06 - ASSESSMENT OF URBAN PRESSURES AND SUDS DESIGN: THE ESTIMATION OF STORMWATER SUSPENDED SOLIDS AND PARTICLE SIZE DISTRIBUTIONS FROM A RESIDENTIAL CATCHMENT

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Abstract
Numerous studies of urban stormwater runoff have linked receiving water impairments to physical effects of the suspended solids, and chronic toxicity from particulate-bound pollutants. The Water Framework Directive (WFD) River Basin Management Plans in Ireland promote the use of Sustainable Drainage Systems (SuDS) to mitigate stormwater pollution. The efficiency of many SuDS devices such as settlement ponds are highly sensitive to the particle size distributions (PSDs) of the suspended solids, however the detailed design of these systems is rarely undertaken due to the limited use of stormwater quality models, and a lack of local data for calibration. While the suspended solids load of urban stormwater has been reported in a number of UK and International Studies, particle size data is rarely reported. Thus, an 18-month study of a residential catchment in south Dublin was undertaken to investigate the size distributions and sediment-bound pollutant concentrations of urban particulate matter arising in a pipe-and-gully stormwater system. Characterisation of traditional drainage systems such as these is vital since they dominate urban drainage infrastructure, and retrofit of systems in urban areas will be necessary to reduce current loadings of contaminated sediments and adapt the urban landscape to future pressures such as climate change. This paper focuses on the characteristics of the suspended solids transported to the outlet of the drainage system, and the development of a model of solids build-up and washoff from urban surfaces. In the context of current research, the novel aspects of the model included its application to the particle range typically transported to the outlets of pipe-and-gully systems, and the differentiation of build-up and washoff in a number of size fractions. The model outputs enabled the annual mass of contaminated sediments and particulate-bound pollutants to be estimated for a residential catchment. When compared to traditional methods of urban pollution assessment, such as the volume-concentration method used in the WFD Urban Pressures Study, the volume-concentration method was found to over-estimate the annual mass of suspended solids, possibly due to the tendency to sample large storms when measuring event mean concentrations (EMCs). The majority of the suspended solids transported to the outlet of the drainage system were fine solids (<100 µm), indicating that long settling times or filtration processes would be required for end-of-pipe retrofit solutions. Another key finding was that heavy metal concentrations in the suspended solids exceeded established receiving water thresholds for eco-toxicity. The study outputs should inform future assessments of Urban Pressures in terms of stormwater effects, and provide a sound basis for the design of new-build and stormwater retrofit solutions.

1 INTRODUCTION
Stormwater runoff is a significant contributor of pollutants to receiving waters, particularly in urban settings. A study of urban pressures in Ireland concluded that stormwater discharges contribute the highest load of nutrients and heavy metals to watercourses in urban areas, followed by discharges from wastewater treatment plants, combined sewer overflows and atmospheric deposition (CDM,

2009). Receiving water impairments most commonly arise from contaminated sediments in the runoff (US EPA, 1983). The particle size distribution is a key parameter in the study of sediment chemistry, transport and fate (Kobriger and Geinopolos, 1984). Although SuDS are common in new developments, existing stormwater collection in Ireland is still dominated by pipe and gully systems (Brady, 2010). In the US, pipe and gully systems represent approximately 65% of surface water infrastructure (Maestre and Pitt, 2005), so an understanding of the processes involved in these systems is critical for impact assessments, and design of retrofit solutions. A comprehensive study of urban drainage in the Greater Dublin area (Dublin City Council, 2005) provided minimal guidance on stormwater pollution mitigation, as it was recognised that: "*More research is required on the quality of catchment runoff and the processes by which pollutants are transported, specifically, data is needed on the relationship between particle size and the pollutant load".* Many urban stormwater models assume that the generation and transport of suspended solids is independent of particle size, however few experimental studies have tested the validity of this assumption. Therefore, an 18-month field study of an urban catchment was undertaken with the overall aim of investigating the role of particle size on the nature and transport of sediments and associated pollutants in urban stormwater drainage.

2 METHODOLOGY

2.1 Sampling site

The sampling site is an urban residential development covering approximately 10 hectares (Ha) located in Kimmage, south Dublin. Housing types are generally terraced, and the housing density is 33 units/Ha. The catchment was previously drained by a 225 mm diameter combined sewer only, however surcharging and flooding of the sewer routinely occurred during heavy rainfall. To alleviate this problem, Dublin City Council constructed a new separate stormwater system to serve roads and paved areas (Figure 1). Roof areas remain connected to the combined system, or discharge to lawns. The new system, completed in November 2010, comprises of a pipe and gully network draining 1.42 Ha of impervious area, and includes a new outfall to the River Poddle. The stormwater drainage system was selected for detailed monitoring, in consultation with Dublin City Council Drainage Division, as the site was considered typical of urban residential development in the city.

