ANALYSIS OF NUTRIENTS WASH-OFF PROCESSES ON URBAN ROAD SURFACES

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ABSTRACT

This paper discusses the outcomes of a research project, which focused on investigating nutrients wash-off processes on typical urban impervious surfaces in different land uses. Rainfall events typical to the region were simulated over selected road surfaces in residential, industrial and commercial areas using a specially designed rainfall simulator. The wash-off samples collected were tested for a range of parameters including total suspended solids (TSS), total dissolved solids (TDS), total organic carbon (TOC), dissolved organic carbon (DOC), phosphate (PO_4^{3-}), total phosphorus (TP), nitrite nitrogen (NO_2^-), nitrate nitrogen (NO_3^-), total kjeldahl nitrogen (TKN) and total nitrogen (TN). Tests were done after separating each sample into five different particle size ranges. Data analysis revealed that nitrogen is primarily washed-off in dissolved form whereas phosphorus washed-off is in particulate form. There was no variation in the wash-off process due to land use. However, a significant variation in wash-off process was observed for different particle size ranges. It was noted that the particle size range <150 µm is associated with most of the nutrients. Therefore, the design of treatment devices targeting sediments below 150 µm is important for the removal of nutrients from road surface runoff in all the land uses. TKN was the most dominant form of nitrogen species in wash-off. Particulate TP wash-off process could be closely replicated by TSS in both fine and coarse particle size ranges.

***Key words*:** nutrients, pollutant wash-off, urban, land uses

1. INTRODUCTION

Urban stormwater runoff has been recognised as a major source of pollutants to receiving water bodies [6, 2]. In this context, road surfaces have been recognised as a major pathway of pollutants to receiving urban water bodies [2]. It is important to have a clear understanding of pollutant processes in order to achieve efficient pollutant removal strategies. In this regard, pollutant wash-off is a key process responsible for stormwater pollution [6]. Furthermore, nutrients are a primary stormwater pollutant [2, 4]. This paper presents the outcomes of an investigation on nutrients wash-off process on urban road surfaces for three different land uses; residential, industrial and commercial.

2. METHODOLOGY

The research sites were selected from Gold Coast, Queensland State, Australia. Three road surfaces were selected from typical residential, industrial and commercial land uses.

Pollutant wash-off studies are commonly based on either the use of natural rainfall wash-off data or the use of artificial rainfall wash-off data [5]. Due to the high variability of rainfall characteristics, the use of wash-off data based on natural rainfall constrains the transferability of research outcomes [7]. Furthermore, the random nature of occurrence of natural rainfall events makes the investigations difficult. Hence, the use of artificial rainfall has become a reliable investigation method in water quality research as it provides better control of physical factors which limit the transferability of research outcomes [7]. Consequently, rainfall simulation was employed for wash-off data collection in the investigations undertaken.

A specially designed rainfall simulator was used to simulate rainfall events typical to the study region. Wash-off samples were collected for six rainfall intensities; 20 mm/hr, 40 mm/hr, 65 mm/hr, 86 mm/hr, 115 mm/hr and 135 mm/hr for different durations in five minute time steps for each road surface. Figure 1 shows the collection of wash-off samples in the field.

Figure 4 Collection of wash-off sample in the field

The particle size of sediments is an important parameter which should be considered for developing an understanding in relation to nutrient wash-off process [10]. Therefore, after transporting the collected wash-off samples to the laborotary they were separated into five particle size ranges. Firstly, the samples were wet sieved using sieve sizes 300 µm, 150 µm and 75 µm. Secondly, in order to obtain the dissolved fraction, the particles passing through the 75 µm sieve was filtered through a 1 µm glass fiber filter paper and the filtrate was obtained. Consequently, the analysis for physico-chemical parameters was conducted on five particle size classes of wash-off samples; >300 µm, 150-300 µm, 75-150 µm, 1-75 µm and <1 µm. The samples were analysed for particle size distribution, 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). The samples were tested based on the standard methods specified in [1,8,9].

