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Sectional analysis of the pollutant wash-off process based on runoff hydrograph

Noraliani Alias[1], An Liu[2*], Prasanna Egodawatta[3], Ashantha Goonetilleke[3]

[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia

[2]Research Centre of Environmental Engineering and Management, Graduate School at Shenzhen, Tsinghua University, 518055 Shenzhen, People's Republic of China
[3]Science and Engineering Faculty, Queensland University of Technology, P.O. Box 2434, Brisbane, Qld 4001, Australia

* Corresponding author:

E-mail: liu.an@sz.tsinghua.edu.cn; Tel: 86-755-26036065; Fax: 86-755-26036709

Abstract: The validity of using rainfall characteristics as lumped parameters for investigating the pollutant wash-off process such as first flush occurrence is questionable. This research study introduces an innovative concept of using sector parameters to investigate the relationship between the pollutant wash-off process and different sectors of the runoff hydrograph and rainfall hyetograph. The research outcomes indicated that rainfall depth and rainfall intensity are two key rainfall characteristics which influence the wash-off process compared to the antecedent dry period. Additionally, the rainfall pattern also plays a critical role in the wash-off process and is independent of the catchment characteristics. The knowledge created through this research study provides the ability to select appropriate rainfall events for stormwater quality treatment design based on the required treatment outcomes such as the need to target different sectors of the runoff hydrograph or pollutant species. The study outcomes can also contribute to enhancing stormwater quality modelling and prediction in view of the fact that conventional approaches to stormwater quality estimation is primarily based on rainfall intensity rather than considering other rainfall parameters or solely based on stochastic approaches irrespective of the characteristics of the rainfall event.

Keywords: Rainfall characteristics; Pollutant wash-off; First flush; Stormwater quality; Stormwater pollutant processes

1 Introduction

Research literature has noted the significant influence exerted by rainfall characteristics on pollutant wash-off and the essential need for an in-depth understanding of the relationship between pollutant wash-off processes and rainfall characteristics for effective stormwater treatment design (Liu et al., 2012a; Carroll et al., 2013). Past research studies commonly consider rainfall characteristics as lumped parameters for investigating the role of rainfall characteristics on pollutant wash-off (for example Egodawatta et al., 2007; Kim et al., 2007; Liu et al., 2012a). However, other research studies have questioned the validity of the adoption of rainfall characteristics as lumped parameters for investigating the pollutant wash-off process (such as Willems, 2001; Andreassian et al., 2001). For example, first flush refers to the initial sector of the runoff hydrograph which can transport a relatively higher fraction of pollutants (Li et al., 2007), while the later part of the hydrograph would transport a decreased pollutant load due to the reduction in easily-detachable pollutants on the surface. Therefore, this gives rise to two important research questions: (1) how does pollutant wash-off in different sectors of the runoff hydrograph vary with rainfall characteristics? (2) What are the key influential rainfall characteristics in terms of the wash-off process in different sectors of the runoff hydrograph?

To provide answers to these two questions, this paper discusses a research study which investigated the influence of rainfall characteristics on the pollutant wash-off process in different sectors of the runoff hydrograph. The knowledge created will contribute to the enhancement of stormwater treatment design, particularly first flush capturing devices. Additionally, the knowledge created can also contribute to improving stormwater quality modelling approaches where commonly, the pollutant wash-off process is replicated based on rainfall intensity rather than considering other rainfall event parameters (SWMM, 2004; MIKE URBAN, 2008) or solely based on a stochastic approach irrespective of the characteristics of the rainfall event (MUSIC, 2011).

2 Materials and methods

2.1 Study sites

The study sites consisted of three small urban residential catchments located at Gold Coast, Queensland State, Australia. These catchments are provided with a range of Water Sensitive Urban Design (WSUD) measures in order to protect the receiving water environment from stormwater pollution. Fig. 1 shows the three study catchments (A, B and C), the location of the monitoring stations, stormwater flow direction and baseline catchment characteristics.

2.2 Data collection and testing

The three catchments have been continuously monitored for stormwater quality and quantity and rainfall since 2007 using automatic monitoring stations established at the outlets to collect flow measurements and stormwater runoff samples and pluviograph stations. Flow measurements were undertaken using calibrated V-notch weirs and samples were collected by stage triggered, peristaltic pumping. Discrete stormwater runoff samples were collected during rainfall events to investigate the variation in water quality during a runoff event. The total number of sampling episodes selected for analysis was 23 rainfall events from the three catchments. The relevant information regarding the selected rainfall events is given in Table S1 and S2 in the Supplementary Information. The samples collected were tested for total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS) which are the primary stormwater pollutants (Goonetilleke et al., 2005; Liu et al., 2012b). Sample testing was undertaken according to test methods specified in Standard Methods for the Examination of Water and Wastewater (APHA, 2005), which are listed in Table S3 in the Supplementary

Information. Sample collection, transport and storage complied with Australia New Zealand Standards, AS/NZS 5667.1:1998 (AS/NZS, 1998).

