Project UEUW02

SUDS POLLUTION DEGRADATION

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EXECUTIVE SUMMARY

Project code: UEUW02

Project Title
SUDS POLLUTION DEGRADATION

Project funders/partners: SNIFFER,
Environment Agency of England & Wales
Scottish Environment Protection Agency
Highways Agency
Department of the Environment Northern Ireland

Background to the Research
SNIFFER Project UEUW01 **SOURCE CONTROL OF POLLUTION** published in February 2008 included field monitoring and artificial dosing experiments. It demonstrated the effectiveness of various SUDS techniques in attenuating and degrading a range of diffuse source pollutants arising from motor vehicles. The project established an evidence base to aid future policy development in this area.

Two aspects of the work could not be finalized by February 2008 and it was decided to continue with these and, since additional work was being undertaken, a third aspect was undertaken. All three aspects are reported in this supplementary report.

Objectives of the Research
The three aspects reported in this supplementary report form the objectives which were;

1. **To continue the degradation study**. Samples had been stored and it was decided to analyse the soil samples after a further period of approximately six months of degradation.
2. **To integrate results from two research programmes.** A separately funded research programme was carried out in parallel with the work undertaken for report UEU01 but was not reported there. This report includes a preliminary integration of the research outputs of both programmes.
3. **To develop a risk assessment flowchart.** A speculative design flowchart was included in the first draft of the final report of UEUW01. It was considered that some further work developing this flowchart was merited.

Key Findings and Recommendations
It is concluded that it is better to control oils and Poly Aromatic Hydrocarbons (PAHs) in soil based SUDS at locations which are periodically wet and dry such as in the base of detention basins, swales or infiltration basins. Basins and swales are good for sediment removal and, by association, oils and PAHs will also be best removed there and not in ponds or wetlands.

This research supports guidance that a soil based system should be used as the primary control of sediments, with the pond or wetland as a polishing component where required.

For the traffic loadings in this study, the degree of contamination found suggests road traffic is a significant source of oil, but SUDS are effectively trapping them, protecting the receiving water environment.

Waste arisings from SUDS serving busy highways will most probably have to be treated as contaminated waste and reduced and recycled. However, the amount of waste which might arise can certainly be minimised using the results of this research.

Results from this study suggest that source control measures such as grass filter strips, swales, and detention areas, should be priority features of sustainable drainage networks serving urbanised areas and highways, where oil contamination may be significant. This is entirely consistent with the treatment train and stormwater management concepts for sustainable drainage systems.

Information to assist in preparing a design flowchart to meet the environmental and other risks posed by pollutants from highways has been considered in this report. A diagram has been included which shows the type of research/ studies required to develop this flowchart.

Recommendations for Uptake
The results will be best used to inform the ongoing improvements to the Design Manual for Roads and Bridges. This work will be taken forward by the Highways Agency.

Key words: Sustainable Urban Drainage Systems, SUDS, Groundwater Protection, Pollutant Breakdown, PAH Studies

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1 INTRODUCTION

1.1 Resumé of SNIFFER Report UEUW01

1.1.1 Objectives of the research reported in SNIFFER Report UEUW01

SNIFFER Report UEUW01 was published in February 2008 following a two year programme of investigations which principally studied the levels of contamination found in the soils of basins, swales and ponds which had been installed alongside motorways and roads for approaching ten years.

The objectives of the research were:

1. Determine the risk of movement of pollutants through soil into groundwater in soft-engineering SUDS;
2. Measure the immobilisation and degradation of priority pollutants and fate of nutrients in soft engineering SUDS;
3. Identify the degradation products in a range of SUDS techniques;
4. Determine the conditions for the optimal breakdown of oil and PAHs in the range of SUDS investigated;
5. Determine the conditions for the optimal nutrient uptake or stabilisation within a range of SUDS techniques;
6. Provide monitoring data for existing SUDS facilities, and conduct experimental work to aid the interpretation of the field site data.

1.1.2 Outline of the studies undertaken for SNIFFER Report UEUW01

The project involved four separate but linked studies of different aspects of SUDS systems addressing the same contaminants in each case.

- Nutrients study – desk top study linking nutrients in agricultural and urban areas.
- Lysimeter study – a semi - field study of twelve lysimeters.
- Pollutant Breakdown – a laboratory based degradation study.
- Field studies – four motorway SUDS and one motorway service area.

1.1.3 Key findings in SNIFFER Report UEUW01

1. The risks to groundwater from passing highway drainage on to soil based SUDS is low. There is evidence of very low rates of downward movement of contaminants.
2. In general, contamination from the highway runoff in the basin soils was found to reduce horizontally from the inlet to the outlet. There was a noticeable difference in the magnitude of horizontal change between the basins studied, most likely as a function of the variation in inlet basin design. Where flow could spread across the broad basin, pollutant concentrations dropped sharply. Where inlet flow was confined to a narrow channel concentrations remained higher. This points towards effective attenuation of pollutants in the soil based systems.
3. The vast majority of heavy metals, PAHs and petroleum hydrocarbons (TPH) are retained in the top 10 cm of soil. This accumulation may impact on soil function with time and has potential implications for long term maintenance. Pollutant levels in the pond sediments were generally higher than in the soil.
4. The highest TPH and PAH contamination found in the study came from one of the filter drain catch pits. Average pollutant concentrations in filter drain sediment

were all lower than found in the upper 10 cm soil samples of the downstream basin suggesting accumulation in the basin soil over time.

5. At the grass filter strip monitored, which was located at a motorway service station, no sediment had accumulated in the downstream filter drain at all, implying that it is all being retained on the grass strip.
6. Metals will accumulate in the surface soil layers of infiltration based SUDS. The tests were on bare soil lysimeters but in practice there would be a vegetative layer that would take up some of the pollutants retained in the soil, reducing further the risk of movement to ground water. The data generated in these experiments would suggest that infiltration based SUDS represent a low risk to groundwater.

1.2 Rationale for the Studies Reported in this Extension Report

Continuation of Degradation Study. Approaching 360 samples for the degradation study remained out of those ‘seeded’ at the start of the study in July 2007. The rationale for preparing these extra samples was that it would be desirable to extend the study beyond the four months remaining of the contract at the time even though resources were not immediately available for the analysis and evaluation of results.

Additional funds were found to carry out continuing analysis of the samples to cover the period October 2007 – June 2008 with the last sample being taken out in June 2008. Each DAT batch required 30 samples to be analysed. This made 120 samples to be analysed on the basis of 50% for TPH and 50% for PAH. In practice a reduced number of samples were actually analysed for the following reasons:

- It was concluded during the extension period that sufficient information could be gathered from analysis of fewer samples tested for TPH and that resources would be wasted by analysing the full number of possible TPH samples.
- Further PAH samples were sent for analysis but the analysis results were inconclusive. The reason for this were not clear but it was decided not to continue with the PAH analysis.

Integration of Results from the two Research Programmes. It was recognised that the information gathered for SNIFFER report UEUW01 did not take into account a parallel research programme undertaken by the research student Fiona Napier. This proposal is to develop the ideas of a risk assessment from the SNIFFER funded work into something of greater value. To develop this would use all of the information from both Fiona’s research programme and from the SNIFFER funded work.

Risk Assessment Flow Chart. The draft final report of SNIFFER Project UEUW01 included two ideas for the start of a flowchart which would be the precursor for a SUDS for highways design guidance. The latter project would only progress if the Highways Agency took a lead role. It was decided that the flowchart was conceptually too big a step for the resources and information available but that a matrix to inform the development of a flowchart would be useful. This is included as Figure 21.

2 CONTINUATION OF DEGRADATION STUDY

2.1 Introduction to Extension of Degradation Study

The degradation study report submitted as part of the UEUW01 Final Report reported the results for oil and PAHs collected after approximately 2 months. While it was possible to report sound conclusions for PAHs, the same could not be said for the oil component. The extreme variability noted in results from replicate samples made it impossible to determine any trend. This variability has been noted in a previous similar study (Flowers et al, 1984), and is almost certainly linked to variations in the bio-availability of oil in individual jars.

It was decided that a more pronounced reduction in concentration would be needed to allow a valid comparison and interpretation of the results, and to this end it was decided to extend the study by a further 6 months giving a maximum degradation period of 280 days. This update reports on the further oil analysis carried out.

In addition, further PAH samples were also sent for analysis. However, the results were inconclusive, and have not been included.

2.2 Introduction to Degradation Study

Microbial activity is the main method of hydrocarbon degradation in soils and sediments (Cerniglia, 1992; Wilson and Jones, 1993), and many factors affect the process. This study was designed to measure the degradation of oil and PAHs under a variety of conditions.

An increasing number of studies investigate how to optimise degradation with a view to enhancing the bioremediation of contaminated sites. While these studies offer a useful starting point for the current study, they are not always applicable to pollutants in SUDS. Bioremediation usually involves active treatment, such as seeding with suitable microbes, tilling of soil or the addition of nutrients, and most studies focus on how these activities can optimise microbial degradation rates. Once a SUD system has been constructed, maintenance at the site is minimal, and usually confined to grass cutting. Soils and sediments will be undisturbed until such times as it is necessary to remove them due to excessive build up, and so any biodegradation of pollutants will be un-enhanced. In light of this, the study undertaken was limited to factors which are directly of relevance to SUDS.

This was a laboratory study, carried out under controlled conditions. Separate batches of soil were dosed with known quantities of either oil or PAH and incubated. Degradation over time was measured by removing samples at various time intervals to determine the concentration of oil or PAH remaining.
Parameters included in study

2.2.1 Moisture content

Basins and swales will fill and drain down, exposing the soil to both anaerobic and aerobic conditions, and a corresponding variety of oxidising-reducing conditions. In contrast, submerged pond sediments will experience a fairly stable anaerobic environment. Pollutant degradation rates can be expected to vary, and this could influence the type of SUD chosen for a particular site.

2.2.2 Temperature

Although temperature is not a parameter which can be altered in SUDS, it is one of the most important factors affecting microbial activity. Temperature has been included as a parameter in the study to examine the effect of seasonal variation in temperature on pollutant degradation in SUDS. It is possible that organic pollutants experience cycles of degradation determined by temperature – rapid breakdown in summer temperatures and slower rates in winter.

2.2.3 Pollutant concentration

It has been reported that the initial pollutant concentration present in soil has a direct bearing on the rate and extent of subsequent degradation (Linz and Nakles 1997). The pollutant burden in roadside SUDS will vary with the volume and pattern of traffic and it would be useful to be able to predict the degradation rates which could be expected under specific conditions. Most of the degradation studies reported in the literature have studied high concentrations typically found at contaminated sites such as old gasworks. This study uses the much lower - but still significant - concentrations measured in in-situ SUDS at roadside sites.

2.2.4 Bioactivity of soil

While it is assumed that most reduction in concentrations will be due to microbial degradation, two control batches using sterilised soil were included to allow an accurate assessment of the percentage of degradation due to physical and chemical processes.

2.2.5 Soil selection

The soil used in the study was the same sandy loam agricultural topsoil used in the lysimeter study. Ideally, the same range of soils used in the lysimeter study could have been included, but for logistic and budgetary reasons this was not possible. The sandy loam was seen as a suitable compromise, representing in many ways a worst-case scenario of a free draining soil with low organic content.

The soil was analysed before commencement of the study for nutrient content, existing PAH and TPH levels, organic content, moisture content, cation exchange capacity and pH. The results are shown in Table 1.

