A set of surrogate parameters to evaluate harvested roof runoff quality

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Abstract: *This paper presents the outcomes of a research project, which focused on developing a set of surrogate parameters to evaluate roof runoff quality using simulated rainfall. Use of surrogate parameters to evaluate roof runoff quality has the potential to enhance the rapid generation of harvested rainwater quality data based on on-site measurements and thereby reduce resource intensive laboratory analysis. Pollutant buildup and washoff samples were collected from a model roof surface placed in a residential suburb in Gold Coast, Queensland State, Australia. The collected samples were tested for a range of physio-chemical parameters which are key indicators of nutrients, solids and organic matter. The analysis revealed that [total dissolved solids (TDS)]; [electrical conductivity (EC),turbidity (TTU)] as appropriate surrogate parameters for dissolved total nitrogen (DTN) and total solids (TS) respectively. No surrogate parameters were identified for phosphorus.*

Keywords: *roof surface pollutants, stormwater pollution, rainwater harvesting, surrogate parameters*

1. INTRODUCTION

Roof surfaces have been identified as important contributor of pollutants into urban stormwater runoff in urban areas. Even during the small rain vents higher fraction of pollutants which are accumulated on urban roof surfaces are washed off and get into the stormwater runoff. Hence, deterioration of receiving water quality is a significant concern. However, there is a growing awarwenss on using harvested ruoff runoff wherer water scarcity is a significant concern. Furthermore, increase attention has been already paid for the potential of using the harvested rainwater for domestic purposes (Evans et al. 2006, Meera and Ahammed, 2006).

Rainwater harvesting is considered as a sustainable water management practice as it provides a feasible approach to reduce the pressure on natural water resources. Currently, harvested roof runoff is primarily used for non potable purposes. However, due to the continuing urbanisation and scarcity of natural water resources, techniques to use rainwater as a potable water supply are increasingly investigated. Zorn and Wheatley (2009) noted that harvested rainwater can be used for a number of domestic purposes such as toilet use and washing machine use without undergoing treatment.

Currently, there has been growing interest also in the use of harvested rainwater as an alternative source for drinking water (Meera and Ahammed, 2006; Zorn and Wheatley, 2009). In determining the end use and the potential success of such an option, the possible problems associated with water quality need to be analysed and the feasibility of using rainwater as a source of water for household use will need to be determined. As noted by several researchers (for example Meera and Ahammed, 2006), harvested rainwater can contain significant amounts of pollutants such as heavy metals, nutrients and pathogens. Evans et al. (2006) stated that the potential pollutants in rainwater harvesting systems are likely to arise from depositions by birds, small mammals, airborne micro-organisms and chemical contaminants. The decay of these pollutants within a rainwater tank can also contribute to pollution. There is no clear agreement on the physico-chemical and microbiological quality and health risk associated with roof harvested rainwater. Several researchers have suggested that the use of roof runoff for potable purposes can lead to a possible health risk (for example Lye, 2002; Evans et al. 2006). In this context, approaches have been made to protect the harvested rainwater quality by implementing control measures such as first flush devices and filters.

Development of effective control measures to safeguard the harvested rainwater quality requires in-depth knowledge on pollutant build-up and wash-off characteristics on roof surfaces. At present, data to generate the requisite knowledge is scarce, partial or sometimes contradictory (Gromaire et al. 1999).
The lack of knowledge on key water quality parameters and pollutant processes on roof surfaces are mainly attributed to difficulties in planning and conducting stormwater quality monitoring programs (Gromaire et al. 1999). Investigation of a large number of water quality parameters is time consuming and resource intensive (US FHWA 2001). Furthermore, dealing with a range of variables in stormwater runoff monitoring programs requires sophisticated knowledge of these variables related to the wash-off process (US FHWA 2001;Martinez 2005). On the other hand, cost effective and robust methods for the continuous measurement of pollutant concentrations are not yet fully developed (Grayson et al. 1996). Therefore, it is important to identify a suite of easy-to-measure surrogate parameters which can be correlated to water quality parameters of interest. The relationships between key water quality parameters and its surrogate parameters will provide a convenient approach to evaluate the quality of roof runoff directly, without carrying out resource intensive laboratory experiments. However, the utility of this approach depends on the quality of correlations between these different sets of parameters (Grayson et al. 1996).

