The influence of particle size on the first flush strength of urban stormwater runoff

D. Morgan, P. Johnston, K. Osei and L. Gill

ABSTRACT

The presence of a first flush (FF) of suspended solids (SS) in stormwater runoff has important implications for the design of treatment facilities, as does the particle size of solids. Whilst numerous studies have examined the FF behaviour of SS, few have disaggregated FF trends by particle size. In this study, the FF behaviour of SS was investigated in five size ranges, sampled from an urban stormwater drainage system located in Dublin, Ireland. A weak FF was exhibited in the gross fraction of SS, with just two events from 14 transporting more than 50% of the SS mass in the first 25% of runoff, implying that treatment structures should be capable of removing SS throughout the storm event. In the majority of rain events, the FF strength increased with decreasing particle size, probably related to the lower intensities required to dislodge solids at the onset of rainfall. Although FF strength was correlated with rain event characteristics, prediction intervals were too broad to confirm FF presence based on rainfall data alone. Therefore, the design of smaller treatment volumes based on an assumption of FF must be justified by local monitoring data.

Key words | first flush, particle size distribution, stormwater runoff, suspended solids

INTRODUCTION

Stormwater runoff from urban impervious surfaces has been linked to receiving water impairments, commonly exhibited in chronic benthic impacts due to sediment-bound pollutants contained in the runoff (Taylor & Owens 2009; Johnson et al. 2013; Rossi et al. 2013). Much research has been devoted to examining the ‘first flush’ (FF), the initial part of the rain event where a high proportion of suspended solids (SS) and other pollutants may be washed from catchment surfaces. The FF is an important phenomenon due to its potential short-term toxicity for receiving water biota (Kang et al. 2008). Furthermore, the design of stormwater treatment systems is often based on the assumption of a FF effect. For example, the water quality storage volumes of detention ponds are commonly sized to intercept the first 10–15 mm of rainfall on the assumption that this contains the most polluted fraction of the rain event (Sansalone & Christina 2004; UK Highways Agency 2006). However, the possibility exists that a flush of pollutants may be observed at the drainage outlet at any time in the storm event, in response to peaks in rainfall intensity or runoff (Aryal et al. 2005).

Many researchers have examined the links between rainfall characteristics and the FF strength of SS. FF strength may be considered as the mass of pollutants transported in the initial storm event volume, although precise definitions vary. While some researchers have identified relationships for specific catchments (Deletic 1998), there has been a greater difficulty in finding common explanatory variables for FF strength across different catchments and surface types (Bertrand-Krajewski et al. 1998; Lee et al. 2002; Hathaway et al. 2012; Charters et al. 2013). This difficulty arises from attempting to represent complex physical transformations which occur during the transport of solids through urban drainage systems by relatively simple regression relationships. One of the confounding factors is the selective transport of SS with respect to particle size in the build-up and washoff of solids from urban surfaces (Zafra et al. 2008; Morgan et al. 2017) and passage through gully pots (Butler & Karunaratne 1995). Other factors influencing FF strength may include re-suspension of previously deposited sediments (Aryal et al. 2005), and the fraction of organic material in the SS, which may have a different washoff signature to the inorganic material (Lee et al. 2004), and be subject to seasonal effects (Stenstrom & Kayhanian 2005).
Suspended solids FF is often analysed in terms of a single size fraction, typically 1.5–1,000 μm, although the upper size limit can vary between studies. This aggregation of particle sizes may mask significant factors influencing FF occurrence. In addition, knowledge of FF behaviour in multiple size fractions is beneficial since (1) urban pollutants preferentially adsorb to smaller particles due to their larger surface area per unit mass (Sansalone & Buchberger 1997) and (2) the efficiencies of stormwater treatment systems such as ponds and hydrodynamic separators are sensitive to particle size (Greb & Bannerman 1997; Arias et al. 2013).

There have been a number of studies of size-fractionated FF. Christina & Sansalone (2005) developed particle number relationships to represent FF behaviour of different size fractions of 2–75 μm SS, concluding that single and multiple-power law models were applicable. Stenstrom & Kayhanian (2005) reported on a comprehensive study of pollutant and seasonal FF from three highway sites in Los Angeles, USA. In this study, limited data (three storm events) were available for the analysis of size-fractionated FF, but it was noted that larger particles were washed out earlier in the storm events than fine particles. From grab sampling of highway runoff, Li et al. (2006) reported that the initial 20% of runoff transported more than 50% of 2–30 μm particles, and 40% of particles greater than 30 μm, indicative of size-selective washoff processes. Zhang & Li (2015) investigated FF in combined sewer overflow (CSO) samples from an urban catchment in Shanghai, China, noting increased FF strength for larger particles, which may have been related to the CSO operation (having a pumped overflow). Whilst the preceding studies have focussed on the pattern and timing of FF, there has been limited study of the relationship between rain event characteristics and the FF strength of SS in different size fractions, which may allow the prediction of a significant FF effect for a given catchment.