Table 1. Results of initial analysis carried out on soil used in lab study

Nitrate	**Total Phosphorus**	**T.O.C.**	**Moisture content**	**pH**	**Total PAH**	**TPH**	**Cation Exchange Capacity**
mg kg-1	mg kg^{-1}	%	%		mg kg-1	mg kg-1	meq/100g
8	414	0.95	7.80	6.01	*	59	7.3

*each individual PAH reported below limit of detection

It was necessary to ensure that nutrient levels could support microbial activity. Nitrogen is considered the main growth limiting factor for soil microbes (Flowers et al, 1984), so the nitrate level of the soil was compared to soils from other studies. This was within the range of reported concentrations (2.5mg kg^{-1} – 29.8mg kg^{-1}: Flowers et al, 1984; Mueller and Shann, 2006), and slightly higher than the values measured in field sites soils sampled for this study (<7 mg kg^{-1}). Accordingly, it was judged unnecessary to add further nutrients to the soil. The study was designed to represent realistic conditions found in SUDS, and the addition of fertiliser is not a standard SUDS maintenance activity. Supplementing the soil could artificially enhance microbial activity in the soil, perhaps giving an exaggerated degradation rate.

The soil showed a background TPH level of 59 mg kg^{-1}, possibly due to the fact that the field has previously been used to grow oilseed rape. As the level of oil being applied in the study (3500 and 10000 mg kg^{-1}) were so much greater, this existing concentration was not seen as a problem. Any existing PAH levels were below the limits of detection.

2.3 Structure of study

The soil was air dried and sieved to 2mm. A portion of soil was sterilised by autoclaving twice (consecutive days) at 121°C and 15 psi for 20 minutes. Glass amber jars (125ml) were used to incubate all samples. Each bottle was given a unique number (1-600), and had 25g ± 0.02g weighed into it. The bottles were then divided into 10 groups of 60 and designated Batch 1-10. The moisture content of the soil in each bottle was adjusted to the required level, and pollutants were added to give the desired concentration. The bottles were then incubated at the relevant temperature. The treatment of each batch is shown in Table 2.

Table 2. Test batch parameters

Soil Test Batch	**Temperature (°C)**	**Moisture content (%)**	**Pollutant applied**	**Pollutant conc** mg kg^{-1}
1	15	40	PAH	15
2	5	40	PAH	15
3	15	40	PAH	30
4	15	90	PAH	15
5	15	40	Oil	3500
6	5	40	Oil	3500
7	15	40	Oil	10000
8	15	90	Oil	3500
9*	15	40	PAH	15
10*	15	40	Oil	3500

*** sterilised soil (all soil used for other batches biologically active)**

The oil applied was a 50/50 mix of 100% synthetic and 100% mineral engine oils. The oil mix was weighed into each bottle using a dropper to give the required concentration.

At designated intervals (DATs - days after treatment), 3 bottles per batch per DAT were removed for analysis.

Oil is a complex mix of HMW and LMW compounds, some of which will also be susceptible to the rapid degradation noted for LMW PAHs. Working on this premise, the same logic has been used for the oil results, and in all calculations and graphs, sterile soil DAT 0 values have been used as the start concentrations for all batches (doubled for Batch 7).

Since no further results were obtained for the PAH degradation, nothing further is reported here.

2.4 Results for Oil

The full results for each batch are shown in Tables 4 - 7. Figure 1 shows the percentage reduction calculated for each batch.

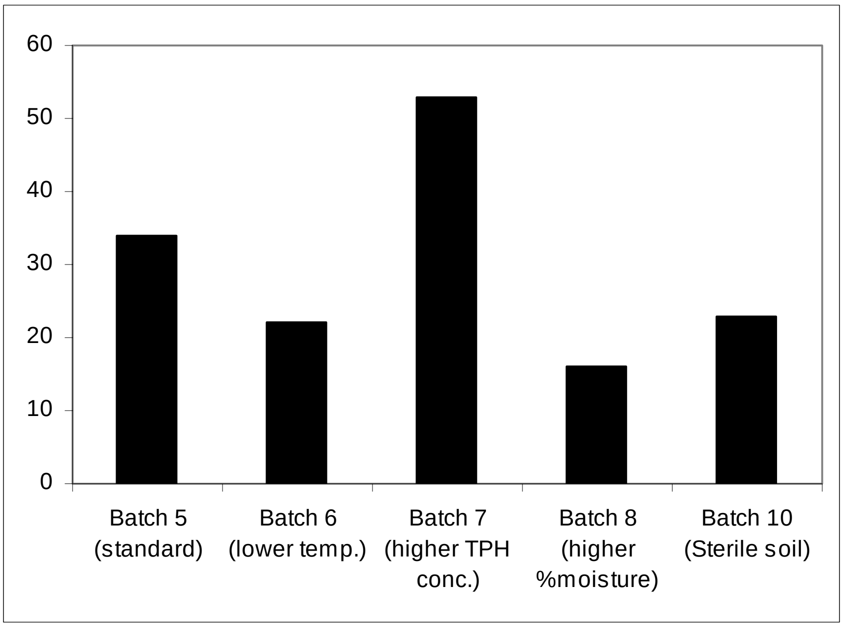

Figure 1. Percentage reduction of oil concentrations after 224 days (based on means)

2.4.1 Effect of biological activity

Table 3. Percentage reduction due to biological activity

		% reduction
Biologically active soil	(Batch 5) (DAT = 224 days)	32
Sterile soil	(Batch 10) (DAT = 211 days)	23

This is perhaps one of the most informative results, as it demonstrates the importance of non-biological processes in oil behaviour in soil. The solvent extraction procedure would release any bound compounds from the soil, which means that the only non-biological process which could result in the permanent removal of oil from the jar would be volatilisation. Compounds volatising into the bottle headspace would be lost as soon as the bottle was opened, resulting in a measured loss for the sterile soil. A similar result was observed in the PAH study, where a 25% reduction was observed in sterile soil, presumably from volatilisation.

These changes may also be observed in Figures 2 & 6.

2.4.2 Effect of temperature (DAT = 222 days)

Table 4. Percentage Reduction due to temperature

		% reduction
15°C	(Batch 5)	34
5°C	(Batch 6)	22

Temperature would be expected to affect both biological and non-biological processes, and this is reflected in the lower reduction in concentrations measured at 5°C. These changes may also be observed in Figures 2 & 3.

2.4.3 Effect of pollutant concentration (DAT = 222 days)

Table 5. Percentage Reduction – Pollutant Concentration

	% reduction
3500 mg kg^{-1} (Batch 5)	32
10000 mg kg^{-1} (Batch 7)	46

The highest reductions measured in the study were observed in the soil which received the highest dose of oil at the beginning of the experiment. This agrees with results reported in other studies. These changes may also be observed in Figures 2 & 4.

2.4.4 Effect of moisture content (DAT = 222 days)

Table 6. Percentage Reduction - Moisture Content

	% reduction
40% moisture (Batch 5)	34
90% moisture (Batch 8)	16

The higher moisture content of the soil in Batch 8 had a distinct inhibitory effect on oil reduction. The fact that the measured reduction was lower than that measured for the sterile soil implies that both biological activity and non-biological processes are affected. These changes may also be observed in Figures 2 & 5.

Table 7. Results for TPH Degradation Tests

Batch 5 (standard)		Batch 6 (5C)		Batch 7 (10000mg kg-1)		Batch 8 (90% moisture)		Batch 10 (sterile soil)	
DAT	TPH mg kg-1	DAT	TPH mg kg-1	DAT	TPH mg kg-1	DAT	TPH mg kg-1	DAT	TPH mg kg-1
0	4256	0	4256	0	12463	0	4256	0	4256
0	4200	0	4200	0	12463	0	4200	0	4200
0	4522	0	4522	0	12463	0	4522	0	4522
3	2380	3	4158	3	12250	3	4674	3	4172
3	4186	3	4116	3	12180	3	4807	3	4088
3	4298	3	4438	3	13160	3	4940	3	4326
7	3920	7	4424	7	12698	7	4351		
7	3934	7	4270	7	12096	7	4237		
7	4004	7	4172	7	11956	7	4294		
14	2702	14	3738	14	7210	14	8094	15	4144
14	3066	14	2996	14	8372	14	7980	15	4060
14	2618	14	3374	14	7070	14	8740	15	4298
28	3458	28	4060	28	17640	28	4085	31	3780
28	3234	28	4256	28	11732	28	5130	31	4004
28	2954	28	4256	28	11536	28	4370	31	3654
42	1988	42	2828	42	5446				
42	1708	42	3836	42	9954				
42	1974	42	2954	42	6930				
59	3962	57	3220	57	9716				
59	2366	57	2464						
59	2982	57	2534	57	10094				
126	3504	124	3300	124	8616	124	4692	113	3876
126	3480	124	3336	124	8964	124	4488	113	3816
126	3564	124	3216	124	9192	124	4352	113	3840
160	3792	160	3780	160	7788	160	4709		
160	3540	160	3948	160	7368	160	4709		
160	3216	160	3564	160	7092	160	4641		
224	3399	222	3487	222	8129	222	3930	211	3324
224	2233	222	3454	222	5797	222	3450	211	3264
224	3157	222	3124	222	6215	222	3465	211	3384
280	3014			280	5775				
280	2981			280	6017				
280	2574			280	5918				

lost in transit
lab error
bottle broken in transit

2.5 Variation of TPH Degradation with Time

The results from the analysis of the samples 'spiked' with oil are shown in figures 2 – 6. The apparent lack of consistency in the first 50 days may be contrasted with the consistent results from DAT 70 onwards.

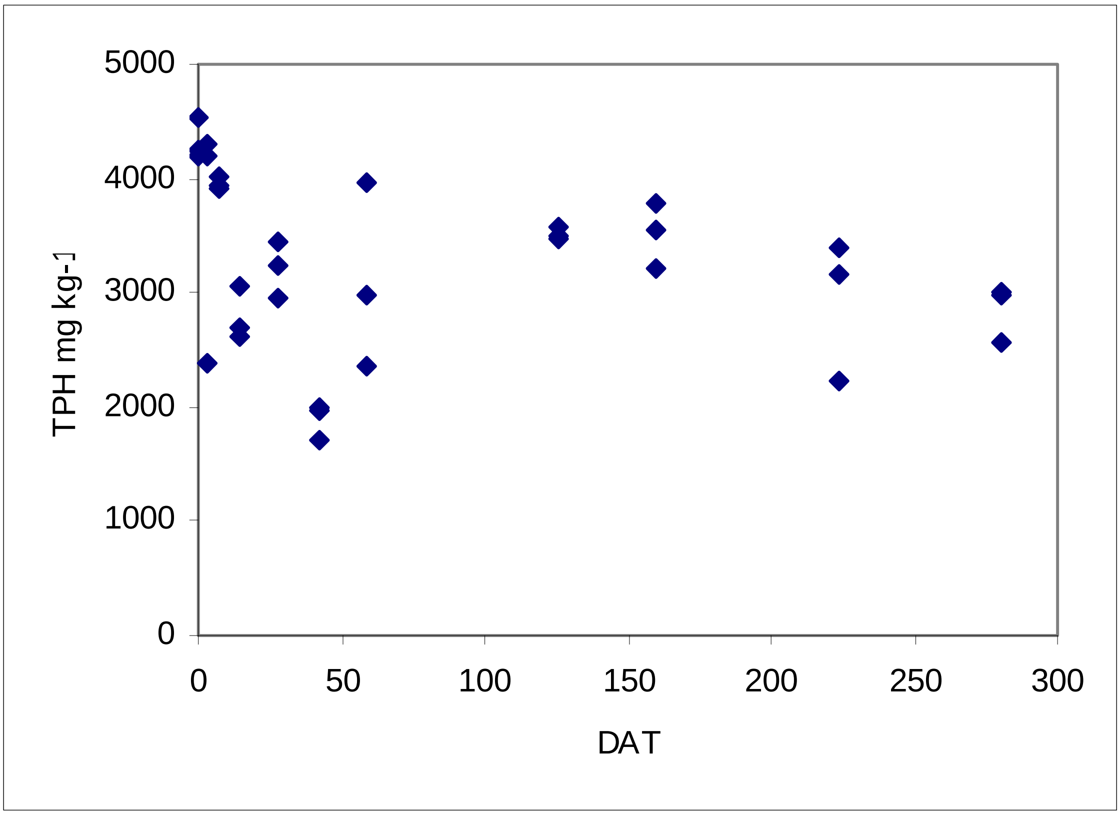

Figure 2. TPH Batch 5 (Standard oil)

