Rainwater utilization and storm pollution control based on urban runoff characterization

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Abstract

The characteristics of urban runoffs and their impact on rainwater utilization and storm pollution control were investigated in three different functional areas of Zhengzhou City, China. The results showed that in the same rain event the pollutant loads (chemical oxygen demand (COD) and total suspended solids (TSS)) in the sampling areas were in the order of industrial area > commercial area > residential area, and within the same area the COD and TSS concentrations of road runoffs were higher than those of roof runoffs. The first flush effects in roof and road runoffs were observed, hence the initial rainwater should be treated separately to reduce rainwater utilization cost and control storm pollution. The initial roof rainfall of 2 mm in residential area, 5 mm in commercial area and 10 mm in industrial area, and the initial road rainfall of 4 mm in residential area and all the road rainfall in commercial and industrial areas should be collected and treated accordingly before direct discharge or utilization. Based on the strong correlation between COD and TSS (R^2, 0.87–0.95) and the low biodegradation capacity (biochemical oxygen demand $BOD_5/COD < 0.3$), a sedimentation process and an effective filtration system composed of soil and slag were designed to treat the initial rainwater, which could remove over 90% of the pollutant loads. The above results may help to develop better rainwater utilization and pollution control strategies for cities with water shortages.

Key words: rainwater utilization; water quality; initial rainwater; sedimentation and filtration

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Introduction

China has suffered from water shortages for a long time, especially in the middle and the northwest regions. About 110 out of 669 Chinese cities are under severe water deficit at present, including Zhengzhou, the capital city of Henan Province in Middle China. As one of the best countermeasures against a water shortage in urban areas, rainwater utilization plays a very important role. It can overcome a shortage of water supply, and in the meanwhile is very effective for runoff control (Kim et al., 2001; Wang et al., 2004a, 2004b; Feng et al., 2006).

The level of contamination in rainwater runoffs has become an increasing concern in rainwater utilization. Nonpoint pollution resulting from urban surface runoff was recognized as one of the major causes of quality deterioration in receiving water bodies (Gnecco et al., 2005; Li et al., 2007a; Lijklema et al., 1993). Previous studies showed that rainwater from different catchments contained different levels of pollutants (Artina et al., 1999; Forster, 1996; Lee and Bang, 2000; Kim et al., 2005; Zhao et al., 2006), indicating different characteristics of pollutants and their accumulation rates. Therefore, runoffs from different underlying surfaces in a city, e.g., roofs and roads in different functional areas, should be characterized, and their impacts on rainwater utilization and pollution control should be studied before effective rainwater utilization was applied.

Runoff during the first flush of a storm event bears the highest concentration of pollutants in urban areas (Li et al., 2007b). Previous studies showed that 80% of pollutant load was carried by the first 30% of the runoff volume (Bertrand-Krajewski et al., 1998), which indicated that different measures should be taken to deal with the initial and the following rainwater separately to reduce the treatment cost for rainwater utilization. However, the finishing time of the first flush was hard to decide in practice according to a certain percentage of the total runoff volume. It is important, therefore, to characterize the collected quantities of the initial rainwater in volume, which may vary with functional areas. As the initial rainwater could not be discharged or utilized directly due to its high pollutant concentrations, cost-effective treatment methods for initial rainwater are needed urgently.

In the present study, we characterized the roof and road runoffs in residential, commercial and industrial areas of

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Zhengzhou City, China. The rainfall volume was used as an important variable to monitor rainfall processes. Based on the runoff characteristics, the quantity of initial rainwater was identified, and an effective treatment method for initial rainwater was proposed.

1 Materials and methods

1.1 Study areas and rain events

In Zhengzhou City, the mean annual precipitation is 640 mm, more than 50% of which falls in the period from June to September in a year. The sampling sites locate in residential (Jinshui District), commercial (Erqi District), and industrial (Zhongyuan District) areas, respectively. Erqi District is the emporium of Zhengzhou, and comprises the railway station, pedestrian street and many market-places. Zhongyuan District is a place where the aluminum plant and the thermal power plant are situated. The three sampling areas are urban areas with a ground impervious ratio of about 85%. The average population densities in the residential, commercial and industrial areas are 42.9, 270 and 80 per hectare, respectively, and the traffic flows in the three areas are 120, 1800 and 200 vehicles/day, respectively. The sampling sites were typical in their corresponding areas which had the average population density and traffic flow. The sampling site and sampling method are described in Table 1.

