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Variability of Metal Composition and Concentrations in Road Dust in the Urban Environment

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***Abstract*—**Urban road dust comprises of a range of potentially toxic metal elements and plays a critical role in degrading urban receiving water quality. Hence, assessing the metal composition and concentration in urban road dust is a high priority. This study investigated the variability of metal composition and concentrations in road dust in 4 different urban land uses in Gold Coast, Australia. Samples from 16 road sites were collected and tested for selected 12 metal species. The data set was analyzed using both univariate and multivariate techniques. Outcomes of the data analysis revealed that the metal concentrations inroad dust differs considerably within and between different land uses. Iron, aluminum, magnesium and zinc are the most abundant in urban land uses. It was also noted that metal species such as titanium, nickel, copper and zinc have the highest concentrations in industrial land use. The study outcomes revealed that soil and traffic related sources as key sources of metals deposited on road surfaces.

***Keywords*—**Metals build-up, Pollutant accumulation, Stormwater quality, Urban road dust.

I. Introduction

DUST accumulating on road surfaces contains a range of pollutant types that originate from different sources. Accumulation and composition of road dust depends on factors such as weather, traffic characteristics, soil characteristics and other land use related activities in the proximity [1]-[3]. Road dust is the primary source of potentially harmful pollutants accumulating in urban waterways.

Among the harmful pollutants, the presence of metals is considered as the most serious due to their toxicity, bioavailability and non-degradable characteristics. However, considering the widely varying composition and heterogeneity in spatial distribution, the risks posed by metals is difficult to assess. In this context, assessing the variability of metals in relation to contributing source characteristics is important.

Past studies such as by Al-Khashman [4] and Al-Momani [5] primarily focused on study areas with limited variability of contributing sources. In this study, composition and variability of metals are discussed based on sites with a wide variety of source characteristics, including traffic, soil and land use. Outcomes of this study enabled understanding the variations in metal build-up on road surfaces under different contributions from a range of sources. This created knowledge to facilitate the development of appropriate management strategies to protect urban waterways from metal pollution.

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II. Materials and Methods

A. Sampling Sites

The study was conducted at Gold Coast, Australia. Study sites consisting of roads sites were selected from the suburbs of Surfers Paradise, Benowa, Nerang, and Clearview Estate (see Fig. 1). Selected sites in these suburbs represent typical urban land uses such as commercial, industrial, residential and mixed use. The sites also represent a significant variation in soil characteristics as the suburbs range from the coastline to the inland. A total of 16 sites were selected with an equal number of roads from each suburb with different traffic volumes.

