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Examining the first flush effect based on the relationship between concentrations and discharge rates in a rain garden inflow

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ABSTRACT

Phosphorus (P) and nitrogen (N) sources are major pollutants in urban stormwater runoff. Low impact development measures have been found effectively in retaining stormwater runoff with respect to their water quantity and quality. However, the removal efficiency of different pollutants varies greatly, this may be affected by the relationship between hydrograph and pollutant concentration of inflow. Based on a 4-year monitoring data of stormwater runoff inflow to an experimental rain garden, this paper presents an analytical study on the relationship between TP and TN concentrations with inflow discharge rate into the rain garden. The results showed that the concentrations of TP changed little during all storm events, ranging from the mean maximum value of 0.96 mg/L to the mean minimum value of 0.29 mg/L; the variation range of TN in single storm event was greater than that of TP. After statistics, 10 out of 17 rainfall events showed the first flush effect in TP, and 16 out of 17 rainfall events showed the first flush effect in TN. The first 20% runoff volume carried the pollutant load of 23.6% for TP, and 29.3% for TN; the first 50% runoff carried 52.0% for TP and 59.9% for TN. The first flush effect appeared more significant in TN than TP. The concentration of pollutant and quantity of discharge (C–Q) relationship curves in initial 30 min (first stage) appeared differently in a clockwise, anti-clockwise, quasi-line, and U shape; most of them were clockwise (6 out of 15 storm events) and anti-clockwise (5 out of 15 storm events). For all monitoring rainfall events, the C–Q relationship in the other remaining time (second stage) showed certain randomness. Finding from this research can provide the basis for formulating reasonable standards in runoff volume reduction and pollutants of TP/TN control.

Keywords: Stormwater; Total phosphorus (TP); Total nitrogen (TN); First flush effect; Concentration–discharge relationship

1. Introduction

Many cities suffer from problems of water shortage and water quality degradation in the urbanization processes; urban stormwater runoff has become major contributor of nonpoint source pollution in recent decades [1]. Nutrients such as nitrogen (N) and phosphorus (P) are contributing to eutrophication of many surface water bodies [2,3]. Low impact development (LID) measures have been adopted to manage stormwater runoff worldwide [4]. Their main functions are to reduce runoff volume and remove the associated pollutants from the source [5,6]. LID strategies that induce onsite infiltration of stormwater runoff can mimic urban predevelopment hydrological regime. However, there are different standards for the stormwater runoff volume reduction, and the current design standards mostly employ runoff reduction rate as the design parameter, which do not take the relationship between runoff reduction and pollutants removal into consideration [7,8]. Therefore, determining the changes of different pollutants with the storm runoff processes are important for design of functional LID practices.

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The pollutants of stormwater runoff mainly come from underlying surface wash-off and atmosphere leaching [9]. Many researchers reported that the first flush phenomenon had significant impact on stormwater quality, especially the pollutant migration; but different climatic and underlying conditions led to the complexity of this process in different places [10,11]. The first flush effect refers to the condition when pollutant concentrations in the initial time are higher than that in the middle and later time of a rainfall event [12]. However, there exists a great difference in determining the first flush effect [13,14]. Pollutants washed by storm change randomly, and they present spatial and temporal variability and complexity. LID facility designs usually aim to certain standard, such as specific pollutant load removal and runoff volume reduction. Therefore, it is important to study pollutants changing with inflow to an LID facility under different design storm events.

Findings on pollutant removal with LID measures in existing studies are not consistent; the reported pollutant removal rates range from high to low values, even increasing pollutant concentrations after LID facilities treatment [15–18]. The inconsistent performances of LID measures on pollutant removal rate may be caused by different inflow processes, including inflow hydrograph and pollutant variation [19]. There is a growing attention paid to the effect of hydrological processes on water quality under different LID measures in recent years [20,21]; some studies examined the potential of improving flow condition of stormwater runoff in LID measures by replacing filling media, or increasing the depth of internal water storage layer to improve flow reduction and removal rate of different pollutants [22,23]. However, few studies have been conducted on the characteristics of pollutants collected from stormwater runoff and the C–Q relationship in LID facilities.

The C–Q relationship often exhibits a cyclical form known as hysteresis [24]. Hysteresis loops of different shapes with respect to total suspended solid, turbidity (TU) and total phosphorus during storm events have been reported in small catchment including headwater urban stream and agricultural drainage area [25–27]. The examination of hysteresis loops can provide information regarding the time-lags between discharge and pollutants. For C–Q relationship of clockwise hysteresis pattern, some researchers ascribed it to pollutant exhaustion, and showed first flush effect [28,29].

In order to study the C–Q relationship of inflow in LID facilities, this paper analyzed TP and TN concentration changes with storm processes based on a 4-year observation for a rain garden in Xi'an, China. The objectives of this research were to:

- assess the characteristics of nitrogen and phosphorus with the stormwater discharge under different storm events
- quantify the first flush effect under different storm events and determine pollutant load of different runoff processes, and
- examine the hysteresis feature of the relationships between concentrations of pollutants (TP and TN) and quantity of discharge rate (C–Q) in a rain garden inflow.

2. Materials and methods

2.1. Site description and data collection

As shown in Fig. 1, the experimental rain garden was located in Xi'an, China (E107.40~109.49°, N 33.42~34.45°). The mean annual precipitation of Xi'an was 554 mm, and 60% of rainfall occurs in the rainy season between July and September. The rain garden collects stormwater runoff from roof of a nearby building, and the catchment roof surface is waterproof with concrete and styrene block copolymers [30]. The experimental device is an infiltrated rain garden. When ponding depth of the rain garden exceeds the design depth, the overflow occurs. Two V-notch weirs were installed at the inlet and outlet of the rain garden for inflow and outflow measurement. Water quality samples were collected behind the weirs during storm events, and water sampling intervals were adjusted according to rainfall intensity changes. Collected water samples were instantly taken to laboratory for analysis using national standard methods.