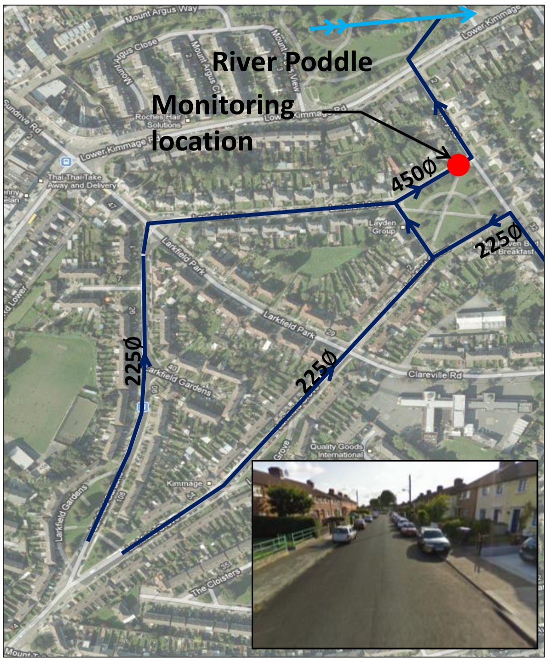

Figure 1: *Kimmage site plan, drainage layout and street view (Map source: Google Maps)*

2.2 Flow measurement and stormwater sampling

Flow was measured at 1-minute intervals by an ISCO 2150 area-velocity probe installed on the outlet the drainage system, as shown in Figure 1. Rainfall was measured at 2-minute intervals on the site using an ISCO 6700 tipping bucket rain gauge. An automatic sampler (ISCO 6712) was used to retrieve stormwater samples by volume-pacing (typically 1-10 m^3/sample), and the sampler intake was secured at the base of the pipe. The sampling equipment was connected to an ISCO 2105G modem, which logged and transmitted data to a dedicated website.

2.3 Sample analysis

Stormwater samples were pre-filtered using a 1-mm nylon mesh. The material retained on the mesh generally comprised of litter and organic matter, and represented a small fraction of the suspended solids mass, so this material was not included in the analysis. A Dekaport® cone splitter was used to ensure that sub-samples of stormwater were representative in terms of suspended solids concentration (SSC) and PSD. The SSC was determined using Standard Method D3977-97(B) (ASTM, 2009). A PSD analysis methodology for suspended solids was developed using a laser diffraction instrument (Malvern Mastersizer 2000®). Analysis of a reference material (Sil-co-Sil® 250) indicated that the results obtained from laser diffraction were comparable to the sieve and sedimentation methods. Samples for heavy metals and phosphorus analysis were prepared in accordance with Method 200.7 (US EPA, 1994) and analysed by inductively-coupled plasma atomic emission spectrometry.

3 RESULTS AND DISCUSSION

3.1 Rainfall and runoff

Rainfall and runoff were recorded on the catchment from February 2011 to August 2012. Total rainfall in this period was 1030 mm. Flow was recorded for 49 of the 109 events (>2 mm) occurring during the monitoring period, or 65% of the total volume. For the remaining events, runoff rates were generally below the measureable range of the flow meter: 20 mm depth, or approximately 0.5 l/s. The relationship between rainfall and runoff is shown in Figure 2. The runoff coefficient of 0.46 was lower than that typically observed for hard standing areas. Whilst the concrete footpaths were impervious to rainfall, observations during rain events indicated that some infiltration of rainfall occurred through the bituminous macadam surfacing, particularly for low rainfall intensities. Approximately 1.3 mm of rainfall was required to generate runoff at the outlet, as illustrated by the intercept term. Three events were excluded from Figure 2 for clarity, ranging from 33.8 mm to 62.8 mm. The runoff coefficient for these events was 1.3, possibly due to a combination of saturation of the macadam surfacing, contributions from pervious surfaces and enlargement of the catchment during extreme rain events. These effects may also have had an influence on the >15 mm events.

