Characteristics of heavy metal pollution in road runoff in the Nanjing urban area, East China

Hongqin Xue, Li Zhao and Xiaodong Liu

ABSTRACT

An extensive field survey was conducted in four types of road area to study heavy metals in road runoff. Eleven rainfall events were monitored from February 2011 to March 2012, which were classified into four categories according to the relationship between peak of the rainfall amount, rainfall duration, and average rainfall intensity. Runoff samples were collected from overpass sections, college areas, residential areas, and road sidewalks. Heavy metal concentrations were obtained to investigate the outflow laws governing heavy metals in runoff. The concentration fluctuations of seven heavy metals were monitored to assess the influence of rainfall characteristics on metal concentrations. To estimate the impact of heavy metals on the water environment, the event mean concentrations (EMCs) were determined to describe the overall pollution degree of heavy metal in runoff, and then the EMC values of heavy metals in runoff were compared with surface water environmental quality standard thresholds. The results indicate that the EMC values of heavy metals varied widely in different rainfall fields and under the same rainfall at different sampling points. Average rainfall intensity has a significant impact on the EMC of heavy metal outflow, followed by maximum rainfall intensity and rainfall amount.

Key words | heavy metals, outflow rules, pollution characteristics, urban road runoff

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HIGHLIGHTS

- Heavy metals in road runoff of different urban areas were researched.
- Outflow laws of heavy metals in road runoff varied between different types of rainfall events.
- The event mean concentration values of heavy metals demonstrated serious pollution of Cd, Pb, Cr, and Ni.
- Except for Mn, other heavy metals (Zn, Cu, Ni, Cd, Cr, Pb) had a positive correlation with rainfall, maximum rainfall intensity, and average rainfall intensity.
- The correlation coefficients between heavy metals in the college area were higher than those in the three areas.

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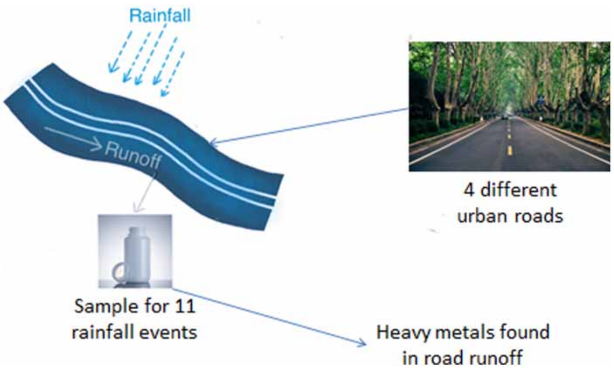
GRAPHICAL ABSTRACT



INTRODUCTION

In recent years, China's transportation system has expanded rapidly. By the end of 2018, the total mileage of national highways exceeded 484 million km. The mileage of urban municipal roads has also been increasing rapidly with accelerating urbanization. However, problems such as air pollution, noise pollution, water pollution, soil pollution, and land resource consumption in road operation have also become increasingly prominent with the increase in road construction (Ghosh & Maiti 2018). The many impermeable pavements have changed the hydrological process of urban drainage, increasing the flow and peak values of urban pavement runoff and advancing the time of the peak value, which provides external dynamic conditions for the occurrence of urban pavement runoff pollution. With increasing urban population, large amounts of pollutants accumulate on the pavement due to the rapid growth of traffic flow (Du *et al.* 2019). These pollutants are suspended in the atmosphere, accumulate on the road surface, or are adsorbed on sediments on the road surface and eventually enter the ecological environment as environmental pollutants through natural processes such as atmospheric action or rainwater runoff (Perdikaki & Mason 1999). Runoff pollution from impervious pavement mainly comes from atmospheric subsidence, road sediment, rain flood deposits, and underground drainage facilities. The circulation of particulate matter in an urban environment proceeds as follows: atmospheric suspended matter → pavement sediment → rain-flood sediment → urban soil. The sources of these pollutants are mostly related to vehicle traffic (Miguel *et al.* 1997), including the operation of motor vehicles, tire wear particles, road building material wear particles, spillage of transport goods, leaked fuel or lubricating oil, particulate matter and de-icing agents produced by vehicle body parts, and vehicle exhaust emissions (Deletic & Orr 2005). In the rainy season, especially during heavy rains, rainfall on impermeable pavement is rapidly transformed into runoff, which scours and carries away large amounts of accumulated pollutants from pavement into water bodies, forming typical non-point source pollution and becoming an important reason for water quality decline and urban estuary pollution. Heavy metal pollutants are not easy to biodegrade and have biological enrichment characteristics, which can directly threaten the survival of higher organisms, including human beings (Pal *et al.* 2018).

In this paper, field monitoring, laboratory experiments, and theoretical analysis are combined to carry out a systematic study of the characteristics of pavement runoff pollution in different urban functional areas. This is of great theoretical and practical significance for improving the quality of the urban water environment, maintaining normal operation of the whole water cycle, promoting sustainable development of the city to study the pollution characteristics of urban road rainfall runoff, especially heavy metal pollution, analyzing the laws governing its outflow variation, grasping the factors affecting its pollution load, and determining appropriate management and control measures.

