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Short communication

Characterising metal build-up on urban road surfaces

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ABSTRACT

Reliable approaches for predicting pollutant build-up are essential for accurate urban stormwater quality modelling. Based on the in-depth investigation of metal build-up on residential road surfaces, this paper presents empirical models for predicting metal loads on these surfaces. The study investigated metals commonly present in the urban environment. Analysis undertaken found that the build-up process for metals primarily originating from anthropogenic (copper and zinc) and geogenic (aluminium, calcium, iron and manganese) sources were different. Chromium and nickel were below detection limits. Lead was primarily associated with geogenic sources, but also exhibited a significant relationship with anthropogenic sources. The empirical prediction models developed were validated using an independent data set and found to have relative prediction errors of 12–50%, which is generally acceptable for complex systems such as urban road surfaces. Also, the predicted values were very close to the observed values and well within 95% prediction interval.

1. Introduction

In the context of developing effective stormwater pollution mitigation strategies to protect the aquatic ecosystem, reliable mathematical replication of the pollutant build-up process is essential. Several empirical equations have been proposed to mathematically replicate solids build-up, e.g. Sartor et al. (1974) and Ball et al. (1998). However, Liu et al. (2012) reported that solids are not a reliable surrogate for estimating the build-up of other pollutants such as nutrients and organic carbon. Therefore, it can be argued that it is necessary to develop specific predictive models to replicate the build-up of other pollutants including metals.

Among stormwater pollutants, metals are of concern due to their persistence in the environment and potential toxicity. In urban areas, road surfaces are regarded as the most significant contributor of metals to stormwater runoff where a high fraction of metals originate from anthropogenic and natural sources (Herngren et al., 2006). Accordingly, this paper presents the outcomes of a research study undertaken to develop reliable empirical predictive equations to replicate metal build-up processes on residential road surfaces. This was based on the characterisation of the metal build-up processes on residential road surfaces.

2. Materials and methods

Three road sites located in residential areas were selected for the metal build-up investigations. These were, Gumbeel Court (GC), Lauder Court (LC) and Piccadilly Place (PP). The road sites are located in a mixed use urban catchment in the Gold Coast region, Queensland State, Australia. Fig. S1 in Supplementary information provides detailed information about the study area characteristics.

Pollutant build-up samples were collected for 1, 2, 3, 5, 7, 14 and 21 antecedent dry days for GC and LC and 1, 2, 7, 14 and 21 days for PP. The build-up samples were collected from three plots from each road surface of size 1.5 m × 2.0 m located in the middle strip of one side of the road at approximately 3 m distance apart. The plots were initially cleaned by repeated vacuuming and the build-up samples were collected from the plot surfaces using a vacuum system at the end of each antecedent dry period. The vacuum system was pre-tested for collection and retention efficiency, which was found to be 97%. Herngren (2005) provides a detailed discussion of pollutant build-up sampling on road surfaces.

As a water filtration system was used in the vacuum system, the collected particulate samples were retained in a water column. The samples were transported to the laboratory and stored under prescribed conditions and were analysed for metals commonly found on road surfaces, namely, aluminium (Al), calcium (Ca), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni) and zinc (Zn) using Method 200.8 for Inductively Coupled Plasma-Mass Spectroscopy (US-EPA, 1994) with TraceSELECT (Product No. 54704) as certified reference material.

3. Results and discussion

In the build-up samples collected from the study sites, Cr and Ni were below the instrument detection limits. Hence, these metals were not included in the data analysis and the results presented in Table 1. The investigated metal loads present in the pollutant build-up samples are given in Table S1 in the Supplementary information.

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Table 1
VARIMAX rotated factor loadings and build-up rate equations for the investigated metals.

Metal	Factor analysis		Prediction model development				
	Factor 1	Factor 2	Rate equation	R^2	*a*	*b*	Load equation
Al	**0.947**	0.145	$6.11\ (D)^{-0.99}$	0.93	6.11	−0.99	$6.11\ (D)^{0.01}$
Ca	**0.630**	0.155	$6.35\ (D)^{-0.90}$	0.99	6.35	−0.90	$6.35\ (D)^{0.10}$
Fe	**0.938**	0.036	$10.93\ (D)^{-1.05}$	0.94	10.93	−1.05	$10.93\ (D)^{-0.05}$
Mn	**0.921**	0.078	$0.18\ (D)^{-0.93}$	0.93	0.18	−0.93	$0.18\ (D)^{0.07}$
Pb	**0.610**	0.261	$0.37\ (D)^{-1.24}$	0.97	0.37	−1.24	$0.37\ (D)^{-0.24}$
Cu	0.275	**0.836**	$0.15\ (D)^{-1.24}$	0.96	0.15	−1.24	$0.15\ (D)^{-0.24}$
Zn	0.021	**0.921**	$1.47\ (D)^{-1.25}$	0.99	1.47	−1.25	$1.47\ (D)^{-0.25}$

Notes: Coefficient of determination (R^2), multiplication build-up coefficient (a), power build-up coefficient (b). The load equations were developed based on build-up load per unit area. The values given in bold indicate the metals that were grouped under Factor 1 and Factor 2.

