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RESEARCH ARTICLE

Annual variation patterns of the effluent water quality from a green roof and the overall impacts of its structure

Hongxiang Chai [1,2] · Yue Tang [1,2] · Xiaojie Su [3,4] · Weijie Wang [1,2] · Hao Lu [1,2] · Zhiyu Shao [1,2] · Qiang He [1,2]

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Abstract
To explore the optimal combination of vegetation type, substrate type, and substrate thickness in a green roof and the interannual variation patterns of the runoff quality, eight green roof units were constructed in Shenzhen, China. Runoff quality of the eight units was monitored for 3 years (24 rainfall events). The rainfall event mean concentrations (EMC) were used to evaluate runoff quality as well as annual pollutant load. An orthogonal $L_8(2^4)$ experiment was designed to verify the significance of different factors. An optimal level of significant factors was selected to determine the optimal design of green roof. The optimal vegetation was *Ophiopogon japonicus*. The optimal substrate was modified perlite, while optimal substrate thickness was 200 mm. A three-year interannual variation analysis was performed on the optimal green roof. It was found that the interannual variation of each runoff quality index is different. The concentrations of SS, COD, and NH_4^+-N in the runoff decreased with years. The concentration of NO_3^--N increased over time, while TP remained stable. The concentration of TN had certain volatility with no significant interannual variation. Overall, the runoff quality of the green roof improves over time. The optimal green roof's runoff quality in the third year including 11 rainfall events was monitored. Results showed that the effluent quality from the green roof was lower than that of precipitation. The average concentrations of SS, COD, NH_4^+-N, TN, and TP decreased respectively by 37.85%, 28.89%, 30.25%, 14.52%, and 12.93%, but NO_3^--N increased by 69.91% comparing to the traditional roof.

Keywords Sponge city · Low impact development · Runoff · Green roof · Interannual variation

Introduction

Rainwater is an important part of the urban and regional water cycle system, playing an extremely important role in regulating water resources and improving ecological environment. China is currently in the stage of rapid urbanization. With the improvement of urbanization and rapid economic development, urban stormwater problems have become more prominent, mainly manifested as serious pollution of runoff, increased risk of urban floods, large loss of rainwater resources, and serious damage to the urban ecological environment (Liu et al. 2017; Xia et al. 2017). In 2013, the Chinese government initiated a "sponge city" program to control floods through LID facilities (Carlson et al. 2015). The sponge city closely integrates the infiltration, retention, storage, purification, utilization, and drainage of rainwater. Its goals include prevention of waterlogging, control of runoff pollution, rainwater utilization, and water ecological recovery (Ren et al. 2017). Green roofs are an important part of the construction of sponge city, especially in green building communities. Compared with traditional roofs, green roofs can reduce runoff volume, delay and reduce peak flow through permeation, retention, storage, and purification (Berndtsson 2010; Mentens et al. 2006; Rowe 2010; Teemusk and Mander 2006). In addition, the green roofs can also provide building with thermal insulation, roof protection as well as environmental benefits such as reducing urban

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✉ Hongxiang Chai
chaihx@cqu.edu.cn

[1] Key Laboratory of Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing University, Chongqing 400045, People's Republic of China

[2] National Centre for International Research of Low-Carbon and Green Buildings, Chongqing University, Chongqing 400045, People's Republic of China

[3] Key Laboratory of Dependable Service Computing in Cyber Physical Society (Chongqing University), Ministry of Education, Chongqing 400044, People's Republic of China

[4] College of Automation, Chongqing University, Chongqing 400044, People's Republic of China

heat islands and alleviating atmospheric pollution (Getter et al. 2009; Susca et al. 2011; Teemusk and Mander 2006; Wong et al. 2003).

Green roofs mainly depend on the retention in planting layers and water storage layers to control runoff quantity. The control of runoff quality is mainly achieved through soil interception, plant absorption, and microbial utilization (Berndtsson et al. 2006). However, the green roofs could also act as a source of pollutants due to soil erosion washout, substrate release, fertilization, and bio-corruption, deteriorating the effluent quality (Kok et al. 2016; Vijayaraghavan et al. 2011). Berndtsson et al. (2009) studied the characteristics of runoff quality from green roofs in Fukuoka and Sweden, revealed that the green roofs in both places were the sources of pollutants, especially the release of dissolved nutrients. Emilsson (2008) analyzed that green roofs can reduce ammonia nitrogen and total nitrogen, but at the same time they were sources of nitrates, total phosphorus, and phosphates.

