Journal of Southeast University (English Edition) Vol. 30, No. 2, pp. 181 – 185 June 2014 ISSN 1003—7985

Characterizing urban road runoff quality in South China: a case study in Shenzhen

Zhang Jianjun[1] Jiang Yizi[2] Liu An[2] Guan Yuntao[2,3] Ye Shaohua[1]

([1]Shenzhen Municipal Design & Research Institute Co., Ltd., Shenzhen 518029, China)
([2]Graduate School at Shenzhen, Tsinghua University, Shenzhen 518055, China)
([3]State Environmental Protection Key Laboratory of Microorganism Application and Risk Control, Tsinghua University, Beijing 100084, China)

Abstract: In order to have an in-depth understanding of road runoff characteristics and the linkages to their influential factors, this paper investigates the road runoff quality in a city of South China, Shenzhen. Four rainfall events with different characteristics are monitored on a typical urban road. It is noted that the road runoff quality is worse than Grade Ⅳ of environmental quality standards for surface water. This means that the road runoff has posed a serious risk to water environment health. Furthermore, the research outcomes indicate that first flush highly varies with rainfall patterns and pollutant species. This means that for road runoff treatment design, rainfall patterns as well as pollutant species should be taken into consideration and this is particularly essential to design first flush capturing devices. Additionally, the threshold of an initial 3 to 5 mm rainfall depth is suggested to the first flush capturing device design. These results provide useful suggestions to the effective road runoff treatment design.

Key words: stormwater pollution; road runoff quality characteristics; first flush; low impact development (LID)
doi: 10.3969/j.issn.1003 – 7985.2014.02.008

Road runoff has received much attention in the area of urban stormwater pollution control[1–2]. Urban road surfaces are a major pathway to produce stormwater pollutants due to traffic activities and its nature of impervious surfaces[3]. In order to mitigate the urban road runoff pollution, structural strategies such as low impact development (LID) have been used in many cities. Unfortunately, the current stormwater treatment system is far from effective on the treatment capacity. This is due to lack of knowledge on the urban road runoff characteristics which are easily influenced by the surrounding environment, such as rainfall characteristics and land use. This highlights the need to have an in-depth understanding of road runoff quality characteristics. This paper investigates the road runoff characteristics in a city of South China, Shenzhen. The developed knowledge is expected to provide a useful insight to stormwater treatment design.

1 Materials and Methods

1.1 Study site

The selected sampling site is a typical urban road with asphalt pavement in Shenzhen city. It is a four-lane two-way road with a mean traffic volume of 750 veh/h. Educational and residential areas are the primary land use types in the sampling site. The urban road runoff samples are collected in a drainage gully with a drainage area of 320 m^2 on the road (see Fig. 1).

Fig. 1 The sampling site

1.2 Sampling and laboratory testing

The runoff samples were collected from four rainfall events with different rainfall characteristics as shown in Tab. 1. The rainfall events which were greater than 10 mm/h of average rainfall intensity were considered as "large events" while the remaining events were "small events". The sampling procedure was undertaken at intervals of 5 min in the first 30 min of each runoff event, followed by the 10-minute interval between 30 and 60 min and then the 30 min after 60 min.

All the samples were tested for suspended solids (SS), chemical oxygen demand (COD), ammonium nitrogen (NH_4^+-N), total nitrogen (TN) and total phosphorus (TP) since these are primary stormwater pollutants[4]. All the parameters were determined according to the standard methods specified in Ref. [5].

Received 2013-09-05.

Biographies: Zhang Jianjun (1970—), male, senior engineer, zhangjj@szmedi.com.cn; Guan Yuntao (corresponding author), male, professor, guanyt@tsinghua.edu.cn.

Foundation items: The National Science and Technology Major Project of China (No. 2012ZX07301-001), the Shenzhen Environmental Research Project, China Postdoctoral Science Foundation (No. 2013M530642).

