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Pollutant characteristics on roof surfaces for evaluation as a stormwater harvesting catchment

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ABSTRACT

This paper presents the outcomes of a study which focused on evaluating roof surfaces as stormwater harvesting catchments. Build-up and wash-off samples were collected from model roof surfaces. The collected build-up samples were separated into five different particle size ranges prior to the analysis of physico-chemical parameters. Study outcomes showed that roof surfaces are efficient catchment surfaces for the deposition of fine particles which travel over long distances. Roof surfaces contribute relatively high pollutant loads to the runoff and hence significantly influence the quality of the harvested rainwater. Pollutants associated with solids build-up on roof surfaces can vary with time, even with minimal changes to total solids load and particle size distribution. It is postulated that this variability is due to changes in distant atmospheric pollutant sources and wind patterns. The study highlighted the requirement for first flush devices to divert the highly polluted initial portion of roof runoff. Furthermore, it is highly recommended to not to harvest runoff from small intensity rainfall events since there is a high possibility that the runoff would contain a significant amount of pollutants even after the initial runoff fraction.

Keywords: Rainwater harvesting; Roof runoff; Stormwater pollution

1. Introduction

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 continuing urbanisation and scarcity of natural water resources, strategies to use rainwater as a potable water supply are increasingly being investigated. There has been growing interest in the use of harvested rainwater as an alternative source for drinking water [1, 2]. [1] noted that harvested rainwater currently can be used for a number of domestic purposes such as toilet use and washing machine use without undergoing treatment.

In determining the end use and the potential success of potable use, the possible problems associated with water quality need to be assessed 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 2, 3] harvested rainwater can contain significant amounts of pollutants such as heavy metals, nutrients and pathogens. [4] 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

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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 4, 5]. 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 [6, 7].

This study was conducted to understand the characteristics of pollutant build-up and wash-off from roof surfaces and hence to contribute to the knowledge needed for improving harvested rainwater quality. In this study, the specific focus was on the primary indicators of rainwater quality including solids, organic matter and nutrients. The research consisted of a series of field investigations and laboratory testing. Data generated from the field investigations were analysed to understand the characteristics of build-up and wash-off processes on roof surfaces. Based on the understanding generated from the data analysis, important recommendations are provided to improve the quality of harvested rainwater.

2. Methods

2.1. Sampling sites and research tools

A residential suburb, in Gold Coast, South East Queensland, Australia was selected for field investigations. 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 [8].

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 (see Fig. 1). 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 to enable pollutant accumulation and lowered to 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.

Fig. 1. Deployment of roof surfaces at the study site.

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 [9, 10]. The specially designed rainfall simulator (see Fig. 2) consisted of an A-frame structure with three Veejet 80100 nozzles connected to a nozzle boom and standing at 2.5 m above ground level. The nozzle boom can swing in either direction with controlled speed and delay. This enables the simulator to be calibrated for different rainfall intensities. A detailed description of the rainfall simulator can be found in [11].

2.2. Sample collection, preservation and testing

2.2.1. Build-up sampling

On each roof surface, half of the area (1.5 m^2) was used to collect pollutant build-up while the other half was used for wash-off sampling (see Fig. 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 Fig. 3). The gutter was thoroughly washed before and after each sample collection. Once the sample collection was completed, the model roofs were lifted to typical roofing height and left at the site until the next sampling episode. Sampling was done three times for each roof surface with samples collected after 8, 6 and 6 antecedent dry days. Even though the researchers have noted that build-up may vary with the antecedent dry days, it was not used as a variable in this study.

