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CHARACTERISTICS OF POLLUTANTS BUILT-UP ON RESIDENTIAL ROAD SURFACES

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ABSTRACT

Pollution build-up in relation to urban stormwater quality is one of the most important pollutant processes that need in-depth investigation. Build-up varies with range of climatic, land-use and regional parameters and illustrates a highly dynamic nature. This paper presents the outcomes of an in-depth investigation into pollutant build-up on typical residential urban road surfaces.

The outcomes of the investigation revealed highly site specific rates of build-up that primarily varied with road surface conditions, traffic volume and surrounding land-use. The rate of build-up was initially in the range of 1 to 2g/m^2/day and decreased when the antecedent dry days increased. The total build-up varied from site to site but did not exceed 6g/m^2. This amount was significantly less compared to numerous previous research studies. It was further noted that particulate pollutant composition varied dynamically when the antecedent dry days increased. It is hypothesised that this is due to the re-distribution of finer particles by the wind and traffic. Analysis of quality parameters revealed that a higher fraction of pollutants is associated with the finer particle size ranges. Furthermore, a relatively high amount of dissolved organic carbon was detected in build-up samples during the study. Dissolved organic carbon enhances the solubility of other pollutants such as heavy metals and hydrocarbons thus increasing their bio-availability.

1. INTRODUCTION

Stormwater pollution is an important environmental issue in modern times. It has been observed that the pollutant loads originating from urban land-uses are significantly higher when compared to rural catchments. Even more critically, the physio-chemical diversity of the urban pollutants is comparatively greater. Such increased loads and the presence of various pollutant types leads to significant degradation of receiving water quality (House et al., 1993; Novotny et al., 1985; Sartor et al., 1974).

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Due to the nature of 'non-point origin' and random occurrence in large volumes, the treatment measures for stormwater pollution are inherently difficult. Higher fraction of pollutants in dissolved form and adsorption of pollutants into finer fraction of solids include further complexities into treatment design. In this context, it is well understood that common 'end of pipe' treatment does very little in mitigating the pollutant issues. As noted by Goonetilleke et al., (2005) a significant part of the problem can be mitigated at the stage of catchment planning and management. The solution that they have suggested is an integrated approach in catchment planning, management and in-situ treatment.

When the solution become increasingly complex and involves a range of integrated action plans, accurate and reliable support tools are needed for successful decision making. Stormwater quality models are important in this regard as they are capable of estimating stormwater quality using given catchment, land-use and climatic conditions. Furthermore, these models have been often used for evaluation of existing management and treatment measures. The models were first developed decades ago and since then incorporate increased capabilities, accuracy and reliability for better decision making. A water quality model is commonly based on mathematical formulations which are used to replicate pollutant processes on catchment surfaces. Two main pollutant processes; build-up and wash-off are commonly replicated by these models. In its simplest form, a stormwater quality model first estimates the pollutant availability on a catchment surface using a pollutant build-up equation. Then it uses pollutant wash-off relationships and rainfall records to estimate the runoff quality. Accuracy and reliability of these models is strongly dependent on the precision of the mathematical formulation of pollutant processes (Akan and Houghtalen, 2003).

In a water quality modelling context, the accuracy and reliability of replicating equations is in two respects. Firstly, both accuracy and reliability is influenced by the capability and robustness of replication equations that are used to reproduce the state of art knowledge of pollutant processes. Secondly, and most importantly accuracy and reliability is influenced by the state of understanding of the pollutant processes. It is well understood that these processes are influenced by a range of factors. Therefore, it is always questionable that the knowledge that exists relating to these processes is adequate to understand these processes.

Pollutant build-up on catchment surfaces is a dynamic process. In a given instant, pollutants are accumulated on a catchment surface and removed due to the influence of re-distribution factors such as wind and vehicular traffic (Namdeo et al., 1999). The rate of pollutant build-up is influenced by factors such as climate, land-use, traffic volume, population density and catchment surface conditions. For example Sartor et al., (1974) noted significant variation of pollutant build-up in US roads due to changes in land-use and road surface conditions. Though similar observations were noted by Ball et al., (1998) in terms of build-up pattern, the significantly less pollutant loads on Australian road surfaces were attributed to the variability of regional and management factors.

