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Evaluation of the methods for quantifying particle wash-off loadings in urban impervious surfaces at small scales

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Abstract

Quantifying road-deposited sediment (RDS) wash-off is critical in estimating pollutant load and for supporting the designs of urban storm water low-impact development (LID) best management practices (BMPs). The objective of this study was to identify a simple and effective small-scale wash-off load estimation and prediction method suitable for BMP engineering. The reliabilities, complexities, and applicabilities of four prediction methods (i.e., the event mean concentration (EMC) equation method, the exponential equation method, and the RDS mass difference before and after rainfall event method, and the RDS index model) were tested for three sites (i.e., a newly built area, and built-up area, and conservation area) during five natural rainfall events. Taking the calculations by the EMC method as standard results revealed the following. (1) The degree of agreement of the methods with the standard results in descending order was exponential equation method > RDS index model > RDS mass difference. (2) The degree of complexity of the studied methods in descending order was exponential equation method > the EMC equation method > the RDS index model > the RDS mass difference. (3) When considering the applicability of the models in terms of LID-BMP engineering, the RDS index model could be considered optimal for supporting the design of urban storm water BMPs.

Keywords Urban surface runoff · Road-deposited sediment · Wash-off · Multimethod · LID service scale

Introduction

Despite recent reductions in point source pollution in China and many other countries, urban runoff pollution contaminated with road-deposited sediments (RDS) remains a considerable environmental problem (Bressy et al. 2012, Gasperi et al. 2014, Zhang et al. 2015a, b). It is generally accepted that RDS from impervious surfaces is an important carrier of pollutants in urban surface runoff (Pitt et al. 2005, Wijesiri et al. 2016a, Zhao et al. 2010). Therefore, the quantification and the prediction of RDS wash-off are critical for the estimation and the reduction of pollutant load in support of the design of urban

storm water best management practices (BMPs) (Haddad et al. 2014, Wijesiri et al. 2016b, Yi et al. 2014).

One of the first methods proposed for the estimation of wash-off load is the event mean concentration (EMC) equation method (Sansalone and Buchberger 1997, Shen et al. 2016); however, it is difficult to use for predictions. A number of mathematical models have been developed to predict RDS wash-off, one of the earliest which is the original exponential equation method (Sartor et al. 1974). The exponential equation method is a function of the available mass and rainfall intensity. The amount of RDS wash-off is expressed in proportion to the surface runoff raised to a certain power. The basic form of this method is the core component of the Storm Water Management Model (Rossman 2007) and it has been adapted by many researchers (Soonthornnonda et al. 2008; Wang et al. 2011, Wijesiri et al. 2015b). Even though the exponential equation method has been used widely to predict RDS wash-off in urban areas, it does have some limitations. For example, it requires considerable sampling work for parameterization, which can be difficult because of the randomness of rain events. Furthermore, the parameters of the exponential equation generally vary with many factors,

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especially topography and rainfall characteristics; thus, uncertainties can occur in the model predictions for pollutant loads in different places appeared when using the same parameter set (Bonhomme and Petrucci 2017, Liu et al. 2012b). Therefore, a simple and effective method that could avoid the process of rainfall sampling and provide accurate predictions of wash-off load was needed.

RDS is an important carrier of pollutants and a source of total suspended solids (TSS) in surface runoff (Wijesiri et al. 2015a). The use of RDS for predictions of wash-off load simplifies the sampling process because RDS sampling is controllable. Some researchers have used the differences of RDS amounts or an RDS index to incorporate the RDS of different grain sizes when estimating wash-off loads (Vaze and Chiew 2002, Zhao et al. 2016). Although these methods have been used in other studies, their prediction capabilities have seldom been verified. Therefore, it is necessary to explore whether simple RDS-related methods could replace continuous sampling work or complex models in providing estimations of wash-off particle loads.

China promoted the "Sponge City" program in 2014, which was intended to overcome the problems of urban storm flooding and urban diffuse pollution (Gao et al. 2015, Mao et al. 2017; MOHURD 2015). However, RDS removal performance needs to be evaluated before and after low-impact development (LID) BMP engineering as part of the assessment of LID-BMP effectiveness (MOHURD 2015). For example, during the operation of LID-BMP constructions, the degradation of the treatment performance of infiltration systems due to clogging has been reported. Therefore, the particle loads during rainfall events should be evaluated to elucidate the long-term particle-trapping performance of infiltration systems.

It is generally acknowledged there is urgent need to provide engineers with a simple and effective tool for the estimation of RDS wash-off load at the LID-BMP design scale. Therefore, this study compared four methods used to estimate small-scale RDS wash-off load. Two were direct sampling or modeling methods: (1) the EMC equation method based on field observations and the exponential equation method based on observations of natural rainfall in a small area. The other two methods calculate wash-off load indirectly based on RDS: the RDS mass difference before and after rainfall event method based on field observations and the RDS index model based on the wash-off percentage of each RDS size fraction using simulated rainfall in a small area. This research had a number of objectives: (1) to compare and analyze the applicability of the four selected methods to the estimation of small-scale RDS wash-off load; (2) to find a simple and effective tool for the estimation of RDS wash-off load for storm water management engineers at the LID design scale; and (3) to validate the applicability of the indirect estimation of particle loads using static RDS.

Materials and methods

Study site description

The study sites were located in Longgang District in Shenzhen, China, which is a mixed of industrial and residential areas. The average annual rainfall of Longgang is 1933 mm and the mean annual temperature is 22.4 °C. The study area has a largely complete pipeline construction and sewage interception network that prevents domestic sewage from polluting the Longgang River; thus, urban runoff contaminated with RDS is one of the most important sources of pollution for the Longgang River during the rainy season.

A considerable amount of small-scale LID-BMP infrastructure will be constructed over the coming years in Shenzhen under the Sponge City program. Thus, RDS wash-off load must be evaluated to support the design of the urban LID-BMP constructions (MOHURD 2015). Following on-site investigations of land use, traffic characteristics, and street management, it was considered that a newly built area (NBA), built-up area (BUA), and conservation area (CA) could be taken as representative of areas modified by LID-BMP constructions. The main characteristics of the study catchments are listed in Table 1. The BUAs typically include the developed industrial and residential areas constructed over a decade ago. They have some open areas, high population density, and high traffic volumes, and the frequency of street cleaning is usually less than twice daily. NBAs represent semi-open sites built less than 10 years ago. They usually include the new residential districts where the traffic volume is low and the frequency of street sweeping is more than twice daily. The time over which an area has built up is the principal standard for determining whether it is categorized as an NBA or a BUA. CAs have high proportions of green space, and they represent typical undeveloped parts of the urban areas of Shenzhen. The locations of the study and of the sampling sites are shown in Fig. 1.

