferies, 2005), and road traffic has now become the largest single source of PAHs to the UK atmosphere (NAEI). The EU Water Framework Directive (2000/60/EC) requires the UK to control diffuse sources of priority pollutants with the goal of protecting water bodies, including groundwater. SUDS are being increasingly employed to control highway runoff and have the potential to protect groundwater and surface water quality by minimising the risks of both point and diffuse

sources of pollution. While these systems are effective at retaining polluted solids by filtration and sedimentation processes (CIRIA, 2000), less is known of the detail of pollutant behaviour within SUDS structures.

The varying nature of highway pollutants and the physical, chemical and biological processes they undergo in the environment means that they can be expected to behave in very different ways. Environmental conditions vary between SUDS. Sediment-bound pollutants in swales and detention basins are exposed to light and air while, in contrast, pollutants bound to aquatic pond sediments face low light levels and anoxic conditions. Consequently there will be differences in pollutant fate, making the selection of the best control method difficult. While guidance is available on how to combine and size SUDS facilities in relation to expected flow volumes, data do not yet exist to allow similar decisions to be made regarding pollutant treatment potential. A particular area of concern is the vertical movement of contaminants in swales and detention basins, as this will determine potential risks to groundwater.

A co-ordinated programme of controlled studies and field measurements at soft-engineered SUDS was undertaken in the UK, observing the accumulation and behaviour of traffic-related heavy metals, oil and PAHs. The project involved collaboration between the researchers, the Scottish Environment Protection Agency, the Highways Authority and the Environment Agency in England. This paper reports on the investigations carried out to assess the risk to groundwater posed by the pollutants accumulating in SUDS, and the fate of key pollutants in the soil. On the basis of that data, a rationale is provided for selecting the optimum management and/or control strategies for reduction of the impact of these pollutants on the aqueous environment to be developed.

METHOD

A range of SUDS types were investigated, including extended detention basins, retention ponds and swales, as shown in Table 1. The careful selection of complementary field sites has allowed comparisons to be made based on SUDS type. Controlled, small-scale studies using specially constructed swales, soil core lysimeters (three soil types) and batch soil experiments have all provided data on the accumulation, degradation, leaching behaviour and factors controlling these processes for PAHs, heavy metals and oils.

Extensive data have been collected in this multi-component project, and interpretation is ongoing. While it is not possible to give full details of each study in this paper, most of the major findings to date are illustrated by the results of the sampling carried out at two motorway detention basins. Accordingly, this paper focuses on the investigations carried out at these sites, with reference to relevant corroborating evidence from the lysimeter soil core study. Full details of the other study components and a full synthesis of all the data and findings are in Jefferies et al. (2008).

M74 Basins

The M74 basins have been in operation for approximately seven years. They receive runoff from the M74 motorway, a major rural highway with free-flowing traffic. At the locations monitored, the motorway is six lanes wide, with an average annual daily traffic (AADT) of 13,000. Both basins drain approximately 18,000 m² of carriageway, and receive piped inflow via roadside filter drains.

Table 1. Study components

Study component	AADT*	Description	Nature of sampling
Field Study			
M74 Detention Basin 27A SW Scotland	13,000	Grassed basin incorporating small lined pool. Piped inflow.	Soil samples at different locations and depths. Submerged sediment samples at different locations.
M74 Detention Basin 29A SW Scotland	13,000	Grassed basin incorporating small lined pool. Piped inflow.	Roadside filter drain samples. Soil samples at different locations and depths. Soil water samples. Submerged sediment samples at different locations and depths.
M74 Retention Ponds 33A & B SW Scotland	13,000	Treatment ponds in sequence (1 st lined, 2 nd unlined). Piped inflow.	Submerged sediment samples at different locations and depths
M74 Retention Ponds 40A & B SW Scotland	13,000	Treatment ponds in sequence (1 st lined, 2 nd unlined). Piped inflow.	Submerged sediment samples at different locations
M42 Hopwood MSA Central England		SUDS treatment train for runoff from HGV park (sheet flow). Train comprises gravel filter strip, grass filter strip, gravel filter trench plus two treatment ponds	Soil samples from grass filter strip, different locations and depths Submerged sediment samples from 2 ponds
A8000 swale Edinburgh	30,000	Roadside swale receiving both piped and sheet inflow	Soil samples at different locations and depths
A90 roadside grass verge, Edinburgh	20,000	Grassed verge receiving road spray	Soil samples at different locations and depths
Experimental Studies			
Experimental swales		Specially constructed swales dosed with pollutants and irrigated	Leachate samples plus destructive soil sampling
Soil core lysimeters		Soil cores (volume 0.11m ³) dosed with pollutants and irrigated	Leachate samples plus destructive soil sampling
Lab-based batch degradation study		Soil samples dosed with oil and PAHs and incubated under various conditions	Soil samples

