Impact of roof surface runoff on urban water quality

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Abstract
The pollutant impacts of urban stormwater runoff on receiving waters are well documented in research literature. However, it is road surfaces that are commonly identified as the significant pollutant source. This paper presents the outcomes of an extensive program of research into the role of roof surfaces in urban water quality with particular focus on solids, nutrients and organic carbon. The outcomes confirmed that roof surfaces play an important role in influencing the pollutant characteristics of urban stormwater runoff. Pollutant build-up and wash-off characteristics for roads and roof surfaces were found to be appreciably different. The pollutant wash-off characteristics exhibited by roof surfaces show that it influences the first flush phenomenon more significantly than road surfaces. In most urban catchments, as roof surfaces constitutes a higher fraction of impervious area compared to road surfaces, it is important that the pollutant generation role of roof surfaces is specifically taken into consideration in stormwater quality mitigation strategies.

Keywords: roof surface runoff, stormwater pollution, urban water quality

INTRODUCTION

It is the water environment that is most adversely affected by urbanisation. Pollutants originating from urban areas dramatically alter receiving water quality (Goonetilleke et al. 2005; Sartor et al. 1974). In order to implement mitigation actions to safeguard the quality of receiving waters, it is important to understand the primary pollutant sources. Road surfaces are commonly regarded as the primary pollutant source in the urban environment (Herngren et al. 2006; Sartor et al. 1974). However, the pollutant contribution from roof surfaces is little understood and could also be a significant pollutant source.

Furthermore, understanding of pollutant processes on roof surfaces is highly relevant as rainwater harvesting is becoming increasingly popular as a sustainable water management practice. However, recent studies have found that there can be health risks associated with the use of untreated rainwater for human consumption due to the possible presence of biological and chemical pollutants in roof runoff. The amount and type of pollutants present on roofs have significant site specific characteristics (Ahmed et al. 2010; Lye 2002).

The physico-chemical pollutants on roof surfaces are due to atmospheric depositions and the degradation of cladding material. The rate of deposition on roofs and the pollutant types vary with a range of site specific factors such as surrounding land use activities, traffic and climatic conditions (Van Metre & Mahler 2003). Microbiological pollutants primarily originate from birds, small mammals and leaves from overlying vegetation and can be site specific in terms of load and constituents (Ahmed et al. 2010).

Though the loads and types of pollutants on roof surfaces are site specific, the physical processes that characterize the build-up of pollutants and wash-off during rainfall events is universal. There is broad understanding on pollutant build-up and wash-off processes on road surfaces (Egodawatta et al. 2007; Herngren et al. 2005b; Sartor et al. 1974). As noted by past researchers, pollutant build-up and wash-off processes on roads can be replicated using a universal set of mathematical equations with appropriate coefficients (Egodawatta et al. 2007; Egodawatta & Goonetilleke 2008). However, the knowledge currently available to develop similar mathematical relationships for pollutant processes on roof surfaces is relatively limited.

Using innovative research tools, an extensive long-term program of research was undertaken at Gold Coast, Queensland State, Australia into pollutant build-up and wash-off processes on urban road and roof surfaces. This paper presents the findings from the study specifically focussing on residential roof surfaces. This includes the development of mathematical equations for the replication of solids build-up and wash-off processes on roofs and developing a detailed understanding of the role of roof surfaces in stormwater runoff pollution. Knowledge on pollutant contributions and build-up and wash-off processes on roof surfaces is important in order to assess their impact on receiving waters and to develop effective pollution mitigation strategies.

MATERIALS AND METHODS

Investigation methodology

Two model roofs of 3 m^2 area with a 20^0 angle were fabricated based on the concept of research on small test plots. The use of small test plots eliminated possible heterogeneity of pollutant distribution over the surface and the surface characteristics of actual roofs. The model roofs as test plots provided a close replication of actual roof surfaces. Two roofing products; corrugated steel and concrete tiles were used for cladding. These are the most widely used roofing materials in the study region. The model roofs were mounted on a scissor lift arrangement as shown in Figure 1(a) and kept in a typical urban area. As such, they could be raised to the typical roofing height to enable pollutant build-up under natural conditions and then lowered to the ground level for pollutant build-up and wash-off data collection (Figure 1b). This approach was adopted in order to eliminate the practical difficulties inherent in investigating pollutant processes on actual roofs. The specific characteristics of the study sites are listed in Table 1.

