Comparing urban runoff quality of a felt roof and an asphalt road in Beijing

Lizhu Hou and Xin Zhang

ABSTRACT

Water pollution and water shortage are two of the most important environmental problems in Beijing, China. Water quality of rainfall from July to August 2011 and runoff from a felt roof and an asphalt road were analyzed chemically and further investigated because these are potential sources for augmenting city supplies. Results indicate that chemical oxygen demand (COD_{Cr}), total phosphorus (TP), total nitrogen (TN), and ammonia nitrogen (NH_4^+-N) concentrations of initial runoff from roofs and roads all exceeded the Class V surface water quality standard developed by the Ministry of Environmental Protection of the People's Republic of China (MEP). COD_{Cr} concentration from road surfaces was more than 313.55 mg/L at the initial runoff stage, decreasing asymptotically to lower levels with increased rainfall duration. There is strong correlation between COD_{Cr}, TP, TN concentrations and that of total suspended solids in road runoff. Runoff from roofs, after treatment by grid filter, flocculation and sedimentation, can be used as city municipal and domestic water except during the initial runoff stage. However, runoff from road surfaces cannot be directly reused. For city planning, this conclusion may benefit the promotion of rainwater as a renewable water supply, and avoid flooding and water scarcity.

Key words | rain harvesting surface, runoff, urban rainfall use, water quality

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INTRODUCTION

Currently, the use of fresh water is a major issue facing human populations. Many complex factors are driving the discussion of this issue, including population growth, land use, urbanization, and pollution. Insufficient availability of drinking water may have negative consequences, such as social upheaval or increasing health problems. Because many solutions have been put forward, there is much interest in the use of collected rainwater. This practice has been used in many countries for hundreds of years, however, it is absolutely necessary to measure harvested rainwater quality because of the potential for health risks from chemical contaminants (Rentz & Öhlander 2012). That is, the feasibility and degree of urban rainwater use are not only dependent on the amount, spatial and temporal distribution of precipitation (Hou *et al.* 2008), but also on runoff quality from various rainwater harvesting surfaces.

Rooftop runoff quality is dependent on both roof type and environmental conditions (local climate and atmospheric pollution). Förster (1999) examined runoff from an experimental roof system that allowed comparison of five different roof materials in urban background conditions, and from house roofs at five locations in the town of Bayreuth, Germany. He found that local sources, dissolution of roof system metal components, and background air pollution are the main sources of runoff pollution, and that variability of runoff quality was extremely high between different roofs; there was also strong variability between individual precipitation events. Abdulla & Al-Shareef (2009) analyzed samples of harvested rainwater from residential roofs in Jordan, indicating that measured inorganic compounds generally matched World Health Organization (WHO) standards for drinking water. Farreny *et al.* (2011) discovered that the conductivity, total suspended solids

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(TSS), total organic carbon, and pH from four different roofs on the UAB University campus in Cerdanyola del Valles (Barcelona metropolitan region of northeast Spain) was generally better than the average quality in the literature (Göbel *et al.* 2007; Melidis *et al.* 2007). Mendez *et al.* (2011) demonstrated that rainwater harvested from roofing materials would require treatment if consumers wished to meet United States Environmental Protection Agency primary and secondary drinking water standards or non-potable water reuse guidelines; at a minimum, first-flush diversion, filtration, and disinfection were recommended. Vialle *et al.* (2011) found that collected roof rainwater in a rural village in southwest France had good physicochemical quality but did not meet drinking water requirements because weather caused unpredictable roof runoff quality.

In recent years, runoff from road surfaces has also been studied. Deletic (1998) found a first-flush phenomenon in storm surface runoff when most of the event load is transported in the initial phase of discharged volume. Normalized cumulative pollutant mass versus normalized cumulative runoff volume curve plotting was used to assess the first flush. However, regression curves are not reliable for prediction of the first-flush load of pollution input into the drainage system (Deletic 1998). Brodie & Egodawatta (2011) performed washoff experiments using rainfall simulators and suspended particle load data collected at a road site in Toowoomba, Australia. They showed that particle loads from these storm events increase linearly with average rainfall intensity. All the above road runoff research focused on improving the aquatic environment. By contrast, our study involves simultaneous analysis of chemical parameters, varying characteristics of pollutant concentrations of runoff, and related rainwater harvesting technologies.

