Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2016.1151382

57 (2016) 25503–25508
November

Taylor & Francis
Taylor & Francis Group

Evaluation for the contribution of different surface runoff to the pollution of wet weather flows in storm sewers

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Received 7 October 2015; Accepted 2 February 2016

ABSTRACT

In recent years, the pollution of surface runoff has raised increasing concern. However, its contribution to the contamination of wet weather flows (WWF) in storm sewers is little evaluated. A simplified mathematical method named Contribution Partition Mathematical Method for Storm Sewers was proposed, which would help small-scale residential communities to learn the contribution of different surface runoff (including roof, internal road, lawn, external road runoff and so on), mistakenly discharged wastewater (MDW) and sewer deposit erosion (SDE) to WWF pollution load in storm sewers. In a case study, internal road was found to be the greatest contributor of WWF pollution, while provided about 50% of organic compounds and total phosphorus (TP), 40% of suspended solids (SS), volatile suspended solids (VSS) and heavy metals. Meanwhile, MDW and SDE also supplied sufficient pollutants to WWF, including about 30% of TP, SS and VSS. Some suggestions were thereby proposed to better assist the local communities on their runoff pollution control.

Keywords: Contribution partition; Runoff pollution; Sewer deposit erosion; Storm sewer; Wet weather flows

1. Introduction

In recent years, due to direct or indirect pollution to the aquatic environment, the urban surface runoff, especially the first flush has attracted ever-increasing attention. According to some reports [1,2], the water quality of wet weather flows (WWF) from storm sewers in Lyon, Sydney and Beijing could reach roughly the same level as that in combined sewer overflows (CSOs), or even sometimes evidently surpassed the contamination degree of CSOs. As a result, in many countries including China, how to better manage the surface runoff pollution so as to protect the urban water environment has been an urgent concern. Meanwhile, characterizing the contribution of different surface runoff to WWF in storm sewers has turned into one of the bases of subsequent pollution control.

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So far, the contribution of different surface runoff, wastewater and sewer deposit erosion (SDE) to CSOs has been extensively evaluated. And the greatest contributors of conventional water-quality indexes such as suspended solids (SS), volatile suspended solids (VSS), chemical oxygen demand (COD), Cu(II), Pb(II) and Zn(II) in CSOs have been identified [3–7]. The results indicated that the predominant source in combined sewers varied according to the type of pollutant [7]. Generally, wastewater contributed most of organic and nitrogenous pollution to WWF, while runoff, especially the roof runoff was the primary source of heavy metals such as Pb(II) and Zn(II) [7,8]. Additionally, SDE has been proved to be an important source for Cu(II) and SS [7]. However, the comparable investigation on storm sewers is little mentioned or reported. A deeper understanding of the specific contribution of different sources to WWF pollution of storm sewers is still needed.

The purpose of this study was to evaluate the contribution of different surface runoff, mistakenly discharged wastewater (MDW) and SDE to the WWF pollution in storm sewers by a proposed mathematical method named Contribution Partition Mathematical Method for Storm Sewers (CPMMSS). A case study was also provided to assist the comprehension and application of CPMMSS. This method was expected to provide reliable reference for the pollution control of local communities without expensive human or consulting costs.

