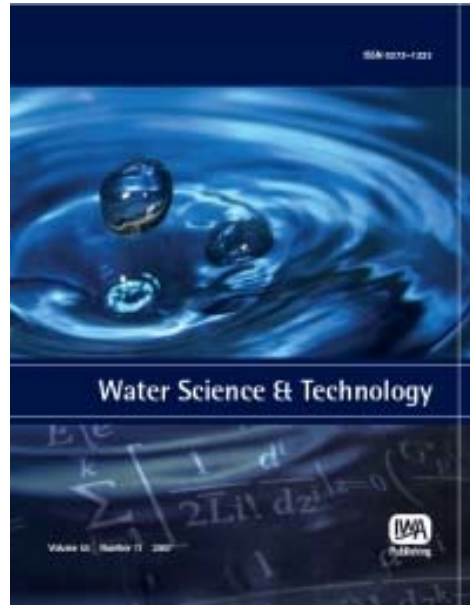


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Evidence of traffic-related pollutant control in soil-based Sustainable Urban Drainage Systems (SUDS)

F. Napier, C. Jefferies, K. V. Heal, P. Fogg, B. J. D. Arcy and R. Clarke

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.

Key words | detention basins, metals, oil, soil, soil water, SUDS

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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 & Jefferies 2005), and road traffic has now become the largest single source of polycyclic aromatic hydrocarbons (PAHs) to the UK atmosphere, responsible for 64% of all emissions in 2005 (NAEI 2005). The EU Water Framework Directive (2000/60/EC) requires the UK to control diffuse sources of priority pollutants, with the goal of protecting both surface and groundwaters. 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 2007), 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 (CIRIA 2007), 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 (University of Abertay and ADAS), 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.

METHOD

A range of SUDS types were investigated, including extended detention basins, retention ponds and swales, and the careful selection of complementary field sites allowed comparisons to be made based on SUDS type. Controlled, small-scale studies using 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 (M74 basins 27A and 29A). Accordingly, this paper focuses on the investigations carried out at these sites, with reference to relevant corroborating evidence from the lysimeter soil core study. Table 1 summarises each component discussed. Full details of the other study components and a fuller synthesis of all 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 both locations monitored, the motorway is six lanes wide, with an average annual daily traffic (AADT) of 13,000. The basins are 500 m apart, both 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
<i>Field study</i>			
M74 Detention Basin 27A	13,000	Grassed basin incorporating small lined pool. Piped inflow	Soil samples at different locations and depths
SW Scotland			Submerged sediment samples at different locations
M74 Detention Basin 29A	13,000	Grassed basin incorporating small lined pool. Piped inflow	Roadside filter drain samples
SW Scotland			Soil samples at different locations and depths Soil water samples Submerged sediment samples at different locations and depths
<i>Experimental studies</i>			
Soil core lysimeters		Soil cores (volume 0.11m ³) dosed with pollutants and irrigated	Leachate samples plus destructive soil sampling

*Annual average daily traffic based on 7-day averages.