2.3 Determination of sector parameters

A parameter 'P' defined as "sector indicator" was determined for the pollutant concentrations and corresponding runoff volumes. It represents the increment in percentage pollutant load washed-off for the respective 10% increment in runoff hydrograph. For example, P2030 represents the percentage of pollutant load washed-off between 20% and 30% of the runoff hydrograph. The corresponding rainfall characteristics were also determined based on 10% increments in effective rainfall. To determine sector rainfall intensity, the effective rainfall intensity corresponding to each pollutant sector indicator was determined. For example, AI2030 represents the average rainfall intensity which occurred between 20% and 30% of effective rainfall depth.

Accordingly, nine 'P' sector parameters (P0010, P1020, P2030, P3040, P4050, P5060, P6070, P7080 and P8090) were determined for each pollutant species per rainfall event. The rainfall characteristics are also determined accordingly (average intensity: AI0010, AI1020, AI2030, AI3040, AI4050, AI5060, AI6070, AI7080 and AI8090; rainfall depth: RD0010, RD1020, RD2030, RD3040, RD4050, RD5060, RD6070, RD7080 and RD8090).

3 Results and discussions

3.1 Univariate data analysis

'P' parameters of TSS, TN and TP were initially investigated using boxplots as shown in Fig. 2. It is evident that all three pollutant species show similar behaviour. In terms of mean value, P0010 shows the highest load percentage washed-off by the first 10% of the runoff hydrograph (20.78% for TSS; 15.13% for TN; 22.26% for TP) while the corresponding values decrease from P1020 to P8090. This confirms first flush occurrence for TSS, TN and TP.

Additionally, it can be observed in Fig. 2 that each P parameter indicates a data range and the range is different for different sectors of the runoff hydrograph. P0010 has the widest range for all three pollutant species, followed by a narrowing trend in the middle sectors (P1020-P4050), which widens again from P5060. As the data was collected from a range of rainfall events, this implies that the pollutant wash-off processes can vary highly with rainfall characteristics. Furthermore, the pollutant loads in different sectors of the runoff hydrograph is affected differently. For example, the initial part and the end of the runoff event could be relatively more influenced and hence have a higher variability than the middle sectors. This highlights the need to further investigate how rainfall characteristics influence the wash-off process in different sectors of the runoff hydrograph.

3.2 Multivariate data analysis

3.2.1 Selection of rainfall parameters

A preliminary analysis was undertaken for identifying appropriate rainfall characteristics to prevent correlating parameters overshadowing critical relationships between rainfall characteristics and the wash-off process (Egodawatta et al., 2006). Accordingly, average intensity and rainfall depth for each sector in relation to effective rainfall, average rainfall intensity for the entire rainfall event (AgI), total rainfall depth (TRD), antecedent dry period

(ADP) and ‘P’ parameters (TN, TP and TSS) were investigated using Principal Component Analysis (PCA).

The use of PCA was due to its versatility for investigating the possible correlations between variables and objects (Kokot et al., 1998). The number of principal components needed was determined using the Scree Plot method (Adams, 1995). StatistiXL software (StatistiXL, 2007) was used for the PCA. Variables included the 27 P parameters (P0010-P8090 for TSS, TN and TP), 9 rainfall intensity sector parameters (AI0010-AI8090), 9 rainfall depth sector parameters (RD0010-RD8090), AgI, ADP and TRD while objects were the 23 rainfall events monitored. Accordingly, a data matrix (48×23) was submitted to PCA. Fig. 3 shows the resulting PCA biplot.

As shown in Fig. 3, TRD and rainfall depth sector parameters (RD0010-RD8090) are strongly correlated while rainfall intensity sector parameters after the first 10% of effective rainfall depth (AI1020-AI8090) are closely associated with each other. However, it is noteworthy that AI0010 vector points in the opposite direction to the other rainfall intensity sector parameters. This means that the influence exerted by rainfall intensity on the wash-off process in the first 10% of effective rainfall depth would be different and hence, need to be investigated separately. This also suggests the inadequacy of using average rainfall intensity for an entire rainfall event (AgI) although AgI shows close relationships with AI1020-AI8090. ADP does not show close correlation with other rainfall characteristics except with AI0010 and thereby could also be considered as an independent parameter. This is also supported by the fact that ADP is an indicator of the pollutant load built-up before a rainfall event (Vaze and Chiew, 2002).