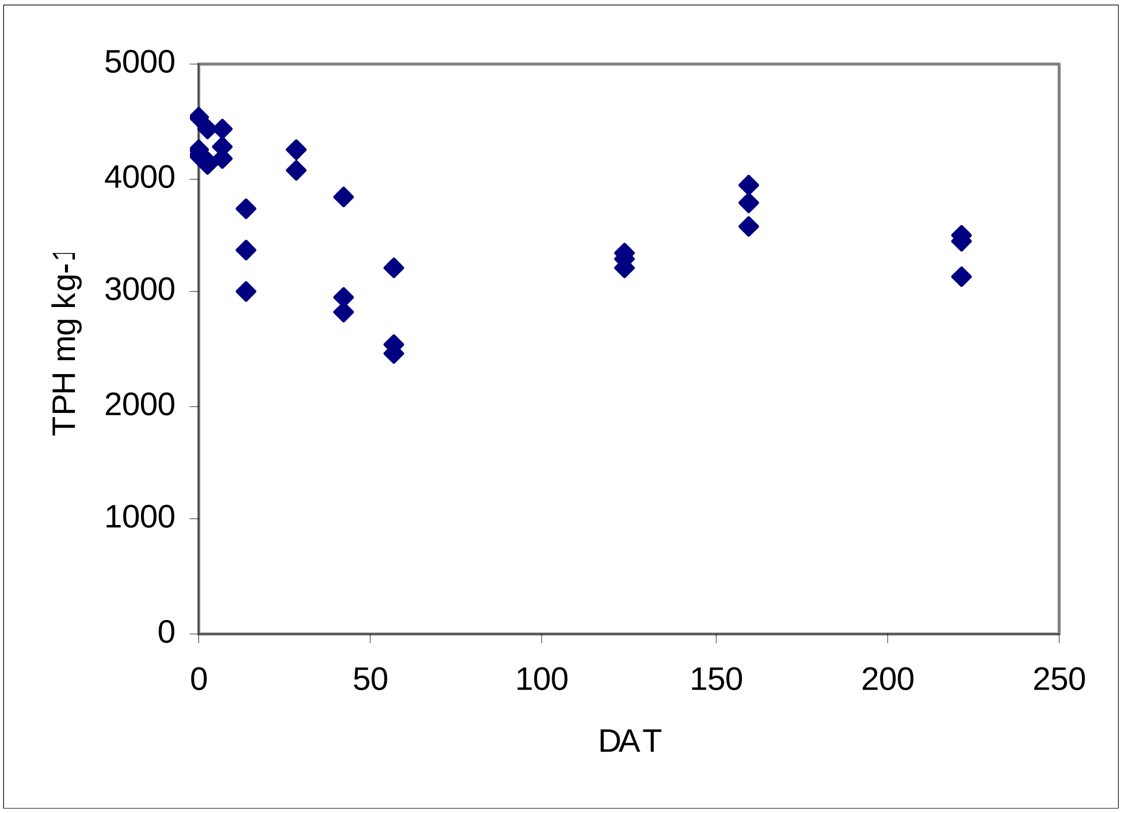

Figure 3. TPH Batch 6 (Lower temperature)

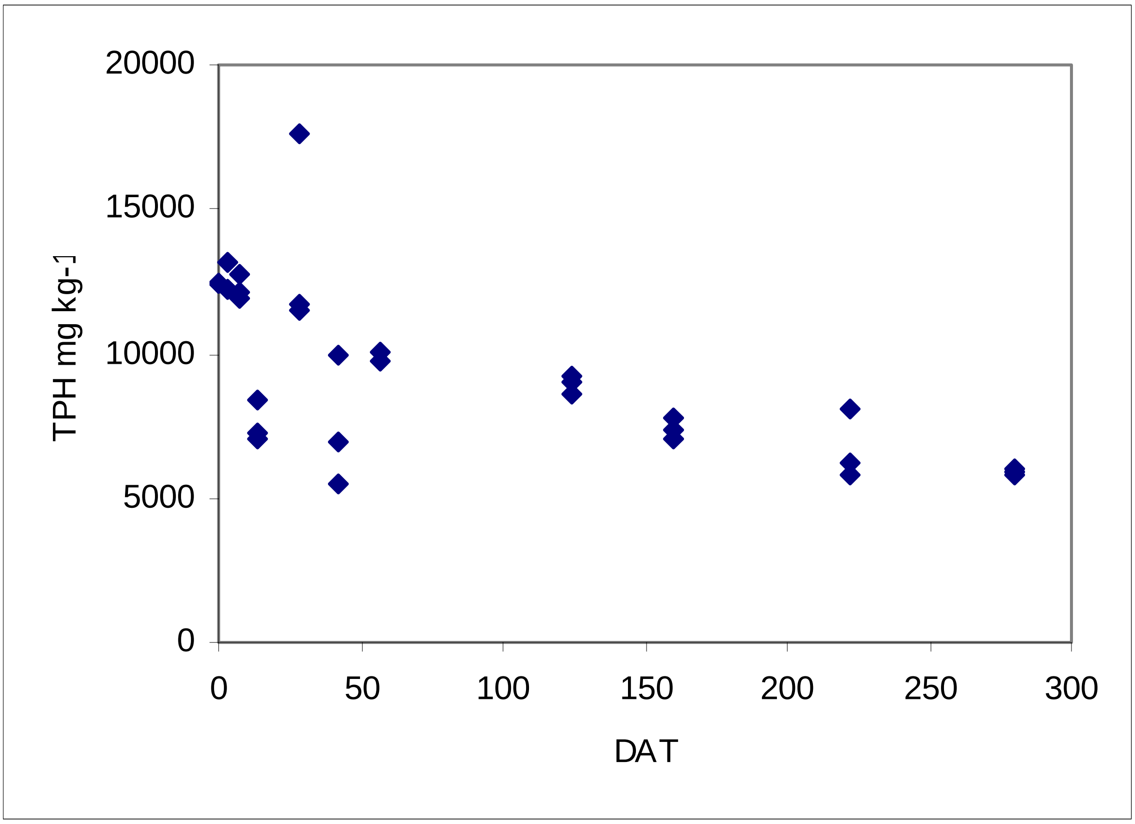

Figure 4. TPH Batch 7 (higher oil concentration)

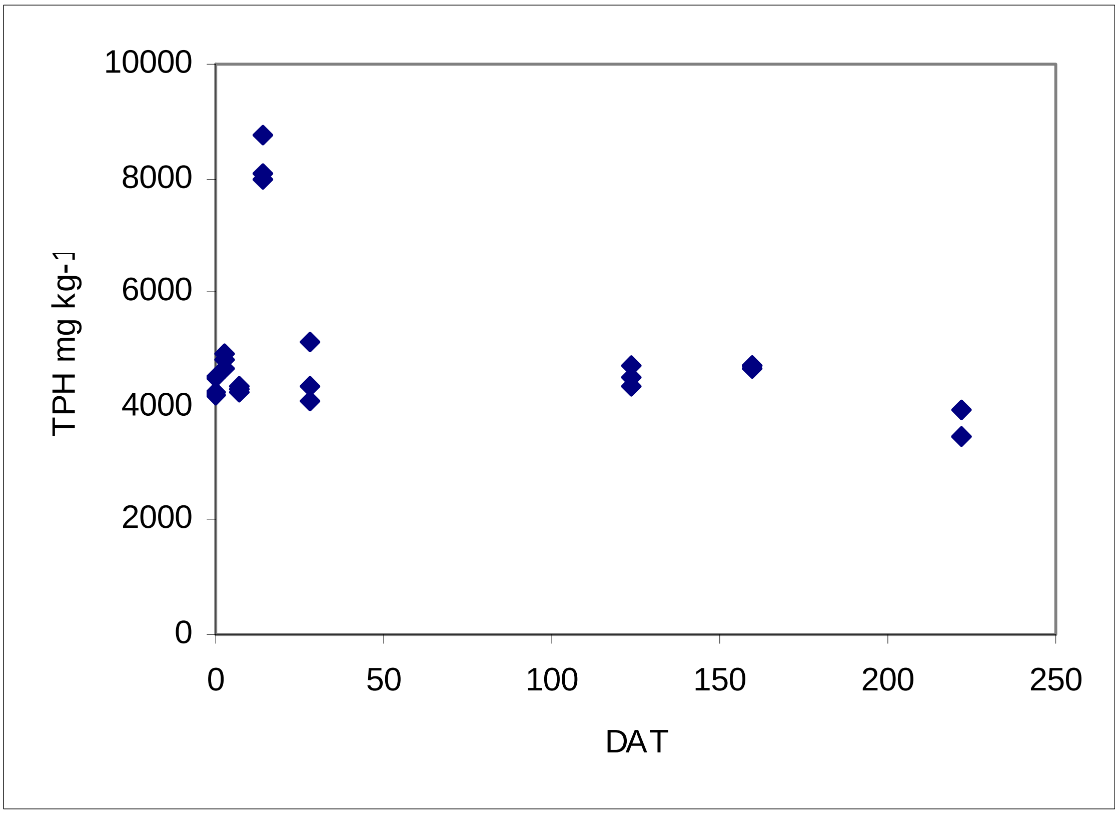

Figure 5. TPH Batch 8 (higher moisture content)

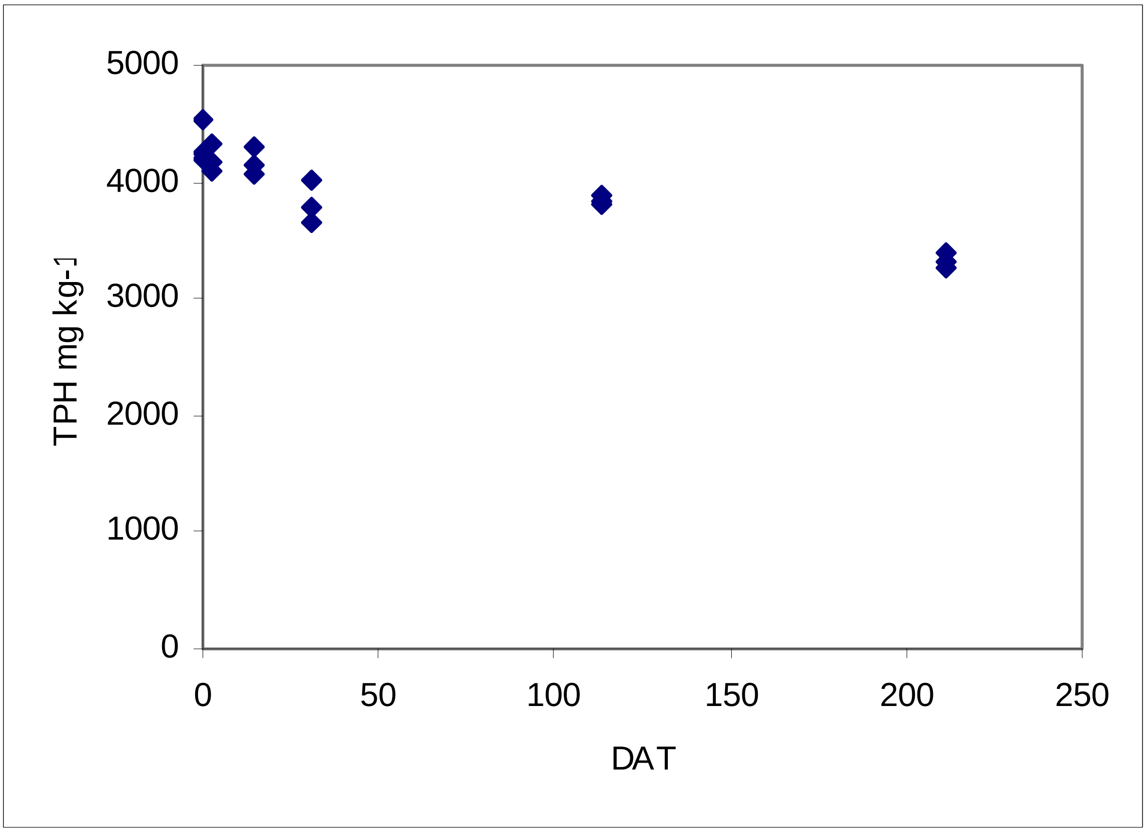

Figure 6. TPH Batch 10 (Sterile soil)