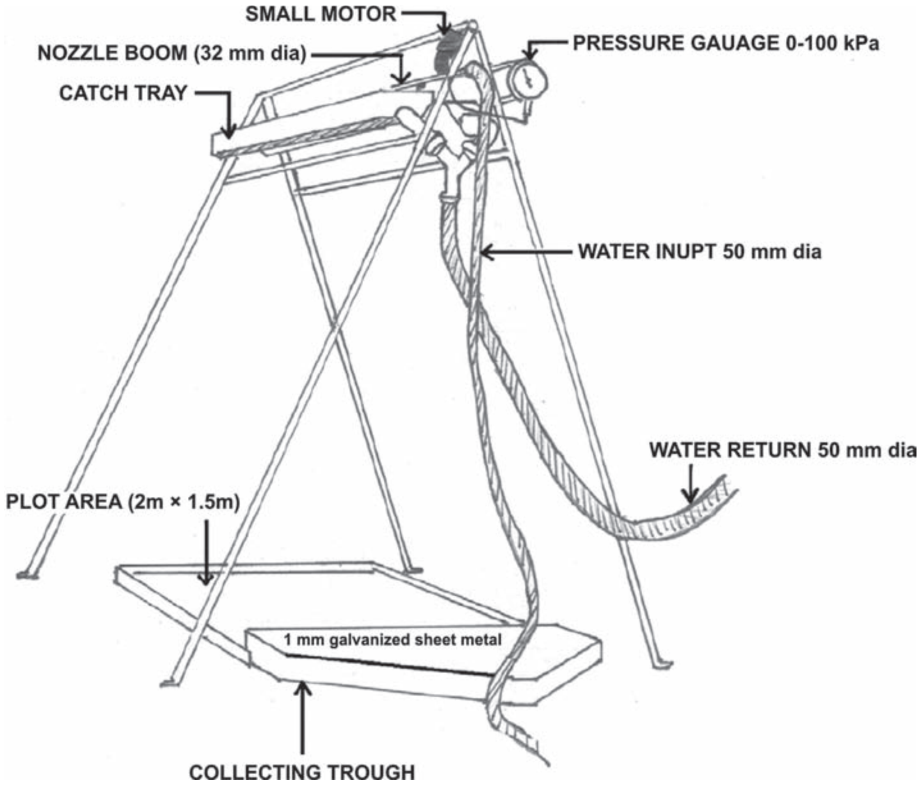

Fig. 2. Schematic diagram of the rainfall simulator used for the study Adapted from Herngren *et al*. (2005).

Fig. 3. Collection of build-up samples.

Fig. 4. Wash-off sample collection from the roof surface.

2.2.2. Wash-off sampling

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 characteristics in the Gold Coast area. The selected intensity range represents more than 90% of the regional rainfall events.

Wash-off sampling was carried out on the remaining half of the roof surface which was not used for build-up investigations. This was carried out by fixing the gutter at the other half of the roof surface (see Fig. 4). 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 Fig. 4. Finally, the model roof was lifted to typical roofing height and left at the site until the next sampling episode.

2.3. Laboratory testing

The build-up samples were first analysed for their particle size distribution using Malvern Mastersizer S instrument. As different types of pollutants show different degree of affinity to different particle size ranges, the physico-chemical parameters of build-up pollutants were analysed for different particle size ranges separately. The build-up samples were separated into five particle size ranges using wet sieving, namely >300 µm, 150–300 µm, 75–150 µm, 1–75 µm and <1 µm for further analysis. The particle size class <1 µm represented the potential soluble fraction of pollutant build-up. The selection of these particle size ranges were based on their recognised importance as critical particle size ranges in the context of adsorption of other stormwater pollutants [12, 13]. The total build-up samples and wet sieved samples 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). Wash-off samples were tested only for TS and particle size distribution. The testing was carried out according to methods specified in [14] and [15, 16].

3. Results and discussions

3.1. Analysis of build-up

The analysis was underpinned by two stages. Firstly, the TS loads and the particle size distribution of the collected build-up samples were analysed primarily to understand the physical characteristics of build-up. Secondly, physico-chemical analysis was carried out to understand the chemical characteristics of pollutant build-up.

As [8] who used same two roof surfaces and noted that the characteristics of pollutant build-up and wash-off are independent of the type cladding material, the samples collected from the two roof surfaces were considered to have similar characteristics. Therefore, build-up data analysis was done using the averaged pollutant loads obtained for each sampling episode for both roof surfaces. Samples were named as BU1, BU2 and BU3 which represented the first, second and third sampling episodes respectively.