2.2. Identification of the first flush effect

The definitions of first flush include concentration first flush and mass first flush. Concentration first flush refers to the concentrations of pollutants in the initial runoff that are significantly higher, while the mass first flush refers to cumulative transport rate of pollutant at the initial stage is greater than that of runoff volume. Geiger [31] defined a first flush phenomenon according to pollutant mass and runoff volume (*M*/*V*) as below:

$$\frac{M(t)}{V(t)}=\frac{\int_0^t Q(t)C(t)dt \Big/ \int_0^T Q(t)C(t)dt}{\int_0^t Q(t)dt \Big/ \int_0^T Q(t)dt} \tag{1}$$

where $M(t)$ is pollutant transport rate at time t, $V(t)$ is storm runoff volume transport rate at time t, $Q(t)$ is runoff flow rate at time t, $C(t)$ is pollutant concentration of runoff at time t, t is storm duration, and T is the total duration of a storm event. At the early stage of a rainfall event, when $M(t)/V(t) > 1$, or curves slope > 45°, the pollutant emission rate in the initial runoff is greater than that of the runoff discharge rate, which indicates the occurrence of first flush.

Bertrand et al. [32] defined the first flush effect, when at least 80% of the pollutant mass is emitted in the first 30% of the runoff volume, or 50% pollutant mass with 25% runoff volume, 40% pollutant mass with 20% runoff volume. Therefore, in this paper, we examined statistics for pollutant load carried by 20%, 30% and 50% runoff volume.

2.3. Normalization of runoff discharge and pollutant concentration

For further study on the C–Q relationship, and to avoid the influence of absolute runoff discharge and pollutants

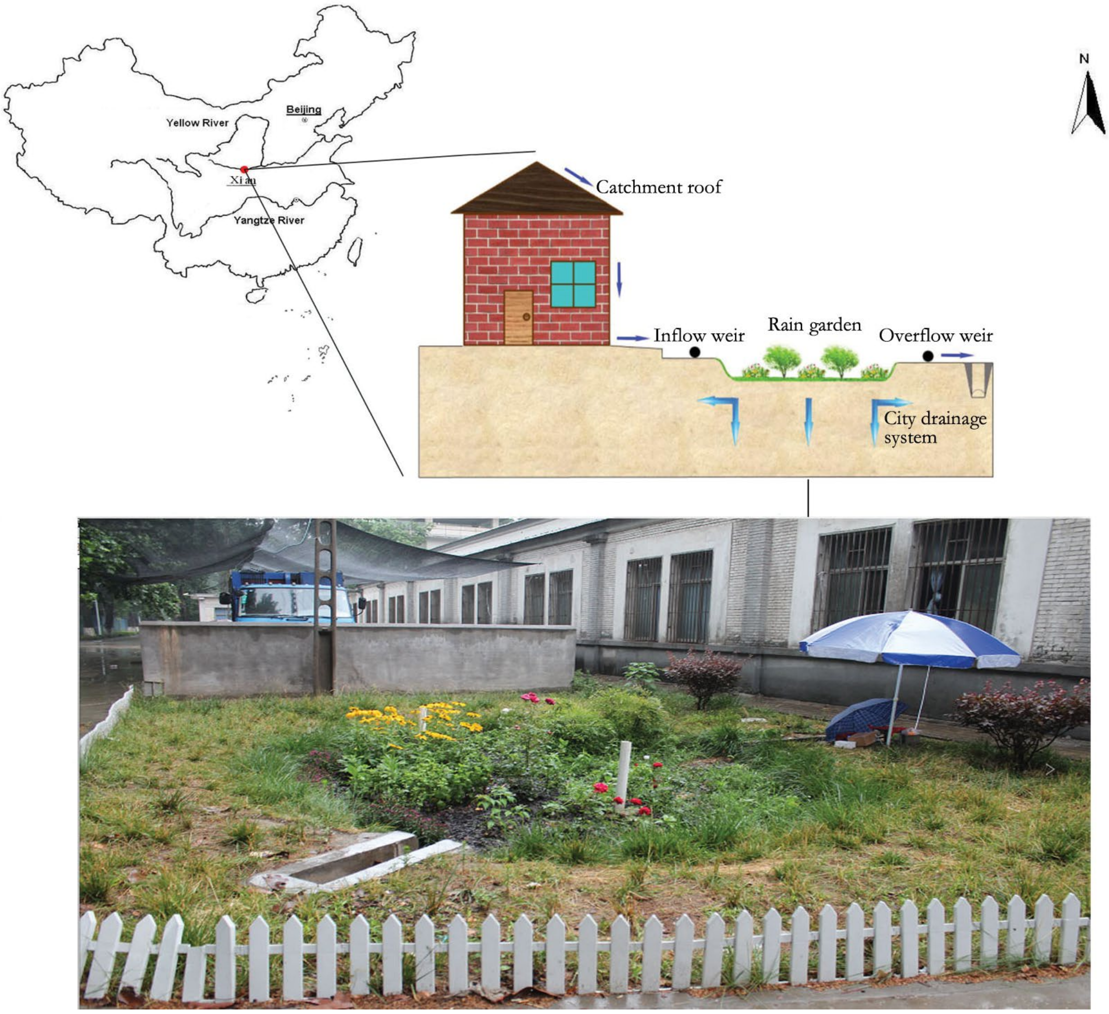


Fig. 1. General location of study area and the experimental rain garden in Xi'an, China; the photo at bottom shows the rain garden after vegetation establishment.

concentration, we used normalized value as expressed in the following equations:

$$Q_n(i) = \frac{Q(i)}{Q_{\max}} \tag{2}$$

$$C_n(i) = \frac{C(i)}{C_{\max}} \tag{3}$$

where $Q_{\max}$ is the maximum runoff discharge and $C_{\max}$ is the maximum pollutant concentration of a storm event, $Q(i)$ and $C(i)$ are the runoff discharge and pollutant concentration at time i, $Q_n(i)$ and $C_n(i)$ are the normalized runoff discharge and pollutant concentration at time i. Rainfall intensity changes rapidly in storm event process, and inflow processes of rain gardens often present multi-peaks and short duration. Therefore, we divided single inflow process into two phases, including the initial 30 min and the remaining time except for initial 30 min. And then, according to plotting normalized inflow discharges and pollutant concentrations for all storm events, statistical analysis was performed to examine the C–Q relationships. Accordingly, we determined whether there exists hysteresis effect in the C–Q relationships for a rain garden inflow as in the watershed scale.