*annual average daily traffic based on 7-day averages

The detention basins vary in various design details, but both consist of an unlined grass basin bisected by a small pond. The layout of each is shown in Figure 1. Inflow at 27A is conveyed along a narrow swale-like channel to the pond. As water level in the pond rises, it spills over into the outlet channel, which is separated from the inlet by a grassed bund. In extreme events, the pond overflows on the far side into an overflow basin, and visual inspection found evidence of this occurring.

Inflow at 29A enters directly into a broad basin. As this basin fills, flow eventually spills into the pond. As the pond fills, the design intention is for water to flow into the outlet basin and on to the outlet. However, visual inspection of the outlet showed no evidence of regular flow.

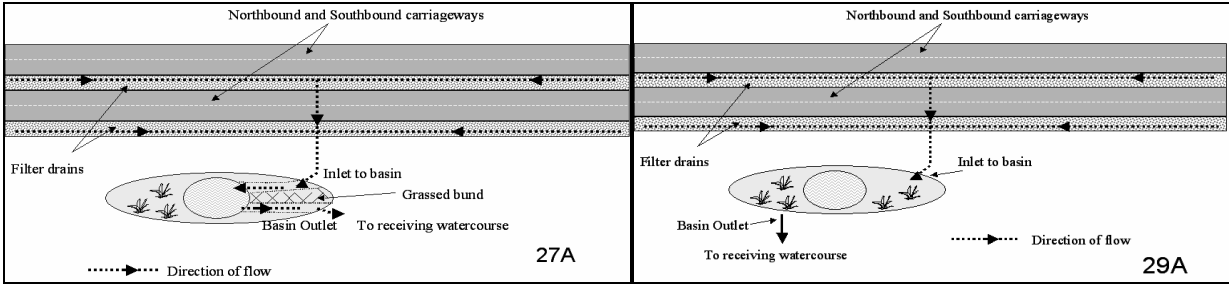


Figure 1. Layout of M74 detention basins 27A and 29A

The sampling strategy at the basins was designed to follow the inflow treatment sequence, i.e. inlet basin ► basin pond ► outlet basin. At Basin 29A, this included sediment from the upstream filter drain, and soil water. The pattern of soil and sediment sampling at the basins is illustrated in Figure 2.

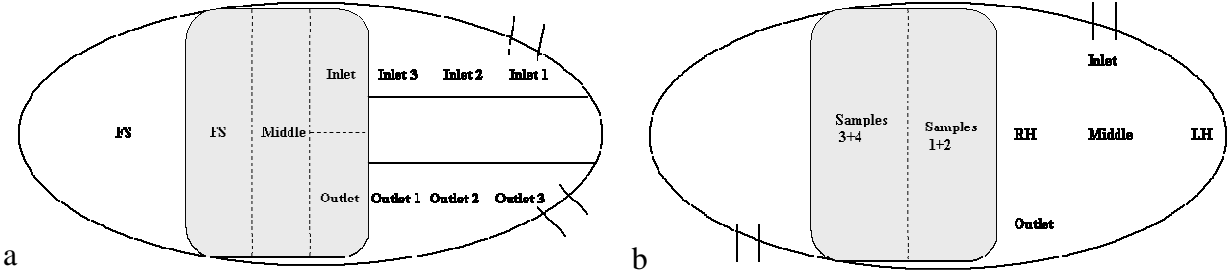


Figure 2. Sampling locations at Basins 27A (a) and 29A (b). Shaded area represents pond .

