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Role of solids in heavy metals build-up on urban road surfaces

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Abstract

Solids are widely identified as a carrier of harmful pollutants in stormwater runoff exerting a significant risk to receiving waters. This paper outlines the findings of an in-depth investigation on heavy metal adsorption to solids surfaces. Pollutant build-up samples collected from sixteen road sites in residential, industrial and commercial land uses were separated into four particle size ranges and analysed for a range of physico-chemical parameters and nine heavy metals including Iron (Fe), Aluminum (Al), Lead (Pb), Zinc (Zn), Cadmium (Cd), Chromium (Cr), Manganese (Mn), Nickel (Ni) and Copper (Cu). High specific surface area (SSA) and total organic carbon (TOC) content in finer particle size ranges was noted, thus confirming strong correlations with heavy metals. Based on their physico-chemical characteristics, two different types of solids originating from traffic and soil sources were identified. Solids generated by traffic were associated with high loads of heavy metals such as Cd and Cr with strong correlation with SSA. This suggested the existence of surface dependent bonds such as cation exchange between heavy metals and solids. In contrast, Fe, Al and Mn which can be attributed to soil inputs showed strong correlation with TOC suggesting strong bonds such as chemsorption. Zn was found to be primarily attached to solids by bonding with the oxides of Fe, Al and Mn. The data analysis also confirmed the predominance of the finer fraction, with 70% of the solids being finer than 150 µm and containing 60% of the heavy metal pollutant load.

Keywords: Heavy metals; Pollutant adsorption; Specific surface area; Stormwater pollutants; Urban water quality

1. Introduction

Numerous researchers have identified the importance of suspended solids in stormwater runoff in view of its impacts on receiving waters as well as acting as a mobile substrate in the transport of other pollutants (Goonetilleke et al. 2009; Hoffman et al. 1985). The majority of road surface stormwater pollutants primarily originate from surrounding soil, atmospheric deposition and traffic related sources such as tire and brake abrasion, combustion exhaust and pavement wear. These particulates are commonly enriched with heavy metals. Presence of heavy metals above threshold concentrations potentially creates an immediate toxic environment while accumulation over a period of time can harm the receiving water environment by affecting the health of the aquatic ecosystem (Shi et al. 2008). However, the extent to which heavy metals are associated with solids particles vary with factors such as traffic characteristics, surrounding land use and road surface conditions (Herngren et al. 2006). A substantial fraction of solids in pollutant build-up on road surfaces originate from soil inputs from adjoining land. Therefore, the surrounding soil also plays a critical role in influencing the surface characteristics of the solids particles. The extent of heavy metals adsorption to solids is influenced by its surface properties (Vdovic et al. 1991; Zhang and Wang 2009). Therefore, in order to understand metal adsorption to particulates and to predict

the mobility of heavy metals in urban systems, knowledge on the influence exerted by particulate properties is essential.

The study discussed in the paper investigated the impact of different urban land uses on heavy metals build-up on road surfaces and the identification of factors that influence their adsorption to solids. Data collection was conducted at a variety of study sites with different background soil profiles and land uses in an urbanized coastal catchment which drains to a major river. The characteristics of the study sites and relationships between solids properties and heavy metals were investigated using univariate statistical methods and multivariate data analysis. The results from the data analysis will contribute to the development of reliable methodology for characterising heavy metal inputs from urban stormwater runoff to receiving waters.

2. Materials and methods

2.1 The study sites

There were two primary criteria applied in the selection of the study sites, based on the research hypothesis. Firstly, it was hypothesised that the physical, chemical and mineralogical characteristics of the soil inputs from the surrounding area plays a key influential role in dictating the particulate characteristics of the road surface build-up. Therefore, the surrounding soil characteristics of the study site locations were considered important. Accordingly, four suburbs were identified. Secondly, it was hypothesised that land use and by implication anthropogenic activities is a key influential factor in relation to the pollutants adsorbed to particulates on road surfaces. Accordingly, within the four suburbs identified, different land uses, namely, residential, commercial and industrial areas were selected. Past research literature has clearly identified vehicular traffic as the primary anthropogenic activity which contributes heavy metals to road surfaces (Adachi and Tainosho 2004; Herngren et al. 2005; Zhang and Wang 2009). Accordingly, within the three land uses, specific study sites were selected such that they encompassed varying traffic density.