MATERIALS AND METHODS

Road rainwater samples were collected from four types of road in Nanjing, China (Figure 1): the main road of a college campus (XY), the water pipe in an overpass section of urban road (LJ), an urban road sidewalk gutter inlet (RX), and a

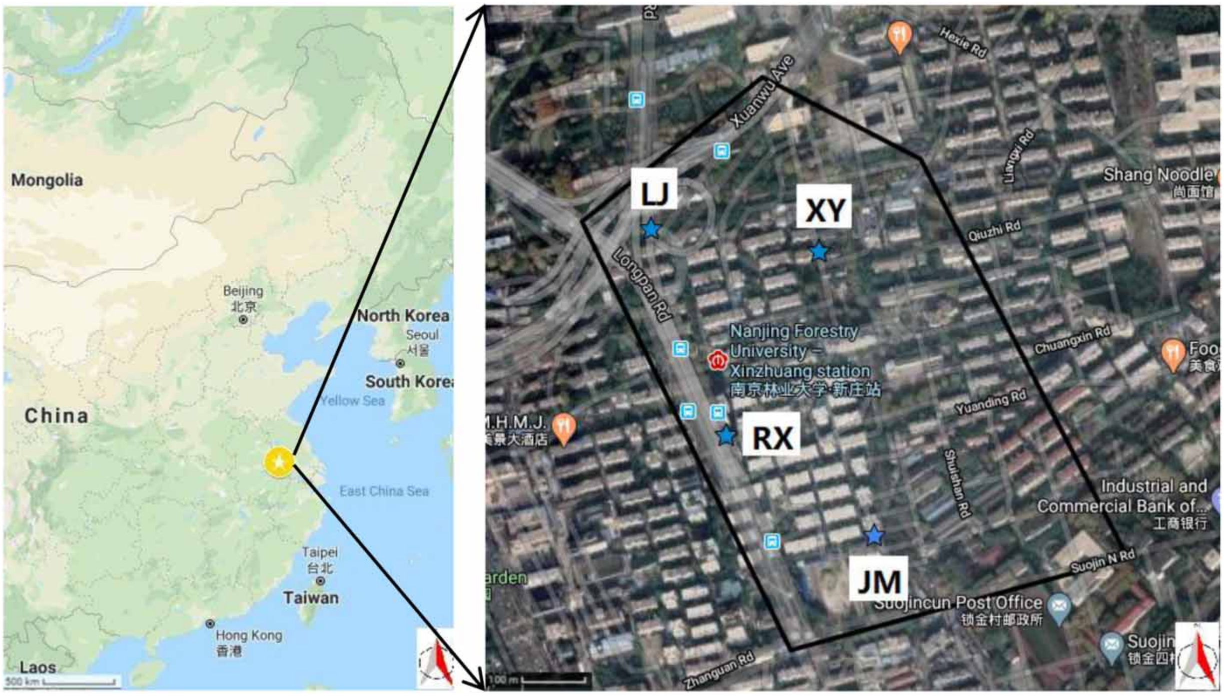


Figure 1 | The studied urban area and sampling sites in Nanjing, China.

rainwater inlet in a residential area (JM); all of which have different materials and traffic flow. Table 1 shows the road materials in the sampling areas.

The sampling bottles used to collect water samples were soaked in dilute nitric acid for 24 h in advance; then they were washed with distilled water and dried. The runoff rainwater at interchanges was collected by the downpipe of the overpass, and other samples were taken from rainwater outlets with low elevation. The start time of rainfall, the start time of runoff formation, and the sampling time were recorded simultaneously during sampling. Samples were taken every 3–5 min in the first 30 min after runoff formation, every 10–15 min in the 30–60 min after runoff formation, and finally every 30–120 min from 60 min after runoff formation to the end of the rainfall event; the sampling interval was adjusted according to the actual rainfall intensity and duration.

Table 1 | Road materials in sampling areas

Sampling sites	Sampling locations	Road material
LJ	Overpass section	Asphalt
XY	College area	Asphalt
JM	Residential area	Cement
RX	Road sidewalk	Asphalt

Experimental instruments included a 7852 automatic recording rain gauge, a TAS-990 Super F atomic absorption spectrophotometer, an Alpha Pure 30 Plus enhanced high-purity water system, a WX-4000 microwave rapid digestion instrument, a PHS-3 precision pH meter, and an electronic balance. Experimental reagents included concentrated hydrochloric acid (HCl, analytical purity), nitric acid (HNO_3, analytical purity), sulfuric acid (H_2SO_4, analytical purity), hydrofluoric acid (HF, analytical purity), and phosphoric acid (H_3PO_4, analytical purity). All utensils used in the experiment were soaked with dilute hydrochloric acid, washed with deionized water, and dried.

The instantaneous water samples were sent to the laboratory shortly after collection. The wet digestion method was used to digest the water samples and determine the total heavy metal content; the mixed solution for digestion consisted of concentrated HNO_3, concentrated HCl with a volume ratio of 1:1, and distilled water. The water samples were filtered by a 0.45-μm mixed-fiber microporous filter membrane and were then used to measure the concentration of the dissolved heavy metals. The concentration of particulate heavy metals was obtained by subtracting the dissolved concentration from the total concentration. The total and dissolved concentrations of the seven heavy metals (Cu, Zn, Pb, Cr, CD, Ni, and Mn) in the water samples were determined by an atomic absorption spectrophotometer.