Citation: Zhang Jianjun, Jiang Yizi, Liu An, et al. Characterizing urban road runoff quality in South China: a case study in Shenzhen. [J]. Journal of Southeast University (English Edition), 2014, 30(2): 181 – 185. [doi: 10.3969/j.issn.1003 – 7985.2014.02.008]

Tab. 1 The rainfall characteristics

Event	Event date	ARI/ $(mm \cdot h)^{-1}$	RD/min	ADD/d	RT
Ⅰ	20120705	13.41	55	4	Large
Ⅱ	20120721	6.71	110	3	Small
Ⅲ	20120722	25.51	30	0	Large
Ⅳ	20120830	11.35	60	1	Large

Notes: ARI represents the average rainfall intensity; RD represents the rainfall duration; ADD represents the antecedent dry days; RT represents the rain types.

1.3 Determination of runoff volume and quality parameters

1.3.1 Pollutant event mean concentration

Event mean concentrations (EMC) rather than instantaneous concentrations are used to initially compare the runoff quality of rainfall events in the study. This is due to the fact that the EMC represents the average pollutants amount for a rainfall event and hence can be considered as an event characterization in terms of stormwater quality[6] while instantaneous concentrations have a relatively high variation with time. Furthermore, this is also supported by the fact that EMC is the parameter adopted to estimate the pollutants load, which is typically used in stormwater quality treatment design[7-8]. The EMC can be expressed as

$$\mathrm{EMC} = \frac{M}{V} = \frac{\int_0^{t_r} C_t q_t \mathrm{d}t}{\int_0^{t_r} q_t \mathrm{d}t} = \frac{\sum C_t q_t \Delta t}{\sum q_t \Delta t} \qquad (1)$$

where M is the total mass of pollutant over an entire event duration, g; V is the total volume of flow over an entire event duration, m^3; t is the time, min; C_t is the time variable concentration, mg/L; q_t is the time variable flow, m^3/min; and Δt is the discrete time interval, min. In this study, the rainfall volume is seen as q_t.

1.3.2 Dimensionless cumulative mass vs. volume curves

The mass-based first flush can be indicated by the dimensionless cumulative mass vs. volume curves (LV curve). In the mass-based first flush, the pollutant load washed-off during the storm event is evaluated. As the first flush is typically defined as the wash-off of a relatively higher pollutant load during the early part of the runoff event, the comprehensive analysis of the variation of cumulative pollutant load L vs. cumulative runoff volume V is important to understand the first flush characteristics. The calculations of the first flush are as follows:

$$M_{t_r} = \frac{M(t_r)}{M_t} = \frac{\sum C_{t_r} q_{t_r} \Delta t_r}{\sum C_t q_t \Delta t} \qquad (2)$$

$$Q_{t_r} = \frac{Q(t_r)}{Q_t} = \frac{\sum q_{t_r} \Delta t_r}{\sum q_t \Delta t} \qquad (3)$$

where M_{t_r} is the dimensionless cumulative mass transported during any measured interval; $M(t_r)$ is the cumulative mass transported during any measured interval, kg; M_t is the total mass transported throughout the duration at each event, kg; C is the pollutant concentration during any measured interval, mg/L; q is the flow rate during any observed interval; t_r is the any time between the initial of runoff and the time coinciding with the cessation of runoff, min; Δt and Δt_r are the time increments between successive measurements, min. Q_{t_r} is the dimensionless cumulative flow rate during any observed interval; $Q(t_r)$ is the cumulative flow rate during any measured interval, m^3/min; and Q_t is the total flow rate observed throughout the duration in each event, m^3/min.

The first flush is observed when the data ascended above the 45° line. The 45° line represents the case when the pollutant loads remain constant throughout the storm runoff. Conversely, dilution is assumed to have occurred when the data fell below the 45° line [9-10]. The deviation of the cumulative pollutant mass curve from the diagonal is used as a measure of the magnitudes of the first flush.

1.3.3 Pollution loads transported by stormwater runoff

To understand the dynamics of the first flush, a calculable definition of the first flush must be chosen. Saget et al. [11] defined the first flush as the percentage of total event pollution load transported by the first 30% of the stormwater runoff volume (FF30). There are three categories of the first flush[12], the high first flush (FF30 ≥ 50%), the medium first flush (30% < FF30 < 50%) and the no-first flush (FF30 ≤ 30%). While Ma et al. [13] considered the corresponding pollutant loads transported by the initial 40% of the runoff volume to define the first flush (FF40). Therefore, in this paper, both FF30 and FF40 are estimated to analyze the first flush characteristics for each rainfall event.