This paper addresses three key questions, supported by detailed field data, relating to the FF of SS transported to the outlet of a stormwater drainage system:

- Does the FF strength of SS vary by particle size?
- Do rain event characteristics influence size-fractionated FF strength?
- What are the implications for stormwater treatment?

FF characteristics were investigated by sampling the outlet of a stormwater drainage system over an 18-month period. Discrete samples were analysed for SS to ascertain FF behaviour. Additionally, analysis of particle size distribution (PSD) in a number of storm events allowed FF behaviour in different SS size fractions to be assessed.

MATERIALS AND METHODS

Site description

The monitored catchment is located in Kimmage, a residential suburb of south Dublin, Ireland. The catchment covers 12.9 hectares (ha), with a housing density of approximately 33 units/ha. The monitored drainage system is a pipe and gully, separate stormwater system draining approximately 1.42 ha of directly connected impervious areas (Figure 1). Roads are surfaced in bituminous macadam, and footpaths are surfaced in concrete, both of which were re-constructed in 2010, along with the surface water drainage system. Although front lawns and driveways accounted for 14% of the total catchment area, the presence of pervious drive-ways, cracks in impervious surfaces, and boundary walls meant that little or no runoff was generated from these areas (based on visual inspection). Approximately 20% of roof areas were connected to the surface water drainage system, the remainder discharged to the combined sewer, or to lawns. The mean longitudinal slope is 1% from south to north; likewise sewer gradients are approximately 1%. These gradients, and the good condition of the sewer network, meant that deposition of SS in the sewer between storm events was likely to be negligible, which was confirmed through a number of visual inspections of the drainage system. Traffic densities varied from 575 to 2,000 vehicles/day on feeder streets (90% of drained area) to 10,500 vehicles/day on the collector street (10% of drained area). For a full description of catchment and drainage system attributes, refer to the Supplementary Information (available with the online version of this paper).

Flow measurement and sampling

The catchment was monitored between March 2011 and August 2012, during which 19 rain events were analysed for suspended solids concentration (SSC), of which eight were also analysed for PSD. For each event, flow was measured at 2-minute intervals using an area-velocity probe (ISCO 2150). Rainfall data were provided by a tipping-bucket rain gauge (0.1 mm/tip, ISCO 674) located on-site. Samples were retrieved at the outlet of the drainage system using an automatic sampler (ISCO 6712), with the sampler inlet secured at the base of the pipe. Whilst stratification of stormwater solids may present difficulties for representative sampling by fixed point sampling inlets (Selbig et al. 2012; Selbig 2013), the method employed was considered robust and suitable to
compare to previous studies. For future studies, the use of depth-integrated sampling should be examined. The capacity of the sampler was 24 1-litre bottles, and sampling was flow-paced in two phases: FF capture (1–5 m³/sample for the first 12 bottles, depending on forecasted rainfall) and whole-event capture (5–10 m³/sample for the remaining bottles). This approach was designed to collect more samples on the rising limb of the hydrograph, where changes in SSC and PSD were more rapid compared to the falling limb.

The capture of samples on the rising limb of the hydrograph is important for FF characterisation (Deletic 1998), particularly for short duration, high intensity rainfall events. Where fewer than two samples were retrieved on the rising limb or at peak flow (PF), these events were excluded from the event record. On this basis, 14 events were suitable for analysing the suspended solids FF and seven events could be analysed for FF across different particle size ranges. A typical storm event hydrograph and sample record are shown in Figure 2.
Sample analysis

The discrete samples were first passed through a 1-mm nylon mesh to remove gross solids. Gross solids generally transport a small fraction of stormwater pollutants and were not present in significant quantities in the samples (<5% by mass of SS). A cone splitter (Dekaport®) was used to provide representative subsamples for the SSC and PSD analyses. SSC was determined by Standard Method D3977-97 (ASTM 2009). PSDs of stormwater solids were measured by a laser diffraction instrument (Malvern Mastersizer 2000) in the size range of 0.1–1,000 μm. Analysis of a reference material (Sil-co-Sil 250®) confirmed that the results obtained by laser diffraction were comparable to sieve and sedimentation methods.