3 INTEGRATION OF RESULTS FROM THE TWO PARALLEL RESEARCH PROGRAMMES

SNIFFER Project UEUW01 produced a very large amount of data. A separate research programme, funded by the University of Abertay Dundee and by SEPA, ran in parallel and it was important that work was undertaken to integrate the outputs from both programmes. While undertaking this integrative work, it was found that one of the most fruitful areas of study was the behaviour of TPH (and to a lesser extent, PAH) and it was decided to concentrate on TPH behaviour.

3.1 Integration of Studies

The different studies are shown in Table 8.

Table 8. Sites included in integrated study

STUDY COMPONENT	AADT	TREAT TRAIN	DESCRIPTION	ISSUES ADDRESSED
Field studies				
[1]M74 Detention Basins 27A and 29A, SW Scotland	13,000	2 / 3	Grassed basins incorporating small lined pool. Piped inflow.	Accumulation in soils. Accumulation in submerged sediments. Pollutants from soil to water.
[1]M74 Pond systems 33A & B, and 40A & B, SW Scotland	13,000	2	Treatment ponds in sequence. Piped inflow.	Accumulation of submerged sediments. Treatment train efficiency
[1]M42 Hopwood MSA, England	400	3	Treatment train for runoff from HGV park (sheet flow).	Treatment train efficiency
[2]A8000 swale Edinburgh	30,000	1	Roadside swale receiving both piped and sheet inflow	Accumulation in soils. Vertical change in concentration
[2]A90 roadside grass verge, Edinburgh	20,000	1	Grassed verge receiving road spray	Accumulation in soils. Vertical change in concentration.
Experimental Studies				
[1]Soil core lysimeters			Soil cores dosed with pollutants and irrigated	Vertical movement
[1]Lab-based batch degradation study			Soil samples dosed with oil and PAHs and incubated under various conditions	Degradation of organic pollutants
[1]Experimental swales			Two swales. Pollutant applied laterally	Complete lack of passage of pollutants.

Notes:
[1] Included in final report for SNIFFER UEUW01
[2] Site from Abertay research programme

In addition to the sites in report UEUW01, two further sites provided valuable data;

- A8000 swale – a grass swale/ basin on a highly trafficked feeder road to the Forth Road Bridge. Traffic was stop / start for long periods every day and higher contamination levels were observed. See Figure 7.
- A90 roadside grass verge. This verge on a main artery to the City of Edinburgh was sampled to be able to compare locations where the contamination was from airborne pollution only. See Figure 9.

At both sites, samples were taken at different locations horizontally and vertically.

Figure 7. A8000 Swale

Figure 8. A8000 Swale

Figure 9. A90 Verge

3.2 Focus on TPH

One of the main findings of SNIFFER Project UEUW01 was the observed contrast between oil concentrations in submerged sediments and soil based systems, even where loadings are similar. Measured concentrations in submerged systems were consistently higher, suggesting that organic pollutant breakdown is reduced in submerged sediments. This is backed by evidence from the lab-based degradation study, which showed the measured reductions in concentrations to be adversely affected by increased soil moisture content. The lab study also highlighted volatilisation as an important mechanism in oil behaviour, a process which occurs readily in exposed (and especially in drying) soil, but not in submerged sediments.

The evidence gathered suggests that oil should perhaps be considered the main pollutant of concern when designing highway SUDS. While road runoff also contains a mix of toxic metals, since they are conservative pollutants these will undergo little change once in a system. In contrast, it is possible to design systems which will encourage breakdown and dissipation of organic pollutants. This premise has influenced further interpretation of the data.

The evidence in this report points to SUDS being able to be designed in such a way as to minimise/reduce the amount of management or recycling of waste products from these systems as part of their maintenance regime. Waste arisings from SUDS serving busy highways will most probably have to be treated as contaminated waste and reduced and recycled. The findings of this report do not suggest a particular waste management strategy. However, the amount of waste which might arise can certainly be minimised using the results of this research.

3.3 Results

3.3.1 A controversial conclusion

It is concluded that it is better to control oils and PAHs in soil based SUDS at locations which are periodically wet and dry such as in the base of detention basins, swales or infiltration basins. The pollutants, once removed from the runoff, will degrade much more readily in a basin or a swale than under water in a pond or wetland. In some respects this is contrary to the guidance in many literature sources which promote the use of basal sediments in ponds or wetlands for this purpose. This promotion tends to be by default since the pond or wetland is almost universally promoted as the best for removing pollutants from runoff and little actual supporting data are quoted. However, the new information in this report tends to be complementary since different SUDS devices have their own efficiencies in removing pollutants in the first place.

If anything, it challenges the mantra that a pond is always best for pollutant removal and brings to the fore the issues inherent in the resulting pond sediments – Oils and PAHs may not break down in a basal sediment so may be more likely to be classified as hazardous waste. Furthermore, basal sediments are normally more difficult to remove than sediments in swales and basins because they are under water.

This research supports guidance that a soil based system should be used as the primary control of sediments, with the pond or wetland as a polishing component where required.

This conclusion should be seen in the context of published information including;

- CIRIA SUDS Design Manual Table 5.7 (CIRIA 2007)
- DMRB 'Vol 4 Section 2 : 3.11 *'Biological degradation of oils and grease is relatively slow, taking several days even in ideal conditions. The biodegradation process is therefore considered to be of less significance in the removal of organic constituents from runoff than settlement. The process is likely to be of significance, however, in the in-situ degradation of accumulating material. Ponds and SF wetlands are probably the best systems for such in-situ transformation as they are more likely to support the requisite aerobic microbes.'* (Highways Agency 2008*).*

3.3.2 Field Study

A summary of the field study results collected are presented in Table 9. Oil concentrations measured at the M74 basins are shown in Figure 10 and Figure 11. In the basin soil, concentrations were found to reduce with depth and distance from inlet. However, at both basins it was observed that oil concentrations increased again in submerged sediments in the pools.

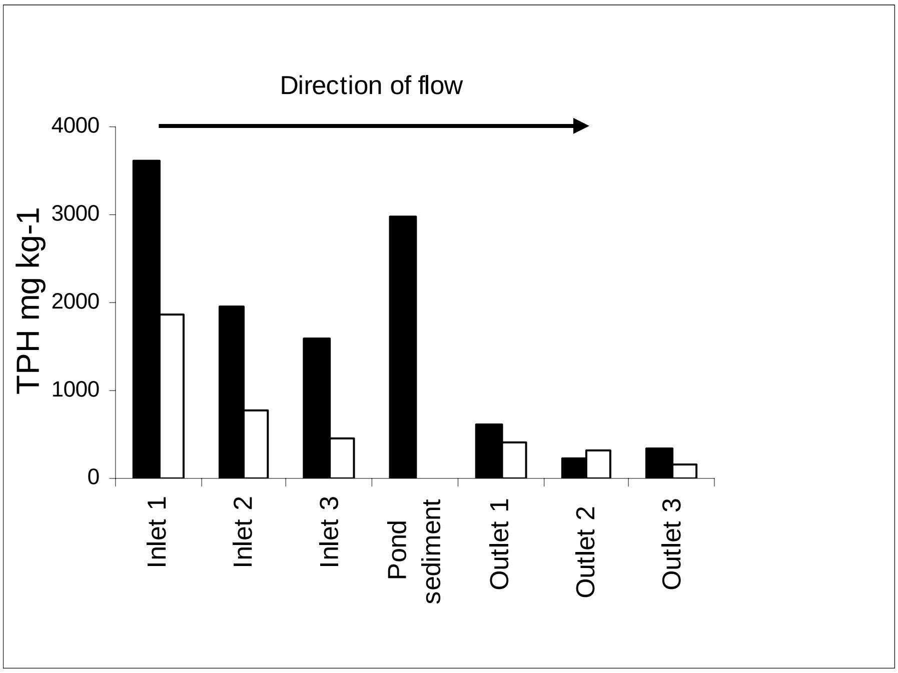

Figure 10. Oil concentrations measured in soils and sediments at M74 Basin 27A

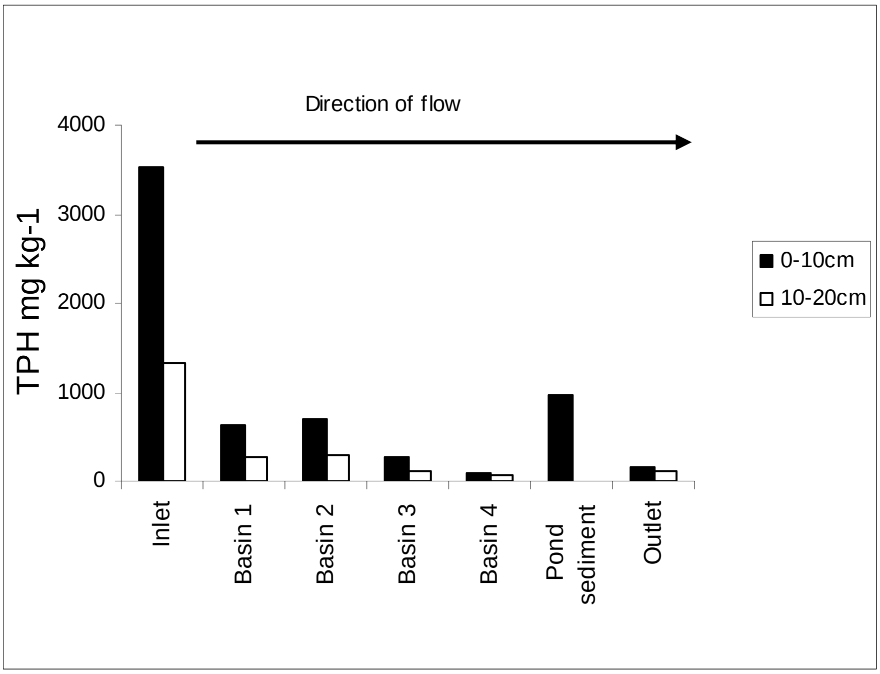

Figure 11. Oil concentrations measured in soils and sediments at M74 Basin 29A

Table 9. Summary of field study results. Reported inlet and outlet values are for discrete spot samples collected at each location. Reported average values are explained in footnote. All concentrations mg kg-1

LOCATION	SOIL DEPTH	A8000 SOIL[1]	A90 SOIL[1,3]	27A BASIN SOIL[2,4]	27A POOL SEDIMENT[2]	29A FILTER DRAIN SEDIMENT[2]	29A BASIN SOIL[2,4]	29A POOL SEDIMENT[2]	HOPWOOD FILTER STRIP SOIL[2,5]
Inlet	0-10cm	11850	1520	3607	4400	-	4868	765	799
	10-20cm	9270	722	1856	-	-	1625	-	120
	20-30cm	4485	-	-	-	-	-	-	-
Outlet	0-10cm	4290	-	337	2634	-	190	2064	-
	10-20cm	-	-	161	-	-	127	-	-
	20-30cm	445	-	-	-	-	-	-	-
Average (n)		6011 (8)	818 (12)	888 (12)	2980 (4)	2563 (6)	914 (10)	1414 (4)	423 (5)

[1] result reported as total hydrocarbons (THC)
[2] result reported as total petroleum hydrocarbons (TPH)
[3] average soil concentration measured in top 20cm of soil at distances of 0m and 1.5m from road edge
[4] average soil concentration measured in top 20cm of soil across inlet and outlet
[5] average soil concentration measured in top 20cm of soil at distances of 1m and 3m from tarmac
[6] average soil concentration measured in top 20cm of soil along base of swale

Note; n = number of samples used in averaging.