The study sites were located in the Gold Coast, Southeast Queensland, which is one of Australia's rapidly developing urban regions. Four suburbs with different soil profiles were selected stretching from inland to the coastline along the Nerang River. For further details refer to Gunawardana (2011). The Nerang River and in particular the lower catchment is an important source of pollutants to the marine environment (the Pacific Ocean), as the river flows through a highly urbanized area in the Gold Coast region. The inland study sites contain clay rich soils. The selected suburbs lie along a 12.5 km traverse with almost equal distance apart between each suburb. A total of sixteen road surfaces were selected representing four road sites from each suburb with varying levels of traffic density. Detailed descriptions of the selected study sites are given in Table 1.

2.2 Build-up sample collection

Pollutant build-up samples from each (road) study site were collected using a dry and wet vacuuming system. The area demarcated for sample collection was initially vacuumed in a

dry state. A domestic vacuum cleaner (Delonghi Aqualand make) with a water filtration system was used to collect the build-up pollutants on the road surfaces. To enhance the collection efficiency of fine particles, the road surface was then made damp using an electric sprayer (Swift 60 L compact sprayer with pressure control) and wet vacuuming of build-up pollutants was then undertaken. The complete collection methodology was tested under controlled field conditions and was found to be 90% efficient in collecting and retaining particulates (Mahbub et al. 2009).

Sample requirement for the envisaged laboratory analyses was about 45 g. As such, build-up samples were collected from 12 to 18 m² of sampling area consisting of four to six plots with each plot having an area of 3 m² (2 m x 1.5 m). Plots were demarcated equally spaced between the median strip and the curb or in the middle of parking spaces, assuming uniform pollutant build-up across the study surface.

Two separate samples were collected from each road surface representing different antecedent dry periods, to allow consideration of the variations in physical and chemical parameters of build-up solids and heavy metal concentrations with the antecedent dry period (Egodawatta and Goonetilleke 2006; Kim et al. 2006). Previous research studies, for example by Egodawatta and Goonetilleke (2006) and Ball et al. (1998) found that the pollutant accumulation in the initial period is rapid and tend to reach equilibrium around seven to nine dry days. Consequently, sampling times were selected such that the antecedent dry period for one sampling episode was less than eight days and the other greater than eight days. The sampling was carried out during different climatic seasons as it was anticipated that there could be variations in the physical and chemical composition of the build-up pollutants; one episode between January to April and the other between May to July in 2010. The collected samples were transferred to polyethylene containers according to the procedures specified in the Australia / New Zealand standards for water quality sampling (AS/NZS 1998). Additionally, the road surface texture depth was measured according to procedures specified in FHWA (2005).

2.3 Laboratory analysis

The particle size distribution was analysed to assess the size composition of the collected build-up samples. Based on the particle size distribution and considering the importance of finer suspended solids in pollutant transport, four particle size ranges were selected for further physico-chemical analysis. Research literature has shown that fine solids particles (<150 μ m) are the most critical in transporting pollutants in stormwater runoff (Goonetilleke et al. 2009; Herngren et al. 2006). However, the threshold value used in past research literature to define finer particles is not consistent. For example, Sartor et al. (1974) and Charlesworth and Lees (1999) used threshold values 246 μ m and 63 μ m, respectively, to define the fine fraction while Goonetilleke et al. (2009) and Herngren et al. (2006) adopted 150 μ m.

The size ranges selected for the current analysis were such that they cover the typical spectrum of size ranges as discussed in research literature. The selected size ranges were; <75

 μ m, 75-150 μ m, 150-300 μ m, and 300-425 μ m. Particles size <75 μ m contained settleable fine particles of 1-75 μ m size. Particles up to 1 μ m were extracted by allowing gravity settling in an Imhoff Cone. Then the extracted wet sieved samples and total build-up samples were analysed for physico-chemical parameters listed in Table 2.