The PSD was measured as the percentage of total volume within each size range, assuming a spherical particle shape. Distributions were calculated in five size fractions: 0.1–10, 10–20, 20–45, 45–90, and 90–1,000 μm. These size ranges were chosen on inspection of the mean PSDs for each event (see Supplementary Information for PSD plots), and chosen to ensure approximately 20% of solids was included in each of the five size ranges, although individual distributions varied across samples and storm events. The size range of 90–1,000 μm covered a wide band of particle sizes, but within this range only 5% was greater than 300 μm, which is consistent with previous research (Aryal et al. 2017). The fractions were combined with the corresponding discrete sample measurement of SSC to generate SS loads in each size fraction, e.g. for a 1-litre sample with an SSC of 50 mg/l, containing 10% of solids in the 0.01–10 μm range, the mass of solids in the 0.01–10 μm range was 5 mg. The methodology assumed a constant density of particles with respect to particle size. Since the specific gravity of stormwater solids is strongly influenced by the fraction of organic material present, the assumption of constant density was examined by testing the organic content of stormwater solids (see Supplementary Information). The organic content for the size ranges examined did not vary greatly around the mean of 52%, apart from particles <10 μm, where the organic content increased. Noting the greater uncertainty of calculated SS loads for <10 μm particles, it was considered feasible to assume constant density for varying particle sizes.

Estimation of FF strength

The definition of the FF has been presented in a number of forms. Geiger (1984, 1987) plotted the normalised cumulative mass (M') of pollutants against the normalised cumulative volume of runoff (V') for a rain event, suggesting that a FF occurred where the initial slope was greater than 45°, or where the offset from the M'V' curve to the bisector
exceeded 0.2. Gupta & Saul (1996) developed this definition as the part of the event up to the maximum divergence of the $M^\prime V^\prime$ curve to the bisector. $M^\prime$ and $V^\prime$ can be obtained from Equations (1) and (2):

$$M^\prime = \frac{m(t)}{M}$$

$$V^\prime = \frac{v(t)}{V}$$

where $m(t)$ = cumulative pollutant mass at time $t$ (g), $M$ = total pollutant mass for rain event (g), $v(t)$ = cumulative runoff volume at time $t$ (l), $V$ = total runoff volume for rain event (l).

The $M^\prime V^\prime$ relationship can also be represented by a power function for separate stormwater systems (Bertrand-Krajewski et al. 1998):

$$M^\prime = V^b$$

where $b$ = first flush coefficient.

A value of $b$ equal to 1 represents a uniform distribution of pollutant mass over the rain event, with values less than 1 indicating a FF effect, and lower values of $b$ equating to a stronger FF effect. Saget et al. (1996) defined the following criteria for FF in terms of $b$: 0–0.185, strong FF; 0.185–0.862, moderate FF; 0.862–1, weak FF; 1–1.159, weak dilution; 1.159–5.395, moderate dilution; and >5.395, strong dilution. Informal definitions of FF have also been proposed, for example, where 50% of the pollutant mass is transported in the first 25% of the runoff volume (50/25 $M^\prime V^\prime$ ratio) (Wanielista & Yousef 1995), 40/20 $M^\prime V^\prime$ ratio (Deletic 1998) and 80/30 $M^\prime V^\prime$ ratio (Bertrand-Krajewski et al. 1998). Of these, the latter is the most restrictive FF definition ($b < 0.185$), which is rarely observed in stormwater runoff. In this study, the proportion of SS mass transported in the first 25% of the runoff volume, $M^\prime V_{25}$, was chosen as the primary measure of FF strength, since it is a transparent measure which is simple to apply and interpret for stormwater designers and regulators. The FF coefficient was also calculated to enable comparison of the findings with previous studies.