Water shortages are a serious problem in Beijing. Its per capita water resource availability is only 300 m^3/year (Wang *et al.* 2005). According to Falkenmark (1989), when per capita water supplies drop below 1,000 cubic meters per year, a country faces ‘water scarcity’. Thus, like most cities, Beijing must conserve its water resources, and has for several years turned its attention to harvesting rainwater for domestic use. However, high water pollution levels in urban runoff is a serious problem that further diminishes the type of water supply. Therefore, the potential for collecting urban rainfall, which amounts to about 200 million m^3 annually in the city, is a research issue with high prospects. In the early 1990s in Beijing, Zhang and Zhang (1991) found that although water quality of roof runoff was poorer than from precipitation, the former could be used for irrigation according to a surface water quality standard (GB3838-88) developed by the Ministry of Environmental Protection of the People’s Republic of China (MEP). With continuing development in Beijing, smoke and dust variations alter the pollution of precipitation. Additionally, runoff quality is affected by roofing diversification and increased traffic. Given increasing reliance on rainwater, studies of its quality, analysis, and evaluation during flood seasons, and investigations of runoff quality from various rain harvesting surfaces (roofs, roads, and others) are imperative. In this research, rainfall and runoff samples from a felt roof and an asphalt road, which are common surfaces in Beijing, were monitored synchronously. The aim was to collect data for assessing urban rainwater quality changes from different rain harvesting surfaces from July to August 2011, thereby evaluating the feasibility of using stormwater for non-potable purposes.

METHODS

Study sites

Beijing is in a warm temperate zone, and is situated between 39°28′–41°05′N and 115°24′–117°30E. According to Urban Planning of Beijing City (2004–2020), the area comprising vehicle lanes of trunk roads was 25.91 km^2 at the end of 2002 and 47.92 km^2 in 2010; roof area was 55.00 km^2 in 2010. The climate is semi-arid; based on monthly precipitation data from the Beijing region between 1724 and 2009, annual mean precipitation is 601.8 mm. Yearly statistics show that most rainfall occurs from June through August, and precipitation in these three consecutive months accounts for more than 80% of the annual amount (Figure 1). Thus, precipitation during these months has value for rainwater resource use. With increasing urbanization, dramatic changes in surface conditions, and frequent human activity, the characteristics of urban precipitation change significantly in Beijing. Research based on precipitation data from different urban areas of the city

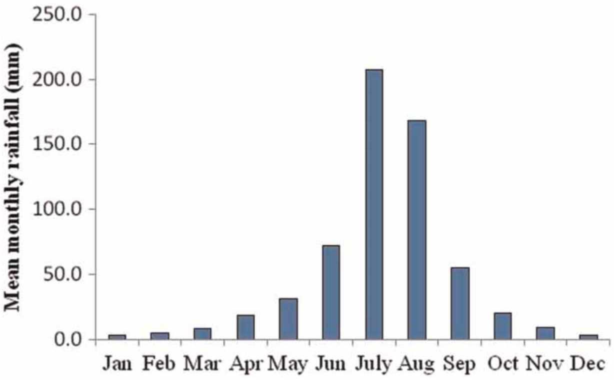

Figure 1 | Mean monthly rainfall, based on daily historical data from 1724 to 2009.

during 1956–2007 shows that precipitation displays characteristics of high intensity and short duration, with durations concentrated within about 60 min and maximum 1 h precipitation about 35 mm. Because of interannual changes and short-duration precipitation, it is necessary to study water quality from different rain harvesting surfaces. In the present study, a composite residential and commercial catchment of Beijing was selected as the study area. The catchment is northwest of the metropolitan center, with an area of 65 km^2 and no known industrial activity (Zhang *et al.* 2008). Chengfu Road (a representative trunk road, with traffic volume of 30,000 vehicles/day) and one building roof at the China University of Geosciences (Beijing) were selected for runoff sampling. The study period was from July to August 2011.

Sampling locations

To monitor, analyze, and evaluate runoff quality from various rain harvesting surfaces, three sampling sites were chosen inside and outside the university, which represent various potential urban rain harvesting surfaces. The sampling locations are as follows:

- Sampling site A, wet deposition. Samplers were placed ~1.5 m above ground in an open area. This design was intended to avoid contamination by leaves, twigs, and dust and sand from soil (Grynkiewicz *et al.* 2003).
- Sampling site B, asphalt felt roof, with catchment area about 37.5 m^2. The roofing material was asphalt felt, which has a higher waterproofing value. This type of roof contains substantial amounts of pollutants that can increase during a hot summer with high rainfall. Samples were collected from a port of a downspout from the roof surface.
- Sampling site C, asphalt pavement road with gate discharge from Chengfu Road. This is an urban trunk road in the Haidian District of Beijing. The number of vehicles on the road was about 2,000 per hour (Zhang *et al.* 2009). The concentration of pollutants is strongly related to traffic intensity (Bjorklund 2011). Samples were collected from road runoff near a road gully, whose catchment area is about 750 m^2.