Each particle size fraction and filtrate were tested for Iron (Fe), Aluminum (Al), Lead (Pb), Zinc (Zn), Cadmium (Cd), Chromium (Cr), Manganese (Mn), Nickel (Ni) and Copper (Cu). According to research literature, these heavy metals are among the most common in pollutant build-up on road surfaces (Herngren et al. 2006). Nitric acid (HNO₃) digestion for heavy metals extraction was carried out in 50 mL polyethylene vials using a hot block. Precision and accuracy of analysis and the digestion procedure was monitored using internal standards, certified reference material and quality control blanks. Multi-element standards supplied by Accustandard were used as calibration standards. Multi-element standards from Sigma-Aldrich were used as the certified reference material. The percentage recovery was in the range of 85% to 115%, which is within the specified limits.

Organic matter is an important element in the cycling of trace metals in aquatic systems (Vdovic et al. 1991). As such, TOC was determined for the four wet sieved particle size ranges. Precision in TOC measurement was determined by replicate measurement of samples, and was found to be within acceptable limits. Surface properties substantially influence pollutant retention by particles in aquatic environments (Eisma 1981). As such, the specific surface area of the air dried wet sieved solids samples was determined using the Ethylene glycol monoethyl ether (EGME) method (Carter et al. 1986). Granular activated carbon (GAC) was employed as a quality control measure to evaluate the accuracy of the EGME method (Sansalone et al. 1997).

2.4 Data analysis

The experimental data formed a large data set. Analysis of such a large data set with multiple variables required analytical approaches capable of clustering similar data together while identifying relationships between variables. In these circumstances, the application of multivariate analytical techniques has been found to be the most appropriate (Petersen et al. 2001; De Bartolomeo et al. 2004; Herngren et al. 2005). In this study, Principal Component Analysis (PCA), which is an analytical tool frequently applied in the analysis of environmental data was used. In the area of water quality, PCA has been successfully used in river water quality investigation (Petersen et al. 2001), for investigating polluted lake sediments (De Bartolomeo et al. 2004) and for investigating relationships between heavy metals and suspended solids in urban stormwater runoff (Herngren et al. 2005). Detailed descriptions of PCA can be found elsewhere (for example Adams 1995).

In PCA, data pre-treatment is carried out to reduce the 'noise' which interferes with the data analysis. Accordingly, the data matrix was column centered and standardised (auto scaled). This was done by subtracting the column mean from each cell value and dividing by the column standard deviation. This ensured equal significance of variables with a standard

deviation of 1 (Kokot et al. 1998). Build-up pollutants were taken as load per unit area of road surface (mg/m^2) .

3. Results and discussion

3.1 Build-up pollutant load

Initially, the overall variability of build-up pollutant loads based on site and land use type was compared. The road surface texture depth, particle size distribution, antecedent dry days and arithmetic mean build-up loads for each suburb are given in Table 3.

Interestingly, the pollutant build-up load in all of the study sites other than Nerang is not proportional to the antecedent dry period. However, previous studies have shown that commonly there is an increase in pollutant build-up load with the increase in dry days. This deviation in the relationship between pollutant load and antecedent dry period was attributed to pre-existing pollutant load on the road surfaces, which would have been influenced by the last rain event as evident from Table 3 (Sartor et al. 1974; Egodawatta et al. 2007).

Also, as evident in Table 3, pollutant build-up load on road surfaces in different suburbs show significant variance. It was concluded that the nature of anthropogenic activities, traffic density, road surface conditions and texture depth and antecedent dry period have influenced the pollutant build-up (Egodawatta and Goonetilleke 2006; Ball et al. 1998). This is quite evident in industrial road surfaces of Nerang, where considerably high pollutant load was recorded, even with shorter dry periods. The relatively high average texture depth would also be a factor influencing pollutant build-up.

Additionally, average values of particle size distribution indicate that over 50% of particles are finer than 75 μ m and over 70% are finer than 150 μ m in all of the study sites. This confirms that the highest fraction of road surface build-up pollutants is in the fine particle size ranges and is easily transported to receiving waters. Furthermore, as the finer particle fraction stays relatively longer in suspension, these particles have a greater potential to impact on the receiving waters (Herngren et al. 2006).