**RESULTS AND DISCUSSION**

**FF strength of SS**

The results of the FF analysis of the complete SS gradation are shown in Figure 3. According to the definitions of Saget et al. (1996) for $b$, 11 of 14 events exhibited a moderate FF effect, one event produced a weak dilution effect, and two exhibited a moderate dilution effect. In terms of the $M^\prime V^\prime$ ratio, the 50/25 criterion for FF was met for just two events, and the median $M^\prime V_{25}$ was just 0.34. This implies that stormwater mitigation strategies that only treat the first 25% of the storm runoff volume are unlikely to capture a significant proportion of the total pollutant mass. The mean FF coefficient of 0.74 determined in this study is comparable to other studies of separate stormwater catchments. Deletic (1998) examined two small impervious surfaces (<300 m²) in Belgrade, Serbia, and Lund, Sweden, having mean $b$ values of 0.73 and 0.85. Hathaway et al. (2012) sampled a larger stormwater catchment (1.94 ha) in Raleigh, North Carolina, USA reporting a mean FF coefficient of 0.75. Lee et al. (2002) examined 15 separate urban catchments in Chongju, South Korea, with $b$ ranging from 0.8 to 1.21. Thus, while $b$ can vary from one site to another, in most cases a significant FF does not appear to be present, which was indeed the result of this study. Therefore, stormwater mitigation strategies should be capable of treating the entire storm event volume.

**Influence of particle size on FF strength**

The FF strength, as measured by $M^\prime V_{25}$, is shown for each size fraction in Table 1. These values were derived from separate $M^\prime V^\prime$ plots of individual particle size fractions for each event. The mean $M^\prime V_{25}$ ratio decreased with increasing particle size, from 0.42 for the <10 μm fraction to 0.34 for the
20–45 μm and 45–90 μm fractions. This pattern is consistent with the findings of Zafra et al. (2008), who observed higher washoff rates of road-deposited sediments for smaller particle sizes, indicating that lower rainfall energy is required to erode and transport the finer solids fraction. It follows that during the initial part of rain events, the finest particles will be eroded first, and so are more likely to exhibit a FF effect than are larger particles. However, the mean M’V_{25} increased from 0.34 to 0.37 between the 45–90 μm and >90 μm fractions. Examining size effects within events, FF strength generally increased with decreasing particle size for events 5, 6, 7 and 8. For these events, a relatively strong FF in the <10 μm and 10–20 μm fractions was observed. However, the FF strength increased with increasing particle size for events 2 and 3 (and to a marginal extent for event 9), which was unexpected. The inconsistent trend of FF strength with respect to particle size has also been reported by Cristina & Sansalone (2005), who examined the FF of particle number densities in source-area runoff. The researchers separated events into flow-limited and mass-limited groups, based on the mean event runoff rate, observing no clear relationships between FF strength and particle size for the flow-limited events, but a larger FF effect for larger particle sizes in the mass-limited events. This would indicate that the FF strength is related to the particle size and antecedent mass of solids available. Referring to Table 1, where the FF strength increased with increasing particle size, the M’V_{25} ratios were low in the <10 μm and 10–20 μm fractions (0.09 and 0.23 for events 2 and 3, respectively). This implied that for events 2 and 3, the FF for fine solids was limited by the available mass.

### Table 1 | M’V_{25} of SS size fractions

<table>
<thead>
<tr>
<th>Event</th>
<th>&lt;10 μm</th>
<th>10–20 μm</th>
<th>20–45 μm</th>
<th>45–90 μm</th>
<th>&gt;90 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.09</td>
<td>0.09</td>
<td>0.12</td>
<td>0.20</td>
<td>0.36</td>
</tr>
<tr>
<td>3</td>
<td>0.23</td>
<td>0.18</td>
<td>0.27</td>
<td>0.45</td>
<td>0.55</td>
</tr>
<tr>
<td>5</td>
<td>0.85</td>
<td>0.70</td>
<td>0.35</td>
<td>0.16</td>
<td>0.14</td>
</tr>
<tr>
<td>6</td>
<td>0.68</td>
<td>0.64</td>
<td>0.56</td>
<td>0.54</td>
<td>0.57</td>
</tr>
<tr>
<td>7</td>
<td>0.31</td>
<td>0.33</td>
<td>0.30</td>
<td>0.24</td>
<td>0.22</td>
</tr>
<tr>
<td>8</td>
<td>0.54</td>
<td>0.53</td>
<td>0.51</td>
<td>0.50</td>
<td>0.48</td>
</tr>
<tr>
<td>9</td>
<td>0.24</td>
<td>0.24</td>
<td>0.25</td>
<td>0.29</td>
<td>0.30</td>
</tr>
<tr>
<td>Min</td>
<td>0.09</td>
<td>0.09</td>
<td>0.12</td>
<td>0.16</td>
<td>0.14</td>
</tr>
<tr>
<td>Max</td>
<td>0.85</td>
<td>0.70</td>
<td>0.56</td>
<td>0.54</td>
<td>0.57</td>
</tr>
<tr>
<td>Mean</td>
<td>0.42</td>
<td>0.39</td>
<td>0.34</td>
<td>0.34</td>
<td>0.37</td>
</tr>
</tbody>
</table>

