Characterization and first flush analysis in road and roof runoff in Shenyang, China

Chunlin Li, Miao Liu, Yuanman Hu, Jiping Gong, Fengyun Sun and Yanyan Xu

ABSTRACT

As urbanization increases, urban runoff is an increasingly important component of total urban non-point source pollution. In this study, the properties of urban runoff were examined in Shenyang, in northeastern China. Runoff samples from a tiled roof, a concrete roof and a main road were analyzed for key pollutants (total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), Pb, Cd, Cr, Cu, Ni, and Zn). The event mean concentration, site mean concentration, $M(V)$ curves (dimensionless cumulative curve of pollutant load with runoff volume), and mass first flush ratio (MFF_{30}) were used to analyze the characteristics of pollutant discharge and first flush (FF) effect. For all events, the pollutant concentration peaks occurred in the first half-hour after the runoff appeared and preceded the flow peaks. TN is the main pollutant in roof runoff. TSS, TN, TP, Pb, and Cr are the main pollutants in road runoff in Shenyang. There was a significant correlation between TSS and other pollutants except TN in runoff, which illustrated that TSS was an important carrier of organic matter and heavy metals. TN had strong positive correlations with total rainfall (Pearson's $r = 0.927$), average rainfall (Pearson's $r = 0.995$), and maximum rainfall intensity (Pearson's $r = 0.991$). TP had a strong correlation with rainfall intensity (Pearson's $r = 0.940$). A significant positive correlation between COD and rainfall duration (Pearson's $r = 0.902$, significance level $= 0.05$) was found. The order of FF intensity in different surfaces was concrete roof > tile roof > road. Rainfall duration and the length of the antecedent dry period were positively correlated with the FF. TN tended to exhibit strong flush for some events. Heavy metals showed a substantially stronger FF than other pollutant.

Key words | event mean concentration, first flush, runoff, site mean concentration, stormwater pollution

Chunlin Li
Miao Liu
Yuanman Hu (corresponding author)
Jiping Gong
Fengyun Sun
Yanyan Xu
State Key Laboratory of Forest and Soil Ecology,
Chinese Academy of Sciences,
Institute of Applied Ecology,
Shenyang 110016,
China
E-mail: *huym@iae.ac.cn*

Chunlin Li
Jiping Gong
Fengyun Sun
Yanyan Xu
University of Chinese Academy of Sciences,
Beijing 100049,
China

INTRODUCTION

As urbanization progresses, urban land use changes, leading to an increase in the area of impervious surfaces and, as a consequence, increases in runoff volume and peak flow rates. Studies have shown that urban stormwater runoff contains a variety of pollutants, such as sediment, micro-organisms, organic material, nutrients, heavy metals, and polycyclic aromatic hydrocarbons (Marsalek & Rochfort 2004; Krometis *et al.* 2009), which can seriously affect public health and threaten environmental quality (Pitt *et al.* 2004; Rauch *et al.* 2012). The most relevant work would be the studies that focused on priority pollutants as defined in the EU Water Framework Directive (Boyd *et al.* 2004; Eriksson *et al.* 2007). The distribution and concentration of these pollutants depend on the characteristics of the urban surface, rainfall conditions, and dry and wet atmospheric deposition (Pitt *et al.* 2004).

Rainfall-induced runoff is the main mechanism for pollutant mobilization and transport in urban areas (Ball & Rankin 2010). Many studies have focused on the quality and characteristics of various pollutants from different urban surfaces (Ball & Rankin 2010). Roof runoff and road runoff are the main contributors to urban non-point source pollution. Heavy metals, such as Zn, Cd, Cu, and Pb, are commonly present in roof runoff as a result of

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corrosion of the metal surfaces of roofing or gutters (He et al. 2001). And the values of chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN) and total phosphorus (TP) were higher on bituminous roofs than green roofs (Teemusk & Mander 2007). Pollutant concentrations of road runoff differ with traffic density, wind drift, the duration and intensity of storm runoff events, antecedent dry weather period and the state of traffic technology (Krein & Schorer 2000). Traffic and human activities are important causes of road runoff pollutants, which include road surface abrasion, tire abrasion, brake pad abrasion, fossil fuels combustion, corrosion, and trash (Krein & Schorer 2000; Gnecco et al. 2005). Gromaire-Mertz et al. (1999) found COD, BOD_5, and total suspended solids (TSS) concentrations of roof runoff of 27, 4, and 17 mg/L, respectively, and the main pollutants in the courtyard and street runoff to be TSS and COD (Gromaire-Mertz et al. 1999). Ball & Abustan (1995) report that up to 85% of phosphorus and 70–80% of nitrogen can be isolated as particulate matter (Ball & Abustan 1995).

