APPLICATION OF MULTIVARIATE DATA ANALYSIS TECHNIQUES IN UNDERSTANDING NUTRIENT BUILD-UP PROCESS ON URBAN ROAD SURFACES

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ABSTRACT

This paper discusses the outcomes of a research project on nutrients build-up on urban road surfaces. Nutrient build-up was investigated on road sites belonging to residential, industrial and commercial land use. Collected build-up samples were separated into five particle size ranges and were tested for total nitrogen (TN), total phosphorus (TP) and sub species of nutrients, namely, NO_2^-, NO_3^-, TKN and PO_4^{3-}. Multivariate analytical techniques were used to analyse the data and to develop detailed understanding on build-up. Data analysis revealed that the solids loads on urban road surfaces are highly influenced by factors such as land use, antecedent dry period and traffic volume. However, the nutrient build-up process was found to be independent of the type of land use. It was solely dependent on the particle size of solids build-up. Most of the nutrients were associated with the particle size range <150 μm. Therefore, the removal of particles below 150 μm from road surfaces is of importance for the removal of nitrogen and phosphorus from road surface solids build-up. It is also important to consider the difference in the composition of nitrogen and phosphorus build-up in the context of designing effective stormwater quality mitigation strategies.

Keywords: Nutrient pollution, Pollutant build-up, Stormwater pollution, Multivariate data analysis

1. INTRODUCTION

Road surfaces have been recognised as a major source of pollutants to receiving urban water bodies [3]. It is important to have a clear understanding of pollutants and pollutant processes in order to achieve efficient and cost effective pollutant removal strategies.

Even though the types of pollutants which significantly influence water quality is known, the effectiveness of mitigation strategies is hampered by the lack of understanding relating to pollutant processes. This is mainly due to the lack of knowledge on multivariate data analysis techniques which are capable of identification of patterns of data variability, relationships among variables and relationships between variables and objects and their applicability in water quality research studies where the analysis of number of variables together and there correlations are needed to a great extent to obtain a detail knowledge which could lead to implementation of effective mitigation strategies.

Pollutant build-up on road surfaces has been identified as one of the key processes responsible for stormwater pollution [2]. Furthermore, nutrients have been identified as a primary stormwater pollutant and in particular nitrogen (N) and phosphorous (P) [3]. N and P are most commonly derived from lawn fertilizer, vehicular traffic, atmospheric deposition, organic matter, detergents and animal waste [3]. Excess nutrients are considered as pollutants when their concentrations are sufficient to allow excessive growth of aquatic plants such as algae in receiving water bodies.

Past research studies which investigated nutrients pollution in stormwater runoff have primarily focussed on the quantification of nutrient loads from different land uses. However, an appreciable knowledge gap exists in relation to nutrients build-up process on urban surfaces. This paper presents the outcomes of an investigation into nutrients build-up processes on urban road surfaces for three different land uses; residential, industrial and commercial conducted using multivariate data analysis techniques.

2. MATERIALS AND METHODS

The research sites were selected from Gold Coast, Queensland State, Australia. Three road surfaces were selected from typical residential, industrial and commercial land uses. Build-up samples on these sites were collected using a domestic vacuum cleaner (See Figure 1) from a 3m^2 plot area and represented 8, 9 and 11 antecedent dry days.

Firstly, each build-up sample was analysed for the particle size distribution using a Malvern Mastersizer S particle size analyser. Particle size of solids is an important parameter to characterise their mobility during wash-off and their association with other pollutants [4]. Secondly, based on the results of the particle size distribution analysis, the build-up samples were separated into five particle size ranges by wet sieving and the potential soluble fraction was determined by filtering through a 1 µm glass fibre filter paper.

As such, each build-up sample was separated into five sub samples; >300 µm, 150-300 µm, 75-150 µm, 1-75 µm and <1 µm. The original build-up sample and wet sieved build-up samples were analysed for total solids (TS), total organic carbon (TOC), phosphate (PO_4^{3-}), total phosphorus (TP), nitrite nitrogen (NO_2^-), nitrate nitrogen (NO_3^-), kjeldahl nitrogen (TKN) and total nitrogen (TN) according to the standard methods specified in [1].