Data collection

An automatic rain gauge of a Hobo U30 automatic weather station was used to measure rainfall intensity. We collected samples during six rain events from different surfaces (including asphalt felt roof and asphalt pavement road) and precipitation, from June to August 2011.

We sampled a turbulent section in the central part of the flow, avoiding touching the bottom or sides of the stormwater conveyance. Sample bottles were filled nearly to the top (meniscus near the rim) by placing their openings in the water flow, not overfilling the bottles. Since it is difficult to define the initial runoff sampling time, runoffs within the first 15–20 min after rainfall start were considered the initial rainfall runoff sample. After a collection period, samples were transported to the laboratory and analyzed as soon as possible, optimally the same day (within a few hours after delivery). If immediate analysis was not possible, samples were stored under appropriate conditions, namely, temperature 4 °C in the dark, with addition of bactericides ($HgCl_2$, chloroform, isopropanol) or frozen at −20 °C (Leister & Baker 1994; Grynkiewicz *et al.* 2003). This is necessary to slow or, optimally, completely halt biodegradation of analytes of interest; many precipitation pollutants undergo biodegradation at room temperature (Grynkiewicz *et al.* 2003).

Analytical method

Samples were taken and then analyzed directly at the Groundwater Circulation Remediation Experimental and

Training Center of the China University of Geosciences (Ministry of Education Key Laboratory).

All liquid samples were analyzed for pH, chemical oxygen demand (COD_{Cr}) measured using a combination of dichromate, sulfuric acid and heat to oxidize the organics in the water sample, total phosphorus (TP), total nitrogen (TN), ammonia nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), nitrite nitrogen (NO_2^--N), and TSS. The COD_{Cr} of water was determined by the potassium dichromate method. All nutrients were analyzed using standard chemical methods. Nitrate was reduced to nitrite by hydrazine in alkaline solution and determined at multiple wavelengths by a colorimetric method, using a HACH DR 5000 flow injection analyzer according to the manufacturer's instructions. Blue-colored ammonia compounds were measured at 420 nm wavelength. TP was measured by the ammonium molybdate method, using ammonia molybdate, ascorbic acid, and sulfuric acid. Ammonium molybdate and sodium bicarbonate were also used in the analyses with automated colorimetry for all water samples, at 700 nm.

RESULTS AND DISCUSSION

General runoff quality from various rain harvesting surfaces

We used the miscellaneous domestic wastewater quality standard (CJ/T48-1999) developed by the Ministry of Construction of the People's Republic of China, and the environmental quality standard of surface water (GB3838-2002) developed by the Ministry of Environmental Protection of the People's Republic of China (MEP) (Table 1), to evaluate the pros and cons of water environment quality. The samples were analyzed and compared, with results also given in Table 1. Averages of parameters COD_{Cr}, TP, TN, and NH_4^+-N from precipitation, roof and road surfaces exceeded the 40, 0.4, 2.0, and 2.0 mg/L values of the Class V surface water quality standard (GB3838-2002), respectively (Table 1). The highest phosphoric content in all samples was 1.85 mg L^{-1}, which was on Chengfu Road. Comparing indicators COD_{Cr}, TP, TN, NH_4^+-N, NO_3^--N, NO_2^-N, and TSS for the three sample types, most average runoff concentrations of these indicators from road surfaces were higher than those from roofs. This was because harvested water quality was affected by surface materials and traffic intensity (Bjorklund 2011).

Runoff from the asphalt felt roof was yellow, which may be explained by the water sample containing airborne sulfur dust. COD_{Cr} concentration in the initial runoff from the asphalt pavement reached 313.55 mg/L. Inorganic nitrogen in roof runoff occurred mainly as NO_3^- and ammonium (NH_4^+) while NO_2^- occurred in smaller proportions (Table 1), similar to the findings of Farreny *et al.* (2011). The maximum NH_4^+-N content in the asphalt felt runoff was 20.29 mg/L. For comparison, Gromaire *et al.* (1999) found that mean suspended solids (SS) and chemical oxygen demand (COD) from four roof runoffs in Paris (interlocking clay tiles, flat clay tiles plus zinc sheets, zinc sheets, slate) were 29 and 31 mg/L, respectively. In a study of a rural village in southwest France (Vialle *et al.* 2011), roof runoff was collected from a commercially available domestic rainwater collection system with 204 m^2 surface area of tiled roof, and then channeled through open zinc gutters and pipes. Average NO_3^--N concentration in this runoff was 2.8 mg/L, which met the 50 mg/L guideline for French drinking water. Through comparison between the present study and relevant research in the literature, we conclude that urban roof runoff pollution in developed Beijing is more serious than in some developed countries, especially regarding SS. The higher value of pollutant parameter in roof runoff may be explained by increased pollutants from roofing membrane material and atmospheric deposition. The roof was black asphalt shingle, which is heat-absorbing and soft. It advances rapidly towards decomposition because of high temperatures and strong sunlight in summer. The more intense the sunshine, the higher the temperature, the more decomposition products of asphalt shingle roofing material dissolved in rainwater, and the higher the roof rainwater runoff COD, which is mainly attributable to solubility of refractory organics.