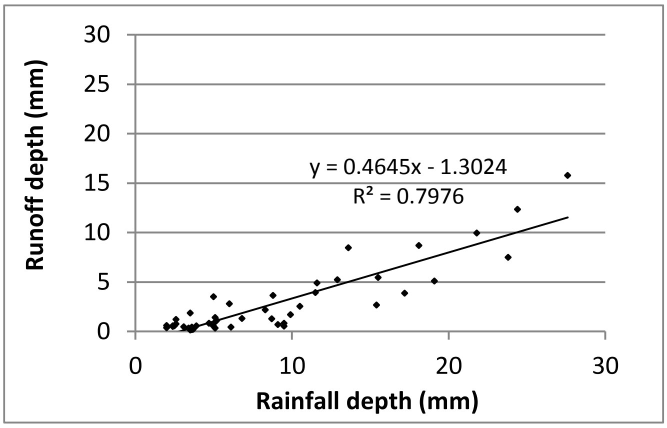

Figure 2: *Runoff depth vs. rainfall depth*

3.2 Summary of stormwater quality

The stormwater quality characteristics for the monitored events are summarised in Table 1. These values were flow-averaged event mean concentrations (EMCs) of the rain event discrete samples, calculated using the mid-point volume method (Charbeneau and Barrett, 1998). The EMCs from the Kimmage catchment are compared in Table 1 to a US database of residential stormwater quality (due to its large sample size: minimum of 690 observations of non-filtered concentrations), and an Irish study of highway runoff (Bruen et al., 2006). The median EMCs of copper (Cu) were comparable to the US values. Levels of lead (Pb) and zinc (Zn) were somewhat lower in this study, which may have reflected differences in traffic loadings. The median EMC of suspended solids was 60% of the US median value, and total phosphorus (TP) was 30% of the US concentration. The lawns and landscaped areas in Kimmage were bounded by walls and kerbs; these physical barriers may have been an effective source control measure (albeit unintentional) to prevent organic matter from entering the drainage system. The highway runoff yielded concentrations of heavy metals and suspended solids which were an order of magnitude higher than the US or Kimmage sites. Daily two-way traffic on the highway site was between 25,000 and 30,000 vehicles/day compared to an average of 1,822 vehicles/day on the Kimmage catchment. Non-filtered (NF) TP concentrations were approximately three times higher on the highway catchment, which again may be linked to the availability of a flow path between the highway landscaping (which is a common visual barrier on Irish highways) and the drainage system. These findings support the approach of separating general urban/residential development from main road land use when mapping potential stormwater pollution hazards (Mitchell, 2005). The filtered to non-filtered ratios (F/NF) for Cu, Zn and TP were approximately 30%, indicating that most of the heavy metals and phosphorus was associated with the particulate fraction. This was supported by correlations between the EMC of suspended solids and the non-filtered pollutants: R^2 values of 0.88 (Cu); 0.83 (Pb); 0.90 (Zn); and TP (0.86). The filtered EMCs of Cu and Zn from the Kimmage catchment did not exceed the 24-hour thresholds for acute biotic impacts specified by the UK Highways Agency (2009). However, when the heavy metal concentrations were converted to sediment bound concentrations (in mg/kg), these were found to exceed probable effect concentrations for toxic effects on receiving water biota as recommended by MacDonald (2000) and the UK Highways Agency (2009). Therefore, the stormwater solids should be prevented from entering sensitive receiving waters, using appropriate measures including SuDS.

Table 1: *Comparison of residential stormwater pollutant EMCs with previous studies*

	SSC	F* Cu	NF** Cu	F Pb	NF Pb	F Zn	NF Zn	F TP	NF TP
This study									
# Observations	19	13	13	13	13	13	13	11	11
Median	29	<5	15	<5	5	16	49	45	124
Residential (Pitt and Maestre, 2005)									
# Observations	978	90	771	108	762	87	784	690	926
Median	49	7	12	3	12	32	73	180	310
Highway (Bruen et al., 2006)									
# Observation	16	16	16	16	16	16	16	16	16
Mean	425	11	90	24	98	35	461	-	460
*Filtered concentration **Non-filtered concentration. All concentrations in µg/l, except SSC (mg/l).									

3.3 Particle size distributions of the suspended solids

The PSD of the suspended solids was measured in 8 rain events from April 2011 to November 2011. For each rain event, discrete samples were selected for analysis at regular intervals, particularly around flow peaks. The even mean PSD was calculated from the following:

$$\bar{\mathbf{M}}_i = \sum_{j=1}^{n} \left(\frac{\mathrm{Vol}_i \cdot \mathbf{M}_j}{100 \cdot \mathbf{M}_t} \right) \qquad \text{Eqn. 1}$$

where, $\bar{\mathbf{M}}_i$ = average event % mass in size fraction (%), i = size fraction index (e.g. 0-10 µm), n = number of event samples, j = sample event index, Vol_i = % volume of particles in size fraction i from laser diffraction analysis (%), M_j = mass of suspended solids for sample j (g), M_t = total event mass of suspended solids (g); and:

$$\mathbf{M}_j = \frac{\mathbf{V}_j \cdot \mathrm{SSC}_j}{1000} \qquad \text{Eqn. 2}$$

where, V_j = volume interval for sample j (l) and SSC_j = suspended solids concentration of sample j (mg/l).

The event mean PSDs are shown in Figure 3. The median particle size from all events was 33 µm. Median particle sizes of 3-75 µm have been measured in previous studies (Li et al., 2006; Selbig and Bannerman, 2011; Arias et al., 2013), and the median particle size for suspended solids is estimated at 35 µm (Burton and Pitt, 2002), so the catchment investigated could be considered representative of typical residential development. The substantial proportion of suspended solids finer than 33 µm from the Kimmage catchment implies that a two-stage process such as sedimentation followed by filtration would be required for effective retrofit solutions (Cristina et al., 2002).