3. Results and discussion

3.1. Characteristics of nitrogen and phosphorus in stormwater runoff

During the 4-year monitoring period, we observed 28 storm events, and 17 storm events had complete hydrological and water quality monitoring data. Only five of them caused overflow from the rain garden. The overflow volumes were generally small; there were no overflow occurred in 2011 and 2012, all inflow infiltrated in the rain garden; there was maximum three overflow events in 2013, but the runoff reduction rate was also as high as 96.8%. The overall flow reduction rate was up to 99.1% during the 4-year monitoring period. At the same time, overflow process usually occurred in the middle and late period of storm event, and the concentrations of TP and TN were approximately equal to the inflow concentrations. Combined with the inflow reduction, the load removal rate of TN and TP were more than 99%.

The pollutants in stormwater runoff mainly come from two sources; the atmospheric deposition and wash-off from underlying surface of the catchment area. For all measured storm events, we calculated the maximum value, three-quarter value, median value, quarter value, and minimum value for concentration distribution of TP and TN during monitoring period. Fig. 2 shows that most of the TP concentrations were less than 1.0 mg/L in all storm events, and the difference value of the five statistics values was relatively small. The mean value of TP concentration at five statistics values for all storm events ranged from 0.29 to 0.96 mg/L, and the standard deviation was 0.23 mg/L. On April 18, 2014, TP concentration was much bigger than other storm event, the maximum concentration reached to 4.97 mg/L, and the median was 1.98 mg/L. The rainy season of the study area is from June to September, and most of the monitored storm events were in this period. April 18 was in the non-rainy season, and climate is generally dry during this period. As shown in Table 1, for the event on April 18, 2014, antecedent dry days before the rainfall event was 7, and the largest rainfall intensity was 0.087 mm/min. For the storm event on July 28, 2013, when the highest rainfall intensity was 0.84 mm/min and the antecedent dry days was 6, the maximum TP concentration was 0.63 mg/L, and the median value was only 0.16 mg/L. In this heavy rainfall event, a relatively low TP concentration was observed, indicating that rainfall pattern significantly affect pollutant load of stormwater runoff.

Generally speaking, higher rainfall intensity results in a greater motivation for washing off the pollutants from the underlying surface. The inflow of the experimental rain garden was concentrated from a building roof; atmospheric deposition was the major contributor to pollutants in the stormwater runoff. The maximum and median TP concentrations were negatively correlated with maximum intensity of rainfall events; the correlation coefficients were –0.22 and –0.38. The maximum and median TP concentrations were positively correlated with antecedent dry days before rainfall events, the correlation coefficients were 0.22 and 0.25, and the correlation coefficients were not significant.

As shown in Fig. 3, the box plot of TN concentration distributions in each rainfall event was much scattered compared with the TP distributions of stormwater runoff. The differences of the five statistics values were relatively bigger than TP concentration. The mean value of TN concentration at five statistics values ranged from 1.58 to 11.61 mg/L, and with the standard deviation of 3.55 mg/L. Similar to TP, the maximum TN concentration was observed on April 18, 2014; the maximum concentration of TN reached 38.92 mg/L, and the median value was 11.58 mg/L. This indicates that TN concentrations are affected by climatic condition that is dry and rainfall is scarce in spring. TP and TN concentrations changed consistently in each storm event; the correlation coefficient between the maximum concentrations of TN and TP was 0.72 for all monitoring events. However, the maximum and median TN concentrations were negatively correlated with maximum rainfall intensities, and positively correlated with antecedent dry days. This suggests that many factors affect concentrations of TP and TN of storm events; though high intensity rainfall may wash off more pollutants, the large amount of stormwater runoff produced by intensive rainfall may dilute the pollutants at the same time. Therefore, pollutant concentrations of stormwater are the combined results of wash off and dilution effects.

3.2. First flush effect of stormwater runoff

Based on the measured rain garden inflow hydrographs, concentrations of TP and TN in water samples, we matched the inflow and pollutant processes under different storm events. During the monitoring period from 2011 to

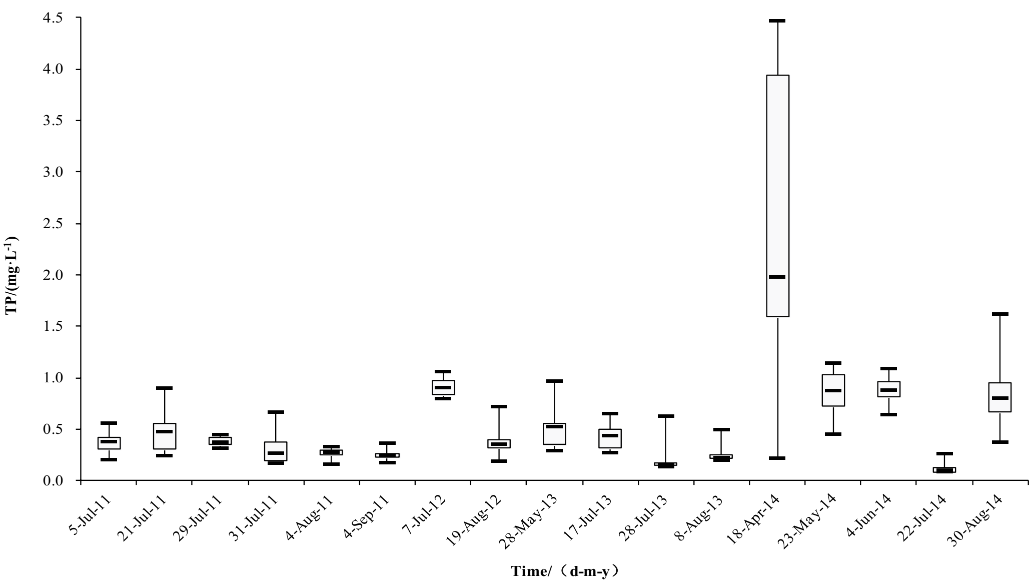


Fig. 2. Distribution of TP in stormwater during the monitoring period.