### Influence of rainfall characteristics on FF strength in total and size-fractionated SS

Table 2 shows the linear correlation coefficient (R²) between single rain event characteristics and M’V_{25}. The rain event characteristics examined were total rainfall (TR), mean rainfall intensity (MRI), peak rainfall intensity (PRI), rainfall duration (DUR), antecedent dry period (ADP), mean flow (MF) and PF. Correlations between the full SS gradation in the complete dataset (14 events) and reduced dataset...
Table 2 | Linear correlation coefficients between single rain event characteristics and M'V25 of SS size fractions

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Full gradation-C</th>
<th>Full gradation-R</th>
<th>&lt;10 µm</th>
<th>10–20 µm</th>
<th>20–45 µm</th>
<th>45–90 µm</th>
<th>&gt;90 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR</td>
<td>−0.15</td>
<td>−0.21</td>
<td>−0.02</td>
<td>−0.01</td>
<td>−0.03</td>
<td>−0.15</td>
<td>−0.36</td>
</tr>
<tr>
<td>MRI</td>
<td>0.24</td>
<td>0.19</td>
<td>0.19</td>
<td>0.25</td>
<td>0.35</td>
<td>0.11</td>
<td>0.04</td>
</tr>
<tr>
<td>PRI</td>
<td>0.20</td>
<td>0.18</td>
<td>0.02</td>
<td>0.05</td>
<td>0.26</td>
<td>0.30</td>
<td>0.15</td>
</tr>
<tr>
<td>DUR</td>
<td>−0.07</td>
<td>−0.23</td>
<td>−0.14</td>
<td>−0.15</td>
<td>−0.15</td>
<td>−0.09</td>
<td>−0.15</td>
</tr>
<tr>
<td>ADP</td>
<td>0.08</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>MF</td>
<td>0.15</td>
<td>0.31</td>
<td>0.15</td>
<td>0.25</td>
<td>0.55</td>
<td>0.30</td>
<td>0.06</td>
</tr>
<tr>
<td>PF</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
<td>0.03</td>
<td>0.12</td>
<td>0.10</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*Correlation with complete dataset.
*Correlation with reduced dataset.

(7 events) are shown in Table 2. The reduced dataset comprises events where SSC and PSD were measured.

In the full gradation of SS, weak positive correlations were observed in the complete dataset for MRI (R² = 0.24), PRI (R² = 0.20), and MF (R² = 0.15). There were also weak negative correlations for TR (R² = −0.15) and DUR (R² = −0.07). These negative correlations could be explained by the fact that large rain events (in terms of rainfall depth) tended to be longer in duration and lower in rainfall intensity. These trends were repeated in the reduced dataset, and in some cases the correlation coefficients were greater than the complete dataset. For example, the R² value for MF increased from 0.15 to 0.31 for the reduced dataset. This may have occurred because the reduced dataset consisted of mostly single flow peak events (5 of 7 events), whereas the complete dataset contained a lower proportion of single peak events (7 of 14 events). Prediction of FF strength using aggregate rain event characteristics is less effective for events with multiple flow peaks since the explanatory variables cannot account for effects such as the order in which the PF occurs, or variations in available washoff mass for successive flow peaks. ADP was not correlated with M’V25. Although the antecedent mass of SS may have influenced FF strength, ADP is not a reliable single predictor of SSCs and loads (Shaw et al. 2010; Sage et al. 2015). Overall, the correlations (positive and negative) in Table 2 were relatively weak, implying that single rain event predictors have limited application in predicting FF strength.

A similar trend occurred for the size-fractionated SS with the highest correlations observed between M’V25 and MRI, PRI and MF, and negative correlations with TR and DUR. Interestingly, the magnitude of the correlation tended to be highest for the 20–45 µm fraction, reducing in adjacent upper and lower size fractions, with the lowest correlations observed for the <10 µm and >90 µm fractions. For example, the correlation between MF and M’V25 for the 20–45 µm solids was 0.55, but just 0.15 for the <10 µm fraction and 0.06 for the >90 µm fraction. This phenomenon was explored further using an MLR approach.