Green roofs with short construction times are more likely to be the source of release of dissolved nutrients (Emilsson 2008). The development of sponge city in China is in the initial stage, and the construction of sponge facilities has not yet achieved obvious benefits. Moreover, a large number of monitoring results in the world showed that the runoff quality of the green roofs had different degrees of deterioration compared with the precipitation (Harper et al. 2015; Mitchell et al. 2017). Studies have shown that the runoff quality of green roofs may improve with the increase of running time (MacAvoy et al. 2016). However, not all the concentrations of pollutants gradually decreased with the increase of the green roof age. Some of the nutrient pollutant annual concentrations showed fluctuations on this matter (Berndtsson et al. 2006). Therefore, this study was initiated with the objective being to analyze the specific interannual variation of each water quality index, including SS, COD, NH_4^+-N, NO_3^--N, TN, and TP.

In this study, water quality of the effluent from eight green roof units in Shenzhen, southern China, during 24 rainfall events within 3 years was monitored. The eight units include different vegetation types, substrate types, and substrate thicknesses. The goal is to explore whether the influence of vegetation type, substrate type, and substrate thickness on each water quality index is significant. Results could be used to obtain the optimal design parameter for green roofs. Furthermore, this study investigates the interannual variation patterns of the optimal green roof based on its effluent quality.

Materials and methods

Study site

Roof rainwater runoff was monitored at a newly developed site surrounded by a commercial office building, road, and plant land in Guangming new district (22.738N, 113.946E), Shenzhen, China (Fig. 1). The area has a subtropical maritime climate, with a mean annual temperature of 22.4 °C. Most of the precipitation occurs during the period between July and September with the highest temperature. Annual average rainfall in summer is relatively stable with an average rainfall of 310 mm per month in Shenzhen.

Green roof design

As shown in Fig. 2, eight green roof units were constructed based on the "Shenzhen Green Roof Design Code," and the vegetation type, substrate type, and substrate thickness were all considered at two different levels (Table 1). The eight units were made of plexiglass and measured 900 mm × 900 mm × 300 mm. The vegetation layer, substrate layer, filter layer, and storage layer were from top to bottom. The green roof assemblies were supported by stainless steel brackets, and the dimensions were 1000 mm × 1000 mm × 700 mm.

Vegetation layer was planted with local drought-resistant crops. The two vegetation types used were as follows: *Ophiopogon japonicus* and Yulong grass. The substrate layer was filled with modified perlite or modified recycled bricks. The modified perlite was formed by the volume expansion of perlite at a temperature of 1000~1300 °C from 4 to 30 times. The internal structure of the perlite was a honeycomb with a bulk density of 70–200 kg/m^3. The modified recycled bricks were made of construction waste that was compressed, and the ratio of construction waste, fine sand, cement, and water was 6:2:1:1. The root length of Yulong grass and *Ophiopogon japonicus* is close to 90 mm. Therefore, considering the load restriction of the roof and the selected plants root growth requirements, the substrate thickness between 100 and 200 mm was appropriate. That is why the substrate thickness was 100 or 200 mm, respectively. Three layers of non-woven fiber geotextiles were set as the filter layer. The storage layer was filled with 100 mm thick ceramic particles.

Sampling and analysis

Drainage water from green roofs exhibits high concentration of nutrients during the warm temperature growing season, particularly total nitrogen and dissolved organic carbon (Buffam et al. 2016; Carpenter et al. 2016). Considering the seasonal changes in the ability of green roofs to control pollution, the three-year monitoring water samples were conducted every summer from July to September. The water quality of the green roofs under the most unfavorable conditions was analyzed. During the rainfall, samples were collected every 5 min until the end of the runoff (Mitchell et al. 2017). The sampling bottle was a 0.6 L polyvinyl chloride bottle, which was rinsed with