Table 1
Rainfall conditions during the experimental period

Time	Rainfall depth	Rainfall duration	Maximum rainfall intensity of 60 min	Recurrence interval	Antecedent dry days
	(mm)	(h)	(mm/min)	(y)	(d)
5-Jul-11	24.8	14.1	0.09	0.24	2
21-Jul-11	15.8	4.3	0.24	0.73	8
29-Jul-11	13.2	17.0	0.10	0.25	8
31-Jul-11	24.2	16.0	0.08	0.20	1
4-Aug-11	5.6	5.3	0.03	0.08	3
4-Sep-11	15.6	13.1	0.06	0.15	10
7-Jul-12	5.1	14.6	0.03	0.08	3
19-Aug-12	27.0	9.5	0.08	0.21	4
28-May-13	36.4	4.0	0.23	0.67	1
17-Jul-13	15.6	18.0	0.04	0.09	1
28-Jul-13	35.2	3.0	0.53	4.84	6
8-Aug-13	10.2	6.9	0.10	0.26	6
18-Apr-14	20.1	11.0	0.09	0.22	7
23-May-14	12.9	6.1	0.07	0.17	3
4-Jun-14	9.1	5.0	0.05	0.14	10
22-Jul-14	44.6	2.5	0.51	4.18	9
30-Aug-14	33.6	9.0	0.12	0.32	17

2014, 17 rainfall events were recorded with complete runoff hydrographs and the associated pollutant data. According to Eq. (1) in Section 2.2, rain garden inflow volume transport rate and pollutant transport rate at different stages of each storm event were calculated. The cumulative inflow volume ratio and cumulative pollutant load ratio of every storm event are plotted in Fig. 4; the 1:1 line represents the cumulative runoff and pollutant emissions are uniform during the storm event process, which shows the equilibrium migration of runoff discharge and pollutant emission during the whole rainfall process. The 1:1 line can be used to determine whether the first flush occurred or not. When the initial of the plotted curve is above the 1:1 line, the pollutant emission rate of the initial runoff is greater than the runoff discharge rate, the first flush occur. Moreover, the further distance between the initial part of the curve and the 1:1 line, the more obvious and strong of the first flush occurred. On the contrary, when the first half section of the curve is below the 1:1 line, the pollutant emission rate is less than the runoff discharge rate, and the first flush effect did not exist.

According to the statistical analysis, TP and TN in 10 rainfall events existed first flush simultaneously, which accounts for 58.8% of all rainfall events. Figs. 4a and b show two cumulative inflow volume and pollutant load curve on July 31, 2011 and April 18, 2014; these two rainfall events had first flush effect obviously. For the other seven rainfall events, the plotted curves of TP and TN were distributed on both sides of the 1:1 line, which means that one of TN and TP exists first flush effect, the other does not exist in a rainfall event. Figs. 4c and d show two cumulative inflow volume and pollutant load curve on August 4, 2011 and May 23, 2014. 10 out of the 17 rainfall events had first flush effect for TP, which accounts for 70.6% of all monitoring rainfall events; 16 out of the 17 rainfall events had first flush effect for TN, which accounts for 94.1% of all monitoring rainfall events. The first flush effect of TN was greater than TP. The percentage of cumulative rain garden inflow volume and corresponding cumulative pollutant load of all storm events are plotted in Fig. 5.

Fig. 5a shows that for all 17 storm events, TP distributed around the 1:1 line; which illustrated that TP emission rate was relatively uniform with runoff discharge rate in the process of rainfall. There were more sample points above the 1:1 line, thus TP appeared weakly first flush. For all monitoring rainfall event, the maximum amount of TP carried in 20% runoff reached 33.6%; the minimum value was 18.0%, and with the average value of 23.6%. The maximum amount of TP carried in 30% runoff was 43.0%; the minimum value was 24.9%, and with the average value of 33.4%. The corresponding amounts of TP carried in 50% runoff were 59.5%, 39.0% and 52.0% at maximum, minimum and average.

Fig. 5b shows that the distribution of TN was more dispersed and far away from 1:1 line. The maximum amount of TN carried in 20% runoff reached 45.4%; the minimum value was 14.4%, and the average value was 29.3%. For 30% runoff, the maximum carrying TN load was 45.4%; the minimum value was 20.5%, and the average value was 39.7%. The corresponding amounts of TN carried in 50% runoff were 72.2%, 41.8% and 59.9% at maximum, minimum and average. Currently, LID design in many places around the world is based on the percentage of total volume. For example, the sponge city construction of China, the total runoff

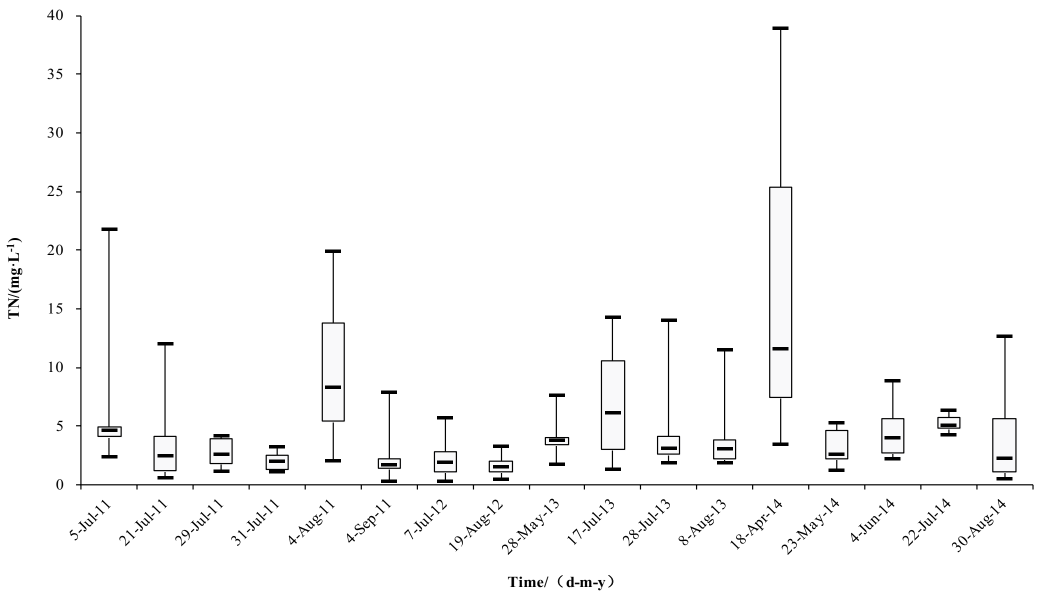


Fig. 3. Distribution of TN in the rain garden inflow during the monitoring period.