Data analysis was conducted using both univariate and multivariate data analysis techniques. Univariate data analysis methods such as mean and standard deviation were applied to understand the primary nature of the variability of physico-chemical parameters. Due to the large number of variables, multivariate data analysis techniques were employed to identify the linkage between nutrient parameters and to define nutrient wash-off process. In this regard, principal component analysis (PCA) which is one of the most widely used pattern recognition techniques was employed [7].

3. RESULTS

3.1 Univariate data analysis

Table 1 shows the mean and standard deviation for the parameters obtained for each particle size range of wash-off samples.

According to Table 1, particle size range <1 µm, which is the dissolved fraction of wash-off shows significantly higher solid concentrations for all the land uses. As this particle size range represents TDS which is an indicator of dissolved pollutants in wash-off, it can be said that this particle size fraction could have a significant impact on water quality. This is further supported by the fact that highest concentration of organic carbon is in this range as evident in Table 1.

The particle size ranges, 1-75 µm and 75-150 µm show relatively higher TSS concentrations for all the land uses. This is supported by the findings of [7], who found a relatively large concentration of TSS in particles below 150 µm in the wash-off irrespective of the type of land use he investigated. Furthermore, these two particle size ranges exhibit relatively higher TOC concentration for all the land uses. This reflects that the importance of the investigation of particle size less than 150 µm in stormwater quality studies.

According to Table 1, particle size range below 1 µm shows the highest concentration for NO2-, NO3- and TKN at all the land uses. Consequently, this particle size contains more than 60% of TN concentration irrespective of the land use. Therefore, it can be said that nitrogen in stormwater runoff is mostly in dissolved form. Furthermore, as shown in Table 1, more than 66 % of the particulate total nitrogen concentration is associated with the particle size range below 150 µm. This strengthens the importance of fine particulates in the nitrogen wash-off process irrespective of the land use. Therefore, an in-depth understanding of the nitrogen wash-off process in the particles below 150 µm is crucial important in order to provide effective treatment facilities to remove nitrogen species from the stormwater runoff.

As evident from Table 1, the particle size range 1-75 µm shows the highest concentration of PO43-. More than 50% of particulate PO43- is attached to this particle size range at all the land uses. Furthermore, as evident in Table 1, TP in the stormwater runoff is strongly associated with the particulate fractions of wash-off, thus confirming the observations of past researchers [10]. Particle size range 1-75 µm in residential land use and the 75-150 µm in the industrial and commercial land uses show the highest concentration of TP. This further confirms the importance of the fine particles in the context of stormwater quality.

However, as shown in Table 1, the particles greater than 150 µm contain higher amount of particulate phosphorus. Consequently, particles greater than 150 µm should also be taken into consideration especially when targeting the removal of phosphorous in the stormwater runoff.

3.2 Principal component analysis (PCA)

Section 3.1 underlined the need for in-depth investigation of different particle size ranges of sediments in nutrient wash-off studies. Consequently, PCA was conducted on the wash-off data to assess the relationships of nutrient parameters with TS, TOC and EC and thereby to identify primary variables which govern the nutrient wash-off processes. In this context, three data matrices were subjected to PCA analysis separately. The selected data matrices were the concentrations of physico-chemical parameters obtained for the dissolved fraction (below 1 µm), particle size ranges below 150 µm (1-75 µm and 75-150 µm) and particle size ranges above 150 µm (150-300 µm and >300 µm). As seen in Table 1, even though the three land uses exhibit different pollutant concentrations, all the land uses showed similar patterns in relation to distributing nutrients to different particle size ranges. Therefore, it can be hypothesised that the nutrient wash-off process is independent of the type of land use. Hence, the concentrations of physico-chemical parameters in all the land uses were included in the data matrix of for the specific particle size range.

Due to the large number of objects a specific convention was adopted for labeling. The letters R, I and C corresponded to the residential, industrial and commercial land uses respectively. The first number indicated the rainfall intensity such that 2, 4, 6, 8, 1, 3 represented 20mm/hr, 40 mm/hr, 65mm/hr, 86mm/hr, 115mm/hr and 135 mm/hr respectively. The second number the duration of each intensity such that 1 represented 0-5 min duration, 2 represented 0-10 min duration and so on. The roman numbers i, ii, iii, iv and v indicated the particle size ranges >300 µm, 150-300 µm, 75-150 µm, 1-75 µm and <1 µm respectively. Figures 2 to 4 show the principal component biplots obtained from the analysis of wash-off data for the, >150 µm (i, ii), 1-150 µm (iii, iv) and the dissolved fraction (v).