The average value of parameter NH_4^+-N in rainfall was 6.92 mg/L in 2011, greater than a 1991 value of 2.09 mg/L (Zhang & Zhang 1991). The average value of NH_4^+-N was 6.29 mg/L for Chengfu Road asphalt pavement in 2011; the same indicator was only 3.51 mg/L for Chegongzhuang West Road in the Haidian District of Beijing in 1991 (Zhang & Zhang 1991). The average value of parameter

Table 1 | Concentrations of COD_{Cr}, TP, TN, NH_4^+-N, NO_3^-N, NO_2^--N, and TSS in rain, and in Chengfu Road and asphalt roof runoff samples, collected in urban areas inside and outside China University of Geosciences (Beijing) between June 2011 and August 2011

Date	Precipitation (mm)	Duration time (hour)	Drying time before rain (hour)	Rainwater harvesting surfaces	COD_{Cr} (mg L^{-1})		TP (mg L^{-1})				TN (mg L^{-1})			NH_4^+-N (mg L^{-1})			NO_3^--N (mg L^{-1})			NO_2^--N (mg L^{-1})			TSS (mg L^{-1})		
					Max	Min	Average	Max	Min	Average	Max	Min	Average	Max	Min	Average	Max	Min	Average	Max	Min	Average	Max	Min	Average
2011-6-23	36.5	4.08	12.33	Asphalt felt roof	95.87	60.51	68.73	1.46	0.11	0.68	8.69	3.46	5.61	7.86	3.49	5.09	1.63	0.61	1.14	0.06	0.02	0.04	238.00	33.00	92.00
				Chenfu Road	106.06	70.70	86.86	0.62	0.39	0.52	9.66	3.96	5.81	5.40	2.26	4.06	3.62	0.99	1.83	0.29	0.03	0.11	1256.00	56.00	412.86
2011-7-1	6.2	1.75	23.83	Asphalt felt roof	255.37	21.87	82.86	0.74	0.36	0.49	24.67	4.19	11.57	20.29	2.26	8.86	16.78	0.55	3.68	0.68	0.03	0.12	108.00	13.00	41.10
				Chenfu Road	101.62	36.61	68.87	1.61	0.42	0.70	14.69	5.23	7.99	9.77	2.81	5.24	6.95	1.43	2.63	0.29	0.09	0.17	1220.00	164.00	502.00
2011-7-16	61	3.25	41.42	Precipitation	76.23	19.65	45.78	0.72	0.46	0.55	7.44	4.00	6.13	6.63	3.63	4.96	0.83	0.45	0.64	0.04	0.02	0.03	102.00	60.00	80.25
				Asphalt felt roof	80.16	18.86	42.44	1.18	0.36	0.52	12.66	4.30	7.85	10.05	2.94	5.93	4.04	1.26	2.48	0.06	0.01	0.03	298.00	12.00	120.88
				Chenfu Road	176.81	5.50	58.55	1.85	0.36	0.80	16.16	6.86	9.39	9.36	3.08	6.67	6.75	1.63	2.78	0.26	0.03	0.09	1634.00	96.00	409.63
2011-7-17	17.2	1.50	7.08	Precipitation	36.93	24.36	31.17	0.11	0.05	0.09	9.35	5.27	7.55	7.45	5.13	6.40	7.53	4.09	5.85	0.05	0.04	0.04	62.00	49.00	53.67
				Asphalt felt roof	61.30	41.65	48.88	0.71	0.11	0.26	11.77	8.17	9.91	8.68	4.72	7.15	9.67	5.85	7.61	0.19	0.11	0.14	195.00	63.00	111.80
				Chenfu Road	129.66	56.58	78.85	0.93	0.05	0.24	12.55	6.54	8.96	7.59	4.72	5.84	9.67	5.66	7.07	1.84	0.35	0.83	1236.00	450.00	723.17
2011-7-25	24.4	1.25	10.58	Precipitation	72.30	32.22	54.03	0.88	0.58	0.67	8.22	1.78	4.68	11.96	4.72	7.21	2.14	1.14	1.47	0.05	0.01	0.03	103.00	16.00	56.75
				Asphalt felt roof	122.59	25.15	48.72	0.80	0.36	0.53	15.46	4.01	8.05	13.05	3.22	7.02	8.40	1.83	3.85	0.28	0.04	0.11	229.00	61.00	129.00
				Chenfu Road	148.52	40.08	91.79	0.98	0.44	0.67	18.43	5.01	10.64	11.96	3.35	6.25	6.47	1.91	4.72	1.87	0.06	1.07	1034.00	134.00	678.00
2011-8-9	70.3	4.5	249.17	Precipitation	51.08	18.86	33.53	0.94	0.50	0.74	18.90	4.05	12.29	12.23	3.35	9.11	20.27	1.87	10.64	0.09	0.01	0.06	174.00	8.00	85.17
				Asphalt felt roof	313.55	29.86	103.93	1.30	0.56	0.82	25.42	5.67	13.15	15.78	5.13	11.17	15.62	3.86	9.03	0.30	0.03	0.11	325.00	18.00	138.75
				Chenfu Road	271.11	34.58	103.39	1.24	0.86	1.07	22.07	3.56	11.42	19.33	3.63	9.67	23.52	1.64	10.26	1.60	0.04	0.51	862.00	80.00	344.86
Average value of different parameters				Precipitation	–	–	41.13	–	–	0.51	–	–	7.66	–	–	6.92	–	–	4.65	–	–	0.04	–	–	68.96
				Asphalt felt roof	–	–	65.93	–	–	0.55	–	–	9.36	–	–	7.54	–	–	4.63	–	–	0.09	–	–	105.59
				Chenfu Road	–	–	81.39	–	–	0.67	–	–	9.04	–	–	6.29	–	–	4.88	–	–	0.46	–	–	511.75
Environment Quality Standard of Surface Water in China (GB3838-2002)				V class	–	–	≤ 40	–	–	≤ 0.4	–	–	≤ 2.0	–	–	≤ 2.0	–	–	–	–	–	–	–	–	–
Miscellaneous Domestic Wastewater Quality Standard (CJ/T48-1999)				Toilet flushing and city greening	–	–	≤ 50	–	–	–	–	–	–	–	–	≤ 20	–	–	–	–	–	–	–	–	≤ 10
				Car washing and housecleaning	–	–	≤ 50	–	–	–	–	–	–	–	–	≤ 10	–	–	–	–	–	–	–	–	≤ 5