Field experiment design of RDS sample collection and RDS wash-off

Field observation of RDS wash-off during rainfall events

Runoff samples were collected on 8/12/2016, 8/26/2016, 5/4/2017, 5/13/2017, and 5/15/2017 and categorized according to their average intensities: < 5 mm/h (low), 5–10 mm/h (medium), and > 10 mm/h (high) categories, respectively (Table 2). Samples were collected from the gully pits beside selected asphalt roadsides (Table 1). The drainage areas of RDS wash-off were 60, 200, and 150 m^2 in NBA, BUA, and CA, respectively.

A stainless steel device was designed specifically based on the size of the gully pits for the sampling and the volume

Table 1 Characteristics of the road study sites

Sampling sites	Catchment area (m²)	Average daily traffic (vehicle/d/m)	Street cleaning method/ frequency of sweeping	Surface condition
NBA	60	608	Mechanical street sweeper/> 2	Asphalt roads with detached housing
BUA	200	3681	Mechanical street sweeper/1	Asphalt roads with old residential buildings
CA	150	698	Mechanical street sweeper/2	Asphalt roads with integrated office buildings

NBA newly built area, *BUA* built-up area, *CA* conservation area

estimation of the surface runoff. Flow quantifying was assessed visually and the accuracy of the flow rates was verified before the device was used for monitoring runoff. A water gauge was installed in the device to observe the water level and to calculate the runoff volume. In addition, the wash-off samples were taken from the device continuously after the surface runoff began until no further runoff was generated. The first four samples were taken at 5-min intervals during the first 15 min after the surface runoff began and subsequent samples were taken at 10-min intervals. The collected samples were later analyzed for TSS (Americ 1971). The EMCs of wash-off particles are shown in Table 3.

RDS sample collection and grain size fraction

RDS samples were collected from the NBA, BUA, and CA 1 day before and 1 day after the five rain events, i.e., 8/12/2016, 8/26/2016, 5/4/2017, 5/13/2017, and 5/15/2017; the rainfall characteristics are listed in Table 2. RDS samples were collected from a 3 × 4-m area using a domestic vacuum cleaner (Philips FC8264) and then analyzed according to grain sizes. Using polyester sieves, the samples were sorted into particle size fractions of < 44, 44–62, 62–105, 105–149, 149–250, 250–450, 450–1000, and > 1000 μm (Zhao et al. 2010), which are typically referred to as clay, very fine sand, fine sand, medium sand, coarse sand, and very coarse sand, respectively (Sutherland 2003). The finest particles were removed from the vacuum system using a brush. Finally, to remove moisture, all the RDS samples were dried at 100 °C for 24 h. Then, they were weighed using an electronic scale immediately after removal from the oven. The RDS amounts both before and after the rain events, and the proportions of fine particles, are listed in Table 3.

Direct and indirect methods for estimation of wash-off loads

To find a simple and effective method for the quantification of small-scale RDS wash-off to support LID-BMP engineering, this study analyzed and compared the two direct and two indirect methods mentioned in Section 1. Concise results of the comparison of the four quantifying RDS wash-off methods are shown in Table 4. It should be noted that we assumed the TSS load of the runoff was equal to the RDS wash-off load in this study.

EMC equation method

EMCs were calculated by integrating the product of runoff rate and concentration and dividing it by total runoff volume (Kim et al. 2007). The total mass emission can be calculated as the sum of runoff volume and runoff concentration. This method has been used widely to calculate pollutant loads during storms (Ju et al. 2011; Qin et al. 2013). The equation is as follows:

$$M_w = \sum_{i=1}^{n} C_i \times V_i, \tag{1}$$

where C_i is pollutant concentration and V_i is runoff flow rate discharged at time t.

Exponential equation method

In the exponential equations, wash-off is calculated based on the pollutants on the catchment surface of a given land use type under the flow conditions of a rainfall-runoff events (Rossman 2007). The equation forms the core element of the Storm Water Management Model and the Model for Urban Sewers and it has also been adapted for pollutant load estimation (Zheng et al. 2014; Soonthornnonda et al. 2008). The equation is as follows:

$$W = C_1 q^{C_2} B, \tag{2}$$

where W is the amount of load (per unit area) (g/m²), C_1 is the wash-off coefficient, C_2 is the wash-off exponent, q is the runoff rate per unit area (mm/h), and B is the pollutant buildup in mass units.