The samples were collected in the period January-June 2007. Soil samples from both basins were collected from two depths (0-10 cm and 10-20 cm) at each location, using a hand trowel. Sediment samples were collected from the ponds, following the pattern shown in Figure 2. Multiple samples (from two depths at 29A, one depth at 27A) were collected from each pond section and bulked to form a composite sample for each section.

Soil water samples from 29A were collected using porous suction-cup lysimeters (see Fig 3). A total of 29 suction samplers were installed across the inlet basin at a depth of 0.9 m. On each of four sampling occasions, between March and June 2007, the soil water collected by these samplers was bulked to give a single composite sample.

Samples of sediment were collected from six separate locations along a 50 m stretch of the filter drain serving Basin 29A. At each location, the trench was excavated using a small digger, and the material removed was deposited on plastic sheeting. Random samples were collected and sieved (5 mm) into a plastic bucket. A very small amount of water was used to

wash the finer sediment off the stone chips, and the resulting sludge formed a composite sample. Sediment from three catchpits was also sampled manually using a plastic scoop.



Figure 3. Soil water collection (a) and filter drain sediment sampling (b) at Basin 29A

Lysimeter soil core study

The lysimeter soil core study was designed to measure the immobilisation and degradation of priority pollutants in soft engineering SUDS and assess any leaching potential.

Soil core lysimeters 0.6m deep (three replicate cores of three soil types selected as representative sand, silt and clay soils) and specially constructed SUDS lysimeters (three replicate cores comprising layers of gravel, sand and a top layer of biologically active topsoil) were dosed with a single application of PAH, TPH and metals. The loading applied is given in Table 3, and is representative of typical contaminant concentrations in highway runoff. The cores were then irrigated with water over a 135-day period (volume based on data for Scottish rainfall), and the drainage water collected for analysis (as shown in Figure 4.). At the end of the study period, the cores were destructively sampled and concentrations of each determinand at different depths were measured.



Figure 4. Soil core collection (a) and leaching study (b)

RESULTS AND DISCUSSION

Table 5 shows the results of analysis of soil and sediment sampling carried out at the basins. The results of the the soil water sampling are given in Table 2. To allow a comparison of overall contamination between the basins, the volume of soil in each basin was estimated and used with the measured pollutant calculations to derive average values (for full method of calculation see Jefferies et al., 2008). Sediment concentrations from each pond were also averaged to allow comparison. The results are given in Table 4.

Table 2. Basin 29A soil water analysis (* concentration below reporting limit)

Date sampled	Cd	Cu	Pb	Ni	Zn	TPH	Total PAH
	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	µg l ⁻¹
23/03/07	*	0.001	*	0.003	*	*	0.33
31/03/07	*	0.009	0.002	0.003	0.010	0.2	0.99
11/05/07	*	0.013	0.001	0.003	0.010	*	0.16
29/06/07	*	0.009	0.002	0.211	0.020	0.1	No sample

Table 3. Results of mass balance calculations for selected pollutants in the soil core lysimeters

Pollutant	Total loading applied /lysimeter mg	% applied pollutants measured in drainage water ¹	% applied pollutants retained or degraded in soil cores ²
Total PAH	137	0.06	99.94
TPH	55000	0.07	99.93
Cu	163	0.45	99.55
Zn	2730	0.31	99.69

¹ value represents the maximum percentage pass-through for any soil type, which was measured in the clay lysimeters.

² value represents the minimum percentage for any soil type, which was measured in the clay lysimeters.

Table 4. Average basin soil and pond sediment pollutant concentrations (dry weight concs.)

	Cd	Cu	Pb	Ni	Zn	TPH	Total PAH
	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹
Filter drain (excluding catchpits)	0.25	66	43	44	388	2563	9.5
27A inlet and outlet channel soil	0.19	44	28	48	160	888	5.6
27A pond sediment	0.40	109	60	43	386	2980	7.9
29A inlet basin soil	0.20	40	32	35	218	914	4.7
29A pond sediment	0.15	21	25	32	127	1414	2.3