Rainfall event characteristics

Rainfall progress and the amount of rainfall were monitored by a 7852 tipper-type self-recording rain gauge to obtain the characteristics of every rainfall event. The measuring accuracy of the rain gauge was 0.2 mm; therefore, it could monitor the relationship between accumulated rainfall and time. The rain gauge was fixed within 300 m of the sampling point without a shelter around it. Rainfall events were monitored from February 2011 to March 2012, and the monitoring data involved 11 rainfall processes. Table 2 shows the characteristics and sampling locations of each rainfall event.

Table 2 indicates that the intensity of the 11 rainfall events varied randomly. To facilitate this study, rainfall events were classified into the following categories according to the relationship between peak of the rainfall amount, rainfall duration and the average rainfall intensity: rainfall events with low intensity and low precipitation (such as April 6, 2011); rainfall events with high intensity and high precipitation (such as June 29, 2011); rainfall events with high rainfall intensity in the initial stage (such as March 21, 2011 and May 10, 2011); and rainfall events with high rainfall intensity in the terminal stage (such as March 30, 2012).

RESULTS AND DISCUSSION

Outflow law of heavy metals in road runoff

Rainfall characteristics (such as rainfall intensity and duration) affect the concentration of heavy metals in runoff. In this part, five representative rainfall events were selected according to the characteristics of rainfall events to analyze variation of heavy metal concentrations in road runoff.

Rainfall event with low intensity and low precipitation

The rainfall event on April 6, 2011 lasted for a long time, maintained low rainfall intensity throughout and had the lowest precipitation among the 11 rainfall events. Figure 2 shows the variation of total heavy metal outflow concentrations in residential areas and college area during the rainfall event. The samples were available after 8 hours of rainfall.

It can be seen from Figure 2 that the heavy metal outflow law for the residential area was similar to that for the campus area in this rainfall event; concentrations of the heavy metals Cr, Cu, Zn, Pb, and Mn fluctuated slightly in the early stage of runoff and decreased to a low level in the end. On the whole, total heavy metal concentrations were maintained at low level, which was similar to former research (Charters *et al.* 2016).

Rainfall event with high intensity and high precipitation

The rainfall event on June 29, 2011 had the highest rainfall amount, the maximum rainfall peak value, and the maximum average rainfall intensity among the elven rainfall events. Runoff samples were collected 10 minutes after the formation of rainfall runoff. Figure 3 shows variation of total heavy metal outflow concentrations in the roadside area and overpass section during the rainfall event.

Table 2 | Characteristics of each rainfall event

Rainfall date	Rainfall duration (min)	Rainfall (mm)	Maximum rainfall intensity (mm/min)	Minimum rainfall intensity (mm/min)	Mean rainfall intensity (mm/min)	Early sunny hours (h)	Sampling sites
2/26/2011	590	7.6	0.0444	0.0059	0.013	209	LJ, JM
3/21/2011	736	17.4	0.1667	0.0043	0.024	20.5	JM, XY
4/6/2011	738	4.2	0.0167	0.002	0.006	79.5	XY, JM
5/10/2011	445	14	0.1818	0.0043	0.031	239	JM, RX
5/22/2011	398	5.4	0.0317	0.0049	0.014	209	RX, LJ
6/29/2011	118	28.8	2	0.0476	0.244	89.5	RX, LJ
7/5/2011	68	11.6	1	0.027	0.171	32.5	XY
9/28/2011	406	8.6	0.1	0.0071	0.021	526	LJ
2/22/2012	324	15.8	0.4	0.0057	0.049	152	LJ, RX
2/29/2012	344	8.4	0.1111	0.0067	0.024	89	XY, RX
3/30/2012	645	9.2	0.4	0.0036	0.014	183	RX, LJ, JM

'Early sunny hours' refers to accumulated sunny time from the last rainfall event to current rainfall event.

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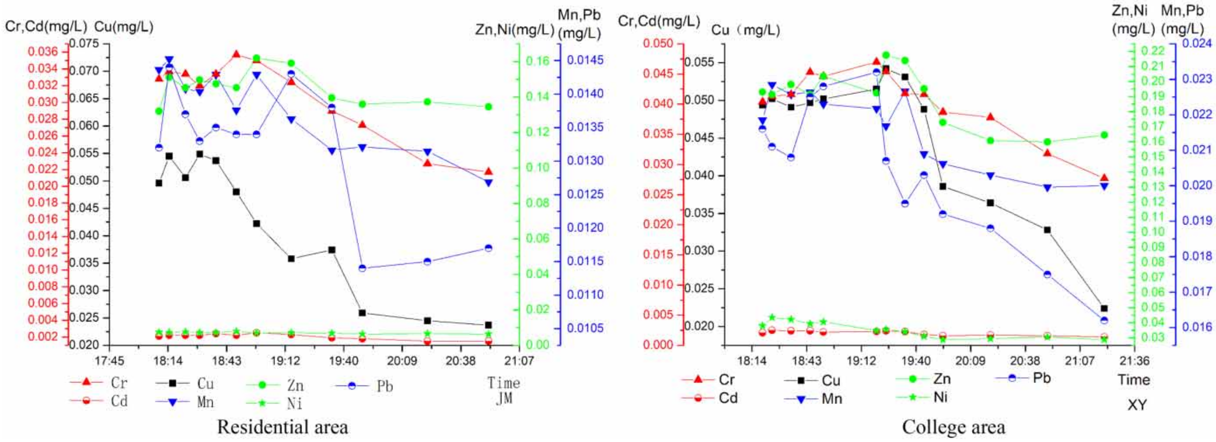

Figure 2 | Outflow concentrations of total heavy metals on April 6, 2011.