2 Results and Discussion

2.1 Comparison of runoff quality

Tab. 2 shows the EMC values for SS, COD, NH_4^+-N, TN and TP as well as the pollutant concentrations for the Grade Ⅳ of environmental quality standards for surface water. It is noted that the mean EMC values of SS, COD, NH_4^+-N, TN and TP are 221.1, 137.5, 1.46, 4.14 and 0.30 mg/L, respectively. Additionally, it is noteworthy that most of pollutant EMCs are higher than Grade Ⅳ of environmental quality standards for surface water. This means that road runoff in Shenzhen city has posed a serious risk to the water environmental health if the road runoff flows into the receiving waters without treatment.

Furthermore, it can be observed that EMCs from these four rainfall events show relatively high relative standard deviation (RSD) values (>35%) regardless of pollutant species. This confirms that the high variability of road runoff quality with different rainfall characteristics as a data set with RSD greater than 10% is considered as having a high variability[14].

Tab. 2 Stormwater runoff quality of four rainfall events

mg/L

Event	SS	COD	NH_4^+-N	TN	TP
20120705	260.7	192.3	0.64	3.03	0.33
20120721	161.0	176.1	3.35	6.72	0.36
20120722	230.6	113.0	1.05	4.37	0.37
20120830	226.8	50.4	0.85	2.75	0.16
Mean	221.0	137.5	1.46	4.14	0.30
RSD/%	78.90	53.58	85.19	45.68	37.22
Grade Ⅳ		30	1.5	1.5	0.3

Note: Grade Ⅳ means Grade Ⅳ of environmental quality standards for surface water (GB3838—2002).

2.2 Variability of runoff quality

Fig. 2 shows the variability of pollutant concentrations with time. It is noted that the trends of pollutant concentrations with time are different among the four rainfall events. The pollutant concentrations in Event Ⅰ and Ⅲ are higher in the initial 10 min than the corresponding values in the remaining portion of rainfall events, which levels off at a certain value. However, the pollutant concentrations in Events Ⅱ and Ⅳ show a relatively higher variation with time throughout the entire rainfall events. For example, the pollutant concentrations at the 40th min in Event Ⅳ are much higher than others. This can be attributed to different rainfall patterns. It is found that Events Ⅰ, Ⅲ and Ⅳ have the high rainfall intensity (RI) in the initial portion of the hyetographs while Event Ⅱ shows the high intensity in both initial and later parts. Therefore, these observations imply that the rainfall pattern could be an important influential factor to affect road runoff quality characteristics. The events with high rainfall intensity occurring in the initial portion can lead to high pollutant concentrations at the beginning of runoff, namely higher magnitude of the first flush.

Additionally, it is also noteworthy that different pollutant species show different runoff characteristics although they experienced the same rainfall event. For example, SS and COD in Event Ⅰ show much higher concentrations in the early runoff portion than the other three pollutants. The trends of exportation for pollutants are also different even in the same rainfall event. This means that the road runoff quality characteristics also vary highly with pollutant species.

Fig. 3 shows the LV curve of the four events. It is noted that the magnitude of the first flush in Event Ⅰ is relatively high compared with the other three events since there are bigger gaps between the LV curve and the 45° line in Event Ⅰ (see Fig. 3). This can be attributed to different rainfall characteristics since Alias[15] has pointed out that the rainfall characteristics are one of the key influential factors in affecting the first flush. Additionally,