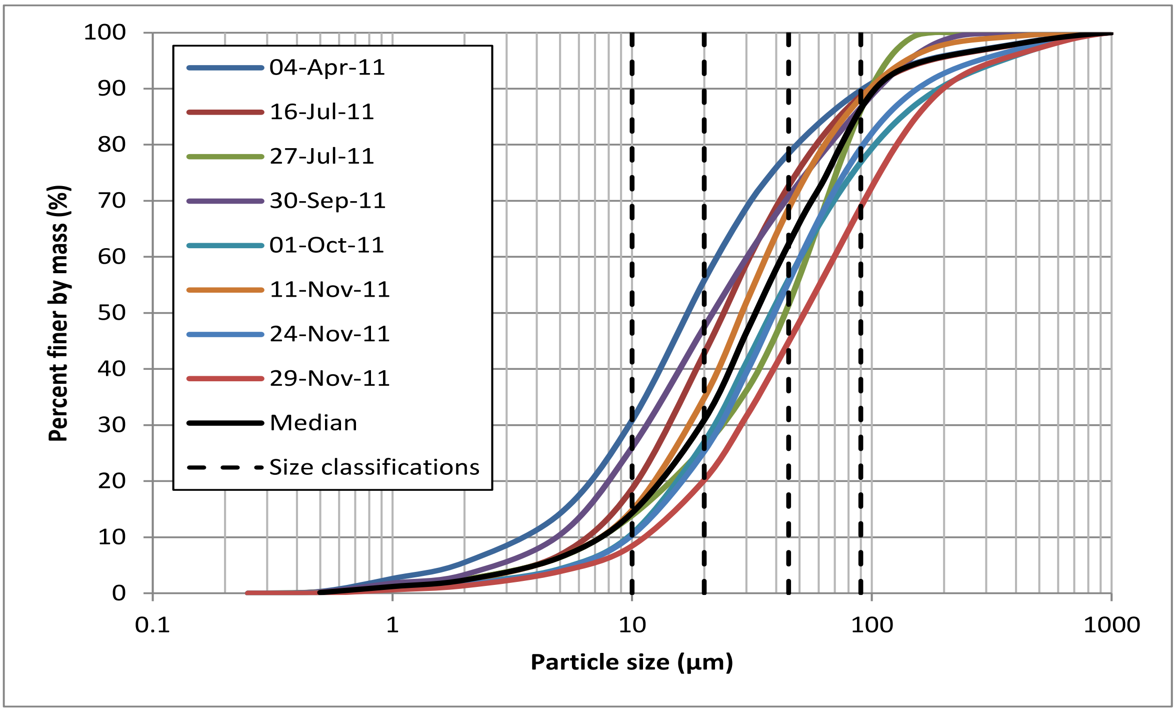

Figure 3: *Event mean PSDs on the residential catchment*

Importantly, 96% of the suspended solids from the Kimmage catchment were finer than 212 µm, on average. Another aspect of this project characterised sediment build-up in 10 gullies around the catchment. Of the material sampled after 1 year of accumulation, just 8% of the gully deposits were finer than 212 µm, indicating a low retention capacity in the gully pots for this size fraction. Also shown in Figure 3 were the sizes used to classify particle ranges for the suspended solids modelling: <10 µm; 10-20 µm; 20-45 µm; 45-90 µm; and 90-1000 µm. These classifications were chosen to ensure a relatively uniform proportion of mass in each size fraction.

3.4 Relationships between the particle size distribution and event characteristics

The average PSDs of the rain events were compared to a number of event characteristics in Figure 4. The median particle size (d_{50}) was used as an indicator of the average event distribution. There was little correlation between the event mean d_{50} and the total rainfall or antecedent dry period (ADP). Both the peak flow and the peak 10-minute rainfall intensity were correlated with the event mean d_{50} (R^2 values of 0.89 and 0.93). One outlier was excluded from the analysis, the event of July 27th. Two events had similar peak flows to the outlier event, April 4th and July 16th, but the ADP was significantly greater for the outlier event (6.2 days vs. 2.1 and 1.0 days). Measurements of sediment accumulation on paved surfaces (discussed in Section 4.1) yielded higher accumulation rates for coarse particles, which may have accounted for the higher d_{50} of the July 27th event. Since the peak flow and peak 10-minute intensity were correlated with each other (R^2 of linear regression of 0.84), it was not possible to separate their effects. However, the analysis indicated that both variables should be included in washoff modelling. The event mean PSD was shown to be sensitive to the rain event characteristics, which indicated that washoff was selective with respect to particle size, although the availability of particles in different size fractions was also an important consideration.