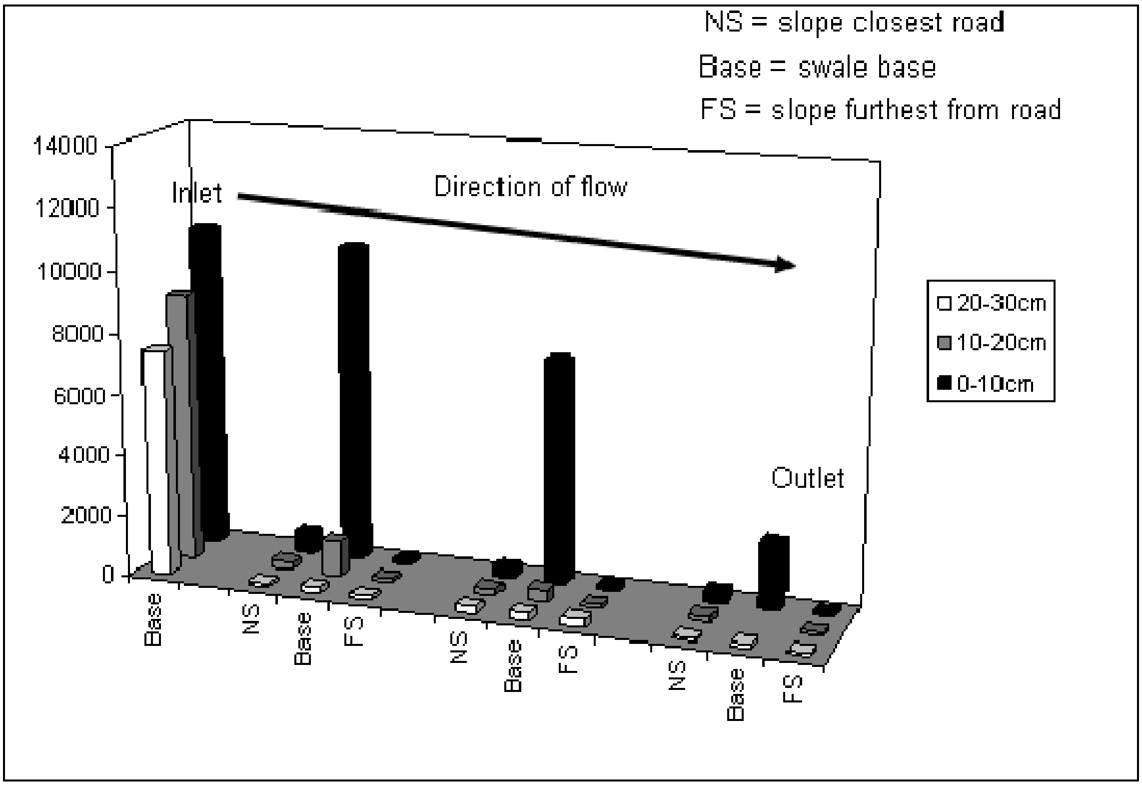

Figure 12. Oil concentrations in soil along A8000 swale (mg kg^{-1})

Concentrations in soil at the A8000 swale (see Figure 12) also reduced with distance from inlet and with depth, with the highest concentrations found in the top 10cm of soil along the swale base. At the A90 verge, oil concentrations reduced with distance from the road edge, and also with depth, as seen in Figure 13.

Figure 12 is contrasted with Figure 13 as follows. The concentrations in the A8000 swale approach an order of magnitude higher than those of the A90 roadside verge. This might be explained by the higher daily traffic totals (although data on traffic flows were not available), but more probably because of the stop/ start nature of the traffic at the A8000 during the morning and evening peak. However, the verge of the A90 (Figure 13) has been undisturbed for 50 years, whereas the A800 swale was only 8 years old at the time of monitoring.

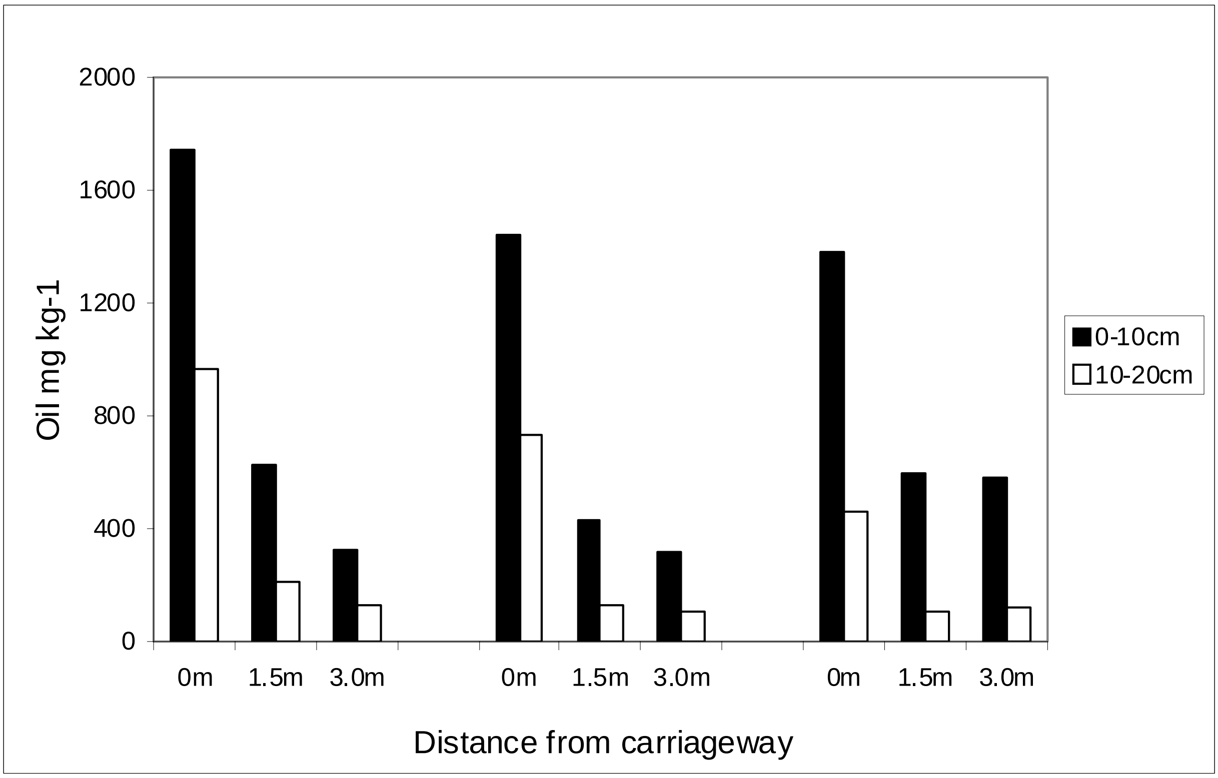

Figure 13. Oil concentrations in soil measured along A90 grass verge

3.3.3 Lysimeter soil core study

Table 10 reports the results of the mass balance calculations carried out on completion of the lysimeter core study. All soil types showed very little oil passing through the cores (<0.07%). With the exception of the sandy soil, all the cores showed the majority of the applied oil (71-81%) to have been degraded during the duration of the study.

Table 10. Oil mass balance for SUD, sand, silt and clay soil core lysimeters

	SUD	SAND	SILT	CLAY
% leached	0.005	0.01	0.01	0.07
% retained	19.3	70.7	23.9	29.4
% degraded	80.7	29.3	76.0	70.5

3.4 Discussion on the Integration of the Results

3.4.1 Oil Accumulation in SUDS

The results of the field study suggest that considerable concentrations of oil are accumulating in SUDS, thus protecting the water environment. Average measured oil concentrations ranged from 6011mg kg^{-1} (A8000 swale) to 423 mg kg^{-1} (grass filter strip at Hopwood HGV park). Since all the sites listed have been in operation for approximately the same length of time (~10yrs), the range of concentrations seems likely to be a result of the differing operating conditions at each locale. For example, the highest oil concentrations were measured at the A8000 swale. This site has the highest AADT (30000) and experiences stop-start traffic, characteristics which previous studies have shown to increase pollutant deposition (eg. Kayhanian et. al. 2003, Zereini et al 2005). Runoff entering the swale also has no upstream pre-treatment. This results in high oil concentrations in soil at the inlet (>10000mg kg^{-1}), as shown graphically in Figure 6. The bulk of the oil contamination is observed in the top 10cm of soil, and this is in agreement with results from the soil core lysimeters and M74 basins. However, at the swale inlet there is notable penetration to 30cm, possibly a consequence of mixing at the piped inflow. While there are regularly areas of standing water along the length of this swale (see Figure 7), only the inlet experiences turbulent flow and it is possible that the subsequent mixing has allowed oil to penetrate deeper.

By comparison, the lowest average oil concentration was measured at the grass filter strip at Hopwood HGV park. While this strip also receives untreated runoff and experiences stop-start (as well as idling) traffic, it has an AADT of only around 400 – greatly reducing the loading. The oldest site studied was the A90 (Figure 9), which has been in operation ~45yrs.

Figure 10 compares oil concentrations in soil along the verge (closest to road) with those found along the base of the A8000 swale. Soil was sampled along a similar length at both locations (~145m). Both sites experience relatively heavy, frequently queuing traffic (Table 8), and are situated close to each other (i.e. experience same climatic conditions). The main difference between the sites is the fact that runoff at the A90 flows directly into roadside drains, with the verge receiving road spray only, while at A8000, runoff from the drainage area is directly into the swale via piped and sheet flow.

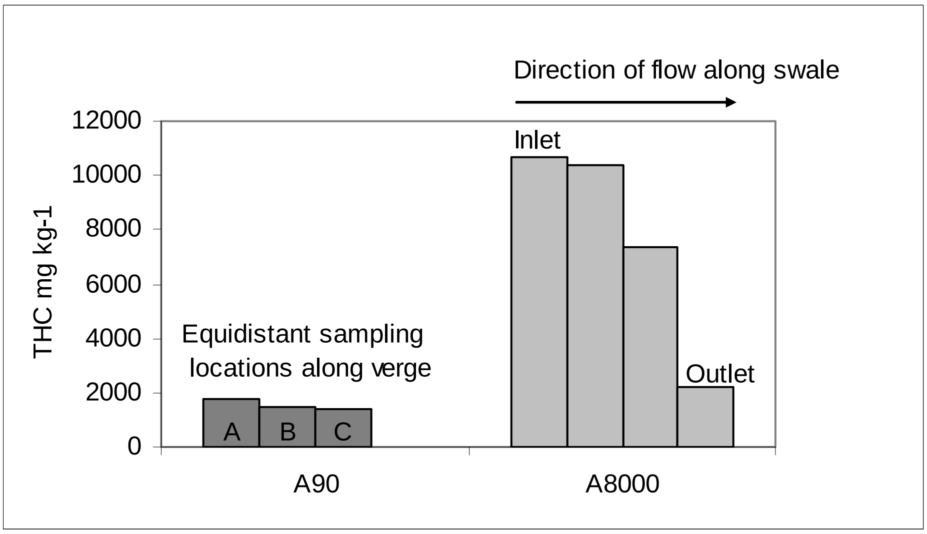

Figure 14. Comparison of oil concentrations measured at A8000 and A90

The much higher levels of oil seen at the A8000 after only 10yrs is therefore an indication of the quantity of oil which has been washed untreated into drains and hence the water environment from the A90 for the past 45 yrs (Figure 14).