2. MATERIALS AND METHODS

2.1. Sampling sites

A residential suburb, in Gold Coast, South East Queensland, Australia was selected for field investigations. The study sites were located within a typical urban residential suburb, Coomera, in Gold Coast. This residential suburb was selected due to its high rate of rainwater harvesting. Furthermore, as loads and types of pollutants on roof surfaces are significantly influenced by the land use, the understanding developed for residential roof surfaces would provide knowledge specific to rainwater harvesting (Egodawatta et al. 2009).

2.2. Research tools

The study was carried out using two model roof surfaces. Use of model roofs with a surface area of 3 m^2 eliminated the possible heterogeneity of the surface characteristics of actual roof surfaces. This in turn will help to enhance the transferability of the research outcomes. The characteristics of the model roofs closely replicated actual roof surfaces. The model roofs were made from two different cladding materials; corrugated steel and concrete tiles. These are the most widely used roofing materials in South East Queensland, where the study sites were located. The model roofs were mounted on a scissor lifting arrangement so that they can be lifted to the typical roofing height for pollutant accumulation and lowered to the ground level for sample collection. This arrangement was used to avoid the practical difficulties inherent in investigating pollutant build-up and wash-off on actual roofs.

Figure 1 Model roof surfaces used in the study

For the study of pollutant wash-off, rainfall simulation was employed in order to eliminate the dependency on natural rainfall. This approach provided greater flexibility and control of the fundamental rainfall parameters such as rainfall intensity and duration and its chemical quality. (Herngren et al. 2006; Egodawatta and Goonetilleke, 2008). The specially designed rainfall simulator (see Figure 2) consisted of an A-frame structure with three Veejet 80100 nozzles connected to a nozzle boom and standing at 2.5 m above the ground level. The nozzle boom can swing in either direction with controlled speed and delay. This enables the simulator to be calibrated for different intensities. A detailed description of the rainfall simulator can be found in Herngren (2005).

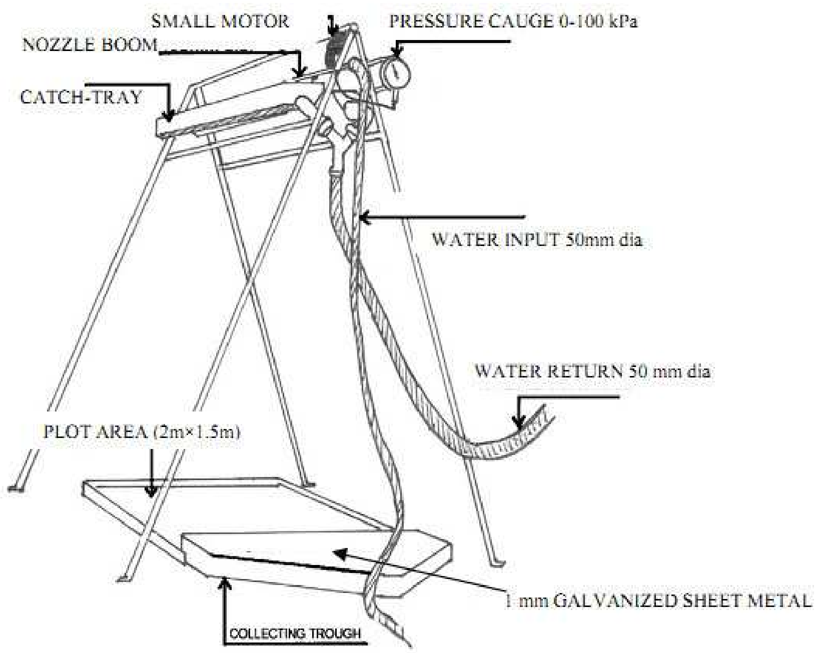


Figure 2 Schematic diagram of the rainfall simulator used for the study (Adapted from Herngren et al. 2005)

2.3. Sample collection and testing

Wash-off sample collection was carried out for six simulated rain events. Average rainfall intensities of 65 and 86 mm/hr intensities were simulated for the first sampling episode, 115 and 135 mm/hr intensities for the second sampling episode and 20 and 40 mm/hr intensities for the third sampling episode. The selection of these rainfall intensities and durations were based on the regional rainfall events in the Gold Coast area. The selected intensity range represents more than 90% of the regional rainfall events (Egodawatta 2007).