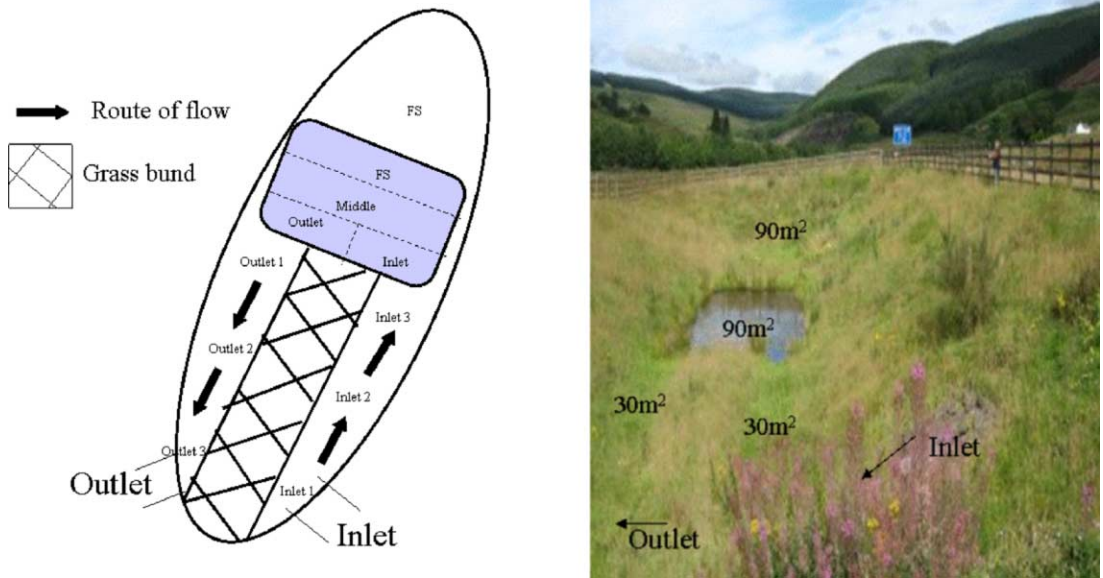


Figure 1 | M74 detention basin 27A, showing sample locations and flow routes.

The detention basins vary in various design details, but both consist of an unlined grass basin bisected by a small lined pond. The layout of each is shown in Figures 1 and 2. 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.

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

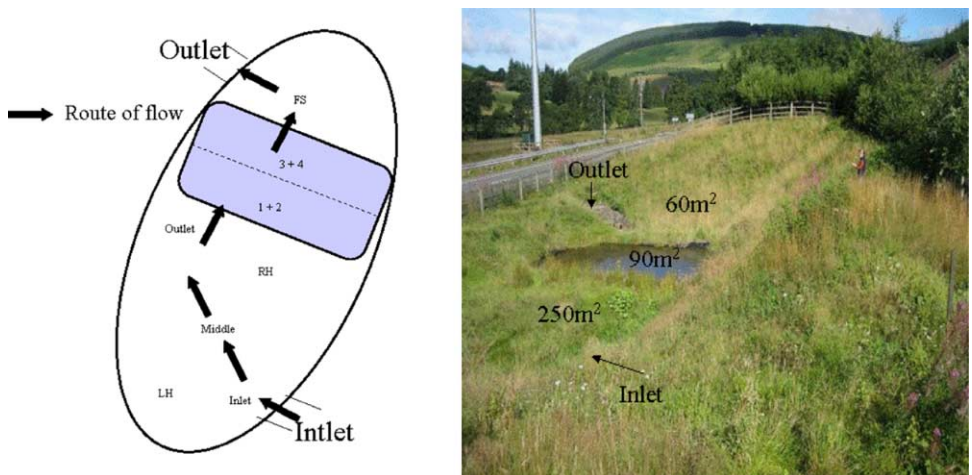


Figure 2 | M74 detention basin 29A, showing sample locations and flow routes.

from the upstream filter drain, and soil water from beneath the basin. The pattern of soil and sediment sampling at the basins is illustrated in Figures 1 and 2.

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 Figure 3a). 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 (see Figure 3b). 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.

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 0.6 m deep were collected (see Figure 4a); three replicate cores of three soil types selected as representative sand, silt and clay soils. In addition, “SUDS” lysimeters were specially constructed; three replicate cores comprising layers of gravel, sand and a top layer of biologically active topsoil. All of the lysimeters were dosed with a single application of PAH, TPH (total petroleum hydrocarbons) and metals. The loadings applied are given in Table 4, and were chosen to be 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 4b). At the end of the study period, the cores were destructively sampled and concentrations of each determinant at different depths were measured. Full details of the methodology and results from this study are given in Jefferies *et al.* (2008).

Analysis

All samples were analysed by TES Brethby at their UKAS accredited laboratories in Burton upon Trent, UK.

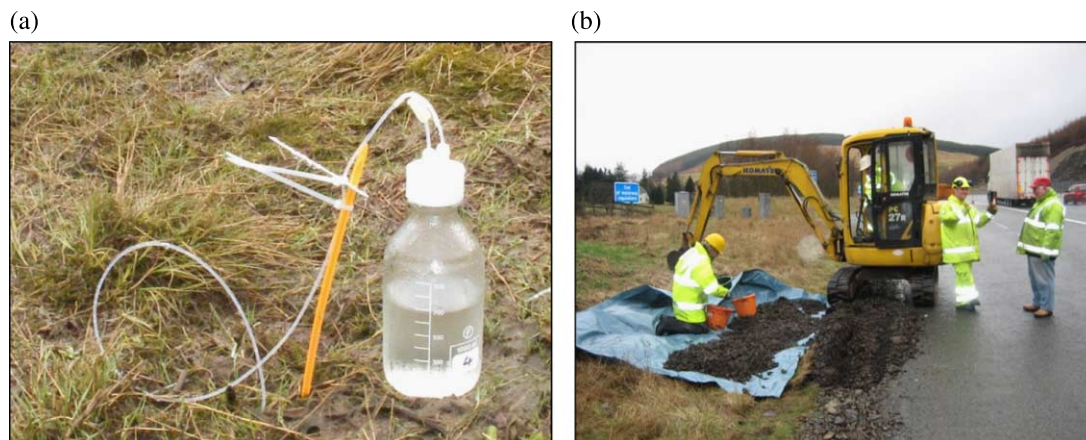


Figure 3 | Soil water collection (a) and filter drain sediment sampling (b) at Basin 29A.