3.4.2 Submerged sediments v exposed soil

A comparison of results from the soil and submerged sediments at the M74 basins suggests that wet conditions do not favour degradation of oil, whereas soils beneath intermittently dry vegetation have lower concentrations.

The field study showed TPH concentrations in submerged sediments in the M74 basin pools to be significantly more contaminated than the soil in the adjacent basins which dry out between rainfall events. At 27A, pollutant concentrations in the submerged pool sediment were double the calculated soil averages, as demonstrated in Table 3. This is contrary to what would be expected given the upstream treatment, and suggests less degradation in the pools than in the surrounding soil.

The data collected at Basin 29A provides further evidence for this hypothesis.

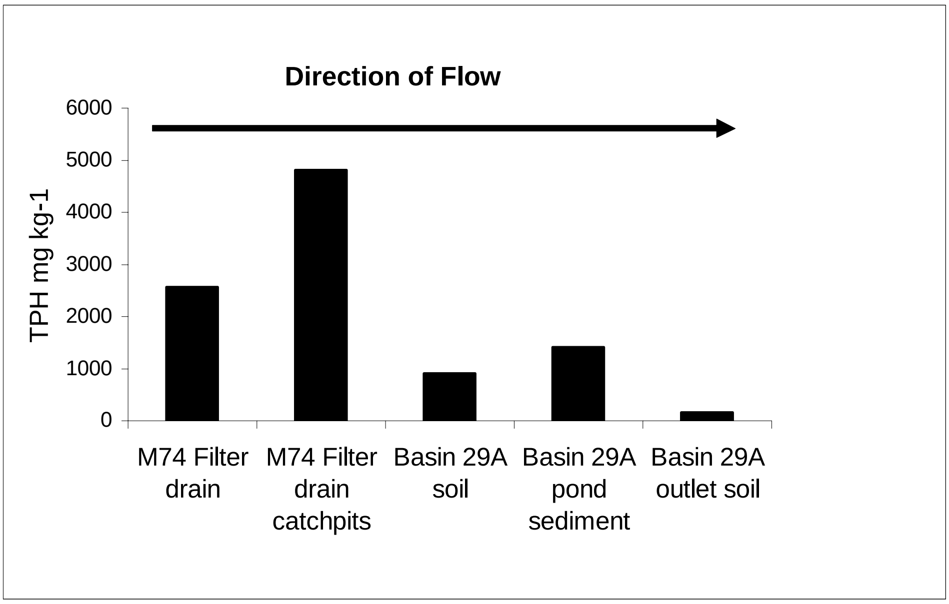

Figure 15. Average oil concentrations measured in components of M74 Basin 29A treatment train

Figure 15 shows oil concentrations measured along the treatment train at M74 Basin 29A. In agreement with the treatment train concept, overall concentrations reduce from the first stage (filter drain) to the last (basin outlet). However, along the length of the treatment process, concentrations actually increase again wherever submerged sediments are encountered – ie catchpits and pool sediment, reinforcing the implication that organic pollutant breakdown is reduced in submerged sediments.

One final piece of evidence that it is better to retain TPH in soil rather than in submerged sediment comes from comparing sediment quality along soil-based and sediment-based SUDS treatment trains at the M74. Table 11 shows the average oil concentrations measured in the inlet and outlet areas of the M74 basin and pond systems. All of these sites have filter drains upstream, experience the same traffic volume and type, and experience the same climatic conditions. The only difference is the fact that treatment at the basins is provided predominantly by runoff passing over vegetated soil, while at the pond systems, treatment is exclusively water based.

Table 11. Comparison of oil concentrations at four M74 SUDS treatment trains, showing differences between inlet and outlet areas

	TPH* (MG KG^{-1})		
	Inlet Area	**Outlet Area**	**% Difference from inlet to outlet**
Basin 27A soil	1704	344	80
Basin 29A soil	914	159	83
Pond System 33 sediment	2658	1409	47
Pond System 40 sediment	2582	2089	20

* calculated average values

At both of the basins, there is a considerable difference between TPH concentrations in the soil in the area of the basin inlets compared to that found in the area of the outlets (80% and 83%). In contrast, at the pond systems, the difference between TPH concentrations in the sediments of the inlet and outlet ponds is not so pronounced (47% and 20%). Despite having similar system inputs, oil concentrations are not only higher in the inlet ponds compared to the basin inlet areas, but remain higher across the treatment system. The inference is that while similar quantities of oil are entering all the systems, more degradation or volatilization is occurring in the soil based systems than in the submerged sediments. A similarly high reduction of oil contamination (80%) from inlet to outlet soil is apparent at the A8000 swale.

3.4.3 Oil degradation

Results from the laboratory degradation experiment also show increased moisture content in soils to have an inhibitory effect on hydrocarbon degradation. Figure 1 shows the percentage reduction in oil concentrations measured under various conditions during the study. The samples which had the highest moisture content (Batch 8) also showed the lowest percentage reduction in concentration. In the PAH degradation study which was run concurrently but for a shorter period, a similar result was observed for the high molecular weight PAHs (see Figure 16). Studies have suggested that oxygen content is a limiting factors in the breakdown of oil in soils (eg. Shin et. al. 2000, Malina, G. and Zawierucha, I. 2007). The more saturated a soil, the less oxygen it will hold (Brady & Wei 1996), and, consequently, the less potential there will be for aerobic microbial degradation. The most extreme example would be submerged sediments in ponds, and this is borne out by the field data gathered during this project. Figure 16 demonstrates the importance of microbial activity in the degradation process. The sterile soil showed that both low (LMW) and high molecular weight (HMW) PAHs were reduced by similar amounts. In contrast, all other batches show a significantly higher reduction in LMW compounds, presumably as a result of microbial action. The observed reductions in the sterilised soil are presumably evidence of physical processes, most likely volatilization.

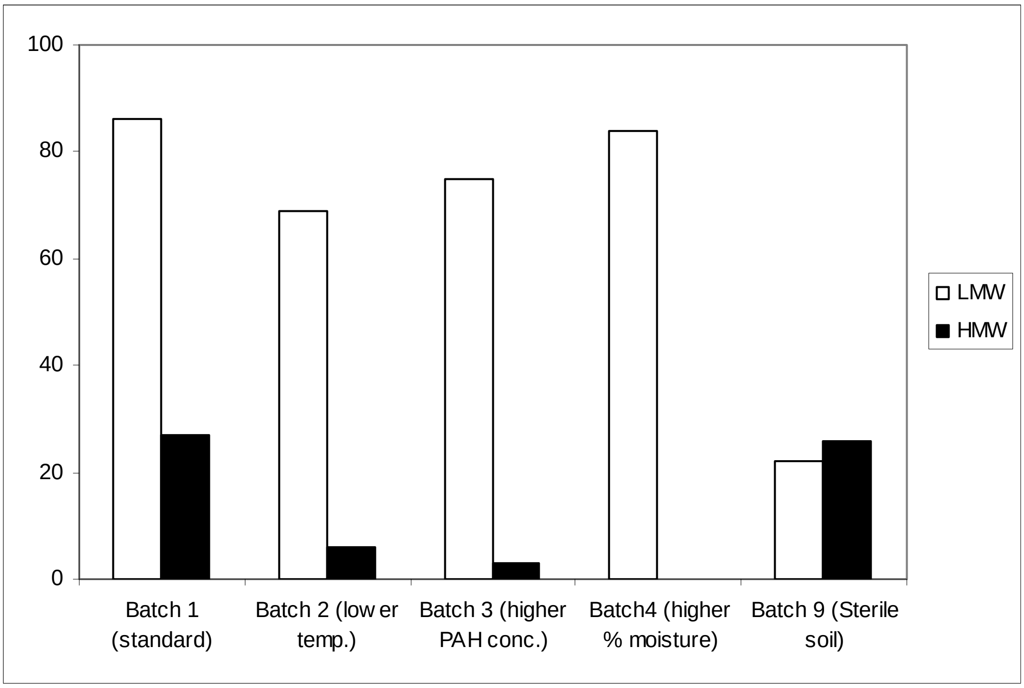

Figure 16. Percentage reduction observed in PAH concentrations after 44 days

3.5 Conclusions and recommendations

For the traffic loadings in this study, the degree of contamination found suggests road traffic is a significant source of oil, but SUDS are effectively trapping them, protecting the receiving water environment. Without SUDS, receiving waters might be exposed to significant oil contamination.

While SUDS facilities of various kinds can be effective in trapping oil from diffuse sources, the study showed oil remaining in submerged sediments, whereas oil contamination of intermittently dry systems, such as detention basins, degrades and is less likely to accumulate to harmful levels.

Results from this study suggest that source control measures such as grass filter strips, swales, and detention areas, should be priority features of sustainable drainage networks serving urbanised areas and highways, where oil contamination may be significant. This is entirely consistent with the treatment train and stormwater management concepts for sustainable drainage systems. The primary role for ponds and wetlands should be as secondary measures for polishing runoff quality and especially for flow balancing as part of pluvial flood management plans, and habitats as part of integrated drainage schemes.

4 RISK / DESIGN TO AVOID RISK

4.1 Risk of Contaminated Soil and Sediment

A prototype prediction tool is being developed using data from the project. (see below). The proposed tool incorporates a number of weighted factors (age, traffic volume, moisture content, pre-treatment, etc) to enable comparisons and predictions of pollutant accumulation in different SUDS in different locations. Although at an early stage, it has potential to become a useful tool for the future, for use in SUDS planning, design and management.