Rainwater samples were collected in four rain events from June to September in 2003. At the beginning, when runoffs appear samples were collected at a 5-min interval, and then during the rain events samples were collected at a 10-min interval. Sampling bottles for road runoff were placed just in front of the major inlet of the drainage system; meanwhile samples for roof runoff were collected from gutters. The rainfall depth was measured at the time when the runoff was formed. The flow rates were calculated from the rainfall depth, crossed area and event duration. The main characteristics of the monitored rain events are summarized in Table 2.

1.2 Analysis methods

According to previous study, total suspended solids (TSS) and chemical oxygen demand (COD) were the main pollutants in urban runoff (Huang et al., 2007). Therefore, TSS, COD and 5-day biochemical oxygen demand (BOD$_5$) were measured in this study using the standard methods of APHA (1998), and potassium dichromate has been used to determine COD.

1.3 Calculation of event mean concentrations of pollutants

Even though pollutant concentrations often varied by several times of magnitude during storm event, the event mean concentrations (EMC) of pollutants could be used to characterize runoff constituents (Sansalone and Buchberger, 1997), which can be defined as total pollutant load divided by total runoff volume (Eq. (1)).

$$\text{EMC} = \sum Q_i C_i / \sum Q_i \tag{1}$$

where, Q_i is the time variable flow and C_i is the time variable concentration.

1.4 Dimensionless cumulative analysis

Data collected during the monitoring processes were synthesized by analyzing the variation of pollutant mass vs. runoff volume in the dimensionless $M(V)$ curves. This kind of data presentation can be used to compare the variation of pollutant loads during rainfall events. Using data from the hydrograph and the pollutograph, the $M(V)$ curves can be calculated by Eq. (2):

$$\frac{\sum\limits_{i=1}^{j} C_i Q_i \Delta t_i}{\sum\limits_{i=1}^{N} C_i Q_i \Delta t_i} = f(\frac{\sum\limits_{i=1}^{j} Q_i \Delta t_i}{\sum\limits_{i=1}^{N} Q_i \Delta t_i}) \tag{2}$$

where, N is the total number of measurements and $j = 1, 2..., n$.

Table 1 Summary of site characteristics

Sample	Location	Sampling site	Surface of catchment	Surface material of catchment	Sampling method
Natural rainwater		S1–S6			Directly from sky
Road runoff	Residential area	S1, S2	Roadway	Cement (2 driveways)	Flowing on a roadway at a drain outlet
	Commercial area	S3, S4		Asphalt (4 driveways)	
	Industrial area	S5, S6		Asphalt (6 driveways)	
Roof runoff	Residential area	S1, S2	Roof of building	Cement/flat roof	Flowing on a roof at a drain outlet
	Commercial area	S3, S4		Cement/flat roof	
	Industrial area	S5, S6		Cement/flat roof	

Table 2 Characteristics of the four rain events

Serial number	Date (y-m-d)	Total rainfall volume (mm)	Rainfall duration (hr)	Rainfall intensity (mm/hr)		ADWP (day)
				Average	Maximum	
1	2003-06-30	22	3	7.3	13.7	20
2	2003-07-11	18	1.67	9	17.3	11
3	2003-07-21	30	4	7.5	21	10
4	2003-08-12	26	7	3.7	8.6	15*

* There was a rainfall event on July 28. ADWP: antecedent dry weather period.

When the slope of $M(V)$ curve is equal to 1, it indicates that the pollutant concentration remains constant during the rainfall event; while when the slope of $M(V)$ curve is greater than 1, it is commonly referred to the occurrence of first flushing effect. If this phenomenon occurs, a large fraction of pollutants will be contained in the initial rainwater.