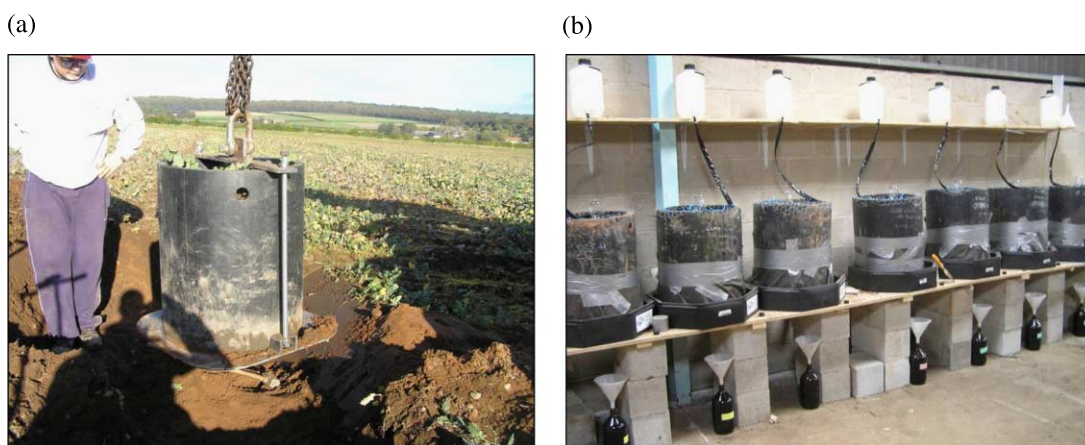


Figure 4 | Soil core collection (a) and leaching study (b).

Soil/sediment samples

Total petroleum hydrocarbons were extracted by ultrasonic enhanced solvent (hexane/acetone) extraction and analysed by GC/FID. Reporting limit for the method was 10 mg kg^{-1} . For metal determination, analysis was by ICP-MS following aqua regia digestion of air-dried samples. Reporting limits were 0.1 mg kg^{-1} for cadmium, 0.5 mg kg^{-1} for copper and lead, and 3 mg kg^{-1} for zinc. PAHs analysis was by GC MS following ultrasonic enhanced solvent (hexane/acetone) extraction. Reporting limit was 0.08 mg kg^{-1} .

Aqueous samples

Total petroleum hydrocarbons were analysed by GC FID following a liquid/liquid (pentane) extraction. Reporting limit for the method was 0.1 mg l^{-1} . PAH analysis was by GC MS following a liquid/liquid (dichloromethane) extraction, with a reporting limit of 0.01 ug l^{-1} . Total metals were analysed by ICP. Reporting limits were 0.0001 mg l^{-1} for cadmium, 0.001 mg l^{-1} for copper and lead and 0.002 mg l^{-1} for zinc.

RESULTS AND DISCUSSION

Table 2 shows the results of analysis of soil and sediment sampling carried out at the basins.

The results of the soil water sampling are given in Table 3, and results of the soil core mass balance calculations are

given in Table 4. 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 concentrations (see Table 2) 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. These results are given in Table 5.

Pollutant accumulation

Soil concentrations at the basin inlets (given in Table 2) were mostly higher than average values for sediments found in the filter drain (see Table 5) implying deposition and accumulation over time in basin soils. Pollutant accumulation in SUDS soils and sediments is a function of the rate of pollutant deposition and the rate of pollutant removal; if pollutants are deposited faster than they are removed, they will accumulate (Butler & Davies 2000). At the basins monitored, runoff is being collected from a large area ($18,000 \text{ m}^2$) and infiltrated over a much smaller area ($<500 \text{ m}^2$). In this situation, deposition $>$ removal, resulting in accumulation. However, the soil pollutant concentrations decrease with distance from inlet and with depth, illustrated by the zinc results shown in Figure 5, and the data in Table 5 show that, despite pollutant hotspots at the inlets, average soil pollutant concentrations across the basins were very similar.