NO_3^--N in rainfall was 4.65 mg/L in 2011, greater than a 1991 value of 0.53 mg/L (Zhang & Zhang 1991). The average value of NO_3^--N was 4.88 mg/L for Chengfu Road asphalt pavement in 2011; the same indicator was only 1.38 mg/L for Chegongzhuang West Road in 1991 (Zhang & Zhang 1991). For NO_2^--N, the rainfall value was 0.04 mg/L in 2011, greater than 0.027 mg/L in 1991 (Zhang & Zhang 1991). The average value of NO_2^--N was 0.46 mg/L for Chengfu Road asphalt pavement in 2011, and only 0.075 mg/L for Chegongzhuang West Road in 1991 (Zhang & Zhang 1991). Hence, the pollution of urban stormwater runoff in 2011 was more serious than in the early 1990s. For comparison, Gromaire *et al.* (1999) found in Paris that mean SS and COD in runoff from six streets were 92.5 and 131 mg/L, respectively. Obviously, the quality of road runoff is affected by multiple factors, including but not limited to, vehicle exhaust, tire wear, lubricants, road abrasion, rust, rubbish, and solid waste. Runoff quality is also influenced by atmospheric deposition. According to Liu *et al.* (2013), nitrogen deposition in China increased by about 60% between the 1980s and 2000s, which was attributed to a rapid increase in human-driven nitrogen emissions from both agricultural and industrial sources. Although this has had great benefits for food and energy production, it has caused water and air pollution that is damaging human health and threatening sensitive ecosystems (Liu *et al.* 2013). This pollution is also causing toxic algal blooms, fish kills, and contributing to climate change (Liu *et al.* 2013).

Changing characteristics of pollutant concentrations of runoff

The accumulation of pollutants is related to rainfall amount and intensity, rain duration, seasonal changes, antecedent dry periods, and other factors (Brezonik & Stadelmann 2002; Bjorklund 2011). As shown by rainfalls on 16 July and 9 August (Table 1), the longer the interval between rainfall events (between 1–16 July and 25 July–9 August), the greater the accumulated volume of pollutants. However, rain flushing capacity on the ground increases with rainfall intensity, as with the rainfall on 9 August.