1.5 Removal of pollutants from initial rainwater

The initial rainwater was settled for 24 hr in a 1-L beaker, and then treated by filtration through the device shown in Fig. 1. The filtrate was collected from the bottom of filter column, and analyzed. The media in the three-layered filter column was topsoil (10 cm), intermediate filter media (80 cm) and filter supporting bed (10 cm). The topsoil was collected from the surface layer of grassland at S1. The soil was mixed with slag, the waste of a boiler plant in Zhengzhou, at a weight ratio of 1:1 to form the intermediate filter media. Filter supporting bed was made up of gravels from Site 1.
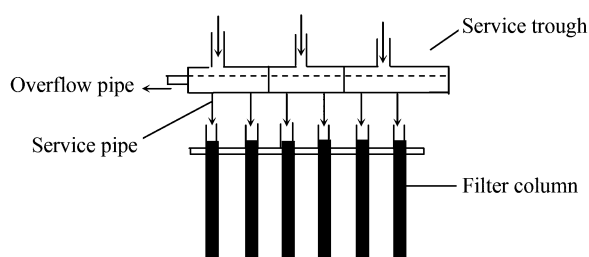

Fig. 1   Rainwater filtration system.

2 Results and discussion

2.1 Characteristics of roof and road runoffs

For the rain event on June 30, 2003, the COD concentrations of the natural rainwater collected directly from sky were determined as 21–35 mg/L in the three sampling areas while those of runoffs were more than 10 times higher. This suggested that most of the pollutants in roof and road runoffs originated from catchment surfaces.

As shown in Fig. 2, the peaks of COD and TSS concentrations in both roof and road runoffs appeared at 5 min. After the peak, the pollutant concentrations decreased rapidly. This indicated that the high pollutant concentrations were caused by the early runoff, flushing the accumulated pollutants from the roof or road. Afterwards, the pollutant concentrations decreased slowly and remained stable in the end. A comparison between the pollutant loads in road runoff and roof runoff revealed that the final stable level of pollutants in road runoff was higher than that in roof runoff. Take the residential area for instance, the final COD and TSS concentrations in roof rainwater were 20–200 mg/L and 17–150 mg/L, respectively, while those in road rainwater were 100–1000 mg/L and 120–1400 mg/L, respectively. These high concentrations may be caused by the accumulation of pollutants on road.

In the same sampling area, the pollutant concentrations in rain events were quite different. The concentration sequence for roof runoffs was June 30 > July 11 > July 21, and that for road runoffs was June 30 > July 11 > August 12 (Fig. 2). The rainwater pollution load was found to be positively correlated to the antecedent dry weather period (ADWP) between two rain events (Li et al., 2007c), which may be because that: (1) the high ADWP allowed more
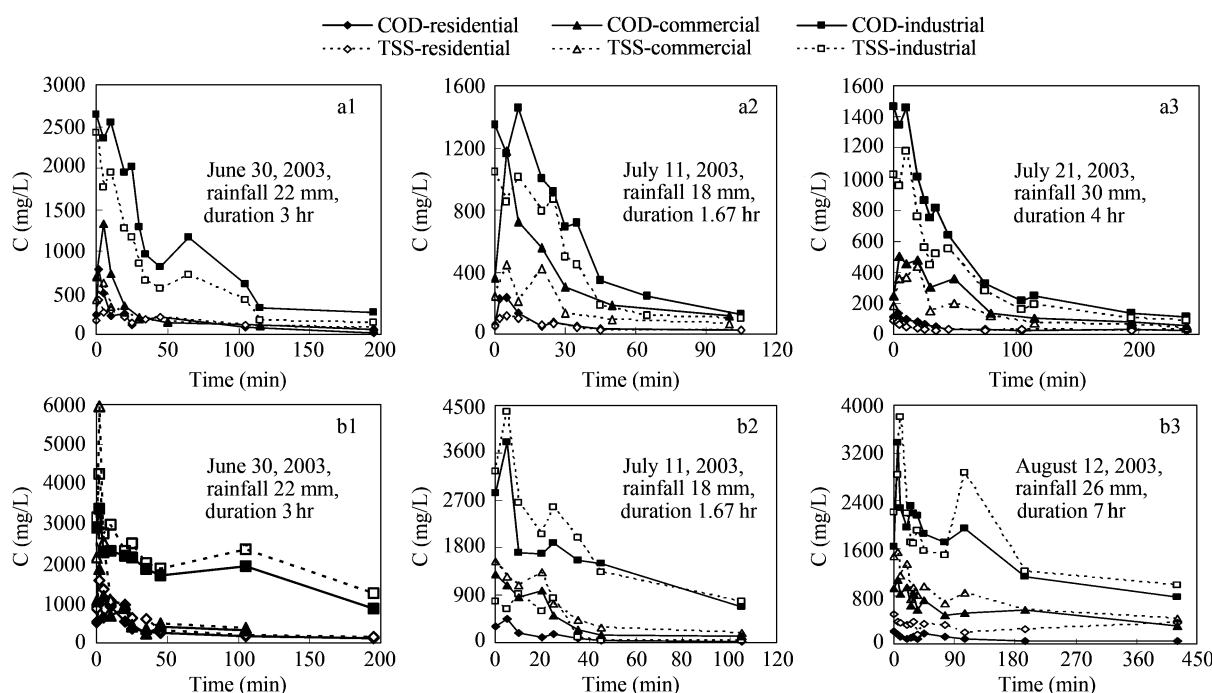