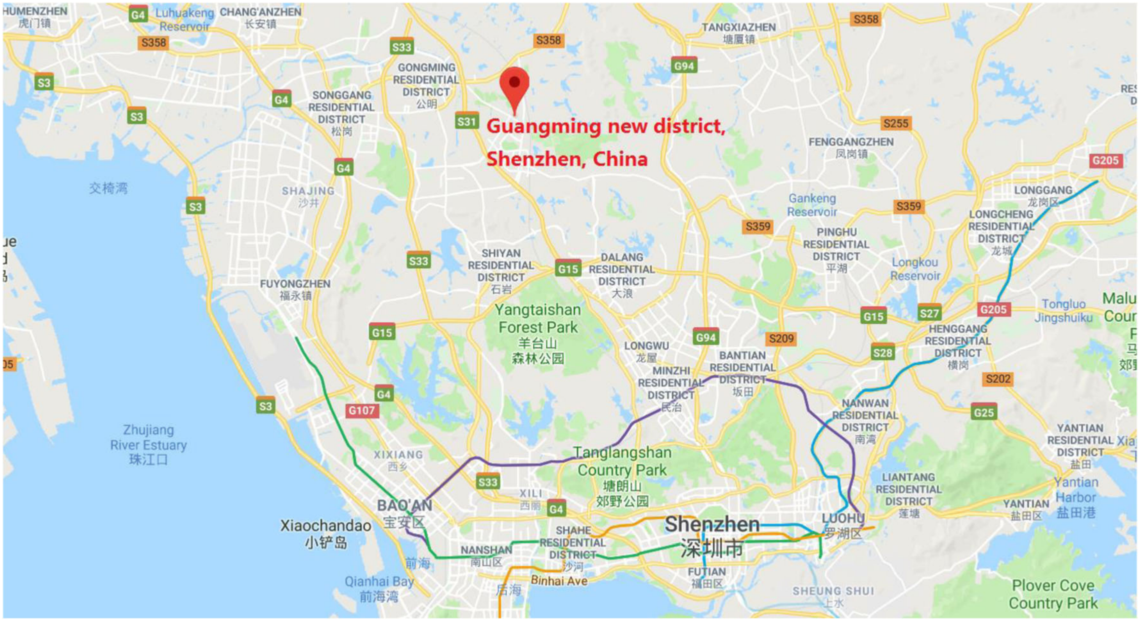

Fig. 1 Location of studied green roofs

distilled water before sampling, then rinsed once with 1 + 3 nitric acid followed by washing three times with distilled water, and then washed once with deionized water (China SEPA 2002). After the samples were obtained, they were immediately prepared for analysis. In accordance with the Standard Methods for the Examination of Water and Wastewater which was published by the American Public Health Association, six indexes of SS, COD, NH_4^+-N, NO_3^--N, TN, and TP were tested (APHA 2005). The test instrument of SS was Rotary vane vacuum pump (TW-1A), while the test instrument of COD was COD digestion device (HACH DRB200). The test instrument of NH_4^+-N, NO_3^--N, TN, and TP was Spectrophotometer (HACH DR5000). The rainfall event mean concentrations (EMC) were used to evaluate runoff quality, and the fluctuation range of EMC value was used to evaluate the stability of runoff water quality, while the average of EMC (EMCs) was used to assess annual runoff quality (Zhao et al. 2007).

Orthogonal experimental design

The runoff quality of green roofs is affected by the vegetation type, substrate type, and substrate thickness (Nagase and Dunnett 2012; Teemusk and Mander 2011; Vijayaraghavan et al. 2011). But it is not clear how these factors affect the specific index of the runoff. In order to study this, orthogonal experiment with three factors and two levels ($L_8 2^4$) was designed. The three factors were vegetation type, substrate type, and substrate thickness. The two levels of vegetation type were *Ophiopogon japonicus* (level 1) and Yulong grass (level 2). Substrate types were modified perlite (level 1) and modified recycled bricks (level 2). Substrate thicknesses were 100 mm (level 1) and 200 mm (level 2). Using the three-year runoff EMCs of six indexes, SS, COD, NH_4^+-N, NO_3^--N, TN, and TP as the response to verify whether the three factors had significant influence on these six indexes. The orthogonal