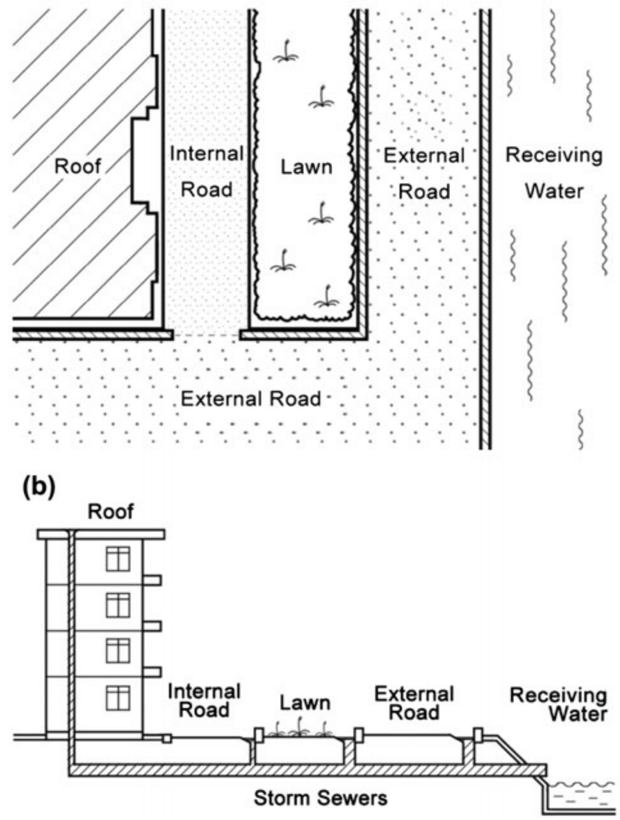

Fig. 1. Diagram of a small-scale residential community with separate drainage systems (sewage pipes were not shown): (a) vertical view and (b) side sectional view.

2. Descriptions of the mathematical methods

Fig. 1 schematically illustrates a small-scale residential community with separate drainage systems (sewage pipes were not shown). Supposing the hydrological volume balances are complete, the following formula is established:

$$V_{TR} = V_{Rf} + V_{IR} + V_{La} + V_{ER} \tag{1}$$

where V_{TR} is the total volume of rainfall, V_{Rf}, V_{IR}, V_{La} and V_{ER} are the rainfall volume on the roof, internal road (IR), lawn and external road (ER), respectively. All the above parameters were in m^3.

According to the hydrological volume balances in wet weather, Eqs. (2) and (3) are also set up:

$$V_{TW} = k_1 V_{RF} + k_2 V_{IR} + k_3 V_{La} + k_4 V_{ER} + V_{MDW} + V_{If} \tag{2}$$

$$V_{Ev} + V_{In} + V_{Rt} = (1 - k_1) V_{Rf} + (1 - k_2) V_{IR} + (1 - k_3) V_{La} + (1 - k_4) V_{ER} \tag{3}$$

where V_{TW} stands for the total volume of WWF discharged into the receiving water, V_{MDW} is the volume of MDW and V_{If} is the volume of groundwater infiltrated into the storm sewer in the studied time (wet weather). k_1, k_2, k_3 and k_4 are the runoff coefficient (RC) of roof, IR, lawn and ER, respectively. V_{Ev} is the rainfall evaporated back to the atmosphere. V_{In} is the rainfall infiltrated into the ground and V_{Rt} is the rainfall retained by the surfaces such as roof, IR, lawn, ER and so on. The unit of V_{TW}, V_{MDW}, V_{If}, V_{Ev}, V_{In} and V_{Rt} are m^3 while for RC, its unit is 1.

Within Eqs. (2) and (3), the following formulae exist:

$$k_1 = (V_{Rf} - V_{Ev1} - V_{In1} - V_{Rt1})/V_{Rf} \tag{4}$$

$$k_2 = (V_{IR} - V_{Ev2} - V_{In2} - V_{Rt2})/V_{IR} \tag{5}$$

$$k_3 = (V_{La} - V_{Ev3} - V_{In3} - V_{Rt3})/V_{La} \tag{6}$$

$$k_4 = (V_{ER} - V_{Ev4} - V_{In4} - V_{Rt4})/V_{ER} \tag{7}$$

where V_{Evi} (i = 1–4) is the rainfall evaporated back to the atmosphere from (1) roof, (2) IR, (3) lawn and (4) ER surfaces. V_{Ini} (i = 1–4) is the rainfall infiltrated into the ground from (1) roof, (2) IR, (3) lawn and (4) ER. V_{Rti} (i = 1–4) is the rainfall retained by the (1) roof, (2) IR, (3) lawn and (4) ER. All the V_{Evi}, V_{Ini} and V_{Rti} are in m^3.