3.1.2 Land use and heavy metal load

The chemical impacts of solids generally exert a greater impact on the receiving water environment when compared to the physical impacts of solids. In this context, average values of heavy metal loads for the four different particle size classes were compared as shown in Fig. 1. As evident in Fig. 1, Fe and Al are the highest metal loadings detected in all of the study sites. Soil inputs to road surfaces could be the possible source of Fe, Al and Mn. Zn was the most abundant metal element other than Fe and Al in all of the particle sizes, independent of the study site. Also, for all study sites, the metal composition pattern was consistently in the order of Fe>Al>Zn. It is postulated that Zn is generated from industrial processes and traffic related activities (Blok 2005). Thus, Zn could be a significant heavy metal element that could be expected in urban water environments. Cd, Cr and Ni are traffic related pollutants that commonly originate from tire wear and brake pad wear (Adachi and Tainosho 2004). Cd was the least detected metal element in all of the study sites. Although the loadings of Mn, Cu, Pb and Ni in different particle sizes varied in different suburbs, for the majority of the study sites, metal loadings decreased in the order of Mn>Cu>Pb>Ni>Cr> Cd for all four particle size classes.

Heavy metal loadings in solids particles increase as the particle size reduces. Similar observations have also been noted by past researchers (for example Herngren et al. 2006; Charlesworth and Lees 1999). The average for all study sites showed that more than one third of the heavy metal loadings (other than Cu) are present in the $<75 \mu m$ particle size range while Cu tends to associate more readily with the 75-150 μm particle size range. However, the variation of metal loadings with respect to land use and particle size can be noted. For example, Fe, Mn, Cd and Ni concentrations in Surfers Paradise were higher in the 150-300 μm particle size range. This indicates that different heavy metals have differing characteristics in their adsorption to particulates.

The highest loads were found at the Nerang industrial sites for the majority of the metal elements for all of the particle sizes. Benowa was second in terms of heavy metal loadings. Metal loading was considerably high in Nerang and Benowa sites, due to industrial activities such as metal work, welding and cement based industries and vehicle service stations in the area. At the opposite end, Clearview Estate residential sites indicated the lowest heavy metal bound particulates. Cu, Cd and Pb were high at Surfers Paradise. This could be attributed to the relatively high traffic in the commercial land use areas which formed the study sites. In summary, the test results show that heavy metal loads are different for sites with different land use, and by implication, traffic characteristics.

3.1.3 Total organic carbon and specific surface area

Fig. 2 gives the variation of TOC (per unit area of road surface) and SSA with particle size. The TOC content increases with the decrease in particle size. Confirming the previous research findings, the smallest particle size range shows significantly high organic carbon content irrespective of location or land use (Herngren et al. 2006; Roger et al. 1998). Variability of TOC content with land use was evident with the highest loading in Benowa and Nerang road surfaces, respectively. This is attributed to the presence of vegetation surrounding the road sites.

The variation of SSA with particle size demonstrates a consistent trend across the four suburbs. SSA of particles smaller than 75 μ m is four times (or more) larger than the SSA of particles in the size range of 300-425 μ m. Similar observations have been noted by Vdovic et al. (1991). Additionally, it is evident that the average SSA decreases exponentially and consistently with the increase in particle size. Theoretical SSA values calculated for spherical particles using the average diameter of the particle size ranges and assuming a specific gravity of 2.65 (same as for sand) also showed consistent variation with respect to particle size, although the variation followed a hyperbolic function. However, the calculated SSA of spherical particles was approximately three orders of magnitude smaller than the measured SSA of the solids. Sansalone et al. (1997) and Vdovic et al. (1991) also noted similar

differences in measured and calculated SSA values. These differences are attributed to factors such as natural road deposited solids having a range of specific gravity values and the particle shape not always being spherical. Furthermore, due to the heterogeneous nature of road deposited solids such as the presence of internal surface area in clay minerals, porosity of particles and surface texture, will increase the SSA (Sansalone et al. 1997).