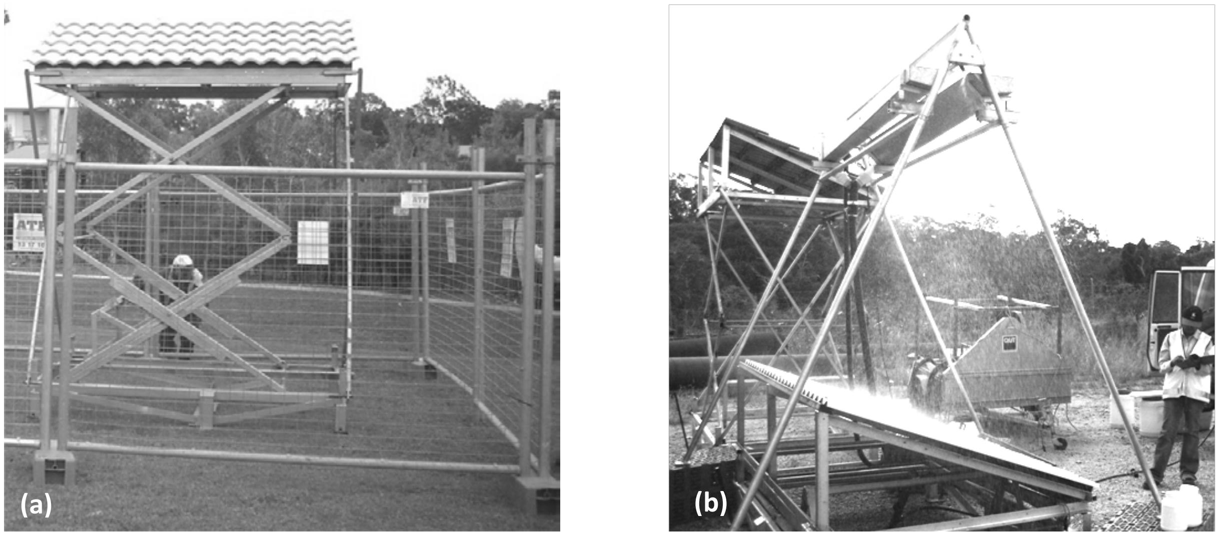


Figure 1 Model roof surfaces: (a) Model roofs with the scissor lift arrangement; (b) Pollutant wash-off investigation using the rainfall simulator

A rainfall simulator was employed to investigate pollutant wash-off from the model roof surfaces (Figure 1b). This was to eliminate the dependency on natural rainfall events due to their inherent uncertainty and variability. The approach adopted provided better control over influential variables such as rainfall intensity and duration. The rainfall simulator was designed to replicate raindrop size and raindrop terminal velocity same as natural rainfall. Details on the design of the rainfall simulator can be found in Herngren et al. (2005a). De-mineralised water spiked to replicate typical rainwater quality in the region was used for the simulations.

Table 1 Study site characteristics and build-up coefficients for total solids (adapted from Egodawatta & Goonetilleke 2008)

Scenario	Surface type and surrounding site characteristics	*a*	*b*
1	Road surfaces in residential areas with relatively high population density (eg. duplex or townhouse dwellings) and close proximity to major arterial roads (less than 1km)	0.29	0.16
2	Road surfaces in residential areas with low population density (eg. single detached housing)	0.165	0.16
3	Roof surfaces close to industrial and commercial activities, close proximity to major arterial road (high anthropogenic activity)	0.43	0.266
4	Roof surface in a residential suburb, minimal anthropogenic activities	0.06	0.266

Roof Surface Investigations

Roof surfaces were investigated separately for pollutant build-up and wash-off. Build-up samples were collected by washing half of each roof surface with de-mineralised water using a soft brush. The runoff was collected in clean plastic containers using a typical roof gutter system. Build-up investigations were conducted for a variable number of antecedent dry days from 1 to 21 days. In the case of rain interruptions, sampling was repeated until samples could be obtained for the specified antecedent dry periods. It was hypothesised that the build-up varies primarily with the antecedent dry days (Egodawatta & Goonetilleke 2008).

Wash-off sample collection was carried out for simulated rain events of 20, 86 and 135 mm/hr intensities on the corrugated steel roof surface and 40, 65 and 115 mm/hr intensities on the concrete tile roof surface. Different rainfall intensities were simulated on the two cladding materials. Egodawatta et al. (2009) had previously identified that pollutant wash-off is not influenced by the type of cladding material. The selected intensity range represents more than 90% of the rainfall events in the study region. Wash-off sampling was carried out on the remaining half of the roof surface which was not used for build-up investigations. For the simulations, the rainfall simulator was placed exactly above the lowered model roof (Figure 1b). Simulations were conducted until relatively clean runoff was observed. The process was repeated for each sampling episode.