Considering the stormwater is usually very large in amount and fast in flow velocity within the storm sewers, the runoff pollutants are supposed to be thoroughly discharged into the receiving water without any new formation of deposit in the sewer pipes. Meanwhile, supposing the hydrological mass balance is complete, according to a chemical mass balance approach [4,7], Eq. (8) is set up:

$$M_{TW} = V_{TW} \cdot C_{TW} = k_1 V_{Rf} \cdot C_1 + k_2 V_{IR} \cdot C_2 + k_3 V_{La} \cdot C_3 + k_4 V_{Rd} \cdot C_4 + V_{If} \cdot C_{IF} + V_{MDW} \cdot C_{MDW} + M_{SDE} \quad (8)$$

where M_{TW} is the total amount of pollutants in WWF of storm sewer. C_{TW} is the pollutant concentration in the WWF out of the storm sewer (g/m^3). C_i (i = 1–4) stands for the pollutant concentration of the (1) roof, (2) IR, (3) lawn and (4) ER runoff. C_{MDW} is the daily averaged pollutant concentration of MDW and C_{If} is the daily averaged pollutant concentration of the groundwater infiltrated into the sewer. W_{SDE} is the total amount of contamination from SDE. M_{TW} and M_{SDE} are in g, while C_{TW}, C_i (i = 1–4), C_{MDW} and C_{If} are in g/m^3.

In order to find out the contribution of different surface runoff, MDW and SDE (WE) to WWF in storm sewers, P_1–P_5 are calculated:

$$P_1 = k_1 V_{Rf} \cdot C_1 / M_{TW} \quad (9)$$

$$P_2 = k_2 V_{IR} \cdot C_2 / M_{TW} \quad (10)$$

$$P_3 = k_3 V_{La} \cdot C_3 / M_{TW} \quad (11)$$

$$P_4 = k_4 V_{Rd} \cdot C_4 / M_{TW} \quad (12)$$

$$P_5 = (V_{MDW} \cdot C_{MDW} + M_{SDE}) / M_{TW} \quad (13)$$

where $P_{i(1–5)}$ is the contribution percentage taken up by: (1) roof, (2) IR, (3) lawn, (4) ER runoff and (5) WE. $P_{i(1–5)}$ is in %.

Besides, except that the concentrations of MDW and infiltrated groundwater are daily averaged, all the other concentrations in the present study are event mean concentrations (EMC), which are calculated according to Li et al.'s study [9].

3. Materials and methods

3.1. Sampling sites and methods

The sampling site is a newly built small-scale residential community in southern China. This community has an area of about 7.6 ha (including 0.6-ha ER around the community) and a population of about 7,000 persons. The surface areas of roof, IR, lawn and ER are calculated from design drawings and validated by practical measurement, with values of about 2.6, 2.0, 2.4 and 0.6 ha, respectively.

Four kinds of surface runoff (roof, IR, lawn and ER) were sampled with 500-ml plastic bottles when the continuous runoff began. Meanwhile, the samples of WWF discharged into the receiving water from storm sewers were also taken. The sampling frequencies were once per 5 min within the first 30-min runoff time and once per 10 min from 30 to 60-min of runoff. After 60-min runoff, the sample interval was prolonged to 30 min. The sampling was stopped when the runoff ended.

3.2. Rainfalls characteristics

During June 2011 and May 2012, five rainfall events were sampled. Their information was shown in Table 1.