The analysis indicated that, although the SSA values determined using a hypothetical spherical particle underestimate the surfaces area, the consistent increase in SSA with respect to particle size is common for road deposited solids. However, non-uniform variation of SSA with particle size have been reported for road dust particles by past researchers such as Sansalone et al. (1997) and Li et al. (2008). This is attributed to the differences in particle structure in different geographical areas.

Road deposited solids are generally coated with organic matter and amorphous or crystalline inorganic material such as metal oxides of Fe, Mn and Al (Hendershot and Lavkulich 1983). It is hypothesised that surface properties of solids are largely influenced by these materials. Even though it is commonly understood that organic matter increases the SSA of particles (Flanagan and Foster 1989), the present study showed that the change in SSA with organic matter was not consistent. For example, particles $<75 \,\mu$ m at Benowa have high TOC. However, the SSA of this particle size range is not proportionately high in keeping with the TOC content. Furthermore, the highest SSA was obtained for the Surfers Paradise samples, but with low organic matter content. This suggests that solids samples could contain material other than organic matter which exerts a significant influence on SSA. These include clay minerals and traffic related material such as tire and brake pad wear, corrosion products and pavement wear. Past researchers have also noted the uncertainty regarding the influence exerted by organic matter on the SSA of particulates (Eisma 1981). Vdovic et al. (1991) concluded that mineral composition is the most significant parameter which influences SSA.

3.2 Principal Component Analysis (PCA)

The role of solids properties in heavy metals adsorption was further investigated using PCA. Variables considered in the analysis were TOC, SSA, TSS and the nine heavy metal elements (a total of 12 variables). Objects represented the 128 samples derived as part of the research study. This sample number consisted of the eight samples collected from each of the four suburbs encompassing of four road sites with two sampling episodes per site and separated into four particle size fractions (4 size classes x 32 samples).

PCA analysis of the data matrix (128 objects x 12 variables) resulted in most of the data variance being explained by the first two principal components (Fig. 3). Objects which exhibited similar variances to the analysed variables have similar PCA scores and formed a cluster when plotted on a biplot. Accordingly, as evident in Fig. 3, finer particles of <75 μ m and 75-150 μ m show separate clusters while the 150-300 μ m and 300-425 μ m clusters overlay on each other. The conclusions noted from the analysis of average parameter values for each of the particle sizes (Fig. 2) are confirmed by the PCA biplot in Fig. 3.

Particles $<75 \ \mu$ m are characterised by relatively high heavy metal loads. The finer particles at Nerang and Surfers Paradise are responsible for a significant portion of the metal elements in the fourth quadrant in the biplot. Strongly correlated variables have the same magnitude and orientation of vectors when plotted, whereas vectors representing uncorrelated variables are orthogonal to each other. According to the biplot, there are two separate groups formed with one consisting of Fe, Al, Mn and Zn and the other consisting of Cd, Cu, Ni, Pb and Cr and within each group there is a strong correlation among the metal elements. This suggests that Cd, Cu, Ni, Pb and Cr originate from the same source, which is postulated to be traffic related activities.

Al, Fe and Mn show strong correlation with TSS. This suggests that Fe, Al and Mn are originating from soil inputs to the solids build-up. Fe, Al and Mn in soil are present in metal oxide form especially in clay minerals and act as a binding agent (Wang et al. 2008). It is hypothesised that the majority of Zn is attached to the solids by forming a bond with the oxides of Fe, Mn and Al due to the strong correlations among the metal elements. Furthermore, Fe, Mn and Al show partial correlation with Cd, Cu, Ni, Pb and Cr which suggest that a fraction of Cd, Cu, Ni, Pb and Cr is also adsorbed to metal oxides. Wen et al. (2008), based on a study of metal transport from a river through to the bay and then to the ocean noted that oxides of Fe, Mn and Al are equally important as a carrier of trace metals in the aquatic environment.

Partial correlation of Fe, Al, Mn and Zn with TOC and SSA indicate that SSA and TOC have an influence on the adsorption of these metal elements to solids. Particles with high specific surface area would adsorb the metal elements, and organic matter would further enhance adsorption by providing binding sites for cation adsorption. As noted by Vdovic et al. (1991), SSA and organic matter content in solids provide substantial binding sites for surface reactive pollutants.