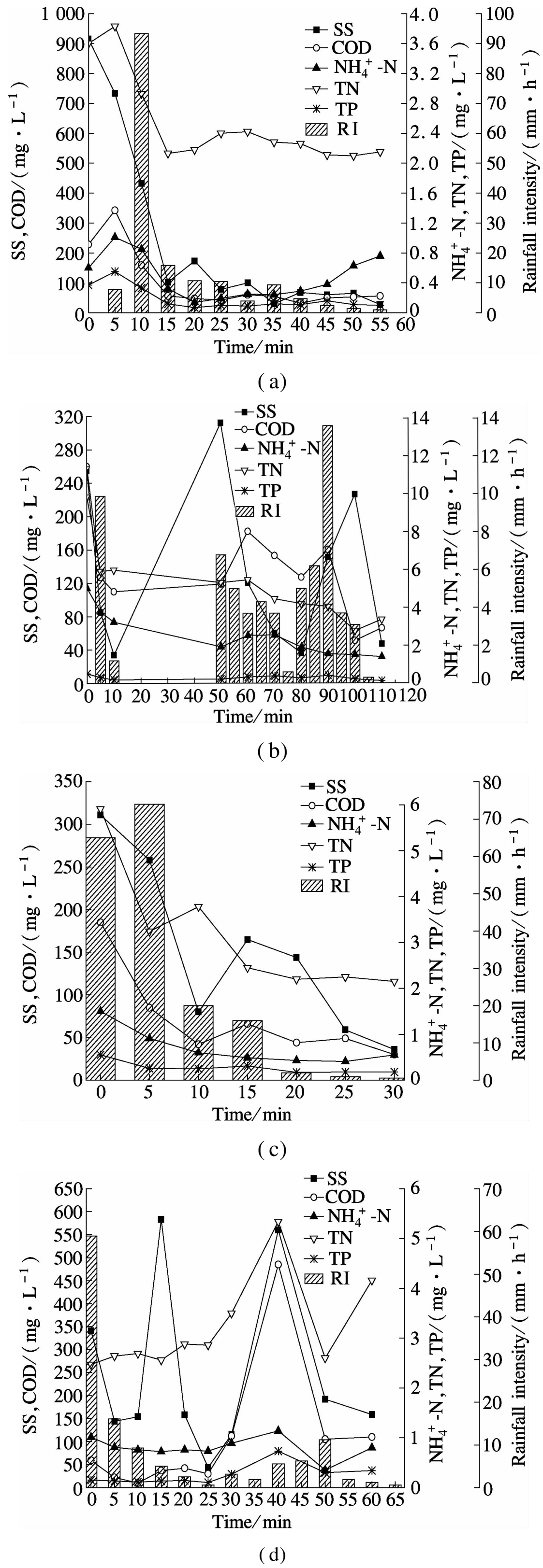

Fig. 2 Variability of runoff quality. (a) Event Ⅰ; (b) Event Ⅱ; (c) Event Ⅲ; (d) Event Ⅳ

it is also noteworthy that the first flush of different pollutants appears differently even in the same rainfall event. For example, in terms of Event Ⅰ, SS and COD represent the higher magnitudes of the first flush while TN is the lowest.

