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Pollutant concentrations and pollution loads in stormwater runoff from different land uses in Chongqing

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Abstract

To investigate the distribution of pollutant concentrations and pollution loads in stormwater runoff in Chongqing, six typical land use types were selected and studied from August 2009 to September 2011. Statistical analysis on the distribution of pollutant concentrations in all water samples shows that pollutant concentrations fluctuate greatly in rainfall-runoff, and the concentrations of the same pollutant also vary greatly in different rainfall events. In addition, it indicates that the event mean concentrations (EMCs) of total suspended solids (TSS) and chemical oxygen demand (COD) from urban traffic roads (UTR) are significantly higher than those from residential roads (RR), commercial areas (CA), concrete roofs (CR), tile roofs (TRoof), and campus catchment areas (CCA); and the EMCs of total phosphorus (TP) and NH_3-N from UTR and CA are 2.35–5 and 3 times of the class-III standard values specified in the Environmental Quality Standards for Surface Water (GB 3838-2002). The EMCs of Fe, Pb and Cd are also much higher than the class-III standard values. The analysis of pollution load producing coefficients (PLPC) reveals that the main pollution source of TSS, COD and TP is UTR. The analysis of correlations between rainfall factors and EMCs/PLPC indicates that rainfall duration is correlated with EMCs/PLPC of TSS for TRoof and TP for UTR, while rainfall intensity is correlated with EMCs/PLPC of TP for both CR and CCA. The results of this study provide a reference for better management of non-point source pollution in urban regions.

Key words: urban land uses; stormwater runoff; pollution load; pollutant concentration; distribution
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Introduction

With the development of urbanization, large areas of natural green lands are replaced by buildings, which leads to a sharp rise of impervious land in urban areas. Compared with land uses, stormwater runoff will be generated more easily with higher, earlier peaks (Zhao et al., 2007). As a result, pollutants accumulated on urban underlying surfaces will be washed into receiving waters directly when rainfall occurs (Brezonik and Stadelmann, 2002). What's worse, the discharge of rainfall-runoff is quite scattered and uncertain, which makes it difficult to manage rainfall-runoff in urban areas. Furthermore, due to the increase of the point source pollution treatment ratio, non-point source pollution in urban areas caused by stormwater flushing has gradually become the major reason for the deterioration of urban water bodies (Wang et al., 2001).

Numerous studies have proved that urban nonpoint source pollution is an important contributor to water quality degradation (Davis and Birch, 2009; Palla et al., 2009; Brown and Peake, 2006). In recent years, a number of studies on urban non-point source pollution have been conducted in many cities of China (Zhang et al., 2010; Balloa et al., 2009; Zhao et al., 2007; Gan et al., 2008; Wei et al., 2010). Their results have shown that the pollutant concentrations of stormwater runoff vary significantly in different rainfall events, with higher values in the early stage and lower values in the medium or later stages. Meanwhile, event mean concentrations (EMCs) of stormwater runoff differ greatly for different land uses. Many similar studies have also been conducted abroad. A large urban and suburban database has been compiled, and stormwater runoff loads and concentrations of 10 common constituents have been characterized for the Twin Cities metropolitan area, Minnesota, USA (Brezonik and Stadelmann, 2002). Pollution loads from urban watersheds at various spatial scales in Paris were studied by Kafi et al.

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(2008), and the results showed that for a given rain event, no scale effect was observed on pollutant concentrations, pollutant contents and loads. Taebi and Droste (2004) analyzed the annual loads of non-point and point source pollution in Isfahan, Iran, and the results indicate that for regions with low precipitation, the annual non-point source pollution load was lower than that from point sources, but the contrary was observed in regions with high precipitation.

However, most of the above studies focused on pollutant concentrations in stormwater runoff. Even though the urban nonpoint source pollution loads were analyzed, rare attention was paid to the rainfall-runoff pollution load of specific underlying surfaces. Stormwater source control is regarded as an alternative solution for managing stormwater in urban areas, which focuses on controlling pollutant production at its source through a series of management measures (Martin et al., 2007). When source control strategies are designed, the nonpoint source pollution loads received by lakes and streams are in need of estimation (Brezonik and Stadelmann, 2002). Therefore, it is essential to fully investigate the pollutant output characteristics of various urban land uses, especially those with simple land use types (Davis and Birch, 2010).

Chongqing is located in the Three Gorges Reservoir area with high environmental sensitivity. Urban non-point source pollution from Chongqing poses a direct threat to receiving water bodies (Fu et al., 2010). However, studies on the non-point source pollution in this area are still insufficient. Thus, it is of great significance to study the pollutant output characteristics of different urban land uses in Chongqing.

1 Materials and methods

1.1 Areas studied

Chongqing lies in Southwest China, inland along the upper reaches of the Yangtze River. With an annual mean temperature of about 18°C, the climate here falls into the category of subtropical humid monsoon climate. The lowest mean temperature in winter is 6°C–8°C, and the highest mean temperature in summer is above 35°C. The extreme temperature reaches 43°C as the highest and –2°C as the lowest. The total sunshine duration is 1000 to 1200 hr. The annual mean rainfall is about 1100 mm, 40% to 50% in summer and only 4% to 5% in winter.