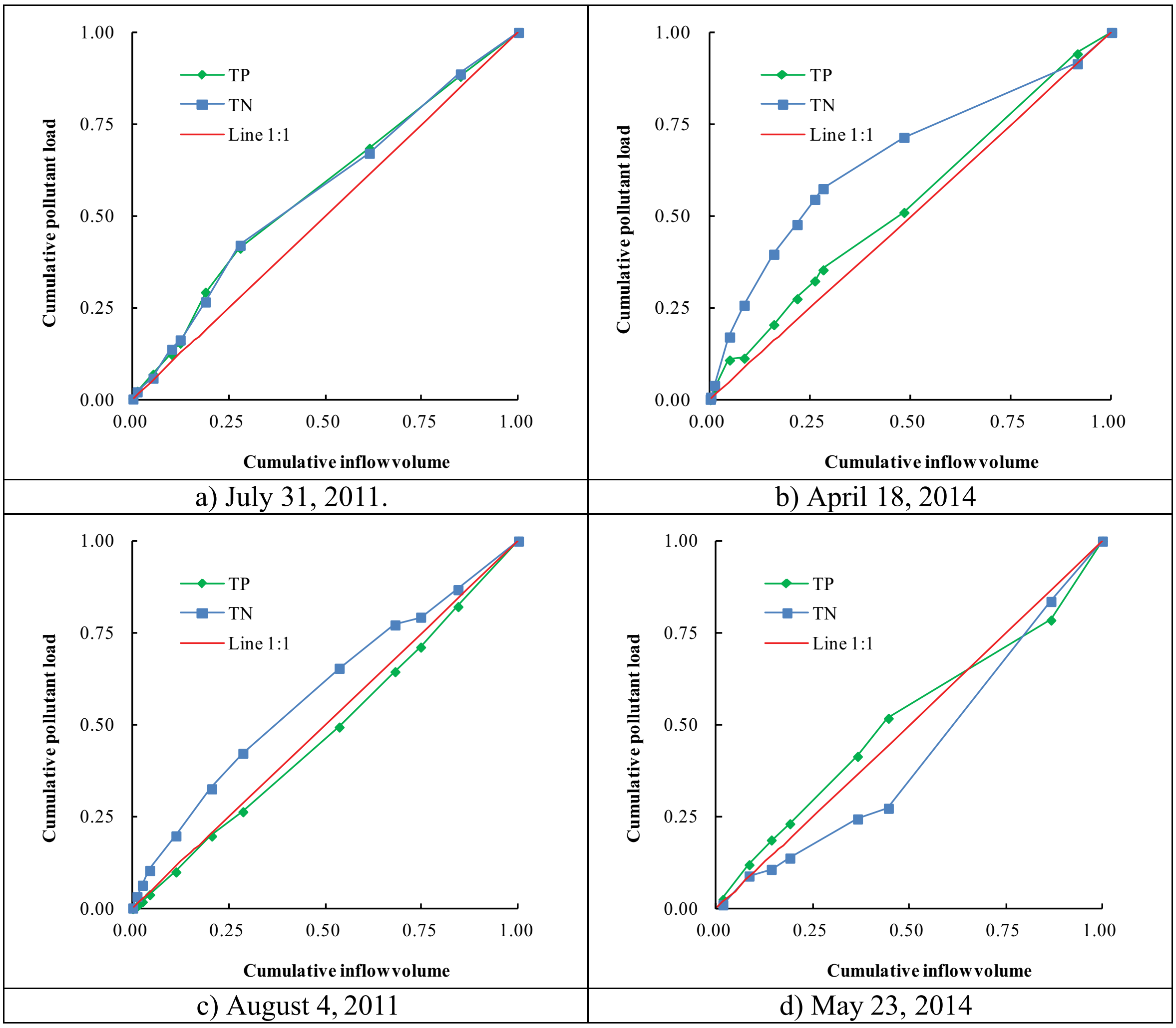
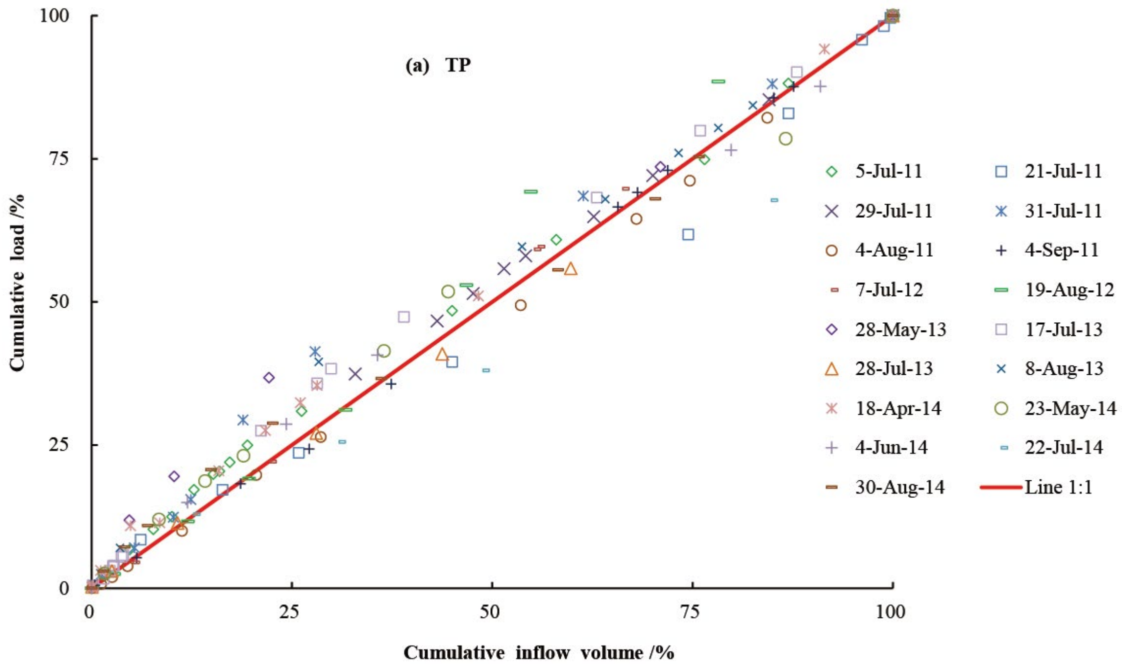