Runoff quality is unpredictable because of its sensitivity to weather (Vialle *et al.* 2011). Brezonik & Stadelmann (2002) found that mean concentrations in pollution events were positively correlated with days since the last event, which supports the idea that pollutants accumulate during dry periods. Abdulla & Al-Shareef (2009) also indicated that rainfall intensity and number of dry days preceding a rainfall event significantly affect rainwater quality (rainfall that is directly collected). Rainfall from 16 July 2011 (relatively high precipitation) and 17 July 2011 (lesser precipitation) were taken as examples (Figure 2). The former event lasted from 20:40 to 23:30 local time, producing 61 mm of precipitation. The previous rainfall was on 1 July, with 6.2 mm of precipitation (Figure 3). The 17 July event lasted from 15:55 to 17:25, producing 17.2 mm. The runoff pollutant parameters COD_{Cr}, TP, TN, NH_4^+-N, NO_3^--N, NO_2^-N, and TSS in runoff from the asphalt felt roof and asphalt pavement surface road varied during the event, as shown by Figure 2. Concentrations of those parameters in the initial stormwater runoff decreased with rainfall duration, which may be attributed to the original surface contaminant load decreasing with surface runoff, via flushing. Nevertheless, runoff indicators COD_{Cr}, TP, TN, NH_4^+-N, and others from asphalt pavement road surfaces sometimes increased with duration. This may be explained by the irregular variation of rainfall, traffic and other factors that contribute to changes of runoff quality. Especially with higher rainfall quantity, taking 16 July as an example, immediate accumulation of pollutants is more evident. If rainfall intensity suddenly increased, so did precipitation quantity and its effect on the ground; thus, pollutant concentration in the runoff tended to rise.

The phenomenon known as the first flush of storm runoff usually assumes that the first phase of runoff is the most polluted (Deletic 1998). For first-flush evaluation, Deletic (1998) constructed cumulative load curves for all monitored water quality characteristics. The pollution load carried by the first 20% of runoff, FF_{20}, was calculated for each recorded event. FF_{20} values were analyzed using standard statistical methods, including multiple regression (Deletic 1998). However, these curves are difficult to apply to actual rainwater harvesting by most householders. Based upon serial analysis of rainfall data, there are curve inflection points in the rainfall process. The quality of runoff from different rainwater harvesting surfaces varied greatly within the first 15 to 20 min of a rain event (referred to as the initial runoff process). The curve inflection point is