Half of the roof surface used for wash off sampling as the other half was used for pollutant build-up sampling (Miguntanna 2009) This was done by fixing the gutter at the other half of the roof surface (see Figure 3). Build-up samples were collected by washing the roof surface four times with approximately 7 L of deionised water. A soft brush was also used to brush the surface while washing. A roof gutter was placed to collect the sample and to direct it to a polyethylene container kept underneath the gutter opening (see Figure 3). The gutter was thoroughly washed before and after each sample collection. For the washoff sampling 20, 86 and 135 mm/hr intensities were simulated on the corrugated steel roof surface and 40, 65 and 115 mm/hr intensities were simulated on the concrete tile roof surface. For the simulations, the rainfall simulator was placed exactly above the lowered model roof. The simulator was raised to maintain 2.5 m average height from roof to nozzle boom of the simulator. Simulations were conducted until relatively clean runoff was observed. The wash-off was directed to the containers which were kept underneath the gutter as shown in Figure 3. Finally, the model roof was lifted to typical roofing height and left at the site until the next sampling episode.

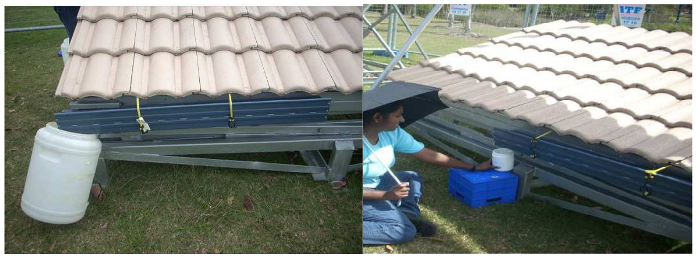


Figure 3 Collection of a) pollutant build-up samples; b) Wash-off samples

Finally, all the collected samples were tested for TS, TOC, NO2-, NO3-, TKN, TN, PO_4^{3-} and TP according to the methods specified in Standard Methods for the Examination of Water and Waste Water (2005).The details of the test methods used is given in Table 1.

Table 1 Details of the test methods used

Parameter	Test Method	Comments
pH	4500H (APHA, 2005)	Combined pH/EC meter was used
Electrical conductivity (EC)	2520B (APHA, 2005)	Combined pH/EC meter was used
Turbidity (TTU)	2130B (APHA 2005)	Turbidity meter was used
Total suspended solids(TSS) and Total dissolved solids (TDS) Total solids (TS)	2540D and 2540C (APHA, 2005) Addition of TSS and TDS taken as TS	Total sample filtered through 1 µm glass fibre filter paper and analysed for TSS. The filtrate tested for TDS.
Total organic carbon (TOC) Dissloved organic carbon (DOC)	Measured using according to the 5310C (APHA, 2005)	Shimadzu TOC-5000A Total Organic Carbon Analyzer was used
Nitrite nitrogen (NO_2^-)	4500 -NO_2^--B (APHA, 2005).	SmartChem 140 discreet analyser was used
Nitrate nitrogen (NO_3^-)	4500 –NO_3^--F (APHA, 2005).	SEAL discrete analyser was used
Total kjeldahl nitrogen (TKN)	351.2. (US EPA 1993)	
Total nitrogen (TN)	Addition of NO_2^-, NO_3^- and TKN	
Ortho-Phosphate (PO_4^{3-})	4500-P-F (APHA, 2005).	SEAL discrete analyser was used
Total phosphorus (TP)	365.4. (US EPA, 1983).	