The urban traffic road (UTR), residential road (RR), commercial area (CA), concrete roof (CR), tile roof (TRoof), and campus catchment area (CCA) in Shapingba District and Jiangbei District of Chongqing were selected for the study. The spatial distribution of monitoring points is shown in **Fig. 1**. The UTR consisted of one section of Yupei Road from Chenjiawan to Yanggongqiao in Shapingba District and Longji Road in Jiangbei District. Sampling was performed at stormwater inlets in UTR. The UTR were all within mixed commercial and residential areas. They were covered with a layer of pitch, and had a gradient 2.0%–2.5%, a cleaning frequency of once per day, and an area 2000 m^2, where 1800 vehicles were running every hour in the daytime. The RR selected from Chongqing University were covered and hardened by concrete, and had a cleaning frequency of once per day and a catchment area about 60 m^2. Sampling was also performed at stormwater inlets in RR. The CR were the building roofs in the campus of Chongqing University, which were overlaid with waterproof materials, and had a concrete structure and a catchment area 200 m^2. Sampling was performed at the bottom of the vertical drain pipes. The TRoof were located in a residential area of Dazhulin Town, Jiangbei District, and had a gradient 45°. Sampling was also performed at the bottom of the drain pipes. The CA were selected from Three Gorges Square, which was a big business centre of Chongqing, and had a catchment area 500 m^2 and a gradient 2.5%. Sampling was performed at stormwater inlets of the catchments. The CCA was in Huxi Campus of Chongqing University, and composed of four typical urban underlying surfaces (e.g., TRoof (1.5 ha), roads (1.7 ha), lawns (1.5 ha) and squares (1.0 ha)). CCA had a total area 5.7 hectares, of which TRoof accounted for 25%, roads 30%, lawns 26% and squares 19%. The stormwater collection network for the Huxi catchments was completely separated from sanitary wastewater, and sampling was performed at the outlet of the catchments,

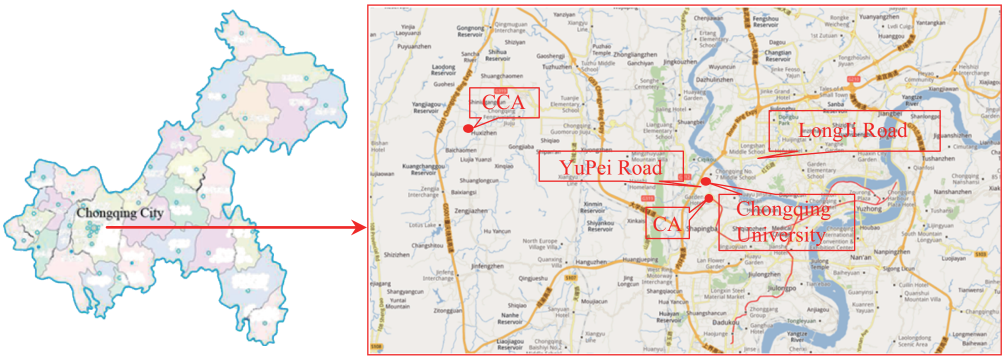

Fig. 1 Spatial distribution of monitoring points.

which was set up in an inspection well.

1.2 Monitoring methods

Samples were collected at specified intervals during the rainfall. Specifically, one sample was collected every 5 min within 30 min after the runoff started, every 10 min during a period of 30 to 60 min, and thereafter every 30 min till the runoff disappeared or became gradually stable. The rainfall was recorded automatically by an automatic rain gauge (JDZ-1, China) placed near the monitoring points. Currently, storm water runoff was designed to be harvested and transported by the urban drainage network, so, the flow rate in the drainage could reflect the runoff volume generated in the urban region studied. In this study, the flow rate in Huxi was monitored in the outlet inspection well using an ultrasonic flow-meter (MH-PM, China) and the measurement procedures were as described below: firstly, the bottom cross-section of the inspection well was reconstructed into a right-angled triangular weir, and then an ultrasonic sensor was fixed at 2.5 m right above the bottom of the weir; secondly during flow monitoring, the water level fluctuation signals were monitored by the ultrasonic sensor and conveyed to the host machine of the flow-meter, and then the host machine calculated and saved the flow values according to a preset computation model. The results could be downloaded after the measurement, and the flow output interval was 2–5 min. At the initial stage after runoff started, the runoff flow changed rapidly and the test interval was set at 2 min. At the last stage, flow rate decreased very slowly and the test interval was 5 min.

Polyvinyl chloride bottles (1.5 L) were used for sampling. Before sampling, all bottles were washed clean (State Environment Protection Administration of China, 2002). Eleven indicators (e.g., TSS, COD, TN, TP, NH_3-N, NO_3^--N, Cu, Zn, Pb, Cd and Fe) were determined. The test methods for all indicators except COD were in accordance with the national standard methods (State Environment Protection Administration of China, 2002). Each measurement was done with three replicates. The mixed water samples were directly digested to test TN, TP, Cu, Zn, Pb, Cd, and Fe. The mixed solutions were filtered using an acetate fiber filter membrane (0.45 μm), and then the resultant filtrates were used to measure NH_3-N and NO_3^--N. COD was measured using the reagent provided by HACH (USA) by first digesting the water samples and then analyzing them with a colorimetric method.