RDS mass difference before and after rainfall event

This method uses a "black-box" approach, which ignores the particle transportation process, to compare the difference of RDS masses before and after rainfall event (Vaze and Chiew 2002). The equation is as follows:
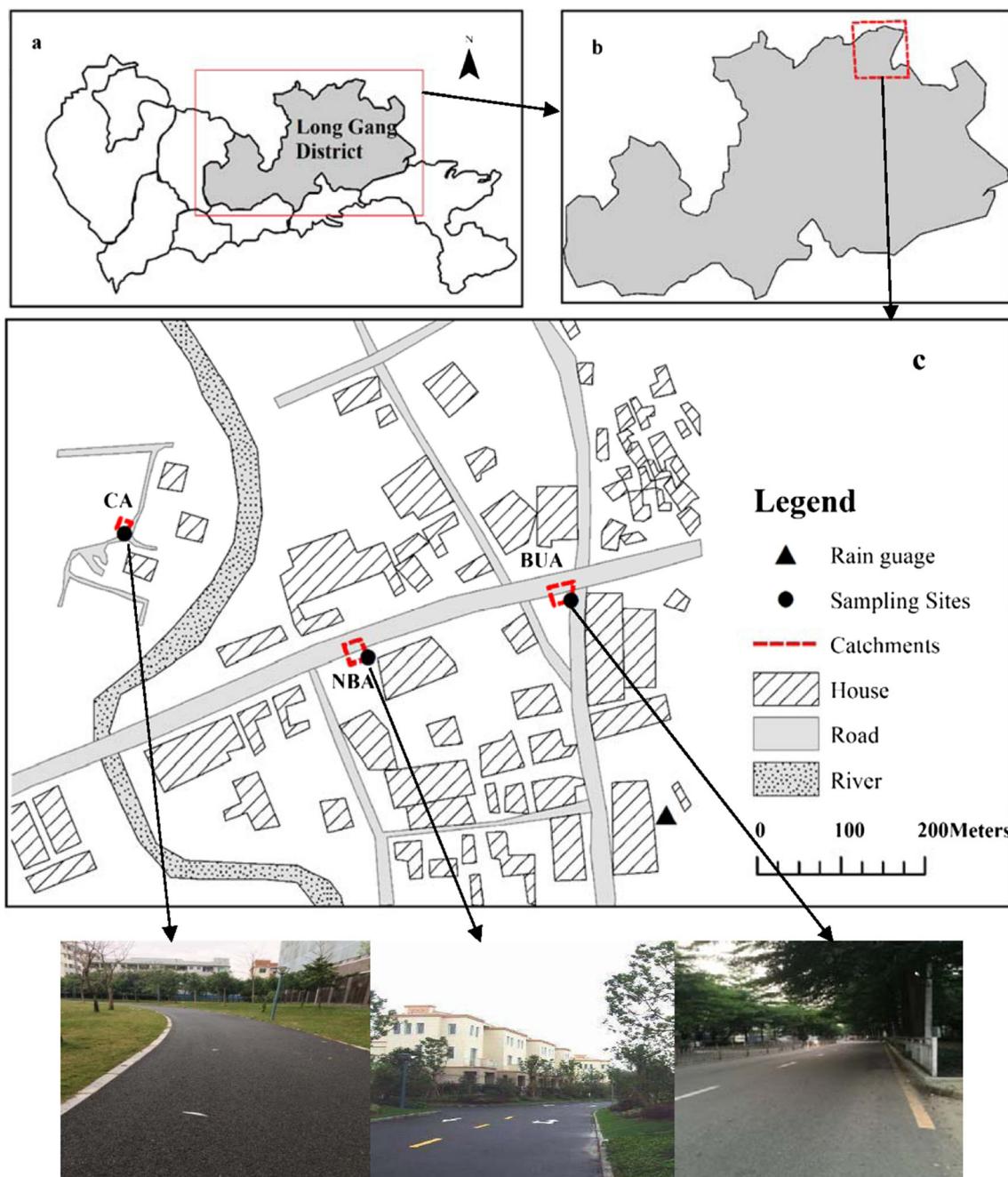
$$M_w = M_{before} - M_{after}, \tag{3}$$

Fig. 1 Study area and sampling site locations in Longgang District, Shenzhen, China. a represents the map of Shenzhen; b represents the map of Longgang District; c represents the map of study catchments and their surroundings. NBA newly built areas, BUA built-up areas, CA conservation areas

Table 2 Rainfall parameters for three rainfall events in the study area

Date of rain event	Rainfall (mm)	Average intensity (mm/h)	Duration (min)	Maximum intensity (mm/min)	Antecedent dry weather period (day)
8/12/2016	9.7	9.7	60	0.7	1
8/26/2016	13.5	13.5	60	1.5	4
5/4/2017	35.6	9.58	223	1.8	7
5/13/2017	14.8	3.43	259	0.6	4
5/15/2017	11.6	1.6	435	0.4	1

The temporal resolution of weather information was 1 min

Table 3 RDS and runoff characteristics for rainfall events in the study area

Rain events		8/12/2016			8/26/2016			5/4/2017			5/13/2017			5/15/2017		
Sites		NBA	BUA	CA	NBA	BUA	CA	NBA	BUA	CA	NBA	BUA	CA	NBA	BUA	CA
RDS	RDS before rain event (g/m²)	6.89	36.29	4.87	6.23	35.91	3.96	15.13	66.695	20.71	14	47.08	16.545	14	45.75	8.64
	RDS after rain event (g/m²)	1.48	30.25	1.44	4.32	18.43	2.80	7.205	55.62	7.97	6.185	45.75	8.64	8.63	32.86	6.13
Proportions of fine particles (<105 µm)		15.34%	9.58%	25.39%	19.22%	9.28%	20.28%	25.55%	21.85%	27.62%	45.68%	27.50%	20.91%	31.79%	22.38%	26.74%
EMC (mg/L)		0.01	0.15	0.05	0.13	0.40	0.07	0.08	0.30	0.08	0.09	0.35	0.02	0.04	0.67	0.05

where M_{before} is the RDS mass before the rain event and M_{after} is the RDS mass after the rain event.

RDS index model

The RDS index model was developed by Zhao et al. (2014). It estimates the RDS potential contribution to surface runoff based on the product of the source and transport factors of RDS. This method is based on a simulation experiment and it has also been adapted for pollutant load estimation (Zafra et al. 2017). The equation is as follows:

$$M_w = \sum_{i=1}^{n} M_i \times F_{wi}, \qquad (4)$$

where M_w is the total mass of RDS wash-off amount (g/m²), M_i is the initial mass of RDS with a corresponding particle size on the surface (g/m²), F_w is the percentage of each RDS size fraction washed off the surface (%), as mentioned in Zhao et al. (2014), and n is the number of particle size fractions.

Results

Results of direct observation and modeling methods

Field observation of surface runoff and estimation of wash-off load by the EMC equation

The variations of TSS concentrations, flow rate, and the estimations of particle wash-off loads by the EMC method during the studied rainfall events are shown in Fig. 2. The observed wash-off loads in the BUA, NBA, and CA ranged from 0.05 to 69.32 g/m² during the five events (Fig. 3). The TSS loads for the NBA, BUA, and CA were 0.09, 1.25, and 0.10 g/m² on 8/12/2016; 0.66, 1.66, and 0.13 g/m² on 8/26/2016; 5.05, 69.32, and 1.50 g/m² on 5/4/2017; 1.75, 4.53, and 0.05 g/m² on 5/13/2017; and 0.85, 7.4, and 0.21 g/m² on 5/15/2017, respectively. Previous studies have indicated that TSS loads in surface runoff are affected by factors such as traffic volume, RDS amount, antecedent dry days, and rainfall characteristics (Alias et al. 2014; Vaze and Chiew 2002). This study found that particle wash-off loads were highest in the BUA because the BUA had the largest RDS amount. The greatest TSS load was found during the 5/4/2017 event, because the average rainfall intensity of that event was greater in comparison with the other rain events.