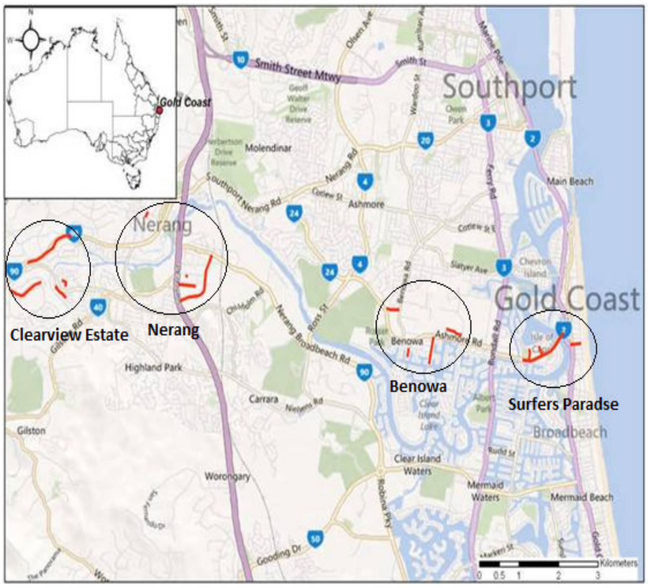

Fig. 1 Map of the sampling sites

B. Sample Collection

Dust samples from each road were collected using a dry and wet vacuuming system (see [6] for details). It consists of a vacuum cleaner with a water filtration system and a pressure controllable sprayer. Dust collection and retention efficiency of the system were tested under controlled field conditions prior to use in the field and was found to be 98%. In this study, dust accumulated on a $3m^2$ (1.5m x 2.0m) road surface plot was collected. This was done in three steps: initial dry vacuuming, wetting the surface using deionized water sprayed at 2 bar pressure for 3 minutes and finally wet vacuuming to collect the remaining particles on the surface. Samples were collected twice from each road representing two antecedent dry periods. This was to investigate the possible variation in road dust accumulation due to the variation in antecedent dry days (ADDs).

C. Laboratory Analysis

Collected samples were fractionated into five different particle size ranges, namely,>425µm, 425µm-300µm, 300µm-150µm, 150µm-75µm and <75µm. Each fraction was tested for Magnesium (Mg), Aluminum (Al), Titanium (Ti), Vanadium (V), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), Rhodium (Rh) and Palladium (Pd), which are commonly available metals in road dust. Nitric acid digestion was carried out to extract the metals in 50mL polyethylene vials using a hot block digester. The metal extracts were analyzed using ICP-MS (Agilent 8800 Triple Quadrupole). Precision and accuracy of the analysis were confirmed using internal standards, certified reference materials, replicate samples and quality control blanks. Multi element custom standards prepared by AccuStandard Inc. were used as calibration standards. Analysis of replicate samples yielded a relative standard deviation of less than 15%. All the test results were blank corrected.

D. Data Analysis

Univariate statistical analysis was performed to identify the basic patterns in the data set. Multivariate data analysis techniques were then used to extract useful latent information from the comparatively large data set.

The statistical test, ANOVA (ANalysis Of VAriance) was used to test the differences in means of different groups for statistical significance. It compares variance due to the between-groups variability (called as Mean square effect) with the within-group variability (called as Mean square error). The two estimates of variances were compared via F test which tests whether the ratio of the two variance estimates (Mean square Effect/ Mean square error) is greater than 1. Large F ratio means the variation among the groups is high. In this study, road dust loads in different land uses (groups) were tested for ANOVA statistical test to check the effect of land use on dust accumulation on road surfaces.

In this study, factor analysis which is a popular multivariate analytical technique was also used [7], [8]. It was used to reduce the number of interrelated variables in the data matrix to a low number of independent factors (orthogonal factors) that can be used to explain the variance in the data [9].In this study, factor analysis on 12 metals (variables) was carried out. To transform the initial factor matrix to easily interpretable form, varimax rotation was then conducted. The factors were extracted so that the eigenvalues were equal or greater than 1. The extracted factors were used to identify key sources of metals in the road dust. The analysis was performed using SPSS 21.0 software. Before input of the data set into the software, the data set was transformed to dimensionless standardized form (see (1)) in order to reduce the noise that could interfere with the analysis.

$$Z_{ik} = \frac{C_{ik} - \overline{C_i}}{\sigma_i} \tag{1}$$

where, C_{ik} is the concentration of metal i in sample k, $\overline{C_i}$ is the mean of the concentration of metal i and σ_i is its standard deviation.

III. Results and Discussion

A. Variability of Road Dust Accumulation in Different Land Uses

As road dust has been identified as a carrier of metals [10], understanding the variability of road dust accumulation is important prior to discussing the variability of metals in urban land uses. Table I shows the range of road dust loads collected from different land uses and for different antecedent dry periods. It is clear that the lowest road dust load was from residential roads for both antecedent dry periods. Highest dust load was collected from an industrial road site at 11 ADDs. This indicates that the land use and underlying differences in traffic volume and source characteristics in the proximity can influence the dust loads deposited on road surfaces. As noted in past studies, the amount of road dust build-up is an increasing function with ADDs with a decreasing rate [11]. In this study, behavior of road dust build-up with ADDs was found to be significantly different. For example, in the mixed land use, minimum load of road dust for 4 ADDs was 1.49 g/m^2, but for 18 ADDs it was 0.67 g/m^2. This could be due to the pre-existing load which was possibly influenced by the last rainfall event and resulting wash-off [12].