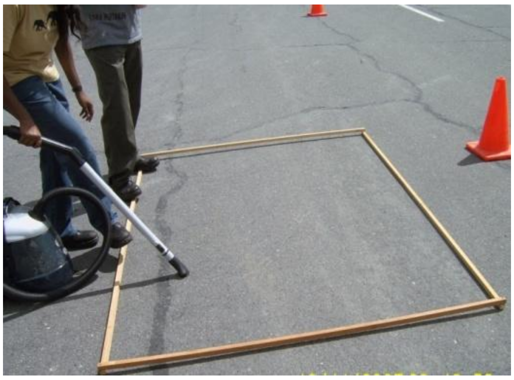

Figure 1 Collection of build-up

Data obtained from laboratory investigations were analysed using both univariate and multivariate data analysis techniques. Univariate data analysis was applied to understand the primary nature of the variability of physico chemical parameters. Most importantly, multivariate data analysis techniques were used to identify the linkages between nutrient parameters, TS, TOC, particle size ranges and land use. In this regard, multicriteria decision making methods (MCDM) namely PROMETHEE and GAIA [6] were selected for the data analysis.

3. RESULTS AND DISCUSSION

The data analysis was conducted in three stages. As most of the primary stormwater pollutants such as nutrients and organic carbon are attached to solids, an understanding of the primary characteristics of solids build-up was considered important prior to developing knowledge on the nutrient build-up process. Secondly, as organic matter has been identified as a major source of nutrients, test results obtained for total organic carbon were analysed [4]. Finally, knowledge on the nutrient build-up process was developed based on the understanding generated on solids and organic carbon build-up. In turn, the knowledge on nutrient build-up process was extended to understand the physico-chemical parameters that influence this process.

3.1. Investigation of primary characteristics of total solids (TS) build-up

As shown in Table 1, the TS load is significantly different between the particle size ranges. For all the road surfaces, the particle size range 75 -150 µm contains the highest percentage of total solids load. Overall, particle size ranges less than 150 µm contains more than 70% of the total solids load for all road surfaces. This suggests that particles below 150 µm are of specific concern in urban areas. As evident in Table 1, the particle size distribution of solids for each road surface is different to each other. This is attributed to factors such as the nature of anthropogenic activities and traffic characteristics and antecedent dry days [4].

Table 1: Amount of TS load in each size range as a percentage of total solids load

Road surface	Solids load as a percentage (%)					TS load (g/m^2)	Antecedent dry days
	<1 µm	1-75 µm	75-150 µm	150-300 µm	>300 µm		
Res	29.33	14.18	42.50	11.82	2.17	2.25	8
Ind	33.01	8.27	48.62	6.60	3.50	3.44	9
Com	26.41	7.36	38.10	19.33	8.81	4.06	11

3.2. Investigation of total organic carbon (TOC) in solids build-up

Several researchers have identified organic matter as a major source of nutrients to solids build-up [5]. Despite the contribution of nutrients from the decomposition of organic matter such as plant debris, Flanagan and Forster (1989) have suggested that the disproportionately larger surface area of organic matter can hold nutrients, thus causing an increase in the nutrients load. Consequently, the understanding of TOC build-up was important to obtain detailed understanding on the nutrient build-up process. The organic carbon load for each particle size range per unit weight of total solids is given in Table 2.

Table 2: TOC in the solids build-up for each road surface

Road surface	Particle size range				
	<1 µm (mg/g)	1-75 µm (mg/g)	75-150 µm (mg/g)	150-300 µm (mg/g)	>300 µm (mg/g)
Residential	16.32	11.43	23.50	5.63	4.25
Industrial	3.08	2.55	5.03	0.78	1.14
Commercial	4.93	2.31	7.39	2.47	3.47

As seen in Table 2, the particle size range 75 -150 µm shows the highest amount of TOC and the overall size range below 150 µm contains the predominant amount of TOC for all road surfaces irrespective of the type of land use.

3.3 Investigation of nutrients build-up process

PROMETHEE and GAIA analysis were conducted using the results obtained for all the wet sieved build-up samples for all the road surfaces. Table 3 shows outcomes of the PROMETHEE analysis. Figure 2 shows the principal component biplot obtained from GAIA analysis. The total data variance of 72.69 % explained by the GAIA biplot indicates that the majority of the information is included in the analysis.