In a storm event, a first flush (FF) phenomenon occurs when the main proportion of the pollution load is transported in the first part of the runoff volume (Sansalone & Buchberger 1997; Ma et al. 2011). However, the peak concentration may vary for different pollutants during the same storm event, or in the same watershed during different storm events. FF patterns have been evaluated in urban stormwater runoff for multiple pollutants including sediments, oil and grease, metals, nutrients, COD, pH, temperature, and conductivity (Sansalone & Cristina 2004). Many factors influence the FF intensity. Watershed area, rainfall intensity, percentage impervious surface, antecedent dry weather period, and sampling methods are the common influences (Deletic 1998; Ma et al. 2011).

As an established industrial base in northeastern China, Shenyang has experienced rapid urbanization. The area of impervious surfaces is increasing rapidly because of various policies in recent years, including the revitalization of the old northeastern industrial base. As a result, non-point source pollution from urban runoff is an increasingly serious problem. It is very important to examine runoff from different surfaces. In the present study, roof and road runoff quality in Shenyang was monitored and analyzed. The objectives of this study were to: (1) gain an overall picture of rainfall runoff non-point pollution in northeast China; (2) identify the characteristics of pollutants discharged from different surfaces; and (3) determine the FF intensity and probability according to different sampling sites, rainfall events, and pollutants.

MATERIALS AND METHODS

Site description

The study area was located in a 24.2 ha catchment in Shenyang, the largest and most important industrial city in northeast China (41°11′51″–43°02′13″N, 122°25′09″–123°48′24″E). It has a temperate continental monsoon climate. The mean annual precipitation is 510–680 mm, most of which falls from June to August. The prevailing wind direction in summer is southwesterly. The catchment is made up of 55.1% high-density residential, 2% commercial, and 42.9% cultural and educational areas. Impervious surfaces cover about 69.3% of the study catchment. Runoff samples were collected from three urban surfaces of Shenyang center: a tiled roof, a concrete roof and a major roadway (Figure 1). The tiled roof chosen for sampling belonged to a three-storey office building and had a 30° slope. The concrete roof was flat, and belonged to a six-storey residential building. The major roadway is a main road of Shenyang with bidirectional four lanes, and about 10,000 vehicles per day. The road was cleaned by manual and mechanical sweeping twice a day.

Sampling and analyses

Samples were collected manually using polyethylene bottles in five rainfall events from July to October 2012. The main characteristics of the rainfall events are summarized in Table 1. Precipitation amounts ranged from 1.3 to 33.8 mm, and the average rainfall intensity ranged from 1.3 to 12.1 mm/h. The antecedent dry weather periods ranged from 5 to 10 days (Table 1).

Samples of roof runoff were collected at pipe outlets and road runoff was collected at the rain grate. Roof runoff was collected from the outlet of the building drainpipe, and road runoff was collected at the rain grate before the stormwater flowed into the sewer. All samples were manually collected by researchers with rich sampling experience. The rainfall depth through the events was recorded by an automatic gauge. Once runoff flow was observed, we collected samples every 10 min for the first 60 min, every 30 min between 60 and 180 min, and then every 60 min beyond 180 min. Samples of road runoff in the October 9 event were not collected because the road was being renovated.

The samples were collected, treated and analyzed in the laboratory within 24 h. All the storm runoff samples were analyzed for TSS, COD, TN, TP, and six typical heavy