2.4. Data analysis

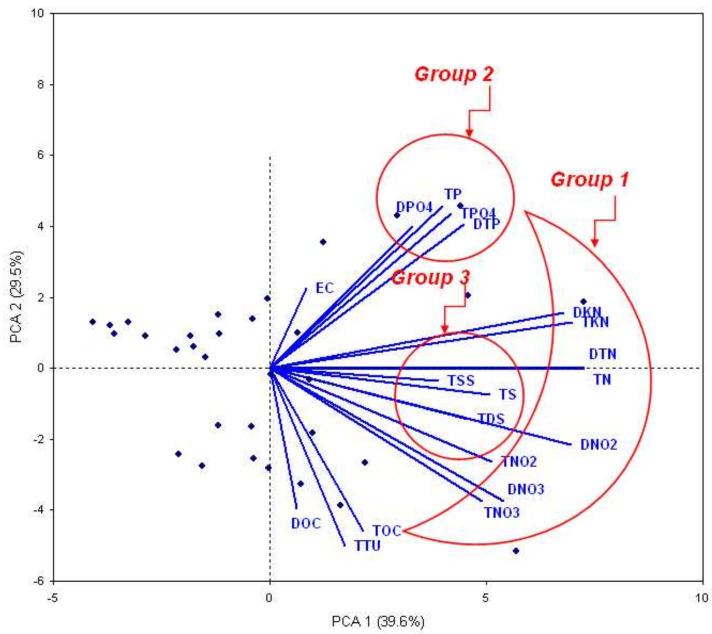
Data analysis was primarily carried out using two common multivariate data analysis techniques; Principal Component Analysis (PCA) and Partial Least Squares regression (PLS). PCA has been widely used as a pattern recognition technique in numerous water quality research studies (for example Settle et al., 2007). In the PCA biplot, vectors representing parameters which form an acute angle are considered as correlated parameters and those which are perpendicular are considered as uncorrelated. PLS is a well known factor analysis method which is principally applied for prediction. Detailed description of PCA and PLS and its applications can be found in research literature (for example Kim et al., 2007; Kokot and Phuong,1998).

2.4.1. Selection criteria for the identification of surrogate parameters

The physio-chemical monitoring of stormwater runoff quality is constrained by a number of factors associated with the measuring of key water quality parameters such as laboratory facilities, sophisticated operational techniques of instruments and extensive resources (Settle et al. 2001). Therefore, the identification of a set of easy to measure parameters as surrogates for key water quality parameters would enhance stormwater quality monitoring studies. Among the parameters given in Table 1, EC, TTU, TSS, TDS, TOC and DOC can be considered as relatively easy to measure. Therefore, special attention was given to finding correlations for nitrogen and phosphorus compounds with pH, EC, TTU, TSS, TDS, TOC and DOC.

3. RESULTS AND DISCUSSION

Figure 4 shows the PCA analysis biplot. The PC1 versus PC2 biplot accounts for almost 70% of data variance. The main purpose of the PCA was to identify the correlated parameters and group them depending on their correlations. Consequently, the potential surrogate parameters were identified for those groups separately. The correlation matrix which is resultant from PCA shows the degree of correlation among the parameters (Table 2). The correlation coefficient greater than 0.50 was considered as strongly correlated parameters and parameters with 0.35-0.50 were considered as having some correlation.



Note: TTU- Turbidity; EC- Electrical conductivity; TNO2- Total nitrite-nitrogen; DNO2- Dissolved nitrite-nitrogen TOC- Total organic carbon; DOC- Dissolved organic carbon; TNO3- Total nitrate-nitrogen; DNO3- Dissolved nitrate- nitrogen; TKN- Total kjeldahl nitrogen; DKN- Dissolved kjeldahl nitrogen; TN- Total nitrogen; DTN- Dissolved total nitrogen; TSS- Total suspended solids; TDS- Total dissolved solids; TS- Total solids; TPO4- Total Phosphates; DPO4- Dissolved Total Phosphates; TP- Total phosphorus; DTP- Dissolved total phosphorus.