As identified above, since AI0010 is separated from other rainfall intensity sector parameters which are strongly correlated with each other, the rainfall intensities from 10% to 90% were averaged (AgI1090) instead of using the individual rainfall intensities (AI1020-AI8090). Accordingly, ADP, AI0010, TRD and AgI1090 were included in the further analysis.

3.2.2 Relationships between wash-off process and rainfall characteristics

To investigate the relationships between the pollutant wash-off process in each sector of the runoff hydrograph and rainfall characteristics, a data matrix (31×23) was submitted to PCA. The variables included the 27 ‘P’ parameters (P0010-P8090 for TSS, TN and TP) and the identified four rainfall parameters (ADP, AI0010, TRD and AgI1090), while the objects were the 23 monitored rainfall events. Fig. 4 shows the resulting PCA biplots.

As shown in Fig. 4A (PC1 vs PC2), the vectors are categorized into three groups based on runoff hydrograph sectors (P parameters) and this is independent of the pollutant species. Group 1 includes P0010 of TSS, TN and TP as well as TRD vector. Group 2 contains P1020-P4050 of TSS, P1020-P5060 of TN and P1020-P5060 of TP along with AI0010 and ADP vectors while Group 3 comprises of P5060-P8090 of TSS, P6070-P8090 of TN and P6070-P8090 of TP plus AgI1090 vector. In terms of Group 2, AI0010 and ADP show close relationships with P1020 and P2030 for the three pollutants. This is also supported by Fig. 4B (PC1 vs. PC3). All the P1020 and P2030 parameters are projected on the negative PC3 axis along with ADP and AI0010 vectors while nearly all of the remaining P parameters in Group 2 (P3040-P4050 of TSS, P3040-P5060 of TN and P3040-P5060 of TP) are projected on the positive PC3 axis. These observations can be interpreted as follows:

Influence of rainfall depth

P0010 correlating with TRP means that the pollutant load percentage transported by the first 10% of the runoff hydrograph is closely related to rainfall depth. This is attributed to the weakly adhered solids available (free solids) on the catchment surface which will easily undergo wash-off (Miguntanna et al., 2013). Consequently, high rainfall depth and resulting high runoff volume can wash-off a relatively large pollutant load.

Influence of rainfall intensity in the initial sector of a rainfall event

The close correlationship between P1020, P2030 and AI0010 implies that rainfall events with high intensity in the initial part tend to readily produce first flush and the influence can last until 30% of the runoff hydrograph. Additionally, the pollutant wash-off during the first 10% of the runoff hydrograph is independent of the rainfall intensity while the wash-off process at 10%-30% of the runoff hydrograph is strongly influenced by the rainfall intensity.

Influence of antecedent dry period

The strong correlation between P1020, P2030 and ADP signifies the influence of pollutant built-up which occurred prior to the rainfall event, on the wash-off process, particularly on the first 10%-30% of the runoff hydrograph. This suggests that ADP can influence the wash-off process up to 30% of the runoff hydrograph.

Influence of rainfall intensity of the middle and end sectors of the rainfall event

The end sectors of the runoff hydrograph (P5060-P8090 of TSS, P6070-P8090 of TN and P6070-P8090 of TP) have a close relationship with AgI1090. This implies that high intensity in the initial sector of a rainfall event does not influence pollutant wash-off at the end part of the runoff hydrograph. Instead, the high intensity after the first 10% of a rainfall event contributes to producing a high pollutant load towards the end part of the runoff hydrograph. As the weakly adhered solids diminish during the early stage of a rainfall event, the strongly adhered solids which depend on the magnitude of the rainfall kinetic energy to detach, are exposed. Therefore, the pollutant load detached towards the end part of a runoff hydrograph is strongly dependent on the rainfall kinetic energy.

It is also noteworthy that in both biplots, all the objects are scattered (Fig. 4A and 4B) and do not cluster based on catchments. This suggests that the influence of rainfall characteristics on the wash-off process can be classified into three stages based on the runoff hydrograph sectors (early, middle and end sectors) and this is independent of catchment characteristics. Furthermore, the differing nature of the influence of rainfall intensity in the initial and the other sectors of rainfall events on the wash-off process implies that, the rainfall pattern plays a critical role in the pollutant wash-off. High intensity at the initial period tends to generate a higher magnitude first flush than in the case of high intensity occurring in middle or later part. This is despite the fact that the total rainfall amount could be the same.