Fig. 4. Cumulative inflow volume and its pollutant load during different storm events.



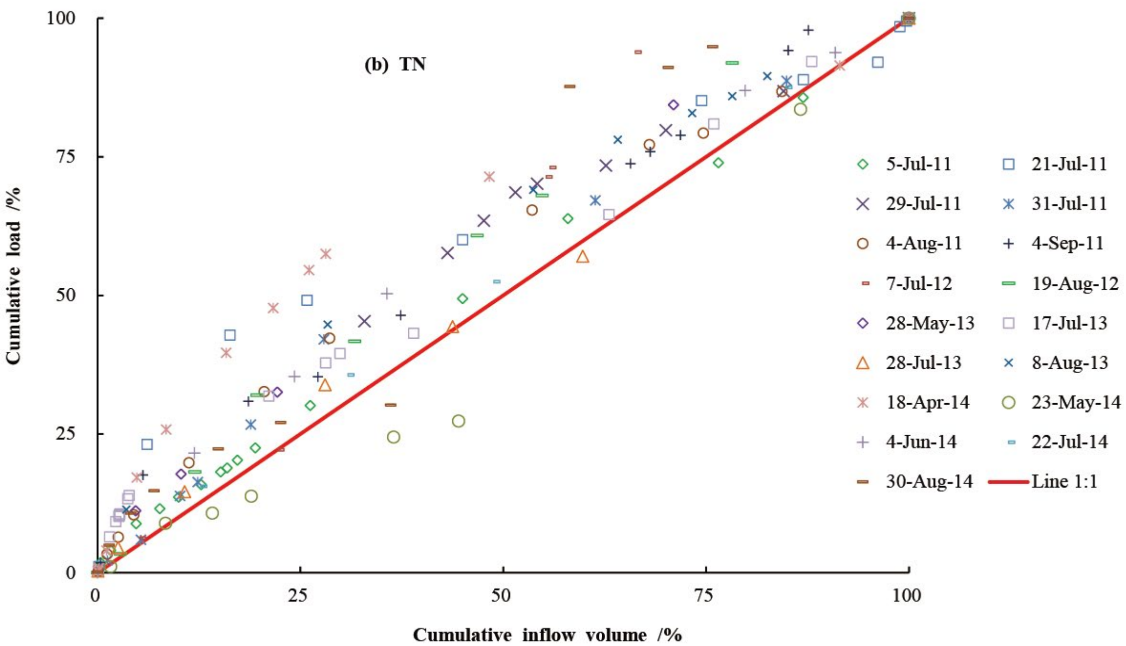


Fig. 5. Percentage of cumulative rain garden inflow and corresponding cumulative pollutant load of all storm events, (a) TP and (b) TN.

volume control rate in different areas was clearly proposed. Compared with TP, TN has a more intense first flush effect. If an LID measure is designed to control a certain percentage of total pollutants, the proportion of TN required to control rainwater runoff is smaller than that of TP. Clearly understanding different proportion of runoff volume carrying the ratio of different pollutant loads in different region helps to guide the engineering design, determine the reasonable design scheme, and intercept the pollutant of the stormwater runoff at the source to the maximum extent.

3.3. Pollutant concentration discharge hysteresis property

Due to the rapid change of rainfall intensity in the event process, the runoff inflow process of rain garden often presents a multi-peak state. Peak and valley of runoff appear alternately and change quickly. Most of the peak duration are short, and sometimes the duration of the flood peak process is only a few minutes. Therefore it is impossible to divide the flow process into several single peak, and make statistical analysis study the C–Q relationship at their rising and falling limb. In this paper, taking the 30th min of the storm event as the critical point, rainfall process was divided into the initial 30 min and other remaining time, and then studied the C–Q relationship of the two phases, respectively. Fig. 6 shows the hydrograph of the stormwater runoff, the changes of TP concentration, and the corresponding analysis of hysteresis characteristics on July 5, 2011.

The rainfall duration was 850 min on July 5, 2011, and this was a typical rainfall process in the study area with multi-peak and long duration. For the storm event of July 5, 2011, the maximum rainfall intensity of 10 min was 0.16 mm/min, and corresponding antecedent dry days before rainfall event was 2 d. As shown in Fig. 6, on the whole, the TP concentration of stormwater runoff in the early stage was slightly bigger than that in the middle and late stage. But as the rainfall process goes on, TP concentration did not show a continuous decrease. On the contrary, TP concentration rose slightly at the end of rainfall process. There was no obvious correlation between TP concentration and runoff flow during the whole rainfall process. However, Aich et al. [26] investigated the suspended-sediment concentration (SSC) dynamics in 3.3 ha catchment; they found that SSC and discharge flow process had a very good correlation, and with the rainfall intensity rising, runoff discharge increase, and the SSC enlarge. Lawler et al. [25] studied the turbidity dynamics with the storm event in urban headwater basin. They proposed an index to quantify the magnitude of hysteresis condition, and the index was quantified by determining the difference at concentration on the rising and falling limbs of the hydrograph using the midpoint river discharge. Researchers found a relatively good correlation between pollutants concentration and flows discharge in large watershed; but our study did not find such phenomenon. In order to further study the C–Q relationship in stormwater runoff, rainfall process was divided into two stages, including the initial 30 min (first stage) and other remaining time (second stage).