Significant amount of work has been done in order to understand the primary characteristics of pollutant build-up on road surfaces (Deletic and Orr, 2005; House et al., 1993; Novotny et al., 1985; Sartor et al., 1974; Vaze et al., 2000). However, more work is still needed to understand the variability inherent to these processes. This paper discusses the outcomes of an in-depth investigation on pollution build-up on residential roads. The study will contribute to the existing knowledge base in relation to pollutant build-up in typical Australian urban residential road surfaces. The investigation encompasses variations in urban form within residential land use and changes in road surface conditions.

2. MATERIALS AND METHODS

2.1 Study Area

Three residential road sections were selected from the Gold Coast region, Queensland State, Australia. Gold Coast is a popular tourist destination in Australia having relatively a high population growth rate. It has a sub tropical climate with wet warm summers and dry winters.

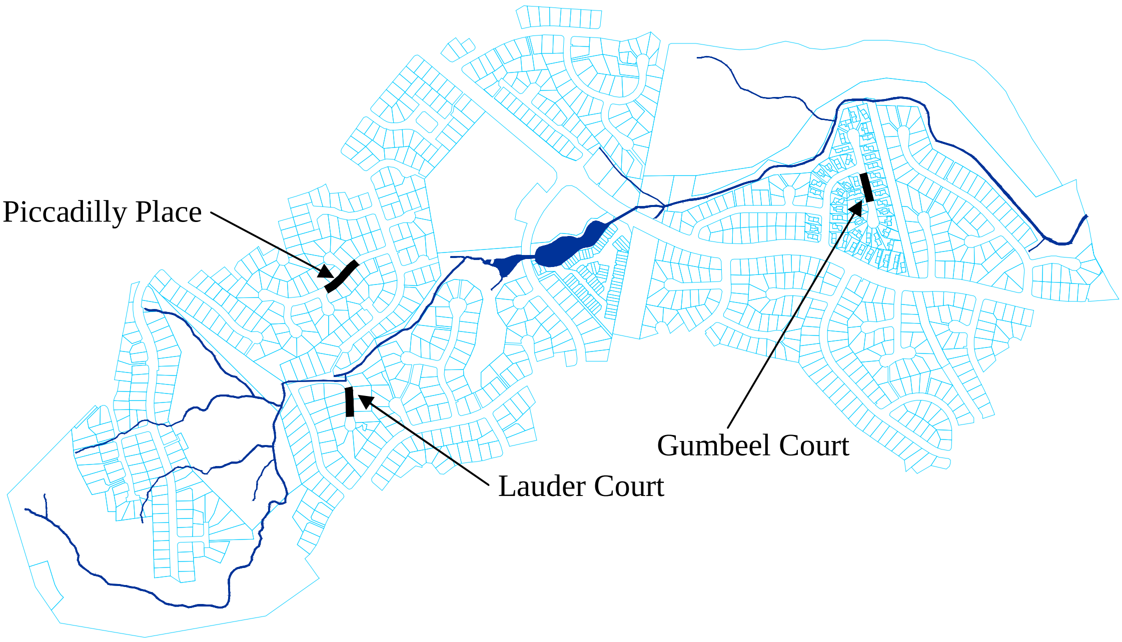

Figure 1 Study catchment – Highland Park

All three road sites were located in the typical residential urban catchment of Highland Park (see Figure 1). Three road sites were selected so that they represent slightly different urban form within residential land use. In addition to urban form, two primary surface parameters; slope and texture depth were measured in order to characterise the road sites. The primary characteristics of the road sites are given in Table 1.

Table 1 Characteristics of selected road sites

Site	Description of the surrounding land-use	Slope (%)	Texture depth (mm)
Lauder Court	Single detached housing	10	0.66
Gumbeel Court	Duplex housing	7.2	0.92
Piccadilly Place	Single detached housing	10.8	0.83

2.2 Experimental Design and Sample Collection

The primary variable which formed the focus of the build-up investigations was antecedent dry period. Sartor et al., (1974) investigated build-up of up to around 12 antecedent dry days, and Ball et al., (1998) investigated build-up of up to 10 antecedent dry days. However, it was not clear from past studies the optimum duration for undertaking pollutant build-up investigations due to variations in investigation technique and site conditions. It was decided to continue build-up investigation up to 21 antecedent dry days for this research. The antecedent dry periods considered were 1, 2, 3, 5, 7, 14 and 21 days.