Particle size range <1 µm (Dissolved fraction)

Following conclusions can be drawn from Figure 2:

- TN is strongly correlated to TKN. This suggests that TKN is the dominant form of nitrogen species in the dissolved fraction of wash-off. This can be further confirmed by Table 2 which shows more than 85 % of TN is attributed to TKN at all the land uses.
- TN is correlated to NO_3^-. This would mean that NO_3^- would also make a considerable contribution to dissolved TN.
- TN is correlated to DOC, but not correlated to TDS. This would mean that the wash-off process for dissolved nitrogen closely follows the wash-off process for DOC. This also confirms what is stated in the first dot point, where TKN was found to be closely correlated to TN. TKN is the organic form of nitrogen.
- There is strong correlation between PO_4^{3-} and TP. This suggests that PO_4^{3-} is the most dominant form of phosphorus in the dissolved fraction of wash-off.
- TP is not correlated to both DOC and TDS. This indicates that only a limited amount of phosphorous is washed-off in the dissolved phase.

Figure 2

Particle size range 1-150 µm (below 150 µm)

As shown in Table 1, NO_2^- was not detected in most of the wash-off samples in this particle size range. This can be attributed to the rapid oxidation of nitrites to nitrates [3]. Therefore, it was not included in the analysis. Following conclusions can be derived from Figure 3:

- TN is strongly correlated to TKN and has no correlation with NO_2^- and NO_3^-. This would mean that TKN is the dominant form of nitrogen species in the fine particles similar to the dissolved fraction of wash-off.
- TN is strongly correlated to TOC and only weakly correlated to TSS. This suggests that wash-off process for TN closely follows the TOC wash-off process in this particle size range. This also confirms what is stated in the first dot point, where TKN was found to be closely correlated to TN. TKN is the organic form of nitrogen.
- The strong correlation between PO_4^{3-} and TP suggests that PO_4^{3-} is the dominant form of phosphorus similar to the dissolved fraction.
- TP is strongly correlated to TSS. This would mean that phosphorus in this particle size range is mostly attached to suspended solids. Consequently, TP wash-off process could be closely replicated by the TSS wash-off process in this particle size range.

Figure 3

Particle size range >150µm

Similar to the particle size ranges below 150 µm, NO_2^- was also not detected in most of the wash-off samples for particles above 150 µm. Therefore, it was not included in the analysis. Following conclusions can be derived from Figure 4:

- TKN is strongly correlated to TN. This suggests that TKN is the most dominant nitrogen species in this particle size range similar to the fine particle size ranges.
- TN is correlated to TOC and not correlated to TSS. This would mean that the TN wash-off process closely follows the TOC wash-off process in this particle size range similar to the fine particle size ranges. This also confirms what is stated in the first dot point, where TKN was found to be closely correlated to TN. TKN is the organic form of nitrogen.
- TP is weakly correlated with PO_4^{3-} in this particle size range. Therefore, unlike the fine particle size ranges, PO_4^{3-} is not be the dominant phosphorus species in this particle size range. Hence, it can be hypothesised that coarse particles would contain other phosphorus forms such as organic phosphorus. This is further confirmed by the correlation between TP and TOC as evident in Figure 4.
- TP is correlated to TSS. This suggests that an appreciable amount of phosphorus is associated with TSS.