3.2.3 Identifying the key influential rainfall characteristics

Factor analysis (FA) was performed to identify the key rainfall characteristics influencing the wash-off process. Principal component extraction method with orthogonal VARIMAX rotation was adopted for the factor analysis. 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 (Abdi, 2003). After careful investigation of the rotated component matrix, three underlying factors were found sufficient. These factors were extracted based on the initial eigenvalue criteria ≥ 1. Table 1 shows the factor analysis results.

It can be noted that the three pollutant species show an almost similar correlation with the factors. P0010 parameters are closely correlated with Factor 2 (0.484 for TSS; 0.825 for TP; 0.775 for TN) while P6070-P8090 parameters are related to Factor 1. However, it is noteworthy that P8090 of TN shows more correlation with Factor 2 (0.609). This is attributed to the fact that nitrogen is primarily present in dissolved form. Therefore, the transport capacity of rainfall events do not significantly influence dissolved pollutants wash-off compared to particulate pollutants (Miguntanna et al., 2013). P1020-P2030 parameters show strong correlationships with Factor 3 while P3040-P5060 are not strongly correlated with any factors even though P5060 of TSS indicates some correlation with Factor 1 (0.514).

Considering the PCA outcomes discussed above, it can be concluded that Factor 1 relates to average rainfall intensity after the first 10% of effective rainfall depth (AgI1090) while Factor 2 and Factor 3 correspond to total rainfall depth (TRD) and average rainfall intensity in the first 10% of effective rainfall depth (AI0010), respectively. These results imply that rainfall depth and rainfall intensity are the key rainfall characteristics which significantly influence the wash-off process. The antecedent dry period does not play an influential role in the wash-off process. In other words, the initial pollutant availability is secondary to the transport capacity of runoff in influencing the pollutant wash-off.

3.3 Implications for stormwater treatment design

The discussions above confirm that pollutant wash-off processes in the early, middle and end sectors of the runoff hydrograph can be influenced by different rainfall characteristics. Therefore, the conventional modeling approach which estimates pollutants wash-off primarily based on rainfall intensity or the adoption of a stochastic approach could be inappropriate. Instead, rainfall depth should also be taken into consideration in pollutant wash-off estimation. This is particularly important in order to model first flush since rainfall depth is the key influential factor in the initial sector of the runoff hydrograph.

These research outcomes also highlight the fact that careful selection of design rainfall events is critical for effective stormwater treatment design. For example, for designing a treatment system to capture the first flush, rainfall events with high rainfall depth or initially high intensity should be selected, whilst for designing systems for treating the entire runoff event or for storage and reuse, the design approach should focus on events with high intensity in the end sectors.

4. Conclusions

This research study introduced innovative sector parameters to investigate the relationship between pollutant wash-off process and different sectors of a runoff hydrograph and rainfall hyetograph. Rainfall depth and rainfall intensity are two key rainfall characteristics influencing the wash-off process compared to the antecedent dry period. This implies that the initial pollutant availability is secondary to the transport capacity of runoff in influencing the pollutant wash-off load. Additionally, rainfall pattern also plays a critical role in the pollutant wash-off process and this is independent of catchment characteristics. The occurrence of high intensity in the initial period of a rainfall event will generate a relatively higher magnitude first flush.

These outcomes provide the essential knowledge to select appropriate rainfall events for stormwater quality treatment design based on the required treatment outcomes such as the need to target different sectors of the runoff hydrograph. This can also contribute to enhancing stormwater quality modelling and prediction.

Supplementary Information

The Supplementary Information section includes baseline data in relation to the selected rainfall events and the laboratory methods used for testing of water samples.