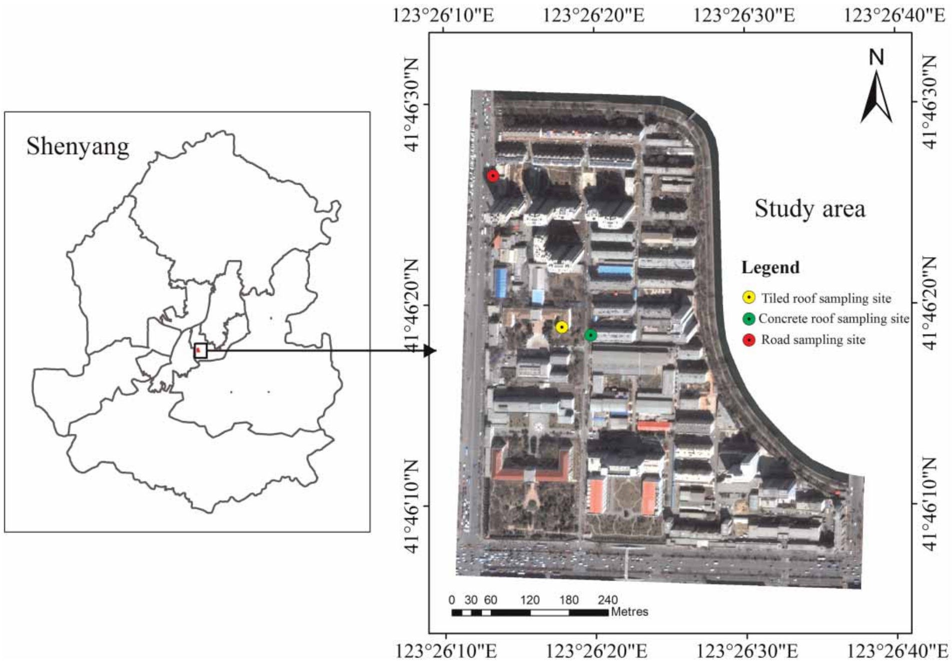

Figure 1 | Study area and sampling sites.

Table 1 | Characteristics of rainfall events

Date (y-m-d)	Rainfall (mm)	Duration (h)	Average intensity (mm/h)	Max rainfall intensity (mm/h)	Antecedent dry weather period (d)	Number of samples
2012-07-10	16.0	6.7	2.4	5.0	5	45
2012-07-22	33.8	2.8	12.1	28.7	10	36
2012-07-28	1.3	0.7	1.8	1.8	5	23
2012-08-28	4.6	3.5	1.3	2.4	9	33
2012-10-09	15.5	3.0	5.1	8.9	6	20

metals (Pb, Cd, Cr, Cu, Ni, and Zn) using standard methods (CEPA 2002a). The pollutants we selected were ubiquitous in the environment and also formed during natural processes and human activities, including motor vehicle emissions, coal burning, tire wear, asphalt leaching, and runoff from different urban surfaces (Mahler *et al.* 2005). Additionally, the 10 pollutants are classified as priority pollutants for stormwater (Eriksson *et al.* 2007).

Event mean concentration and site mean concentration

The event mean concentration (EMC) is used to report the average concentration of a constituent for an event based on samples collected throughout the whole rainfall event. We calculated the EMC as the total mass load of a constituent from a site during a storm event divided by the total runoff water volume that was discharged during the storm (Sansalone & Buchberger 1997). The EMC is computed for the entire rain event. For individual sampling sites, a site mean concentration (SMC) can be used. For the SMC, we used a weighted mean value calculated with weighted event runoff volumes (Langeveld *et al.* 2012):

$$\mathrm{SMC} = \frac{\sum_{i=1}^{n} \mathrm{EMC}_i V_i}{\sum_{i=1}^{n} V_i} \tag{1}$$

where EMC_i (mg/L) is the EMC of event i at a certain sampling site; V_i (m^3) is the volume of event i. The SMC value is affected by uncertainties because of the variability of EMCs and the number of events used. In this study, the SMC was used to compare the pollutant concentration from different sampling sites.

First flush

The FF has been determined based on the dimensionless cumulative curve of pollutant load with runoff volume (Deletic 1998), the so-called $M(V)$ curves. According to Geiger, the FF occurs when the curve has an initial slope greater than 45°, and when the maximum gap between the $M(V)$ curve and the bisector is greater than 0.2, and when the flush becomes stronger as the gap increases (Geiger 1987). The FF effect is designed to compare the fraction of the total pollution load exported for some fraction of the runoff delivered, typically from some point in the first part of the cumulative runoff curve. The mass FF (MFFn) ratio was optimized statistically using indicators which were relevant for storms and water quality data. It is defined as follows:

$$\mathrm{MFF}_n = \frac{\int_0^T C_t Q_t d_t / M}{\int_0^T Q_t d_t / V} \quad (2)$$

where n is the percentage of cumulative volume of runoff, and T (min) is the time from runoff occurrence to when the n% cumulative runoff is observed; M (g) is the total mass of a pollutant during a rainfall event; V (m^3) is the total volume of runoff; C_t (mg/L) is the concentration of a pollutant at time t; Q_t (m^3/min) is the discharged runoff flow rate at time t; and t (min) is time. In this research, the first 30% of the cumulative volume was used to calculate the MFF_{30}.

RESULTS

Characteristics of runoff water quality

Runoff hydrographs and pollutographs for the three sampled urban surfaces for the July 10 and July 22 events are shown in Figure 2. The hydrographs and pollutographs illustrate that pollutant concentrations were high in the first half-hour and that the peak concentrations of pollutants occurred before the flow peaks. After reaching the peak concentration, the concentration of pollutants (TSS, TN, TP, COD, Cd, Pb, Cr, Cu, Ni, and Zn) significantly decreased with increasing runoff, such that concentrations of the pollutants were lower at peak flow (Figure 2). The pollutant concentration peaks were caused by early runoff and represent flushing of the accumulated pollutants from the roofs and streets before the major runoff flow arrived at the outfalls (Lee & Bang 2000).

