Sedimentation and Sediment Quality in Sustainable Urban Drainage Systems

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1. INTRODUCTION

Sustainable Drainage Systems (SUDS) include retention basins and wetlands that provide permanent storage to attenuate storm runoff by storing and delaying a portion of storm hydrograph flows. Water quality improvements also occur in retention basins and wetlands through the operation of chemical (e.g., precipitation), physical (e.g., sedimentation, adsorption) and biological processes (e.g., plant uptake of nutrients, microbial degradation of hydrocarbons). As a result of these processes, sediment, and some of the associated contaminants, accumulates in SUDS over time.

Sedimentation and sediment quality in SUDS are therefore of concern for a number of reasons (Yousef et al., 1994). Sediment accumulation will reduce the storage volume over time, decreasing the effectiveness of the SUDS in flow attenuation. The SUDS performance in improving water quality will also be adversely affected due to the reduced residence time as storage volume is infilled with sediment. Furthermore, where unlined SUDS overlie permeable geology, contaminants accumulated in sediment may leach into aquifers. This is of particular concern in areas such as south-east England where groundwater is an important source of potable water. Due to the above concerns, removal of accumulated sediments is likely to be required from SUDS retention basins and wetlands as part of long-term maintenance. To estimate the costs of sediment removal and disposal, assessments of the frequency of sediment removal, sediment volumes and sediment quality are required.

In this paper results are presented for a four-year survey of sedimentation and sediment quality in four SUDS (three retention basins and one wetland) in Scotland. To assess the extent of contamination of SUDS sediments, metal concentrations measured in the SUDS sediments are compared with sediment standards and other aquatic sediments. Finally recommendations are made for SUDS sediment disposal, based on these studies.

2. SEDIMENTATION IN SUDS

2.1 Methods

Since 1999, annual surveys of sediment depth have been conducted in four SUDS which are part of the stormwater management facilities at Duloch Park, a 5 km² new residential, light retail and industrial development in Dunfermline, Central Scotland (Roesner et al., 2001). The SUDS surveyed were all planted in 1998 and comprise three retention basins (Halbeath Pond, Linburn Pond and Pond 7) and a wetland. Once a year sediment depths are measured from sediment cores collected with an aquatic sediment corer from 30-40 locations, regularly spaced along two-three transect lines in each SUDS. The transects are arranged so that approximately the same locations are sampled every year. The sediment depth data were interpolated within an ARC-VIEW Geographical Information System (GIS) to estimate sedimentation within each SUDS.

2.2 Results

The pattern of sedimentation varies spatially within each SUDS, depending on design. For example, in Linburn Pond (Figure 1) the largest sediment depths occur in the primary basin close to the main inlet, with less sedimentation in the secondary basin. From data on sediment depth, sediment density and SUDS water storage volume (Spitzer, 2001), preliminary estimates of sediment accumulation rates and frequency of removal have been made for the Halbeath and Linburn retention basins (Table 1). Annual wet sediment input was calculated as the difference
between total wet sediment volume (mean sediment depth multiplied by surface area for each SUDS) for adjacent years. Annual mass of sediment input was calculated as the difference between total dry sediment mass (wet sediment volume multiplied by the mean density of dry sediment for each SUDS) for adjacent years. Annual sediment washoff from the catchment was calculated by dividing the annual dry mass of sediment input by the catchment area of each SUDS. The time for each basin to infill with sediment was simply obtained by dividing the water storage volume of each SUDS by the annual wet sediment input volume, although accumulated sediment will require removal before the volume is totally infilled.

**Figure 1.** Interpolated sediment depth (m) in Linburn Pond, July 2001

**Table 1.** Characteristics and sedimentation estimates for two retention basins. Values are means of 1999-2002. Minimum and maximum values for 1999-2002 are shown in brackets.