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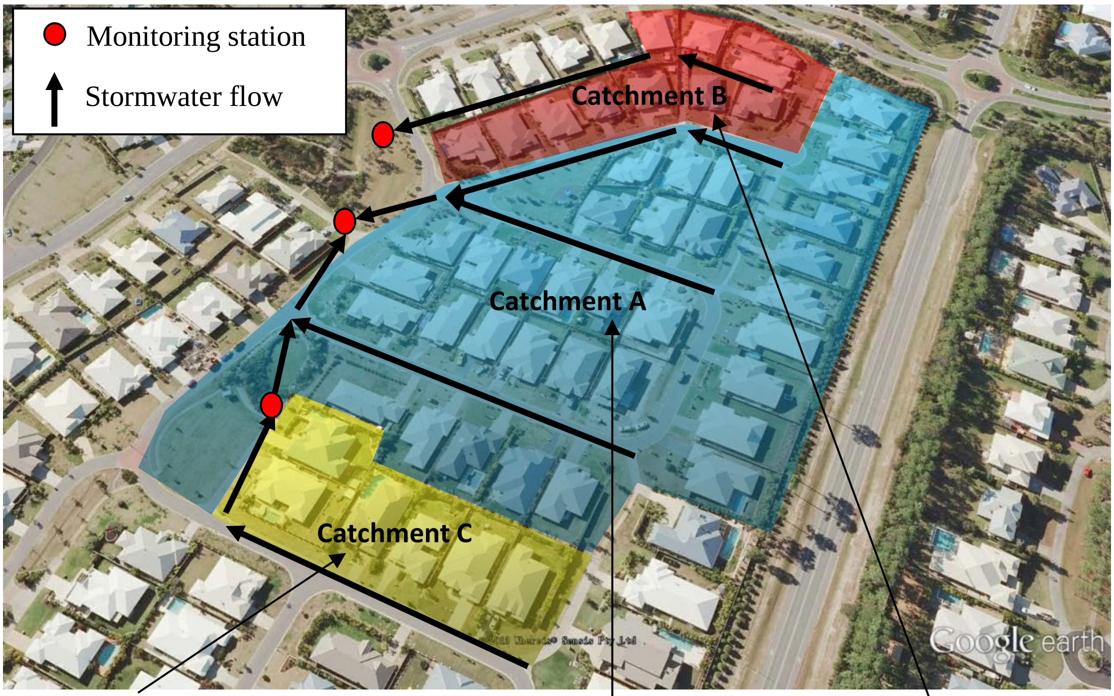
Table 1 Factor analysis results

P	TSS			TP			TN		
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
0010	-0.620	**0.484**	-0.378	-0.230	**0.825**	-0.346	-0.384	**0.775**	-0.222
1020	-0.519	-0.021	**0.761**	-0.235	0.187	**0.916**	-0.097	-0.074	**0.872**
2030	-0.050	-0.235	**0.668**	-0.239	-0.212	**0.804**	-0.243	-0.150	**0.829**
3040	0.013	-0.503	0.328	0.005	-0.736	0.247	0.020	-0.615	0.445
4050	0.103	-0.685	0.135	-0.145	-0.823	-0.046	-0.071	-0.885	-0.006
5060	0.514	-0.536	-0.024	-0.201	-0.475	-0.126	-0.384	-0.668	-0.153
6070	**0.839**	-0.037	-0.241	**0.854**	-0.177	-0.131	**0.901**	0.007	0.043
7080	**0.744**	0.105	-0.428	**0.894**	0.010	-0.230	**0.708**	0.393	-0.442
8090	**0.515**	0.108	-0.364	**0.737**	0.205	-0.395	0.369	**0.609**	-0.593



C: 6 houses; 0.7ha; mild slope; 52% of impervious surface (15% is roads and 37% is roof)

A: 35 houses; 4.4ha; steep slope; 48% of impervious surface (22% is roads and 26% is roof)

B: 15 houses; 1.0ha; steep slope; 47% of impervious surface (0% is roads and 47% is roof)

