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Runoff pollution characterization and first flush effect of urban roof catchment

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ABSTRACT

Roof runoff pollution has been given considerable attention to ensure the safety of roof rainwater utilization. A residential roof catchment located in Handan, China, was selected as a study site. The water quality of roof runoff was analyzed at 15 storm events during 2014–2016. The median concentrations of chemical oxygen demand (COD), ammonia nitrogen, total nitrogen, total phosphorus and sulphane are 104, 8.53, 10.60, 0.21 and 14.31 mg/L, respectively; these values all exceed the class V of environmental quality standards for surface water in China. A strong linear correlation is established between COD and other pollutants. All the Pearson's coefficients (r) are more than 0.8. COD could be considered surrogates for other pollutants. During storm events, the concentration change of runoff pollutants could be fitted well by the exponential function. The selected storm events present the first flush effect in varying degrees. Approximately 80% of the pollutant load is transported in the first 36%, 53%, 57%, 26% and 38% of the volume for five storm events. The first flush effect is evidently related with rainfall depth and antecedent dry days. Furthermore, water quality depth (WQD) can be used as a definitive parameter for runoff pollution control. WQD presents different values to reach diverse stormwater management targets.

Keywords: Runoff pollution characterization; Correlation analysis; First flush effect; Cumulative load ratio; Cumulative runoff ratio; Water quality depth

1. Introduction

Hydrology is evolving from a pure science to a more applied one [1]. The general view of the hydrology as a balance under natural condition is being changed by a scientific approach to show the effect of the humans on the hydrological system [2] and how this affect the risk for human societies [3] and the soil resources [4]. The traditional hydrological balances at watershed scales for water and sediment balances is being transformed into a more applied approach to solve problems which should be seeing from nature base solutions [5–7]. The use of urban roof runoff is a proper solution to the need of more water for modern societies, which should be seen as a solution within a framework that shows water as a key resource to achieve the sustainability.

To ensure the safety of roof rainwater utilization, roof runoff pollution has attracted considerable research attention [8]. During the early 1956, some researchers began to focus on roof runoff pollution and suggested the first flush effect in the process [9]. In the following years, Gikas and Tsihrintzis [10] suggested that roof runoff quality is affected by rainwater quality, rainfall intensity and roof type (material, slope and proportion). Sansalone and Cristina [11] attempted to refine multiple definitions of the first flush effect; these definitions are deemed to a consistent framework eventually. Taebi and Droste [12] and Sansalone and Buchberger [13] demonstrated the quantification of first flush and analyzed the relationship among the parameters of first flush effect, roof characteristics

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(slope and roof roughness), rainfall intensity and duration. Furthermore, Van Lienden et al. [14] monitored the build-up/wash-off and transport pollutant characteristics of repetitive rainfall runoff.

Currently, the definition of first flush effect is still in dispute amongst researchers. Modugno et al. [15] investigated the first flush effect occurrence by determining the distribution of pollutant mass and showed that the first 30% of stormwater runoff washed off carries approximately 60% of total suspended solid (TSS). A strong correlation is also established between chemical oxygen demand (COD) and TSS concentration. Millar [16] reported that the algorithm of exponential relationship is commonly used to analyze the first flush effect between pollutant runoff and its volume. Ma et al. [17] concluded that most of the total event pollution load is carried by the medium (40%) and runoff depth (30%). Many quantified definitions have emerged according to the dimensionless cumulative curve. In the first 20%–40% of runoff volume, 45%–80% of total pollutants are transported [18–21]. These results are almost obtained at the small catchments. For large catchments, the rule of runoff flush may present a different phenomenon. Charbeneau and Barrett [22] proposed that not all rainwater runoff corresponds with the first flush effect due to the random changes in pollutant concentration in some rainfalls. Qin et al. [23] also described the middle or final flush process using exponential wash-off model in a typical urbanizing catchment. Thus, the first flush effect in urban runoff is also in dispute among many researchers [24]. However, most researchers suggested that transferring or treating the first portion of runoff is economically advantageous for runoff pollution control, especially for small catchments, such as roof surface. Characterizing the first flush effect is practical and considerably important.

The present study focuses on the range and median of main pollutants in urban roof runoff and reveals the correlation of main pollutants. In addition, the change of pollutant concentration in runoff over rainfall depth is analyzed on the basis of the exponential wash-off algorithm. The first flush effect is defined using the values of the cumulative load ratio (CLR) against the cumulative runoff ratio (CRR). The water quality depth (WQD) value under different targets of stormwater management is also discussed.