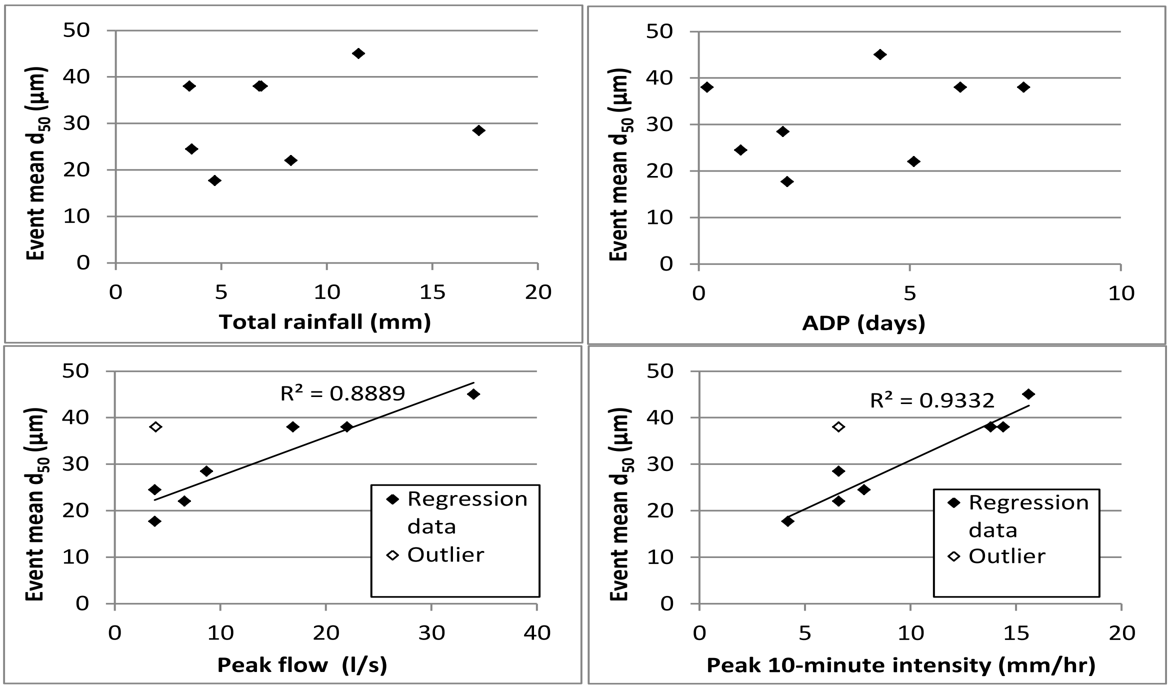

Figure 4: *Relationship between event mean d_{50} and rain event characteristics*

4 MODELLING OF SUSPENDED SOLIDS BUILD-UP AND WASHOFF

4.1 Sediment build-up

Most urban stormwater quality models are based on the build-up of sediment on catchment surfaces over dry days, which is washed off by subsequent rainfall. Sediment accumulations in a number of size fractions were measured on the Kimmage catchment during dry periods. The accumulation patterns are summarised in Figure 5 for fine particles (<212 µm). This size fraction was important as it typically bypassed the gully pots, and was transported to the outlet as suspended solids. As shown in Figure 5, a linear model of sediment build-up was appropriate for the Kimmage catchment. However, there was a large degree of spatial variability. This may have been attributable to the traffic densities: Priory Road Square, zone 2 (575 vehicles/day); Larkfield Gardens, zone 3 (1109 vehicles/day); Larkfield Gardens, zone 1 (1109-10315 vehicles/day). The sediment build-up rate measured on road surfaces varied between 0.07 g/m^2.day and 0.77 g/m^2.day. Due to the wide range observed, the build-up rate was designated as a calibration parameter in the suspended solids model.

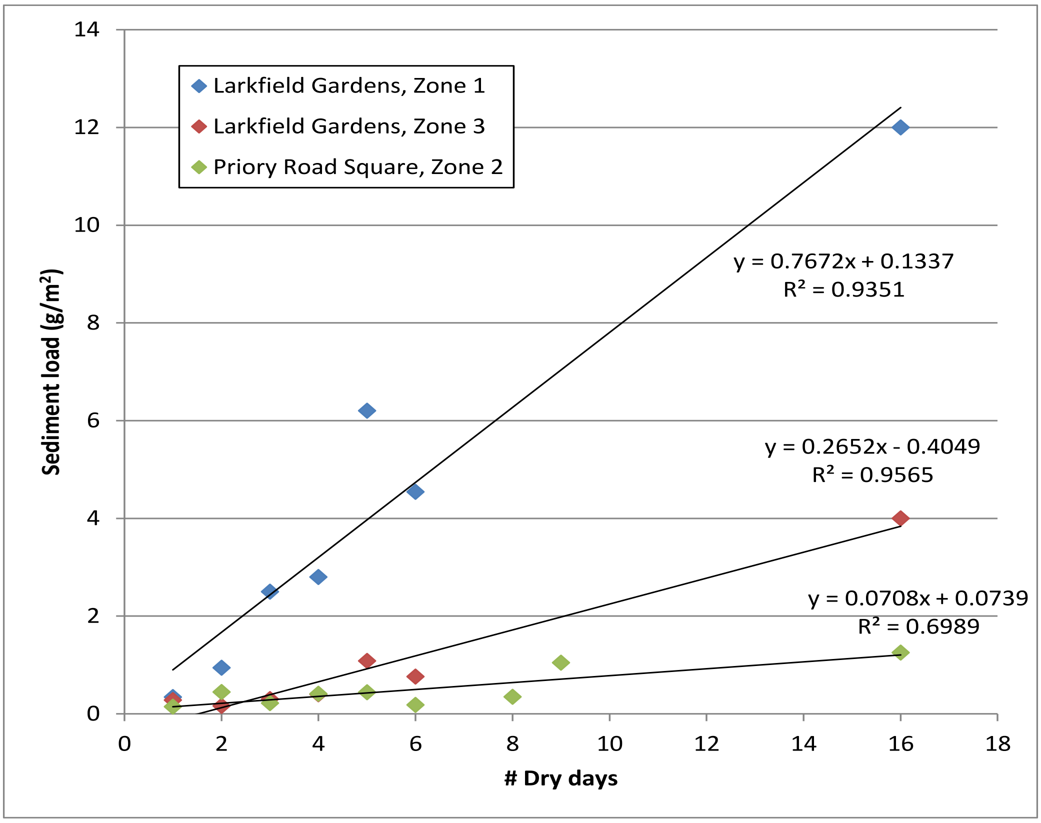

Figure 5: *Pavement sediment load vs. # Dry days*

4.2 Sediment washoff

Washoff of sediment from impervious surfaces on the Kimmage catchment was represented by an exponential function, as proposed by Sartor and Boyd (1972). This formulation is incorporated into a number of stormwater quality models including the US EPA Stormwater Management Model (SWMM), where the mass of material remaining on the pavement is given by (Nix, 1994):

