Research on the characteristics of the water quality of rainwater runoff from green roofs

Kena Gong, Qing Wu, Sen Peng, Xinhua Zhao and Xiaochen Wang

ABSTRACT

This paper investigates the water quality characteristics of rainwater runoff from dual-substrate-layer green roofs in Tianjin, China. The data were collected from four different assemblies and three types of simulated rains. The storm-water runoff quality was monitored from early June through late October 2012 and from July through late November 2013. The results revealed that the runoff water quality would be improved to some extent with the ageing of green roofs and that the quality retention rate better reflected the pollutant retention capacity of the green roof than the pollutant concentration in the runoff water. The investigation clearly demonstrated that green roofs also effectively reduced the chemical oxygen demand and turbidity value and neutralised acid rain to stabilise the pH of the runoff.

Key words | green roof, quality retention rate, roof age, water quality

Kena Gong
Qing Wu
Sen Peng (corresponding author)
Xinhua Zhao
Xiaochen Wang
School of Environmental Science and Engineering,
Tianjin University,
Tianjin 300072,
China
E-mail: *pengsen@tju.edu.cn*

Xinhua Zhao
State Key Laboratory of Hydraulic Engineering Simulation and Safety,
Tianjin University Tianjin 300072,
China

INTRODUCTION

With the rapid development of urbanisation, the population has become concentrated in urban areas, and the amount of impermeable surfaces in urban areas has been increasing, accompanied by flood disasters, water pollution, and urban heat islands (Sun *et al.* 2012). Simultaneously, the amount of green land in urban areas has decreased because of the limited and expensive urban land. The roof area, which corresponds to a high proportion of the urban area, has raised concerns. Green roofs have been proposed as an important means to increase the amount of vegetated area in densely built urban areas. As previously reported, green roofs have positive effects on urban settings, such as considerable aesthetic value (Wang 2010), reduction of building energy consumption (Tang *et al.* 2010) and urban heat islands (Fang 2008), noise reduction (Van Renterghem & Booteldooren 2009), air pollution abatement (Currie & Bass 2008), and improvement of urban biodiversity (Brenneisen 2006). From the perspective of water management, green roofs have been found to play an important role in easing the municipal pipe network pressure because of their ability to retain and detain storm water (Bengtsson *et al.* 2005; Mentens *et al.* 2006; Bliss *et al.* 2009). In addition, green roofs are usually considered to significantly contribute to improving the runoff water quality.

Although the amount of research on the improvement effect of green roofs on the water quality of rain runoff has been increasing, the results are not consistent because of the different conditions and environmental backgrounds used in the studies. This inconsistency makes the water quality characteristics of rain runoff very uncertain. The investigation of the runoff water quality based on two full-scale green roofs indicated that both extensive and intensive green roofs were sinks for pollutants (Berndtsson *et al.* 2009). Vijayaraghavan *et al.* (2012) reported that the concentrations of most chemical compounds in runoff from green roofs are highest at the beginning of rain events and subside subsequently. The concentrations of chemical compounds in the roof runoff strongly depend on the nature of the substrates used in the green roof and the rainfall. The results indicate that green roofs could mitigate acid rain and degrade ammonia nitrogen, whereas the mean concentrations of total nitrogen (TN), total phosphorus (TP) and NO_3-N in storm runoff were found to be higher than that in rainwater for two types of green roofs constructed in Chongqing, China (Wang *et al.* 2012). Zhou *et al.* (2010) indicated that an urban green roof (from Hunan, China) has a high removal efficiency for suspended solids, chemical oxygen demand (COD), TN and TP in the rainwater runoff. The consequences of the studies regarding the time variations in the water quality of rain runoff from green roofs differ. Schrader & Böning (2006) observed that the release of organic matter and TN concentrations in the

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runoff from old roofs is higher than that from young roofs in Germany. Van Seters *et al.* (2007) reported that the presence of nitrogen and phosphorus in the runoff from green roofs (in Toronto) was reduced significantly 1 year after implementation of the green roofs. Teemusk & Mander (2007) reported that the concentration of nutrients in runoff water depends on the operation time, but the pH value was stable.