1.3 Data analyses

A total of 20 rainfall events were monitored during August 2009 and September 2011. All the rainfall factors are shown by rainfall event in **Table 1**. The EMC (mg/L) referred to the weighted event mean concentrations of storm water runoff pollutants, which had been widely used to calculate the storm water runoff pollution load from each underlying surface (Zhao et al., 2007). The calculation method is shown in Eq. (1):

$$\mathrm{EMC} = \frac{M}{V} = \frac{\int_0^t C_t Q_t \mathrm{d}t}{\int_0^t Q_t \mathrm{d}t} \approx \frac{\sum C_t Q_t \Delta t}{\sum Q_t \Delta t} \tag{1}$$

where, V (m^3) is total storm water runoff volume; M (g) is the mass of pollutants; Δt (min) is time interval; Q_t (m^3/min) is storm water runoff quantity within the time interval; C_t (mg/L) is pollutant concentration within the time interval.

The time when the rainfall events occurred and when the surface runoff formed was recorded to eliminate the

Table 1 Parameters of rainfall events

Event date (m/d/year)	Antecedent dry day (days)	Total rainfall (mm)	Rainfall duration (min)	Rainfall intensity (mm/hr)	Monitoring point
8/3/2009	4	20	60	19.8	RR
8/9/2009	6	12.3	33	22.2	RR, UTR
8/10/2009	1	13.4	60	13.2	RR, UTR
8/17/2009	7	6.6	34	12	RR, UTR
8/19/2009	2	2.1	20	6	UTR
4/10/2010	2	3.6	90	2.4	CR
6/19/2010	6	17.1	255	4.02	TR, CA
7/4/2010	5	21.8	160	8.4	CR, TRoof, UTR, CA, RR
7/9/2010	3	59.3	75	47.4	TRoof
8/21/2010	6	3.6	90	2.4	CR, TRoof
9/5/2010	4	1.5	60	1.5	CR, TRoof
4/15/2011	15	6	80	4.5	UTR
4/21/2011	4	6.4	50	7.68	CA
6/5/2011	5	9.1	160	3.6	CR
6/13/2011	2	2.4	20	72	CCA
6/16/2011	3	8.5	53	9.6	UTR, CR
7/21/2011	6	7	25	16.8	UTR, CR
7/27/2011	4	3.7	15	15	CCA , RR
8/3/2011	2	1.7	30	3.42	CCA
8/4/2011	0.5	23.3	440	3	CCA

UTR: urban traffic road; RR: residential road; CA: commercial area; CR: concrete roof; TRoof: tile roof; CCA: campus catchment area.

retardation of runoff formation; therefore, the simultaneity of runoff formation and rainfall event occurrence could be ensured. Since CR, TRoof, CA and UTR in this study had a small catchment area, the EMC for a given underlying surface was calculated using accumulated precipitation instead of stormwater runoff volume (Zhang et al., 2011; Francey et al., 2010). EMC was calculated according to Eq. (2):

$$\mathrm{EMC} = \frac{M}{V} = \frac{\int_0^t 10^{-3} \times C_t F_t \phi A \mathrm{d}t}{\int_0^t 10^{-3} \times F_t \phi A \mathrm{d}t} \approx \frac{\sum 10^{-3} \times C_t F_t \phi A \Delta t}{\sum 10^{-3} \times F_t \phi A \Delta t} = \frac{\sum C_t F_t \Delta t}{\sum F_t \Delta t} \quad (2)$$

where, F_t (mm/min) is rainfall within the time interval; A (m^2) is catchment area; ϕ is runoff coefficient ($\phi = 0.9$).

The pollution load producing coefficients (PLPC) for urban underlying surfaces were calculated from the unit pollutant loading rate (Lee and Bang, 2000), as shown in Eqs. (3) and (4). Equation (3) was used for CCA, while Eq. (4) was used for the other 5 land uses.

$$L = K \times R \times \sum C_i \times \Delta t_i / (\sum \Delta t_i \times A_i \times I_i) \quad (3)$$

$$L = \frac{R \times 10^{-6} \times \sum C_t \times F_t \times \Delta t \times A \times \phi}{A \times F_{\mathrm{total}} \times 10^{-6}} = \frac{R \times \sum C_t \times F_t \times \Delta t \times \phi}{F_{\mathrm{total}}} \quad (4)$$

where, L (kg/(km^2·year)) is unit pollutant loading rate; K ($\times 10^{-3}$) is conversion constant; C_i (mg/L) is the mean concentration of the composite sample during Δt_i interval (hr); ΔQ_i (m^3/hr) is stormwater runoff quantity in sampling Δt_i interval; $\Sigma \Delta t_\mathrm{i}$ (hr) is rainfall duration; R (mm/year) is annual total rainfall intensity; A_i (km^2) is watershed area; I_i (mm/hr) is rainfall intensity; F_{total} (mm) is total rainfall.

2 Results and discussion

2.1 Distribution of pollutant concentrations in stormwater runoff from urban underlying surfaces

Statistical analysis was conducted for all water samples, as shown in **Table 2**. For UTR, high variability was observed in the case of TSS (36 to 2384 mg/L, coefficient of variance (CV) = 0.96), COD (22 to 1260 mg/L, CV = 0.74), TN (1.6 to 20 mg/L, CV = 0.62), NH_3-N (1.1 to 11 mg/L, CV = 0.53), NO_3^--N (0.1 to 7.5 mg/L, CV = 0.74), TP (0.12 to 7.0 mg/L, CV = 1.2), Fe (5.1 to 19.5 mg/L, CV = 0.47), Cu (0.06 to 0.29 mg/L, CV = 0.54), and Zn (0.19 to 1.5 mg/L, CV = 0.62); however, the variability of Pb (0.4 to 0.7 mg/L, CV = 0.14) and Cd (0.037 to 0.06 mg/L, CV = 0.18) was relatively low, which meant that the washing effect of surface runoff had a low effect on the concentrations of Pb and Cd. For the other five land uses, similar trends were also observed.