Figure 5 also demonstrates the differing patterns of pollutant accumulation within the individual basins.

Table 2 | Analysis results for soil and sediment sampling at Basins 27A and 29A (dry weight concentrations)

	Cd (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Pb (mg kg ⁻¹)	Zn (mg kg ⁻¹)	pH	TPH (mg kg ⁻¹)	Total PAH (mg kg ⁻¹)
Basin 27A							
Basin soil							
Inlet (1) upper	0.4	155	73	562	7.7	3,607	12.19
Inlet (1) lower	0.2	60	32	211	8.2	1,856	5.01
Inlet (2) upper	0.4	116	58	395	7.5	1,947	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	1,591	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	4,400	10.97
Outlet (P)	0.4	90	52	312	6.9	2,634	6.78
Middle (P)	0.4	124	68	450	7.0	2,753	7.27
FS (P)	0.3	85	53	305	7.0	2,134	6.58
Basin 29A							
Filter drain							
1	0.25	64	43	376	8.9	3,718	11.94
2	0.21	52	34	274	8.7	1,756	5.29
3	0.20	62	45	379	8.9	2,687	8.02
4	0.31	84	51	528	9.3	2,361	12.10
5	0.29	80	50	459	9.2	2,423	11.87
6	0.21	53	35	315	9.2	2,435	7.52
Catchpit 1	0.18	37	22	160	8.9	1,000	2.37
Catchpit 2	0.35	83	53	423	9.0	7,426	15.07
Catchpit 3	0.43	107	56	590	8.2	6,002	25.40
Basin soil							
Inlet upper	0.58	198	107	1,050	7.7	4,869	16.71
Inlet lower	0.31	51	37	280	8.7	1,625	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

Table 2 | (continued)

	Cd (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Pb (mg kg ⁻¹)	Zn (mg kg ⁻¹)	pH	TPH (mg kg ⁻¹)	Total PAH (mg kg ⁻¹)
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	<0.10	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	1,387	2.31
3	0.10	9	17.8	59	7.2	182	1.63
4	0.16	25	28.2	138	6.9	3,946	3.34

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 the comparison of pond sediment pollutant concentrations at both basins shown in Table 5. There was a noticeable difference in soil and pond sediment quality 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.

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 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 (4,809 mg kg⁻¹) was almost

Table 3 | Basin 29A soil water analysis

Date sampled	Cd (mg l ⁻¹)	Cu (mg l ⁻¹)	Pb (mg l ⁻¹)	Zn (mg l ⁻¹)	TPH (mg l ⁻¹)	Total PAH (µg l ⁻¹)
23/03/07	<0.0001	0.001	<0.001	<0.002	<0.1	0.33
31/03/07	<0.0001	0.009	0.002	0.010	0.2	0.99
11/05/07	<0.0001	0.013	0.001	0.010	<0.1	0.16
29/06/07	<0.0001	0.009	0.002	0.020	0.1	No sample

Table 4 | 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*	% applied pollutants retained or degraded in soil cores†
Total PAH	137	0.06	99.94
TPH	55,000	0.07	99.93
Cu	163	0.45	99.55
Zn	2,730	0.31	99.69

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

†Values represent the minimum percentage for any soil type, which was measured in the clay lysimeters.

double the average from the rest of the filter drain (2563 mg kg⁻¹).

Previous studies have suggested that oxygen content is a limiting factor in the breakdown of oil in soils (e.g. [Shin *et al.* 2000](#); [Malina & Zawierucha 2007](#)). The more saturated a soil, the less oxygen it will hold ([Brady & Weil 1996](#)), and, consequently, the less potential there will be for aerobic microbial degradation. However, it has also been reported that periodic *anaerobic* conditions in normally aerobic soils can enhance hydrocarbon solubility, making compounds such as PAHs more available for degradation or transformation under aerobic conditions ([Pravecek *et al.* 2005](#)). The results from the M74 basins seem to confirm these findings; concentrations of oil in the submerged pond sediments, a permanently anaerobic environment, are considerably higher than in the basin soils, which are exposed to a variety of oxidation-reduction conditions as the basins fill and drain.