$$P_r(t) = P_0 \cdot e^{-kt} \qquad \text{Eqn. 3}$$

where $P_r(t)$ = mass remaining on the pavement surface at time t (kg), P_0 = initial mass on the pavement surface (kg), k = coefficient (s^{-1}), t = time (s), and:

$$k = R_c \cdot r^n \qquad \text{Eqn. 4}$$

where R_c = washoff coefficient (mm^{-1}), r = runoff rate over subcatchment (mm/s) and n = washoff exponent.

The runoff rate, r, was calculated as the flow rate measured at the outlet of the drainage system divided by the contributing hard standing catchment area. Eqn. 4 was solved using a finite difference approximation. The sediment build-up and washoff model was implemented using Matlab (Release 2013a, Mathworks Inc.).

4.3 Model calibration

The suspended solids model was run continuously at 2-minute intervals over the 18-month monitoring period. The calibration parameters were: the sediment build-up rate; the washoff coefficient, R_c; and the washoff exponent, n. The bounds on the calibration parameters were based on recommended values (Huber and Dickinson, 1992). Initially, the evaluation function used was the Nash-Sutcliffe

Efficiency (NSE), however this function was found to be overly-sensitive to the timing of peaks in SSC, and resulted in a biased estimates of total event mass. Instead, a multi-criteria evaluation function was developed which considered the total mass and peak SSC of each rain event:

$$T_{err} = TM_{err} + PC_{err} \qquad \text{Eqn. 5}$$

$$TM_{err} = \sum\left(\frac{|TM_{obs}(i) - TM_{mod}(i)|}{\overline{TM}_{obs}}\right) \qquad \text{Eqn. 6}$$

where, T_{err} = total error, TM_{err} = total mass error, TM_{obs} = observed total event mass (kg), i = calibration event index, TM_{mod} = computed total event mass (kg) and $\overline{TM}_{obs}$ = mean of total mass for calibration events (kg).

$$PC_{err} = \sum\left(\frac{|PC_{obs}(i) - PC_{mod}(i)|}{\overline{PC}_{obs}}\right) \qquad \text{Eqn. 7}$$

where, PC_{err} = peak concentration error, PC_{obs} = observed peak SSC (mg/l), PC_{mod} = computed peak SSC (mg/l) and $\overline{PC}_{obs}$ = mean peak SSC for calibration events (mg/l).

The Matlab *GlobalSearch* algorithm was used to adjust the calibration parameters automatically in order to minimise T_{err}. Analysis of the initial model outputs revealed that peaks in SSC were represented to a reasonable extent where high flows were generated by high rainfall intensity (Figure 6 (a)). However, where high flows were generated by low intensity rainfall over a longer duration, the SSC was over-estimated by the model (Figure 6 (b)). This occurred because the washoff coefficient, k, in Eqn. 4 was dependant on the runoff rate only, on the assumption that runoff was proportional to rainfall. Since significant infiltration occurred on the Kimmage catchment, washoff of solids was in fact related to the runoff rate and rainfall intensity.

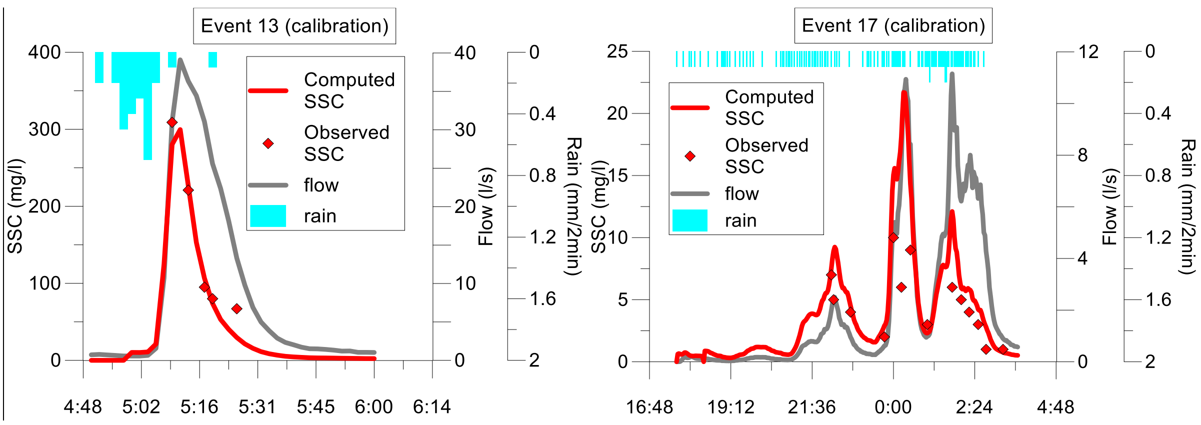

Figure 6: *Rain, flow, computed SSC and observed SSC for (a) Event 13 and (b) Event 17*

The rainfall intensity was therefore included in the determination of k as follows:

$$k = I_c \cdot R_c \cdot r^n \qquad \text{Eqn. 8}$$

$$I_c = (1 + i_{10}(t))^{I_e} \qquad \text{Eqn. 9}$$

Where, I_c = rainfall intensity coefficient, i_{10} = antecedent 10-minute rainfall depth (mm) and I_e = intensity exponent.