Laboratory testing

Build-up and wash-off samples were transported to the laboratory immediately after collection, for testing. Sample handling and preservation was undertaken according to stipulated standards (AS/NZS 1998). The samples collected were separated into total and dissolved samples and were tested for, total solids (TS), total organic carbon (TOC), nitrite nitrogen (NO_2^-), nitrate nitrogen (NO_3^-), total Kjeldahl nitrogen (TKN), total nitrogen (TN), phosphate (PO_4^{3-}) and total phosphorus (TP). The testing was carried out according to methods specified in APHA (2005), US EPA (1983) and US EPA (1993).

RESULTS AND DISCUSSION

Suspended solids were considered as the primary pollutant in the data analysis undertaken. The analysis undertaken consisted of deriving mathematical equations to replicate solids build-up and wash-off processes on roof surfaces and the analysis of the wash-off behaviour of a range of pollutant types.

Replication of pollutant build-up

The processes of pollutant build-up and wash-off on impervious surfaces can be considered as generic (Sartor et al. 1974). It is commonly known that pollutant build-up on road surfaces can be replicated using a decreasing rate increasing function (Ball et al. 1998; Egodawatta & Goonetilleke 2008; Sartor et al. 1974). It has also been noted that pollutant build-up on road surfaces can be best replicated using a power form of equation (Ball et al. 1998).

The outcomes from the overall research study relating to pollutant processes on road surfaces provided the baseline knowledge for the roof surface analysis. Based on the data analysis undertaken, it was found that the build-up on roof surfaces can be mathematically replicated using a power form of build-up replication equation same as for road surfaces (Egodawatta & Goonetilleke 2008; Egodawatta et al. 2009). The generic build-up replication equation recommended is given as Equation 1 below:

$$B = aD^b \tag{1}$$

Where:

B Build-up load (g/m^2)

D Antecedent dry days (days)

a Multiplication build-up coefficient (dimensionless)

b Power build-up coefficient (dimensionless)

In order to estimate pollutant build-up, accurate determination of the build-up coefficients, *'a'* and *'b'* is essential. The multiplication build-up coefficient *'a'* was found to vary with site specific characteristics such as land use, surrounding traffic and surface cover characteristics. The power build-up coefficient *'b'* is unique for a particular surface type. Based on the analysis undertaken, coefficient *'b'* was estimated to be 0.16 for road surfaces and 0.266 for roof surfaces irrespective of the cladding material. Similarly, the measured build-up data from the field investigations was used to develop multiplication build-up coefficient *'a'* for the selected sites. Table 1 above gives the values obtained for TS for roofs in comparison with the values obtained for road surfaces.

Replication of pollutant wash-off

As noted by Sartor et al. (1974), pollutant wash-off on road surfaces can be best replicated using an exponential equation. In the overall study, a modified wash-off replication equation derived for road surfaces was used as the initial platform (Egodawatta et al. 2007). In the modified equation, a parameter referred to as fraction wash-off *(Fw)* is included which is the weight ratio of the cumulative wash-off pollutants to the initially available pollutants (build-up). The definition of *Fw* enables the elimination of the influence of initially available pollutants on the wash-off process and accordingly, the results from different sites can be compared.

Secondly, the exponential pollutant wash-off equation was modified by introducing the coefficient, 'capacity factor' (C_F). C_F defines the capacity of a specific rainfall intensity to mobilise pollutants available on impervious surfaces. It was observed during the field investigation of road surfaces that only a fraction of the available pollutants are mobilised during a simulated rain event. This observation has also been confirmed by other researchers in relation to natural rainfall on road surfaces (for example, Vaze & Chiew 2002). Therefore, C_F has a value ranging from 0 to 1 depending on the rainfall intensity. Other factors such as surface condition, characteristics of the available pollutants and slope of the surface which may also have an influence on wash-off are incorporated into the wash-off coefficient *(k)*. Based on the study outcomes, the format of the wash-off equation proposed is given as Equation 2 below:

$$Fw = C_F(1 - e^{-kIt}) \tag{2}$$

Where:

Fw Fraction wash-off (dimensionless);
C_F Capacity factor (dimensionless);
I Rainfall intensity (mm/hr); and
k Wash-off coefficient (dimensionless).