Previous studies of the runoff water quality from green roofs focus on the concentration of pollutants, whereas little attention has been paid to the total mass of pollutants. The evolution of the water quality of rain runoff from green roofs over time was often overlooked in previous studies. To enhance our knowledge on this topic, the present study was conducted to analyse the total mass of pollutants, the water quality evolution over time, and the variation in COD, turbidity and pH. To achieve this goal, four pilot-scale green roof trays with artificial rainfall devices were constructed on a normal roof under the climate of the Tianjin area.

EXPERIMENTAL SETUP AND METHODS

Study site and green roof design

The common construction of green roofs involves five layers: the uppermost layer is a vegetation layer, followed by a dual-substrate layer, a filter layer, a drainage layer and a waterproof layer (Figure 1). The dual-substrate layer consists of two parts: (1) the uppermost layer is a thin layer (S1: 5 cm) with a nutritional substrate for plant growth and (2) the lower layer is a thick media layer (S2: 5–30 cm) for water detention and the reduction of nutrient pollutants. The filter layer, in the form of a geotextile material, prevents small particles from being washed from the substrate layer. The drainage layer was designed to collect rainwater and allow excess water to be drained off. The functions of the waterproof layer include waterproofing and protection against root penetration (Li & Cheng 2012; Wang *et al.* 2013).

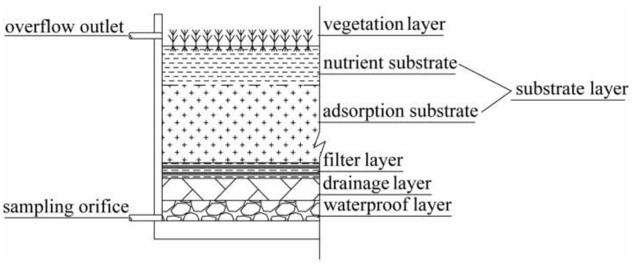

Figure 1 | Sketch of the structure of a green roof.

The green roof test plot was established on the Environmental Experimental building in March 2012 on the campus of Tianjin University, Tianjin, China. The roof systems were constructed in plastic trays with dimensions of 0.53 m × 0.76 m using the same principles as that used for full-scale vegetated roofs. The height of each of the assemblies was different because of the different substrate depths. These assemblies were placed on a 3° slope to simulate a common roof design. The roof runoff was collected from the lower end of the assembly through sampling orifices for nutrient analysis. *Sedum lineare*, which is commonly found in northern China, was selected for the present study because of its ability to survive in low nutrient conditions, drought conditions, and extreme temperature. Once planted, the vegetation kept growing naturally without either fertilisation or artificial watering. After a year of continuous operation, the vegetation was in a good growing condition, and the coverage reached over 90%. The nutrient substrate used in the study was a commercial substrate called BAOLVSU (S1), which is specially made for green roofs based on an inorganic material and organic and inorganic fertilisers. The substrate (S1) is lightweight and exhibits good draining and containing abilities, which are good properties for the growing of plants. A perlite and vermiculite mixed (1:1) substrate (S2) was used as the adsorption substrate for nutrient adsorption and water retention. All assemblies (A1–A4) had a similar nutrient substrate (S1) depth of 5 cm but different adsorption substrate (S2) depths (5, 10, 20, and 30 cm).

Simulations with artificial rain and chemical analysis

The experiments were performed from early June through late October 2012 (initial study period) and from July through late November 2013 (second study period). To study the influence of different rainfall densities and durations on the runoff quality, rain simulations with artificially mixed rainwater were performed on assemblies A1–A4 with three different rainfall densities (R1–R3) using a movable multifunctional artificial rain generator. The simulated storm pattern (Table 1) and water quality (TN: 2.5 ± 0.1 mg/L; NO_3-N: 1.5 ± 0.05 mg/L; NH_4-N: 1.2 ± 0.05 mg/L; TP: 0.5 ± 0.02 mg/L; COD: 30 ± 1.5 mg/L; turbidity: 4 ± 0.5 NTU; pH: 6.5 ± 0.1) corresponded to real rain events in Tianjin, China. Before the start of the experiments, all green roof assemblies were kept dry for 72 h to ensure that the substrate moisture was less than 20%. The