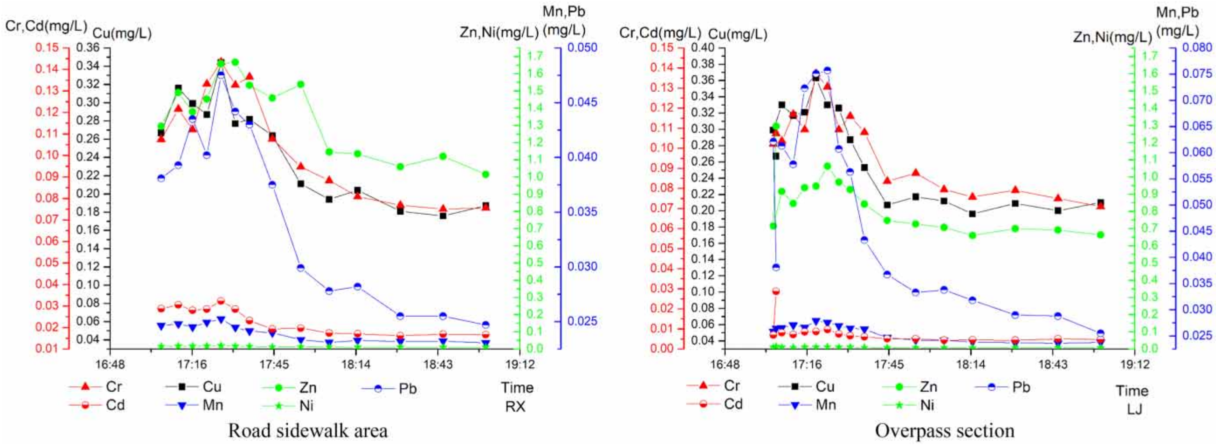

Figure 3 | Outflow concentrations of total heavy metals on June 29, 2011.

Figure 3 shows total heavy metal outflow concentrations soon reached peak values under the serious scour effect of rainwater in the early stage of a rainfall event, then declined significantly after 45 minutes of runoff formation in road sidewalk area and 1 hour in overpass section area; the heavy metal concentrations at both sampling points were maintained at a low level at the end of runoff. On the whole, the fluctuation range of heavy metal concentrations on sidewalk area was smaller than that in overpass section areas. The concentration of heavy metals Cr, CD, Zn, and Pb was higher than other heavy metals in the two areas.

Two rainfall events with high rainfall intensity in the initial stage

The rainfall events on March 21, 2011 and May 10, 2011 had high rainfall intensity in the initial stage, runoff samples could be collected about 10 minutes after the start of rainfall. The outflow law in Figures 4 and 5 illustrate that outflow concentrations of heavy metals soon reached the peak values after dramatic fluctuation in the initial period of runoff, and then decreased significantly to a stable level 90 minutes after runoff formation. The stable heavy metal concentrations were approximately one-fifth to one-half of the peak concentrations, indicating that rainwater with high intensity in the early stage scoured off most pollutants in the road surface. The concentrations of some heavy metals increased slightly in the late stage of runoff, which was probably caused by traffic pollution.

The rainfall events of March 21, 2011 and May 10, 2011 had the maximum rainfall intensities in the early stage. In this kind of rainfall event, the runoff rainwater pollution in the early stage was more serious due to the strong scouring effect, which is called the first flush effect (Qianqian *et al.*