Field observation of surface runoff and estimation of wash-off load by the exponential equation

The exponential equations were calibrated and then used to estimate the wash-off loads of the five rain events. The parameters of the exponential equations used for the three sites are

Table 4 A concise comparison of four quantifying RDS wash-off methods

Methods	Observed variables	Advantage	Disadvantage
EMC equation method[1]	• The particle concentrations and flow volume during wash-off process	• Easy to calculate; represents the actual RDS wash-off process; applicability to small and large scales	• Hard to observe due to uncertainty of rainfall events and difficulty of sampling work; hard to observe surface runoff quantity and SS concentration based on the characteristics
Exponential equation method[2]	• Particle buildup amount, runoff rate, and wash-off loads for several rainfall events (for calibration of C_1 and C_2).	• widely used in SWMM, HSPF, and STORM; applicability to small and large scales	• Hard to observe due to uncertainty of rainfall events and difficulty of sampling work; requires substantial amounts of parameterization and calibration data
RDS mass difference[3]	• Mass of particles before and after rain event	• Easy to sample and calculate; requires two parameters; does not observe the natural rainfall events	• Takes the actual RDS wash-off as a "black-box"; applicability to small scale; requires the RDS amount before and after rainfall event
RDS index model[4]	• Particle mass of different size	• Easy to sample; easy to calculate; does not observe the natural rainfall events; only requires the RDS amount before rainfall event	• Look-up table of the wash-off percentage (F_w, %) of RDS on each grain size fraction in the literature; requires grain size fraction of RDS; the potential RDS contribution to surface runoff

[1] Bach et al. 2010, Bertrand-Krajewski et al. 1998

[2] Baek et al. 2015, Egodawatta 2007, Rossman 2007

[3] Vaze and Chiew 2002, Zhao et al. 2016

[4] Zhao et al. 2014

shown in Table 5, and the calculated wash-off loads were shown in Fig. 4. The discrepancies in the parameters (Table 5) associated with the different sites suggest that the pollutant parameters were affected by geographical characteristics (Baek et al. 2015). The particle loads in the NBA, BUA, and CA were 0.25, 3.27, and 0.04 g/m² on 8/12/2016; 0.160, 1.570, and 0.035 g/m² on 8/26/2016; 3.61, 67.43, and 1.76 g/m² on 5/4/2017; 0.58, 6.24, and 0.16 g/m² on 5/13/2017; and 1.45, 5.07, and 0.17 g/m² on 5/15/2017, respectively (Fig. 4). The estimated wash-off loads were similar to the results obtained using the EMC method with errors ranging from 0 to 89%. The errors were derived only from the calibration processes, which explains why the estimated wash-off loads were similar.

Results of indirect RDS-related methods

Prediction of wash-off loads in surface runoff by the RDS difference method

Variations in the RDS amount 1 day before and 1 day after the five rainfall events were observed (Fig. 5). The rainfall events on 8/12/2016, 8/26/2016, 5/4/2017, 5/13/2017, and 5/15/2017 reduced the total RDS mass obviously by 6.28, 1.91, 7.93, 6.20, and 5.37 g/m² in the NBA; 6.04, 17.48, 11.08, 1.33, and 12.89 g/m² in the BUA; and 3.44, 1.16, 12.74, 7.91, and 2.51 g/m² in the CA, respectively. The removal amounts showed obvious differences related to different rainfall characteristics. The RDS removal amount varied from 1.16 to 17.48 g/m², i.e., much higher than the wash-off loads estimated by the EMC method (Fig. 2). A possible reason for this is redeposition and resuspension of solids, resulting in some RDS particles being washed out of the study catchments and deposited in other areas; thus, the effective RDS wash-off loads could be much smaller. Both the RDS removal amount and the wash-off percentage in the 5/4/2017 rain event were higher than the RDS removal amounts in the other rain events because the long durations of the rain events resulted in thorough RDS wash-off and the low possibility of sediment redeposition. In general, RDS reductions based on RDS mass differences were much higher than the wash-off loads estimated by the EMC method.