Table 1 | The simulated storm pattern

	R1	R2	R3
Duration (min)	60 ± 2	40 ± 2	25 ± 2
Total volume (L)	35 ± 1	36 ± 1	34 ± 1
Effective area (m^2)	0.41 ± 0.05	0.41 ± 0.05	0.41 ± 0.05
Intensity (L/h)	35 ± 3	55 ± 3	80 ± 3

runoff was collected through sampling orifices in the assemblies using pre-cleaned plastic cans every 5 or 10 min. In addition, the ambient temperature, substrate moisture and runoff reserved volume were also recorded.

RESULTS AND DISCUSSION

Evolution of rain runoff water quality over time

Because of soil erosion and plant growth, the water quality characteristics of rain runoff from green roofs may vary with the extension of the green roof operation time. To analyse the evolution of the rain runoff water quality over time, the present study obtained statistics from the monitoring of the water quality from green roofs in 2012 and 2013.

Total phosphorus

In 2012, the concentration of TP in the runoffs from all of the assemblies was higher than that in rainwater, and had an average concentration between 0.61 and 2.32 mg/L. The concentration of TP reached the maximum of 2.32 mg/L in the A1 runoff during R1, and this amount was 4.64-fold greater than the amount in rainwater; during R3, the concentration of TP in the A3 runoff reached the minimum, that is, 0.61 mg/L, which was 1.22-fold greater than that of the rainwater. Table 2 indicates that all four assemblies acted as a source for TP at different artificial rain events during the initial study period (2012). However, during the second study period (2013), the concentration of TP in each assembly was lower than the concentration in the artificial rainwater; that is, the green roofs began to have a removal effect for TP. The maximum concentration of TP was 0.32 mg/L, which was 64% of the level in the rainwater. In addition, the minimum value was 0.13 mg/L, which was only approximately 26% of the level in the precipitation.

Ammonia nitrogen

The experimental results for the A1, A2, A3 and A4 assemblies (Table 2) revealed that the green roofs had a removal effect for ammonia nitrogen (NH_4-N) during all rain events. The runoff concentration of NH_4-N in each assembly was lower than the concentration in rainwater in both 2012 and 2013. Moreover, the runoff quality in 2013 was much better than that in 2012. In 2012, the concentrations of NH_4-N in the runoffs were in the range of 0.3 to 1.0 mg/L, whereas the concentration was below 0.61 mg/L in 2013.

Nitrate nitrogen

Table 2 indicates that the average concentrations of nitrate nitrogen (NO_3-N) in the runoffs were higher than that in the rainwater only when the adsorption substrate depth

Table 2 | Statistical results of the pollutant average concentrations in the runoffs from all four assemblies at different artificial rain events

		TN		NO_3		NH_4		TP	
		2012	2013	2012	2013	2012	2013	2012	2013
A1	R1	2.80	1.69	1.72	1.24	0.97	0.37	2.32	0.32
	R2	2.73	1.72	1.65	1.17	0.98	0.48	1.93	0.30
	R3	2.45	1.82	1.36	1.12	1.03	0.61	1.64	0.24
A2	R1	2.40	1.55	1.64	1.15	0.65	0.33	1.35	0.24
	R2	2.24	1.49	1.48	1.01	0.67	0.39	1.22	0.23
	R3	2.18	1.52	1.35	0.94	0.74	0.46	1.17	0.20
A3	R1	1.84	1.14	1.33	1.01	0.43	0.09	0.80	0.23
	R2	1.85	1.10	1.27	0.89	0.50	0.15	0.73	0.22
	R3	1.71	1.13	1.00	0.85	0.66	0.19	0.62	0.19
A4	R1	1.65	0.93	1.24	0.89	0.34	–	0.72	0.13
	R2	1.58	0.80	1.05	0.76	0.46	–	0.65	0.17
	R3	1.56	0.82	0.96	0.72	0.54	0.04	0.61	0.19

was between 5 cm (A1) and 10 cm (A2) during the initial study period (2012), the concentrations of NO_3-N in the effluents of A3 and A4 being lower than the concentration in the rainwater. In 2013, the average concentration of NO_3-N from all of the assemblies was between 0.72 and 1.24 mg/L under the same raining conditions, and this value is lower than that in the rainwater.