Sample collection was undertaken on 1.5m x 2.0m road surfaces plots. These plot surfaces were selected from the middle strip of one side of the road at approximately 3m distance apart. Plots were initially cleaned by repeated vacuuming. At the end of each antecedent dry period, particulate pollutants were collected from plot-surfaces using the vacuum system (see Figure 2). Vacuuming was done three times in perpendicular directions in order to ensure that all the particulate material was collected. A timber frame was used to locate the plot boundary during sample collection.

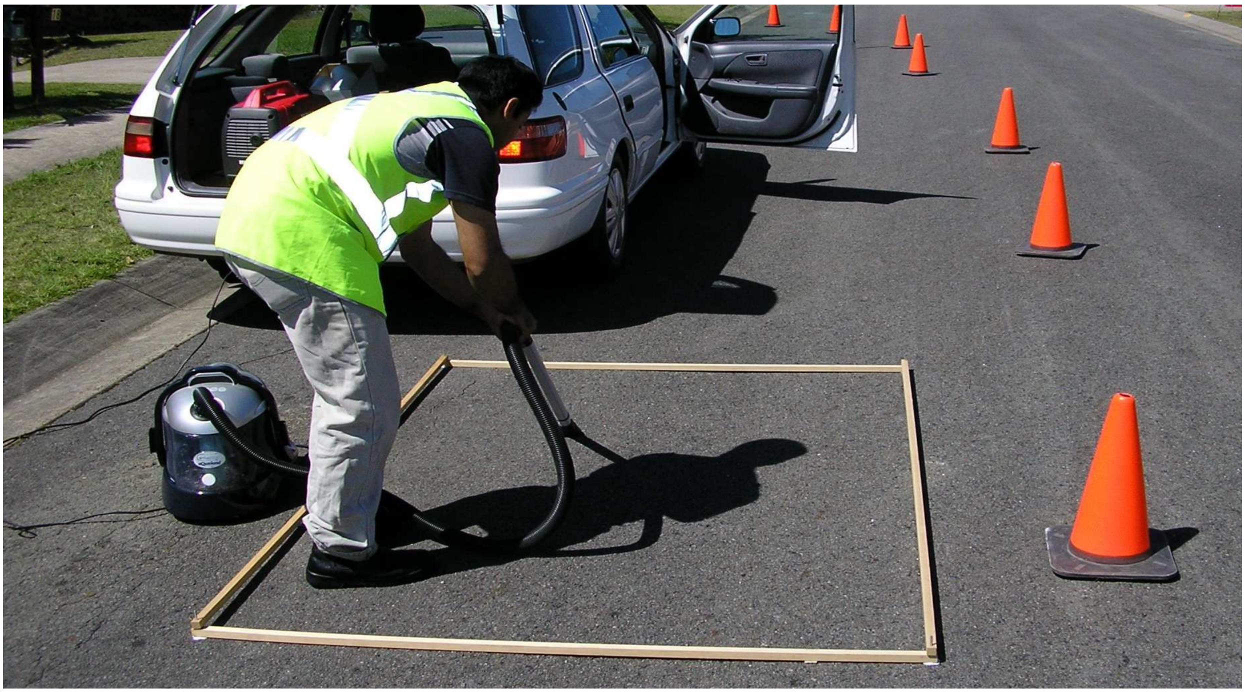

Figure 2 Sample collections from road surface plots

The vacuum system consisted of a water filtration system and a small circular foot with a coarse brush attached to the end. The water filtration system was selected in order to improve particle retention within the collection system. It has been observed that wet filtration is more effective in retaining finer particles (Bris et al., 1999). A small circular foot with a coarse brush was used in order to enhance the collection efficiency of particles. The vacuum system was pre-tested for collection and retaining efficiency which was found to be 97%.