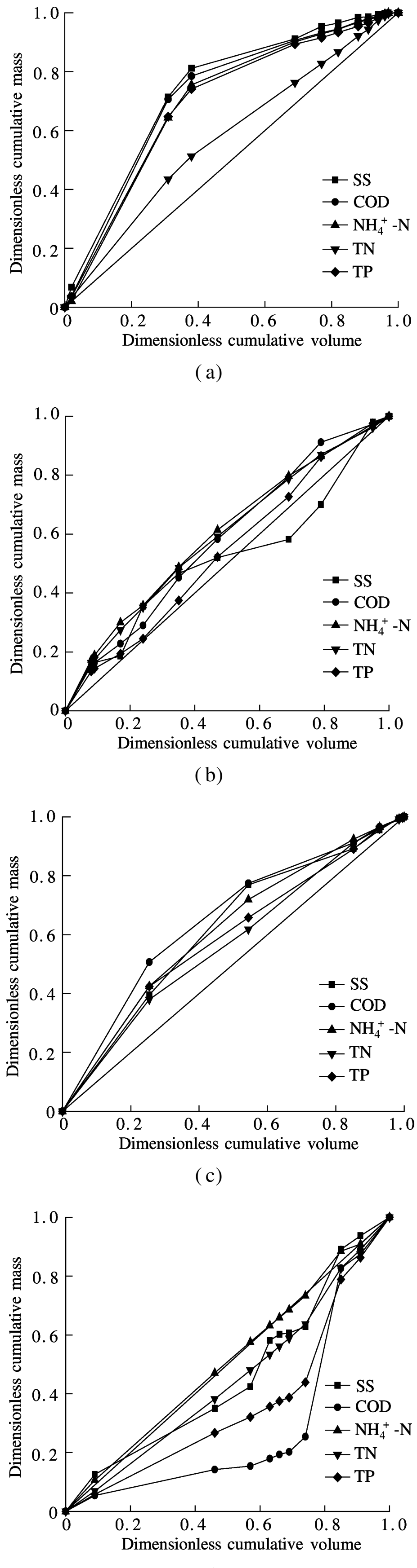

Fig. 3 Dimensionless cumulative mass and volume curves for four rain events. (a) Event Ⅰ; (b) Event Ⅱ; (c) Event Ⅲ; (d) Event Ⅳ

This could be due to their natures of solubility since nitrogen is primarily present in the dissolved form. However, the first flush phenomenon is more complex in Event Ⅱ while there is no first flush occurrence in Event Ⅳ. This further confirms the conclusions that the first flush can vary highly with rainfall characteristics as well as the pollutant species. This means that for road runoff treatment design, the rainfall pattern as well as the pollutant species should be taken into consideration and this is particularly essential to design first flush capturing devices.

2.3 Pollution loads transported by stormwater runoff

Adequately sizing the stormwater treatment system is important in the design process due to the cost-effectiveness. In the case of the design volume being too small, a large number of rainfall events will exceed the capacity of the treatment device. Alternately, if the design volume is too large, there will be increased cost as well as further treatment being negligible after a certain threshold[16]. This highlights the need to determine a threshold of the runoff volume which can carry an appropriate portion of pollutant loads. This is undertaken by investigating the pollutant loads transported by the runoff.

Tab. 3 shows the results of FF30 and FF40 for SS, COD, NH_4^+-N, TN and TP. It presents a medium first flush since the mean values of FF30 for SS, COD, NH_4^+-N, TN and TP are 44%, 43%, 43%, 37% and 42%, respectively. The corresponding values of FF40 for SS, COD, NH_4^+-N, TN and TP are 54%, 52%, 54%, 46% and 49%, respectively. Since the first 30% and 40% of the runoff volume correspond to the initial 3 to 5 mm and 4 to 8 mm rainfall depth according to the rainfall characteristics, the initial 3 to 5 mm rainfall depth is suggested as the cut-off threshold. The initial 30% of runoff volume carries more than 40% of pollutant loads and would be more effective and economical than intercepting the initial 8 mm rainfall depth corresponding to the initial 40% of runoff volume.

3 Conclusion

This paper shows that the road runoff quality is worse than Grade Ⅳ of environmental quality standards for surface water in Shenzhen. This means that the road runoff has posed a serious risk to water environment health. Furthermore, the research outcomes indicate that the first flush varies highly with the rainfall pattern and pollutant species. This means that for road runoff treatment design, the rainfall pattern as well as pollutant species should be taken into consideration and this is particularly essential to design first flush capturing devices. Additionally, a threshold, the first 3 to 5 mm rainfall depth, is suggested as the first flush capturing device design. These results provide a useful insight to the effective road runoff treatment design.

Tab. 3 Results of FF30 and FF40 for SS, COD, NH_4^+-N, TN and TP ($n=4$) %

Parameter	SS		COD		NH_4^+-N		TN		TP	
	FF30	FF40	FF30	FF40	FF30	FF40	FF30	FF40	FF30	FF40
Max	70	80	70	79	57	69	44	52	65	75
Min	25	30	10	15	31	41	23	31	20	25
Mean	44	54	43	52	43	54	37	46	42	49

References

[1] Mahbub P, Goonetilleke A, Ayoko G A, et al. Analysis of build-up of heavy metals and volatile organics on urban roads in gold coast, Australia [J]. *Water Science and Technology*, 2011, **63**(9): 2077 - 2085.

[2] Brigitte H, Rita H, Alexander S, et al. Runoff pollutants of a highly trafficked urban road — correlation analysis and seasonal influences [J]. *Chemosphere*, 2010, **80**(9): 991 - 997.