Prediction of wash-off loads in surface runoff by the RDS index models

The total wash-off loads of RDS of different grain sizes calculated using the RDS index models ranged from 0.19 to 2.39 g/m² (Fig. 6). The particle loads for the NBA, BUA, and CA were 0.32, 1.27, and 0.26 g/m² on 8/12/2016; 0.30, 1.10, and 0.19 g/m² on 8/26/2016; 4.09, 15.62, and 5.53 g/m² on 5/4/2017; 6.63, 2.92, and 0.91 g/m² on 5/13/2016; and 1.06, 2.57, and 0.58 g/m² on 5/15/2016, respectively. The above results were much lower than obtained using the RDS difference method but similar to those derived using the EMC method, except in the CA. Because the RDS index model considered the RDS wash-off ability based on different grain
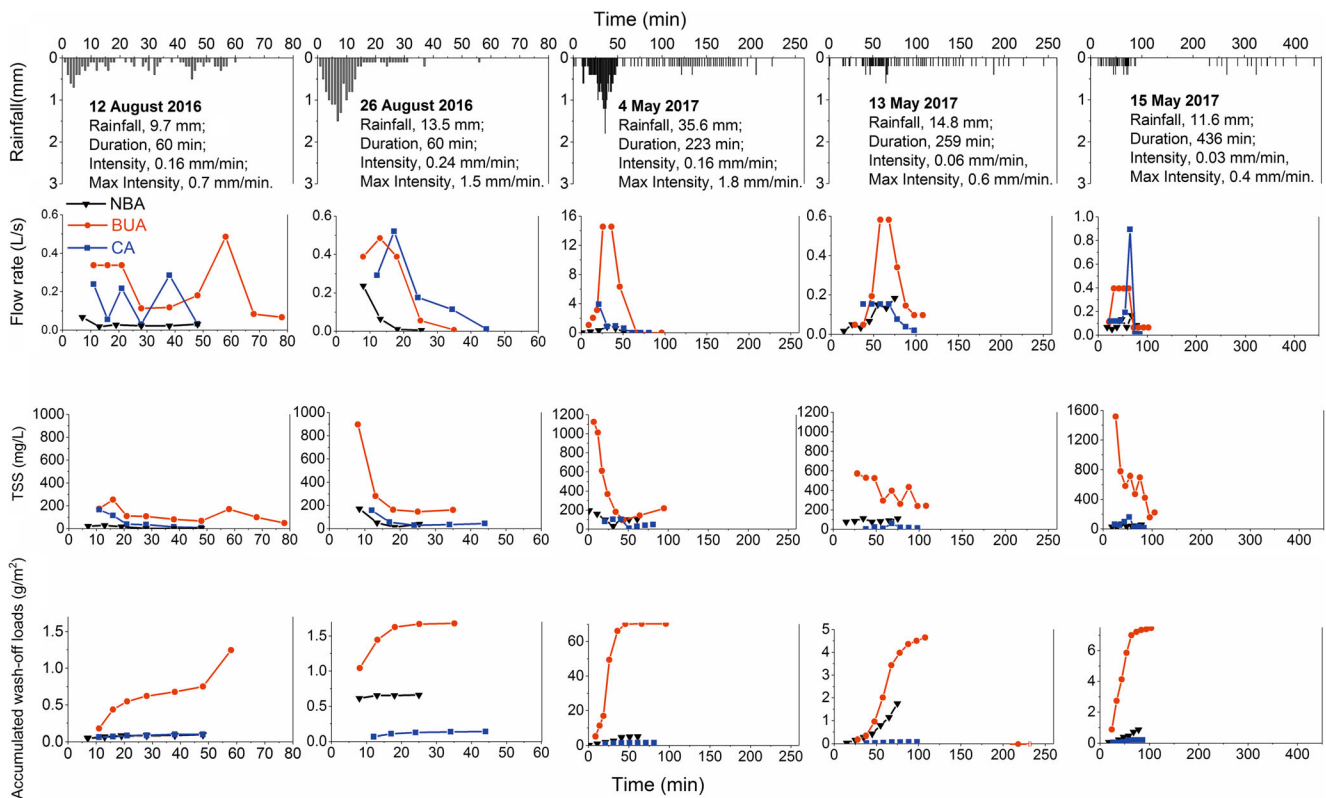
Fig. 2 The particle loads during the wash-off process in five events. NBA newly built area, BUA built-up area, CA conservation area

sizes under different rainfall characteristics, its results were more reasonable and closer to those obtained using the EMC methods. The errors of the estimated wash-off loads in the CA were larger because of the lower RDS amount before rain events. In general, the results derived from the RDS index model were close to those obtained using the EMC method.
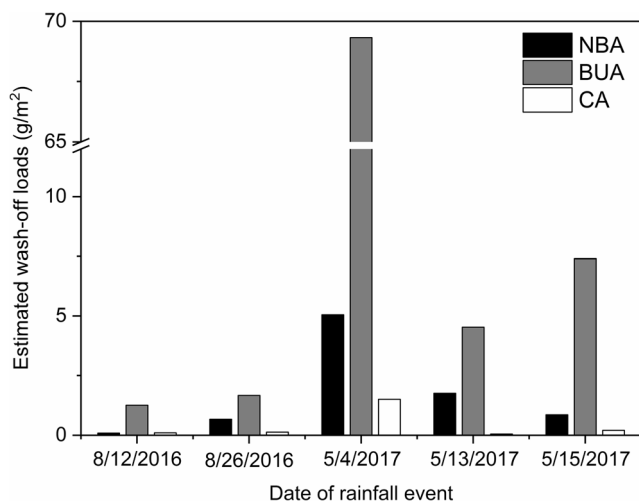

Fig. 3 The estimated wash-off particle loads by EMC methods in five events. NBA newly built area, BUA built-up area, CA conservation area

Discussion

Reliability of prediction methods

For all methods, prediction reliability is essential in application to the quantification of runoff particle loads. To verify their reliability, a multimethod multisite approach is useful for elucidating the uncertainties of assessment results that occur commonly when a single method is used at a single site (Wang et al. 2011; Li et al. 2010). In this study, four methods with differing degrees of complexity were selected to quantify

Table 5 Calibrated parameters of exponential equations in study sites

Sampling sites	Calibrated parameters	
	C_1[a]	C_2[b]
NBA	0.0088	0.8435
BUA	0.012	0.9551
CA	0.0044	1.01

[a], [b] C_1 and C_2 are wash-off coefficient and wash-off exponent of the equation $W = C_1 q^{C_2} B$; W, q and B are based on observed data, q is the average runoff rate per unit area (mm/h), and B is the pollutant buildup in mass units accounting for the previously removed load (g)
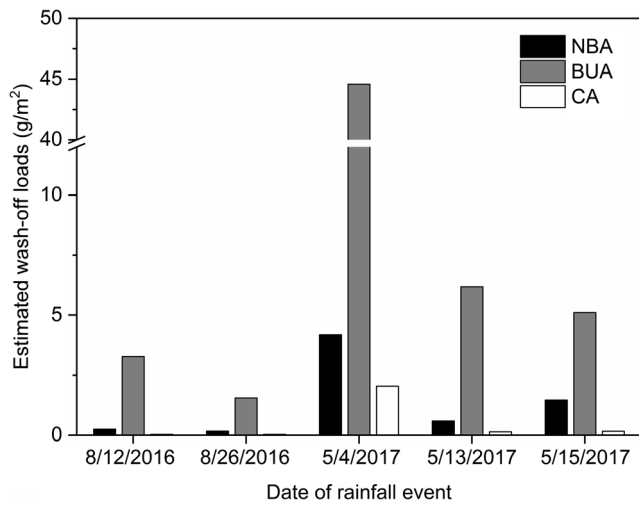
Fig. 4 The estimated wash-off particle loads by exponential equations in five events. NBA newly built area, BUA built-up area, CA conservation area
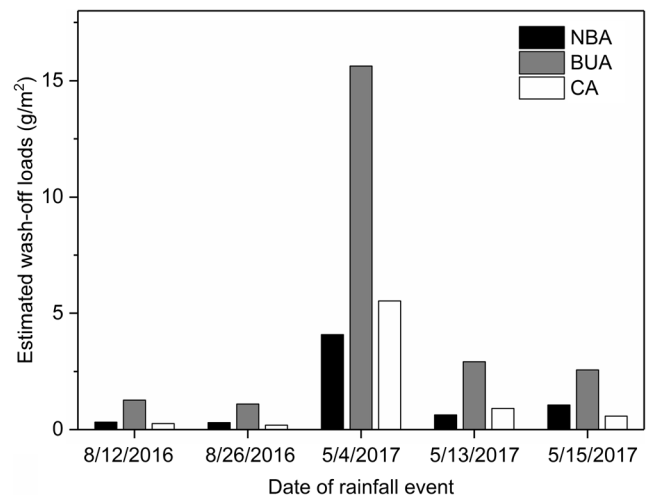

