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Taxonomy of factors which influence heavy metal build-up on urban road surfaces

An Liu[a,*], Chandima Gunawardana[b], Janaka Gunawardena[c], Prasanna Egodawatta[d], Godwin A. Ayoko[d], Ashantha Goonetilleke[d]

[a] College of Chemistry and Environmental Engineering, Shenzhen University, Shenzhen 518060, People's Republic of China
[b] Department of Civil Engineering, Faculty of Engineering, University of Peradeniya, 20400 Sri Lanka
[c] Logan City Council, P.O. Box 3226, Logan City DC., Qld 4114, Australia
[d] Science and Engineering Faculty, Queensland University of Technology (QUT), P.O. Box 2434, Brisbane, Qld 4001, Australia

HIGHLIGHTS

- Factors were ranked in terms of their influence on heavy metals (HM) build-up.
- Traffic volume was ranked first while land use was ranked second.
- HM build-up load increases with increasing traffic volume but variability decreases.

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ABSTRACT

Heavy metals build-up on urban road surfaces is a complex process and influenced by a diverse range of factors. Although numerous research studies have been conducted in the area of heavy metals build-up, limited research has been undertaken to rank these factors in terms of their influence on the build-up process. This results in limitations in the identification of the most critical factor/s for accurately estimating heavy metal loads and for designing effective stormwater treatment measures. The research study undertook an in-depth analysis of the factors which influence heavy metals build-up based on data generated from a number of different geographical locations around the world. Traffic volume was found to be the highest ranked factor in terms of influencing heavy metals build-up while land use was ranked the second. Proximity to arterial roads, antecedent dry days and road surface roughness has a relatively lower ranking. Furthermore, the study outcomes advances the conceptual understanding of heavy metals build-up based on the finding that with increasing traffic volume, total heavy metal build-up load increases while the variability decreases. The outcomes from this research study are expected to contribute to more accurate estimation of heavy metals build-up loads leading to more effective stormwater treatment design.

1. Introduction

Heavy metals deposited (build-up) on urban roads, which are primarily attached to road dust, is of particular concern in the urban water environment since stormwater runoff transport these pollutants to receiving waters, degrading water quality [1,2]. Due to their high toxicity [3,4], accurate estimation of heavy metal loads is essential for the design of effective stormwater treatment strategies.

Heavy metal build-up on urban road surfaces is complex and multifaceted, influenced by a range of factors. These can be categorised as; external factors (such as traffic volume [5], land use [6], distance to arterial roads [7,8] and road surface roughness [9]), inherent factors (such as heavy metal species [10] and particle size distribution [2,11]) and climate related factors (antecedent dry days [12]). Past studies have reported on the individual role of these influential factors and their relationship with heavy metals build-up, as evident from the references cited above. However, few research studies have undertaken a comprehensive analysis of these factors and their role in heavy metals build-up. This can be attributed to two primary reasons. Firstly, it is difficult to investigate a wide range of influential factors during an individual research

* Corresponding author.
E-mail address: liuan@szu.edu.cn (A. Liu).

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study due to the specific study focus. For example, Gunawardena et al. [13] investigated the role of traffic volume and land use characteristics on heavy metals build-up while Gunawardana et al. [14] focused on the adsorption of heavy metals to road deposited solids for different particle sizes. Secondly, it is essential to select appropriate data analysis techniques which have the capability to undertake the requisite investigations as these factors differ in terms of their characteristics, order of magnitude and the degree of influence on heavy metals build-up.

Although previous researchers have reported that the factors which were categorised above as external, inherent and climate related factors, play specific roles in relation to heavy metals build-up on urban road surfaces, they do not exert an equal influence. Consequently, there are obvious benefits in ranking them in order to identify the most critical factors for more accurate estimation of heavy metal build-up loads, for improved stormwater quality modelling, for enhanced interpretation of modelling outcomes and for the effective design of stormwater treatment measures.

It is equally important to understand how the heavy metals build-up vary with the highly ranked influential factor/s (critical factor/s) [15], because the accurate accounting of variability is closely related to the accuracy of interpretation of modelling outcomes. This is primarily related to stormwater quality modelling uncertainty. Among sources of model uncertainty, the variability of input parameters can undermine model performance because lumped parameters are commonly used to represent the entire catchment characteristics without adequately considering their specific characteristics [16]. This is particularly important when specific characteristics are highly ranked in terms of their influence on pollutants processes such as pollutant build-up. Therefore, understanding the variability in heavy metals build-up can help in the formulation of a robust modelling strategy to enable the nature of the variability in heavy metal build-up loads associated with highly ranked factors to be taken into consideration. Additionally, it can also assist in the more accurate interpretation of the modelling results by taking into account the variability of input parameters.