Pollutant accumulation

Soil concentrations at the basin inlets (given in Table 5) were mostly higher than average values for sediments found in the filter drain (see Table 4), implying accumulation over time in basin soils. In general, the soil pollutant concentrations decreased with distance from inlet and with depth as demonstrated for zinc in Figure 5. Figure 5 also demonstrates the differing patterns of pollutant accumulation within the individual basins. Pollutant concentrations in the upper soil layer at the inlet of 29A were almost double those at 27A probably reflecting the different inlet designs of the basins. At 29A, inflow velocity quickly dissipates as flow enters the broad basin, depositing contaminated sediments close to the inlet. Inflow velocity at 27A is maintained longer in the narrow inlet channel, allowing sediments to be transported further. This theory is supported by a comparison of pond sediment pollutant concentrations at both basins in Table 4. There was a noticeable difference in soil and pond sediment quality

Table 5. Analysis results for soil and sediment sampling at Basins 27A and 29A (dry weight concs.)
 (*concentration below detection limit)

	Cd	Cu	Pb	Zn	pH	TPH	Total PAH
Basin 27A							
Basin soil	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹		mgkg ⁻¹	mg kg ⁻¹
Inlet (1) Upper	0.4	155	73	562	7.7	3607	12.19
Inlet (1) Lower	0.2	60	32	211	8.2	1856	5.01
Inlet (2) Upper	0.4	116	58	395	7.5	1947	7.42
Inlet (2) Lower	0.2	43	29	159	7.6	769	3.36
Inlet (3) Upper	0.3	67	40	246	7.4	1591	6.23
Inlet (3) Lower	0.1	22	19	89	7.5	452	2.20
Outlet (1) Upper	0.2	30	25	118	7.4	623	19.12
Outlet (1) Lower	0.1	24	14	69	7.7	404	5.39
Outlet (2) Upper	0.1	20	20	79	7.3	228	2.01
Outlet (2) Lower	0.1	19	15	74	7.5	309	1.67
Outlet (3) Upper	0.1	21	19	85	7.3	337	2.14
Outlet (3) Lower	0.2	17	19	68	7.4	161	1.74
FS Upper	0.1	18	21	80	7.3	205	2.95
FS Lower	0.1	15	19	65	7.4	124	1.53
Pond sediment							
Inlet (P)	0.5	136	66	475	7.1	4400	10.97
Outlet (P)	0.4	90	52	312	6.9	2634	6.78
Middle (P)	0.4	124	68	450	7.0	2753	7.27
FS (P)	0.3	85	53	305	7.0	2134	6.58
Basin 29A							
Filter drain							
1	0.25	64	43	376	8.9	3718	11.94
2	0.21	52	34	274	8.7	1756	5.29
3	0.20	62	45	379	8.9	2687	8.02
4	0.31	84	51	528	9.3	2361	12.10
5	0.29	80	50	459	9.2	2423	11.87
6	0.21	53	35	315	9.2	2435	7.52
Catchpit 1	0.18	37	22	160	8.9	1000	2.37
Catchpit 2	0.35	83	53	423	9.0	7426	15.07
Catchpit 3	0.43	107	56	590	8.2	6002	25.40
Basin soil							
Inlet Upper	0.58	198	107	1050	7.7	4869	16.71
Inlet Lower	0.31	51	37	280	8.7	1625	5.28
Middle Upper	0.20	40	34	219	8.4	868	6.65
Middle Lower	0.11	19	24	86	8.1	347	5.87
RH Upper	0.15	20	25	119	7.7	340	2.13
RH Lower	0.13	21	18	74	7.7	134	1.59
LH Upper	0.22	38	34	218	7.8	808	4.38
LH Lower	0.11	16	20	85	8.2	322	3.06
Outlet Upper	0.10	8	18	63	7.0	127	1.64
Outlet Lower	0.10	8	15	57	7.3	70	1.54
FS Upper	0.13	18	22	102	7.4	190	1.64
FS Lower	*	13	17	74	7.7	127	1.60
Pond sediment							
1	0.19	26	29.7	155	7.0	142	1.95
2	0.15	23	25.5	156	7.0	1387	2.31
3	0.10	9	17.8	59	7.2	182	1.63
4	0.16	25	28.2	138	6.9	3946	3.34

between the basins. At 29A, most pollutant concentrations in the pond sediments were lower than the average soil values, with the exception of TPH. However, at 27A, pollutant concentrations in the pond sediment were double the calculated soil averages. Comparing both basin sediment qualities, 27A pond sediments had pollutant concentrations consistently higher than those at 29A; up to five times higher in the case of copper. As the basins receive similar loadings, and both have filter drains upstream, any difference must be a result of differences in basin design. It seems likely that the higher contaminant concentrations in the pond sediment at 27A were a result of more contaminated sediments reaching the pond.