2.3 Laboratory Analysis

As a water filtration system was used, the collected particulate samples were retained in a water column in the vacuum cleaner compartment. These water columns with particles were transferred to plastic containers and transported to the laboratory. Since particulate matter being adopted as the indicator pollutant, the primary emphasis was to determine parameters such as total suspended solids (TSS) and particle size distribution. Testing for TSS was undertaken according to test method No. 2540D (APHA, 1999). Particle size distribution was determined using a Malvern Mastersizer S particle size analyser. The analyser used was a reverse Fourier lens of 300mm diameter and was able to analyse particles in the range of 0.05-900µm. In this range, the manufacturer has specified a reading accuracy of ±2% of the volume median diameter (Malvern Instrument Ltd. 1997). Apart from primary water quality parameters, pH, electrical conductivity (EC), total carbon (TC), total organic carbon (TOC) and dissolved organic carbon (DOC) were determined.

3. RESULTS AND DISCUSSION

3.1 Variations of Pollutant Load

The weights of suspended solids collected during each sampling episode are plotted in Figure 3. As seen in Figure 3, build-up in Lauder Court and Piccadilly Place sites are similar, compared to relatively higher accumulation rates in the Gumbeel Court site. Gumbeel Court road site is situated in a duplex town house area where the population density and traffic volume is high compared to the other sites. Furthermore, the Gumbeel Court road site is comparatively flatter and has a rougher surface texture. These could be the primary reasons for the increase in build-up at Gumbeel Court. This highlights the influence of surrounding land-use, traffic volume and road surface condition on pollutant build-up. For all three sites, high pollutant accumulation rates were detected during the first one to two days. The accumulation rates were in the range of 1 to 2 $g/m^2/day$. The rate of accumulation reduces and total build-up asymptote to a constant value as antecedent days increases. Similar characteristics of build-up were noted by Ball et al., (1998) and Sartor et al., (1974).

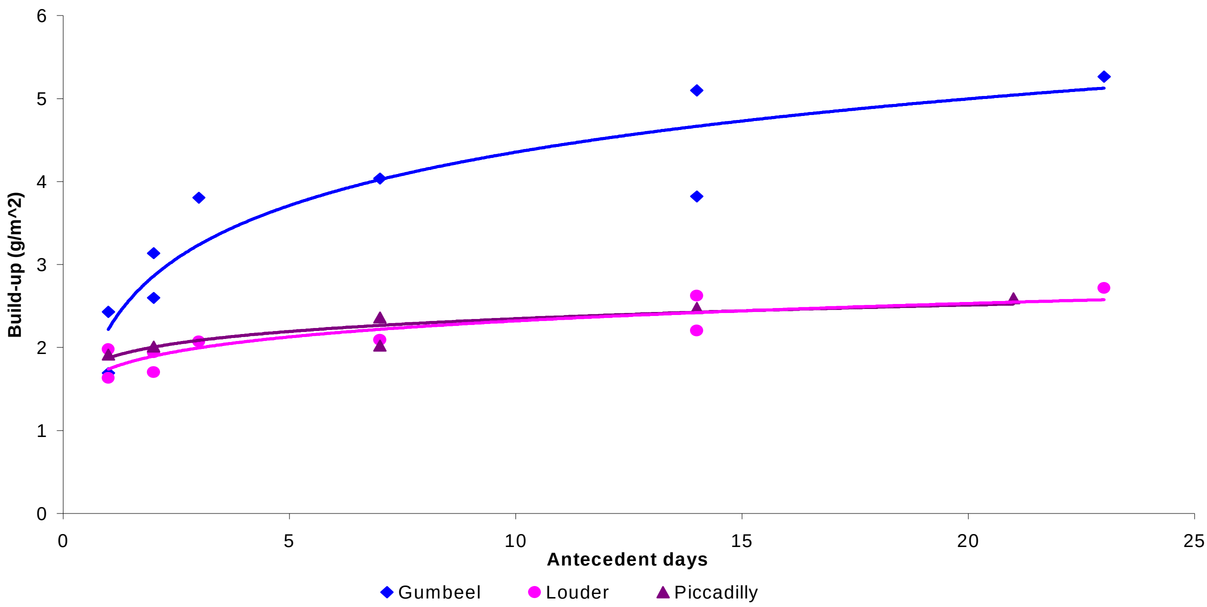

Figure 3 - Pollutant build-up on three road sites

The observed build-up patterns could be mathematically replicated using a power function. Similar power function was recommended by Ball et al., (1998) to mathematically replicate build-up on road side kerbs. The power function used was in the form of:

$$B = aD^b$$

Where,

B = Build-up load on road surface (g/m^2);