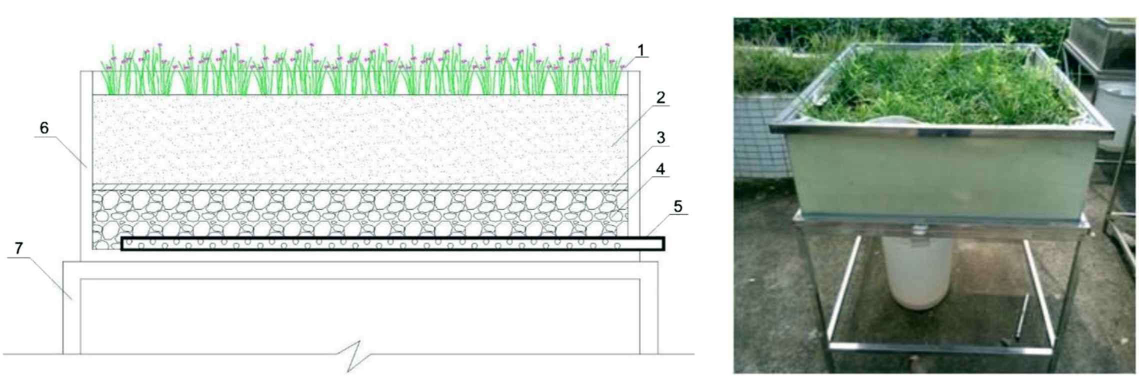

Fig. 2 Green roof profile (1 vegetation layer, 2 substrate layer, 3 filter layer, 4 storage layer, 5 perforated collector, 6 Perspex outer wall, 7 stainless steel bracket) and a picture of studied green roof

Table 1 The structure parameters of green roofs

Green roof's number	Vegetation type	Substrate type	Substrate thickness (mm)
1#	*Ophiopogon japonicus*	Modified perlite	100
2#	*Ophiopogon japonicus*	Modified perlite	200
3#	*Ophiopogon japonicus*	Modified recycled bricks	100
4#	*Ophiopogon japonicus*	Modified recycled bricks	200
5#	Yulong grass	Modified perlite	100
6#	Yulong grass	Modified perlite	200
7#	Yulong grass	Modified recycled bricks	100
8#	Yulong grass	Modified recycled bricks	200

experiment form is shown in Table 2. Software named Minitab was used to analyze the orthogonal experiment (Fig. 3).

Results and discussion

This study monitored the water quality of precipitation, 1–8# green roofs and traditional roof of 24 rainfall events in July to September from 2013 to 2015. The results of three-year precipitation monitoring showed that the rainfall water quality in Shenzhen, southern China was good. The EMCs of precipitation quality were basically consistent every year. It means that the average influent quality of the green roofs was basically the same in these 3 years. Therefore, the annual variation of effluent quality of green roofs could be discussed.

Significant analysis

The results of orthogonal experiments (Fig. 3) showed that the vegetation type had a significant impact on COD ($p = 0.092$, $\alpha = 0.1$). Moreover, the *Ophiopogon japonicus* controlled COD better than Yulong grass. The impact of substrate type on NH_4^+-N was significant ($p = 0.019$, $\alpha = 0.1$). The modified perlite had a better adsorption on NH_4^+-N relative to the modified recycled brick. The substrate thickness also had a significant impact on NH_4^+-N ($p = 0.043$, $\alpha = 0.1$). When substrate thickness was 200 mm, the NH_4^+-N had a lower effluent concentration. In addition, the impacts of vegetation type, substrate type, and substrate thickness on other indexes were not significant ($p > 0.1$, $\alpha = 0.1$).

Vegetation type had a significant impact on COD. Yulong grass is difficult to adapt to environmental conditions. Therefore, some deaths occurred in the second year because of the long drought period. Yulong grass was replaced by weeds in the third year. The runoff quality was deteriorated during the period without vegetation coverage. Due to lack of fixation of plant roots, the substrate layer's ability resisting rainstorms scouring was weakened. In addition, the substratum soil sank, leading to the permeability coefficient of the substrate layer decreasing. As a result, substrate was easy to get blocked to influence the effluent quality (Archer et al. 2002; Le Coustumer et al. 2012), that caused a sudden deterioration of the runoff water quality, resulting in the COD concentration increasing significantly.