The form of Eqn. 9 was such that the value of I_c was 1 during periods without rainfall. Brodie (2007) found that the mass of material washed off small subcatchments was related to the square of the antecedent 6-minute rainfall intensity; however, the 10-minute intensity was used in Eqn. 9 to allow for the transport time of solids through the pipe network. The revised model also disaggregated suspended solids into a number of size fractions. The 8 events monitored for PSD were used to calibrate the values of build-up rate, n, R_c and I_e. For verification of the model, the computed SSC in each size fraction was summed to compare to the remaining monitored events, where SSC was measured in one size fraction (<1000 µm). The calibrated parameter values for each size fraction are shown in Table 2. The build-up rate in each size fraction reflected their proportions in the measured PSDs (Figure 3); e.g. the 20-45 µm range dominated the PSD and had the highest build-up rate. There was less variation in the model parameters for the washoff process in the three central size fractions, which suggests that the washoff of 10-90 µm solids may have occurred as an agglomeration. However, the 0-10 µm and 90-1000 µm washoff parameters were significantly different.

Table 2: *Calibrated model parameters of suspended solids model for different size fractions*

Size fraction	**Build-up rate**	**n**	**R_c**	**I_e**	**T_{err}**
µm	g/m^2.day		mm^{-1}		
0-10	0.0022	2.36	3520	1.72	6.9
10-20	0.0030	2.28	2924	1.47	7.1
20-45	0.0043	2.27	3037	1.47	7.1
45-90	0.0024	2.27	3871	1.51	9.3
90-1000	0.0015	2.30	3075	2.72	10.1
Total	0.0134				

The model predictions improved with decreasing particle size, as evidenced by the reducing total error statistic in Table 2. The effect of particle size on model performance is also shown in Figure 7, where the computed event total masses are plotted against the measured values. Referring to Figure 7(a), the least bias (y = 0.92x) was achieved for the 0-10 µm fraction, with a similar performance for the 10-20 µm fraction (Figure 7(b)). The degree to which the model under-predicted the observed total event mass increased with particle size. This indicates that for larger particles, the catchment may not have been source-limited, and washoff loads depended on event characteristics. Urban stormwater quality models including SWMM and Hydraulic Simulation Program – Fortran (HSPF) assume similar build-up and washoff patterns for all suspended particle sizes, but the outputs of this study would suggest that size fractionation of suspended solids is necessary, although the benefits of modelling individual fractions would need to be weighed against the increased requirement for monitoring data relating to particle size. The accuracy of predictions reduced with increasing particle size, which may have been related to the assumption of a limited store of large particles on the pavement surfaces. The gully pots may also have been influential in this regard, as they would have been expected to retain a proportion of the larger solids, particularly those greater than 200 µm.