Figure 4

4. CONCLUSION

The primary outcomes from the analysis of nutrient wash-off process on urban road surfaces for different land uses are:

1. Nutrient wash-off process varies with the particle size ranges of sediments but it is not a function of the type of land use.
2. TKN is the most dominant form of nitrogen species in the wash-off irrespective of the particle size range of sediments and type of land use.
3. Nitrogen and phosphorus wash-off processes are significantly different to each other whereas nitrogen is primarily washed-off in dissolved form and phosphorus is in particulate form.
4. Particle size ranges below 150 μm contains higher amount of particulate nutrients in stormwater runoff irrespective of the land use. Consequently, the design of best management practices targeting sediments less than 150 μm would be important for the removal of nutrients from stormwater runoff from road surfaces.
5. However, the particles greater than 150 μm contain higher amount of particulate phosphorus. Consequently, particles greater than 150 μm should also be taken into consideration especially when targeting the removal of phosphorous in the stormwater runoff.
6. Particulate TP wash-off process is closely correlated by the TSS in both fine and coarse particle size ranges.

5. REFERENCES

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Table 1 Concentration of physico-chemical parameters

Particle size range	Mean/Std	TS	TOC	NO_2^-	NO_3^-	TKN	TN	PO_4^{3-}	TP	pH	EC
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)		(µS/cm)
Residential											
<1	**Mean**	**121.57**	**9.40**	**0.003**	**0.110**	**1.862**	**1.975**	**0.012**	**0.017**		
	Std	36.85	2.78	0.002	0.058	0.761	0.761	0.009	0.011		
1-75	**Mean**	**9.98**	**1.57**	**nd**	**0.051**	**0.158**	**0.210**	**0.038**	**0.126**		
	Std	4.07	1.67	-	0.018	0.169	0.168	0.036	0.080		
75-150	**Mean**	**11.72**	**0.95**	**0.001**	**0.038**	**0.133**	**0.172**	**0.016**	**0.092**	**6.67**	**35.84**
	Std	7.51	0.20	0.001	0.015	0.208	0.209	0.013	0.055	0.27	5.60
150-300	**Mean**	**7.76**	**0.84**	**0.001**	**0.030**	**0.008**	**0.030**	**0.009**	**0.109**		
	Std	3.61	0.18	0.001	0.015	0.020	0.015	0.014	0.069		
>300	**Mean**	**6.73**	**0.96**	**nd**	**0.029**	**0.000**	**0.030**	**0.014**	**0.116**		
	Std	2.92	0.26	-	0.018	0.000	0.017	0.025	0.071		
Industrial											
<1	**Mean**	**311.08**	**8.03**	**0.002**	**0.149**	**1.164**	**1.315**	**0.479**	**0.590**		
	Std	86.04	3.44	0.002	0.054	0.377	0.417	0.131	0.161		
1-75	**Mean**	**253.76**	**2.20**	**nd**	**0.030**	**0.259**	**0.294**	**0.981**	**1.163**		

	Std	100.54	1.99	-	0.015	0.234	0.241	0.492	0.486		
75-150	**Mean**	**118.65**	**1.28**	**nd**	**0.013**	**0.146**	**0.159**	**0.364**	**1.549**	**7.21**	**49.09**
	Std	61.72	0.81	-	0.016	0.135	0.140	0.296	0.509	0.51	34.46
150-300	**Mean**	**49.98**	**0.70**	**nd**	**0.010**	**0.058**	**0.068**	**0.138**	**1.464**		
	Std	19.35	0.22	-	0.012	0.072	0.074	0.111	0.470		
>300	**Mean**	**30.85**	**0.83**	**nd**	**0.016**	**0.063**	**0.078**	**0.167**	**1.465**		
	Std	11.62	0.26	-	0.022	0.119	0.134	0.202	0.472		
Commercial											
<1	**Mean**	**739.58**	**23.24**	**0.036**	**0.241**	**4.362**	**4.639**	**0.356**	**0.429**		
	Std	233.53	12.55	0.021	0.094	2.437	2.536	0.242	0.298		
1-75	**Mean**	**117.71**	**2.10**	**nd**	**0.070**	**1.058**	**1.128**	**0.629**	**0.851**		
	Std	56.12	0.75	-	0.015	0.685	0.691	0.235	0.327	**7.46**	**466.61**
75-150	**Mean**	**54.18**	**0.85**	**nd**	**0.114**	**0.808**	**0.922**	**0.017**	**1.086**	0.20	50.34
	Std	24.89	0.20	-	0.040	1.799	1.806	0.035	0.643		
150-300	**Mean**	**22.44**	**0.72**	**nd**	**0.123**	**0.163**	**0.286**	**0.005**	**1.055**		
	Std	6.62	0.14	-	0.018	0.201	0.209	0.016	0.634		
>300	**Mean**	**20.06**	**1.16**	**nd**	**0.107**	**0.653**	**0.760**	**0.006**	**1.081**		
	Std	7.87	0.56	-	0.014	0.885	0.894	0.018	0.649		