The reduction of NH_4^+-N concentration in the effluent mainly depends on the charge adsorption and the nitrification between two rainfall events. As the soil particles carry negative charge, the NH_4^+ which from precipitation or fertilizer was absorbed. Absorbed NH_4^+-N was converted to NO_3^--N by the nitrification during dry period (Mentens et al. 2006). Compared to the modified recycled brick, modified pearlite had better control effect on NH_4^+-N. The reason is that porous modifier can improve substrate layer ventilation condition. The fact is that ventilation capacity of modified perlite is better than modified recycled brick. Good ventilation condition of modified pearlite promoted the proliferation and survival of nitrifying bacteria, thereby promoting the transformation of nitrogen and

Table 2 Orthogonal experiment table

Substrate	Substrate thickness	Vegetation type	Error	SS	COD	NH_4^+-N	NO_3^--N	TN	TP
1	1	1	1	41.8	26.2	0.50	0.44	1.03	0.17
1	1	2	2	48.3	35.4	0.59	0.33	1.00	0.19
1	2	1	2	28.1	24.1	0.41	0.37	0.94	0.18
1	2	2	1	65.2	32.1	0.48	0.42	1.16	0.22
2	1	1	2	42.1	23.4	0.66	0.35	0.96	0.22
2	1	2	1	42.7	39.6	0.61	0.37	1.29	0.17
2	2	1	1	27.4	23.8	0.55	0.46	1.20	0.23
2	2	2	2	37.9	35.8	0.59	0.38	1.21	0.16