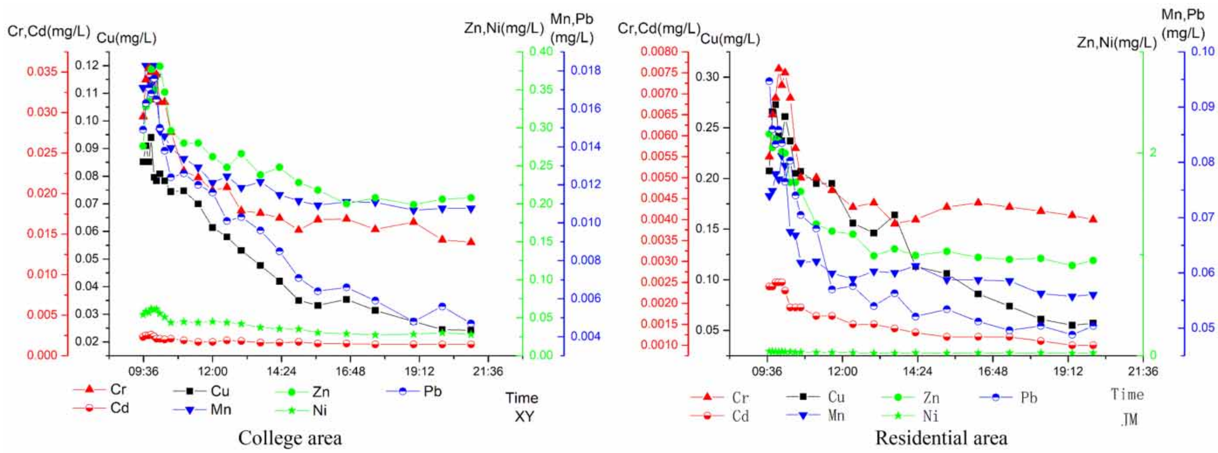

Figure 4 | Outflow concentrations of total heavy metals on March 21, 2011.

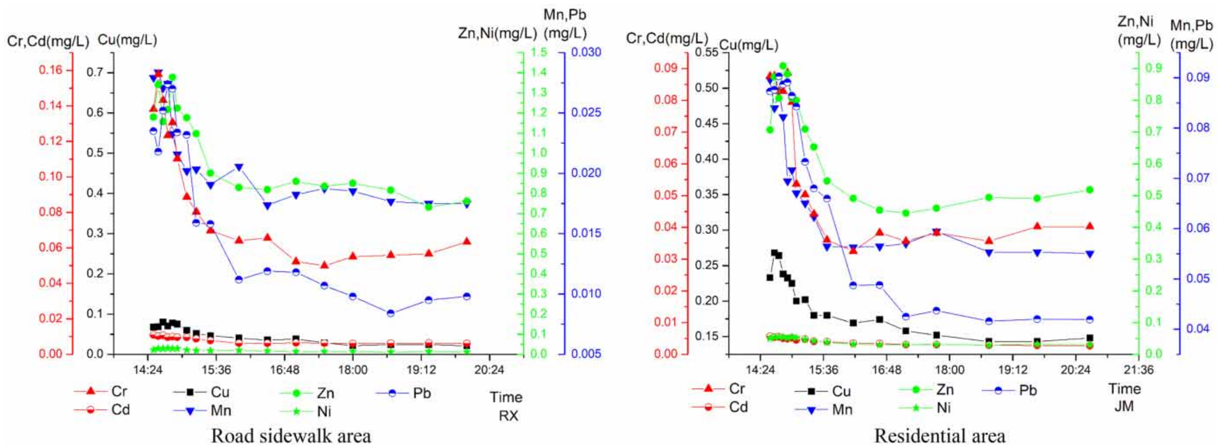

Figure 5 | Outflow concentrations of total heavy metals on May 10, 2011.

2011); rainwater in this stage contained not only heavy metals, but also suspended solids, chemical oxygen demand, oil, and grease (Wang *et al.* 2013).

Rainfall event with high rainfall intensity in the terminal stage

The rainfall events on March 30, 2012 had high rainfall intensity in the terminal stage, heavy metal concentrations in the overpass section and road sidewalk area reached peak values after 2 hours of rainfall, maintained a stable level for a period of time and then reached an obvious peak value again; the second peak value may be caused by the sudden increased scouring effect of rainwater. From Figure 6 we can see that the second peak values were lower than the first peak values. A possible reason for this may be that small particles were washed away by the light rainfall in the initial stage, but the peak of rainfall intensity in the terminal stage was strong enough to wash away sediments of larger particles.

A common law can be concluded from the above five rainfall events: the peak values of heavy metal concentrations usually appeared following peak values of rainfall intensity, but there was a lag effect which meant the peak values of heavy metal concentrations appeared 3–15 minutes after peak values of rainfall intensity. In many rainfall events, the concentrations of some heavy metals increased slightly in the later stage of runoff, which may be caused by new pollutants generated by traffic; this phenomenon also existed in other researches (Conley *et al.* 2009). There are two forms of heavy metal pollutants, soluble and insoluble (Tian *et al.* 2012). In the early stage of runoff formation,

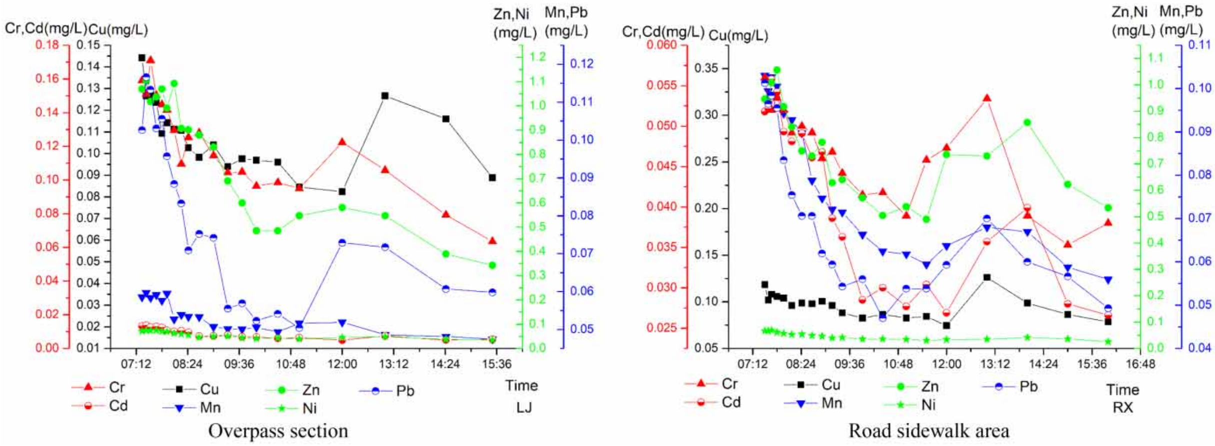

Figure 6 | Outflow concentrations of total heavy metals on March 30, 2012.