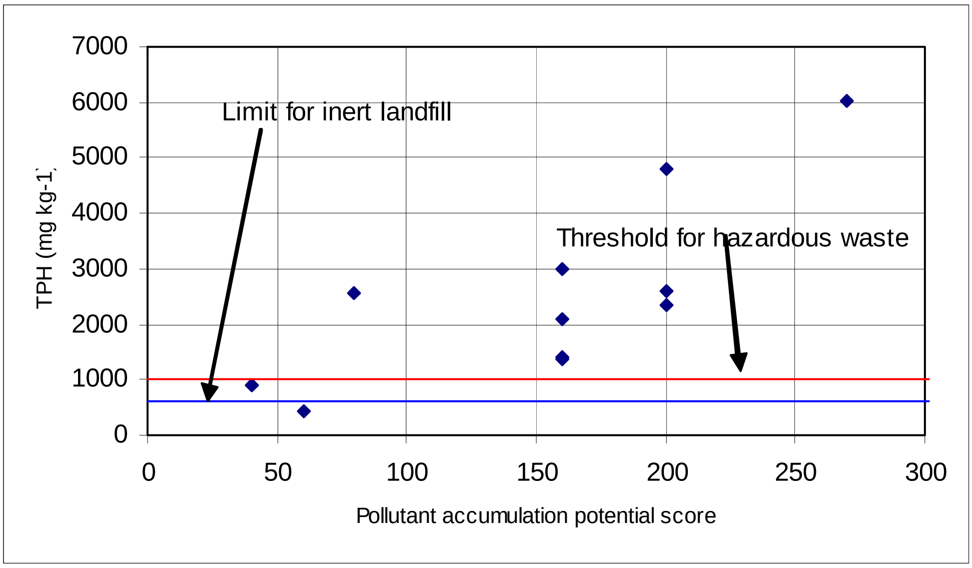

Figure 17. Potential accumulation of Hydrocarbons after 10 years – based on AADT, traffic pattern, moisture content, upstream treatment

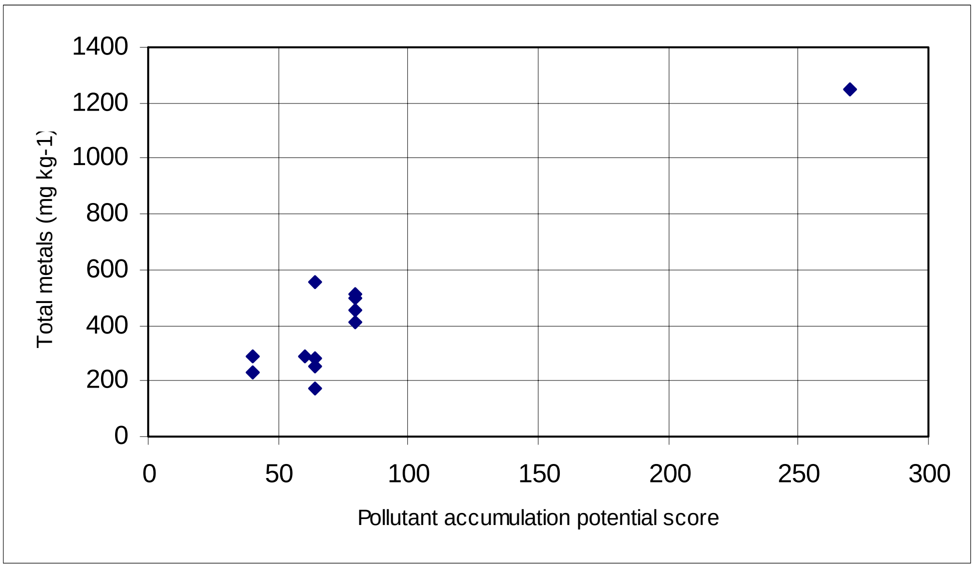

Figure 18. Potential accumulation of Heavy Metals after 10 years – based on AADT, traffic pattern, moisture content, upstream treatment

More data are required to develop and refine this potential tool further and SEPA has put forward (August 2008) an in-house continuation project to build on this early work.

4.2 Evidence for Developing a Risk Based Design

This section summarises the evidence gathered in the project which is likely to be of use in the development of a risk-based SUDS design tool.

- Of the pollutants retained by the soil in a SUDS, an extremely high percentage is retained in the upper layers. This effect is illustrated in Figure 19 which is data from a detention basin on the M74.
- Reduction in sediment pollutant concentrations between upper 10cm layer and the lower layers. This effect applies to a wide range of pollutants and has been observed at all sites where sediments were sampled at more than one depth.
- This effect was repeated in the three different soils tested in the lysimeters which showed that, of the twelve columns, the greatest amount of contaminants passing the top 10cm was 0.045%. this was in a Lysimeter comprising very sandy soil.
- There is a comparable reduction with distance. This effect can be seen in Figure 19 and in Figure 12.
- Roadside verge information produced comparable results, although at lower concentrations. This is shown in Figure 13.
- Suction lysimeters confirm that, even though the soil concentrations were as in Figure 19 or Figure 20, contaminants in the soil water were virtually undetectable.
- An experimental swale was constructed at Dundee airport (see Table 8) and dosed with contaminants. The swale was lined and it was expected that a pollutant balance could be undertaken but no contaminants were detected in the outlet. This meant that the pollutant budget could not be carried out. However, this test did show that the soils retained 100% of the pollutants.

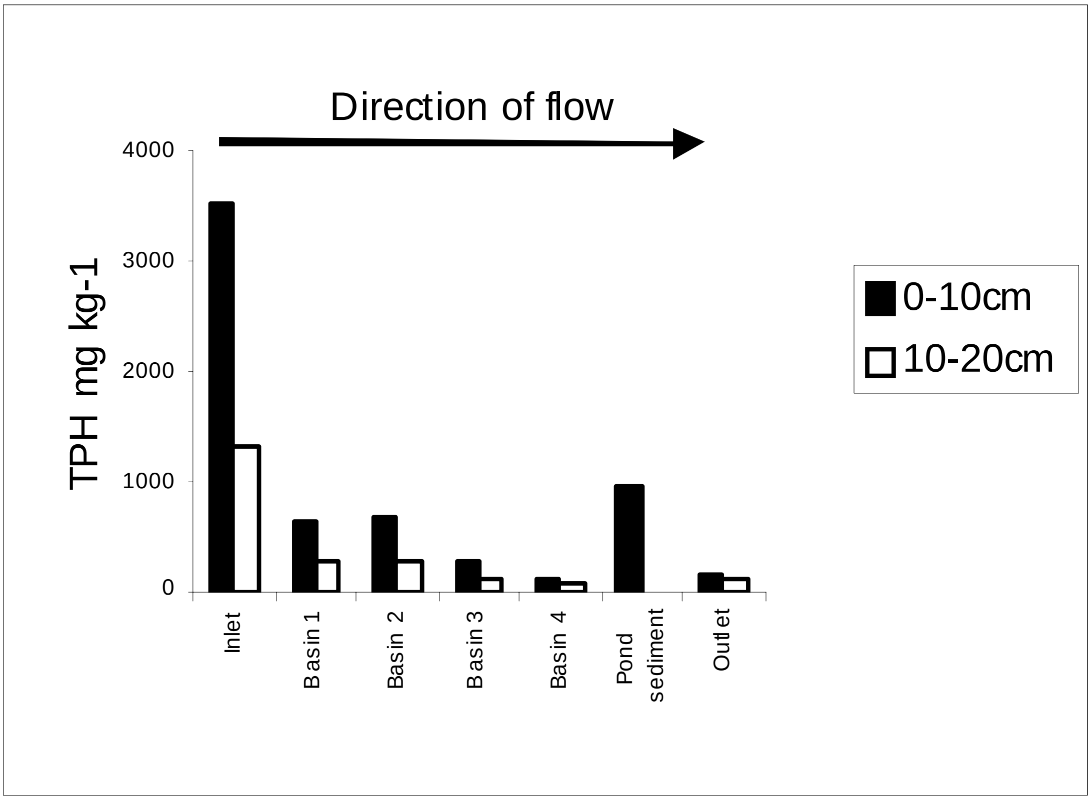

Figure 19. Change of contaminant concentration in soil of a basin and a pool (M74)

This supplementary report is primarily concerned with the behaviour of oil based substances. The reason for concentrating on oils (expressed throughout as TPH) was the sheer mass of data that were gathered.

It is contended that conclusions which are drawn for TPH also map across to the other determinands which were assessed – acknowledging that others may be conservative, non-degradable pollutants. Figure 19 is included to illustrate this point. Although it is not contended that there is a statistical relationship between zinc (as an exemplar heavy metal), the similarities between Figure 20 and Figure 12 are self evident.

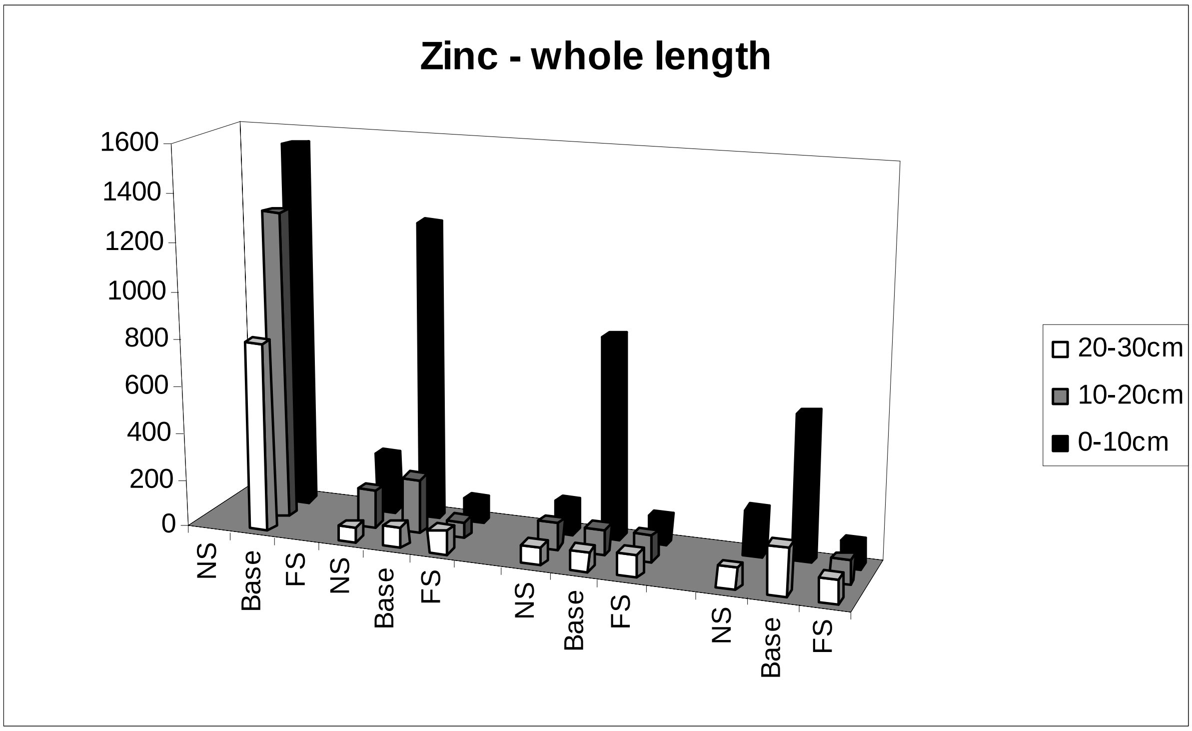

Figure 20. A8000 Swale Zinc concentrations

4.3 SOIL-Based SUDS Design flowchart

This section addresses the possibility of a risk-based SUDS design flowchart based on the data gathered in this project. In a preliminary version of the main report a flow chart was hypothesised and it was hoped to take this forward. Unfortunately, the time available and the information from the project were limited and no flowchart has been developed.

However, the information in the following sections points the way towards how such a flowchart might be developed. Only indications of the stages which would be necessary to develop such a tool are included, primarily to pose the questions required to drive an information gathering programme.

4.3.1 Flowchart Context

The purpose of a design flowchart would be to produce a design procedure for soil-based SUDS components which match the risks posed by the highway to surface waters or ground waters.

SUDS design starts from the point of view that there is likely to be no control over the following parameters when designing a highway SUDS;

- Area of highway drained
- Traffic flow
- Local soil type and conditions
- Level of water table.

4.3.2 Design Guidance

The flowchart should address a number of potential issues which influence SUDS design and operation including;

- Risks to receiving waters will have been identified by the EA.
- The propensity for the production of sediment in the location where the SUDS is to be located. More erodible soils will produce more sediment which in turn may require to be removed depending on the design.
- The likely behaviour of water and pollutants once in the SUDS component.
- What then would be the best set of design criteria to address the risks.

Soil conditions are probably best indicated by the HOST classification. HOST has been developed by the MaCauley Institute for all of the UK. Although currently HOST is a hydrology based approach, it is reasonable to assume that it could be modified to incorporate the ability of the different soils to control pollutants.