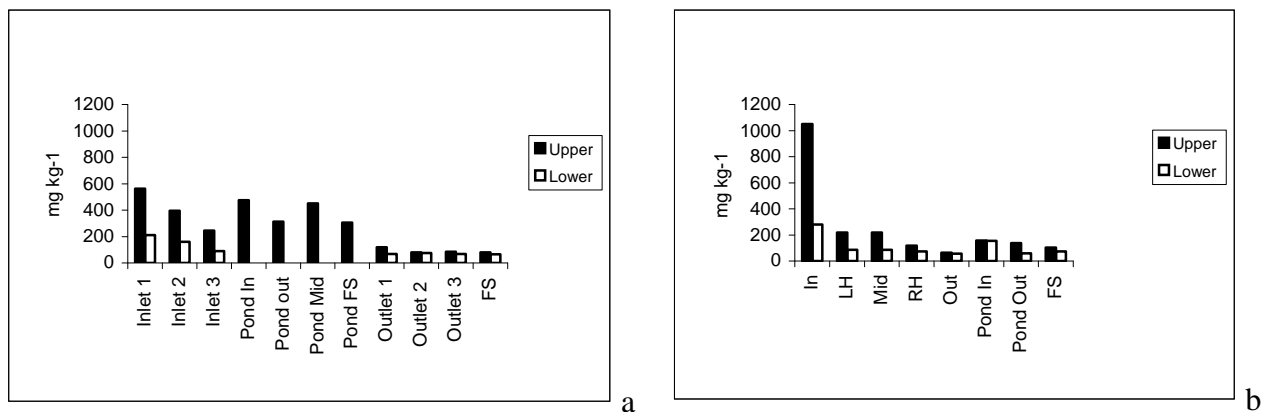


Figure 5. Zinc concentrations (dry weight) measured at Basins 27A (a) and 29A (b)

The data in Table 5 show that, despite pollutant hotspots, average soil pollutant concentrations across the basins were very similar.

Submerged sediments

The field study showed that the TPH and total PAH concentrations in the submerged sediments in the basin ponds are substantially higher than in the soil in the adjacent basins which dry out between rainfall events. Results show that while soil pollutant concentrations reduced with distance from inlet, concentrations then increased in the pond sediment. This pattern was observed for the metal pollutants also, but is most pronounced for the organic pollutants, as illustrated by TPH in Figure 6. This suggests that degradation of the organic

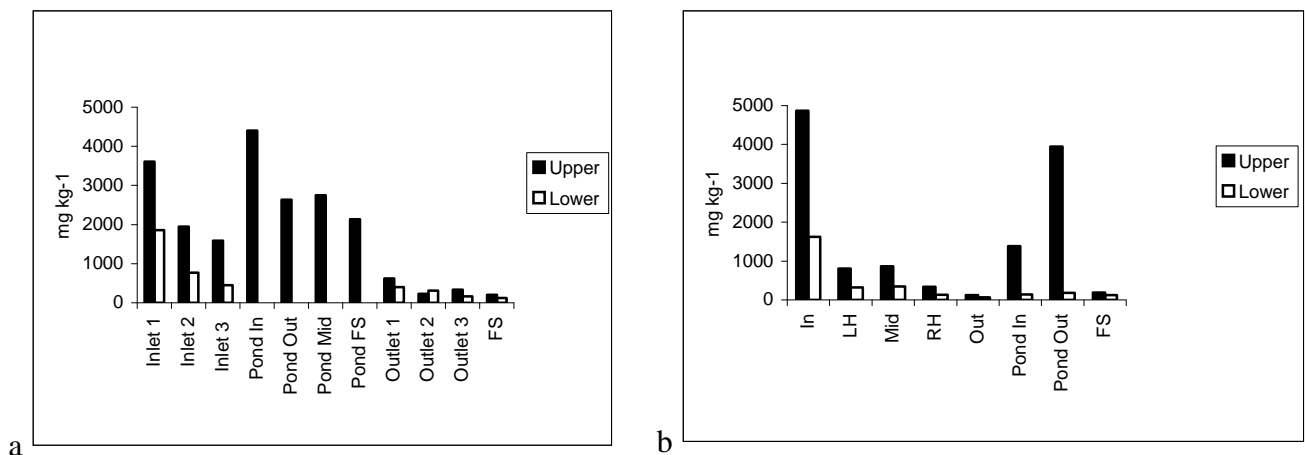


Figure 6. TPH concentrations (dry weight) measured at Basins 27A (a) and 29A (b)