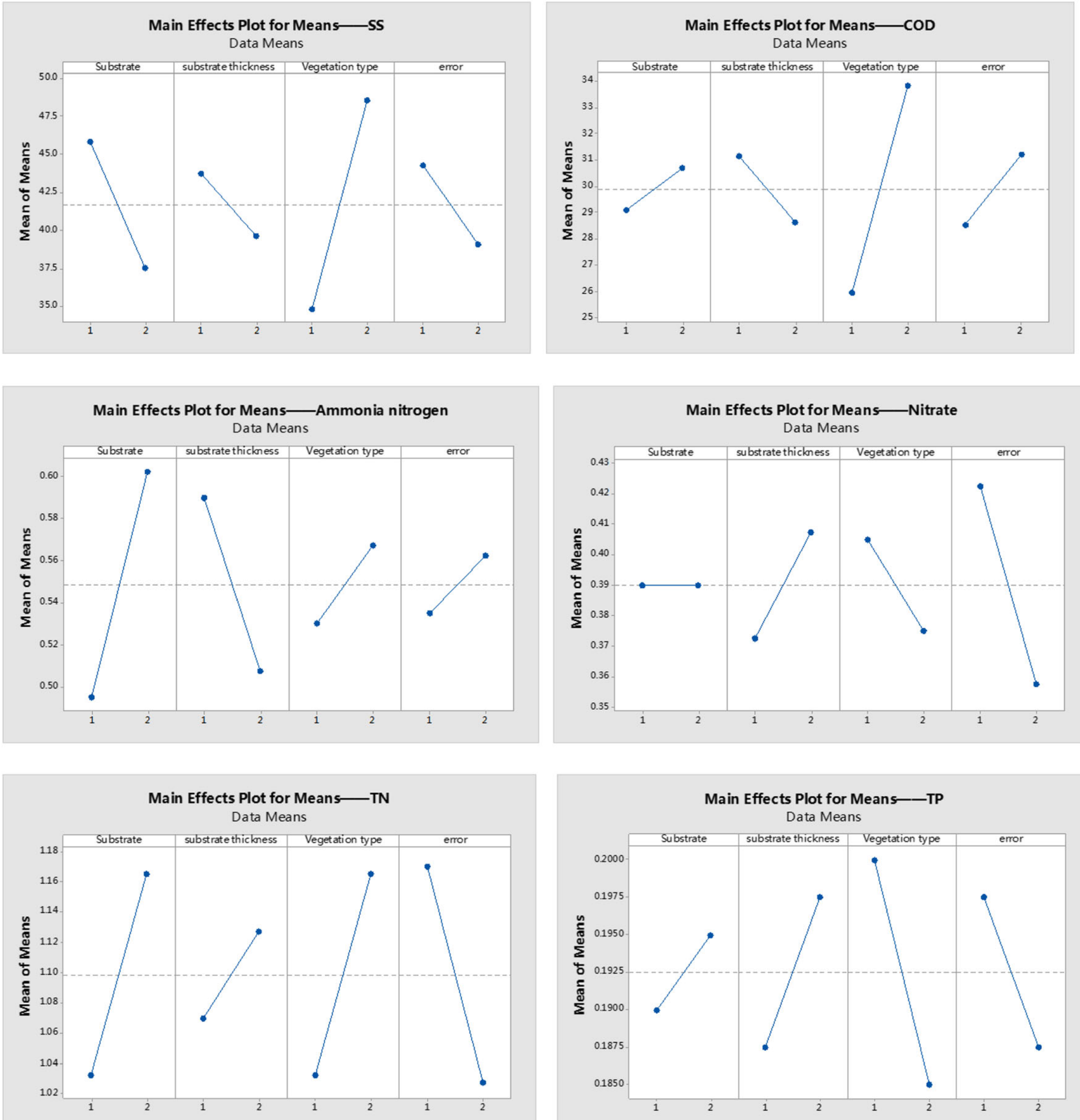

Fig. 3 Significant analysis

reducing the NH_4^+-N concentration of effluent. With the thickness of the substrate layer increasing, more NH_4^+ could be adsorbed, thus promoting the conversion of the nitrogen. Therefore, the nitrogen could be controlled better through adsorption, retention, and conversion.

Orthogonal experiment results showed that vegetation type, substrate type, and substrate thickness had no significant effect on other indexes. SS is mainly affected by the substrate. But the bulk density of the modified perlite and recycled bricks was similar. Therefore, the retention capacity of SS was basically the same. When the thickness of the substrate layer reached to 100 mm, green roofs had the ability to resist storm erosion. The particles of substrate layer especially in the lower layer were not easy to wash into the storage layer to influence the effluent quality. Phosphorus removal in the system mainly depends on substrate adsorption, chemical precipitation, and plants uptake. Substrate thickness had little effect on phosphorus removal from the results. It was found that there was no significant difference in the adsorption capacity of phosphorus between the modified perlite and recycled bricks. In addition, the uptake of phosphorus by plants was similar too. That means the phosphorus in green roofs runoff mainly came from the nutrients which were carried to promote plant growth (Mitchell et al. 2017).

From the results of orthogonal experiment, it was concluded that the optimal green roof was 2# green roof. The vegetation was *Ophiopogon japonicus*. The substrate was modified perlite, while the substrate thickness was 200 mm.

Interannual variation analysis of runoff quality

Interannual variation analysis of runoff quality of optimal green roof

As shown in Fig. 4, the EMCs and fluctuations of SS and COD in the effluent from the 2# roof were reduced with years. That means the ability of controlling pollutants of 2# green roof became stable over time. The EMCs of SS decreased from 31.2 mg/L in the first year to 21.5 mg/L in the third year, while that of COD decreased from 35.0 to 21.2 mg/L.

The average SS and COD concentrations of the effluent from 2# roof were basically the same for the first 2 years and significantly reduced in the third year. In the first year, the plants roots did not effectively fix the soil. Moreover, the planting soil was shallow and soft, resulting in rainstorm affecting it greatly. As shown in the results, the effluent EMC of SS and COD was high and unstable. In the second year, due to the long dry period, the vegetation did not have a good environment for growing. Therefore, the ability of fixing soil and absorbing organic matters by plants and microorganisms was weakened, making the effluent EMCs of SS and COD basically consistent with the first year. The reasons why effluent EMCs of SS and COD in the third year were significantly reduced were that the vegetation grew well which means the plants roots developed well. In addition, the natural sedimentation of the substrate layer enhanced the scour resistance. As a result, the ability of green roof to retain SS and COD was enhanced, so that the effluent EMCs of SS and COD reduced significantly in the third year.

As shown in Fig. 5, the EMC of NH_4^+-N, NO_3^--N, and TN of the 2# green roof runoff fluctuated greatly because of green roofs purification capacity, dry, and wet deposition (Zhang et al. 2015). It could be concluded that the ability of nitrogen control was unstable in the 3 years. The EMCs of NH_4^+-N in consecutive 3 years were 0.53 mg/L, 0.30 mg/L, and 0.40 mg/L in turn, showing a trend of decreasing with years. The EMCs of NO_3^--N were 0.33 mg/L, 0.21 mg/L, and 0.58 mg/L, respectively. The EMCs of TN in consecutive 3 years were 1.02 mg/L, 0.71 mg/L, and 1.07 mg/L, fluctuating greatly. The EMCs of TP were relatively stable which varied within 0.17~0.20 mg/L.