Fig. 6 Wash-off load of particles calculated with RDS index models in three sites. NBA newly built area, BUA built-up area, CA conservation area

runoff particle loads at three sites during five natural rainfall events (Table 6). It was assumed that the results of runoff particle loads calculated by the EMC equation method could

be set as standard results. When taking the results calculated by the EMC equation as standard results, the degree of agreement of the methods to the standard results in descending
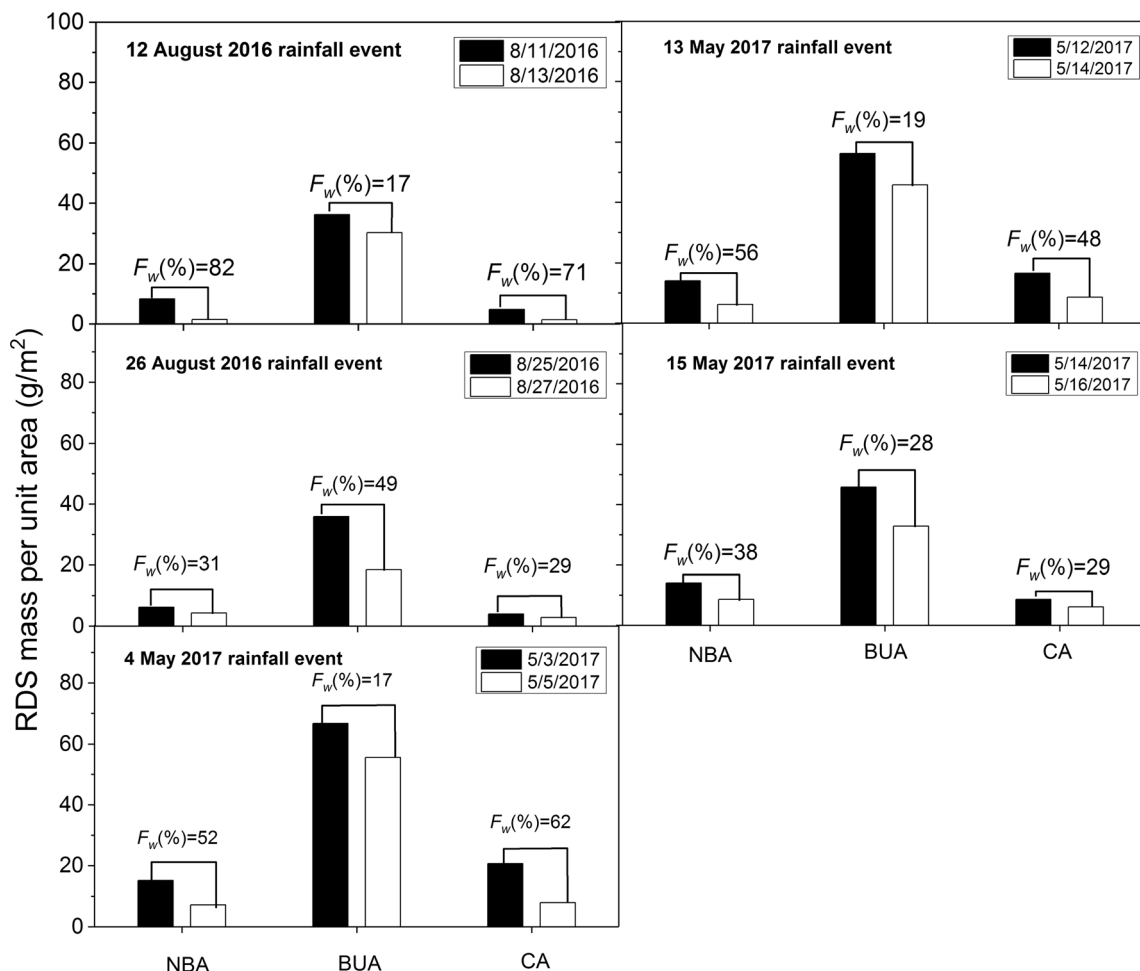

Fig. 5 Mass of RDS before and after rain events. F_w is the percentage of road-deposited sediments washed off the surface. NBA newly built area, BUA built-up area, CA conservation area

Table 6 Errors of exponential equation, RDS mass difference, and RDS index model

Rainfall date	Methods		Errors		
			NBA (%)	BUA (%)	CA (%)
8/12/2016	Direct model	Exponential equation	36	33	0
	Indirect RDS-related methods	RDS mass difference	7556	383	3330
		RDS index model	256	2	160
8/26/2016	Direct model	Exponential equation	89	53	30
	Indirect RDS-related methods	RDS mass difference	189	953	792
		RDS index model	55	34	46
5/4/2017	Direct model	Exponential equation	29	3	17
	Indirect RDS-related methods	RDS mass difference	57	84	749
		RDS index model	19	77	269
5/13/2017	Direct model	Exponential equation	67	38	220
	Indirect RDS-related methods	RDS mass difference	254	70.6	15,720
		RDS index model	64	36	1720
5/15/2017	Direct model	Exponential equation	71	31	19
	Indirect RDS-related methods	RDS mass difference	532	74	1095
		RDS index model	25	65	176

order was exponential equation method > the RDS index model > the RDS mass difference. The results of the RDS-related methods were generally higher than those derived using EMC methods or the modeling method, although the differences varied between events and between sites. The TSS obtained using the EMC method ranged from 0.05 to 69.32 g/m². The results of the modeling methods (0.04 to 67.43 g/m²) based on continuous observations were similar to those of the EMC methods. The estimated loads of the RDS index models were between 0.19 to 15.62 g/m², i.e., a less extreme trend than the observation results. This was because the mobility of particles and their associated pollutant concentrations are determined by the rainfall intensity. When choosing the parameter Fw for the load calculation, the average rainfall intensity can ignore the instantaneous variations. Therefore, this method might overestimate particle loads when the observation result is small and underestimate particle loads when the observation result is large. The results of the RDS mass difference method were much higher than derived by the EMC method because the former method ignores RDS redeposition. Generally, when the actual rainfall intensity was close to the standard rainfall intensity level, the results calculated using the multimethod multisite approach implied that the RDS index model method could be a useful tool for the estimation of runoff particle loads.