As evident in Table I, there is variability in accumulated road dust even within land uses. ANOVA was conducted to test this observation. The result of the ANOVA test is shown in Table II. It indicated that F ratio was greater than 1 (1.457) and it describes that the variation of road dust accumulation related to different land uses is significant. However, as the F value was very close to 1, the variability within land uses is also comparatively significant. This is attributed to the variability of contributions from different sources of dust at a particular road site.

B. Variability of Metals in Road Dust

Fig. 2 shows the concentrations of 12 metal species investigated at each land use. As evident in Fig. 2, the most dominant metals in all urban land uses are Fe, Al and Mg. It is commonly known that these metals are found in soil [13]. Therefore, this suggests that the primary source of Fe, Al and Mg is soil. However, contribution of these metals can also be from other sources. As seen in Fig. 2 (b), Fe shows high variability of concentration in industrial land use compared to others suggesting possible release of Fe by industrial activities.

As seen in Fig. 2, the least detected metals were Rh and Pd in all land uses. However, concentrations of these metals are comparatively high in industrial and residential land uses compared to commercial and mixed land uses. Rh and Pd are generally products released from catalytic converters of vehicles [14]. Palacios [15] noted that the release of Rh and Pd depends highly on the type and age of the catalytic converters. They further noted that the variability in the concentrations of Rh and Pd released from fresh catalytic converters is higher than that from aged products. The presence of these two metals is justifiable as vehicular activities are common in all land uses. However, it is difficult to draw firm conclusions about the distribution of these two metals in different land uses due to their variations with the type and age of catalytic converters in vehicles and the amount of traffic in the particular area.

TABLEI
ROAD DUST LOAD IN SITES

Land use	Road dust (min-max) (g/m^2)	ADDs
Commercial	0.41 - 4.53	4
	0.41 - 8.03	18
Mixed	1.49 - 4.52	4
	0.67 - 1.37	18
Industrial	0.92 - 3.47	5
	0.19 - 9.24	11
Residential	0.21 - 0.35	5
	0.33 - 0.65	11

TABLEII
ANOVA TEST RESULTS

Source of variation	Sum of squares	Degree of freedom	Mean squares	F- test
Effect	20.5	3	6.833	1.457
Error	131.3	28	4.689	

The highest mean concentrations of Ti, Ni, Cu and Zn were observed in the industrial land use while V is high in the commercial land use. These metals are mainly deposited on road surfaces as part of brake dust and/or tire dust [16]. Therefore, high concentrations of these metals can be expected as there are high vehicular traffic activities in industrial and commercial land uses.

Moreover, the concentration and variability of each metal (except Fe) in residential land use are comparatively low (Fig. 2 (c)). This could be due to the consistency in vehicular traffic activities and the absence of metal emitting sources within the residential land uses compared to other land uses.

C. Factor Analysis

From the analysis in Section III-B, it is clear that the spatial variability of metal concentrations is primarily affected by variable contributions from sources of road dust. Therefore, it is important to initially identify key sources and their characteristics in the urban environment. Key sources were identified based on the outcomes of factor analysis. Factor analysis was carried out separately for each land use. Each data matrix comprised of 48 samples (4 sites, 6 samples per site – original sample and its 5 fractions of different particles sizes and 2 sampling episodes) and 12 metal elements.

Outcomes of the factor analysis of the data matrix for the commercial, industrial, residential and mixed land uses are presented in Table III. Two factors in each land use (accounting for greater than 74% of total variance) were extracted.