As evident in Table 3, the finer fraction of solids build-up is the most polluted. Furthermore, all the particle size ranges ranked first are below 150 µm for all the road surfaces. These are the most polluted objects. On the other hand six out of eight least polluted objects are greater than 150 µm. Furthermore, Figure 2 shows that all the particle size ranges with positive scores on PC1 are below 150 µm. On the other hand, the variables NO2-, TKN, TN, PO43- and TP show positive loadings on PC1. This confirmed the higher affinity of nutrients to the particle size range below 150 µm irrespective of the land use. Nutrients in these size ranges can be easily washed-off with the stormwater runoff and impose a significant threat to receiving waters. This is of serious concern as the investigation of solids build-up showed that particle size range smaller than 150 µm contains the majority of the TS load. Therefore, the stormwater quality mitigation strategies designed to remove nutrients from road surfaces should be capable of trapping the particle size range below 150 µm.

Table 3: PROMETHEE II ranking

Sample	Net Φ	Ranking order
75-150C	0.42	1
75-150I	0.19	2
<1C	0.10	3
1-75I	0.08	4
75-150R	0.06	5
<1I	0.04	6
<1R	0.05	7
150-300C	-0.01	8
1-75C	-0.04	9
>300C	-0.05	10
1-75R	-0.10	11
>300I	-0.17	12
150-300I	-0.18	13
150-300R	-0.19	14
>300R	-0.21	15

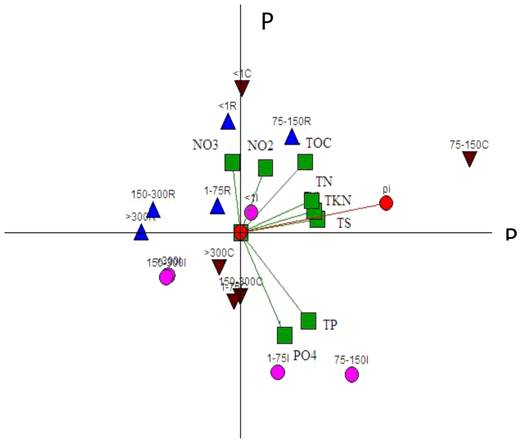

Figure 2: GAIA analysis for all the road surfaces (Δ = 72.69%)

Note: ●, ▲, ▼ - different particle size ranges of solids, R-residential, I-industrial, C-commercial, TS-total solids, TOC-total organic carbon, NO_2-nitrite-nitrogen, NO_3-nitrate-nitrogen, TKN-total kjeldahl nitrogen, TN-total nitrogen, PO_4– phosphates, TP-total phosphorus

Table 3 further indicates that the particle size range 75-150 µm for all road surfaces ranks highest, which highlights the highly polluted nature of this particle size range. On the other hand, the GAIA biplot (Figure 2) shows particle size range 75-150 µm for all road surfaces with high PC1 scores. Furthermore, TN and TP vectors show high positive loadings on PC1. This suggests that particle size range 75-150 µm is the most significant for the nutrient build-up process. Notably, the decision axis π vector points towards the particle size range 75-150 µm confirming the significance of this particle size range in the nutrient build-up process.

The findings from the PROMETHEE and GAIA analysis were further evaluated using the raw data. The amount of nutrients available per unit weight of solids in each particles size range was determined for each road surface. Figure 3a, 3b, 3c provides the graphical representation of nutrients loads available in each particle size range for each road surface.