As a whole, the effluent EMC of NH_4^+-N decreased with years. The lowest EMC appeared in the second year. The reason is that the amount of adsorbed NH_4^+ is closely related to rainfall amount, rainfall intensity, and the number of days of drought. In the second year, the dry period was longer than the other 2 years, and the rainfall amount was less. NH_4^+-N is converted into NO_3^--N by nitrification during the longer dry period, resulting in the NH_4^+-N concentration of the effluent from the green roof lower than precipitation. With the gradual stabilization of the green roof, the number of nitrifying bacterial flora has gradually increased, making the EMC of NH_4^+-N reducing with years.

The change of the nitrogen-imparting forms in nature influences each other. That means the concentration of NO_3^--N is closely related to NH_4^+-N and TN (Mentens et al. 2006). NH_4^+-N could be converted into NO_3^--N through nitrification by nitrifying bacteria. Therefore, the NO_3^--N concentration of the effluent from the 2# green roof was not only affected by NO_3^--N from precipitation and substrate nutrients, but also affected by NH_4^+-N and nitrifying. During the monitoring period, the effluent EMCs of NO_3^--N increased over time, with the most significant increase in the third year. The reason may be that the nitrifying bacteria grew stably, resulting in stable nitrification during the drought period. The NH_4^+-N adsorbed by the substrate could be more effectively converted into NO_3^--N (Blecken et al. 2010; Lucas and Greenway 2008). Maybe that caused the EMC of NO_3^--N fluctuated greatly. However, the EMC of NO_3^--N in precipitation was stable every year. It was estimated that the green roof was still not stable after 3 years.

The source of TN in the green roof runoff is divided into two parts. One is the nitrogen carried by the rainfall which is mainly the ammonia nitrogen. The other part is from the scouring of the substrate, including ammonia nitrogen, nitrate nitrogen, and organic nitrogen. As shown in Fig. 4, the EMCs of TN in the first and third year of the runoff were comparable. Due to the light rain, longer drought and fewer monitoring rainfall events in the second year, the EMCs of NH_4^+-N and