As it can be seen in Table III, in each land use factor 1 has high loadings for Mg, Al, Ti, V, Cr, Mn, Fe, Ni, Cu, and Zn. As discussed in Section III-B, Fe, Al and Mg are the most abundant metals found in soil. The other metals are also found in minor quantities in soil [17]. However, the high loading of Cu, Zn, Ni, and V in factor 1 indicates the accumulation of tire, brake dust and road surface wear [16], [18], [19] in the road dust in addition to soil. Therefore, it can be concluded that one source of metals in road dust is a mixture of soil and traffic related sources such as brake, tire dust and road surface wear.

As shown Table III, factor 2 has strong correlation with Pd and Rh in each land use. As noted in Section III-B, these two metals are primarily released as vehicle exhaust from catalytic converters of the vehicles. Accordingly, factor 2 is related to vehicle exhaust and it is identified as another source of metals in road dust.

From the factor analysis, it can be concluded that accumulation of metals in road dust is primarily due to soil and traffic related sources in all urban land uses. However, according to the analysis in Section III-B, there can be a difference in contributions of metals from each of the key sources for different land uses. To determine contributions from sources in each land use, more advanced analysis is needed.

IV. CONCLUSIONS

The primarily conclusions derived from this study are:

- The road dust load and metal concentrations have significant variations within and between urban land uses.
- The most abundant metals in all urban land uses are Mg, Al and Fe while Ti, Ni, Cu, and Zn are abundant in industrial land use.
- Factor analysis identified two sources of metals in road dust. Soil mixed with traffic related sources namely tire dust, brake dust and road surface wear was identified as one source and the other source was vehicle exhaust. These two sources are common to all urban land uses (commercial, industrial, residential and mixed).