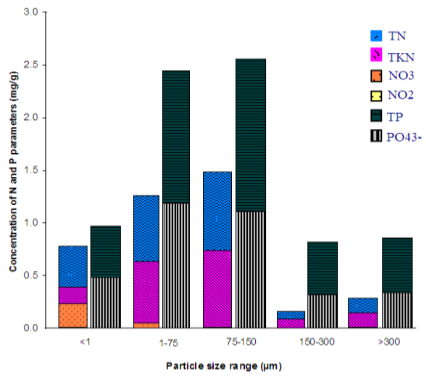

Figure 3a: Residential road

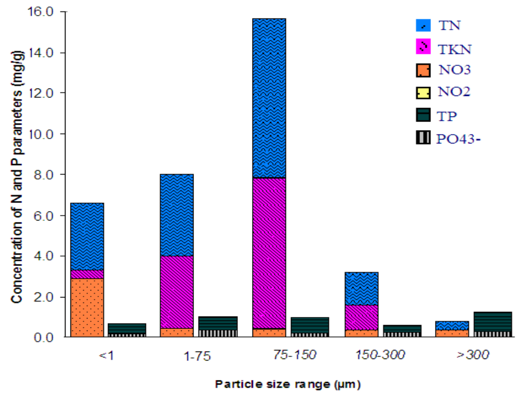

Figure 3b: Industrial road

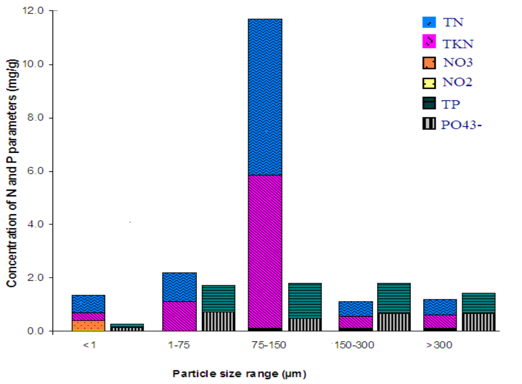

Figure 3c: Commercial road

According to Figure 3a, 3b, 3c, the highest TN load is in the particle size range 75 -150 µm for all the road surfaces. The particle size range 75 -150 µm shows the highest TP load for both industrial and commercial road surfaces. The residential road surface shows the second highest amount of TP for the same particle size range. Therefore, it can be argued that the particle size range 75-150 µm exerts the strongest influence on the nutrient build-up process irrespective of the type of land use.

The nitrogen build-up on road surfaces is primarily in organic form where TOC exerts a strong influence. According to Figure 2, TN is strongly correlated to TOC and TKN which is the organic form of nitrogen. As evident in Figure 3a, 3b, 3c, more than half of the TN amount is attributed to TKN for most of the particle size ranges. This indicates that TKN is the most dominant nitrogen species in the solids build-up on road surfaces. The importance of TOC to nitrogen build-up process is further confirmed by the highest amount of both TOC and TN in the particle size range 75 -150 µm as noted in the investigation of TOC in solids build-up (Table 2) and Figure 3a, 3b, 3c.

Unlike nitrogen build-up, phosphorus build-up is mostly in inorganic form. As shown in Figure 2, TP is strongly correlated to PO_4^{3-}. As evident in Figure 3a, 3b, 3c, more than half of the TP content is attributed to PO_4^{3-} in a majority of the different particle size ranges for all the road surfaces. This suggests that PO_4^{3-} which is the inorganic form of phosphorus is the most dominant form of phosphorus.

It is important to note that the nutrients build-up process is solely dependent on the particle size of solids rather than the type of land use. All objects in the GAIA biplot (Figure 2) are discriminated based on the particle size range of the solids and not on the type of land use. This strengthens the importance of the design of the stormwater quality mitigation strategies based on the understanding on underlying process of nutrient build-up rather than the nutrient loads which could vary with the type of land use. Consequently, it could lead to a more robust approach for the design of stromwater quality mitigation strategies targeting the removal of nutrients from stormwater runoff.

4. CONCLUSIONS

Targeting of the finer fraction (particles below 150 µm) of solids should be the fundamental to stormwater quality mitigation strategies for the removal of nutrients from road surfaces irrespective of the type of land use. Nutrient build-up process is solely dependent on the particle size of the solids build-up and it is not dependent on the type of land use. Furthermore, in the context of designing stormwater quality mitigation strategies, it is also imperative to note that the difference in the nitrogen and phosphorus build-up processes in terms of their composition. The nitrogen build-up on road surfaces is primarily in organic form, whereas phosphorus build-up on road surfaces is primarily in inorganic form. Therefore, the design of stormwater quality mitigation strategies should take into consideration the differences between the composition of nitrogen and phosphorus build-up to be more effective instead of the design of a common set of approaches. Additionally, the application of multivariate data analysis techniques can be recommended as viable in deriving detail knowledge in water quality research studies.

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