3.3. Method modification based on the practical conditions

As the selected community is a newly built one with ideal separate drainage system, the rainwater pipe is in good condition. The amount of groundwater infiltrated into the storm sewers is insignificant and negligible. Furthermore, compared to stormwater, the amount of MDW (about 0.022 ± 0.028 m^3/min) is comparatively small and irregular. Thus, it could be treated as another form of sewer deposit and its volume could be ignored. Then, M_{MDW} and M_{SDE} can be considered as a whole (M_{WE}). Eqs. (2) and (8) could be rewritten as:

$$V_{TW} = k_1 V_{Rf} + k_2 V_{IR} + k_3 V_{La} + k_4 V_{ER} \quad (14)$$

$$M_{TW} = V_{TW} \cdot C_{TW} = k_1 V_{Rf} \cdot C_1 + k_2 V_{IR} \cdot C_2 + k_3 V_{La} \cdot C_3 + k_4 V_{ER} \cdot C_4 + M_{MDW} + M_{SDE} \quad (15)$$

After deducting the contribution percentages of roof, IR, lawn and ER, the contribution of WE could be obtained through Eq. (16).

Table 1
Characteristics of the five rainfall events

Date	Rainfall depth (mm)	Rainfall length (h)	Max rainfall intensity (mm/h)	Average rainfall intensity (mm/h)	Antecedent dry days (d)
24 August 2011	8.2	2.73	24	3.0	0.75
13 October 2011	14.5	8.67	18	1.7	0.25
22 February 2012	14.0	2.78	42	5.0	5.63
20 March 2012	3.6	1.05	18	3.4	6.46
09 May 2012	11.4	1.93	54	5.9	4.46

$$P_1 + P_2 + P_3 + P_4 + P_5 = 1 \tag{16}$$

In addition, in the practical operations, it is usually difficult to determine the accurate volumes of different surface runoff. However, within a small-scale residential community, the average rainfall intensity could be considered homogeneous in various surfaces. Therefore, Eq. (17) is established, which could avoid the necessity of measuring the exact runoff volumes:

$$V_{\mathrm{Rf}}:V_{\mathrm{IR}}:V_{\mathrm{La}}:V_{\mathrm{ER}} = S_{\mathrm{Rf}}:S_{\mathrm{IR}}:S_{\mathrm{La}}:S_{\mathrm{ER}} \tag{17}$$

S_{Rf}, S_{IR}, S_{La} and S_{ER} are the surface areas of roof, IR, lawn and ER, respectively. All the surface areas are in m^2.

3.4. Parameter setting

Generally, the RC varies a lot in different rain events [10]. Due to some practical reasons, a fixed RC value was set for each surface in the five rainfalls based on previous studies: namely 0.95, 0.90 and 0.70 for roof, IR and ER, respectively [10–12]. Besides, the lawn in the studied community was built as sunken one. In all the five rain events, due to the limitation in rainfall depth (Table 1), no overflows were found. Therefore, its RC was set as zero and its contribution to WWF pollution was nil in this case study.

3.5. Analytical methods

COD, soluble COD (SCOD), dissolved organic carbon (DOC), total phosphorus (TP), SS, VSS, total Zn (II), Cu(II) and Pb(II) concentrations were measured according to Standard Methods [13].

4. Results and discussion

4.1. Average EMC of different surface runoff and WWF

The average EMC of different surface runoff and WWF in five rainfalls were shown in Table 2 as a reference.

4.2. Contribution percentages to organic compounds and TP

Fig. 2 presents the contribution of different sources to organic compounds and TP in WWF. IR was found to be the largest contributor to the WWF pollution in storm sewers. For COD, SCOD, DOC and TP, its average contribution percentages in five rainfalls all approached or exceeded 50%, namely 52.4 ± 7.5, 50.6 ± 11.0, 50.5 ± 11.8 and 49.8 ± 8.7%, respectively. The serious pollution in IR could be attributed to four main reasons: the leaked pollutant from daily life of residents, the accumulated dry deposition, the wet deposition of the time and the pollutants from vehicle emission [14,15]. Apart from IR, WE was the second dominant source to the WWF pollution, with contribution percentages of 20.1 and 30.9% for COD and TP, respectively. It indicated that despite limited in volume, WE was still a significant pollution source and should not be ignored.