D = Antecedent dry days; and

a and b = Build-up coefficients.

The build-up coefficients, a and b, for the proposed replication equation was developed using method of least square. The fundamental technique was to obtain coefficients so that sum of square of difference between observed and predicted build-up is minimal. Two parameters sets were developed for townhouse regions and single detached housing regions. It was considered highest variability of build-up is associated to surrounding land-use and population density. The parameters obtained are shown in Table 2.

Table 2 Build-up coefficients for road surfaces

Road Site	**Characteristics**	***a***	***b***
Gumbeel Court	Townhouse region with high population density	2.90	0.16
Lauder Court	Single detached housing regions	1.65	0.16
Piccadilly Place	with low population density	1.65	0.16

Though the variation of build-up agrees with past research studies, the total amount of solids collected shows significant variations. As seen in Figure 3, the amount of pollutants collected from road surfaces ranged from 2 to $6g/m^2$. Sartor et al., (1974) observed around 113g/m of solids in residential road side kerbs, whereas, Ball et al., (1998) observed only around 4 to 15g/m. However, outcomes of both research studies are not completely comparable with this research, as samples were not collected from the roadside kerbs. Vaze and Chiew, (2002) noted that the build-up load is highly variable depending on the site location was in the range of 8 to $40g/m^2$ for road surfaces that they investigated in Melbourne, Australia. Their study sites were located close to Melbourne CBD. Deletic and Orr, (2005) observed 5 to $25g/m^2$ of solids in the median strip of the residential roads in Aberdeen, Scotland. Compared to the above outcomes noted, the pollutant loads collected during this research was significantly less. This could be mainly due to differences in regional, climatic, land-use, traffic volume and road surface conditions. The road sites selected for this research were within predominantly residential areas and road surfaces were in fair to good condition with limited through traffic.

3.2 Variations of Particulate Composition

Pollutant build-up encompasses highly dynamic characteristics. Re-distribution of pollutants is the primary cause of this dynamic nature and the movement of finer particle sizes are the most dominant after their initial deposit on road surfaces (Namdeo et al., 1999). Harrison and Wilson (1985) noted that particles up to 240μm can be subjected to re-suspension due to air movements. According to them, vehicular induced wind is the main factor that influences re-distribution in roadside localities whereas natural wind transport finer dust particles over large distances.

The dynamic nature of pollutant build-up was evident during the particle size distribution analysis of build-up samples. The Malvern Mastersizer S particle size analyser was used to obtain the particle size distribution for individual samples and results were in volumetric percentages. The analysis was done separately for three sites. However, it was noted that there were significant similarities among sites. Therefore, the average distributions were calculated for the three sites and are presented in Figure 4.