The trends of the arithmetic mean concentrations of TSS, COD and TP of the land uses in this study were almost the same (e.g., the pollutant concentrations of UTR were the highest, followed by CA, while the other four land uses were the lowest). The concentrations of TN and NH_3-N were very similar (e.g., arithmetic mean concentrations of UTR, RR and CA were very close to each other, and similar concentrations were also found among CR, TRoof and CCA, but the concentrations of the former land uses were apparently greater than the latter ones). For NO_3^--N, Pb and Cd, the mean concentrations for different land use types did not vary so much (except the NO_3-N concentration for CCA). The arithmetic mean concentrations of Cu, Zn and Fe for all land use types were fairly consistent (e.g., UTR > CA > CR > CCA).

If the median values were less than the mean ones, this signifies that most of the concentrations are low (Maniquiz et al., 2010). In this study, the median values of pollutant concentrations were smaller than the mean values for most samples. Although the range of pollutant concentrations was large, most samples had a relatively low concentration level.

2.2 EMCs distribution for different land use types

Compared with the variation rate of pollutant concentrations during rainfall events, the response speed of the receiving water to the input of stormwater runoff was lower. Therefore, the statistical analysis of EMCs was much more important for investigating the long-term pollution load in urban stormwater runoff (Charbeneau and Barrett, 1998). Usually more than one storm event was monitored at a site and the average EMC (AEMC) was then calcu-

Table 2 Distribution of pollutant concentrations in urban runoff from six land uses (unit: mg/L)

Site		TSS	COD	TN	TP	NH_3-N	NO_3^--N	Cu	Zn	Pb	Cd	Fe
UTR	Median	394	319	7.3	0.9	4.0	2.1	0.13	0.732	0.58	0.053	13.0
	Mean	631 ± 608	418 ± 311	8.1 ± 5.0	1.2 ± 1.4	4.3 ± 2.3	2.3 ± 1.7	0.13 ± 0.07	0.69 ± 0.43	0.58 ± 0.08	0.051 ± 0.009	11.8 ± 5.6
CCA	Median	6	31	2.9	0.1	0.4	1.0	0.039	0.136	0.546	0.057	1.0
	Mean	31 ± 76	38 ± 22	2.7 ± 1.0	0.13 ± 0.05	0.52 ± 0.40	1.1 ± 0.6	0.04 ± 0.01	0.17 ± 0.14	0.55 ± 0.06	0.058 ± 0.002	1.4 ± 1.5
CA	Median	85	129	7.2	0.46	3.4	1.7	0.09	0.42	0.55	0.054	7.1
	Mean	110 ± 91	139 ± 86	7.3 ± 4.0	0.45 ± 0.28	4.1 ± 2.0	2.1 ± 1.3	0.10 ± 0.05	0.65 ± 0.47	0.59 ± 0.13	0.055 ± 0.006	9.2 ± 4.6
CR	Median	30	59	4.9	0.15	1.2	1.9	0.042	0.225	0.53	0.052	2.0
	Mean	69 ± 90	83 ± 73	5.9 ± 3.6	0.19 ± 0.2	1.7 ± 2.0	2.2 ± 1.2	0.05 ± 0.02	0.33 ± 0.27	0.54 ± 0.11	0.053 ± 0.007	2.7 ± 2.9
TRoof	Median	20	31	3.7	0.06	1.1	1.5	–	–	–	–	–
	Mean	43 ± 55	52 ± 51	4.3 ± 3.1	0.11 ± 0.12	1.3 ± 1.1	2.2 ± 2.1	–	–	–	–	–
RR	Median	52	95	7.2	0.18	4.3	2.3	–	–	–	–	–
	Mean	112 ± 131	95 ± 52	6.8 ± 3.1	0.4 ± 0.4	4.2 ± 2.2	2.3 ± 0.4	–	–	–	–	–

–: not tested.

lated (the mean of all measured EMCs) (Francey et al., 2010). To further determine the pollutant concentrations in stormwater runoff for various land use types, we calculated the AEMCs, and also reviewed the study results of other researchers (**Table 3**).

For UTR, the EMCs of most pollutant indicators were higher than the other land use types. The AEMC of TSS measured for six land use types was UTR (597 mg/L) > CA (140 mg/L) > RR (89 mg/L) > CR (65 mg/L) > TRoof (37 mg/L) > CCA (35 mg/L). It could be found that the AEMC of TSS from UTR was far more than those from CA (4.3 times), RR (6.7 times), CR (9.2 times), TRoof (16 times) and CCA (17 times). The AEMC of COD was in the same sequence as TSS, i.e., UTR (408 mg/L) > CA (2.4 times) > RR (4.6 times) > CR (5.3 times) > TR (8.5 times) > CCA (10 times).

