Stormwater particle characteristics of five different urban surfaces

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Abstract
Five stormwater monitoring sites were established in late 2004 within inner city Toowoomba, Australia. The monitoring sites had small catchments (50 to 450m² area) representative of urban impervious areas (galvanized iron roof, concrete carpark and bitumen road pavement) and pervious areas (grassed and exposed bare soil). Flow-weighted samples were taken at each site to determine the event mean concentration of Non-Coarse Particles (NCP), defined as particles less than 500µm in size. Overall, runoff from 24 storms with rainfalls from 2.5mm to 48.5mm was sampled during the period December 2004 to June 2005. This paper describes the characteristics of the sampled stormwater particles including size distribution, inorganic content and mass loading generated from each surface type. On an equal area basis, the road surface produced the highest NCP load during small-to-moderate storms less than 20mm rainfall.

Keywords
Urban runoff, stormwater characteristics, particle size distributions, stormwater monitoring

INTRODUCTION
Stormwater runoff from urban areas has long been identified as a significant cause of poor water quality in creeks and rivers. Pollutants washed off urban surfaces include sediments, litter, organic matter, nutrients, heavy metals, oils and pesticides. This study, undertaken as part of PhD research, focused on suspended solids only, in particular Non-Coarse Particles (NCP) less than 500µm in size. The purpose of the study was to measure the amount of NCP washed off various types of urban surfaces during storms. The results will assist in identifying the dominant sources of pollution in urban catchments and assist in providing more effective stormwater management.

METHODOLOGY
Selected Surfaces
Stormwater runoff was monitored from five different types of urban surface located within inner city Toowoomba, Australia. All monitoring sites were established within a 70m radius to limit the effects of spatial variability in rainfall. The surface areas that were monitored ranged from 50 to 450m² and further details are provided in Table 1.

Table 1. Basic properties of the urban surface monitoring sites at Toowoomba.

<table>
<thead>
<tr>
<th>Site</th>
<th>Description of surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>52 m² corrugated galvanized iron roof at 25° pitch with Colorbond ® gutter</td>
</tr>
<tr>
<td>Road</td>
<td>450 m² bitumen pavement of inner city street, moderate condition, with concrete kerb at 0.9% grade, no gutter, 3500 vehicles/day traffic load.</td>
</tr>
<tr>
<td>Carpark</td>
<td>56 m² four-bay concrete parking area, rear of dentistry, concrete kerb</td>
</tr>
<tr>
<td>Grass¹</td>
<td>56 m² couch turf lawn established from turf in December 2004, 1% grade</td>
</tr>
<tr>
<td>Bare soil</td>
<td>59 m² exposed krasnozem soil overlaying silty clay loam, 1% surface grade</td>
</tr>
</tbody>
</table>

¹. Grass plot also had the same soil conditions as the bare soil plot
Site Monitoring
The objective of the study was to quantify the NCP load (in mg/m²/event) washed from each surface during a number of storms. At each site, a flow-weighted composite sample of runoff was collected to determine the Event Mean Concentration (EMC). NCP loads were estimated by multiplying the EMC and runoff volume for each storm event.

In order to reliably obtain a composite sample for these small catchments, a new type of sampling device was designed and tested as part of the study (Brodie and Porter 2004; Brodie 2005). Referred to as the flow splitter, the device is shown in Figure 1. A flow splitter was installed at each of the five sites and a typical installation is shown in Figure 2. A tipping-bucket raingauge was used to measure rainfall depths at 0.25mm increments. This data was recorded by a data logger and routinely downloaded during the monitoring period.

![Figure 1](image1.png) showing a flow splitter [A] which collects a constant proportion of runoff and directs the sample to a plastic storage container [B]

![Figure 2](image2.png) showing the roof sampler. Flow from roof gutter [A] is screened [B] to remove debris and directed to the flow splitter which is housed in a locked box [C]

Laboratory Analysis
After each storm, the runoff samples were collected and analyzed to determine the NCP concentration in mg/L. This required a laboratory technique adapted from the Suspended Sediment Concentration Method used by the US Geological Survey (ASTM 2002).

Particle wash-off behavior, stormwater treatment and contaminant associations such as adsorption of heavy metals are closely allied to particle size. On this basis, NCP was further divided into three particle size ranges: Very Fine Particles (VFP) less than 8µm in size, Fine Particles (FP) between 8 to 63µm and Medium Particles (MP) between 63 to 500µm. Brodie (2005) provides a rationale for the selected particle size ranges.

Whole-of-sample screening was conducted to determine the MP concentration followed by sub sampling and sequential filtration to isolate the FP and VFP fractions. A volatile suspended solids analysis using Standard Method 2540-E (APHA 1998) was made for each particle size range to determine organic content.
Monitoring Period
On average, Toowoomba receives an annual rainfall of 950mm typically over 103 rain days. This paper will outline results for the period from December 2004 to June 2005. A total rainfall of 370mm was recorded and data was collected for 24 storms with rainfalls ranging from 2.5mm to 48.5mm. The monitoring work was conducted under drier than average conditions.