<table>
<thead>
<tr>
<th></th>
<th>Halbeath</th>
<th>Linburn</th>
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<tbody>
<tr>
<td>Water storage volume (m³)</td>
<td>4600</td>
<td>15495</td>
</tr>
<tr>
<td>Catchment area (ha)</td>
<td>13.5</td>
<td>67.5</td>
</tr>
<tr>
<td>% Catchment area developed</td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>Annual wet sediment input (m³)</td>
<td>16.2 (-131, 183)</td>
<td>50.7 (-275, 501)</td>
</tr>
<tr>
<td>Annual mass of sediment input</td>
<td>51 (-186, 377)</td>
<td>126 (-236, 597)</td>
</tr>
<tr>
<td>(t dry weight)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual sediment washoff from</td>
<td>3.8 (-14, 28)</td>
<td>1.9 (-3.5, 8.8)</td>
</tr>
<tr>
<td>catchment into basin (t ha⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dry weight)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time for basin to infill with</td>
<td>285 (25, ∞)</td>
<td>305 (30, ∞)</td>
</tr>
<tr>
<td>sediment (to nearest 5 years)</td>
<td></td>
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</tbody>
</table>
Table 1 shows that there is considerable inter-annual variability in sedimentation estimates for each SUDS and in some years sediment appears to be lost from the basins. This may be due to sediment compaction over time, sampling artefacts and/or inter-annual variability in rainfall and washoff of sediment from the catchment. A higher mean annual rate of sediment washoff occurs into the Halbeath basin than the Linburn basin due to the greater development of the Halbeath catchment and the lack of upstream sedimentation facilities in the Halbeath catchment. In the Linburn catchment, sedimentation has been observed in the six detention basins upstream of the retention basin, thereby reducing the sediment input to the retention basin.

3. SEDIMENT QUALITY IN SUDS

3.1 Methods

Selected sediment cores from the sediment depth survey described in Section 2.1 were retained for laboratory analysis. After drying and crushing, standard methods were used to determine the physical properties of the sediment (pH, moisture content, dry bulk density, organic matter content as loss on ignition, and particle size analysis by sieving into coarse sand, fine sand and silt, and clay fractions). Total metal concentrations (cadmium – Cd, chromium – Cr, copper – Cu, iron – Fe, nickel – Ni, lead – Pb, zinc – Zn) in the sediment were measured by atomic absorption spectrophotometry of acid digests (nitric and hydrochloric acid) of ashed samples. The total nitrogen and phosphorus content of the sediments was determined by automated colorimetry on digests produced by the Kjeldahl method (concentrated sulphuric acid digestion with copper sulphate catalyst tablets). All analyses were conducted in duplicate with appropriate blanks and certified reference materials. The sediment concentration data were interpolated within an ARC-VIEW GIS to examine spatial patterns of sediment quality in each SUDS. In 1999 and 2000, three sediment samples from each SUDS were also analysed for hydrocarbons by the Scottish Environment Protection Agency laboratory at Riccarton, Edinburgh.

3.2 Results

Sediment quality was spatially variable within each SUDS, as shown in Figure 2 for nickel concentrations in Halbeath Pond sediment. The highest nickel concentrations occur in sediment deposited near the inlet to Halbeath Pond, probably due to transport attached to particulates. Chromium and nickel concentrations increased in sediment in all basins from 1999/2000 to 2001/2002 (Figure 3). These increases are statistically significant between years (p < 0.05, one-way ANOVA and Tukey multiple comparison tests) and are probably caused by increasing traffic as site development has progressed. Chromium and nickel are often elevated in highway drainage due to corrosion of metal plating and wear of bearings and other moving parts in engines (Makepeace et al, 1995).
Figure 2. Interpolated nickel concentrations (mg kg$^{-1}$ dry weight) in sediment, Halbeath Pond, July 2000

Figure 3. Mean sediment chromium concentrations in four SUDS, Dunfermline, Scotland 1999-2002. Error bars are maximum and minimum concentrations.
4. ASSESSMENT OF CONTAMINATION IN SUDS SEDIMENTS

4.1 Comparison of SUDS sediment results with sediment quality standards

The concentrations of various parameters measured in the sediment samples from the Duloch Park SUDS were compared with three different standards to assess (i) whether the sediments are contaminated compared with other aquatic sediments, (ii) whether the sediments are toxic to aquatic life within the SUDS and, (iii) if the sediments pose a risk after removal from the SUDS.

Mean metal concentrations in sediment for each SUDS were compared with the Swedish Environmental Protection Agency’s classification of aquatic sediment quality (Swedish EPA, 1991) to assess whether the SUDS sediments have higher levels of metals than background concentrations. All SUDS sediments contained low or very low cadmium and zinc concentrations and low concentrations of lead and copper. All sites have moderate-high sediment chromium and nickel concentrations.