2. Samplings and methods

2.1. Samplings

This study was carried out at the city of Handan, which is located in the south part of Hebei Province, China, between 36°20′–44′ of latitude north and 114°03′–40′ of longitude east. Handan is a warm-temperate zone with semi-humid continental monsoon climate. The mean annual temperature is 13.5°C, and the rainfall depth is 558.5 mm. Sampling was performed at the down pipe outlets in a residential roof area (approximately 108 m^2), which was covered with a layer of asphalt and showed a gradient of 1.0%–2.0%.

Samples were collected manually at specified intervals during storm events. During the initial phase of events, sampling was performed at 5–10 min intervals. Subsequently, the sampling interval was extended to 10–30 min until the runoff disappeared or the concentration of runoff pollutants became stable gradually. At least five discrete samples were collected in a storm event.

In each storm event monitoring, the main rainfall characteristics, such as duration, depth, intensity and antecedent dry day, were recorded by a telemetry rain gauge (SL_1, China). The samples were tested for COD, ammonia nitrogen (NH_3–N), total nitrogen (TN), total phosphorus (TP) and sulphane (SO_4^{2-}) according to water and exhausted water monitoring analysis method. The samples were tested in laboratory within 24 h.

A total of 15 rainfall events were monitored from 2014 to 2016. The characteristics of each storm event are shown in Table 1.

Table 1
Rainfall characteristics of monitored events

No.	Date	Depth (mm)	Duration (min)	Intensity (mm/h)	Antecedent dry day (d)
1	05/21/2014	12.2	1,370	0.53	3
2	07/02/2014	15.2	115	7.93	5
3	07/10/2014	22.8	1,250	1.09	8
4	07/11/2014	29.8	1,050	1.70	1
5	08/16/2014	10.7	40	16.05	11
6	04/25/2015	7.1	45	9.47	8
7	05/13/2015	5.3	113	2.81	18
8	06/07/2015	12.7	68	11.20	25
9	07/12/2015	16.6	183	5.44	35
10	07/16/2015	20.2	228	5.32	4
11	06/23/2016	4.1	120	2.05	53
12	06/26/2016	6.1	675	0.54	3
13	07/14/2016	9.1	80	6.83	18
14	07/21/2016	23.4	48	29.25	2
15	08/03/2016	24.3	310	4.70	4

2.2. Methods

On the basis of the exponential wash-off algorithm, Millar [16] proposed the following expression for the instantaneous concentration of storm runoff from an impervious surface:

$$C_t = C_0 e^{-wH} \quad (1)$$

where C_t is the instantaneous concentration of runoff pollutants at time t (mg·L^{-1}), C_0 is the initial concentration of runoff pollutants at a storm event (mg·L^{-1}), w is the empirical wash-off coefficient (mm^{-1}) and H is the cumulative runoff depth during a storm event (mm).

Generally, the first flush effect is defined by the values of CLR against those of CRR. When the values are higher than 1 during the storm event, the first flush effect occurs. Otherwise, no first flush effect is observed. The CLR and CRR values could be determined by Eqs. (2) and (3):

$$\text{CLR} = \frac{m(t)}{M} = \frac{\int_0^t Q_i C_i \,\mathrm{d}t}{\int_0^T Q_i C_i \,\mathrm{d}t} \quad (2)$$

$$\text{CRR} = \frac{v(t)}{M} = \frac{\int_0^t Q_i \,\mathrm{d}t}{\int_0^T Q_i \,\mathrm{d}t} \quad (3)$$

where $m(t)$ is the cumulative pollutant mass until time t (g), $v(t)$ is the cumulative runoff volume until time t (m^3), M is the total pollutant mass over entire storm event (g), V is the total runoff volume over the entire storm event (m^3), Q_t is the flow rate at time t (m^3/min), C_t is the pollutant concentration at time t (g/m^3), T is the runoff duration (min) and t is the sampling time (min).

3. Results and discussion

3.1. Characteristics of runoff water quality

During the storm events, the monitored pollutant concentration ranges of COD, NH_3–N, TN, TP and SO_4^{2-} are 2–1,208, 1.22–17.30, 3.10–21.80, 0.06–3.04 and 0.20–31.90 mg/L, respectively. Moreover, the median concentrations are 104, 8.53, 10.60, 0.21 and 14.31 mg/L. The summary of runoff water quality is shown in Table 2. Compared with class V of the Environmental Quality Standards for Surface Water (GB 3838-2002) [25], all the median concentrations of the pollutants remarkably exceed the water quality standard. Therefore, discharging untreated runoff into surface water is harmful.