The AEMC of TN for UTR (8.6 mg/L) was similar to that for CA (8.2 mg/L), and it was 1.2, 1.5, 2.15 and 3.3 times higher than those from RR, CR, TRoof, and CCA. The AEMC of TP for TRoof and CCA met the class-III standard (0.2 mg/L) specified in the Environmental Quality Standards for Surface Water (GB 3838-2002). For RR and CR, the AEMC values of TP were same (0.2 mg/L), which met the class-IV standard (0.3 mg/L), while those for UTR and CA were respectively 5 and 2.35 times higher than the class-III standard value. As for NH_3-N, the AEMC for CCA (0.58 mg/L) met the class-III standard (1.0 mg/L); the AEMC for TRoof (1.2 mg/L) and for CR (1.8 mg/L) met the class-IV standard (1.5 mg/L), and the class-V standard (2.0 mg/L), respectively; but the AEMC for UTR, RR and CA was about 3 times higher than the class-III standard value. For NO_3^--N, the highest AEMC (2.5 mg/L) was found in the water samples from CA, followed by UTR, TRoof and CR (1.9–2.1 mg/L). As for the heavy metals in the urban stormwater runoff, the AEMC of Fe was the highest. Runoff from UTR carried the highest concentration of Fe (10.35 mg/L), which was 1.4, 2.1, and 8.6 times higher than those from CA, CR and CCA, respectively. The AEMC of both Cu (0.04–0.118 mg/L) and Zn (0.17–0.56 mg/L) met the class-III standard (1.0 mg/L). With respect to Pb and Cd, the AEMC values for UTR, CA, CR and CCA were close to each other (e.g., 0.55–0.59 mg/L and 0.05–0.07 mg/L), and were both over 10 times higher than the class-III standard value.

The statistical analysis on the CV of the EMC for each indicator showed that the CV of TSS, COD, TN, TP, NH_3-N and NO_3^--N for the six land use types were 0.57–1.13, 0.35–0.73, 0.32–0.53, 0.32–1.0, 0.32–0.69 and 0.38–0.94 respectively, which meant there were huge differences among the EMCs in different rainfall events, especially for TSS. The CV of Pb and Cd were lower among heavy metal pollutants (e.g., 0.003–0.07 and 0.23–0.28). However, the CV of Fe, Cu and Zn were higher, and especially the CV of Fe even reached as high as 1.0. The reasons for such a phenomenon might be traffic load, antecedent dry day, rainfall duration, rainfall intensity, experimental errors, insufficiency of data, etc (Maniquiz et al., 2010). Meanwhile, gasoline consumption and tire wear of vehicles, as well as atmospheric sedimentation, can also be metal pollution contributors (Maniquiz et al., 2010).

By comparison, the AEMC values of TSS, COD, TN, TP, Pb and Cd from UTR found in this study were all higher than the results obtained by Gan et al (2008) (e.g., 415.7, 308, 7.32, 0.39, 0.118 and 0.0016 mg/L, respectively), but the AEMC values of Cu and Zn were similar to or lower than the results of Gan et al (2008). For roofs, the study findings in Wuhan were similar to (for TSS and COD) or greater than (for TN and TP) the CR results in this study (Zhao et al., 2007). The AEMC of COD (90 mg/L) from roads in Wuhan Zoo was near to the value from RR found in this study, but the AEMC values of TSS and TN were lower than our study results. This might be related to the sources of the pollutants in the areas studied. The studied areas in USA, Paris and Isfahan of Iran were all comprehensive urban watersheds, where the water quality of stormwater runoff was closely related to the layout of land uses, drainage systems and environmental background. In general, the AEMC values of TN and Zn in Paris (26.8 and 1314 mg/L) were much higher than our study results, while the AEMC values of Pb and Cd (0.166 and 0.0023 mg/L) were lower. Moreover, the AEMC values of Cu and COD (0.117 and 389 mg/L) were close to our study results for UTR (Kafi et al., 2008). Compared with our study results, the concentrations of Zn and Pb found in the study conducted in Isfahan of Iran were lower, but the COD concentration (649 mg/L) was much higher (Taebi and Droste, 2004). In comparison with the related statistical results from USA, it could be found that all the pollutant concentrations were at a lower level than our study results, except for TSS (Brezonik and Stadelmann, 2002). The differences among studies demonstrated the uncertainty and randomness of urban non-point source pollution and further accumulation is still required.

2.3 PLPC distribution for different land use types

To investigate urban nonpoint pollution loads of different land use types and provide a basis for urban stormwater runoff management, the PLPC of six land use types were analyzed and compared with results obtained from other studies (**Table 4**).

The PLPC of TSS, COD and TP from UTR were significantly higher than those from other types of land use, which coincided with what was shown by the AEMC. The average PLPC of TSS and COD (e.g., 82 and 357 ton/(km^2·year)) found in Isfahan, Iran (Taebi and Droste, 2004) were close to our study results (e.g., 85 ton/(km^2·year)) from RR for TSS and 404 ton/(km^2·year) from UTR for COD), which might be correlated to the land use types of the areas monitored. In this study, the

Table 3 Comparison of event mean concentration (EMC) values obtained in this study and previous publications (unit: mg/L)