Figure 4 PCA biplot for all the physico- chemical parameters for roof Surfaces

Table 2 Correlation matrix obtained from PCA

Correlation Matrix																			
	EC	TTU	TSS	TDS	TS	TOC	DOC	TNO2	DNO2	TNO3	DNO3	TKN	DKN	TN	DTN	TPO4	DPO4	TP	DTP
EC	1.000																		
TTU	-0.170	1.000																	
TSS	0.585	0.338	1.000																
TDS	0.245	0.504	0.755	1.000															
TS	0.413	0.463	0.914	0.956	1.000														
TOC	-0.400	0.724	0.105	0.194	0.167	1.000													
DOC	-0.496	0.551	-0.017	0.057	0.028	0.716	1.000												
TNO2	-0.477	0.444	0.037	0.234	0.161	0.584	0.475	1.000											
DNO2	-0.160	0.502	0.401	0.647	0.580	0.499	0.297	0.814	1.000										
TNO3	-0.059	0.669	0.181	0.190	0.199	0.641	0.403	0.685	0.598	1.000									
DNO3	0.002	0.697	0.246	0.267	0.275	0.664	0.408	0.649	0.601	0.978	1.000								
TKN	0.065	-0.073	0.338	0.457	0.434	0.104	-0.064	0.563	0.756	0.239	0.250	1.000							
DKN	0.053	-0.125	0.260	0.416	0.373	0.041	-0.112	0.559	0.732	0.198	0.215	0.974	1.000						
TN	-0.007	0.153	0.366	0.508	0.478	0.297	0.071	0.693	0.865	0.458	0.464	0.965	0.921	1.000					
DTN	0.001	0.147	0.317	0.503	0.453	0.270	0.043	0.704	0.866	0.505	0.578	0.947	0.954	0.972	1.000				
TPO4	0.229	-0.515	0.132	-0.019	0.047	-0.346	-0.335	0.109	0.175	-0.136	-0.132	0.651	0.674	0.511	0.522	1.000			
DPO4	0.148	-0.431	0.065	-0.125	-0.049	-0.288	-0.280	0.080	0.083	-0.107	-0.116	0.491	0.495	0.383	0.375	0.948	1.000		
TP	0.328	-0.541	0.187	0.014	0.092	-0.403	-0.389	0.027	0.122	-0.197	-0.182	0.636	0.660	0.480	0.493	0.980	0.896	1.000	
DTP	0.396	-0.438	0.300	0.192	0.253	-0.367	-0.342	0.101	0.223	-0.167	-0.128	0.656	0.682	0.511	0.535	0.877	0.777	0.894	1.000

Figure 4 and Table 2 leads to the following conclusions:

- TNO3, DNO3, TNO2, DNO2, TN, DTN, TKN and DKN are strongly correlated to each other (See group 1);
- TPO4 ,DPO4, TP and DTP are strongly correlated to each other (See group 2);
- and
- TSS, TDS and TS are strongly correlated to each other (See group 3).

Based on the conclusions derived from the PCA biplot and the correlation matrix, potential surrogate parameters were identified for nitrogen, phosphorus and solids separately.

I. Identification of potential surrogate parameters for nitrogen compounds

All nitrogen compounds show good correlation to each other (Figure 4 and Table 2). According to several research findings, TN in roof surface runoff is a significant stormwater pollutant (Huang et al. 2007). Exploring the raw data matrix as seen in Table 3, the dissolved fraction of TN is the dominant form of nitrogen in roof surface runoff which is around 80%. Consequently, DTN was selected as the most representative parameter for all nitrogen compounds. The surrogate parameters identified for DTN would be the surrogate parameters for all nitrogen compounds.

Table 3 Mean concentrations of nitrogen compounds

	nitrogen parameter (mg/L)				**Percentage in the dissolved fraction (%)**	
Site ID	TKN	DKN	TN	DTN	TKN	TN
Roofs	0.54	0.44	0.70	0.57	80	81

According to PCA, DTN was strongly correlated to TDS. Therefore, TDS was selected as the best indicator of dissolved total nitrogen. This selection was further supported by the correlation coefficient of TDS and TN which is 0.503 (Table 2). This correlation was evident in raw data matrix also by indicating DTN decreases with decreasing TDS concentrations for all the intensities. Hence, TDS can be considered as a potential surrogate parameter for DTN in roof surface runoff.