Load Computation
The sample volume that was captured provided a measure of the amount of runoff that was generated from each surface. This measurement was used to check estimates of runoff volume predicted by a hydrological model of each surface. Sample volumes up to 80L were obtained for analysis. The urban drainage model, DRAINS (O’Loughlin and Stack 2003), was used to estimate runoff flow rates. The measured EMC and estimated runoff volume was multiplied to determine the NCP load (in mg/m²) washed off the surfaces during each storm.

RESULTS AND DISCUSSION
Runoff Characteristics
The sites included the impervious road, carpark and roof surfaces and the pervious grassed and bare soil areas. The runoff characteristics of the pervious surfaces were very different to the impervious ones because of infiltration of rainfall into the soil.

Runoff was generated from the impervious surfaces once rainfall exceeded only 1mm depth. As shown in Figure 3, generally 15 to 20mm of rainfall infiltrated into the ground before runoff occurred from the grass and bare soil plots (an exception being that bare soil yielded minor runoff during an 8mm storm with a very high intensity of 40 mm/hr). Pervious runoff occurred during less than 20% of storms within the monitoring period.

Figure 3 shows the mean runoff that was estimated from each surface type in response to rainfall. Figure 4 shows box-plots of NCP EMCs for each type of surface for December 2004 to June 2005.
Event Mean Concentrations

Box-plots of NCP EMCs are presented as Figure 4 and show the median, minimum (min), maximum (max), first quartile or 25 percentile (q1) and third quartile or 75 percentile (q3) concentrations. The box-plots indicate that each surface exhibits a significant variation in EMC, with typically a 10 to 100-fold difference between minimum and maximum values.

Median NCP EMCs for impervious surfaces varied from 10mg/L for the roof, 45mg/L for the carpark, through to 255mg/L for the road surface. On the limited occasions that grass runoff occurred, the resulting EMCs were similar to carpark runoff. Bare soil EMCs were significantly higher (median 640mg/L).

Particle Size and Composition

VFP (particles less than 8µm) represented a small proportion of the particle mass; typically less than 20%. This was the case for all surfaces. With the exception of the carpark and bare soil runoff, the dominant particle size fraction tended to be FP (8 to 63µm range) representing typically 60% of the total mass (refer Figure 5). The distribution of particle mass for the road runoff was consistent with results from similar Australian studies, as reported by Lloyd and Wong (1999). The FP fraction in carpark and bare soil samples was generally less than 40 to 50% of the particle mass.

Figure 5 shows box-plots of the %FP by mass for each type of surface for December 2004 to June 2005. Figure 6 shows box-plots of the NCP %inorganic for each type of surface for December 2004 to June 2005.

NCP particle mass for all surfaces was mainly inorganic in content, as shown in Figure 6. For the road surface, the median inorganic content was 77%, comparable with the 72% median based on TSS and VSS data for highway runoff measured for nine storms at Louisiana, USA (Sansalone and Tittlebaum 2001), but higher than the 45% median determined by Gromaire-Mertz, Garnaud et al. (1999) for street runoff over seven storms within central Paris, France. The median inorganic content for bare soil runoff was also 77%. The runoff from the other surfaces had more organic matter, with the median inorganic content falling into the 60 to 65% range.
NCP Load Statistics
Median values and ranges of NCP loads are provided in Table 2 for each surface. The load generated by each surface varies significantly for different storms.

<table>
<thead>
<tr>
<th>Site</th>
<th>Measured runoff events</th>
<th>Median load</th>
<th>Load range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>21</td>
<td>90</td>
<td>32-1180</td>
</tr>
<tr>
<td>Road</td>
<td>20</td>
<td>1500</td>
<td>160-7500</td>
</tr>
<tr>
<td>Carpark</td>
<td>22</td>
<td>500</td>
<td>74-2600</td>
</tr>
<tr>
<td>Grass</td>
<td>2</td>
<td>500</td>
<td>74-910</td>
</tr>
<tr>
<td>Bare soil</td>
<td>5</td>
<td>6000</td>
<td>90-15800</td>
</tr>
</tbody>
</table>

Table 2 provides only a simplistic indication of the relative amounts of NCP washed off the various surfaces. The absence of runoff from pervious surfaces in storms less than 20mm rainfall should be taken into account when analyzing the loads from these surfaces.

NCP Loads Depend on Rainfall and Runoff
Particle loads vary from storm to storm depending on a number of factors. Storm characteristics, such as rainfall depth, intensity and duration, all influence the amount of particles washed off. Any comparison of the NCP loads generated based on surface type should be made over a number of storm events to allow for this variation.

Such a comparison was made for the five surface types and for the 24 storms that were monitored between December 2004 and June 2005. NCP load estimates were grouped according to various rainfall ranges and averaged. The mean values are plotted as a stacked graph against the nominated rainfall ranges in Figure 7 and they represent the load that 1m² of each surface type generates, on average, for the storms that occurred during the monitoring period.