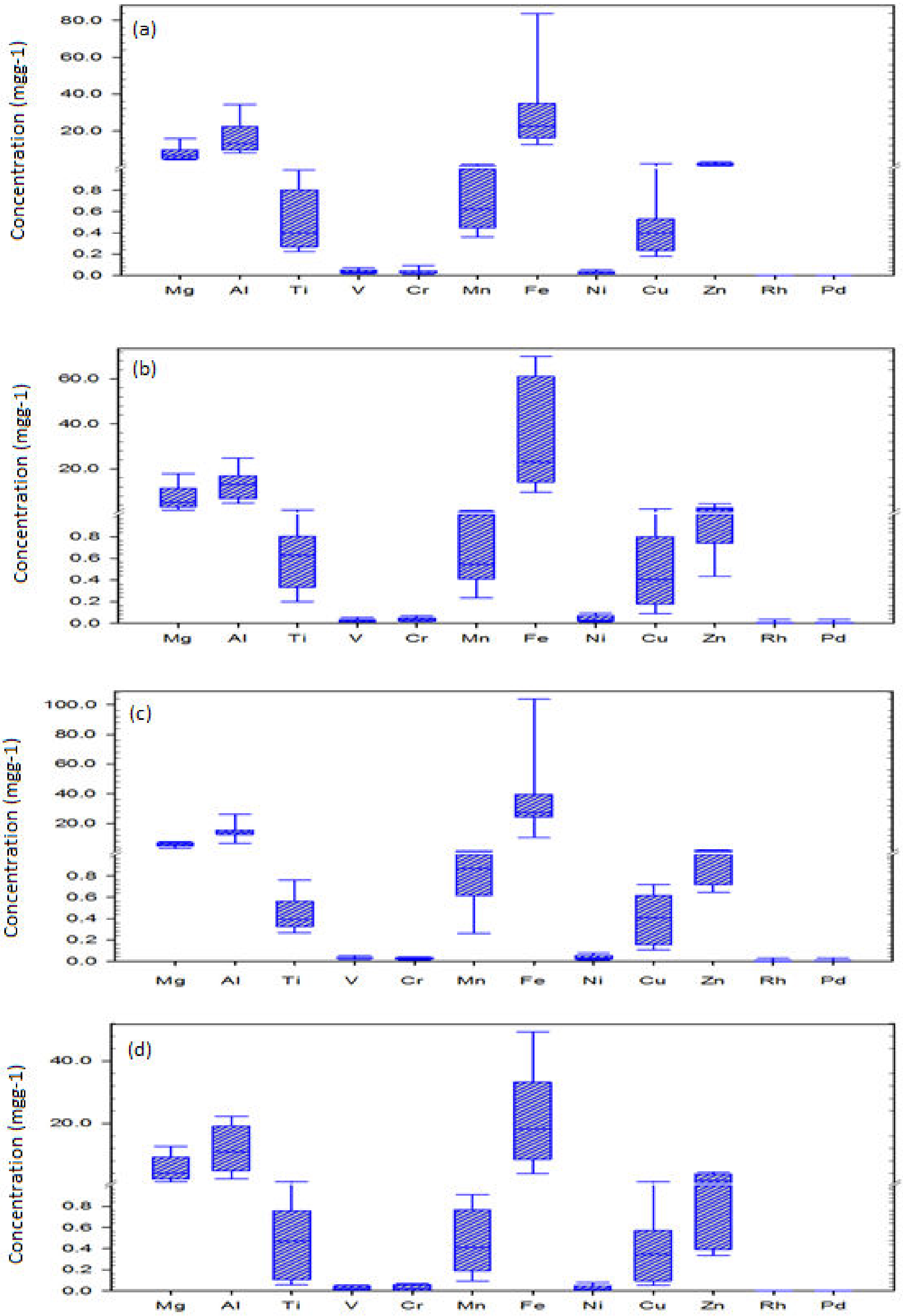

Fig. 2 Metal concentrations in road dust in different land uses Commercial (b) Industrial (c) Residential (d) Mixed

TABLE III
ROTATED FACTOR MATRIX FOR DIFFERENT LAND USES
(A) COMMERCIAL (B) INDUSTRIAL (C) RESIDENTIAL (D) MIXED

(a)

Metal	Factor 1	Factor 2
Mg	**0.782**	0.304
Al	**0.987**	-0.090
Ti	**0.769**	-0.233
V	**0.983**	0.000
Cr	**0.959**	-0.012
Mn	**0.982**	-0.029
Fe	**0.965**	-0.115
Ni	**0.876**	0.341
Cu	**0.837**	-0.163
Zn	**0.949**	0.116
Rh	-0.040	**0.805**
Pd	-0.003	**0.890**
Cumulative variance %	69.40	84.11

(b)

Metal	Factor 1	Factor 2
Mg	**0.895**	0.056
Al	**0.978**	-0.094
Ti	**0.867**	-0.153
V	**0.988**	-0.096
Cr	**0.942**	-0.061
Mn	**0.917**	-0.067
Fe	**0.945**	-0.082
Ni	**0.794**	-0.113
Cu	**0.864**	-0.034
Zn	**0.923**	-0.122
Rh	-0.081	**0.996**
Pd	-0.081	**0.996**
Cumulative variance %	69.57	86.85

(c)

Metal	Factor 1	Factor 2
Mg	**0.926**	-0.091
Al	**0.972**	-0.097
Ti	**0.959**	-0.107
V	**0.965**	-0.061
Cr	**0.924**	-0.017
Mn	**0.921**	-0.083
Fe	**0.732**	-0.201
Ni	**0.936**	0.073
Cu	**0.853**	-0.216
Zn	**0.807**	-0.247
Rh	-0.098	**0.990**
Pd	-0.100	**0.990**
Cumulative variance %	68.03	85.97

(d)

Metal	Factor 1	Factor 2
Mg	**0.902**	-0.110
Al	**0.917**	-0.115
Ti	**0.717**	0.019
V	**0.968**	-0.023
Cr	**0.812**	0.330
Mn	**0.891**	0.210
Fe	**0.901**	-0.146
Ni	**0.705**	-0.072
Cu	**0.473**	0.397
Zn	**0.859**	0.280
Rh	-0.027	**0.907**
Pd	-0.078	**0.942**
Cumulative variance %	56.96	74.90

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