3.1.1. Total solids load

Table 1 shows the average TS loads obtained from each sampling episode. The build-up loads collected from the three sampling episodes are in the same order and closely comparable with the amounts recovered from roof surfaces in past research studies [17, 18]. [18] noted that build-up on roof surfaces can vary in the range of 160–1200 mg/m^2. According to [8] who carried out investigations using the same roof surfaces but in a different location with significantly different land use activities, the pollutant build-up for 7 days of antecedent dry period was around 800 mg/m^2. This is considerably higher than the build-up load found in this research study. This highlights the highly variable nature of pollutant build-up loads for different sites. This variability could be attributed to the significant influence exerted by factors such as the nature of anthropogenic activities in the area and site specific characteristics such as urban form and climatic conditions which were not investigated in this study [6, 18].

3.1.2. Particle size distribution

Particle size distribution of the build-up samples collected is shown in Fig. 5. As evident in Fig. 5, around 80% of the solids are finer than 150 µm for all the build-up samples. This indicates that the build-up on roof surfaces contains a significant amount of fine particles. Fineness of solids build-up could be attributed to the fineness of atmospheric depositions. The presence of large amounts of fine particles in solids build-up is an important factor to be taken into consideration from the perspective of stormwater harvesting, as high amounts of pollutants are generally attached to the finer fraction of solids [for example 12, 19].

3.1.3. Physico-chemical characteristics of solids build-up

Table 2 shows nutrients and organic carbon loads obtained for each sampling episode per unit area of the roof surface. As evident in Table 2, pollutant loads exhibited significant variation among the three sam-

Table 1
Average TS load.

Sample ID	Total solids load	Antecedent dry days
BU1	190 mg/m^2	8
BU2	190 mg/m^2	6
BU3	180 mg/m^2	6

pling episodes. For example, TOC in BU1 and BU2 are more than three times that for BU3 sampling episode. Such variation in the pollutant loads has occurred with no changes in the site and land use characteristics and minimal variation to the TS load. Since no abnormal anthropogenic activity was observed in the near vicinity of the selected site during the investigation period, the variability of pollutant loads was attributed to activities a distance away producing significant atmospheric pollutants. This underlines the need to consider the variation of pollutant loads on roof surfaces as a function of time in addition to the variability of pollutant loads with land use. This can add an extra degree of complexity to harvested rainwater quality control measures. In this context, understanding the build-up process of pollutants is imperative for the evaluation of the rainwater quality and design of treatment facilities targeting the optimum removal of pollutants.

As the time variability of pollutant loading could be attributed to their sources at long distances, understanding the transport mechanism of these pollutants is important to understand the build-up process. Transport of these pollutants is primarily dependent on the particle size where fine particles are capable of travelling long distances. For this purpose, the pollutant loads for each particle size range was analysed (see Table 3). As shown in Table 2, pollutant loads in BU2 is significantly higher compared to BU1 and BU3. Furthermore, as evident in Table 3, the fine particle size range (particles <150 µm) show higher loads of all the pollutants in the build-up load in BU2 compared to that of the coarser particle size range (particles >150 µm).This confirms the highly polluted nature of fine particles in the second day sampling episode. It was noted that on the day of the second sampling episode (BU2) it was relatively windy compared to the first and third sampling episodes. Therefore, it can be surmised that these fine particles may be travelled from long distances due to the wind effect. Furthermore, as seen in Table 3, a relatively higher amount of organic matter is present in the particle size range <150 µm. This could also be attributed to the atmospheric depositions where a range of sources such as industrial emissions could contribute high loads of organic matter.

Additionally, as evident in Table 3, particle size range <150 µm invariably contains higher pollutants loads compared to the particle size ranges >150 µm for all the sampling episodes. As noted in Fig. 5, this is the dominant particle size range in roof surface solids build-up. As these particles can be easily washed-off with the runoff, it can exert a strong influence on the quality of harvested rainwater. This implies the need for exercising care in the use of harvested roof runoff for potable purposes.