Fig. 2   Pollutant concentrations of rainwater collected from roof runoffs (a) and road runoffs (b) in residential, commercial and industrial areas.

pollutants to be accumulated, (2) the accumulated pollutant loads could be washed off by previous rainwater.

2.2 Pollutant concentrations in runoffs

Based on the Eq. (1), EMC values of COD and TSS for each storm event were investigated. The results are presented in Table 3. The results showed that EMC of pollutants for road runoffs was higher than that of roof runoffs in each sampling area. For the same rain event, the pollutant concentrations in three areas were in the following order: industrial area > commercial area > residential area. The reason may be that, in industrial area more pollutants are produced and deposited on the urban surfaces; and the densities of vehicular traffic and human activities in commercial area are higher than those in residential area. Therefore, the difference of pollutant loads in different functional areas on different underlying surfaces should be taken into account for the development of rainwater utilization strategies and the design of treatment facilities.

As shown in Table 3, EMC of COD and TSS in road runoff in Zhengzhou City (150.2–1949.8 mg/L and 489.5–2400.4 mg/L, respectively) were remarkably higher than those in other cities, such as Wuhan City in Hubei Province (50–1162.5 mg/L and 40–1326.3 mg/L, respectively) (Li et al., 2007c). This may be mainly caused by the different precipitation, ADWP as well as pollutant accumulation in the two cities. The precipitation in Wuhan City was 1400 mm/yr while that in Zhengzhou City was 640 mm/yr, and the ADWP in Wuhan was shorter than that in Zhengzhou City. Therefore, the more pollutants accumulated in road and roof before rain events in Zhengzhou which was attributed to the higher pollutant loads in runoffs. This

indicated that due to the different characteristics of runoff in different cities, different rainwater utilization strategies should be developed accordingly.

2.3 Dimensionless cumulative analysis

The first flush of storm runoffs is usually assumed the most polluted (Deletic, 1998), thereby, the first flush phenomenon in urban regions should be taken into account in rainwater utilization process. The $M(V)$ curves of COD related to roof and road runoffs for all monitored events are showed in Fig. 3. When the $M(V)$ curve was above the bisector, the first flush was expected to occur (Gnecco et al., 2005). The results showed that the roof and road runoffs in the three sampling areas (Fig. 3) were characterized by the occurrence of first flush, which suggested that most of the pollutant loads were contained in the initial parts of runoff volume in the three functional areas. Therefore, the initial runoff should be collected and treated separately before discharge or utilize to cut down the cost of treatment during utilization process and to control storm pollution.

2.4 Quantification of collected initial rainwater

The quantification of collected initial rainwater in roof and road runoffs in different functional areas were carried out based on the data of the three rain events on June 30, July 11 and July 21.

The variation of pollutant concentrations vs. rainfall is presented in Fig. 4. The pollutant concentrations decreased with rainfall volume. In the initial 2, 5 and 10 mm rainfall for roof runoff in residential, commercial and industrial areas, respectively, the pollutant concentrations decreased rapidly, followed by a slow decrease. For road runoff,
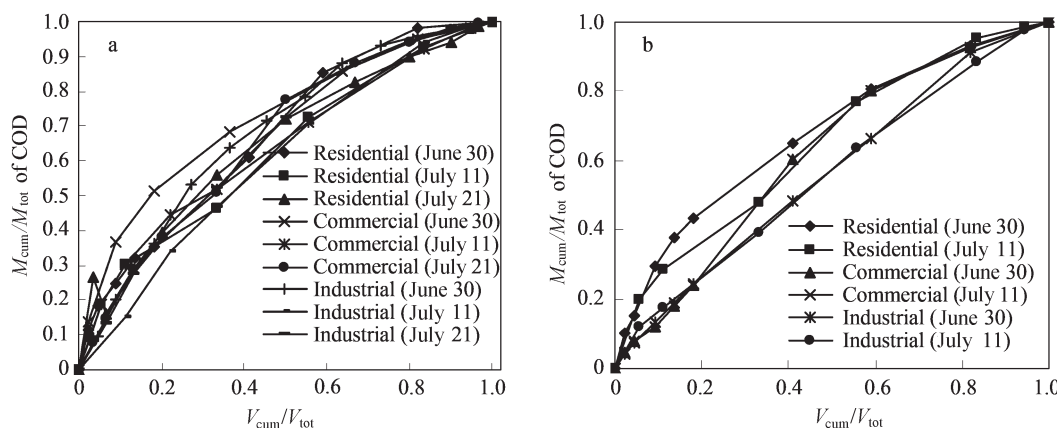