Due to the limited sample size (7 events) for MLR analysis, combinations were limited to three explanatory variables of the seven listed in Table 2 (Austin & Steyerberg 2013). Of the 35 possible combinations of three-variable MLR models, the five best-performing models, in terms of the correlation coefficient with total solids M’V25, are shown in Table 3. Interestingly, the ADP appeared in all of the top performing models, which indicated that the available mass of solids was an important factor for FF strength. The storm duration also appeared in four of the five models. These findings were consistent with those of Gupta & Saul (1996), who identified ADP and DUR, along with PRI and PF, as the best predictors of FF loads of SS.

The highest correlation coefficients were again evident in the 20–45 µm size range, and tended to decrease around this size range, with zero correlations in the >90 µm fraction for all events. For the fine solids, it is likely that the available SS mass on the pavement surface was influential. The catchment sampled in this study was also subject to measurement of solids build-up rates during dry weather (Morgan et al. 2017). The build-up rates of sediment on road surfaces decreased consistently with decreasing particle size; for example, the <150 µm solids build-up rate was approximately 30% of the build-up rate of the 150–600 µm solids. This supports the theory that FF effects for fine solids may have been influenced more by the limited mass available for washoff than rain event characteristics. For example, if low quantities of fine solids were available at the start of the event, they may have been eroded in a sporadic fashion as they may have been adhered to larger particles or the road surface. Conversely, where a significant mass of fine particles...
was available, erosion and FF patterns may have been more consistent with rain event characteristics. Examining the limited correlations for coarser particles, the influence of the drainage system must be considered. Solids in the >90 μm range, and to a lesser extent the 20–45 μm range, may have been susceptible to deposition in the gully pots and along the pipe network. Consequently, a FF effect may be observed for solids in source-area runoff but not for solids transported to the outlet of the drainage system.

The correlation coefficients were lower in the 20–45 μm fraction than in the total gradation of SS. This may have been partly due to the additional PSD analysis step, which would have introduced additional experimental error. In some cases, such as models 3 and 5, the correlation coefficients were significantly lower (or zero) in the size-fractionated models.

To investigate the usefulness of FF prediction with MLR, model 1 was examined in greater detail for the full gradation and 20–45 μm fractions in Table 4. A 95% prediction interval (PI) was calculated for M’V_{25}, using the mean values of ADP, DUR and MF from the dataset (4 days, 4 hours, and 3 l/s, respectively). For the full gradation model, all of the model coefficients were significant (p-value < 0.05). In the 20–45 μm model, the coefficients were significant, apart from ADP, which was marginally significant. For the full gradation model the 95% PI for M’V_{25} was 0.28–0.53. This was a relatively wide interval that included values of M’V_{25} that would indicate no FF, and values which satisfied the 50/25 definition of a FF. When applied to the 20–45 μm model, the 95% PI was even greater (0.14–0.59). Therefore, the application of the MLR has limited benefit in identifying the likelihood of a strong FF effect on the catchment, using rainfall characteristics alone. Furthermore, if the model was to be applied to a different catchment, re-calibration of the model coefficients would be required.

**Implications for stormwater management**

The design of stormwater treatment systems is commonly based on the assumption of a FF. For example, the UK Highways Agency recommends treating at least 10 mm of runoff on the basis that this is often the most seriously polluted (UK Highways Agency 2006). Similarly, a minimum water quality treatment volume of 12.7 mm has been applied in the USA (Sansalone & Cristina 2004). However, the findings of this research, which are consistent with some previous studies, demonstrate that a significant mass FF is uncommon for SS transported to the outlet of stormwater drainage systems. Therefore treatment structures, such as detention ponds, should be effective in treating SS throughout the storm event, not just the initial runoff. Where a strong suspended solids FF is present, this study indicates that it is most likely to occur in the <20 μm fraction. If treatment structures are designed to target the FF, they should be capable of removing this particle size range. Settlement of fine particles is possible in large detention structures, typically greater than 75% removal for <20 μm solids (Greb & Bannerman 1997; Ferreira & Stenstrom 2013). Where treatment volumes are limited, a FF filtration component could be incorporated to ensure retention of fine solids (Pitt et al. 2008).