The concentrations of roof pollutants reached a steady state after approximately 3 hours' discharge for the event on July 10. The concentrations at the steady state of TSS, TN, TP, and COD were 40, 0.5, 0.03, and 21 mg/L, and those of Cd, Pb, Cr, Cu, Ni, and Zn were 0.01, 0, 20, 0.2, 0, and 0.1 μg/L, respectively, for the tile roof. For the concrete roof, the concentrations at the steady state of these pollutants (in the same name order) were 5, 0.5, 0.05, and 20 mg/L, and 0.02, 0, 17, 0.5, 0, and 0.2 μg/L, respectively. The concentrations in road runoff have a high fluctuation, but as the accumulated pollutants were discharged, the concentrations became steady. However, in the July 22 event, there was an obvious increase in road runoff pollutant concentrations at 15:00, and in particular, the concentrations of Cd, Pb, Cr, Cu, Ni, and Zn rose rapidly. This can be explained by a traffic jam, as the sampling site was on a main road of Shenyang, and there was traffic congestion during rush hour. Large quantities of pollutants were produced by the combination of road abrasion, tire abrasion, brake pad abrasion, oil loss, corrosion, and human activities, while moving vehicles led to changes in pollutant concentrations.

Comparison of EMC and SMC

The ranges of pollutant concentrations from runoff from the three urban surfaces were wide and the variation coefficients of the sampling sites ranged from 0.4 to 1.9. Road runoff had the highest pollutant EMCs, followed by concrete roof runoff and then tiled roof runoff, in decreasing concentration order (Table 2). Traffic and human activities produced large amounts of pollutants, which were easily flushed by rain water and churning wheels. There are 50 cm walls on the top of the concrete roof. These walls and the flat roof were more conducive to the accumulation of pollutants when compared with the tiled roof. The EMC of COD in rainfall runoff on July 10 was significantly higher than for the other four rainfall events, perhaps because this event was the longest duration (6.7 h) of the five events. Prolonged rainfall may be conducive to flushing organic material, and may result in an increased load of organic pollutants in runoff.

The EMC values for TSS, TP and Pb in tiled roof runoff were 18.55–7.34 and 0.01–0.25 mg/L, and 0.01–2.06 μg/L; for the concrete roof runoff they were 6.99–94.29 and 0.06–0.18 mg/L, and 0–22.88 μg/L, while for road runoff they were 364.99–1,208.07 and 0.23–1.13 mg/L, and 25.89–171.07 μg/L, respectively. The SMC values for TSS, TN, and Pb in traffic road runoff were 5–270 times higher