Fig. 6a shows that C–Q relationship of TP was disorderly at the whole rainfall process, and no obvious laws were found. Fig. 6b presents the C–Q relationship of the first stage, the C–Q relationship of the first stage emerged clockwise hysteresis pattern, and such clockwise hysteresis was commonly ascribed to pollutant exhaustion and first flush effect [26,28]. For the first stage of all monitoring rainfall events, we analyzed their C–Q relationships. Due to sudden rainfall, the initial rainfall water samples were not collected on July 29, 2011 and July 7, 2012. 6 out of the other 15 rainfall events C–Q relationship appeared clockwise as shown in Fig. 6b. The C–Q relationship at the second stage of rainfall process was disorderly shown as Fig. 6c. After statistics, the C–Q relationship of all monitoring rainfall events showed certain randomness at the second stage.

For the C–Q relationship of TP at the first stage, in addition to the clockwise pattern, Fig. 7 shows other three C–Q features, including quasi-line figure shown as Fig. 7a (on August 4, 2011), inverted U shape shown in Fig. 7b (July 17, 2013), and anti-clockwise shown in Fig. 7c (May

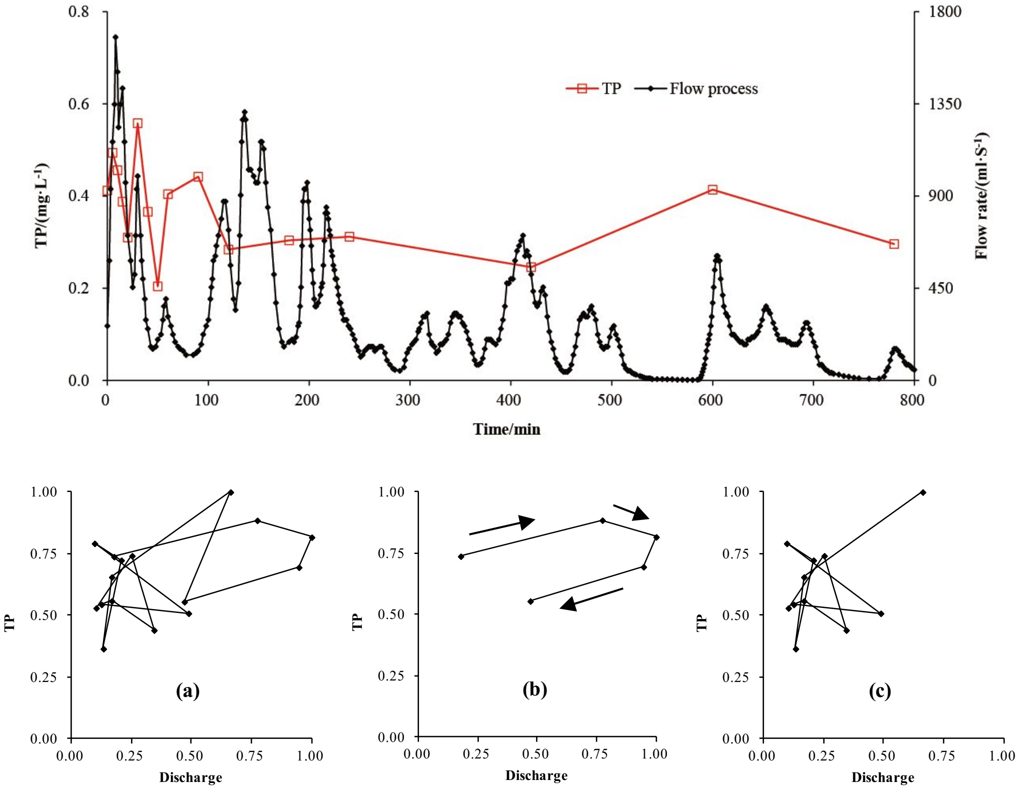


Fig. 6. Hydrograph and TP concentration of an event on July 5, 2011, and (a) the whole rainfall process, (b) initial 30 min, and (c) other remaining time corresponding analysis of hysteresis characteristics.

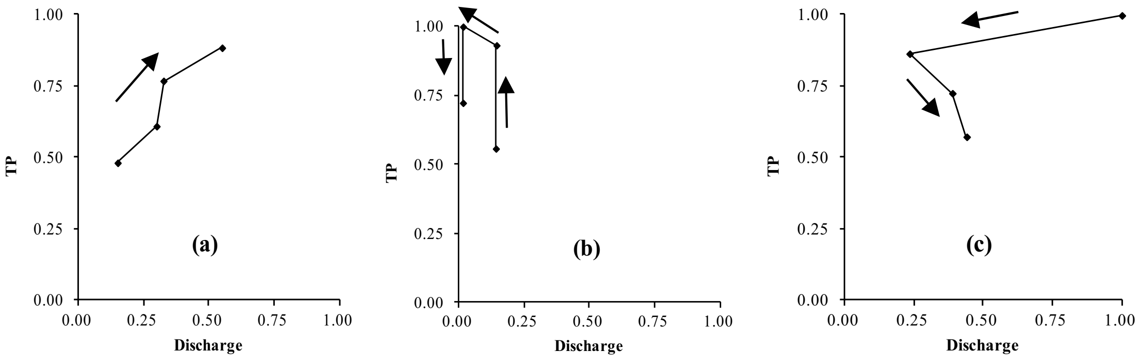


Fig. 7. Analysis of TP hysteresis characteristics at the first stage, (a) August 4, 2011; (b) July 17, 2013; and (c) May 23, 2014.

23, 2014). After C–Q relationship statistics, there were two storm events with quasi-line feature, two storm events with inverted U shape, and five storm events with anti-clockwise feature.