Fig. 1 Study catchments

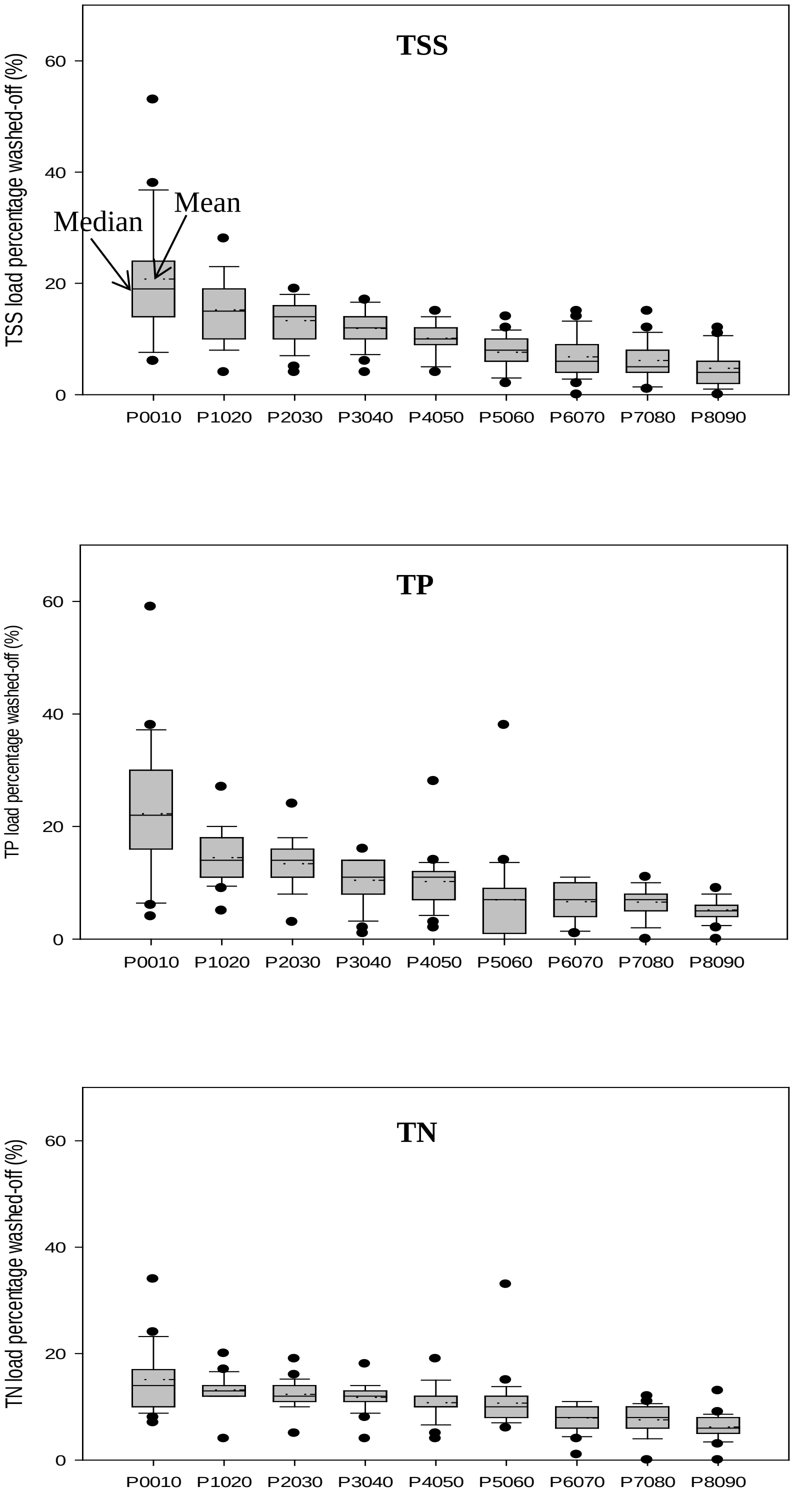


Fig. 2 Pollutant load percentages washed-off (X axis is the nine P sector parameters representing the increment in percentage pollutant load washed-off for the respective 10% increment in runoff hydrograph)