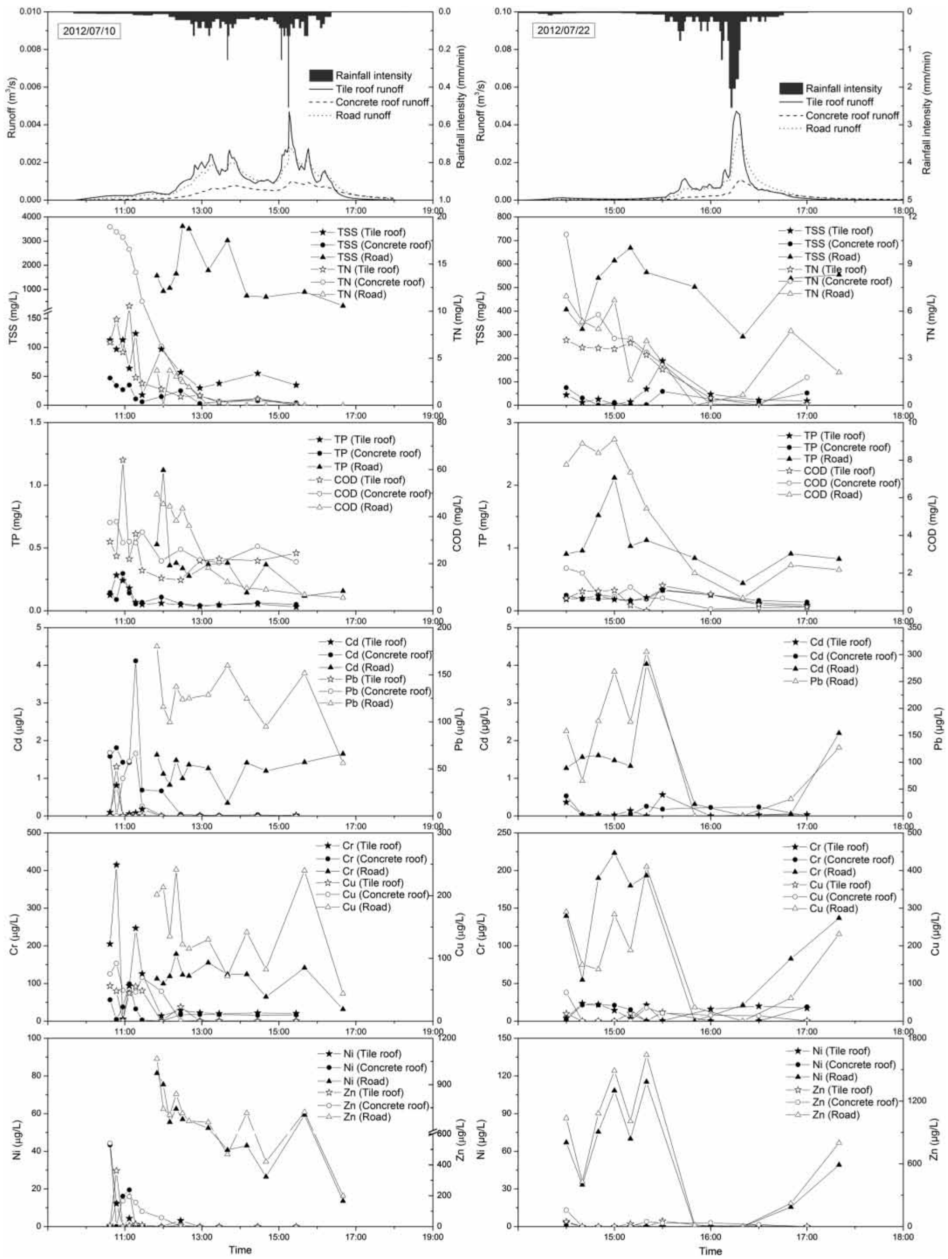

Figure 2 | Hydrographs and pollutographs for the different surfaces for the July 10 and July 22 events.

than those in the runoff from tiled or concrete roof. These high concentrations reflect pollutant accumulation on the road in both dry and wet weather.

The SMC values of TSS and COD were higher in tiled roof runoff than in the concrete roof runoff. The 30° slope of the tiled roof may have meant that the flush from the roof was more concentrated. Cr, Cu, and Zn were the most significant pollutants in the roof runoff. The monitored downpipe was made of steel, so the heavy metal concentrations were probably from the corrosion of pipe material.

Comparison of FF intensity and probability

The flush intensity differs according to rainfall characteristics and surface condition. We have assumed that a moderate flush occurs when $1 < MFF_{30} < 2$; when $MFF_{30} \geq 2$, a strong flush appears. The dimensionless $M(V)$ curves have been calculated to compare pollutant loads from all monitored rainfall events (Figure 3). It is clear that FF occurred for all pollutants. Plots showed fairly even distribution of storms on either side of the 45°

Table 2 | EMC and SMC of pollutants in surface runoff

	Tiled roof runoff		Concrete roof runoff		Road runoff	
Pollutants	EMC (min–max)	SMC	EMC (min–max)	SMC	EMC (min–max)	SMC
TSS (mg/L)	18.55–70.34	34.93	6.99–94.29	28.81	364.99–1208.07	639.73
TN (mg/L)	0.36–2.50	0.83	0.60–9.85	1.01	0.13–3.79	1.74
TP (mg/L)	0.01–0.25	0.10	0.06–0.18	0.13	0.23–1.13	0.60
COD (mg/L)	0.41–22.31	5.88	0.20–23.56	5.02	1.77–10.97	4.74
Cd (μg/L)	0.02–0.21	0.07	0.07–0.74	0.16	0.26–3.94	0.83
Pb (μg/L)	0.01–2.06	0.24	0–22.88	1.31	25.89–171.07	64.69
Cr (μg/L)	1.05–20.58	16.93	0.54–26.26	8.31	52.67–160.68	76.75
Cu (μg/L)	1.28–21.66	6.05	2.84–25.44	10.57	48.05–254.77	88.42
Ni (μg/L)	0.06–4.99	0.80	0.28–13.74	1.98	11.34–72.17	24.12
Zn (μg/L)	2.11–109.10	15.64	6.20–40.00	14.49	168.40–1,073.54	336.44

line for TSS and TN. However, TN tended to exhibit strong FF in some events. Most storms for COD were likely to be above the 45° line. Heavy metals appeared to have a substantially stronger FF than the other four pollutions.