Pollutant wash-off is also a generic process and the variation of the surface type, from road to roof, can be incorporated by adjusting the *'k'* value. Based on this premise, the coefficients for roof surfaces were derived based on the field data collected. In summary, the recommended *'k'* value obtained for road surfaces was 8 x 10^{-4} and for roof surfaces was 9.33 x 10^{-3} (Egodawatta & Goonetilleke 2008).

Based on the field investigations and the knowledge developed for road surfaces, the C_F value for roof surfaces was found to vary same as the road surfaces for the same three different rainfall intensity ranges. The values obtained are given in Table 2 below.

Table 2 Comparison of C_F values for road and roof surfaces (Egodawatta et al. 2007; Egodawatta & Goonetilleke 2008)

Rainfall intensity	C_F Value	
	Road surfaces	Roof surfaces
20 - 40mm/hr	0.3 - 0.5	0.75 - 0.91
40 - 90mm/hr	0.5	0.91
90 - 115mm/hr	0.5 - 1	0.91 - 1.0

It is evident that the C_F values for roofs are significantly high compared to road surfaces. This would mean that even for small rainfall intensity events, a significant fraction of pollutants available will wash-off. For example, a rainfall intensity of 20 mm/hr will result in 75% wash-off of the build-up pollutants whilst at high intensities the percentage wash-off can reach 100%. This can be interpreted as first flush behaviour of roof surface and will significantly contribute to first flush of the catchment.

Roof surface solids contributions

As part of the overall research study, the build-up and wash-off replication equations developed for road and roof surfaces were used to model stormwater pollutant contributions from three small urban catchments, namely, Alextown, Birdlife Park and Gumbeel, in Gold Coast, Australia. Characteristics of the catchments are given in Table 3 below. It is commonly known that stormwater quality models are subjected to inherent uncertainty primarily due to differences in model structure and input parameters compared to nature (Kanso et al. 2005; Frein et al. 2009). However, outcomes of stormwater models are essential for decision making. Unlike typical modelling approaches where calibration is used for extracting the most suitable coefficient sets for a given model structure, the use of measured data for the development of replication equations and coefficients as adopted in this modelling approach reduces the inherent uncertainty in stormwater quality estimation. Furthermore, the derivation of different sets of coefficients for roads and roofs further strengthens the scientific robustness of the modelling approach.

Outcomes of the modelling exercise were analysed to assess the contributions of total solids from road and roof surfaces separately. Driveways were modelled same as roofs as these areas have low traffic volume. Outcome of the modelling exercise is presented in Figure 2.

Figure 2 shows that the contributions from roof surfaces (total solids in this instance) significantly exceeds the contributions from road surfaces and thereby confirms the importance of roof surfaces as an urban stormwater pollutant source. This is attributed to two primary factors.

- The roof area percentage is higher than the road area for all catchments.
- Use of scenario 3 parameters (in Table 1) for the modelling exercise. Scenario 3 is for a catchment with a high level of anthropogenic activities which replicates regions with close proximity to major arterial roads and the presence of industrial and commercial activities.

Table 3 Characteristics of the study catchments

Catchment	Land use	Extent	Impervious fraction		
			Roads	Roofs	driveways
Alextown	Townhouses	2.2 ha	10.5%	38.1%	8.6%
Birdlife Park	Detached housing	8.1 ha	12.4%	23.4%	11.2%
Gumbeel	Duplex housing	0.8 ha	10.3%	19.2%	11.2%

