Abstract
Oil has been identified as a major contaminant of highway runoff, and perhaps the most significant diffuse source urban pollutant. This paper assesses the trapping and degradation of road runoff derived oil, in soft engineering SUDS. The occurrence and distribution of oil associated with road traffic, was measured in soils and pond sediments from several different types of SUDS at locations in the UK. These were: a roadside swale (and a grass verge) along two major approach roads into Edinburgh; a pair of extended detention basins serving the M74 Motorway, and a grass filter strip serving a lorry parking area at Hopwood Services on the M40. Samples were also taken of sediment from a gravel filter drain along the M74, as part of treatment train evaluation. Conclusions include recommendations on use of source control features such as swales, filter strips and detention basins, as priority features that can facilitate degradation of oil.

Key-words
Oil, degradation, SUDS, BMPs, soil, traffic, treatment train.

1. Introduction
Oil pollution associated with the urbanised environment is recognised as a major issue and a cause of poor quality in urban watercourses [1]. A national survey of small urban watercourses in Scotland [2] found high concentrations of oil in the stream sediments sampled (see Table 1). The streams sampled received untreated runoff and no known trade effluent or sewage discharges. Levels in almost half were found to be above the concentration threshold for classification as special waste, indicating the importance of urban pollutants in relation to exceedence of sediment quality standards and waste disposal criteria.

Oil pollution in such circumstances is a classic diffuse pollution problem: contaminated hard surfaces such as roads and yards are scoured by rainfall, mobilising pollutants, including surface oil and also oil adsorbed onto particulates. The origins of the contamination include drips and road spray wash-off from vehicles, from plant and machinery, from stores, and from various wastess, as well as ad hoc cleaning of vehicles and plant. A spectrum of spills adds to that – from very minor at fuelling sites, or in admixture with waste liquids in casual disposal to nearby surface water drains, to major leaks and spills involving storage installations and road tankers [1].

Management of urban and highway diffuse pollution in the UK is increasingly by use of Sustainable Drainage Systems (SUDS), known as best management practices or BMPs in the US (discussed in Campbell et al 2004 [3]). Many of these management techniques focus on trapping suspended matter, either by sedimentation in a pond or detention basin, or filtration through grass in swales or across filter strips. Pollutants are often associated with suspended matter, including adsorbed oil, and taking pollutants out of the drainage flow is a primary aim of SUDS. Many studies on SUDS performance have focused on hydraulic performance and/or water quality improvements, and properly designed and constructed SUDS are generally accepted to attenuate flows and improve the quality of contaminated runoff; (for example grass filter strips have been identified as more effective than oil separators for dealing with lightly contaminated runoff [4]. The contaminants removed from the runoff, however, have the potential to accumulate in SUDS soils and sediments, with implications for groundwater quality and 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.

Table 1. Range of oil concentrations measured sediments from 9 urban streams in Scotland [2]

<table>
<thead>
<tr>
<th>Min.</th>
<th>Max.</th>
<th>Mean (n=26)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured concentration (mg kg⁻¹)</td>
<td>21.9</td>
<td>3382.7</td>
</tr>
</tbody>
</table>
The key aims of the research reported in this paper were to quantify oil contamination entering SUDS, and estimate the fate of the oil within different SUDS systems in order to optimise the management of runoff-related hydrocarbons.

2. Methodology
This multi-component project was undertaken over an 18 month period between Oct 2006 and April 2008. A summary of the field sites monitored, the experimental studies carried out and the sampling and analysis undertaken are given in Table 2. Metals and nutrients were also analysed at all sites, but this paper focuses solely on oil.

Two methods were used for oil analysis (see 2.4), one reporting total hydrocarbons and one reporting total petroleum hydrocarbons. For traffic derived oil contamination the values obtained by the two techniques should differ only slightly, and that difference should be consistent. The method used for each study component is given in Table 2.

2.1 Field study
Soil and pond sediment samples were collected from several different types of in-situ SUDS at locations in the UK (see Table 2) and analysed for oil contamination. Some of the sites are shown in Figures 1, 2 and 3. The selection of complementary sites allowed comparisons to be based on SUDS type.

2.2 Lysimeter soil core study
This study was undertaken to measure the leaching potential of different soil types exposed to typical concentrations of traffic related pollutants. Destructive sampling at the end of the project also provided information on pollutant movement through the soil core and degradation of organic compounds.

Soil core lysimeters (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 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 (see Figure 4). At the end of the study period, the cores were destructively sampled and concentrations of each determinand at different depths were measured.

2.3 Laboratory degradation study
This lab-based experiment was designed to measure the degradation of oil and PAHs under varying environmental conditions, and was carried out under...
controlled conditions using the loamy sand topsoil tested in the lysimeter experiments. Separate batches of soil were dosed with known quantities of either oil or PAH and incubated under varying conditions. Parameters studied were bioactivity of soil, temperature, start concentration and soil moisture content. Degradation was measured by removing samples at various time intervals to determine the concentration of oil or PAH remaining.

2.4 Analysis methods

Analysis of the samples collected was carried out by two different laboratories. Samples from the all of the M74 sites, Hopwood and the soil core lysimeter and laboratory degradation studies were analysed by TES Bretby. Analysis was by GC/FID, preceded by ultrasonic enhanced solvent (hexane/acetone) extraction. The method reports total petroleum hydrocarbons (TPH) in the range C8-C40.

Samples from the A8000 swale and A90 roadside verge were analysed at the SEPA trace organics lab at Riccarton, Edinburgh. Samples were analysed by infrared spectroscopy following Soxhlet extraction with carbon tetrachloride and clean-up through Florisil solid-phase extraction column. Results were reported as total hydrocarbons (THC).