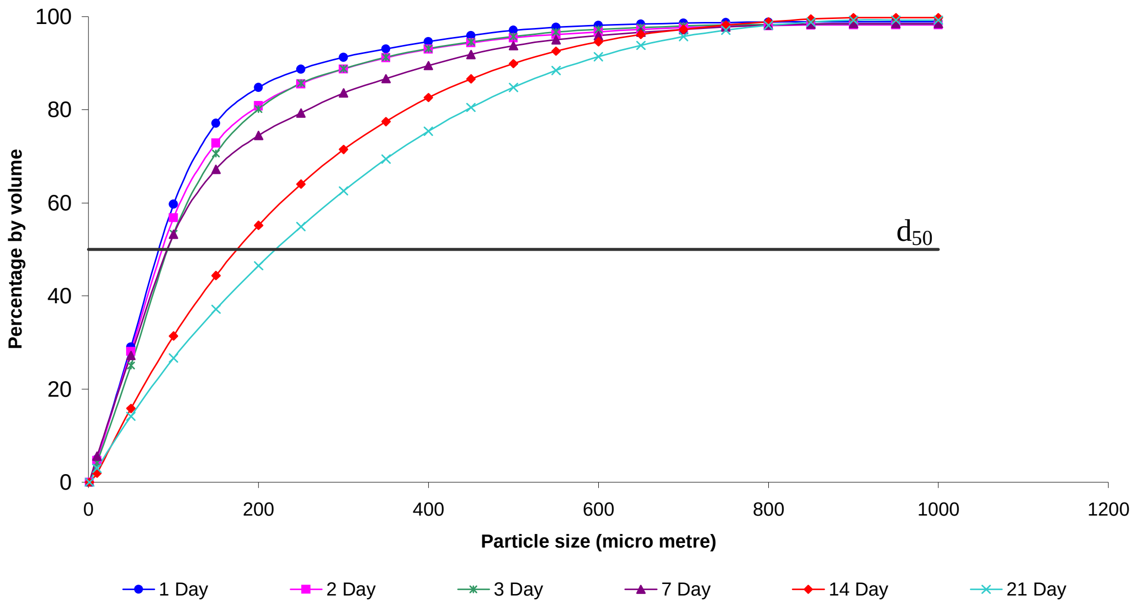

Figure 4 Average particle size distribution of samples

As seen in Figure 4, the particle size distribution curve moves from left to right indicating the increase of coarser fraction with antecedent dry days. The average d_{50} values for 1 to 7 days were in the range of 75 to 100µm, whereas it was around 200µm for 14 days and 250µm for 21 days. This suggested that, though the change of build-up is limited, the solids composition changes continuously by accumulating coarser particles and re-distributing finer particles when the antecedent dry period increases. During the process, a higher fraction of finer particles are more likely to deposit outside the road surfaces where the turbulence is minimal.

3.3 Variation of Qualitative Parameters

Qualitative parameters for build-up samples were analysed using principal component analysis (PCA) which is one of the more widely used multivariate analytical methods in water quality research (Bengraine and Marhaba, 2003; Petersen et al., 2001). PCA is essentially a pattern recognition technique which can be used to understand the correlations among different variables and clusters among objects (Kokot et al., 1998).

The PCA technique is used to transform the original variables to a new set of Principal Components (PCs) such that the first PC contain most of the data variance and the second PC contains the second largest variance and so on. The analysis will produce the same number of PCs as the original data set. However, the first few PCs contain most of the variance. Consequently, it is possible to reduce the data variability without loosing much of the useful information from the original data set. Detailed descriptions of PCA can be found elsewhere (Adams, 1995; Kokot et al., 1998).

A Biplot gives a diagrammatical presentation of PCA outcomes. It represents loadings of each variable in the form of a vector and scores of each object (samples) in the form of a data point. The angle between vectors is the indicator of the degree of correlation between variables. An acute angle between two vectors indicates a strong correlation of variables whereas an obtuse angle indicates negative correlation. A right angle between variables indicates no correlation.