The FF intensity and probability differ according to different sampling sites, rainfall events, and pollutants (Figure 4). Based on the median and mean value in boxplots, the order of FF intensity in different surfaces was concrete roof > tile roof > road. The FF phenomenon occurred in roof runoff for 80% of events, but for 72% of events for road runoff. In road runoff, a strong flush only occurred for 10% of events. However, strong flushes occurred for 33 and 41% of events in tile and concrete roof runoff.

The rainfall event with the maximum rainfall intensity (July 22) had the lowest flush probability, 54% for total flush, and only 14% for strong flush. The FF probabilities on July 10 and October 9 were higher than that for the other event. These results may be related to rainfall depth, which was 16.0 mm on July 10, 15.5 mm on October 9 and 33.8 mm on July 22. Therefore, as rainfall depth increases within a certain range, the FF phenomena are more likely to happen, while beyond the range, the probability will decrease. The rainfall event on July 10 had the highest probability of a strong flush, about 53%. The high probability of a strong flush on July 10 was probably from the long rainfall duration, as long duration events are conducive to the mobilization and transport of pollutants.

The total FF ratio of TN was very low (63%). However, TN tended to exhibit strong flush for 42% of events. Looking at the behavior of the different pollutants, it indicates that FFs occurred most frequently for heavy metals. The probabilities of Cd (92.9%) and Pb (92.7%) in the total flush were the largest. Pb had a perfect FF in tiled and concrete roof runoff in the July 10 rainfall event, which meant that 100% of Pb was transported with 30% of the water at the very beginning of the event. The total FF probabilities of COD, Cu and Zn were more than 85%, and the strong flush probabilities of TN, Pb, Ni, and Zn were more than 40%.

DISCUSSION

Comparison of surface runoff pollution

A comparison of EMCs of surface runoff among Beijing (Ren *et al.* 2013), Nanjing (Zhang *et al.* 2011), Chongqing (Zhang *et al.* 2012a, b), Xi'an (Chen *et al.* 2011), and Shenyang showed that the COD concentrations in roof and road runoff in Shenyang were significantly lower than in other cities (Table 3). The EMCs of TSS in roof runoff in Shenyang were lower than in Beijing and Chongqing, and it was lower in road runoff in Shenyang than in Xi'an, but higher than in Beijing and Chongqing. Heavy metals in road runoff in Shenyang were also higher than in Chongqing and Xi'an. This could indicate poor quality of road runoff in the investigated area in Shenyang.

The SMC of TSS in road runoff was three times higher than the second category of the wastewater discharge standards (200 mg/L) (CEPA 1996). Many studies have shown that urban road runoff is the most important pathway for heavy metal pollutants into water (Pitt *et al.* 2004). In this study, heavy metal concentrations in road runoff were very high, and in particular the Pb and Cr concentrations were