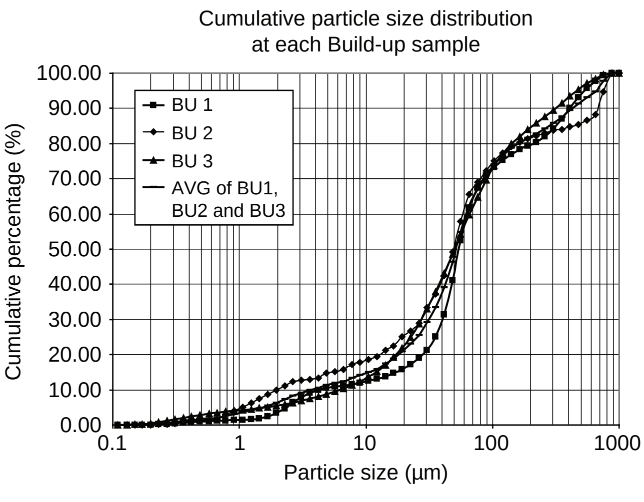

Fig. 5. Cumulative particle size distribution of each build-up sample.

3.2. Analysis of wash-off

Analysis of pollutant build-up revealed that even though the solids load on roof surfaces are similar for each sampling episode, there are significant differences in terms of associated pollutants. This implies the possible variation of pollutants with factors such as closeness to their sources and time. Such variability confirms the deposition of any type of pollutant on a roof surface for any land use in a specific time period.

According to several research findings (for example 9), solids is not only a significant stormwater pollutant in its own right, but also act as a mobile substrate for the transport of other stormwater pollutants such as nutrients, heavy metals and hydrocarbons. Therefore, suspended solids can be used as a surrogate to replicate the

Table 2
Pollutant loads in each build-up sample (mg/m^2).

Sample Name	TOC	NO_2^-	NO_3^-	TKN	TN	PO_4^{3-}	TP
BU1	31.99	0.50	1.07	2.88	4.46	1.30	1.40
BU2	48.85	0.71	1.40	4.25	6.35	2.97	3.54
BU3	9.94	0.54	1.15	1.33	3.01	1.68	1.88

Table 3
Amount of pollutants in different particle size fractions (mg/g).

Particle size class (μm)	TOC (mg/g)	NO_2 (mg/g)	NO_3 (mg/g)	TKN (mg/g)	TN (mg/g)	PO_4^3 (mg/g)	TP (mg/g)
BU1 < 1	62.69	1.42	3.11	3.43	7.96	0.92	1.09
BU1-1-75	14.86	0.06	0.18	0.97	1.21	2.06	2.14
BU1-75-150	79.21	0.36	0.91	7.11	8.38	0.42	0.50
BU1-150-300	8.12	0.38	0.92	1.36	2.66	1.52	1.84
BU1 > 300	7.43	0.42	0.73	1.67	2.82	1.36	1.59
BU2 < 1	80.68	2.63	4.52	7.39	14.54	0.98	1.21
BU2-1-75	31.55	0.05	0.08	1.66	1.79	5.23	6.82
BU2-75-150	90.40	0.78	1.08	10.27	12.13	3.05	3.17
BU2-150-300	18.84	0.28	1.02	1.73	3.03	3.33	3.41
BU2 > 300	11.27	0.22	0.90	2.21	3.33	3.10	3.43
BU3 < 1	22.62	1.59	3.53	1.62	6.74	0.81	1.13
BU3-1-75	4.18	0.08	0.29	1.48	1.85	2.39	2.57
BU3-75-150	9.58	0.65	1.26	1.47	3.38	1.66	1.86
BU3-150-300	6.89	0.21	0.55	1.69	2.45	2.22	2.54
BU3 > 300	7.35	0.25	0.74	1.16	2.15	1.88	2.00

Note: TOC-Total organic carbon; NO_2^--nitrite-nitrogen; NO_3^--nitrate-nitrogen; TKN-Total kjeldahl nitrogen; TN-Total nitrogen; TPO_4^{3-}-Total Phosphates; TP-Total phosphorus.

wash-off behaviour of other pollutants. This is further supported by the findings of this study as high amount of nutrients and organic carbon were attached to the fine solids as noted above (Table 3). The variation of solids wash-off with different rainfall intensities and durations was analysed to understand the pollutant wash-off process on roof surfaces.