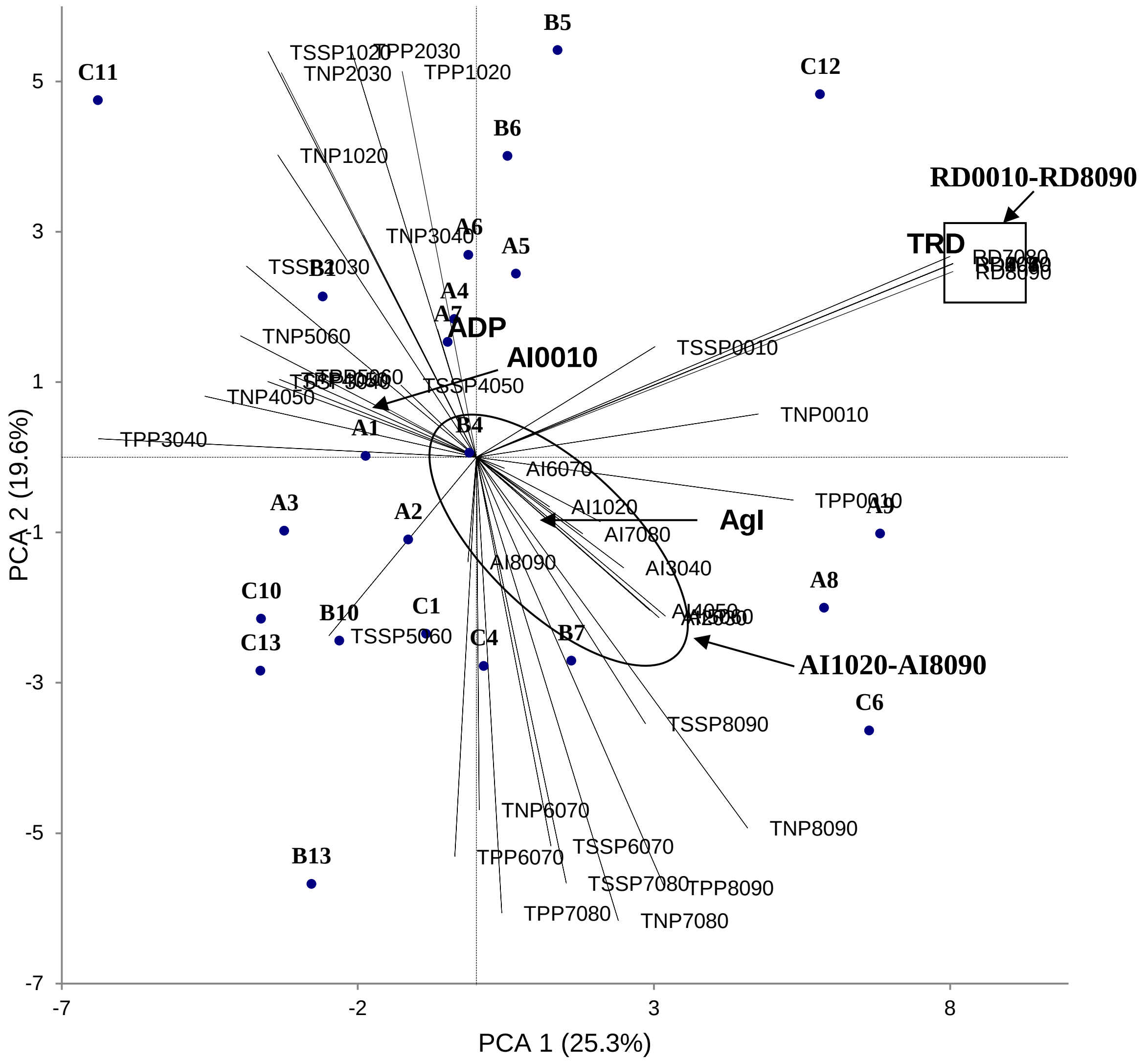


Fig. 3 PCA biplot for determining appropriate rainfall parameters (A, B and C represent three catchments; digitals following A, B and C represent rainfall event ID; TRD=total rainfall depth; AgI=average rainfall intensity; ADP=antecedent dry period; RD=rainfall depth in sectors; AI=average intensity in sectors)