Complexity of prediction methods

Simplicity and ease of use are prerequisites for a method to become popular in its application. Certain factors such as input data availability, including the flexibility of field sampling,

parameter estimation through calibration, and the complexity of the simulation process determine the degree of complexity of prediction methods (Liu et al. 2012a, Rossman 2007; Sage et al. 2015). By estimating the wash-off loads at various sites under different rainfall characteristics, this study found that the degree of complexity of the studied methods in descending order was the exponential equation method > the EMC equation method > the RDS index model > the RDS mass difference. When taking both reliability and complexity into consideration, it was found that the RDS index model method was more advantageous than the other methods for the estimation of runoff particle loads.

Applicability of prediction methods for wash-off particle loads

As LID-BMP construction is becoming increasingly popular in China, a simple and effective tool is needed for the estimation of amount of RDS wash-off driven by natural rainfall events at the LID-BMP service scale. Typically, LID-BMP construction sites are often scattered and comprise small parcels of land with high spatial heterogeneity, which would involve considerable preliminary parameterization work and uncertainty in the calculated wash-off load results (Bonhomme and Petrucci 2017, Kanso et al. 2005; Wijesiri et al. 2016c). In this study, the RDS wash-off process was observed and the wash-off particle load in runoff was estimated at three sites at the LID-BMP service scale. The results suggest that the RDS index model could be used as a simple and effective tool for LID-BMP engineering.

Conclusions

This study used a multimethod multisite approach to compare and analyze the applicability of four methods for quantifying small-scale wash-off particle load in runoff. The four methods (i.e., the RDS mass difference before and after rainfall event method, the EMC equation method, the exponential equation method, and the RDS index model) were applied to estimate the particle load in runoff during five natural rainfall events in three urban areas in Longgang District (Shenzhen, China). When taking the results calculated by the EMC equation as standard results, the degree of agreement of the methods with the standard results in descending order was exponential equation method > RDS index model > RDS mass difference. When considering all factors (e.g., flexibility of field sampling, number of parameters, and complexity), the degree of complexity of the studied methods in descending order was exponential equation method > EMC equation method > RDS index model > RDS mass difference. Consequently, with consideration of the applicability of the prediction methods to LID-BMP engineering, the results suggested that the RDS index model could be adopted as a simple and effective tool for supporting the design of urban storm water BMPs.

References

Alias N, Liu A, Goonetilleke A, Egodawatta P (2014) Time as the critical factor in the investigation of the relationship between pollutant wash-off and rainfall characteristics. Ecol Eng 64:301–305. https://doi.org/10.1016/j.ecoleng.2014.01.008

Americ PJB (1971) Standard methods for the examination of water and waste water. Am J Public Health Nations Health 4:113-X

Bach PM, Mccarthy DT, Deletic A (2010) Redefining the stormwater first flush phenomenon. Water Res 44(8):2487–2498. https://doi.org/10.1016/j.watres.2010.01.022

Baek SS, Choi DH, Jung JW, Lee HJ, Lee H, Yoon KS, Cho KH (2015) Optimizing low impact development (LID) for stormwater runoff treatment in urban area, Korea: experimental and modeling approach. Water Res 86:122–131. https://doi.org/10.1016/j.watres.2015.08.038

Bertrand-Krajewski JL, Chebbo G, Saget A (1998) Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. Water Res 32(8):2341–2356. https://doi.org/10.1016/S0043-1354(97)00420-X

Bonhomme C, Petrucci G (2017) Should we trust build-up/wash-off water quality models at thescale of urban catchments? Water Res 108: 422–431. https://doi.org/10.1016/j.watres.2016.11.027

Bressy A, Gromaire MC, Lorgeoux C, Saad M, Leroy F, Chebbo G (2012) Towards the determination of an optimal scale for stormwater quality management: micropollutants in a small residential catchment. Water Res 46(20):6799–6810. https://doi.org/10.1016/j.watres.2011.12.017

Egodawatta PK (2007) Translation of small-plot scale pollutant build-up and wash-off measurements to urban catchment scale. Stormwater Quality Modelling

Gao J, Wang R, Huang J, Liu M (2015) Application of BMP to urban runoff control using SUSTAIN model: case study in an industrial area. Ecol Model 318:177–183. https://doi.org/10.1016/j.ecolmodel.2015.06.018

Gasperi J, Geara D, Lorgeoux C, Bressy A, Zedek S, Rocher V, El SA, Chebbo G, Moilleron R (2014) First assessment of triclosan, triclocarban and paraben mass loads at a very large regional scale: case of Paris conurbation (France). Sci Total Environ 493:854–861. https://doi.org/10.1016/j.scitotenv.2014.06.079

Haddad K, Egodawatta P, Rahman A, Goonetilleke A (2014) Assessing uncertainty in pollutant wash-off modelling via model validation. Sci Total Environ 497-498C:578–584

Ju YL, Kim H, Kim Y et al (2011) Characteristics of the event mean concentration (EMC) from rainfall runoff on an urban highway [J]. Environ Pollut 159(4):884–888

Kanso A, Chebbo G, Tassin B (2005) Stormwater quality modelling in combined sewers: calibration and uncertainty analysis. Water Sci Technol J Int Assoc Water Pollut Res 52(3):63–71

Kim LH, Ko SO, Jeong S, Yoon J (2007) Characteristics of washed-off pollutants and dynamic EMCs in parking lots and bridges during a storm. Sci Total Environ 376(1-3):178–184. https://doi.org/10.1016/j.scitotenv.2006.12.053

Li X, Weller DE, Jordan TE (2010) Watershed model calibration using multi-objective optimization and multi-site averaging. J Hydrol 380(3-4):277–288. https://doi.org/10.1016/j.jhydrol.2009.11.003

Liu A, Egodawatta P, Guan Y, Goonetilleke A (2012a) Influence of rainfall and catchment characteristics on urban stormwater quality. Sci Total Environ 444C:255–262