Moreover, roof runoff took up about 15% of the contamination in WWF. ER achieved the lowest contribution percentage in all surfaces (about 10%), although it bore even busier traffic than IR. This situation was caused by three aspects: ER's smaller surface area compared to roof, its lower RC due to pervious characteristic and less leakage from domestic waste.

From the viewpoint of specific variation, the contribution of IR and ER runoff in COD, SCOD, DOC and TP was relatively stable. However, the percentages took up by roof runoff and WE fluctuated in a larger range than IR and ER runoff, especially in TP. With respect to TP, the dry and wet deposition usually was not a prominent source. For example, the average TP concentration in direct rainfall just reached 0.04 ± 0.02 mg/L in the present study. However, the daily life of people generated a great amount of phosphorous contamination. For instance, the grey water was a widely acknowledged source for TP. It was reported that the ortho-phosphate concentration in grey water could reach as high as 11.3 mg/L [16]. That was why WE contributed more TP to WWF in storm sewers, while roof runoff provided less.

Table 2
Average EMC of different surface runoff and WWF in five rainfalls (mg/L)

Sources	COD	SCOD	DOC	TP	SS	VSS	Zn(II) × 10^{-3}	Cu(II) × 10^{-3}	Pb(II) × 10^{-3}
Roof	23.3 ± 8.0	14.6 ± 4.7	5.5 ± 1.8	0.05 ± 0.02	46 ± 18	9 ± 4	51 ± 18	5 ± 2	3 ± 2
IR	103.7 ± 33.3	72.0 ± 28.5	27.0 ± 11.1	0.51 ± 0.37	142 ± 44	55 ± 15	81 ± 36	17 ± 7	8 ± 4
ER	90.8 ± 23.4	58.0 ± 15.1	21.8 ± 5.3	0.42 ± 0.27	136 ± 33	62 ± 16	119 ± 44	24 ± 10	15 ± 5
WWF	76.5 ± 21.0	53.3 ± 13.8	20.0 ± 5.7	0.37 ± 0.22	127 ± 39	46 ± 16	77 ± 29	13 ± 5	7 ± 3

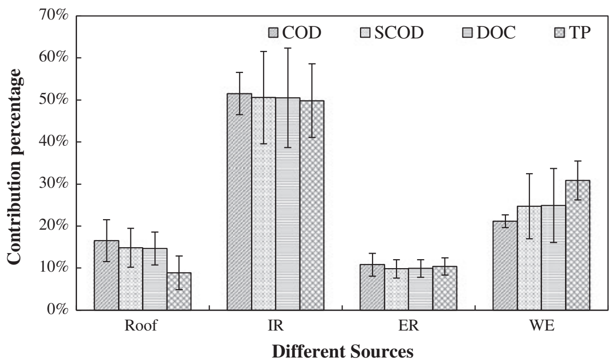

Fig. 2. The average organic compounds and TP contribution of different sources to the WWF pollution in storm sewers.

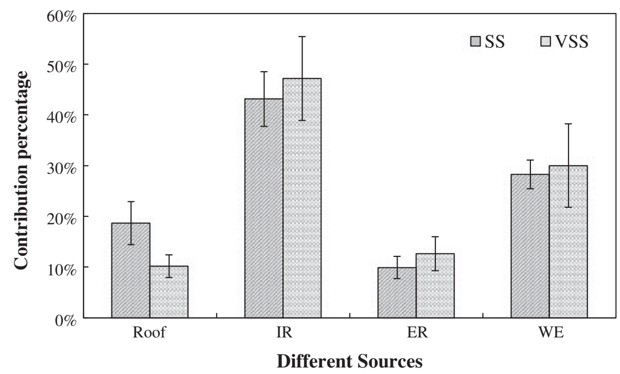

Fig. 3. The average SS and VSS contribution of different sources to the WWF pollution in storm sewers.