Figure 6 shows the variation of TS concentration with rainfall duration for all the intensities. As evident in Fig. 6, TS concentrations decrease exponentially with the rainfall duration for all the intensities. This general trend of variation is in agreement with TS wash-off behaviour on roof surfaces as observed by past researchers [19, 20, 21]. Variations of solids concentrations in the wash-off for different intensities show that concentrations for higher intensities reduce rapidly with rainfall duration. This could be attributed to the higher wash-off capacity of high intensity rainfall events where most of the roof surface pollutants are removed during the initial period of the rain event. As explained by [8], rainfall events with a relatively lower intensity does not have capacity to immediately wash-off a high fraction of the available pollutants on roofs.

As evident in Fig. 6, the observed concentration for 20 mm/h reduced to less than 50 mg/L approximately after 5 min and it stays above 25 mg/L for the entire 12 min length of the simulated rain. This suggests that the possibility of having significant amount of pollutants in roof runoff even after relatively long duration of a small intensity rain event. As roof surface can contain a varied range of pollutants irrespective of the land use,

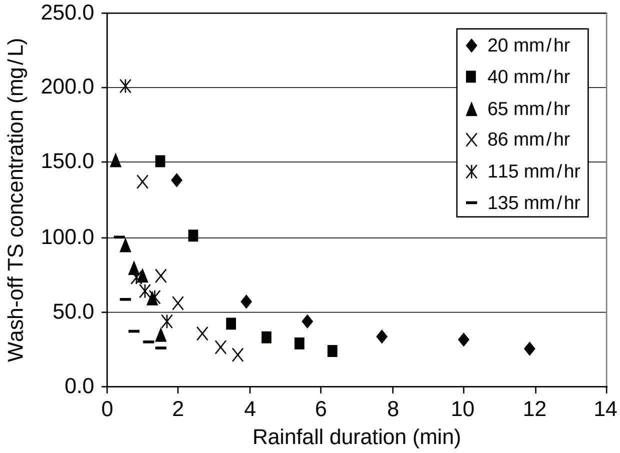

Fig. 6. Variation of TS concentration with rainfall duration and intensity.

the pollutants in even the latter part of runoff for low intensity rain events could contain toxic substances.

It is clear that the initial portion of runoff originating from roof surfaces contain a significant amount of pollutants. This indicates the necessity of a first flush device to remove the initial portion of runoff from roofs. However, as seen in Fig. 6, it is difficult to prescribe a volume of runoff so that pollutant concentration in the remaining runoff is below a threshold level. This confirms that conventional first flush devices that capture a prescribed volume of runoff will not function effectively to reduce rainwater tank contamination. This observation has also been confirmed by [8].

4. Conclusions

- Roof surfaces are efficient catchment surfaces for the deposition of fine particles which can travel over long distances. More than 80% of the particulate matter in roof build-up is finer than 150 µm. Particle size fraction <150 µm is the most polluted fraction in solids build-up. Therefore, this could have a significant impact on the quality of the harvested rainwater.
- Pollutants associated with the solids build-up on roof surfaces can vary with time even with minimal changes in the TS load and particle size distribution. Variability with time adds an extra complexity to the pollutant build-up on roof surfaces. It can be postulated that this variability is due to changes in distant atmospheric pollutant sources and wind patterns.
- It is recommended that the earlier part of the runoff should not be harvested in order to minimise the contamination of the rainwater collected.