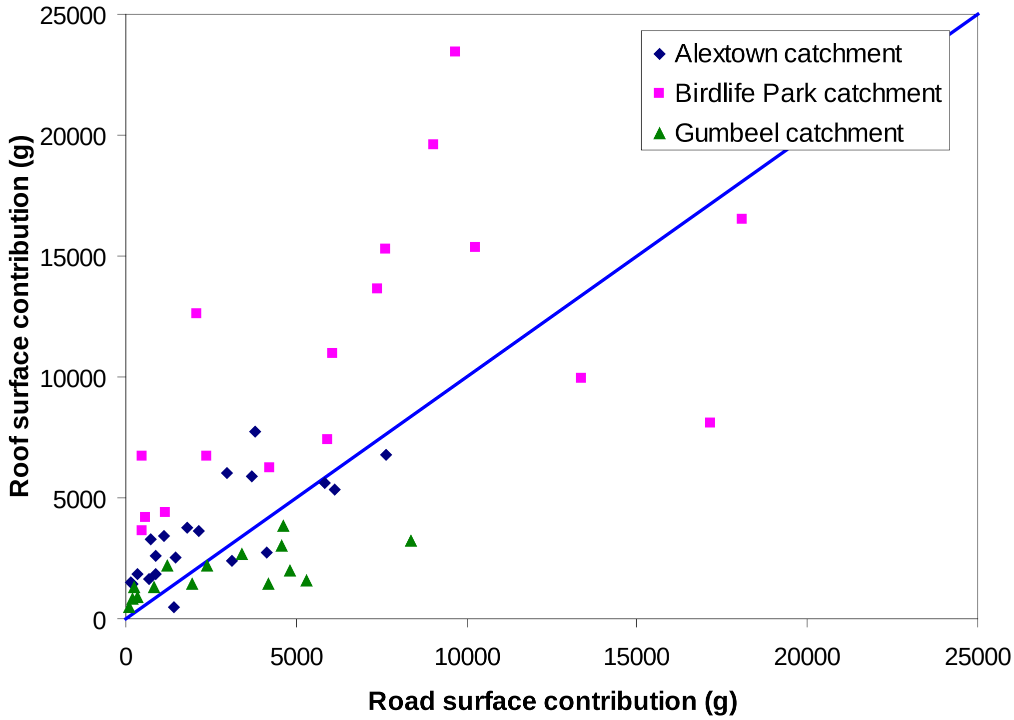


Figure 2 Pollutant contributions from road and roof surfaces

As shown in Table 1, the multiplication build-up coefficient for scenario 4 for a catchment with minimal anthropogenic activities is 0.06. This is a significant reduction compared to the value used for the modelling exercise, which is 0.43. Consequently, for a build-up multiplication coefficient of this range, the importance assigned to roof surfaces as a stormwater pollutant source is reduced. This suggests that the provision of effective buffer zones from major traffic activities and other anthropogenic activities can be an effective mitigation strategy for roof generated stormwater pollution. Furthermore, catchments located a distance from major traffic activities would be the most appropriate for rainwater harvesting.

Contributions of other pollutants

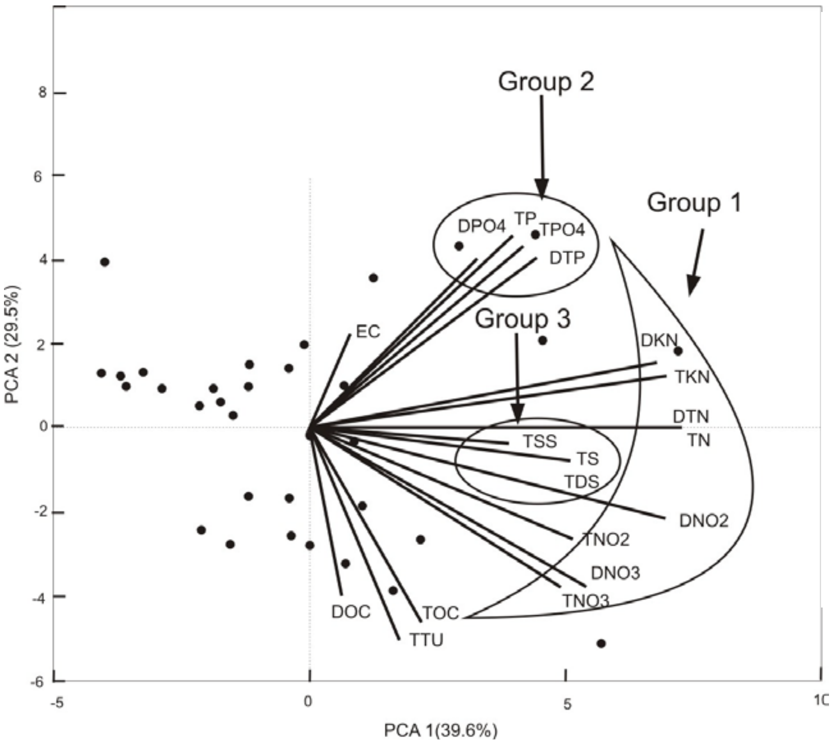
The discussion so far was focused on solids build-up and wash-off characteristics on roof surfaces. However, as noted by Goonetilleke et al. (2009) and Murakami et al. (2008), other pollutants can be more important than the physical presence of solids in stormwater runoff under specific circumstances in relation to stormwater pollution and rainwater harvesting. Additionally, other pollutants that create significant impacts on receiving water quality such as total organic carbon (TOC), total nitrogen (TN) and total phosphorus (TP) were also selected for analysis as associated pollutants. These pollutants are regarded as creating the most significant impacts on sensitive receiving water ecosystems (Healthy Waterways 2003). Table 4 gives the range of the availability of these pollutants as a ratio of total solids, for the build-up samples collected from roof surfaces.