In this context, the research study undertook a comprehensive analysis of the range of factors identified in past research, which influence heavy metals build-up (attached to dust on the road surfaces). These factors included traffic volume, land use, distance to arterial roads, road surface roughness, antecedent dry days and particle size distribution. Data in relation to these factors were obtained from a comprehensive study undertaken by the authors as well as three previous research studies. The data was analysed employing a range of data analysis techniques as appropriate, including stepwise linear regression (SLR), principal component analysis (PCA) and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE). The objectives of the study were: (1) to rank the relevant factors in terms of their influence on heavy metals build-up; and (2) to analyse the variability of heavy metal build-up with the top-ranked factor/s. The study outcomes were validated using data obtained from seven previous research studies. The outcomes from this study will contribute to the accurate estimation heavy metals build-up loads and more effective heavy metal targeted treatment design.

2. Methods and materials

2.1. Study sites

The study sites were located at Gold Coast, Australia, where an arterial highway called Pacific Highway traverses the whole region from the north to the south. The Pacific Highway which is 960 km long and links Sydney to Brisbane is a major transport route along the central east coast of Australia. A total of 27 urban road sites were selected close to the highway with different distances to the highway and having differing traffic characteristics, land use and road surface roughness. The data used in the research study were primarily obtained from three previous studies. This included 16 urban road sites selected by Gunawardana [17] while 11 road sites were selected by Gunawardena [18] and Mahbub et al. [19]. The sampling was conducted in two episodes for 16 road sites by [17], where one episode was for shorter antecedent dry days (ADD) and another one was for longer ADD. For the remaining 11 road sites, the ADD was 7 [18,19]. Accordingly, a total of 43 build-up samples (16 road sites $\times$ 2 sampling episodes +11 road sites) were collected. Data related to ADD for each sample are provided in Table S3 in the Supporting information. The study sites are shown in Fig. 1.

2.2. Study approach

The total heavy metal loads and road dust loads per unit area were initially investigated. This was to derive a general understanding of heavy metal build-up loads on the road surfaces. Then, the study was divided into two stages. The first stage was to comprehensively analyse key factors and to rank them in terms of their influence on heavy metals build-up. The second stage was to investigate the variability in heavy metals build-up with the top-ranked factor identified in the first stage. As identified in past research literature, the influential factors investigated were average daily traffic volume (DTV), distance to highway (DHW, representing the distance to the closest arterial road), commercial area fraction (C), industrial area fraction (I), residential area fraction (R), antecedent dry days (ADD) and road surface texture depth (STD, representing road surface roughness). The heavy metal species investigated were Cr, Mn, Ni, Cu, Zn, Cd and Pb since these are metal pollutants commonly present in stormwater runoff from traffic areas [8,11,13,20,21]. Fig. 2 illustrates the study approach adopted, including data analysis techniques used and the type of data used in each stage.

2.2.1. Stage 1

The dataset used in this stage was obtained from three recent publications [17–19] and data generated from an independent research study undertaken by the authors. It is noteworthy that although the data were obtained from the three previous publications, the studies were all undertaken at Gold Coast, Australia and sample collection, transport and laboratory testing were carried out using identical methods. This ensured the compatibility of the data sets used.

The dust samples from each road site were collected using a vacuum system for subsequent testing for the heavy metals attached to the road dust. The detailed information regarding road dust build-up sample collection, transport and laboratory testing is provided in the Supporting information. A total of 43 data points (mean values of duplicate samples) including total heavy metal loads attached to road dust, loads associated with four particle size ranges (<75 μm, 75–150 μm, 150–300 μm and >300 μm) and seven influential factors were obtained. Table S1 in the Supporting information gives the data availability which formed the basis for the study for this stage and explains how the data were derived (from previous publications or measured by the authors). Table S2 in the Supporting information gives the collection methods used for obtaining the influential factors. The values for the influential factors (Table S3) and heavy metal loads (Table S4–S9) are provided in the Supporting information.

Stepwise linear regression (SLR) was initially undertaken to determine the important factors according to their influence on heavy metals build-up and subsequently principal component analysis (PCA) was undertaken to validate the results obtained from SLR. SLR is a systematic method for adding and removing