rainwater had less scouring power on particles, and the contact time between rainwater and pavement sediments was longer before runoff formation. This meant that soluble pollutants could dissolve into runoff rainwater in the early stage of runoff under long-term contact, and non-soluble pollutants were brought into runoff under the scouring effect of rainwater with high intensity (Wang *et al.* 2017). Small particles carried into rivers and lakes can change the turbidity of water and affect the aquatic environment, and absorb other pollutants (such as heavy metals) because of the particles' large specific surface area (Hui *et al.* 2017).

The event mean concentration of heavy metals in road runoff

The uncertainty of rainfall characteristics, regional characteristics, and other factors made the pollutant discharge concentrations of road runoff continuously change with the rainfall process in different rainfall events in the same region or in the same rainfall event in different regions (Dong *et al.* 2014). To describe the overall pollution degree of heavy metal in road runoff, the event mean concentration (EMC) was introduced for two reasons, on the one hand, the monitored rainfall area cannot fully represent the rainfall situation of the whole region; on the other hand, the change rate of pollutant concentrations in runoff is greatly lower than that in the receiving water body. Table 3 illustrates EMC values of heavy metals Cu, Cr, Zn, Pb, Mn, Cd, and Ni in the 11 rainfall events, and Figure 7 presents the statistical analysis results for the EMC values.

Table 3 demonstrates that the EMC values for heavy metals varied widely in different rainfall events, and the heavy metal concentrations at different sampling points in the same rainfall event were also very different. There were two orders of magnitude difference between the maximum and minimum values of heavy metals Cr and Cd and one order of magnitude difference between the maximum and minimum for other heavy metals. The EMC values of heavy metals in urban road runoff were higher than other research results on highways. This difference occurred probably because urban roads are more affected by various human social activities (Huber *et al.* 2016).

Compared with the surface water environmental quality standard threshold (Ministry of Ecology and Environment of the People's Republic of China, 2008), the EMC values of Cu in all the monitored runoff water samples were better than the class I water quality standard threshold. A total of 19% of Cr's EMC values were better than the class I standard threshold, 33.3% were worse than the class II standard threshold, 33.4% were worse than the class IV standard threshold, and 14.3% were worse than the class V standard threshold. A total of 28.6% of Zn's EMC values were higher than the class III standard threshold, and the rest were lower than the class II standard threshold. A total of 23.8% of Pb's EMC values were higher than the class IV standard threshold, 57.14% were higher than the class II standard threshold, and the rest were lower than the class I water quality standard. A total of 33.4% of Cd's EMC values were higher than the class V standard threshold, 33.3% were higher than the class IV standard threshold, and the rest were lower than the class II standard threshold.

Sources of pollutants in road runoff were analyzed. The samples were taken from urban road sections which were less influenced by industry and agriculture except for some construction sites nearby. From the EMC values we can

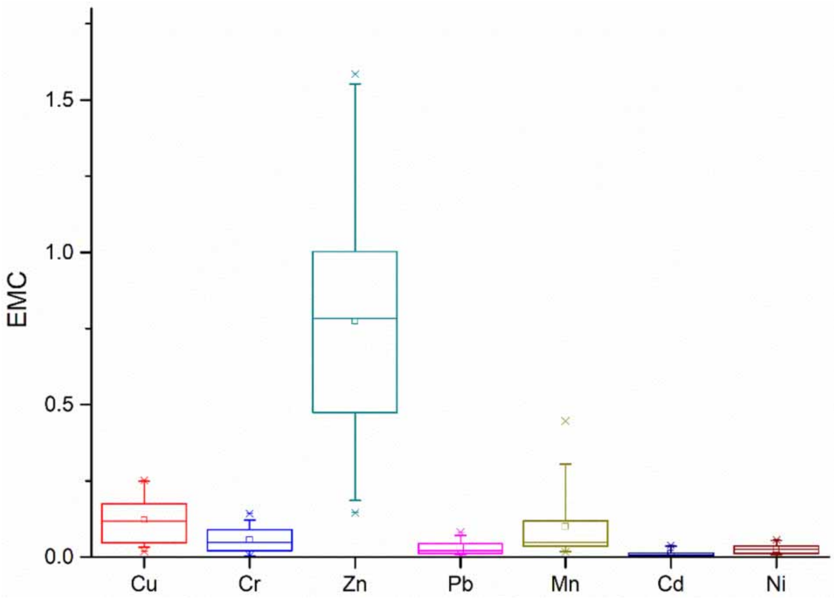

Figure 7 | Statistical distribution of EMC for heavy metals.