Table 2
Values of pollutants in runoff samples collected in different storm events

No.	Parameters	Concentration (mg/L)		Class V[a] (mg/L)
		Minimum/maximum	Median	
1	Chemical oxygen demand (COD)	1/1,208	104	40
2	Total phosphorus (TP)	0.06/3.04	0.21	0.4
3	Total nitrogen (TN)	3.10/21.80	10.60	2.0
4	Ammonia nitrogen (NH_3–N)	1.22/17.30	8.53	2.0
5	Sulphane (SO_4^{2-})	0.20/31.90	14.31	–

[a]Obtained from the Environment Quality Standards for Surface Water (GB 3838-2002).

3.2. Correlation analyses of runoff pollutants

Some researchers [26,27] indicated that the correlation among runoff pollutants is relatively close. According to the monitoring data, a strong linear correlation is observed between COD and other pollutants. All the Pearson's coefficients (r) are more than 0.8, which is used to rank the correlation [28]. The results are shown in Table 3. Hence, COD could be considered surrogates for other pollutants to discuss other aspects of runoff pollution in the sections below.

Table 3
Correlation between each pair of runoff pollutants

Correlation coefficient (r)[a]	COD	TP	TN	NH_3-N	SO_4^{2-}
COD					
TP	0.981				
TN	0.930	0.965			
NH_3–N	0.997	0.977	0.943		
SO_4^{2-}	0.901	0.833	0.985	0.926	

[a]Data in the table are all correlation coefficients (r).

3.3. Variations of runoff water quality during storm events

Data from five storm events with rainfall depths of 7.1–25.1 mm were selected to analyze the variations of runoff water quality during storm events. The results are shown in Fig. 1.

The change of COD in each storm runoff shows a similar tendency that high concentration appears at the beginning of the rainfalls. Subsequently, the concentration decreases gradually until it stabilizes around a low value. Nevertheless, the results showed that the initial value and decreasing rate of COD in each event are different. For the roof runoff, pollution source is mainly obtained from atmospheric deposition. The long antecedent dry day results in a large amount of pollutants accumulated on the roofs [29].

In the present study, the concentration change of runoff pollutant could be fitted well by Eq. (1). The highest concentration of initial runoff occurs in No. 2 storm event that presents 53 antecedent dry days. Therefore, the initial concentration of roof runoff may be closely related with antecedent dry days. When the initial value of the pollutant concentration increases, the concentration decreases accordingly. This result is attributed to the smoother roof surface than that of other catchments, such as road, pavement and greenbelt. In addition, the particle size of runoff pollutants obtained from atmospheric deposition is commonly small [30]. When the runoff is formed, most pollutants can be washed off by the roof runoff.

3.4. Analysis of first flush effect

According to Eqs. (2) and (3), the CLR and CRR values until each sample time could be calculated. Afterwards, the curves of CLR against CRR at each selected storm event are plotted in Fig. 2.

Fig. 2 shows that all the curves of CLR against CRR in each selected storm event are above the 45° line, thereby suggesting a first flush effect. However, 80% of the pollutant load is transported in the first 36%, 53%, 57%, 26% and 38% of the volume for the five storm events. According to the definition of the first flush effect proposed by McCarthy et al. [21], the curves of No. 4 and 5 storm events exhibit a strong first flush effect. On the contrary, other events exhibit a weak first flush effect. The first flush effect is clearly related with rainfall depth and antecedent dry days. This correlation is probably because of the large low concentration runoff ratio that causes high rainfall depth (No. 5 storm event) at a later period to the whole runoff. Moreover, long antecedent dry days before storm events (No. 4 storm event) could result in a strong first flush effect because of the high pollutant concentration in storm runoff.

For urban stormwater management, water quality volume is an important concept applied to several criteria or manuals in different countries [31]. This concept was proposed on the basis of the first flush effect, which is often replaced by WQD [32]. The curves of the CLR are plotted against rainfall depth using Eq. (2), as shown in Fig. 3.

Determining the value of WQD according to the target ratio of runoff load decrease is convenient. The WQD presents different values to reach diverse stormwater management target. For severely polluted catchment, the runoff load decrease ratio could be set to 80%, and the recommended value of WQD is 5 mm accordingly. Furthermore, the ratio could be 60% for a rainwater utilization system. The WQD value should be 2–3 mm so as to collect large water volume. Fig. 3 illustrates that the curves of all the storm events are in accordance with the results, except for No. 5 storm event. Although the runoff load decrease ratio at No. 5 storm event is not the same as the value of WQD, its pollutant concentration is lower than that of other events because of its low initial concentration (COD < 50 mg/L). Thus, the presented results are acceptable.