As the finer particle size ranges of solids indicated strong adsorption characteristics with heavy metals, the physico-chemical parameters of the fine fraction was analysed separately. The resulting PCA biplots for two different fine particle sizes of <75 μ m (matrix of 32 objects x 12 variables) and 75-150 μ m (matrix of 32 objects x 12 variables) are shown in Fig. 4(a) and 4(b) respectively. Fe, Al and Mn in both particle size ranges again show strong correlation with TSS. It further confirms that a significant fraction of these metal elements consist of soil inputs to road deposited solids. Negative correlation of SSA and TOC indicate that the SSA of these particle size fractions is influenced by substances other than organic matter. Furthermore, the loading of SSA and scores of Surfers Paradise objects on PC2 confirm that highly urbanized areas have particulates with high SSA. This underlines the influence of traffic related pollutants on SSA of road deposited solids.

Evaluating the high positive loadings and scores on PC1 in Fig. 4, it can be postulated that a comparatively larger fraction of heavy metals are generated in the Nerang and the Surfers Paradise suburbs. This is attributed to the influence of industrial and commercial activities (and by implication high traffic) in these areas. Due to the strong correlation of TOC with Fe,

Al and Mn, it is evident that the availability of these metal elements is enhanced by TOC. SSA appears to have no influence on the availability of Fe, Al and Mn in solids. SSA is an important parameter in the adsorption of Cd in $<75 \,\mu\text{m}$ and Cr in 75-150 μm size particles. Zn is always strongly associated with Fe, Mn and Al as noted above. Furthermore, a significant fraction of Cu, Ni and Pb would adsorb to Fe, Al and Mn oxides.

The data analysis revealed that suspended solids play an important role in the bio-availability of metals in stormwater runoff. Heavy metals adsorbed by organic matter and/or metal oxides associated with solids could desorb under changed chemical conditions in receiving waters (Ellis 1976). As predicted by Munksgard and Parry (2001), considerable changes can occur in chemical conditions in receiving waters, even within relatively short distances and time periods. Particulate metals being bio-available would exert significant environmental risk to receiving waters. Hence, it is important to provide appropriate mitigation strategies to reduce solids loads in stormwater runoff. In this context, solids particles <150 µm are the most critical due to their high heavy metal loading. Typical stormwater management strategies for removal of solids such as sedimentation and filtration become more significant in this regard. However, the bioavailability of heavy metals can be enhanced due to microbial degradation of organic matter or chemical changes in water. Consequently, reduction of retention time of stormwater in retention/detention basins and measures to control pH changes can be implemented to reduce the potential risk posed by the bioavailability of heavy metals. The knowledge derived in relation to the influence of organic matter and surface area on heavy metal adsorption to build-up solids presented here along with the solids wash-off and first flush characteristics published elsewhere (for example Egodawatta et al. 2007; Goonetilleke et al. 2005) can contribute to improving the design of effective stormwater quality mitigation strategies.

4. Conclusions

The research study evaluated the influence of land use and traffic parameters on physical and chemical characteristics of solids in pollutant build-up on road surfaces. The study outcomes can be applied to define the role of solids in the transport of heavy metals to receiving waters. Important findings from the study include:

- More than 70% of solids particles build-up at the study sites (road surfaces) were finer than 150 µm. These particles can stay relatively longer in suspension in water and consequently exert a stronger impact on receiving waters. This size range also contains 60% on average of the heavy metals load. Industrial land use was found to be the most critical in build-up solids loads and industrial and commercial land uses were critical in terms of heavy metals contributions.
- It was found that land use primarily and by implication traffic characteristics exert a significant influence on solids and heavy metal loads on road surfaces. Traffic can generate finer particles with high heavy metal loads such as Lead (Pb), Zinc (Zn), Cadmium (Cd), Chromium (Cr), Nickel (Ni) and Copper (Cu). Multivariate data analysis revealed the different source characteristics of these metals in comparison to

Iron (Fe), Aluminium (Al) and Manganese (Mn) which are considered to be derived from soil sources.