Mean, minimum and maximum hydrocarbon, metal and nutrient concentrations in sediment for each SUDS from 1999-2002 were compared with severe effect levels contained within the Ontario Provincial sediment quality guidelines. Aquatic sediments containing these concentrations are considered heavily polluted and likely to affect the health of sediment-dwelling organisms (OMME, 1993). Table 2 shows that mean iron concentrations exceeded the severe effect level in Halbeath Pond, Linburn Pond and the Wetland and in some samples from Pond 7. Furthermore, some samples from all sites exceeded the severe effect levels for chromium and nickel. Some samples from Linburn Pond and Pond 7 exceeded the severe effect level for total nitrogen and some samples from all sites, apart from Pond 7, exceeded the severe effect level for total phosphorus. Some samples from Linburn Pond and Pond 7 exceeded the severe effect level for hydrocarbons. Although the mean sediment quality within each SUDS does not appear to pose a threat to aquatic life, “hotspots” of contamination occur at each site, particularly near the inlets. Iron concentrations in many sediment samples exceed the Ontario Provincial guidelines, probably due to the background geochemistry of the Dunfermline area.

Comparison of mean, minimum and maximum metal concentrations with the threshold concentrations for different land uses (e.g., the UK ICRCL threshold trigger concentrations for contaminated land (ICRCL, 1987)) indicate the potential disposal routes for sediment excavated from SUDS (e.g. spreading on land, landfill). Table 2 shows that trigger concentrations were exceeded only by some samples from all sites for nickel. Consequently disposal by land spreading should be acceptable for most SUDS sediments, although elevated nickel concentrations in some sediments could affect plant health.

4.2 Comparison of SUDS sediment quality data with other aquatic sediments

In a wider, literature-based, study the quality of SUDS sediments was compared with other aquatic sediments to assess the extent of contamination of SUDS sediments (Heal and Drain, 2003). In addition to the primary sediment quality data from the Dunfermline SUDS, aquatic sediment data were obtained from relevant scientific journal papers, conference proceedings and reports, identified from WWW searches, the Web of Science database and personal communication with authors. In total 396 datapoints were suitable for analysis and were divided into six categories: SUDS (21 datapoints), Uncontrolled (58 datapoints), Contaminated (12 datapoints), Gully Pot (72 datapoints), Dunfermline (198 datapoints) and Background (35
datapoints). SUDS contains sediment data from SUDS sites other than Dunfermline, whilst Uncontrolled contains data from a wide variety of other watercourses (rivers, estuaries, wetlands, canals). Contaminated contains data for sediment/soil mixture at sites which are known to receive contaminated sediment/soil, e.g., sites for the disposal of dredged sediment. The Gully Pot category contains data for gully pot sediment in the UK from the survey by Pratt et al., (1987). The Dunfermline category contains the results of the SUDS sediment surveys reported in Section 3.2. Background contains data from sites identified as unpolluted and assumed to be representative of ‘natural’ background metal concentrations.

Data analysis focussed on Cd, Cr, Cu, Ni, Pb and Zn since these are the most commonly measured metals in aquatic sediments, especially in SUDS retention basins and wetlands, and are also the metals of greatest concern for biological impacts. The data were analysed by principal components analysis (PCA) to identify the similarity of SUDS sediments to other aquatic sediments utilising all the metal data. The causes of any patterns identified in the dataset by PCA may not have any physical basis, but the technique is the most appropriate for identifying patterns in large multivariate datasets, as in this study. In PCA the interrelationships within the dataset are reduced to a number of principal components (PCs). A PC is defined as the linear combination of the original variables that explains the variation in the data. Each data entry has a score (taking values between –1 and 1) of how well it maps on to each PC. The higher the modulus of the score, the more strongly the data point is correlated to that PC. The first PC accounts for the largest amount of variation in the dataset and the second PC the next largest amount of variation. Scores for PCs 1 and 2 are normally plotted against each other in a scatter plot to identify groups of related data (Figure 4). Aquatic sediments with similar metal characteristics should plot in similar locations on the scatter plot.