**Table 3 | Linear correlation coefficients of MLR models of SS size fractions**

<table>
<thead>
<tr>
<th>MLR model</th>
<th>Predictors</th>
<th>Full gradation</th>
<th>&lt;10 μm</th>
<th>10–20 μm</th>
<th>20–45 μm</th>
<th>45–90 μm</th>
<th>&gt;90 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ADP DUR MF</td>
<td>0.93</td>
<td>0.05</td>
<td>0.16</td>
<td>0.81</td>
<td>0.18</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>ADP MRI TR</td>
<td>0.86</td>
<td>0.07</td>
<td>0.19</td>
<td>0.77</td>
<td>0.26</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>ADP DUR PF</td>
<td>0.83</td>
<td>0.00</td>
<td>0.00</td>
<td>0.38</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>ADP DUR PRI</td>
<td>0.78</td>
<td>0.20</td>
<td>0.27</td>
<td>0.71</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>ADP DUR PRI</td>
<td>0.75</td>
<td>0.00</td>
<td>0.00</td>
<td>0.32</td>
<td>0.22</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Table 4 | Coefficients and PIs for full-gradation and 20–45 μm MLR models**

<table>
<thead>
<tr>
<th>Predictor</th>
<th>20–45 μm MLR</th>
<th>Full gradation MLR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
<td>p-value</td>
</tr>
<tr>
<td>ADP</td>
<td>0.036</td>
<td>0.067</td>
</tr>
<tr>
<td>DUR</td>
<td>–0.061</td>
<td>0.046</td>
</tr>
<tr>
<td>MF</td>
<td>0.044</td>
<td>0.029</td>
</tr>
</tbody>
</table>
There were reasonable correlations between multiple rain event characteristics and FF strength (R² of 0.75 to 0.93), but the wide PIs for M’V₂₅ did not allow identification of a FF effect using the 50/25 criterion, and re-calibration of the model coefficients would be required to apply the MLR models elsewhere. The purpose of such models would be to identify catchments with a potential for a significant FF effect. In these cases, smaller treatment volumes could be justified. However, the high uncertainty associated with the MLR model predictions imply that reduced treatment volumes should only be applied where a FF effect has been confirmed with field data.

CONCLUSIONS

The FF of SS from the outlet of an urban residential drainage system was investigated, in both the complete gradation and in different size fractions. Of the 14 events where the complete SS gradation was analysed, 11 of the 14 events exhibited a moderate FF effect, according to the definition of Saget et al. (1996). However, the 50/25 criterion was met in just two events, and the median M’V₂₅ was 0.34, suggesting that a significant FF effect was uncommon, which was consistent with a number of previous studies.

Of the seven events where the FF was examined in multiple size fractions, the FF strength increased with decreasing particle size for four events, and the highest M’V₂₅ ratios were observed for the <10 μm fraction. This was expected, since the erosive power required to dislodge and transport finer particles would have been lower; thus finer particles would have been transported to the outlet earlier in the rain event. In two of the remaining events (and to a limited extent in one event), the FF strength increased with increasing particle size. It is hypothesised that these events were mass limited for finer particles.

The relationship between FF strength and rain event characteristics was investigated. Weak positive correlations were observed between FF strength and MRI, PRI and MF. Weak negative correlations were observed for TR and DUR. Several MLR models were examined, with the highest correlation coefficients recorded for models containing ADP and DUR, which was consistent with the findings of Gupta & Saul (1996). Within SS size fractions, correlation coefficients were highest for the 20–45 μm MLR models, reducing in the upper and lower ranges, with zero correlation recorded for the >90 μm models. The lower correlations for the finer fractions were attributed to the limited mass of solids available for washoff. For the >90 μm solids, the dominant processes were likely to be capture and re-suspension in the gully pots rather than rain event characteristics, hence the lack of correlations in this size fraction. For future research, continuous models of build-up and washoff of SS should be used to investigate the role of antecedent mass in determining FF strength.

The study findings have important implications for stormwater management. A significant FF effect has been demonstrated to occur in a small proportion of events, but it is more likely to occur for finer solids, particularly the <10 μm fraction. Therefore, stormwater best management practices (BMPs) should be designed to treat the entire rain event volume. Where BMP components are installed to target the FF, they should be capable of removing the <10 μm fraction, possibly through filtration. The wide PIs for FF strength derived using MLR models implied that these models have limited application. If such models are used to justify reduced stormwater treatment volumes, on the assumption of a strong FF presence, they should be verified with local data.

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REFERENCES