TS=TSS and TOC=TOC for particles size ranges 1-75 µm, 75-150 µm, 150-300 µm, >300 µm; TS=TDS and TOC=DOC in particle size range below 1 µm

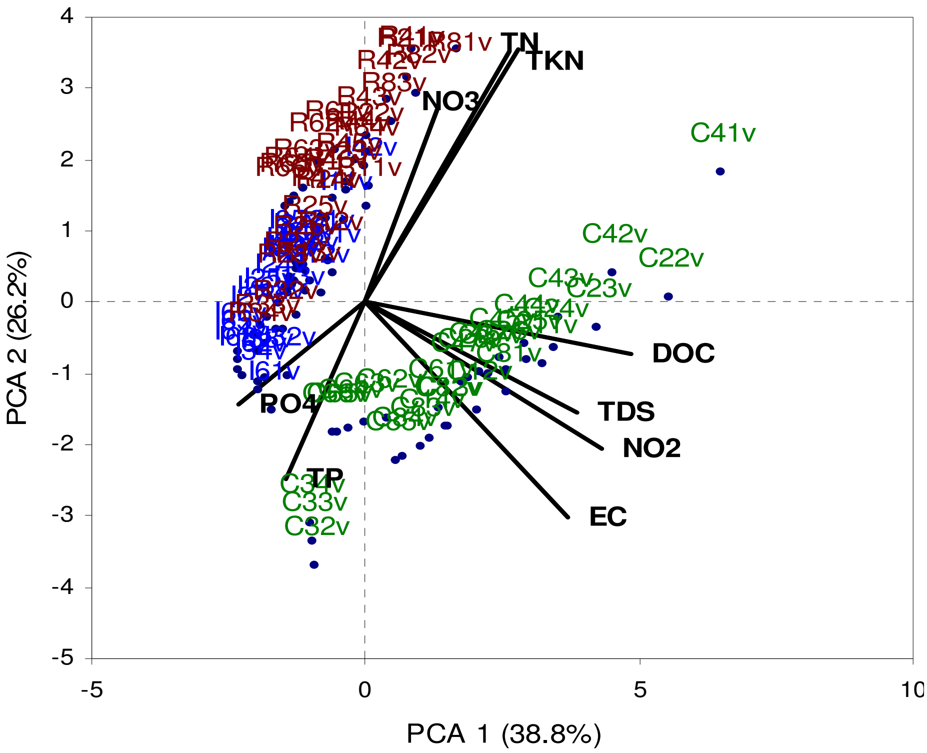

Figure 5 PCA analysis of the dissolved fraction of wash-off at all the land uses (NO3=NO_3^-; NO2=NO_2^- ; PO4= PO_4^{3-})