Liu A, Goonetilleke A, Egodawatta P (2012b) Inherent errors in pollutant build-up estimation in considering urban land use as a lumped parameter. J Environ Qual 41(5):1690–1694. https://doi.org/10.2134/jeq2011.0419

Mao X, Jia H, Yu SL (2017) Assessing the ecological benefits of aggregate LID-BMPs throughmodelling. Ecol Model 353:139–149. https://doi.org/10.1016/j.ecolmodel.2016.10.018

Ministry of Housing and Urban-Rural Development (2015) Sponge city construction technology guide—construction of LID facilities, China Architecture & Building Press (in Chinese)

Pitt R, Williamson D, Voorhees J, Clark S (2005) Review of historical street dust and dirt accumulation and washoff data. Journal of Water Management Modeling. https://doi.org/10.14796/JWMM.R223-12

Qin H, Tan X, Fu G, Zhang Y, Huang Y (2013) Frequency analysis of urban runoff quality in an urbanizing catchment of Shenzhen, China [J]. J Hydrol 496(2):79–88. https://doi.org/10.1016/j.jhydrol.2013.04.053

Rossman LA (2007): Storm water management model user's manual

Sage J, Bonhomme C, Ali SA, Gromaire MC (2015) Performance assessment of a commonly used "accumulation and wash-off" model from long-term continuous road runoff turbidity measurements. Water Res 78:47–59. https://doi.org/10.1016/j.watres.2015.03.030

Sansalone JJ, Buchberger SG (1997) Partitioning and first flush of metals in urban roadway storm water. J Environ Eng 123(2):134–143. https://doi.org/10.1061/(ASCE)0733-9372(1997)123:2(134)

Sartor JD, Boyd GB, Agardy FJ (1974) Water pollution aspects of street surface contaminants. J Water Pollut Control Fed 46(3):458–467

Shen Z, Liu J, Aini G, Gong Y (2016) A comparative study of the grain-size distribution of surface dust and stormwater runoff quality on

typical urban roads and roofs in Beijing, China. Environ Sci Pollut Res 23(3):2693–2704. https://doi.org/10.1007/s11356-015-5512-5

Soonthornnonda P, Christensen ER, Liu Y, Li J (2008) A washoff model for stormwater pollutants. Sci Total Environ 402(2-3):248–256. https://doi.org/10.1016/j.scitotenv.2008.04.036

Sutherland RA (2003) Lead in grain size fractions of road-deposited sediment. Environ Pollut 121(2):229–237. https://doi.org/10.1016/S0269-7491(02)00219-1

Vaze J, Chiew FHS (2002) Experimental study of pollutant accumulation on an urban road surface. Urban Water 4(4):379–389. https://doi.org/10.1016/S1462-0758(02)00027-4

Wang L, Wei J, Huang Y, Wang G, Maqsood I (2011) Urban nonpoint source pollution buildup and washoff models for simulating storm runoff quality in the Los Angeles County. Environ Pollut 159(7): 1932–1940. https://doi.org/10.1016/j.envpol.2011.03.019

Wijesiri B, Egodawatta P, Mcgree J, Goonetilleke A (2015a) Influence of pollutant build-up on variability in wash-off from urban road surfaces. Sci Total Environ 527-528C:344–350

Wijesiri B, Egodawatta P, Mcgree J, Goonetilleke A (2015b) Incorporating process variability into stormwater quality modelling. Sci Total Environ 533:454–461. https://doi.org/10.1016/j.scitotenv.2015.07.008

Wijesiri B, Egodawatta P, Mcgree J, Goonetilleke A (2016a) Understanding the uncertainty associated with particle-bound pollutant build-up and wash-off: a critical review. Water Res 101:582–596. https://doi.org/10.1016/j.watres.2016.06.013

Wijesiri B, Egodawatta P, Mcgree J, Goonetilleke A (2016b) Assessing uncertainty in stormwater quality modelling. Water Res 103:10–20. https://doi.org/10.1016/j.watres.2016.07.011

Wijesiri B, Egodawatta P, Mcgree J, Goonetilleke A (2016c) Assessing uncertainty in pollutant build-up and wash-off processes. Environ Pollut 212:48–56. https://doi.org/10.1016/j.envpol.2016.01.051

Yi C, Shuai J, Zhao Z, Shi P, Tao F (2014) Simulating the impact of watershed management for surface water quality protection: a case study on reducing inorganic nitrogen load at a watershed scale. Ecol Eng 62:61–70

Zafra C, Temprano J, Suárez J (2017) A simplified method for determining potential heavy metal loads washed-off by stormwater runoff from road-deposited sediments.[J]. Sci Total Environ 601-602: 260–270. https://doi.org/10.1016/j.scitotenv.2017.05.178

Zhang J, Pei H, Krebs P (2015a) The build-up dynamic and chemical fractionation of Cu, Zn and Cd in road-deposited sediment [J]. Sci Total Environ 532:723–732. https://doi.org/10.1016/j.scitotenv.2015.06.074

Zhang W, Li T, Dai M (2015b) Influence of rainfall characteristics on pollutant wash-off for road catchments in urban Shanghai. Ecol Eng 81:102–106. https://doi.org/10.1016/j.ecoleng.2015.04.016

Zhao H, Li X, Wang X, Tian D (2010) Grain size distribution of road-deposited sediment and its contribution to heavy metal pollution in urban runoff in Beijing, China. J Hazard Mater 183(1-3):203–210. https://doi.org/10.1016/j.jhazmat.2010.07.012

Zhao H, Zhao J, Yin C, Li X (2014) Index models to evaluate the potential metal pollution contribution from washoff of road-deposited sediment. Water Res 59:71–79. https://doi.org/10.1016/j.watres.2014.04.012

Zhao H, Chen X, Hao S, Yan J, Jiang Z, Zou C, Xie W (2016) Is the wash-off process of road-deposited sediment source limited or transport limited? Sci Total Environ 563–564:62–70

Zheng Y, Lin Z, Li H, Ge Y, Zhang W, Ye Y, Wang X (2014) Assessing the polycyclic aromatic hydrocarbon (PAH) pollution of urban stormwater runoff: a dynamic modeling approach [J]. Sci Total Environ 481(2):554–563. https://doi.org/10.1016/j.scitotenv.2014.02.097