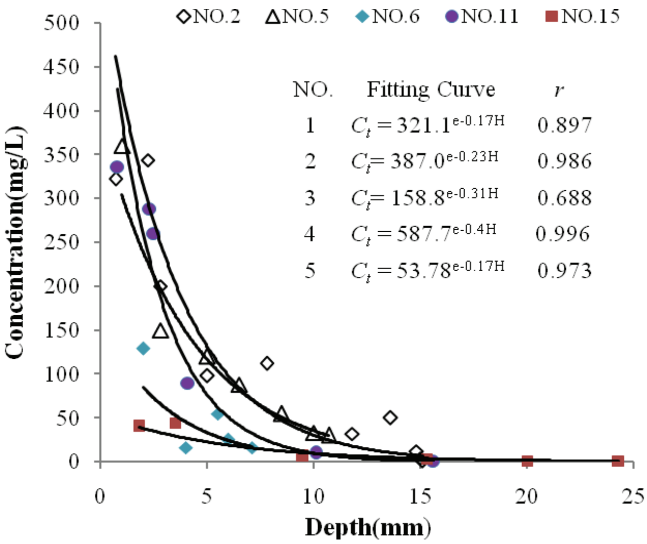

Fig. 1. Change of COD in runoff over rainfall depth.

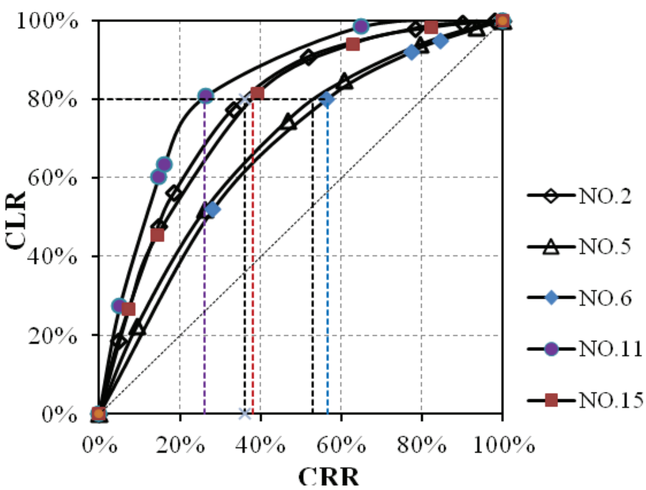

Fig. 2. Curves of cumulative load ratio (CLR) against cumulative runoff ratio (CRR) at each selected storm event.

4. Summary

In this study, the water quality of roof runoff is analyzed at 15 storm events from 2014 to 2016. The major conclusions can be summarized as follows:

(1) The ranges of COD, TP, TN, NH_3–N and SO_4^{2-} are 1–1,208, 0.06–3.04, 3.10–21.80, 1.22–17.30 and 0.20–31.90 mg/L, respectively. All the median concentrations remarkably exceed the class V of Environment Quality Standards for Surface Water (GB 3838-2002).

(2) A strong linear correlation is observed between COD and other pollutants. All the Pearson's coefficients (r) are

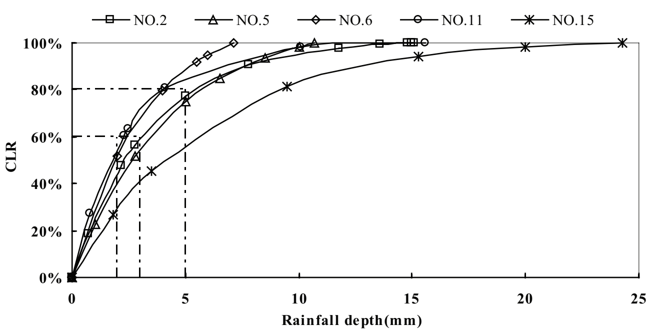

Fig. 3. Curves of the CLR against rainfall depth.

more than 0.8. COD could be considered surrogates for other pollutants.

(3) During storm events, the concentration change of runoff pollutants could be fitted well by the exponential function. Analysis of the curves of CLR against CRR showed that the selected storm events present the first flush effect in varying degrees. Approximately 80% of the pollutant load is transported in the first 70%, 57%, 53%, 26% and 38% of the volume for the five storm events. The first flush effect is related with rainfall depth and antecedent dry days evidently.

(4) WQD can be used as a definitive parameter for runoff pollution control. WQD presents different values to reach diverse stormwater management targets. For severely polluted catchment, runoff load decrease ratio could be set to 80%, and the recommended value of WQD is 5 mm accordingly. Moreover, for a rainwater utilization system, when the ratio could be set to 60%, the value of WQD should be 2–3 mm so as to collect large water volume.

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