Total nitrogen

The variation of TN was similar to that of NO_3-N. In 2012, all green roof assemblies with the exception of A1 performed a removal effect for TN during different rain events. The average concentration of TN in the A1 runoff was higher than that in the rainwater during R1 and R2. The maximum average concentration of TN was 2.80 mg/L, and the minimum concentration in the other assemblies was 1.56 mg/L, which was 62.4% of the level of TN in the rainwater. In 2013, the average concentrations of TN in the runoffs were much lower than the concentration of TN in the rainwater, and the minimum concentration in the runoff was 0.80 mg/L, which was only 32% of the concentration of TN in the rainwater.

In general, the concentrations of N and P in the runoffs were significantly reduced after the green roofs had been in operation for 1 year. This result is consistent with Van's study in Toronto (Van Seters *et al.* 2007). The results indicated that the runoff water quality improved to some extent as the green roof aged. In particular, this effect was most obvious for TP. Green roofs always acted as a removal agent for NH_4-N.

Quality retention rate

The total masses of a pollutant in simulated rainwater and runoff are defined as m_0 and m_1, respectively, and the mass of this pollutant retained by a green roof is m_2. The three quantities satisfy the following equation:

$$m_2 = m_0 - m_1 \tag{1}$$

The quality retention rate is defined as the percentage of m_2 to m_0, and this value is used to evaluate the pollutant retention capacity of a green roof from the aspect of total mass according to the principle of mass conservation. The quality retention rate is more reflective of the real removal efficiency of a green roof than is the concentration. Thus, the quality retention rate was chosen for the evaluation of the pollutant retention capacity in this study. The computational formula for the quality retention rate is as follows:

$$\pi = \frac{m_0 - m_1}{m_0} \times 100\% \tag{2}$$

In the equation: π – quality retention rate, %; m_0 – total mass of a pollutant in the simulated rainwater, g; m_1 – total mass of a pollutant in the runoff, g.

The pollutant concentration in the simulated rainwater is c_0, and the concentration in the runoff is c_1; the rainfall volume is P, the runoff volume is R, and the molar mass of the pollutant is M. The relationship between these quantities is expressed below:

$$m_0 = P \times c_0 \times M \tag{3}$$

$$m_1 = R \times c_1 \times M \times 100\% \tag{4}$$

Thus,

$$\pi = \frac{c_0 - c_1 \times \frac{R}{P}}{c_0} \times 100\% \tag{5}$$

and

$$\frac{R}{P} = 1 - \omega \tag{6}$$

In the equation, ω – rainwater retention rate, %.

Thus,

$$\pi = \frac{c_0 - c_1 \times (1 - \omega)}{c_0} \times 100\% \tag{7}$$

In the equation, π – quality retention rate, %; ω – rainwater retention rate, %; c_0 – pollutant concentration in the simulated rainwater, mol/L; c_1 – pollutant concentration in the runoff, mol/L.

Dissolved inorganic nitrogen and phosphorus can be easily absorbed by organisms, which makes these pollutants a significant threat to water quality. This study selected two representative indicators (TN and TP) to analyse the total mass retention capacity of green roofs.

Green roofs have an effect on rainwater runoff reduction, as illustrated in Table 3. The magnitude of this effect mainly depended on the thickness of the substrate and the rain intensity. A thicker substrate depth was associated with a better rainwater runoff reduction capacity. In

Table 3 | The experimental results for the rainwater and quality retention rate for assemblies A1–A4 during different artificial rain events