Site		TSS	COD	TN	TP	NH_3-N	NO_3^--N	Reference
UTR	Median	710	442	8.9	0.96	5.0	1.8	This study
	Mean	597 ± 342	408 ± 206	8.6 ± 4.3	1.0 ± 0.8	4.5 ± 1.9	2.1 ± 0.9	
CCA	Median	23	41	2.7	0.14	0.53	1.1	
	Mean	35 ± 40	43 ± 20	2.6 ± 0.8	0.14 ± 0.04	0.58 ± 0.37	1.12 ± 0.55	
CA	Median	81	142	10.2	0.59	4.8	2.5	
	Mean	140±139	172±114	8.2±4.3	0.47±0.3	4.3±1.4	2.5±0.97	
CR	Median	65	69	6.0	0.15	1.9	1.0	
	Mean	65 ± 37	77 ± 27	5.6 ± 1.9	0.2 ± 0.15	1.8 ± 1.26	1.9 ± 0.8	
TRoof	Median	26	39	3.7	0.09	1.0	1.2	
	Mean	37 ± 37	48 ± 35	4.0 ± 2.0	0.12 ± 0.12	1.2 ± 0.5	2.1 ± 2.0	
RR	Median	68	78	6.7	0.15	4.6	–	
	Mean	89 ± 45	89 ± 45	7.1 ± 3.4	0.2 ± 0.2	4.5 ± 2.7	–	
Paris*	Range	36–421	56–569	20-36	–	–	–	Kafi et al., 2008
	Median	266	400	25	–	–	–	
	Mean	264	389	26.8	–	–	–	
Highway in Guangzhou, China	Range	102.7–835.6	75–518	0.74–19.2	0.15–0.68	–	–	Gan et al., 2008
	Median	447.4	323	7.15	0.39	–	–	
	Mean	415.7	308	7.32	0.39	–	–	
Siosepol catchments in Isfahan, Iran	Range	43–467	139–2542	1.22–22.38	0.064–0.79	–	–	Taebi and Droste, 2004
	Arithmetic mean	161	561	6.65	0.274	–	–	
	EMC	149	649	6.75	0.274	–	–	
United States	Median	113	55	1.41	0.266	–	–	Smullen et al., 1999
	Mean	174	66.1	1.67	0.337	–	–	
Roofs in Wuhan, China	Range	62–74	48–110	6.4–10.4	0.67–0.93	–	–	Zhao et al., 2007
	Arithmetic mean	68	79	8.4	0.8	–	–	
Roads in Wuhan, China	Mean	56	90	4.7	0.41	–	–	Zhao et al., 2007

		Cu	Zn	Pb	Cd	Fe		Reference
UTR	Median	0.118	0.56	0.59	0.048	10.35		
	Mean	0.118 ± 0.004	0.56 ± 0.15	0.59 ± 0.04	0.048 ± 0.011	10.35 ± 2.4		
CCA	Median	0.04	0.17	0.561	0.07	1.3		
	Mean	0.04 ± 0.002	0.17 ± 0.03	0.561 ± 0.002	0.07 ± 0.018	1.3 ± 1.2		
CA	Median	–	–	–	–	–		
	Mean	0.09	0.46	0.55	0.05	7.5		
CR	Median	0.08	0.32	0.564	0.05	5.0		
	Mean	0.08 ± 0.56	0.32 ± 0.19	0.564 ± 0.002	0.05 ± 0.013	5.0 ± 5.2		
Paris*	Median	0.056–0.175	0.172—3.199	0.022–0.425	0.0005–0.013	–		Kafi et al., 2008
	Median	0.119	1.120	0.118	0.0012	–		
	Mean	0.117	1.314	0.166	0.2.33	–		Gan et al., 2008
Highway in Guangzhou, China	Range	0.0010–0.570	0.390–4.400	0.012–0.427	0.0004–0.0051	–		
	Median	0.120	1.780	0.0743	0.001	–		
	Mean	0.140	1.760	0.1182	0.0016	–		Taebi and Droste, 2004
Siosepol catchments in Isfahan, Iran	Range	0.0015–2.386	0.018–0.558	–	–	–		
	Arithmetic mean	0.243	0.278	–	–	–		
United States	EMC	0.453	0.314	–	–	–		Smullen et al., 1999
	Median	0.0548	0.140	0.131	–	–		
	Mean	0.0666	0.176	0.175	–	–		

* Nitrogen concentration in Paris was expressed as total Kjeldahl nitrogen (TKN).

catchments studied had small areas and relatively simple land use types. However, the basins studied in Isfahan were large scale regions with a complicated layout of land use. Storm water runoff in Isfahan with high COD and low TSS pollution load may be attributed to the sedimentation of pollutants washed by the rainfall-runoff. Zhao et al. (2007) found that in Wuhan Zoo the average PLPC of TSS and COD for roofs and roads were 72 and 83 ton/(km^2·year), 62.2 and 99.6 ton/(km^2·year), respectively, which might be related to the similarity in pollutant sources and accumulation of these two underlying surfaces. In this study, the average PLPC of nitrogen pollutants like TN, NH_3-N and NO_3^--N from UTR, CA and RR were significantly higher than those from CR, TRoof and CCA. Average PLPC of Fe, Cu and Zn from CA (13.6, 0.13 and 0.75 ton/(km^2·year)) and UTR (11.1, 0.124 and 0.6 ton/(km^2·year)) were significantly higher than those from CR (4.95, 0.08 and 0.32 ton/(km^2·year)) and CCA (0.1, 0.0024 and 0.01 ton/(km^2·year)); meanwhile, the average PLPC of Pb and Cd from UTR, CA and CR (0.558–0.7 and 0.049–0.06 ton/(km^2·year)) were much higher than those from CCA (0.033 and 0.004 ton/(km^2·year)).