References

[1] C. Zorn and D. Wheatley, Rainwater Harvesting – An option to reduce demand on the Akaroa potable water supply. A report submitted in partial fulfilment of the requirements for the BE (Hons) Degree in Natural Resources Engineering, University of Canterbury, New Zealand (2009).

[2] V. Meera and M.M. Ahammed, Water quality of rooftop rainwater harvesting systems: a review, Journal of Water Supply Research and Technology, 55 (4) (2006), 257–268.

[3] K. Zhu, L. Zhang, W. Hart, M. Liu and H. Chen, Quality issues in harvested rainwater in arid and semi arid Loess Plateau of northern China, Journal of Arid Environments, 57 (2004) 487–505.

[4] C.A. Evans, P.J. Coombes, and R.H. Dunstan, Wind, rain and bacteria: the effect of weather on the microbial composition of roof-harvested rainwater, Water Research, 40 (2006) 37–44.

[5] D.J. Lye, Health risk associated with consumption of untreated water from household roof catchment systems, Water Resources Association, 38 (2002) 1301–1306.

[6] M.C. Gromaire-Mertz, S. Garnaud, A. Gonzalez and G. Chebbo, Characterisation of urban runoff pollution in Paris, Water Science and Technology, 39 (1999) 1–8.

[7] R. Yufen, W. Xiaoke, O. Zhiyun, Z. Hua, D. Xiaonan and M. Hong, Stormwater runoff quality from different surfaces in an urban catchment in Beijing, China, Water Environment Research, 80 (8) (2008) 719–724.

[8] P. Egodawatta, E. Thomas and A. Goonetilleke, Understanding the physical processes of pollutant build-up and wash-off on roof surfaces, Science of the Total Environment, 407 (2009) 1834–1841.

[9] L. Herngren, A. Goonetilleke and G.A. Ayoko, Analysis of heavy metals in road-deposited sediments, Analytica Chimica Acta, 571 (2006) 270–278.

[10] P. Egodawatta and A. Goonetilleke, Modelling pollutant build-up and wash-off in urban road and roof surfaces, Proceedings of Water Down Under Conference, Adelaide, Australia (2008).

[11] L. Herngren, A. Goonetilleke, R. Sukpum and D.Y. De Silva, Rainfall simulation as a tool for urabn water quality research, Enviromental Engineering Science, 22 (3) (2005), 378–383.

[12] L. Herngren, Build-up and wash-off process kinetics of PAHs and heavy metals on paved surfaces using simulated rainfall. Queensland University of Technology – Thesis, Brisbane, Australia (2005).

[13] J.D. Sartor and B.G. Boyd, Water pollution aspects of street surface contaminants. Report No. EPA-R2-72/081, US Environmental Protection Agency, Washington, DC, USA (1972).

[14] APHA, Standard methods for the examination of water and waste water. Washington, D.C: American Public Health Association (2005).

[15] US EPA, Method 365.4: Phosphorous, total (Colorimetric, automated, block digester AA II). US EPA Environmental Protection Agency, Washington, DC. EPA/600/4-79/020 (1983).

[16] US EPA, Method 351.2: Determination of total kjeldahl nitrogen by semi automated colorimetry. US EPA Environmental Protection Agency, Washington, DC. EPA/600/4-79/020-(1993).

[17] H. Furumai, Y. Hijioka and F. Nakajima, Modelling and field survey of wash-off behaviour of suspended particles from roofs and roads. Conference Proceeding Paper, American Society of Civil Engineers (2001).

[18] P.C. Van Metre and B.J. Mahler, The contribution of particles washed from rooftops to contaminant loading to urban streams, Chemosphere, 52 (2003) 1727–1741.

[19] J. Vaze and F.H.S. Chiew, Nutrient loads associated with different sediment sizes in urban stormwater and surface pollutants, Journal of Environmental Engineering, 130 (4) (2004) 391–396.

[20] U. Quek and J. Forster, Trace metals in roof runoff, Water, Air and Soil Pollution, 68 (1993) 373–389.

[21] J. Forster, Variability of roof runoff quality, Water Science and Technology, 39 (55) (1999) 137–144.