4.3. Contribution percentages to SS and VSS

For the average contribution percentage of SS and VSS in five rainfalls (Fig. 3), obviously roof runoff achieved a higher value in SS, while IR and ER runoff were just the opposite. These phenomena could be explained by the fact that the granular matter in the atmosphere was the main source of SS and VSS for roof runoff. After the dry and wet deposition, roof runoff only achieved a VSS/SS mass ratio of 19.5 ± 0.7% in five rains, which were evidently lower than the corresponding value in WWF (35.6 ± 2.0%). Therefore, roof runoff provided less VSS than SS in percentages.

Nevertheless, for IR and ER runoff, apart from the dry/wet deposition, the tyre debris from the traffic, the fallen leaves from shade trees, as well as the leaked pollutants from daily life all led to increases in SS and VSS concentrations. Meanwhile, the VSS/SS mass ratios of the above sources were usually very high, which resulted in total values of 38.6 ± 1.3 and 45.0 ± 1.6%, respectively, in IR and ER runoff. This was why IR and ER runoff acquired higher contribution percentages in VSS than SS. In addition, the WE supplied almost the same level of SS and VSS to WWF. Its contribution percentages were near 30% and second only to IR.

4.4. Contribution percentages to heavy metals

In the viewpoint of heavy metals, the contribution percentage also varied from metal to metal (Fig. 4). For example, ER runoff supplied more Pb(II) than Zn (II) and Cu(II) to WWF, which was mainly caused by the vehicle emission and corrosion [15–17]. Besides supplying a lot of Pb(II) due to the same reason, IR also supplied a considerable percentage of Cu(II). These Cu^{2+} ions may partly come from the leakage from vehicle tyres and brake [18], and partly from the

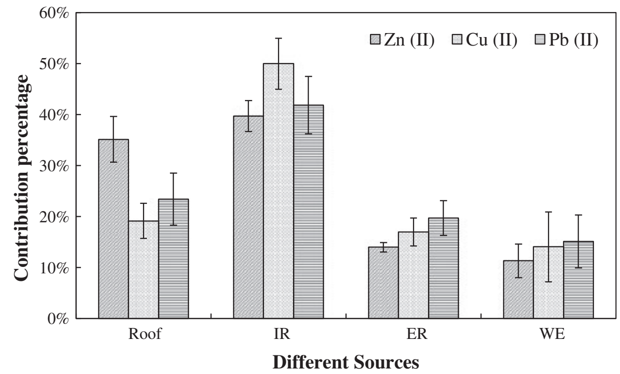

Fig. 4. The average Zn(II), Cu(II) and Pb(II) contribution of different sources to the WWF pollution in storm sewers.

erosion of lamp-standard and lamp-chimney of street lamps. Furthermore, the Zn(II) concentrations in roof clearly surpassed Cu(II) and Pb(II), which should be attributed to the corrosion of zinc materials in roof [19]. Besides, the contribution percentages of three metals in WE were approximately at the same levels.

Based on the above results, the local communities were recommended to clean the IR regularly to reduce its pollution level. Meanwhile, the mistaken connection between rainwater pipes and sewage pipes should be re-checked and corrected. If possible, the sewer deposit in storm sewers should be cleared in advance, especially before the rain season.

5. Conclusions

A simplified mathematical method named CPMMSS was proposed, which would provide convenient and cost-effective support for small-scale residential areas with separate drainage systems to learn the contribution of different kinds of surface runoff, MDW and SDE to the WWF pollution in storm sewers. In the case study, IR was found to be the greatest contributor of WWF pollution in storm sewers, which provided about 50% of organic compounds and TP, 40% of SS, VSS and heavy metals. MDW and SDE also played an important role in WWF pollution of storm sewers and supplied over 30% of TP, SS and VSS. The local communities were recommended to clean the IR regularly and clear the sewer deposit in storm sewers before the rain season.

Acknowledgements

The authors wish to thank the Department of Housing and Urban-Rural Development of Fujian Province in China (RD24) and National Major Science and Technology Project on Water Pollution Control and Management of China (2013ZX07304-003) for the financial support of this study.