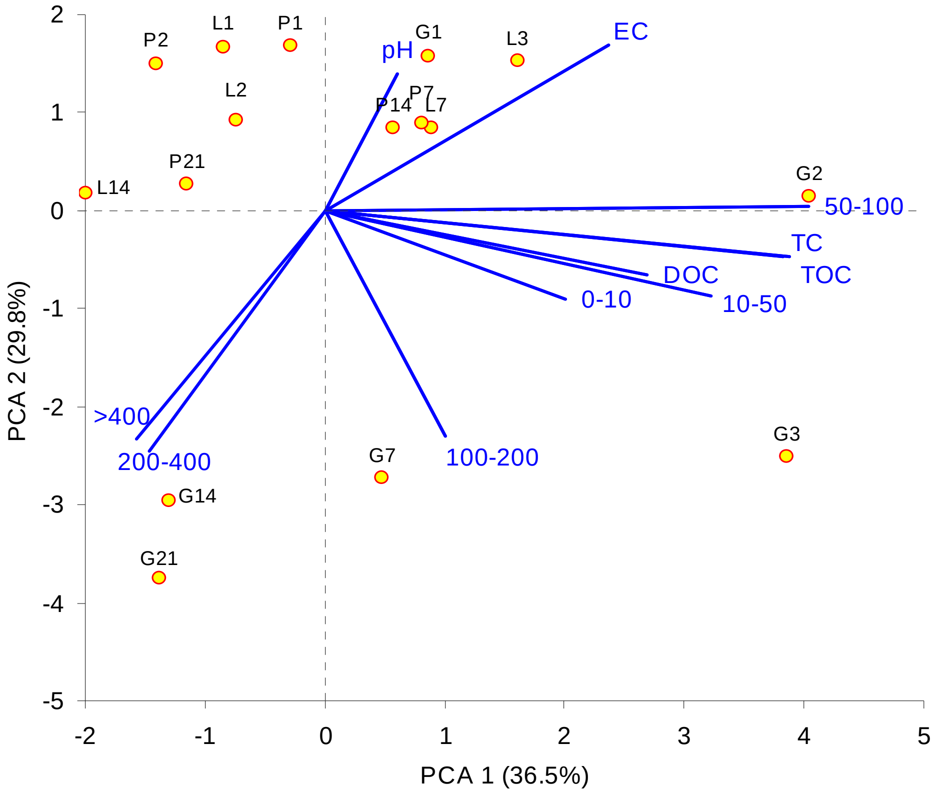

Figure 5 Qualitative parameters for build-up samples: Biplot of data against the first two principal components

Figure 5 shows the analytical outcome of qualitative parameters for the build-up samples. Apart from the qualitative parameters, the calculated weights of particulate solids separated into six size categories were used for the analysis. This was done to understand the qualitative behaviour of different particle size classes. As seen in Figure 5, particulate pollutants can be separated into two main groups. The finer fraction, less than 100µm show strong correlation to TC, TOC, and DOC. Furthermore, both pH and EC shows partial correlations with the finer fraction. This suggested that relatively more pollutant is associated with the finer fraction. This further strengthens the concept established by previous research studies such as Ball et al., (1998) and Sartor et al., (1974).

During the laboratory analysis significant amount of DOC were noted in build-up samples. As noted by Gromaire-Mertz et al., (1999), a high fraction of organic carbon in residential road surfaces can be attributed to the presence of trees and adjacent grassed areas. As hypothesised by Sartor et al., (1974), the high degradability of organic carbon due to low structural strength would be the primary reason for presence of higher amount of DOC. Similar finding was noted by Herngren et al.,

(2006) in their build-up investigations in the Gold Coast region. They also noted the correlation of heavy-metal pollutants with carbon compounds. The presence of carbon compounds in stormwater, especially in dissolved format enhances the solubility of pollutants such as heavy metals and hydrocarbons (Hamilton et al., 1984; Warren et al., 2003). This increases the presence of pollutants in dissolved form. The pollutants in dissolved form are more readily bio-available.

Coarser fraction of particulate pollutants, particularly particles greater than 200μm show strong negative correlation to pH and EC and partial negative correlation with carbon compounds. This suggests that relatively very little other pollutants are associated with the coarser fraction.

4. CONCLUSIONS

Analysis of road surface build-up led to following conclusions:

- Three road sites investigated showed significant variation in terms of build-up load. This suggested a highly variable nature of build-up with land-use, traffic and road surface characteristics.
- Higher rate of build-up was observed during the first two days and relatively low rates when the antecedent days increase. The build-up rate during the initial period was 1 to 2 g/m^2/day.
- Composition of build-up particulate pollutants showed significant variation with antecedent dry days. The particle size distribution curve moved from left to right indicating the accumulation of higher fraction of coarser particles when the number of days increases.
- The qualitative analysis revealed that most of the build-up pollutants is associated with finer particulate fraction (<100μm).
- A higher fraction of dissolved organic carbon was present in build-up samples. This would enhance the solubility of other pollutants such as hydrocarbons and heavy metals and hence lead to increased bio-availability of these pollutants.

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