N.B. As the two methods measure and report different organic fractions, it is not possible to compare absolute values between sites. There is, however, supporting evidence to suggest that oil contamination at the sites can be broadly compared quantitatively. At the M74 basins, strong relationships were observed between the traffic related metals (Cu and Zn), TPH and PAHs (all R²>0.94), as would be expected at sites heavily impacted by traffic. The same strong relationships were seen at A8000 and A90, indicating that hydrocarbon concentrations at all locations were dominated by the traffic inputs.

3. Results

3.1 Field study

A summary of the field study results collected are presented in Table 3. Oil concentrations measured at the M74 basins are shown in Figure 5. 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. Concentrations in soil at the A8000 swale (see Figure 6) also reduced with distance from inlet and with depth, with the highest concentrations found in the top 10cm of soil along the swale base.
Table 3. 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.

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil Depth</th>
<th>A8000 soil¹</th>
<th>A90 soil²,³</th>
<th>27A basin soil⁴,²</th>
<th>27A pool sediment²</th>
<th>29A filter drain sediment²</th>
<th>29A basin soil⁵,²</th>
<th>29A pool sediment²</th>
<th>Hopwood filter strip soil²,⁵</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet 0-10cm</td>
<td>11850</td>
<td>1520</td>
<td>3607</td>
<td>4400</td>
<td>-</td>
<td>-</td>
<td>4868</td>
<td>765</td>
<td>799</td>
</tr>
<tr>
<td>10-20cm</td>
<td>9270</td>
<td>722</td>
<td>1856</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1625</td>
<td>-</td>
<td>120</td>
</tr>
<tr>
<td>20-30cm</td>
<td>4485</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Outlet 0-10cm</td>
<td>4290</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>10-20cm</td>
<td>-</td>
<td>-</td>
<td>161</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>20-30cm</td>
<td>445</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (n)</td>
<td>6011</td>
<td>818</td>
<td>888</td>
<td>2980</td>
<td>2563</td>
<td>914</td>
<td>1414</td>
<td>-</td>
<td>423</td>
</tr>
</tbody>
</table>

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

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Figure 5. Oil concentrations measured in soils and sediments at a. M74 Basin 27A and b. M74 Basin

Figure 6. Oil concentrations in soil along A8000 swale (mg kg⁻¹)

Figure 7. Oil concentrations in soil measured along A90 grass verge
At the A90 verge, oil concentrations reduced with distance from road edge, and also with depth, as seen in Figure 7.

### 3.2 Lysimeter soil core study

Table 4 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 4. Oil mass balance for SUD, sand, silt and clay soil core lysimeters

<table>
<thead>
<tr>
<th></th>
<th>SUD</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>% leached</td>
<td>0.005</td>
<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
</tr>
<tr>
<td>% retained</td>
<td>19.3</td>
<td>70.7</td>
<td>23.9</td>
<td>29.4</td>
</tr>
<tr>
<td>% degraded</td>
<td>80.7</td>
<td>29.3</td>
<td>76.0</td>
<td>70.5</td>
</tr>
</tbody>
</table>

### 3.3 Degradation study

Figure 8 shows the percentage reduction in oil concentrations measured under the various conditions, shown in Table 5.

Table 5. Lab oil degradation study: test conditions

<table>
<thead>
<tr>
<th>Test Batch</th>
<th>Temp (°C)</th>
<th>Moisture content (%)</th>
<th>Oil conc. applied mg kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>15</td>
<td>40</td>
<td>3500</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>40</td>
<td>3500</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>40</td>
<td>10000</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>90</td>
<td>3500</td>
</tr>
<tr>
<td>10*</td>
<td>15</td>
<td>40</td>
<td>3500</td>
</tr>
</tbody>
</table>

* sterilised soil

4. Discussion

#### 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 6011 mg 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. [5][6]). 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 demonstrated graphically in Figure 6. The bulk of the oil contamination is observed in the top 10cm of soil, and this 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 3), 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 9. A90 verge

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 (see Table 2), and are situated close to each other (ie. 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. 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 10).

### 4.2 Submerged sediments vs 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 11 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 6 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 6. Comparison of oil concentrations at four M74 SUDS treatment trains, showing differences between inlet and outlet areas

<table>
<thead>
<tr>
<th></th>
<th>TPH* (mg kg⁻¹)</th>
<th>Inlet Area</th>
<th>Outlet Area</th>
<th>% Difference from inlet to outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin 27A soil</td>
<td>1704</td>
<td>344</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Basin 29A soil</td>
<td>914</td>
<td>159</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>Pond System 33 sediment</td>
<td>2658</td>
<td>1409</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Pond System 40 sediment</td>
<td>2582</td>
<td>2089</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

* 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.

### 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.

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*Figure 10. Comparison of oil concentrations measured at A8000 and A90*

*Figure 11. Average oil concentrations measured in components of M74 Basin 29A treatment train*
degradation. Figure 8 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, a similar result was observed for the high molecular weight PAHs (see Figure 12). Studies have suggested that oxygen content is a limiting factors in the breakdown of oil in soils (e.g. [7][8]). The more saturated a soil, the less oxygen it will hold [9], 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 12 demonstrates the importance of microbial activity in the degradation process. The sterile soil showed both low (LMW) and high molecular weight (HMW) PAHs, being reduced by a similar amount. 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 sterilized soil are presumably evidence of physical processes, most likely volatilization.

![Figure 12. Percentage reduction observed in PAH concentrations after 44 days](image)

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 are exposed to significant oil contamination. While SUDS facilities of various kinds can be effective in trapping oil from diffuse sources, this study showed oil remaining in submerged sediments, whereas oil contamination of intermittently dry systems, such 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.

Acknowledgments

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