PCA was conducted on the aquatic sediment dataset in Minitab v.11, based on the correlation matrix. PCs 1 and 2 accounted for 41.2 and 22.5%, respectively, of the variation in the data. Some distinct trends in the dataset are apparent in the plot of PC 2 scores against PC1 scores (Figure 4). There is a trend from least contaminated samples near the origin to most contaminated furthest from the origin. The background sediment samples plot at the origin, indicating, as expected, that these samples did not have high scores for any metals on PC1 and PC2. Most samples from the controlled category and Dunfermline sites in 1999 and 2000 are clustered near the origin and the background samples, showing that the metal content of many SUDS sediments is indistinguishable from background sediment quality. However, samples from the Dunfermline SUDS sites in 2001 and 2002 plot away from the origin in the upper left hand sector of the graph, indicating that they are more contaminated than other SUDS sites, but have a different metal composition compared to sediments in the contaminated and gully pot categories that plot in the bottom left hand sector of the plot.
Table 2. Comparison of metal, nutrient and hydrocarbon concentrations in Dunfermline SUDS sediments with standards for aquatic sediments and contaminated land. Values are means for each SUDS 1999-2002 with minimum and maximum values in brackets. All units are mg kg\(^{-1}\) dry weight except where indicated. Values in bold exceed aquatic sediment and/or contaminated land standards. N = 6 for hydrocarbons and 29-98 for other determinands.

<table>
<thead>
<tr>
<th>Determinand</th>
<th>Halbeath Pond</th>
<th>Linburn Pond</th>
<th>Pond 7</th>
<th>Wetland</th>
<th>Ontario Provincial sediment quality guidelines</th>
<th>UK ICRCL Threshold trigger concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Severe effect level</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>0.11 (0-1.1)</td>
<td>0.11 (0-1.62)</td>
<td>0.0</td>
<td>0.01</td>
<td>(0-1.62)</td>
<td>0.01 (0-0.73)</td>
</tr>
<tr>
<td>Cr</td>
<td>33.6 (7.45-236)</td>
<td>51.9 (14.2-377)</td>
<td>40.0</td>
<td>37.3</td>
<td>(17.5-245)</td>
<td>37.3 (9.47-402)</td>
</tr>
<tr>
<td>Cu</td>
<td>14.5 (8.99-22.3)</td>
<td>17.1 (8.06-46.7)</td>
<td>14.3</td>
<td>16.9</td>
<td>(8.4-24.0)</td>
<td>16.9 (4.58-46.8)</td>
</tr>
<tr>
<td>Fe (%)</td>
<td>4.21 (2.59-6.08)</td>
<td>4.28 (2.30-8.78)</td>
<td>3.90</td>
<td>7.54</td>
<td>(1.18-7.37)</td>
<td>(2.19-20.2)</td>
</tr>
<tr>
<td>Ni</td>
<td>33.5 (10.8-194)</td>
<td>43.2 (11.8-183)</td>
<td>34.4</td>
<td>35.4</td>
<td>(13.3-145)</td>
<td>(7.72-208)</td>
</tr>
<tr>
<td>Pb</td>
<td>13.9 (6.59-27.2)</td>
<td>22.0 (9.90-118)</td>
<td>16.5</td>
<td>15.5</td>
<td>(8.65-38.0)</td>
<td>(0-53.5)</td>
</tr>
<tr>
<td>Total N</td>
<td>1092 (425-2396)</td>
<td>1923 (344-4484)</td>
<td>1521</td>
<td>3157</td>
<td>(646-3216)</td>
<td>(574-12173)</td>
</tr>
<tr>
<td>Total P</td>
<td>1096 (232-5167)</td>
<td>766 (221-3713)</td>
<td>674</td>
<td>748</td>
<td>(263-1377)</td>
<td>(103-4650)</td>
</tr>
<tr>
<td>Zn</td>
<td>49.3 (15.8-115)</td>
<td>83.7 (50.2-238)</td>
<td>65.6</td>
<td>76.7</td>
<td>(38.2-119)</td>
<td>(42.2-152)</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>89.2 (22.3-288)</td>
<td>523 (38.1-1510)</td>
<td>515</td>
<td>171</td>
<td>(38.4-2430)</td>
<td>(28.8-541)</td>
</tr>
</tbody>
</table>