		ω		$1-\omega$		π(TN)		π(TP)	
		2012	2013	2012	2013	2012	2013	2012	2013
A1	R1	23.0	19.9	0.77	0.80	13.76	45.82	– 257.28	49.52
	R2	19.8	17.3	0.80	0.83	12.58	43.07	– 209.57	50.36
	R3	15.3	15.0	0.85	0.85	16.99	38.22	– 177.82	59.19
A2	R1	26.3	22.8	0.74	0.77	29.25	51.98	– 98.99	62.92
	R2	22.4	19.3	0.78	0.81	30.55	51.89	– 89.34	62.87
	R3	18.6	16.9	0.81	0.83	29.18	49.40	– 90.48	66.77
A3	R1	46.4	44.4	0.54	0.56	60.60	74.64	14.24	74.41
	R2	40.6	37.4	0.59	0.63	56.04	72.44	13.28	72.44
	R3	28.9	26.4	0.71	0.74	51.30	66.72	13.26	72.02
A4	R1	68.9	66.9	0.31	0.33	79.47	87.67	55.22	91.38
	R2	58.6	58.3	0.41	0.42	73.92	86.68	46.18	85.82
	R3	47.3	46.9	0.53	0.53	67.06	82.58	35.71	79.82

contrast, the rainwater retention rate decreased with an increase in the rainfall intensity for the same adsorption substrate depth. Because of the particular concentrations of pollutants in the simulated rainwater, the quality retention rate depended on the runoff concentration c_1 and the rainwater retention rate w.

In 2012, the concentration of TP in the rain runoff through each assembly was higher than the TP in the rainwater (Table 2). However, as shown in Table 3, the quality retention rate of TP for all of the assemblies with the exception of A1 and A2 (the substrate thickness is between 5 and 10 cm) in 2012 was greater than 0, which indicates that A3 and A4 had a removal effect for TP, even though the concentration in the runoff was higher than that in the rainwater. The results indicated that the removal efficiency of the pollutants was also dependent on the water volume reduction within the green roof. Only for A1 was the runoff concentration of TN higher than that of the rainwater (Table 2). However, the quality retention rate in all four assemblies was greater than 0 during the three different rain events (Table 3), with a maximum of 79.47% during R1 for A4. This result indicated that green roofs could reduce the TN from rainwater effectively. In 2013, the quality retention rates of TN and TP were both greater than 0, and the maximum of TN and TP were 87.67% and 91.38%, respectively.

The quality retention rate can better reflect the pollutant retention capacity of a green roof than the pollutant concentration in the runoff water. Many studies compared the pollutant concentration in rainwater and runoff water. For such studies, a green roof is considered a source of contaminants if the runoff water concentrations are higher than the rainwater concentrations. Note that this comparison does not consider the runoff volume reduction due to a green roof. In contrast, the quality retention rate can reflect the removal efficiency of pollutants; only if the value is greater than 0 is a green roof considered a sink of pollutants.

The variation in COD, turbidity and pH

The results indicated that green roofs could effectively reduce the COD value in the runoff, with the average concentration varying between 9.3 and 28.0 mg/L, and the variation in the COD concentration largely depended on the adsorption substrate layer depth. However, the effect of rainfall intensity was uncertain. All four assemblies reduced the turbidity of the runoffs, with the average value varying between 0.70 and 0.98 NTU, which was far below the value for the simulated rainwater. The main reasons for this discrepancy could be the type of nutrient substrate used, the dual-substrate layer, or the contribution of the filter layer. The experimental results revealed that the variety in the turbidity values in the runoff largely depended on the material type of the substrate layer and had little relationship to the substrate layer depth and to the rainfall intensity. The green roofs could effectively neutralise acid rain to pH values between 8.25 and 8.63, which achieved the standard V (pH 6–9) of *Environmental Quality Standards for Surface Water* (GB3838-2002 2002). This neutralisation is an important environmental benefit that contributes to lowering the degree of acidification of natural water recipients (Berndtsson 2010).

CONCLUSIONS

The present study investigated the runoff water quality from green roofs with four assemblies during three different simulated rains in 2012 and 2013. The dual-substrate-layer structure was used in all four assemblies tested in this investigation. The results revealed that the concentrations of N and P in the runoffs were significantly reduced after the green roofs had been operational for 1 year, and the runoff water quality improved to some extent as the green roof aged. The results also indicated that the quality retention rate better reflected the pollutant retention capacity of a green roof than did the pollutant concentration in the runoff water, which does not consider the runoff volume reduction obtained with a green roof. Our investigation clearly indicated that green roofs also effectively reduced the COD and the turbidity value and neutralised acid rain to stabilise the pH of the runoff.