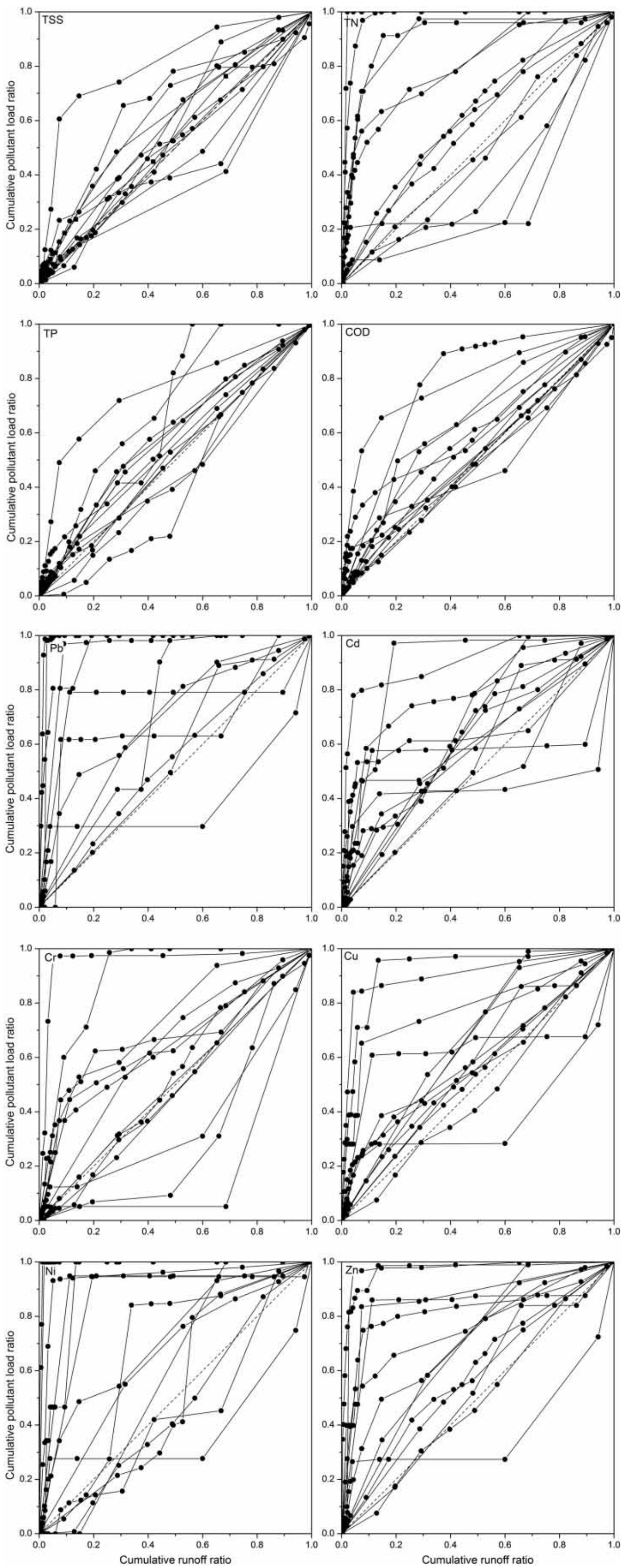

Figure 3 | *M*(*V*) curves for pollutants in different runoffs.

higher than the class V surface water standard (100 μg/L), the recommended guideline for agricultural and general landscape water (CEPA 2002b).

Correlation between TSS and other pollutants

Many studies have suggested that pollutants produced by urban surfaces are mainly transported in association with sediment (Chebbo & Bachoc 1992; Pitt *et al.* 1995). The correlations between TSS and other pollutants were estimated. There were positive correlations between TSS and all other pollutant concentrations except TN (Table 4). From data collected by the Gnecco *et al.* (2005) study at Villa Cambiaso, a strong relationship between COD and TSS concentrations clearly emerged. Several studies have also demonstrated good correlations between suspended solids and the particulate-bound fraction of heavy metals (Pitt *et al.* 1995; Sansalone & Buchberger 1997). The correlation coefficients between TSS and COD and heavy metals were relatively large, and ranged from 0.3 to 0.5, which showed that most of the pollutants were transported with the solids. TSS are not only a major pollutant in runoff, but also an important vector for organic matter and heavy metals. With this information, we can effectively control pollutant discharges by urban street cleaning, interception, precipitation, or filtering of storm runoff.

Influence factors of EMC

The correlations between pollutants and rainfall conditions were studied to investigate the main factors influencing the pollutants (Table 5). Only the EMCs of TN, TP, and COD have a strong relationship with rainfall conditions. There were strong positive correlations between TN and total rainfall (Pearson's $r = 0.927$), average rainfall (Pearson's $r = 0.995$), and maximum rainfall intensity (Pearson's $r = 0.991$). There was also a strong correlation between TP and rainfall intensity (Pearson's $r = 0.940$). This suggests that nutrient discharges increase when the precipitation and intensity of a rainfall event increase. There was a significant positive correlation between COD and rainfall duration (Pearson's $r = 0.902$, significance level $= 0.05$), from which we can deduce that longer rainfall events promoted organic matter transport in runoff.