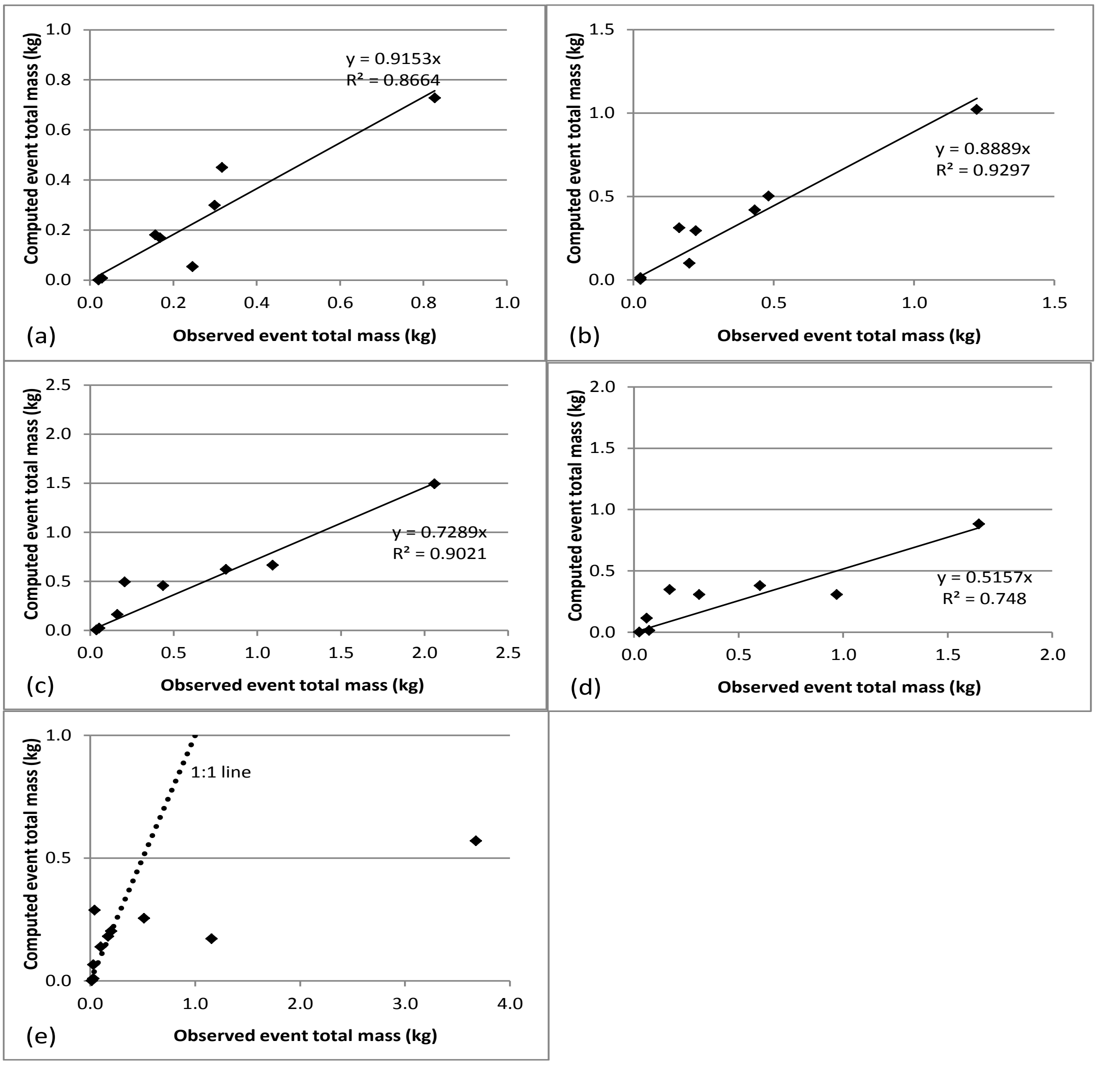

Figure 7: *Computed event total mass vs. observed total mass for (a) 0-10 µm (b) 10-20 µm (c) 20-45 µm (d) 45-90 µm and (e) 90-1000 µm fractions for calibration events*

4.4 Estimation of annual suspended solids yield

Using the calibrated parameter values shown in Table 2, the annual suspended solids yield from the catchment was estimated in each size fraction. To account for seasonal effects, the mass was calculated over one year, from August 15th 2011 to August 15th 2012, although the model was run continuously for the 18-month period. The annual mass in each size fraction is shown in Table 3, totalling 60.1 kg of suspended solids.

Table 3: *Annual mass of suspended solids from the Kimmage catchment for different size fractions*

Size fraction	Annual mass of suspended solids
µm	kg
0-10	10.1
10-20	13.3
20-45	19.1
45-90	10.9
90-1000	6.7

Total	60.1

A common approach which has been used to estimate the annual load of suspended solids is the volume-concentration method (Mitchell et al., 2001). The annual mass of suspended solids was calculated using this method (Eqn. 10) with the following inputs: total rain in the 12-month period (0.735 m); weighted-average EMC (35 mg/l); average runoff coefficient (0.46), and the area contributing to the drainage system (1.42 Ha).

$$\text{Annual mass} = R_T \cdot A \cdot c_v \cdot WEMC = 168\ \text{kg} \qquad \text{Eqn. 10}$$

where, R_T = annual rainfall (m), A = catchment impervious area (m^2), C_v = volumetric runoff coefficient and WEMC = weighted event mean concentration (kg/m^3).

The annual mass calculated from the volume-concentration method exceeded the modelled value by a factor of 2.8. If the runoff coefficient was higher, as would be the case with many urban catchments, the disparity would have been higher still. The primary reason for the divergence was the weighted EMC was presumed to represent the average concentration of rain events occurring during the monitoring period. In fact, samples can be biased towards larger rain events because stormwater sampling equipment is generally less effective at sampling small storms; for example, area-velocity flow meters may require a minimum flow for accurate readings. Furthermore, it is convenient to target larger events when demonstrating removal efficiencies for SuDS devices, or when attempting to calibrate models. However, it has been shown that in the absence of continuous simulation, this approach can over-estimate annual solids loads.

5 CONCLUSION

This study of a residential stormwater drainage system has highlighted the importance of solids in transporting urban pollutants. The sediment and pollutant concentrations from the residential catchment were significantly lower than those of an Irish study of highway runoff, justifying the differentiation of these land uses in urban stormwater quality models. However, the residential sediment-bound concentrations exceeded established eco-toxicity thresholds. The fine distribution of the suspended solids may necessitate a multi-phase treatment process where stormwater treatment is required, such as discharges to sensitive waters. A continuous build-up and washoff model was developed and calibrated for a number of size fractions. The annual mass of suspended solids from the volume-concentration method was 2.8 times higher than the output from the continuous model. Therefore, estimates based on this method should carefully consider the appropriateness of the EMC values used. The outputs of the study should assist in future assessments of urban runoff impacts and the design of mitigation measures.

6 ACKNOWLEDGEMENTS

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