Table 4 Comparison of pollution load production coefficient (PLPC) values obtained in this study and previous publications (unit: ton/(km^2·year))

Site		TSS	COD	TN	TP	NH_3-N	NO_3^--N	Reference
UTR	Median	703	438	8.5	0.95	5.0	1.8	This study
	Mean	589 ± 342	404 ± 204	8.5 ± 4.2	1.0 ± 0.8	4.4 ± 1.9	2.1 ± 0.9	
CCA	Median	2.1	5.0	0.27	0.017	0.09	0.09	
	Mean	3.5 ± 4.3	4.2 ± 2.3	0.24 ± 0.12	0.014 ± 0.007	0.05 ± 0.04	0.10 ± 0.07	
CA	Median	80	140	10	0.6	4.8	2.5	
	Mean	129 ± 148	153 ± 137	7.8 ± 4.8	0.47 ± 0.30	4.1 ± 1.8	2.5 ± 1.0	
CR	Median	56	68	5.9	0.15	1.85	2.0	
	Mean	61 ± 36	76 ± 26	5.5 ± 1.9	0.2 ± 0.14	1.77 ± 1.17	1.9 ± 0.8	
Paris*	Range	1.1–35	1.8–57	2–3	–	–	–	Kafi et al., 2008
	Median	27	39	2	–	–	–	
	Mean	35	35	2.28	–	–	–	
Roofs in Wuhan	Range	66.8–77.2	51.6–114.4	6.85–10.8	0.72–0.97	–	–	Zhao et al., 2007
	Mean	72	83	8.8	0.85	–	–	
Roads in Wuhan		62.2	99.6	5.15	0.45	–	–	Zhao et al., 2007
Siosepol catchments in Isfahan		82	357	–	–	–	–	Taebi and Droste, 2004

		Cu	Zn	Pb	Cd	Fe		Reference
UTR	Median	0.124	0.6	0.63	0.05	11.1		This study
	Mean	0.124 ± 0.008	0.6 ± 0.2	0.63 ± 0.10	0.05 ± 0.02	11.1 ± 3.5		
CCA	Median	0.0024	0.01	0.033	0.004	0.1		
	Mean	0.0024 ± 0.002	0.01 ± 0.01	0.033 ± 0.020	0.004 ± 0.002	0.1 ± 0.1		
CA	Median	–	–	–	–	–		
	Mean	0.13	0.75	0.7	0.06	13.6		
CR	Median	0.08	0.32	0.558	0.049	4.95		
	Mean	0.08 ± 0.06	0.32 ± 0.18	0.558 ± 0.002	0.049 ± 0.013	4.95 ± 5.13		
Paris[a]	Range	1.8–15	54–172	4–22	0.06–0.21			Kafi et al., 2008
	Median	10	102	13	0.14			
	Mean	10.3	116	12	0.13			

* Nitrogen pollution load in Paris was expressed as TKN; the pollution load unit for TSS, COD and TKN was kg ha active^{-1}; Cu, Zn, Pb and Cd was g ha active^{-1} (Kafi et al., 2008).

Atmospheric dry and wet deposition is the main pollution source for urban roofs. Besides atmospheric deposition, pedestrian activity is also an important source of CCA and CA pollution accumulation. However, the most significant pollution contributors for UTR are traffic volume caused by various vehicles, and commercial activities brought by roadside shops (such as restaurants, vehicle repair shops). Thus, the diversity of average PLPC may be attributed to the characteristics of pollution accumulation on different urban surfaces, physical and chemical effects during runoff delivery or experimental errors, and so on.

3 Correlation analysis between EMC or PLPC and rainfall factors

SPSS18.0 statistical software was used to analyze the Pearson correlation coefficients (PCC) between rainfall factors and EMC or PLPC, and the results are shown in **Table 5**. The PCC between ECM or PLPC and rainfall factors were quite different because of the difference of pollutant build-up and wash-off features on various kinds of urban surfaces.

For UTR, only rainfall druation was correlated with EMC and PLPC of TP significantly. Although ADD also contributed to the EMC and PLPC of the pollution indicators, the correlation level was not significant. During the rainfall events, the nonpoint pollution would be discharged continuously on UTR due to the vehicles running. Thus, the friction and wash-off effects would produce more pollution on UTR during rainy days. The longer the rainfall events lasted, the greater the EMC and PLPC would be. However, a negative correlation was found between RI and EMC or PLPC, which might be caused by the conversion correlation between RI and RD. Meanwhile, a similar phenomenon was also observed for RR.

For CR, a positive relation was observed between ADD and EMC/PLPC of TN, while that between RI and EMC/PLPC of TP was also significant. Unlike the other urban surfaces, the main pollutant source of CR was atmospheric precipitation; therefore, the greater the ADD and RI were, the higher the EMC and PLPC would be. However, a positive correlation between RD and EMC/PLPC of TSS was found for TRoof. The different correlations might be caused by the difference in gradient between TRoof and CR. The larger gradient of TRoof might lead to a stronger wash-off intensity even in a minor rainfall event, which might be the reason why longer RD produced a larger number of pollutants on TRoof.

For CCA, there was a significant positive correlation between RI and EMC/PLPC of TP. For other pollutant indicators and rainfall factors, less significant correlations, such as positive correlation between RI and EMC/PLPC,