References

[1] M.G. Carleton, Comparison of overflows from separate and combined sewers: Quantity and quality, Water Sci. Technol. 22(10–11) (1990) 31–38.
[2] C.Y. Liu, W. Che, Z.Y. Dong, Sewer water quality comparison of separate discharge and combined overflow, Water Wastewater Eng. 33(4) (2007) 51–55.
[3] M.C. Gromaire-Mertz, G. Chebbo, M. Saad, Origins and characteristics of urban wet weather pollution in combined sewer systems: The experimental urban catchment “Le Marais” in Paris, Water Sci. Technol. 37 (1) (1998) 35–43.
[4] M.C. Gromaire, S. Garnaud, M. Saad, G. Chebbo, Contribution of different sources to the pollution of wet weather flows in combined sewers, Water Res. 35(2) (2001) 521–533.
[5] M. Kafi-Benyahia, M.G. Gromaire, G. Chebbo, Spatial variability of characteristics and origins of urban wet weather pollution in combined sewers, Water Sci. Technol. 52(3) (2005) 53–62.
[6] P. Soonthornnonda, E.R. Christensen, Source apportionment of pollutants and flows of combined sewer wastewater, Water Res. 42 (2008) 1989–1998.
[7] J. Gasperi, M.C. Gromaire, M. Kafi, R. Moilleron, G. Chebbo, Contributions of wastewater, runoff and sewer deposit erosion to wet weather pollutant loads in combined sewer systems, Water Res. 44 (2010) 5875–5886.
[8] G. Chebbo, M.C. Gromaire, The experimental urban catchment ‘Le Marais’ in Paris: What lessons can be learned from it? J. Hydrol. 299 (2004) 312–323.
[9] H. Li, T. Li, C.Y. Li, Research on the characteristics of urban roof runoff in Shanghai cultural and educational area, Environ. Sci. 29(1) (2008) 47–51.
[10] T.S.W. Wong, C.K. Lim, Effect of loss model on evaluation of Manning roughness coefficient of experimental concrete catchment, J. Hydrol. 331 (2006) 205–218.
[11] MC of PRC, Specifications of drainage design for highways (JTJ 018–97), Ministry of communications of the People’s Republic of China, Beijing, 1997.
[12] R. Farreny, T. Morales-Pinzón, A. Guisasola, C. Tayà, J. Rieradevall, X. Gabarrell, Roof selection for rainwater harvesting: Quantity and quality assessments in Spain, Water Res. 45 (2011) 3245–3254.
[13] American Public Health Association (APHA), Standard Methods for the Examination of Water and Wastewater, APHA, Washington, DC, 1998.
[14] W. Zhu, B. Bian, L. Li, Heavy metal contamination of road-deposited sediments in a medium size city of China, Environ. Monit. Assess. 147 (2008) 171–181.
[15] J.Q. Yuen, P.H. Olin, H.S. Lim, S.G. Benner, R.A. Sutherland, A.D. Ziegler, Accumulation of potentially toxic elements in road deposited sediments in residential and light industrial neighborhoods of Singapore, J. Environ. Manage. 101 (2012) 151–163.
[16] M. Lamine, L. Bousselmi, A. Ghrabi, Biological treatment of grey water using sequencing batch reactor, Desalination 215 (2007) 127–132.
[17] S. Garnaud, J.M. Mouchel, G. Chebbo, D.R. Thévenot, Heavy metal concentrations in dry and wet atmospheric deposits in Paris district: Comparison with urban runoff, Sci. Total Environ. 235 (1999) 235–245.
[18] E.R. McKenzie, J.E. Money, P.G. Green, T.M. Young, Metals associated with stormwater-relevant brake and tire samples, Sci. Total Environ. 407 (2009) 5855–5860.
[19] M.C. Gromaire, P. Robert-Sainte, A. Bressy, M. Saad, B. De-Gouvello, G. Chebbo, Zn and Pb emissions from roofing materials-modelling and mass balance attempt at the scale of a small urban catchment, Water Sci. Technol. 63(11) (2011) 2590–2597.