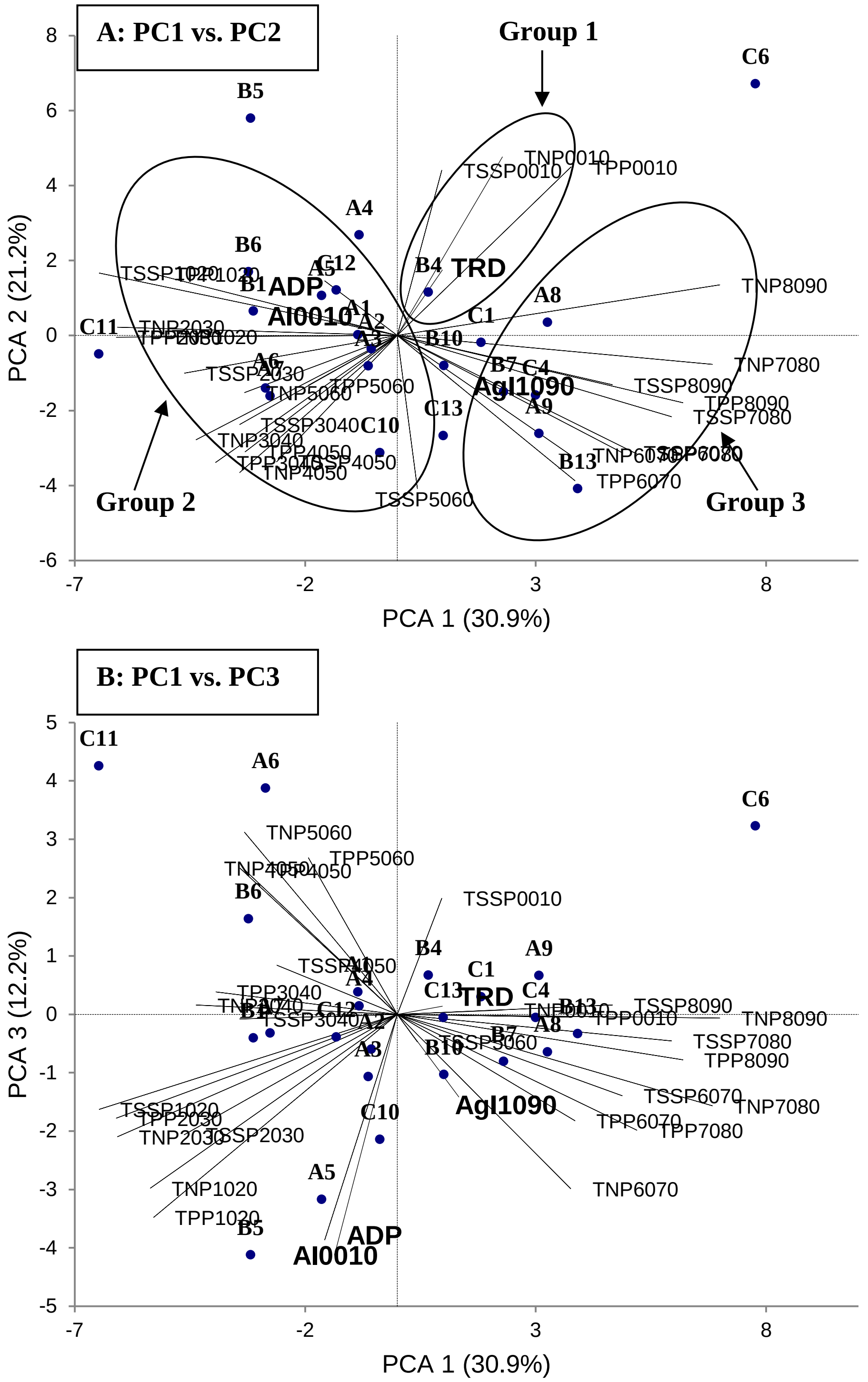


Fig. 4 PCA biplots for investigating relationships between wash-off and rainfall characteristics (AI1090=average rainfall intensity after the first 10% of rainfall events; other labels refer to Fig. 3)

SUPPLEMENTARY INFORMATION

Sectional analysis of the pollutant wash-off process based on runoff hydrograph

Noraliani Alias[1,3], An Liu [2*], Prasanna Egodawatta[3], Ashantha Goonetilleke[3]

[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia

[2]Research Centre of Environmental Engineering and Management, Graduate School at Shenzhen, Tsinghua University, 518055 Shenzhen, People’s Republic of China
[3]Science and Engineering Faculty, Queensland University of Technology, P.O. Box 2434, Brisbane, Qld 4001, Australia

The selected rainfall events and their characteristics

A total of 13 rainfall events were selected for analysis after assessment of the available data. However, suitable rainfall-runoff records and water quality data for the 13 rainfall events was not available for all of the three catchments. Three events were common for all three catchments, while the rest of the events comprised of data suitable for one or two catchments. Accordingly, the total number of sampling episodes selected for analysis totalled 23 rainfall events. Rainfall depth, rainfall intensity and antecedent dry period were selected as the primary rainfall characteristics for this research study due to their important role in influencing pollutant wash-off (Jacinthe et al., 2004; Mahbub et al., 2012). The baseline data in relation to the rainfall events are given in Table S1 and Table S2.

Table S1 Selected rainfall events, rainfall characteristics and applicable catchments

Event ID	Total rainfall depth (mm)	Average intensity (mm/h)	Antecedent dry period (h)	Catchments
1	1.4	6	23.65	A, B, C
2	1.4	21	9.24	A
3	0.8	12	216	A
4	2.2	3	164	A, B, C
5	3.2	7.38	396	A, B
6	3.2	4	24	A, B, C
7	2.6	13	202	A, B
8	4.2	18	9	A
9	5.8	7.9	3	A
10	0.8	8	170.4	B, C
11	0.8	1.6	20	C
12	5.8	6.69	16	C
13	0.6	1.833	4	B, C

Table S2 EMC values for the selected rainfall events

Event ID	EMC values (mg/L)		
	TSS	TN	TP
A1	16.26	0.62	0.02
A2	118.99	0.04	0.10
A3	91.34	2.41	0.12
A4	27.57	0.82	0.00
A5	106.48	3.17	0.23
A6	35.93	0.95	0.04
A7	72.29	2.32	0.12
A8	29.93	0.81	0.02
A9	62.50	3.75	0.38
B1	13.44	0.44	0.02
B4	28.63	0.70	0.02
B5	26.20	0.88	0.02
B6	12.36	0.78	0.02
B7	15.93	1.49	0.02
B10	9.17	1.07	0.01
B13	32.93	0.62	0.04
C1	27.49	0.89	0.07
C4	69.22	0.62	0.02
C6	7.73	0.38	0.01
C10	41.28	1.52	0.08
C11	10.93	0.27	0.02
C12	12.45	0.68	0.01
C13	63.27	1.60	0.32

Table S3 Sample testing methods

Parameters	Test method (APHA 2005)	Apparatus	Comments
TSS	2540C		
NO_2^--N	4500-NO2-B	Smartchem 140; Westco Block Digestor 40/20 (digestion for TP and TKN)	TN= NO_2^- + NO_3^- + TKN
NO_3^--N	4500-NO3-E		
TKN	4500-Norg-B		
TP	4500-P-B		

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