Table 5 Analysis of Pearson correlations between rainfall factors and EMC/PLPC

Monitored sites	Pollution indicator	EMCs				PLPC			
		ADD	TR	RD	RI	ADD	TR	RD	RI
UTR	TSS	0.431	0.100	0.511	–0.514	0.427	0.096	0.509	–0.520
	COD	0.213	–0.435	0.076	–0.770*	0.213	–0.435	0.076	–0.770*
	TN	0.661	–0.221	0.166	–0.341	0.679	–0.201	0.180	–0.326
	TP	0.287	0.404	0.775*	–0.521	0.287	0.404	0.775*	–0.521
	NH_3-N	0.598	–0.105	0.256	–0.397	0.626	–0.079	0.279	–0.383
RR	TSS	0.471	–0.584	–0.134	–0.549	0.451	-0.590	-0.102	–0.593
	COD	0.448	–0.485	0.119	–0.745	0.448	-0.485	0.119	–0.745
	TN	0.495	0.347	0.661	–0.748	0.495	0.347	0.661	–0.748
	TP	0.181	0.375	0.879*	–0.801	0.181	0.375	0.879*	–0.801
	NH_3-N	0.322	0.644	0.613	–0.280	0.322	0.644	0.613	–0.280
CR	TSS	0.506	0.568	–0.190	0.713	0.445	0.624	–0.141	0.711
	COD	0.515	0.338	–0.001	0.557	0.515	0.338	–0.001	0.557
	TN	0.761*	–0.109	–0.085	0.066	0.758*	–0.109	–0.074	0.049
	TP	0.436	0.009	–0.526	0.877**	0.431	0.015	–0.520	0.875**
	NH_3-N	0.257	–0.077	–0.431	0.703	0.238	–0.077	–0.414	0.683
	NO_3^--N	-0.503	–0.550	–0.340	–0.626	–0.544	–0.452	–0.109	–0.777
TR	TSS	0.619	–0.300	0.883*	–0.464	0.619	–0.300	0.883*	–0.464
	COD	0.507	–0.161	0.726	–0.261	0.507	–0.161	0.726	–0.261
	TN	0.260	–0.812	0.054	–0.774	0.260	–0.812	0.054	–0.774
	TP	0.628	–0.329	0.828	–0.466	0.628	–0.329	0.828	–0.466
	NH_3-N	–0.473	–0.253	–0.342	–0.196	–0.473	–0.253	–0.342	–0.196
	NO_3^--N	–0.081	–0.697	–0.515	–0.532	–0.081	–0.697	–0.515	–0.532
CCA	TSS	–0.044	–0.196	–0.211	0.974*	–0.209	–0.080	–0.084	0.938
	COD	0.788	–0.442	–0.532	0.519	0.267	0.147	0.057	0.532
	TN	0.762	–0.704	–0.764	0.713	0.100	0.174	0.101	0.656
	TP	0.627	–0.348	–0.433	0.666	–0.067	0.418	0.347	0.481
	NH_3-N	0.534	–0.483	–0.544	0.849	0.385	–0.354	–0.411	0.890
	NO_3^--N	0.512	–0.764	–0.785	0.885	0.189	–0.225	–0.271	0.928

* Correlation was significant at the level of 0.05 (2-tailed); ** correlation was significant at the level of 0.01 (2-tailed).
ADD: antecedent dry day; TR: total rainfall; RD: rainfall duration; RI: rainfall intensity.

positive correlation between ADD and EMC, negative correlation between TR/RD and EMC, and so on, could be observed. However, the PLPC of COD, TN and TP from CCA had a positive correlation with TR and RD, and the possible explanation was that the pollution load had a functional relationship with pollutant concentrations and stormwater runoff volume.

Through a statistical analysis of non-point source pollution in the Twin Cities metropolitan area, Minnesota, USA, Brezonik and Stadelmann (2002) found that the pollution loads had a positive correlation with TR and RI but a negative correlation with ADD, while EMC were correlated positively with ADD but negatively with TR and RD. Compared with the analysis results from CCA in this study, the findings by Brezonik and Stadelmann (2002) are consistent with ours in the aspect of the correlation between EMCs and rainfall factors. However, when it comes to the correlation between pollution load and rainfall factors, the results in this study are contrary to the conclusion of Brezonik and Stadelmann (2002); more similar case studies are needed to explain this phenomenon.

4 Conclusions

The results from this study can be summarized as follows: (1) For a given land use type, the concentrations of TSS and COD were significantly higher than other pollutant indicators monitored. According to the value of coefficient of variance, the concentrations of all pollution indicators except Cd and Pb varied greatly for different land uses, which indicate considerable fluctuation in pollutant concentrations during rainfall events. Meanwhile, most water samples had relatively low pollutant concentrations. (2) The EMCs of TSS and COD for UTR were remarkably higher than those for RR, CA, CR, TRoof, and CCA. Furthermore, the EMCs of TN for RR, UTR, and CA were close to each other but all higher than those for CR, TRoof, and CCA. For CCA and TRoof, the EMCs of TP and NH_3-N met the class-III standard (GB 3838-2002). Among the heavy metals, the EMCs of Fe, especially for UTR, were the highest; moreover, the EMCs of Cu and Zn met the class-III standard (GB 3838-2002). However, the EMCs of Pb and Cd far exceeded the concentrations specified in the Environmental Quality Standards for Surface Water (GB 3838-2002). (3) The PLPC analysis showed that the pollution loads of TSS, COD and TP were mainly from UTR. Meanwhile, UTR, CA and RR were the major contributors for TN, NH_3-N, NO_3-N, Fe, Cu, Zn, Pb and Cd, which provides an important reference for the management of urban rainfall runoff. (4) The analysis of correlations between rainfall factors and EMCs/PLPC indicated that the rainfall factors that had influence on EMCs/PLPC varied according to different land uses. Rainfall duration, which was correlated with EMCs/PLPC of TSS for TRoof, was also correlated with EMCs/PLPC of TP for UTR, and rainfall intensity was correlated with EMCs/PLPC of TP for both CR and CCA.

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