- Particles smaller than 150 μ m show a high SSA and TOC content highlighting the linkage of these parameters with relatively high loads of heavy metals. The particle size range 150-300 μ m and 300-425 μ m did not show significant variations in SSA and TOC.
- It was found that SSA contributes to the association of traffic related Cd and Cr with solids indicating surface dependent adsorption characteristics similar to ion exchange or surface precipitation. On the other hand, presence of TOC in build-up pollutants enhances the association of Fe, Al and Mn with solids by a mechanism different to surface dependent adsorption. The oxides of Fe, Al and Mn enhances the association of Zn with solids.

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Suburb	Street name	eet name Notation Land use		Population density (residents/km2)	Soil	
Clearview Estate	Merloo DR	C 1	Residential			
	Yarrimbah DR	C 2	Residential	1227.0	Dermosols and Kurosols	
	Winchester DR	C 3	Residential	1227.0		
	Carine CT	C 4	Residential			
Nerang	Stevens ST	N 1	Industrial		Dermosols and	
	Lawrence DR	N 2	Industrial	420.4		
	Hilldon CT	N 3	Industrial	429.4	Kurosols	
	Patrick RD	N 4	Industrial			
Benowa	Strathaird Rd	B 1	Industrial			
	Mediterranean DR	B 2	Commercial	1597 6	Anthroposols (man-made soils) and Dermosols	
	De Haviland AV	В 3	Residential	1382.0		
	Village High RD	B 4	Residential			
Surfers paradise	Hobgen ST	S 1	Commercial			
	St Paul's PL	S 2	Commercial	2606 1	Anthroposols (man-made soils) and Dermosols	
	Via Roma	S 3	Commercial	5090.1		
	Thornton ST	S 4	Commercial			

Table 1 - Study sites description

Table 2 - Parameters and test methods

Parameter	Test Method Malvern Mastersizer S Particle Size Analyzer				
Particle size distribution					
Total suspended solids (TSS)	Method 2540 D (APHA, 1999)				
Heavy metals	Inductively Coupled Plasma – Mass Spectrometry (ICP-MS),				
	Method 200.8 (US EPA, 1994)				
Total organic carbon (TOC)	Shimadzu TOC-5000A Total Organic Carbon analyser, Method				
	5310C (APHA, 1999)				
Specific surface area (SSA)	Ethylene glycol monoethyl ether (EGME) method (Carter et al.				
	1986)				

Suburb	Road texture depth range (mm)	Antecedent dry days	Last rainfall event (mm)	Particle size distribution (%)					_ Arithmetic
				<75 μm	75-150 μm	150- 300 µm	300- 425 µm	>425 μm	mean TSS load (g/m ²)
Clearview	0.76-0.92	8	1.4	82.0	10.6	5.66	0.91	0.53	1.79±0.93
Estate		17	42.6	48.1	9.15	11.2	8.38	23.2	0.81±0.27
Nerang	0.93-1.14	5	3.8	63.0	18.8	10.8	5.00	2.39	3.5 ± 2.05
		9	1.2	45.4	15.3	11.3	10.2	17.8	7.03 ± 3.86
Benowa	0.80-0.91	8	9	83.5	4.1	5.34	4.84	2.26	1.39±0.42
		14	1.4	71.9	9.77	7.87	4.88	5.55	0.78 ± 0.48
Surfers	0.63-1.11	4	2.2	66.0	8.43	12.3	8.32	4.95	2.22±1.24
Paradise		10	42.6	47.0	18.5	16.3	6.07	12.2	1.79±0.29

Table 3 - Build-up pollutant load characteristics



Fig. 1. Heavy metal loads in different particle sizes of solids



Fig. 2. Comparison of specific surface area and organic matter with particle size





C: Clearview Estate, N: Nerang, B: Benowa, S: Surfers Paradise

second character: from 1-8 represents the sample number;

(●): 300-425 µm, (▲): 150-300 µm, (■): 75-150 µm, (♦): <75 µm)



Fig. 4. PCA biplot of all sites for finer particle size ranges (a) particles 75-150 μm and (b) particles smaller than 75 μm

C: Clearview Estate, N: Nerang, B: Benowa, S: Surfers Paradise;

second character: from 1-8 represents the sample number