Table 4 Variation of pollutant to solids ratio for the roof surfaces

Pollutant type	Pollutant to solids ratio
TOC	0.07 – 0.8
TN	0.02 – 0.1
TP	0.01 – 0.06

As evident in Table 4, the range of TN and TP is comparatively low and may not provide high pollution potential. However, the range of TOC suggests the possibility of having a higher portion of roof surfaces solids in organic form. In addition to being a important pollutant in its own right, organic carbon can also enhance the adsorption of other pollutants such as heavy metals to solids and can be influential in determining their solubility and hence, bioavailability. This may cause significant threats to the receiving water ecosystem.

The analysis of pollutants associated with solids was further extended to understand the relationships between the parameters tested for roof surface wash-off. This included a range of nutrient species. The analysis was undertaken using principal component analysis (PCA) which is a widely used pattern recognition technique in water quality research. PCA transforms multivariable data matrices to a set of principal components (PCs) so that the first few PCs contain most of the useful information. Figure 3 shows the PCA biplot for PC1 versus PC2, which accounts for around 70% of the data variance. A biplot is a graphical representation of PCA outcomes where variables are displayed in the form of vectors and events displayed in the form of data points. In this study, the biplot was used to identify correlations between variables and event clustering. Further details of PCA can be found elsewhere (for example, Adams 1995).



Note: TNO2- Total nitrite-nitrogen; DNO2- Dissolved nitrite-nitrogen; TOC- Total 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; TDS- Total dissolved solids; TS- Total solids; TPO4- Total Phosphates; DPO4- Dissolved Total Phosphates; TP- Total phosphorus; DTP- Dissolved total phosphorus

Figure 3 PCA biplot for all the physico-chemical parameters for roof surfaces wash-off

The main purpose of PCA was to identify the correlations among the different pollutant species and to group these clusters accordingly. This was to identify the characteristics of wash-off behaviour of different pollutant types. Based on the patterns observed in Figure 3, three major correlating clusters are identified. They are:

- Group 1: TNO3, DNO3, TNO2, DNO2, TN, DTN, TKN and DKN
- Group 2: TPO4 ,DPO4, TP and DTP
- Group 3: TDS and TS

Correlation of Group 1 and Group 3 variables suggests similar wash-off behaviour of TN and its sub-species from roof surfaces, to TS. As discussed in Section 3.2, solids wash-off from roof surfaces is nearly complete and occurs within the initial period of a rainfall event (Egodawatta & Goonetilleke 2008; Egodawatta et al. 2009; Miguntanna et al. 2010). This suggests similar wash-off behaviour for total nitrogen and its sub species.

Relatively low correlations are shown by Group 3 variables with Group 2 variables, and Group 3 variables with TOC. This suggests that the wash-off of phosphorus species and organic carbon does not show similarities to TS wash-off behaviour. The wash-off of phosphorus species and organic carbon could be delayed compared to solids and may not be contributing significantly to the first flush pollutant load. This highlights the possible limited effectiveness of first flush devices used in rainwater harvesting. Furthermore, this also highlights the potential limited effectiveness of mitigation actions targeting first flush in stormwater runoff.

CONCLUSIONS

The primary conclusions derived from this study in relation to roof surfaces are as follows:

- Roof surfaces are a significant pollutant source in urban catchments and under certain circumstances its contribution may even exceed the pollutant contribution from road surfaces. Therefore, roof surfaces may need to be specifically taken into consideration in urban water quality modelling.
- The mathematical equations developed for pollutant build-up and wash-off on roof surfaces are similar to those for road surfaces, but with different coefficients.
- Roof surface pollutant wash-off can be termed as a first flush with most of the available pollutant load being removed quite readily by stormwater runoff, unlike road surfaces.
- Contributions of nitrogen and phosphorus species from roof surfaces can be relatively low. However, roofs can be a significant contributor of solids and organic carbon loading.
- Organic carbon and phosphorus compounds show wash-off characteristics different to solids and nitrogen. The wash-off of organic carbon and phosphorous is possibly in the latter part of storm events with limited contribution to the first flush load.
- Devices that target the removal of pollutant loading from first flush may have limited effectiveness due to varied wash-off behaviour of different pollutant species.

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