Quasi-line: As shown in Fig. 7a, TP concentration was increasing with the enlargement of rainfall intensity; the TP concentration showed a quasi-linear increasing with runoff flow rate. The average rainfall intensity of the initial 30 min was 0.02 mm/min. The runoff flow rate was 42.13 mL/s at the very beginning, with the rainfall intensity enlargement, and the flow rate increased to 154.52 mL/s by the time of 30 min. As the rainfall intensity enlargement, the TP wash-off mass was increasing from the underlying surface, but the overall rainfall intensity was relatively small, which did not reach the threshold value of the maximum wash-off from the underlying surface. The wash-off effect of rainfall to underlay surface was greater than dilution effect for TP during the initial 30 min. However, for C–Q relationship, only two rainfall events present quasi-line, and there were not enough data to find the exact threshold value of rainfall intensity and wash-off.

Inverted U shape: Compared with quasi-line feature, the inverted U type had a much smaller inflow rate in the first 30 min, and the maximum flow appeared at the starting time, and the maximum flow rate in the first 30 min was only 0.14 times of the maximum inflow rate in the whole rainfall process. TP concentration increased quickly at the very beginning stage, but with the rainfall intensity reduced, TP wash-off mass decreased. Compared with TP wash-off reducing, runoff flow rate declined more apparently. In other words, the pollutants wash-off process lagged behind the flow process, which resulted in TP concentration increasing. To the later, TP concentration decreased significantly. The rainfall intensity was too small to wash off the pollutant, and TP concentration decreased significantly.

Anti-clockwise: Compared with the other features, the flow rate of anti-clockwise was much bigger in the first 30 min. The initial flow was up to 1,585.46 mL/s, and the corresponding TP concentration was also the largest. Then, the flow rate decreased, and TP concentration reduced. When the flow rate increased again, TP concentration decreased significantly. In the later stage, the dilution effect of runoff was obviously greater than that of wash-off effect.

For most storm events, the C–Q characteristic of TN was similar to that of TP. Especially, the C–Q relationship of storm events presented clockwise or anti-clockwise, which showed the same characteristic exactly in TP and TN. But for the storm event at August 4, 2011, as shown in Fig. 8a, the plotting curve of C–Q relationship presented decreasing trend quasi-line (the curve of TP was rising trend at August 4, 2011) At the very beginning of the storm event, the minimum inflow rate corresponds to the maximum TN concentration, and then, as the inflow rate increased, the TN concentration decreased. The decreasing trend quasi-line feature was resulted from the first flush effect and the later dilution. Compared with TP, another difference happened at July 17, 2013, as shown in Fig. 8b, the plotting curve of C–Q relationship was U shape (the curve of TP was inverted U shape). The reason for this difference was mainly for the difficult and easy level of each pollutant washing off, at the same time, combined the instantaneous change of inflow process, which made the C–Q relationship much more complexity.

Based on the rapid changes in pollutants concentration at the initial 30 min of storm events, we made comprehensive analysis of C–Q relationship for all monitoring rainfall events with different characteristics. The C–Q relationship curve in initial 30 min presented clockwise, anti-clockwise, quasi-line, and U shape patterns. Different C–Q relationships are mainly affected by rainfall characteristics. The size of rainfall intensity and the distribution of rainfall intensity have comprehensive effects on pollutants washing off and dilution. After the first 30 min, for the limitation of pollutant monitoring interval, C–Q relationship remains to be further studied. Currently, LID design in many places around

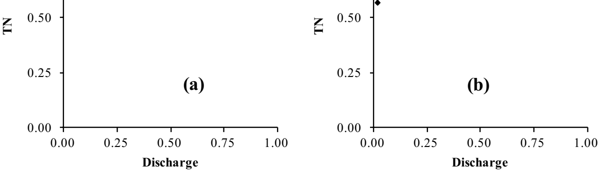


Fig. 8. Analysis of TN hysteresis characteristics at the first stage, (a) August 4, 2011 and (b) July 17, 2013.

the world is based on the runoff control rate. In this paper, we combined with the C–Q relationship of different pollutants, analyzed the first flush effect feature of different rainfall events, and determined the total amount of pollutant load carried by different proportion of storm runoff. The quantitative correspondence between the stormwater runoff control rate and pollutants load retention is conducive to the design LID measures much more accurately.

4. Conclusions

Based on a 4-year monitoring study on inflow rate and pollutant concentrations of stormwater runoff in a rain garden, this paper presents a comprehensive analysis on the distribution of TP and TN concentrations and the characteristics of flush effect in a rain garden, then study the stormwater C–Q relationship of all the monitoring storm events. The key findings of this paper were:

- the concentrations of TP varied little in one storm event. The mean value of TP concentration at five statistics values for all storm events ranged from 0.29 to 0.96 mg/L, and the standard deviation was 0.23 mg/L; while the range of TN concentration was wider. The mean value of TN concentration at five statistics values ranged from 1.58 to 11.61 mg/L, and with the standard deviation of 3.55 mg/L.
- The first flush effect was more significant in TN than TP; 10 out of the 17 rainfall events had first flush effect for TP, which accounted for 70.6% of all monitoring rainfall events; 16 out of the 17 rainfall events had first flush effect for TN, which accounted for 94.1% of all monitoring rainfall events. For all monitoring rainfall event, the first 20% runoff volume carried the pollutant load of 23.6% for TP; the first 30% runoff carried 33.4%; and the 50% runoff carried 52.0%. The corresponding carrying pollutant values for TN were 29.3%, 39.7%, and 59.9% in 20%, 30% and 50% of first runoff volume, respectively. (3) The C–Q relationship curve in initial 30 min had some patterns, including clockwise, anti-clockwise, quasi-line, and U shape; most of them are clockwise (6 out of 15 storm events), anti-clockwise (5 out of 15 storm events). The other remaining time of all monitoring rainfall events showed certain randomness. Most of the C–Q characteristic of TN is similar to that of TP.

The pollutant concentration characteristics of stormwater runoff are much more complex. For determining reasonable standard and design of LID practices to better control pollution sources, understanding the characteristics of different pollutants with the rainfall processes is much more important. Finding from this research can provide the basis for formulating reasonable standards in runoff volume reduction and pollutants of TP/TN control.

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