3.1. Outlier detection

The data matrix consisting of the metal build-up loads were subjected to cluster analysis to identify any outliers. Cluster analysis facilitates the identification of objects that are similar. The objects that are located away from a dense cluster can be considered as outliers (Almeida et al., 2007). The centroid clustering method was employed to cluster the data points and the squared Euclidean distance was used to measure the similarity between data points. The resulting dendrogram obtained (Fig. 1) shows that data points, P7-2 and G2-3, are significantly far from the rest suggesting that these are outliers. These outliers are attributed to sampling and/or testing errors. Accordingly, these two data points were not included in further analysis.

3.2. Factor analysis

Metals present in road surface pollutant build-up are contributed by natural and anthropogenic sources. The common natural source is soil, whilst traffic activities are the main anthropogenic source, especially in residential areas where industrial and commercial activities are not significant (Gunawardena et al., 2013; Herngren et al., 2006). In this study, it was hypothesised that the metal build-up processes are influenced by their source of origin, i.e. metals contributed by geogenic (natural) and anthropogenic sources follow different build-up processes. A factor analysis was performed to test this hypothesis.

Principal component extraction method with orthogonal VARIMAX rotation was adopted for the factor analysis. The VARIMAX technique rotates the original factors such that the factors are strongly correlated with a specific set of variables, while weakly correlated with the others. As such, each variable is generally associated with one factor simplifying the interpretation of a complex data set (Abdi, 2003). The factors were extracted based on the initial eigen value criteria ≥1. Table 1 shows that Al, Ca, Fe and Mn are correlated with Factor 1, since they have relatively higher loadings in relation to Factor 1, while Cu and Zn are correlated with Factor 2, because their loadings in relation to Factor 2 are higher. Pb has a factor loading of 0.610 (≈70%) in relation to Factor 1 and 0.261 (≈30%) for Factor 2. Thus, Pb is primarily correlated with Factor 1, but some correlation also exists with Factor 2. Ca is primarily contributed by soil and was included in the analysis as a surrogate for investigating metal build-up related to geogenic sources (Wang et al., 2005). As such, Factor 1 corresponds to build-up attributed to geogenic sources, while Factor 2 relates to the build-up process attributed to anthropogenic sources.

Accordingly, Al, Ca, Fe and Mn, which are common geogenic metals in Australian soil (Singh and Gilkes, 1992), can be expected to follow the build-up process inherent to geogenic sources. In contrast, Cu and Zn, which are contributed primarily by traffic sources (Sansalone et al., 1996), can be expected to follow the build-up process related to anthropogenic sources. Though Pb is regarded as an anthropogenic metal, factor analysis shows that it is primarily associated with geogenic sources (Factor 1). Pb is mainly contributed to the urban environment from the combustion of fossil fuel (Vile et al., 2000). Leaded fuel was phased out in Australia more than a decade ago. Thus, the Pb present on the road surfaces could not have been contributed by fuel combustion. Pb detected in the samples would have accumulated in soil from the past usage of leaded fuel and eventually contributed to the road surface build-up. Therefore, the build-up process of Pb is mainly associated with geogenic sources. However, there is some correlation of Pb with the

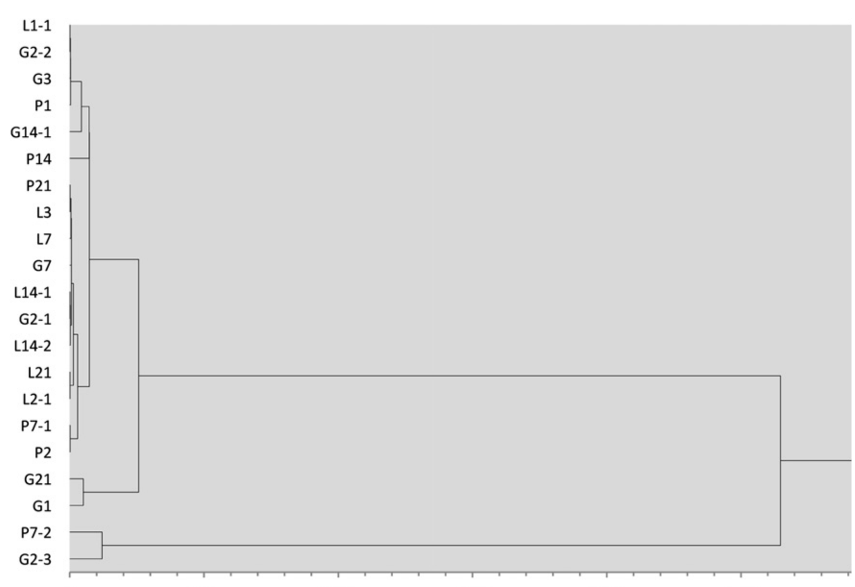

Fig. 1. Dendrogram from hierarchical cluster analysis (Naming convention: 'X' is sampling sites; L – Lauder Court; G – Gumbeel Court; P – Piccadilly Place; 'a' is the antecedent dry days; 'b' is replicate number).