pollutants in the submerged sediments is slower than in the exposed soil. A similar pattern occurred in the filter drain, where the average TPH concentration measured in the submerged sediment in the catchpits (4809 mg kg⁻¹) was almost double the average from the rest of the filter drain (2563 mg kg⁻¹).

Pollutant movement

At the basins, soil was sampled at two depths. At all sampling locations, higher concentrations were found in the top 10 cm of soil. In general, the magnitude of the vertical change in soil concentration measured at the basins decreased with distance from the inlet. Traffic-related metals (Cu/Pb/Zn) were strongly correlated in the upper and lower soil layers at the basin inlets ($R^2 > 0.99$), but these correlations decreased in strength with distance from the inlet, suggesting that the lower concentrations in the 10-20 cm layers were not simply a measurement of background levels.

One explanation for the change in vertical concentration is sediment accumulation over time, with later deposits being more contaminated than earlier deposits. However, it is extremely unlikely that 20 cm of soil has accumulated in the basins in the seven years since their construction, especially with filter drains upstream. A more likely explanation is the downward migration of pollutants through the soil. However, evidence from the soil core lysimeter suggests that any downward migration of pollutants occurs slowly. The lysimeter study was conducted over a 4-month period, and destructive soil sampling at the end of the study showed that >99% of the applied metal pollutants were retained in the top 10 cm of soil, with < 0.45% leaching through the 0.6 m soil cores. In the case of the organic pollutants, only <0.07% of the organic pollutants leached through the cores, with the remainder either degraded or retained in the top 10 cm of soil. Nevertheless as pollutants accumulate in soil in soft engineering SUDS over time, it is possible that more downward movement could occur. However, analysis of soil water from Basin 29A shows very low pollutant concentrations at 0.9 m, even after seven years in operation.

Implications for SUDS design

Evidence from this study suggests that the top 10 cm of soil is very important in pollutant attenuation. The soil core lysimeter study showed that most of the applied pollutants which were retained in the soil cores were found in the upper 10 cm of soil. This information is supported by field results where pollutant concentrations were consistently higher in upper than lower soil layers. However, in the construction of some infiltration devices (eg soakaways) the topsoil is normally removed and runoff is discharged into underlying formations. It may be appropriate to revisit this practice to improve pollutant removal performance and also minimise the risk of groundwater contamination.

The results from the basins suggest that basin design should be 'wide and shallow' rather than 'narrow and deep' to allow adequate time for sediment retention. The difference in pond sediment quality between the basins shows the important role of upstream sediment removal in minimising the subsequent contamination of aquatic sediments, especially by organic pollutants. Additionally, the difference in contamination levels observed in soil and sediment at each basin indicates that organic pollutants receive more effective treatment in exposed soil than in submerged sediments. This evidence suggests that it is desirable that highway runoff should pass through a swale or detention basin prior to entering a pond. Passing over / through vegetation and soil will enhance the removal of pollutants from the runoff and the control of pollution.

CONCLUSIONS

The key findings from the data presented can be summarised as follows:

- Inlet design influenced the pattern of contamination in the basin soils, but did not affect total average soil pollutant concentrations. However, inlet design had a noticeable effect on average sediment quality in the basin ponds.
- The degradation of organic pollutants in submerged sediments is slower than in exposed soil.
- Any downward movement of pollutants through the soil appears to be slow, with most pollutants retained in the top 10 cm of soil.
- The results highlight the importance of sediment removal from contaminated runoff to minimise subsequent contamination of downstream pond sediments, especially by organic pollutants. It is recommended that highway runoff should pass through a swale or detention basin prior to entering a pond.

Interpretation of data from additional study components not reported on in this paper is ongoing, and will be reported in future publications.

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