It is clear from Figure 7 that, on a per square metre basis, the NCP load contributed by the roof is negligible. Carpark loads are moderate and less significant than the road loads. The bare soil produced a high load for rainfalls exceeding 15 to 20mm and, with the road surface, was the dominant contributor to NCP loadings. The grass surface contributed relatively small loads at rainfalls exceeding 25mm.

The relative contribution that each surface makes to overall NCP load can be seen in Figure 8. In this plot, the loads are expressed as a percentage of the load totaled for all five surfaces. It demonstrates that the road surface contributes 50 to 70% of the total NCP for storms less than 15 to 20mm. This proportion diminishes in larger storms due to increasing bare soil loads.

It should be noted that the comparison is based on equal areas (in this case 1m²) of each surface type. In reality, an urban catchment would consist of unequal proportions of each surface which would change the results. Initial analysis using typical surface compositions found in residential areas suggest that the broad trends discussed above may also be applicable to urban catchments in general. The next phase of the study will investigate ways that the surface data can be applied to represent various urban land uses. It should also be noted that the comparison has been made for the historical sequence of storms that occurred during the monitoring period. The results may change if a different mix of storms is used in the analysis.
Cumulative NCP Loads
As generally is the case, minor rainfalls occur in Toowoomba on a more frequent basis than larger storms. For example, daily rainfalls in excess of 40mm occur on only 3 rain days, on average, throughout the year compared with 37 rain days for rainfalls less than 5mm.

Due to their more frequent occurrence, the loads associated with small storms, when totaled, may represent a sizable portion of the load generated during a year or a season. The cumulative load defined as the sum of loads for a number of storm events thus provides a useful basis to compare the various surfaces.

On this basis, the cumulative loads from each surface were calculated for the 24 storms that occurred during the monitoring period. To provide a relative context, the cumulative load for each surface was presented as a ratio of the roof load. This analysis was also done for the runoff volumes and the results are compiled as Table 3.

Table 3. Cumulative NCP loads and runoff volumes from each surface for December 2004 to June 2005 storms, expressed as a ratio of the roof estimates

<table>
<thead>
<tr>
<th>Site</th>
<th>Cumulative runoff</th>
<th>Cumulative NCP load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Road</td>
<td>0.98</td>
<td>14.8</td>
</tr>
<tr>
<td>Carpark</td>
<td>0.98</td>
<td>4.8</td>
</tr>
<tr>
<td>Grass</td>
<td>0.14</td>
<td>0.6</td>
</tr>
<tr>
<td>Bare soil</td>
<td>0.20</td>
<td>14.7</td>
</tr>
</tbody>
</table>

1. For reference, cumulative runoff = 349mm and cumulative NCP load = 3600 mg/m² for the roof
All of the impervious surfaces produced similar runoff quantities, but the cumulative NCP load from the road was approximately 15 times the roof load and significantly greater than the carpark load (5 times). The cumulative load from the bare soil was similar in magnitude to the road load (15 times) but was associated with significantly less runoff. Grass NCP load was relatively minor (0.6 times). All of these loads are on an equal area basis.

Although the monitored surfaces are typical examples found in urban areas, it is anticipated that particle loads would vary within surfaces of the same general type. For example, Sartor and Boyd (1972) found that TSS load from road pavements was dependent on surface texture and condition. The surface grade of the bare soil plot was relatively flat (1%) and previous studies indicate that sediment mobilization increases significantly with slope (Zingg 1940; Musgrave 1947). On this basis, the relative NCP load contributions given in Table 3 are indicative only.

**Small-to-Moderate Storms**

It is becoming recognized that urban runoff from the more frequent storms (generally less than 15 to 20mm) is potentially a major cause of environmental impact to downstream waterways. Urban development leads to a substantial increase in the frequency of these 'small-to-moderate' runoff events, which in undeveloped catchments may be absent due to infiltration. The flows and pollution associated with these events can lead to a wide range of impacts, including channel erosion, reduced biodiversity, more variable water temperatures and poor water quality (Walsh, Leonard et al. 2004).

On this basis, the NCP loads generated from urban surfaces in small-to-moderate storms are of particular interest. On a per m² basis, the road surface generated the highest NCP load under conditions of less than 20mm rainfall and is thus likely to be an important contributor to adverse environmental effects. Road drainage is also generally efficient in conveying stormwater directly to waterways which increases the impact potential.

**CONCLUSIONS**

Measurements of the Non-Coarse Particle (NCP) load washed from five different urban surfaces located in Toowoomba, Australia were made during storms from December 2004 to June 2005. Impervious surfaces (a roof, carpark and a road) were monitored in addition to pervious surfaces (grassed and bare soil areas). The road had the highest NCP load/m² for small-to-moderate storms less than 20mm rainfall. This outcome is significant as many adverse environmental impacts are caused by urban runoff from these more frequent events. No runoff occurred from the pervious surfaces in the storms less than 15 to 20mm due to infiltration, except for a single high intensity event. At higher rainfalls, the bare soil loads were significant.

**REFERENCES**