Fig. 3 $M(V)$ curves for COD in roof (a) and road (b) runoffs. V_{cum}/V_{tot}: cumulative volume/total volume of runoff; M_{cum}/M_{tot}: cumulative mass/total mass of COD in runoff.

Table 3   Event mean concentrations (EMC) of COD and TSS in runoffs

Pollutants	Sampling date	Residential area		Commercial area		Industrial area	
		Roof runoff	Road runoff	Roof runoff	Road runoff	Roof runoff	Road runoff
COD (mg/L)	2003-6-30	215.3–289.1	396.2–532.1	366.8–432.6	1142.9–1432.1	1056.8–1556.9	1536.9–1949.8
	2003-7-11	80.3–91.2	150.2–276.3	318.5–385.1	580.9–863.4	605.8–902.5	1369.7–1891.0
	2003-7-21	65.4–81.2	–*	125.8–285.2	–*	534.3–896.7	–*
TSS (mg/L)	2003-6-30	159.7–249.2	662.4–724.7	259.8–416.6	1134.9–1343.6	789.2–1024.2	1867.2–2245.7
	2003-7-11	63.1–98.4	489.5–559.8	165.6–232.9	808.3–1156.9	453.7–709.3	2201.2–2400.4
	2003-7-21	36.9–58.5	–*	110.3–199.6	–*	432.5–647.6	–*

* Due to the lack of investigators, the road runoffs in rain event on July 21 were not collected, therefore, no data was available here.
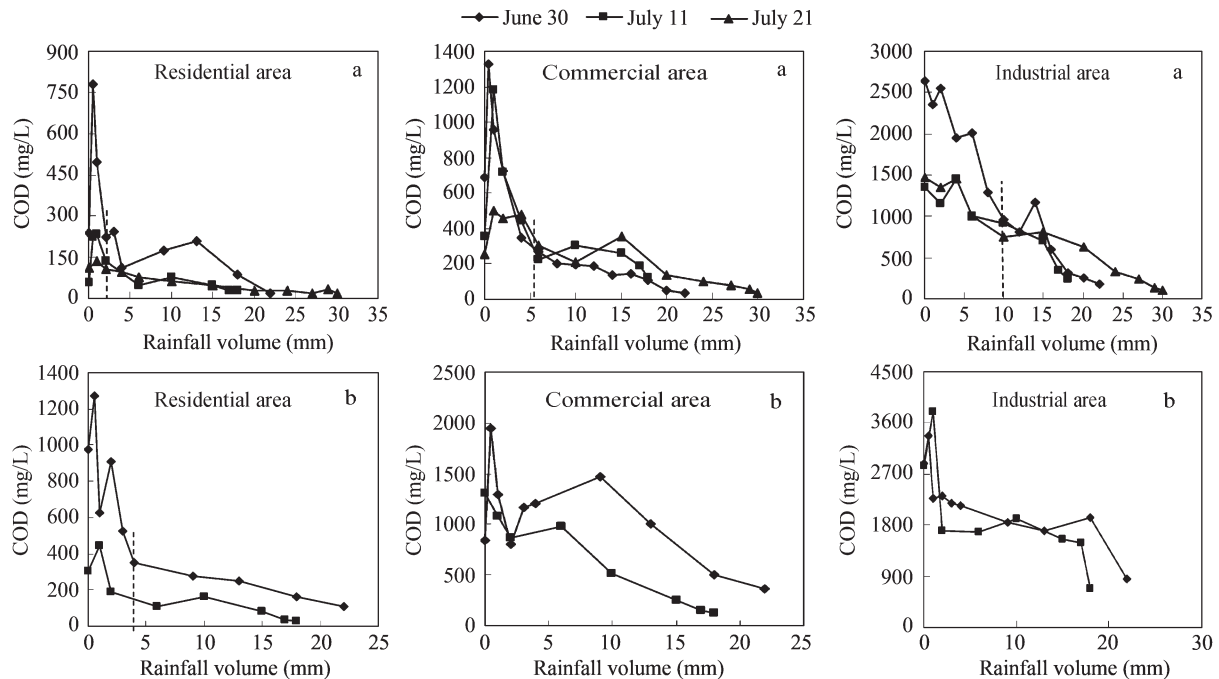
Fig. 4   Rainwater COD as a function of roof (a) and road (b) runoff volume for residential area, commercial area, and industrial area.