Table 3 | EMC values of heavy metals in road runoff in 11 rainfall events (mg/L)

Date	Sampling site	Cu	Cr	Zn	Pb	Mn	Cd	Ni
2/26/2011	LJ	0.1439	0.0077	1.5851	0.0187	0.1957	0.0029	0.0377
	JM	0.0322	0.0043	1.0030	0.0079	0.0177	0.0009	0.0267
3/21/2011	JM	0.1577	0.0048	1.2875	0.0617	0.1186	0.0016	0.0303
	XY	0.0562	0.0216	0.2644	0.0103	0.0825	0.0017	0.0410
4/6/2011	XY	0.0434	0.0398	0.1859	0.0200	0.0449	0.0019	0.0342
	JM	0.0370	0.0295	0.1452	0.0128	0.0605	0.0019	0.0069
5/10/2011	JM	0.1738	0.0439	0.5524	0.0558	0.3054	0.0036	0.0360
	RX	0.0405	0.0731	0.9115	0.0137	0.4470	0.0073	0.0171
5/22/2011	RX	0.0181	0.0899	1.1071	0.0325	0.0357	0.0117	0.0206
	LJ	0.0924	0.0541	0.3705	0.0297	0.0309	0.0051	0.0249
6/29/2011	RX	0.2496	0.1075	1.3625	0.0354	0.0481	0.0231	0.0139
	LJ	0.2472	0.0934	0.7882	0.0439	0.0468	0.0059	0.0081
7/5/2011	XY	0.1859	0.0044	1.5527	0.0625	0.0513	0.0099	0.0075
9/28/2011	LJ	0.2513	0.0788	0.5733	0.0111	0.0236	0.0240	0.0543
2/22/2012	XY	0.1765	0.1423	0.8103	0.0087	0.0821	0.0131	0.0085
	LJ	0.1632	0.0906	0.5125	0.0178	0.0382	0.0093	0.0111
2/29/2012	XY	0.1461	0.0151	0.4738	0.0098	0.0423	0.0060	0.0054
	RX	0.0465	0.0529	0.7828	0.0084	0.1562	0.0352	0.0209
3/30/2012	RX	0.0960	0.0490	0.7956	0.0713	0.2249	0.0384	0.0452
	LJ	0.1173	0.1212	0.7565	0.0814	0.0233	0.0090	0.0562
	JM	0.0769	0.0452	0.4280	0.0390	0.0172	0.0222	0.0269
Minimum		0.0181	0.0043	0.1452	0.0079	0.0172	0.0009	0.0054
Maximum		0.2513	0.1423	1.5851	0.0814	0.4470	0.0384	0.0562
Median value		0.1173	0.0490	0.7828	0.0200	0.0481	0.0073	0.0249
Average value		0.1215	0.0557	0.7738	0.0311	0.0997	0.0112	0.0254

see that the overall pollution degree of Cu was relatively low, Cu mainly comes from metal plating, wear of bearings and brake parts (Budai & Clement 2011), pesticides and fungicides; the overall pollution degree of Zn was also relatively low, the main sources of Zn include tire wear and engine lubricating oil; Cr, Ni, and Cd generated serious pollution in road runoff, the main source of Cr in road runoff was tire wear; Ni may come from gasoline, lubricating oil, bearing wear, brake part wear, and asphalt pavement; Cd mainly comes from tire wear; Pb pollution was serious, Pb in the urban road surface sediments mainly comes from gasoline and motor vehicle exhaust. Pb is added to gasoline as an explosion-prevention agent; it is firstly oxidized to PbO and PbO_2 in the combustion process and then it reacts with additives in gasoline (such as CH_2Cl_2 and CH_2Br_2) to produce $PbCl_2$, $PbBr_2$, or $PbBrCl$, and finally these lead compounds are adsorbed to automobile exhaust particles and enter the road environment (Sezgin et al. 2004).

Influencing factors of heavy metal pollution in road runoff

The factors influencing the runoff characteristics include many aspects, such as rainfall precipitation, intensity and duration; traffic flow and vehicle type; road cleaning method and maintenance status; land function and geographical characteristics. In this research, many of the above factors hardly change, such as pavement material, traffic flow, atmospheric deposition situation, and road cleaning method; however, rainfall intensity, rainfall, duration and antecedent sunny days varied greatly at one sampling site in the studied 11 rainfall events, so the characteristics of rainfall events were selected to analyze their impact on heavy metal concentration in road runoff. Pearson correlation coefficients between rainfall characteristics (rainfall, rainfall intensity, antecedent sunny days) and runoff concentrations of heavy metal pollutants in the overpass section area are given in Table 4 to evaluate the impact of rainfall characteristics on metal outflow pollution.

Table 4 illustrates that average rainfall intensity had a significant impact on the EMC of heavy metal outflow, followed by maximum rainfall intensity and rainfall amount. These results are consistent with those of other researchers (Shinya et al. 2003; Crabtree et al. 2006; Qianqian et al. 2011). Except for Mn, all heavy metals had a positive correlation with rainfall, maximum rainfall intensity, and average rainfall intensity. The results indicate that the cumulative number of sunny days had little effect on the EMC of heavy metal outflow.