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. This is entirely in agreement with other

studies (e.g. [Ward 1990](#); [Winiarski *et al.* 2006](#)). 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 (all $R^2 > 0.99$), 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. Evidence from this study, however, indicates that any such movement of pollutants occurs slowly. Destructive soil sampling at the end of the lysimeter soil core 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

Table 5 | Average basin soil and pond sediment pollutant concentrations (dry weight concentrations)

	Cd (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Pb (mg kg ⁻¹)	Ni (mg kg ⁻¹)	Zn (mg kg ⁻¹)	TPH (mg kg ⁻¹)	Total PAH (mg kg ⁻¹)
Filter drain (excluding catchpits)	0.25	66	43	44	388	2,563	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	2,980	7.9
29A inlet basin soil	0.20	40	32	35	218	914	4.7
29A pond sediment	0.15	21	25	32	127	1,414	2.3

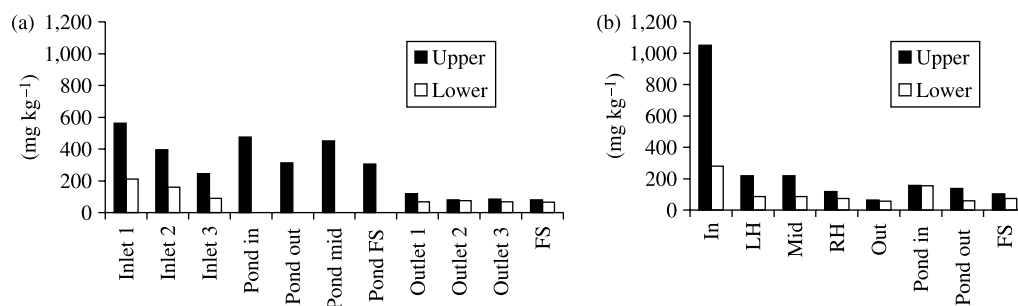


Figure 5 | Zinc concentrations (dry weight) measured at Basins 27A (a) and 29A (b).

either degraded or retained in the top 10 cm of soil. The lysimeter test only ran for a total of four months, but analysis of soil water from Basin 29A showed very low pollutant concentrations at 0.9 m, even after seven years in operation. Other authors have observed pollutants being retained in surface layers of SUDS soil and sediments in even older facilities (e.g. *Yousef & Lin 1992*; *Mikkelsen et al. 1997*; *Dechesne et al. 2004*), also indicating limited downward movement. While there is always the potential for attenuated pollutants to become mobilised due to physico-chemical changes in soils and sediments (*Clozel et al. 2006*) evidence from this study suggests that any movement is likely to be minimal.

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 (e.g. 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. 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.

Results from this study suggest that organic pollutant breakdown is slower in submerged sediments than in soil-based systems, which will affect residual soil/sediment contamination. Contaminants removed from the runoff accumulate in SUDS soils and sediments, with implications

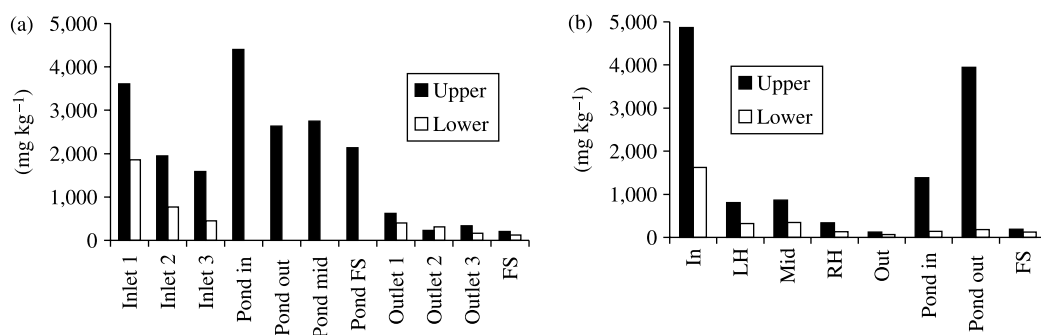


Figure 6 | TPH concentrations (dry weight) measured at Basins 27A (a) and 29A (b).

for the eventual disposal of contaminated sediments. While metal pollutants will remain until physically removed, organic pollutants have the potential to degrade under suitable conditions. It therefore makes sense to promote drainage infrastructure that not only attenuates pollutants, but also facilitates their degradation where possible.

CONCLUSIONS

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

- Any downward movement of pollutants through the soil appears to be slow, with most pollutants retained in the top 10 cm of soil.
- The degradation of organic pollutants in submerged sediments is slower than in exposed 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.

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