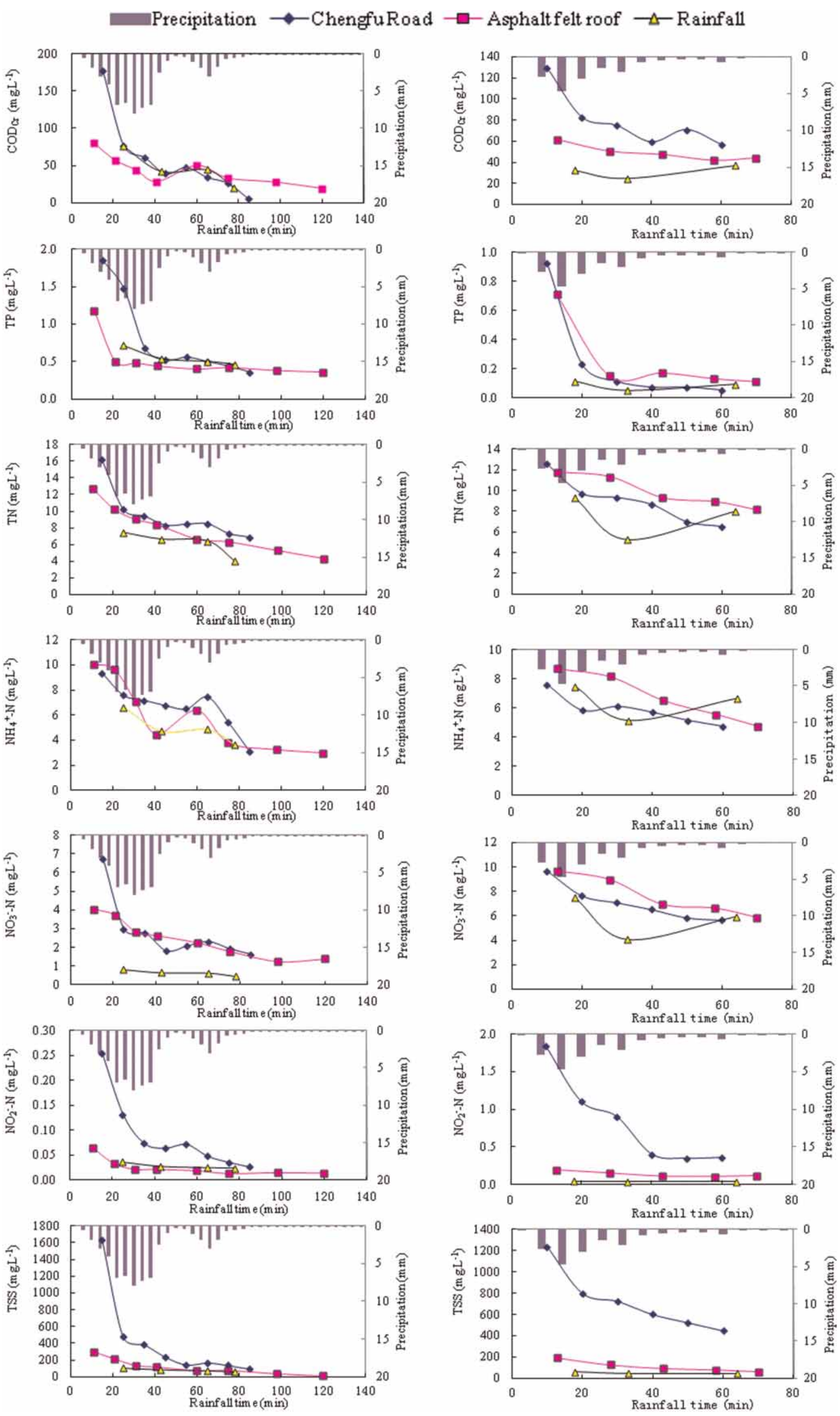

Figure 2 | COD$_{Cr}$, TP, TN, NH4^{+}-N, NO$_3^-$-N, NO$_2^-$N, and TSS concentrations in runoff from different harvesting surfaces: left is 16 July 2011, right is 17 July 2011; rainfall time is the time (minutes) from the beginning of the rain event.

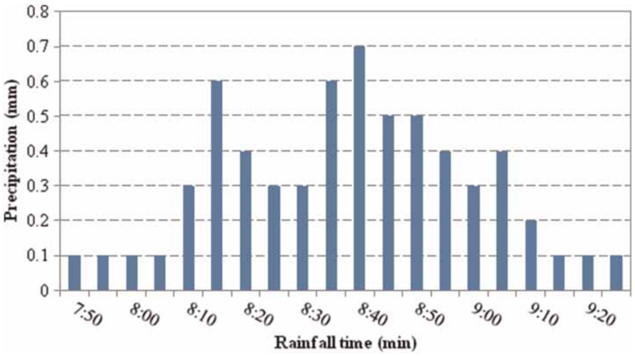

Figure 3 | Rainfall event on 1 July. Total precipitation is 6.2 mm.

mainly influenced by rainfall intensity and time interval between consecutive rainfall events. The critical rainfall value at the inflection point was approximately 2–3 mm, determined by analyzing water quality of runoff and rainfall processes. The first 2–3 mm of rainfall is more seriously polluted because of the washing effect of initial runoff. Mendez *et al.* (2011) indicated that average nitrite concentration of the first flush was significantly higher than that of rainwater harvested after the first flush, for all roofs. After the inflection point, runoff quality satisfied critical values of the Class V water quality standard (with the exception of asphalt pavement road runoff). Therefore, although the quality of rainwater from different surfaces tended to be similar to each other and be constant at the end of the events, quality varied between surfaces. Roof runoff after the inflection point could be reused directly for irrigation. However, this runoff should be treated with methods such as a grid filter, flocculation and sedimentation, if used for car washing, landscaping, and toilet flushing. In contrast, road runoff use is more complicated.

Relationship of pollutant parameters and management strategies

To harvest roof rainwater of good quality for consumption, householders wish to use one of the various alternatives for roof washing, and dispose or abandon the first flush of rainwater from roofs because it picks up most of the dirt, debris, bird droppings, and contaminants from the roof and gutters during dry periods. Therefore, in designing rainwater tanks for urban areas, the primary treatment of initial rainwater must be considered. The main chemical indicators are COD_{Cr}, TP, TN, and NH_4^+-N. Abdulla & Al-Shareef (2009) reported that the simplest of such systems in Jordan consisted of a standpipe and gutter downspout, situated ahead of the downspout from the gutter to tanks or cisterns. If rainwater is used for irrigation, NO_2^--N disposal should be considered, to avoid causing secondary pollution.

The relationships of pollutant parameters COD_{Cr}, TP, TN, and TSS can be expressed as:

$$y = ax + b; \tag{1}$$

where y represents pollutant concentrations of COD_{Cr}, TP, TN; x is TSS concentration; a and b are fitted coefficients.