REFERENCES

Bengtsson, L., Grahn, L. & Olsson, J. 2005 Hydrological function of a thin extensive green roof in southern Sweden. *Nordic Hydrology* **36** (3), 259–268.

Berndtsson, J. C. 2010 Green roof performance towards management of runoff water quantity and quality: a review. *Ecological Engineering* **36**, 351–360.

Berndtsson, J. C., Bengtsson, L. & Jinno, K. 2009 Runoff water quality from intensive and extensive vegetated roofs. *Ecological Engineering* **35** (3), 369–380.

Bliss, D. J., Neufeld, R. D. & Ries, R. J. 2009 Storm water runoff mitigation using a green roof. *Environmental Engineering Science* **26** (2), 407–417.

Brenneisen, S. 2006 Space for urban wildlife: designing green roofs as habitats in Switzerland. *Urban Habitats* **4** (1), 27–36.

Currie, B. A. & Bass, B. 2008 Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosystems* **11**, 409–422.

Fang, C. F. 2008 Evaluating the thermal reduction effect of plant layers on rooftops. *Energy Nature* **40**, 1048–1052.

GB3838-2002 2002 National Standards of the People's Republic of China: Environmental Quality Standards for Surface Water GB3838-2002. General Administration of Environmental Protection/General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Beijing, China.

Li, S. J. & Cheng, X. T. 2012 Roof greening and rainwater collection affecting the rain flood adjustment in Fuzhou, Fujian province. *China Flood & Drought Management* **22** (2), 16–20.

Mentens, J., Raes, D. & Hermy, M. 2006 Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning* **77**, 217–226.

Schrader, S. & Böning, M. 2006 Soil formation on green roofs and its contribution on urban biodiversity with emphasis on Collembolans. *Pedobiologia* **50** (4), 347–356.

Sun, T., Ni, G. H., Tang, L. H. & Zhang, S. H. 2012 Experimental study on green roof stormwater retention. *Journal of Hydroelectric Engineering* **31** (3), 44–48.

Tang, M. F., Zheng, S. K. & Yang, Z. J. 2010 Thermal performance and energy analysis of green roof. *Journal of Civil, Architectural and Environmental Engineering* **32** (2), 87–90.

Teemusk, A. & Mander, Ü. 2007 Rainwater runoff quantity and quality performance from a green roof: the effects of short-term rain events. *Ecological Engineering* **30**, 271–277.

Van Renterghem, T. & Booteldooren, D. 2009 Reducing the acoustical facade load from traffic with green roofs. *Building and Environment* **44**, 1081–1087.

Van Seters, T., Rocha, L. & MacMillan, G. 2007 Evaluation of the runoff quantity and quality performance of an extensive green roof in Toronto, Ontario. In: *Proceedings of the Greening Rooftops for Sustainable Communities*, Minneapolis.

Vijayaraghavan, K., Joshi, U. M. & Balasubramanian, R. 2012 A field study to evaluate runoff quality from green roofs. *Water Research* **46** (4), 1337–1345.

Wang, J. L. 2010 A study of the color compatibility of the Crassulaceae plants in roof greening in Central Shanxi Province. *Chinese Agricultural Science Bulletin* **26** (19), 201–205.

Wang, S. M., He, Q., Zhang, J. H. & Li, J. 2012 The concentrations distribution and composition of nitrogen and phosphor in stormwater runoff from green roof. *Acta Ecologica Sinica* **32** (12), 3691–3699.

Wang, X. C., Zhao, X. H. & Peng, C. R. 2013 A field study to evaluate the impact of different factors on the nutrient pollutant concentrations in green roof runoff. *Water Science & Technology* **68** (12), 2691–2697.

Zhou, S. J., Ren, B. Z. & Deng, R. J. 2010 Removal efficiency of pollutants in rainwater runoff by green water-storing roof. *China Water & Wastewater* **26** (5), 38–41.

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