a proposed land use = parks, playing areas and open spaces  

b any uses where plants grow
5. DISPOSAL ROUTES FOR SUDS SEDIMENTS

Removal of sediment from SUDS may be required for a number of reasons to: (i) sustain water storage volume for flow attenuation; (ii) maintain water residence times for maximum contaminant removal from water by settlement; (iii) protect water quality, within and downstream of the SUDS, if the sediment is deemed too contaminated; (iv) protect aquatic ecosystems, within and downstream of the SUDS, if the sediment is deemed too contaminated; (v) increase water depth for amenity. In some circumstances, however, removal can be detrimental to environmental quality (Su et al., 2002), increasing the availability of contaminants and causing physical disturbance to communities. In these cases doing nothing is an option (OMEE, 1993).

If sediment removal is selected as the most appropriate action for the SUDS the next step is to identify an appropriate disposal pathway for the sediment. Disposal options in order of increasing cost are: bankside disposal, land spreading, sediment reuse, treatment followed by land spreading, treatment followed by reuse, disposal to a licensed site (Bates and Hooper, 1997). Transport costs to a suitable site will also have to be considered. In the UK all waste is licensed unless it can be spread on adjacent land or agricultural land. In the latter case the sediment must be demonstrated to be beneficial to the soil quality (e.g., it will improve the soil nutrient status or increase the organic content) and the metal content still has to comply with agricultural use limits. If these criteria are met sediment is exempt under the Waste Management Licensing Regulations 1994 (Brooke et al., 1996). It has been suggested that land spreading could be used for sediment disposal if non-consumptive crops are grown (Harmsen, 1997), such as bio-fuels. However, possible future changes in EU waste management directives may limit application to agricultural land as a disposal route for SUDS sediment.
On the basis of mean metal concentrations measured in sediment from the Dunfermline SUDS, SUDS sediment is likely to be exempt from the UK Waste Licensing Regulations 1994. This means that spreading on adjacent land or on agricultural land would be acceptable for most SUDS sediment. If SUDS sediment is not exempt from the UK Waste Management Licensing Regulations 1994 it would have to be disposed to a licensed disposal site. This is more expensive than other disposal routes since chemical and physical characterisation of the sediment would need to be conducted by a certified laboratory and restrictions on the moisture content of material accepted at most licensed sites means that drying or dewatering of sediment would be necessary prior to disposal, (Brooke et al, 1996). Furthermore, SUDS sediments with high organic matter content may be classed as biodegradable and not inert, restricting the number of sites that would accept the sediment and increasing disposal costs. It is expected that the regulations for disposal of inert waste will be tightened in the future.

6. CONCLUSIONS

The sediment survey of the Dunfermline SUDS shows that sedimentation rates vary between years, probably due to changes in site development and storm flows. The SUDS management train appears to be effective in trapping sediment in detention basins upstream of retention basins, thereby reducing the costs of sediment removal from retention basins. Sediment quality varies spatially in the Dunfermline SUDS, with the highest contaminant concentrations occurring near the inlets. Metal concentrations in SUDS sediment increased as the Dunfermline site developed, probably due to increased traffic. Mean metal concentrations of sediment from the Dunfermline SUDS complied with different sediment quality standards, although “hotspots” of contamination occur within each SUDS.

The wider literature survey of metals concentrations in SUDS and other aquatic sediments showed that there is a wide range of sediment quality in SUDS. Some SUDS sediment is of a similar quality to uncontaminated background samples, whilst other SUDS sediment is of a similar quality to contaminated soils. Sediment from most SUDS sites is likely to be exempt from the UK Waste Management Licensing Regulations 1994 and may be disposed of by spreading on adjacent land or on agricultural land.

The decision on if and when to remove sediment from a SUDS is site-specific and depends on a number of factors, including: design water storage volume, design sediment storage capacity structure, contaminant concentrations in sediment, sedimentation rates, quality of aquatic ecosystem, costs of sediment removal and disposal, the impacts of sediment removal on SUDS ecosystem and water quality. A framework for further testing of SUDS sediments and guidance for removal and disposal of SUDS sediment as apart of routine maintenance are needed, although it is likely that the disposal of SUDS sediment will need to be assessed on a site-by-site basis.

7. ACKNOWLEDGEMENTS

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8. REFERENCES