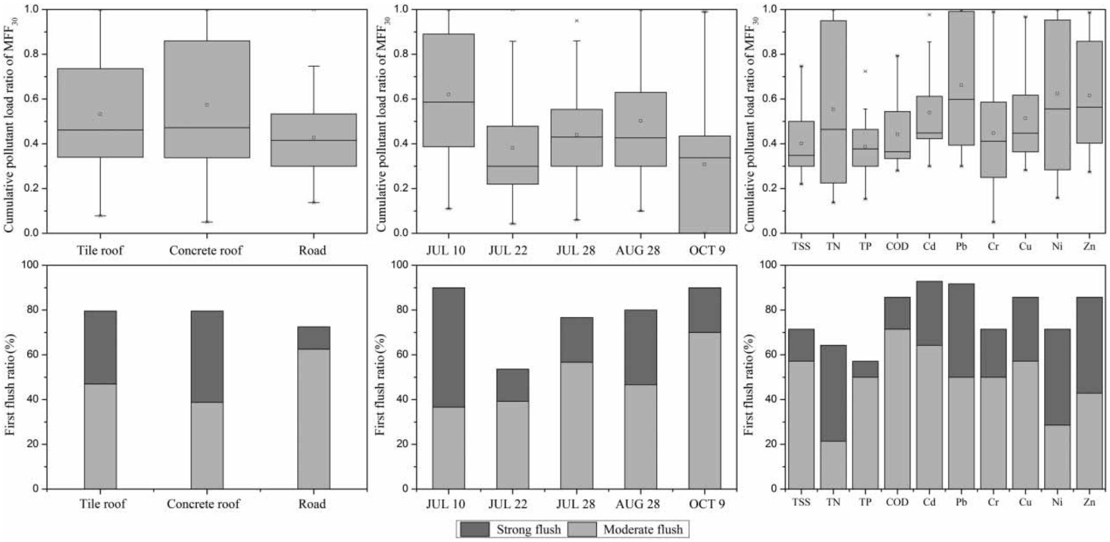

Figure 4 | The MFF_{30} cumulative pollutant load and FF probability of different sampling sites, rainfall events and pollutants. Moderate flush: $1 < MFF_{30} < 2$; strong flush: $MFF_{30} \geq 2$. FF ratio refers to the moderate and strong flush events as a proportion of the total event.

Table 3 | Comparison of EMCs of surface runoff in various locations in China

Sources	Locations	TSS (mg/L)	TN (mg/L)	TP (mg/L)	COD (mg/L)	Cd (μg/L)	Pb (μg/L)	Cu (μg/L)	Zn (μg/L)
Roof	Beijing	0.6–187.0	0.1–24.1	0.0002–2.4	0.4–650.3	–	–	–	–
	Nanjing	–	–	–	–	0.05–1.2	2.0–61.3	7.7–36.9	32–468
	Chongqing	6.1–116.0	1.5–8.2	0.02–0.3	16.5–108.5	0.6–0.7	2.6–6.0	2.9–11.6	13.8–47.2
	Shenyang	7.0–94.3	0.4–9.9	0.01–0.25	0.2–23.6	0.02–0.7	0–22.9	1.3–25.4	2.1–109.1
Road	Beijing	5.4–451.9	2.3–8.2	0.2–0.3	22.3–310.6	–	–	–	–
	Xi'an	421–6,932	–	–	245–1,902	–	16–148	–	146–423
	Chongqing	253.8–874.0	2.1–5.0	0.5–1.0	60.8–208.0	0.5–0.5	2.2–3.5	0.9–4.7	4.2–10.1
	Shenyang	365.0–1,208.1	0.1–3.8	0.2–1.1	1.8–11.0	0.3–3.9	25.9–171.1	48.1–254.8	168.4–1,073.5

–: No data.

Table 4 | Pearson correlation between TSS and other pollutants

Pollutants	Correlation	TN	TP	COD	Cd	Pb	Cr	Cu	Ni	Zn
TSS	Pearson correlation	– 0.130	0.288[a]	0.399[a]	0.179[b]	0.507[a]	0.360[a]	0.409[a]	0.317[a]	0.475[a]
	Significant level	0.139	0.001	0.000	0.041	0.000	0.000	0.000	0.000	0.000

[a]Correlation is significant at the 0.01 level.
[b]Correlation is significant at the 0.05 level.

CONCLUSIONS

The pollutant concentration peaks occurred in the first half-hour after the runoff first appeared and preceded the flow peaks for all the events. TN is the main pollutant in roof runoff, and TSS, TN, TP, Pb, and Cr are the main pollutants in road runoff in Shenyang. The quality of road runoff in Shenyang was significantly poorer than in other cities in China. TSS is an important vector for organic matter and heavy metals. Pollutant discharge in runoff is affected by various factors. Nutrient discharges increase with increased rainfall depth and intensity.

Table 5 | Correlation between pollutants and rainfall conditions

Pollutants	Correlation	Rainfall (mm)	Duration (h)	Average intensity (mm/h)	Max rainfall intensity (mm/h)	Antecedent dry weather period (d)
TN	Pearson correlation	0.927[a]	– 0.11	0.995[b]	0.991[b]	0.67
	Significant level	0.02	0.86	0.00	0.00	0.22
TP	Pearson correlation	0.85	– 0.05	0.900[a]	0.940[a]	0.76
	Significant level	0.07	0.94	0.04	0.02	0.14
COD	Pearson correlation	0.18	0.902[a]	– 0.17	– 0.12	– 0.42
	Significant level	0.77	0.04	0.78	0.84	0.48

[a]Correlation is significant at the 0.05 level.
[b]Correlation is significant at the 0.01 level.

Prolonged rainfall events promoted organic matter transport in runoff.

The intensity of the FF varied by surface, and was most intense for the flat roof, followed by the sloping roof and then the road. Rainfall duration and the length of the antecedent dry period were positively correlated with the FF. Initially, rainfall intensity was positively correlated with the FF, but when the dilution effect was greater than the flushing effect, the correlation changed to negative. Heavy metal pollutants frequently occurred in the FF, while TN was likely to occur in strong flushes.

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