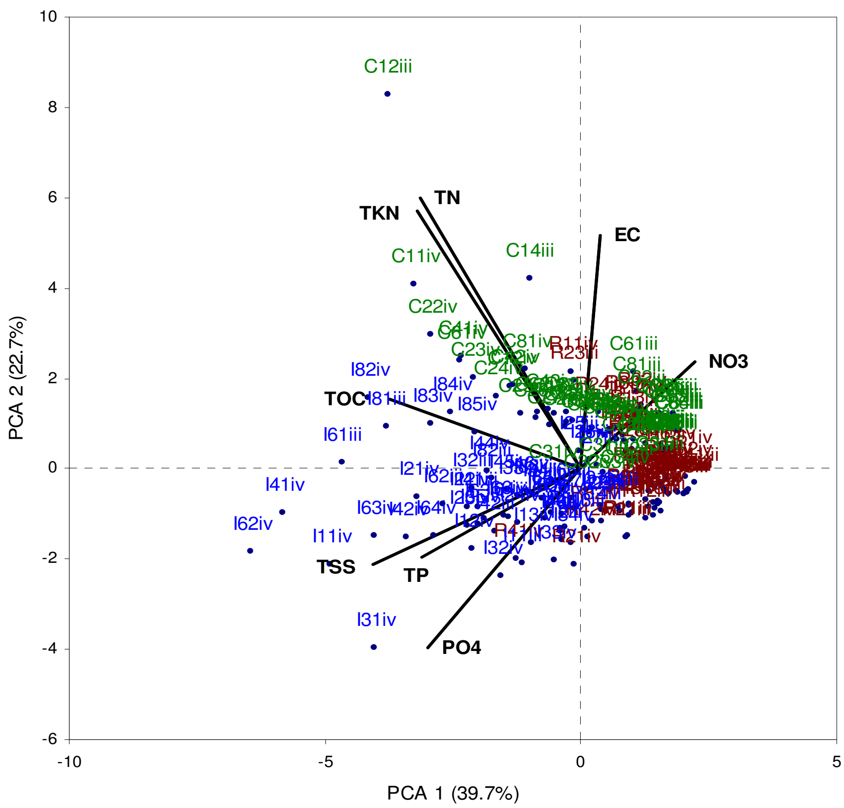

Figure 6 PCA analysis of the particle size range below150 µm in the wash-off at all the land uses

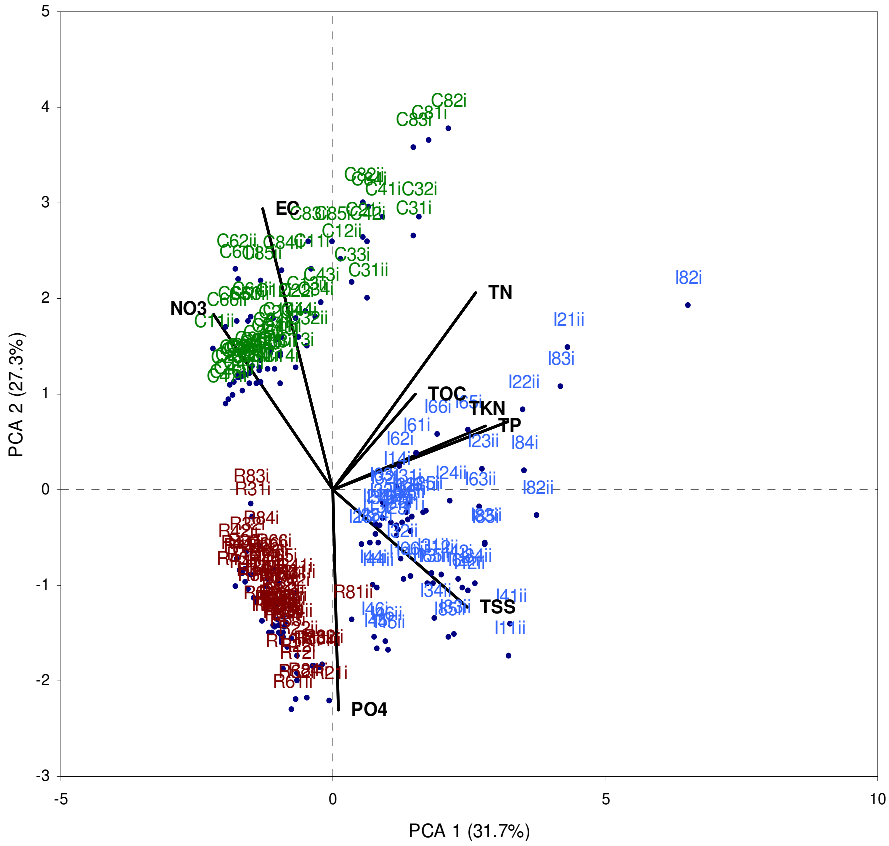

Figure 7 PCA analysis of the particle size range >150 µm in the wash- off at all the land uses