the discharge of initial 4 mm rainfall in residential area could remove the most part of pollutants. The COD concentrations in road runoff in commercial and industrial areas during every rain event were significantly higher than others. Therefore, all the rainwater in these areas should be collected for treatment.

The results showed that the quantities of collected initial rainwater varied with functional areas and underlying surfaces, due to the amount of pollutants accumulated on underlying surfaces, rainfall intensity, as well as ADWP and first flush effect (Taebi and Droste, 2004). The pollutant loads were found to be positively correlated to the ADWP between two rain events ($R^2 = 0.95$, $p < 0.01$) (Li et al., 2007a). However, in present study the quantities of collected initial rainwater in the three rain events were roughly the same for every sampling area even though ADWP was different for the three rain events, which implied that ADWP might has little effect on the quantities of collected initial rainwater under studied conditions. As shown in Fig. 5, the high intensity of rain events all occurred in the initial period, while previous studies showed that the highest intensity of rain event could also appear in the later period and a part of the pollutants in rainwater could be contained in the later rainwater (Li et al., 2007b). In this situation, further study is needed to deal with the quantities of collected initial rainwater.

2.5 Relationship between TSS and COD

The relationship between TSS and COD was studied to investigate the source of pollutants for develop corresponding initial rainwater treatment methods. From data collected in the three sampling areas, a strong relationship between COD and TSS concentrations in runoff can be observed clearly, as shown in Fig. 6. Moreover, it could be considered that most of COD was absorbed by suspended
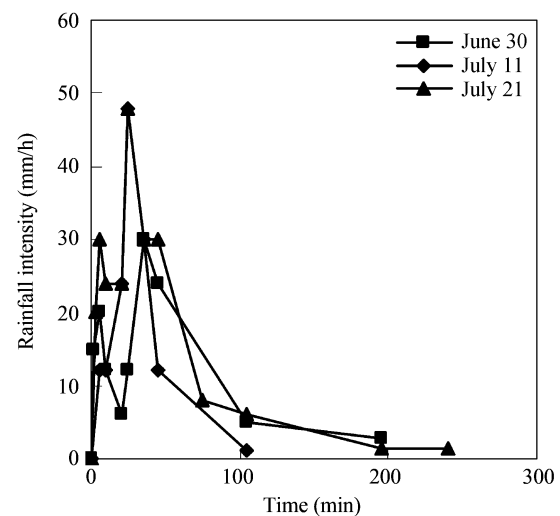

Fig. 5   Rainwater intensity during the three rain events.

solids (Thomson et al., 1997; Gnecco et al., 2005; Huang et al., 2007), which suggested that treatment methods such as sedimentation would be effective in the removal of TSS and COD.

2.6 Biodegradation of initial rainwater

In order to identify a method for initial rainwater treatment, the biodegradation of rainwater was used as an important index, and hence the BOD_5 and COD of initial rainwater were measured. As shown in Table 4 the ratio of