Correlation analysis between heavy metals in road runoff

The correlation coefficients between heavy metals at each sampling point were analyzed to look for relations between the investigated parameters, as shown in Table 5.

The correlation coefficients between heavy metals varied greatly in different sampling sites. There were positive correlations for Zn–Mn, Cr–Mn, and Cr–Pb in the overpass section, the correlation coefficients were 0.89, 0.66, 0.65 respectively; there were significant positive correlations for Cu–Pb, and Cu–Mn in residential area, the correlation coefficients were 0.91 and 0.8 respectively, and moderate correlations for Cu–Ni, Pb–Ni, and Pb–Mn in residential area, the correlation coefficients were 0.7, 0.75, 0.69 respectively; there were good positive correlations for Pb–Ni and Cd–Ni in road sidewalk area, the correlation coefficients were 0.86 and 0.7 respectively; positive correlations for college area were more common – there were significant correlations between many heavy metals in college area, indicating that these heavy metals may share a common source and transportation process, and the distribution of these heavy metals may be controlled by the same factors (Qianqian et al. 2011; Ghosh & Maiti 2018).

CONCLUSIONS

The laws governing heavy metal outflow were different for different rainfall events. During rainfall events with low

Table 4 | Linear correlation coefficients between rainfall characteristics and EMC of heavy metals in overpass section

	Cu	Cr	Zn	Pb	Mn	Cd	Ni
Rainfall	0.6139	0.3890	0.0480	0.1296	−0.1653	0.1546	0.6660
Maximum rainfall intensity	0.5471	0.4069	0.0316	0.3038	−0.1873	0.2126	0.5630
Average rainfall intensity	0.6020	0.2818	0.0283	0.1367	−0.1338	0.1997	0.6380
Antecedent sunny days	0.3625	−0.1005	−0.1483	−0.4394	−0.1507	0.8773	0.6586

Table 5 | Linear correlation coefficients of heavy metals in different sampling locations

		Correlation coefficients						
Sampling locations	**Pollutants**	**Cu**	**Cr**	**Zn**	**Pb**	**Mn**	**Cd**	**Ni**
Overpass section	Cu	1						
	Cr	0.17	1					
	Zn	0.26	0.35	1				
	Pb	0.15	0.65	0.08	1			
	Mn	0.18	0.66	0.89	0.24	1		
	Cd	0.42	0.38	0.24	0.12	0.4	1	
	Ni	0.03	0.1	0.3	0.29	0.1	0.47	1
Residential area	Cu	1						
	Cr	0.25	1					
	Zn	0.51	0.5	1				
	Pb	0.91	0.34	0.46	1			
	Mn	0.8	0.47	0.16	0.69	1		
	Cd	0.12	0.54	0.3	0.12	0.29	1	
	Ni	0.7	0.33	0.54	0.75	0.63	0.14	1
Road sidewalk	Cu	1						
	Cr	0.49	1					
	Zn	0.34	0.58	1				
	Pb	0.08	0.25	0.15	1			
	Mn	0.31	0.31	0.06	0.04	1		
	Cd	0.07	0.07	0.18	0.57	0.05	1	
	Ni	0.24	0.24	0.03	0.86	0.32	0.7	1
College area	Cu	1						
	Cr	0.54	1					
	Zn	0.78	0.65	1				
	Pb	0.52	0.34	0.89	1			
	Mn	0.26	0.28	0.24	0.19	1		
	Cd	0.93	0.65	0.9	0.7	0.43	1	
	Ni	0.65	0.69	0.55	0.29	0.81	0.76	1

intensity and low rainfall amount, the variation of heavy metal outflow concentrations was small, and the outflow concentrations remained within a small variation range. Heavy metal outflow concentrations in rainfall events with heavy rainfall intensity at the initial stage were higher and then decreased until they reached a relatively stable outflow concentration at the end, showing a significant initial scour effect. A secondary concentration outflow peak of heavy metals appeared following the period of intense rainfall in the rainfall event with a late rainfall intensity peak.

The results of EMC analysis of the average heavy metal concentrations in road runoff showed significant heavy metal pollution in road runoff rainwater. Compared with the surface water environmental quality standard threshold, 33.4% of the EMC values for Cr were worse than the class IV standard threshold, and 14.3% were worse than the class V standard threshold; 28.6% of the EMC values for Zn were higher than the class III standard threshold; 23.8% of the EMC values for Pb were higher than the class IV standard threshold; 33.3% of the EMC values for Cd were higher than the class V standard threshold, and 33.4% were higher than the class IV standard threshold; 61.9% of the EMC values for Ni and 23.8% of those for Mn exceeded the standard threshold.

Average rainfall intensity had a significant impact on the EMC of heavy metal outflow, followed by maximum rainfall intensity and rainfall amount. Except for Mn, all heavy metals had a positive correlation with rainfall amount, maximum rainfall intensity, and average rainfall intensity.

The correlations between heavy metals at different sampling points were quite different: correlations between heavy metals in campus areas were relatively common, which showed that these heavy metals may share common sources and transportation process, and the distribution of these heavy metals may be controlled by the same factors on campus.

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