Unfortunately this may not be a particularly straightforward task. HOST is based on the soil physical properties and while the ability of soils to control pollutants will be partially affected by the time it takes water to move through the soil, the chemical and biological properties of the soil will also be important in this regard. So while it may be reasonable to assume HOST could be modified to incorporate the ability of the different soils to control pollutants – it will be a significant undertaking.

Generally speaking sandy soils will let water pass through quickly while clay soils will not (unless they crack). Sandy soils have little clay material in them and therefore will be much less likely to bind metals while clay soils will be the most chemically sticky. The soil texture does not take account of any organic matter in the soil and this plays a significant role in pollutant behaviour. A sandy soil with organic matter present will be much more likely to hold onto organic pollutants than a sandy soil with no organic matter. The clay content and organic matter content of the soil are possibly the most important parameters to look at when considering how pollutants will behave in the soil and not only the texture.

I spite of these reservations, it is still considered worthwhile attempting to produce a generalised procedure for the capability of soils to reduce pollutants. This may use HOST or some other mapped characteristic as a starting point.

4.3.3 Best basin/ swale arrangement and guidance

The outcomes of this research can be best put into practice by having an underdrained basin or swale in which the maximum amount of runoff as possible has contact with the soil base. Even limited contact with a free draining soil will remove a very significant proportion of oils and PAHs present in the runoff while at the same time being easy to maintain and giving the best conditions for pollutant breakdown.

Figure 21 is included as design guidance information. The suggestions in this figure, which are based on this ‘best case’ scenario, are intended to provide direction for possible future research.

Filter Drain
Prime function – removal of sediments

Understand performance particularly ability to trap priority substances.	Ensure drain does not become waterlogged.

Basin Shape

Wide and Shallow is the best shape – increases the surface area of contact with the soil. Recommendations to optimise surface area & velocity during less than design storm.	Long and thin – a good compromise because of the extended contact provided. Recommendations to optimise surface area & velocity in less than design storm.	Small area and deep – poorest because of reduced contact area. Avoid the possibility of re-entraining sediments.

Base of basin Wet or Dry

Permanently wet – does not permit degradation. Leads to more contaminated sediment and potential disposal issues.	Periodically wet and dry – the best conditions for retention of pollutants. Sedimentation is maximised. This research shows degradation potential best.	Extremely well drained is less than ideal since contact time between water and soil is too short

Soil Type

Develop a working relationship between a nationally applicable soil classification system and the ability of soil to remove pollutants. The study used three different soil types. The most prominent candidate would appear to be the HOST (Hydrology of Soil Type) classification.

	Clayey Soil	Loamy Soil	Sandy Soil
Water	When clay is saturated, flow is completely prevented. Pollutant removal depends on sedimentation. When soil is dry it cracks and allows rapid flow downwards.	Probably the best soil for control of TPH and PAH. Recommended minimum depth of 300mm. Install drainage below soil if required. Water movement horizontal/ vertical in basin base.	Rapid flow downward discourages removal of N & P from the runoff water. Increase surface area of SUDS. Same is true of oils and PAHs but not so significant because of attachment to sediments.
Contaminants	Unlikely to travel below top 10cm	More than 99.5% of contaminants retained in top 10cm	May be more risk of downward movement. Good penetration of solids. Pollutant removal in sandy soil.
Construction	Design needs to rely only on detention. More sophisticated construction will become clogged by clay particles Improve behaviour by mixing with organic matter. Increases contact area for nutrient removal. Use impermeable liner if soil likely to dry out completely.	Least risk of producing a poor design because loam has the best combination of flow and pollutant retention properties.	Need for filter drain less important because sediment from highway may actually improve performance of basin or swale. Modify top layer by addition of clay in growth zone. This will dramatically improve pollutant removal. The beneficial effect of clay can be very long lasting.
Maintenance	Higher inspection costs.	Lower maintenance.	Low maintenance because risk of clogging likely to be lowest. Free draining soil will be well aerated permitting degradation of TPH and PAH.

Figure 21. SUDS Design Guidance Supporting Information

Information in RED indicates areas where more knowledge might be desirable

5 CONCLUSIONS AND RECOMMENDATIONS

It is concluded that it is better to control oils and PAHs in soil based SUDS at locations which are periodically wet and dry such as in the base of detention basins, swales or infiltration basins. The pollutants, once removed from the runoff, will breakdown much more readily into harmless compounds in a basin or a swale than under water in a pond or wetland. In some respects this is contrary to the guidance in many literature sources which promote the use of basal sediments in ponds or wetlands for this purpose. This promotion tends to be by default since the pond or wetland is almost universally promoted as the best for removing pollutants from runoff and little actual supporting data are quoted. However, the new information in this report tends to be complementary since different SUDS devices have their own efficiencies in removing pollutants in the first place. Basins and swales are good for sediment removal and, by association, oils and PAHs will also be best removed there and not in ponds or wetlands.

This research supports guidance that a soil based system should be used as the primary control of sediments, with the pond or wetland as a polishing component where required.

For the traffic loadings in this study, the degree of contamination found suggests road traffic is a significant source of oil, but SUDS are effectively trapping them, protecting the receiving water environment. Without SUDS, receiving waters might be exposed to significant oil contamination.

The evidence in this report points to SUDS being able to be designed in such a way as to minimise/reduce the amount of management or recycling of waste products from these systems as part of their maintenance regime. Waste arisings from SUDS serving busy highways will most probably have to be treated as contaminated waste and reduced and recycled. The findings of this report do not suggest a particular waste management strategy. However, the amount of waste which might arise can certainly be minimised using the results of this research.

Results from this study suggest that source control measures such as grass filter strips, swales, and detention areas, should be priority features of sustainable drainage networks serving urbanised areas and highways, where oil contamination may be significant. This is entirely consistent with the treatment train and stormwater management concepts for sustainable drainage systems. The primary role for ponds and wetlands should be as secondary measures for polishing runoff quality and especially for flow balancing as part of pluvial flood management plans, and habitats as part of integrated drainage schemes.

Information to assist in preparing a design flowchart to meet the environmental and other risks posed by pollutants from highways has been considered in this report. The flowchart will be populated by undertaking the type of research/ studies indicated in Figure 21.

6 DISSEMINATION ACTIVITIES

A number of dissemination activities took place during the lifetime of the project. These were as follows;

- The Scottish Transport Conference, SECC Glasgow October 2007. Presented in Seminar E (SEPA): Addressing the environmental impact of transport through policy, planning and research.

- Presentation at 1st National SUDSnet Conference, Coventry University 17 November 2007.

    - Napier F., Jefferies C. and Fogg P. (2007) Traffic related pollutants in soft engineered SUDS: an experimental and field approach.

- Presentation by Fiona Napier at Transport Conference June 2008.

- Presentation by Chris Jefferies to Sustainable Drainage Scotland Working party at meeting in Edinburgh on 18th August 2008.

- Paper presented by Chris Jefferies at 11th Conference on Diffuse Pollution (IWA DIPCON 2008):-

    - Jefferies C., Napier F., Fogg P., D'Arcy B.J. and Heal K.V. (2007) The fate of traffic related pollutants in soft engineering SUDS: an experimental and field approach. Proc 11th International Conference on Diffuse Pollution, Belo Horizonte, Brazil August 2007.

- Paper presented by Brian D'Arcy at 12th Conference on Diffuse Pollution (IWA DIPCON 2008) :-

    - Napier F., D'Arcy B.J., Jefferies C., Fogg P., Lowe W. and Clarke R. (2008) Oil and SUDS: managing a priority urban pollutant. Proc 12th International Conference on Integrated Diffuse Pollution Management (IWA DIPCON 2008). Khon Kaen University, Thailand; 25-29 August 2008.

- Papers presented at 11th International Conference on Urban Storm Drainage, Edinburgh September 2008:-

    - Heal, K.V., Bray, R., Willingale, S.A.J., Briers, M., Napier, F., Jefferies, C. and Fogg, P. (2008) Medium-term performance and maintenance of SUDS: a case-study of Hopwood Park Motorway Service Area, UK. Proceedings 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 31 August-5 September 2008.

    - Napier F., Jefferies C., Heal K.V., Fogg P., D'Arcy B.J., and Clarke R (2008) Evidence of traffic-related pollutant control in soil-based Sustainable Urban Drainage Systems (SUDS). Proceedings 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 31 August-5 September 2008.

7 REFERENCES

Brady, N.C. and Weil, R.R. The nature and properties of soils. 1996 Prentice Hall: NJ

Campbell N, D'Arcy B, Frost A, Novotny V and Sansom A (2004) Diffuse pollution: an introduction to the problems and solutions. (pp 74—77, 122-125, and 132-141). IWA Publishing, London. ISBN: 1 900222 53 1

Cerniglia C.E., 1992. Biodegradation of polycyclic aromatic hydrocarbons *Biodegradation* 3, 351-368

CIRIA 2007 The SUDS Manual Report. No C697 Construction Industry Research and Information Association, Classic House, 174 – 180 Old Street London EC1V 9BP.

Ellis JB and Chatfield PR (2006) Diffuse urban oil pollution in the UK. Urban Water Journal Vol. 3, No. 3, September 2006, 165-173.

Flowers, T.H., Pulford, I.D. and Duncan, H.J 1984 Studies on the breakdown of oil in soil *Environmental Pollution Series B, Chemical and Physical* 8 (1) 71-82.

Highways Agency (2008) Design manual for Roads and Bridges. Available at; http://www.standardsforhighways.co.uk/dmrb/

Horner RR, Skupien JJ, Livingston EH and Shaver HE (1994) Fundamentals of Runoff Management: Technical and Institutional Issues. (Chapt. 8, pp 125). Terrene Institute, Washington DC.

Kayhanian, M., Singh, A., Suverkropp, C. and Borroum, S. 2003 Impact of annual average daily traffic on highway runoff pollutant concentrations. Journal of Environmental Engineering, 129 (11) 975-990.

Linz, D.G., and D.V. Nakles (ed.) 1997. Environmentally acceptable end points in soil. Am. Academy of Environ. Eng., New York

Malina, G. and Zawierucha, I. 2007 Potential of bioaugmentation and biostimulation for enhancing intrinsic biodegradation in oil-contaminated soil. Bioremediation Journal, 11 (3): 141-147.

Shin, W.S., Tate, P.T., Jackson, W.A., Pardue, J.H. 2000 Bioremediation of an experimental oil spill in a salt marsh. Proceedings of Wetlands & Remediation: An International Conference. p33-40

Mueller K.E. and Shann, J.R. (2006) PAH dissipation in spiked soil: Impacts of bioavailability, microbial activity, and trees *CHEMOSPHERE* 64 (6) 1006-1014

Scholes L., Revitt M.D., Ellis J.B. A systematic approach for the comparative assessment of stormwater pollutant potentials. Journal of Environmental Management 88 (2008).

Wilson C, Clarke R, D'Arcy BJ, Heal KV and Wright PW (20005). Persistent pollutants urban rivers sediment survey: implications for pollution control. Water Science & Technology. Vol. 51, No. 3-4, pp217-224.

Wilson, S.C., Jones, K.C., 1993 Bioremediation of soil contaminated with polynuclear aromatic hydrocarbons (PAHs): A review *Environmental Pollution* 81 229-249.

Zereini, F.; Alt, F.; Messerschmidt, J.; Wiseman, C.; Feldmann, I., Von Bohlen, A.; Müller, J.; Liebl, K.; Puttmann,W. Concentration and Distribution of Heavy Metals in Urban Airborne Particulate Matter in Frankfurt am Main, Germany, *Environmental Science and Technology*, 2005, Vol. 39, pp. 2983-2989.