Table 4 BOD_5 and COD_{Cr} concentrations in roof runoff

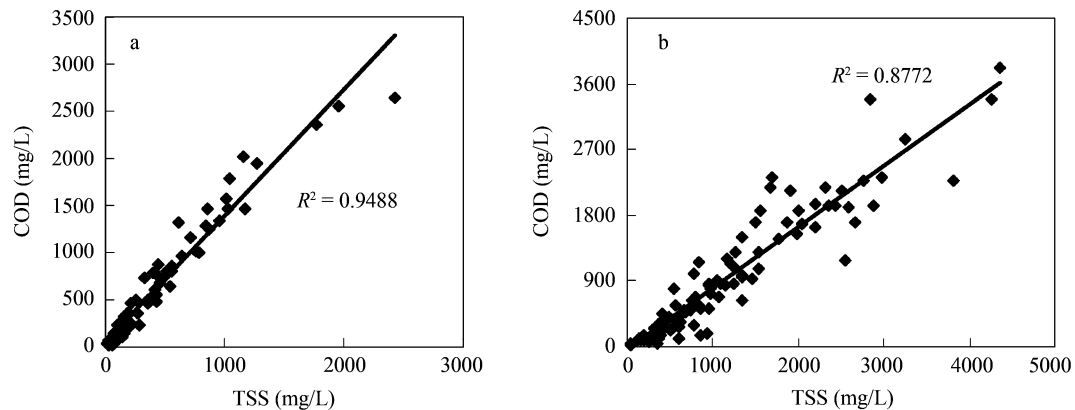| Sampling location	COD (mg/L)	BOD_5 (mg/L)	BOD_5/COD
Commercial area	1329.3	279.2	0.21
Residential area	778.4	186.8	0.24
Industrial area	315	56.7	0.18

Fig. 6 Relationship between TSS and COD of roof runoff (a), and road runoff (b).

Table 5 Effect of sedimentation and filtration on the removal of COD and TSS in rainwater

Initial rainwater		After sedimentation		After filtration		Removal efficiency (%)		Water sample volume (mL)	Treatment time (min)	Processing rate (L/(m²·hr))
COD (mg/L)	TSS (mg/L)	COD (mg/L)	TSS (mg/L)	COD (mg/L)	TSS (mg/L)	COD	TSS			
1635.6	1445.5	436.7	597	82.1	150	95	89.6	100	15	200
627.0	1966.1	246.4	580	26	54	95.9	97.3	100	12	250
391.3	460.5	171.8	268	10.3	32	97.4	93.1	100	10	300
228.3	383.2	111.4	256	31.6	20	86.2	94.8	100	10	300
571.3	755.6	127.4	306	9.44	38	98.3	95	100	10	300
358.0	547.5	136.4	219	17.1	25	95.2	95.4	100	10	300

BOD_5 to COD was 0.21 0.24, and 0.18 for samples collected from commercial, residential, and industrial areas, respectively, which suggested a low efficiency of rainwater biodegradation. Therefore, the physicochemical methods rather than the biological methods should be employed for the initial rainwater treatment.

2.7 Treatment methods for initial rainwater

The above studies showed that the pollutants were mainly in particulate form (Fig. 3), and the biodegradation of rainwater was low. Therefore, the physical methods, such as sedimentation and filtration, should be used for the initial rainwater treatment. Previous studies showed that the land treatment system, such as wetlands, could intercept effectively the pollutants in runoff (Davis and Birch, 2006). The effect of sedimentation and filtration using local soils on the removal of COD and TSS from initial rainwater was studied. Due to the low permeability of the local soils, the filter was designed to be composed of soil and slag at a weight ratio of 1:1. The results are listed in Table 5, showing that 86.2%–98.3% of COD and 89.6%–97.3% of TSS were removed by the sedimentation and filtration system. After the treatment, the rainwater quality met the corresponding integrated wastewater discharge standard (GB 8978-1996), and could be discharged directly or utilized together with the later portion of rainwater after further treatment. The processing rate of filter was 200–300 L/(m²·hr) which indicated that the filter had high treatment capacity and could treat a large amount of runoffs. Comparing to the conventional filter composed of gravel, this filter was low-cost and easily available. Therefore, the infrastructure based on the processes of sedimentation and filtration (Scholz and Yazdi, 2009)

could be used as an effective method for initial rainwater treatment. Further studies would be required to assess the efficiency of the treatment system for the other pollutants and the decomposition of pollutants residue in the filter.

3 Conclusions

The results showed that the pollutant concentrations in runoffs from two underlying surfaces in three functional areas in Zhengzhou City were different based on the data from four rainfall events, and followed the order of industrial area > commercial area > residential area, and road runoff > roof runoff. The initial rainwater and all rainwater of road runoff in commercial and industrial areas should be collected and treated before discharge or utilization due to their high pollutant load. Infrastructure with sedimentation and filtration processes could effectively remove the pollutants from rainwater using a filter composed of local soil and slag.

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