[3] Liu A, Goonetilleke A, Egodawatta P. Inherent errors in pollutant build-up estimation in considering urban land use as a lumped parameter [J]. *Journal of Environmental Quality*, 2012, **41**(5): 1690 - 1694.

[4] Lee J Y, Kim H J, Kim Y J, et al. Characteristics of the event mean concentration (EMC) from rainfall runoff on an urban highway [J]. *Environmental Pollution*, 2011, **159**(4): 884 - 888.

[5] Wei F S, Qi W Q, Bi T, et al. *Water and wastewater monitoring analysis method.* [M]. 4th ed. Beijing: China Environmental Science Press, 2002: 105 - 107; 210 - 220; 243 - 284. (in Chinese)

[6] Adams B J, Papa F. *Urban stormwater management planning with analytical probabilistic models* [M]. New York: John Wiley & Sons, 2000.

[7] Weiss P T, Gulliver J S, Erickson A J. Cost and pollutant removal of stormwater treatment practices [J]. *Journal of Water Resources Planning and Management*, 2007, **133**(3): 218 - 229.

[8] Taewon K, Kyungik G. Determination of the removal efficiency of a vortex-type facility as a best management practice using the dynamic event mean concentration: a case study of a bridge in Yong-In city in Korea [J]. *Environmental Earth Sciences*, 2012, **65**(3): 937 - 944.

[9] Barco J, Papiri S, Stenstrom M K. First flush in a combined sewer system [J]. *Chemosphere*, 2008, **71**(5): 827 - 833.

[10] Kim G, Yur J, Kim J. Diffuse pollution loading from urban stormwater runoff in Daejeon city, Korea [J]. *Journal of Environmental Management*, 2007, **85**(1): 9 - 16.

[11] Saget A, Chebbo J, Bertrand-Krajewski J. The first flush in sewer system [J]. *Water Science and Technology*, 1996, **33**(9): 101 - 108.

[12] Kim L H, Kayhanian M, Zoh K D, et al. Modeling of highway stormwater runoff [J]. *The Science of the Total Environment*, 2005, **293**(1/2/3): 163 - 175.

[13] Ma Y, Ma Y W, Wan J Q, et al. Characterization of rainfall runoff pollution transportation in different underlying surface of Dongguan City [J]. *China Environmental Science*, 2011, **31**(12): 1983 - 1990. (in Chinese)

[14] Hamburg M. *Statistical analysis for decision making* [M]. Philadelphia: The Dryden Press, Harcourt Brace College Publishers, 1994.

[15] Alias N. First flush behavior in urban residential catchments [D]. Brisbane, Queensland, Australia: Queensland University of Technology, 2013.

[16] Guo J C Y, Urbonas B, MacKenzie K. Water quality capture volume for storm water BMP and LID designs [J]. *Journal of Hydrologic Engineering*, 2014, **19**(4): 682 - 686.

华南地区城市道路径流污染特性:以深圳市为例

张健君[1] 蒋沂孜[2] 刘 安[2] 管运涛[2,3] 叶少华[1]

([1] 深圳市市政设计研究院有限公司, 深圳 518029)

([2] 清华大学深圳研究生院, 深圳 518055)

([3] 清华大学国家环境保护环境微生物利用与安全控制重点实验室, 北京 100084)

摘要:为了解析华南地区道路径流污染特性及其影响因素,对华南地区典型城市深圳市道路进行了 4 场降雨的径流样品采集及分析. 结果显示道路径流水质劣于地表水 4 类环境质量标准,说明道路径流已经成为影响城市水环境质量的重要威胁. 同时研究发现初期冲刷效应受到降雨类型和污染物种类的双重影响,因此在针对道路径流处理设施特别是初雨截流装置的设计时,需要同时考虑降雨类型与污染物种类. 另外,建议华南地区的初雨截流量为 3 ~ 5 mm 的初期降雨. 这些研究结果能为有效的道路径流处理设施设计提供有用的建议.

关键词:暴雨污染; 道路径流污染特性; 初期冲刷; 低影响开发

中图分类号:X501