II. Identification of potential surrogate parameters for phosphorus compounds

As in Figure 4 and Table 2 all phosphorus compounds are strongly correlated to each other with correlation coefficients of greater than 0.750. TP is the sum of all forms of phosphorus. Exploring the raw data matrix, it was noted that around 65% of total phosphorus is in particulate form (See Table 4). Therefore, TP can be considered as the indicator parameter for phosphorus in urban roof surface.

Table 4 Mean concentrations of phosphorus compounds

	Phosphorus parameter (mg/L)				**Particulate percentage (%)**	
Site ID	$TPO4^{3-}$	DPO_4^{3-}	TP	DTP	PO_4^{3-}	TP
Roof surface	1.80	0.64	1.85	0.64	65%	66%

According to Figure 5 TTU and TOC show negative correlation with TP. According to Table 2, correlation coefficient of TP with TTU and TOC are-0.541 and -0.403 respectively. However, exploring the raw data matrix, this negative correlation was not evident for all the intensities. It indicates TP concentration decreases with decreasing TOC and TTU concentrations which suggests positive correlation among the parameters. This pattern of variation was contradictory to the observations noted in PCA analysis. Therefore, identification of surrogate parameters for phosphorus was not successful.

III. Identification of potential surrogate parameters for TSS, TDS and TS

The identification of surrogate parameters for solids is also important as it can provide a convenient method to measure TSS, TDS and TS which are the key indicators of solids in roof runoff, based on simple field measurements such as EC and TTU. According to PCA it was noted that TSS is strongly correlated to EC and TDS is strongly correlated to TTU with correlation coefficients of 0.585 and 0.504 respectively. However, the correlation of TSS with EC and TDS with TTU are contradictory to the findings of several researchers who noted that EC and TTU as potential surrogate indicators for TDS and TSS respectively (Gippel 1995; Zeng and Rasmussen 2005). Furthermore, the correlation of TSS with EC and

TDS with TTU were not clear in the raw data matrix also. Therefore, identification of potential surrogate parameters for TSS and TDS was not successful for roof surface wash-off. However, TS shows limited correlation to EC and TTU with correlation coefficients of 0.413 and 0.463 respectively. As evident in raw data matrix also TS decreases with decreasing EC and TTU for most of the intensities. Therefore, both EC and TTU were considered as potential surrogate indicators for TS in roof surface runoff.

Table 5 presents the summary of the potential surrogate parameters which were obtained for nitrogen compounds, phosphorus compounds and solids in the runoff from both road and roof surfaces.

Table 5 Potential surrogate water quality parameters for nitrogen, phosphorus and solids

Constituent	Key indicator	Potential surrogate parameter
Nitrogen	Dissolved total nitrogen(DTN)	Total dissolved solids (TDS)
Phosphorus	Total phosphorus (TP)	Not found
Solids	Total suspended solids(TSS) Total dissolved solids (TDS) Total solids (TS)	Not found Not found Electrical conductivity(EC) Turbidity (TTU)

4. CONCLUSIONS

It is evident that roof surfaces as a significant contributor to stormwater pollutant load in urban area. The study was focus on identification of a set of easy to measure parameters as surrogates for key water quality parameters which would enhance harvested rainwater monitoring. For this purpose, PCA was used as a principal data analysis tool for identification of surrogate water quality parameters. It was noted that Dissolved total nitrogen (DTN) can be used as a representative parameter for all nitrogen compounds in wash-off while Total phosphorus (TP) can be used as a representative parameter for phosphorus compounds. The study identified Total dissolved solids (TDS) as a potential surrogate parameter for nitrogen. In addition, it was found that both Turbidity and EC can be used as surrogate parameters for Total solids (TS). However, the study was failed to identify surrogate parameters for phosphorous. The surrogate parameters have the potential to enhance the harvested roof runoff quality investigations without resource intensive laboratory based analysis of key water quality parameters. This knowledge is essential for providing effective mitigation actions to safeguard the harvested roof runoff quality in urban land uses.

5. ACKNOWLEDGMENTS

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