From Table 2, we see that most coefficients of determination exceed 0.80. COD_{cr} concentration increased nearly in proportion with TSS. This may be explained by the

Table 2 | Regression coefficients (a, b) and determination coefficients (R^2) describing linear relationships ($y = ax + b$) between TP and COD_{Cr}, TP and TSS, and TN and TSS for roof runoff and Chengfu Road runoff

		TP-COD_{Cr}			TP-TSS			TN-TSS		
Date	**Surface type**	***a***	***b***	R^2	***a***	***b***	R^2	***a***	***b***	R^2
2011-7-16	Roof runoff	0.1912	19.324	0.826	0.0024	0.2247	0.7315	0.0288	4.3632	0.9735
2011-7-17	Roof runoff	0.143	32.896	0.9441	0.0045	0.2451	0.8378	0.0277	6.8091	0.8609
2011-7-25	Roof runoff	0.3967	2.4485	0.6217	0.0021	0.2541	0.8736	0.0448	2.2724	0.625
2011-8-9	Roof runoff	0.7017	6.5719	0.7775	0.0019	0.5524	0.7438	0.0574	5.1965	0.9644
2011-7-16	Chenfu Road runoff	0.0998	17.659	0.9523	0.001	0.4053	0.7905	0.0057	7.0778	0.9731
2011-7-17	Chenfu Road runoff	0.0917	12.498	0.9358	0.0011	0.5872	0.9035	0.0075	3.5197	0.9578
2011-7-25	Chenfu Road runoff	0.1059	20.006	0.9231	0.0004	0.3637	0.772	0.0095	4.2101	0.6338
2011-8-9	Chenfu Road runoff	0.2503	17.093	0.834	0.0004	0.9436	0.801	0.0184	5.0841	0.7512

contribution of solids in the transmission of COD_{cr}, TP, and TN, and also reflects that TN and TP are mostly in the form of particulate nitrogen and phosphorus (similar to Goonetilleke *et al.* (2005)). Brodie & Egodawatta (2011) also found that road particle loads during storm events increase linearly with average rainfall intensity. Through removal of SS, COD_{cr} concentration decreases, which reduces the organic load of the pipe network and thereby diminishes the processing load of sewage treatment plants.

Some studies (Mikkelsen *et al.* 1997; Birch *et al.* 2005) have shown that relevant best management practices such as runoff regulation, sedimentation, and filtration may effectively control the total volume of stormwater pollutants, especially with regard to runoff water from trafficked roads. Urbaniak *et al.* (2013) found that the purification of inflowing stormwater of the middle, newly constructed III reservoir was enhanced because of the sediment traps and sand separators equipment at the stormwater outlets and ecotone zones around its catchment. Additionally, rainwater use practice using porous pavements (Hou *et al.* 2008) and multilayer infiltration systems (Hou *et al.* 2013) could effectively control non-point source pollution, thereby improving the ecological environment. Moreover, to meet critical values for firefighting, irrigation, car washing, toilet, and water cooling uses, pro-treatment processes such as aeration coagulation, sedimentation, disinfection (Bright *et al.* 2010; Ojo *et al.* 2012), nitrification and denitrification (Cooper *et al.* 2010), and adsorption for urban rainfall-runoff metals (Liu *et al.* 2005) must be implemented for Chengfu Road runoff and considered in urban management.

CONCLUSIONS

Stormwater runoff samples from various rain harvesting surfaces were collected, and runoff water quality was analyzed. The urban roof runoff pollution in developed Beijing is more serious than in some developed countries, especially regarding SS. Pollution of urban stormwater runoff in 2011 was more serious than in the 1990s. The main pollutants for the rain harvesting surfaces were organics, nutrients, and SS. Runoff quality is affected by atmospheric deposition, roofing materials, road type, rainfall intensity, precipitation amount, and rainfall intervals.

Initial runoff was more seriously polluted. Pollutant concentration decreases gradually with increased rainfall duration, eventually reaching relatively stable values. There were curve inflection points in each event, which mainly depended on rainfall intensity and time since the last rainfall event.

Runoff water quality is greatly influenced by the harvesting surface. Water quality is best for precipitation, followed by roof and road asphalt pavement runoffs. Runoff after the initial stage has lower COD_{Cr}, NH_4^+-N concentrations for both precipitation and roof runoff, and both satisfy the miscellaneous domestic wastewater quality standard for toilet flushing, city greening, car washing and housecleaning, given physical treatment such as with a grid filter, flocculation and sedimentation. Pollution of runoff from the asphalt pavement road surface was more serious, and it cannot be used as a direct water supply for green irrigation, car washing, or artificial fountains. Pro-treatment processes such as aeration coagulation, sedimentation, disinfection, nitrification and denitrification are necessary for road surface runoff use.

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