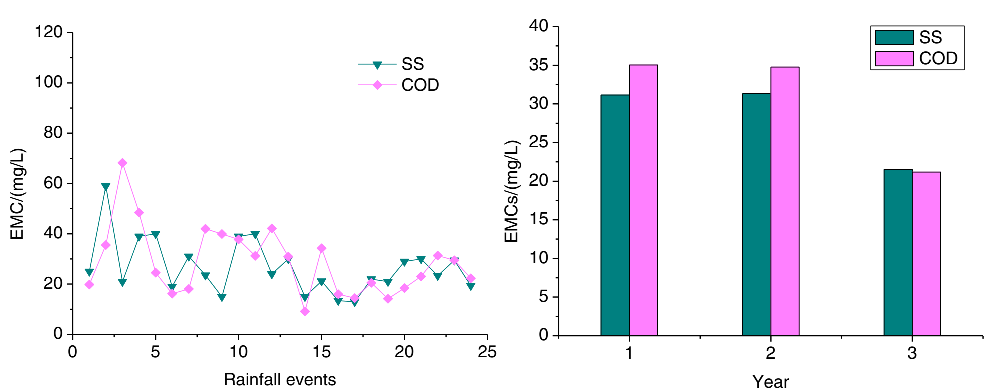

Fig. 4 EMC and EMCs of SS and COD of optimal green roof

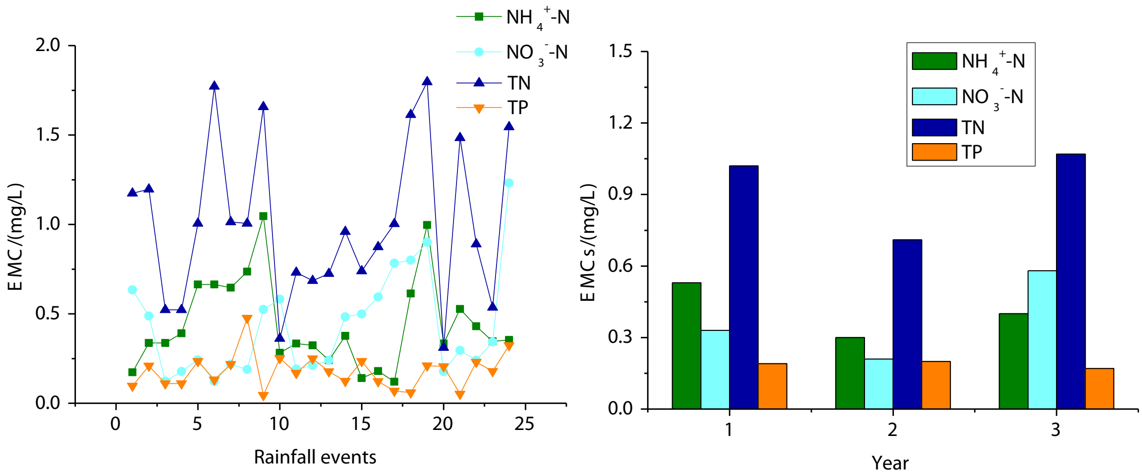

Fig. 5 EMC and EMCs of NH_4^+-N, NO_3^--N, TN, and TP of optimal green roof

NO_3^--N were generally lower. Therefore, the EMCs of TN was lower in the second year. According to the above-mentioned interannual variation of NH_4^+-N and NO_3^--N, the EMCs of NH_4^+-N decreased while NO_3^--N increased with years, resulting in the interannual variation of TN was not obvious.

Teemusk and Mander's research on the changes of runoff quality from green roofs in Estonia found that the total phosphorus and phosphate concentrations did not gradually decrease with running time, but the average annual concentration was volatile (Teemusk and Mander 2011). However, Mark E. Mitchell's research on phosphorus in green roof showed that the TP concentration decreased with year (Mitchell et al. 2017). But the EMC of TP of 2# green roof runoff in this study remained stable. The reason may be that phosphorus in green runoff was mainly derived from the substrate. In order to ensure the normal growth of plants, it was necessary to apply phosphorus fertilizer. Therefore, the TP concentration in the substrate did not change significantly during the years, making the effluent EMCs of TP stable.

Runoff quality of optimal green roof

To investigate the water quality of optimal green roof(2# green roof) after running for three years, the runoff quality of the 2# green roof in the third year (the 11 rainfall events are shown in Table 3) was compared with water quality of precipitation and effluent from a traditional roof (Fig. 6). The green roof runoff quality was influenced by factors such as substrate type, substrate thickness, vegetation type, rainfall intensity, drought days, and human activities. Substrate type, substrate thickness, and vegetation type are controllable factors. These factors can be optimized artificially. The rainfall intensity, drought days, and human activities are uncontrollable factors. They comprehensively affect green roof runoff quality. From Table 3 and Fig. 6, it could be concluded that the effects of rainfall intensity and drought days on water quality were not very significant. The reason might be that the runoff quality was influenced by many uncontrollable factors. Therefore, the effect of rainfall intensity or drought days on water quality was not significant.

However, under the comprehensive influence of various factors, the average value (EMCs) of green roof had a certain relative relationship with precipitation and traditional roof (Fig. 6). For the EMCs of SS, COD, TN, and TP, traditional roof > 2# green roof > precipitation. As for the EMCs of NH_4^+-N, traditional roof > precipitation > 2# green roof. On the contrary, for the EMCs of NO_3^--N, 2#green roof > traditional roof > precipitation. Overall, the water quality indexes of green roof runoff were higher than that in precipitation except NH_4^+-N. Compared with traditional roof, the effluent quality from 2# green roof was generally better than traditional roof. However, the NO_3^--N of 2# green roof was higher than that of traditional roof.

Table 3 The 11 rainfall events in 2015

Rainfall events	Drought days before rainfall (d)	Rainfall amount (mm)	Duration of rainfall (min)	Rainfall intensity (mm/h)
1	1.0	6.10	33	11.09
2	2.0	4.20	30	8.40
3	1.5	112.00	36	186.70
4	2.0	6.60	89	4.40
5	2.0	51.60	125	24.80
6	1.0	19.80	98	12.10
7	1.0	23.10	132	10.50
8	5.5	25.80	34	45.50
9	3.0	17.90	24	44.80
10	4.0	15.30	37	24.80
11	3.5	21.90	72	18.20

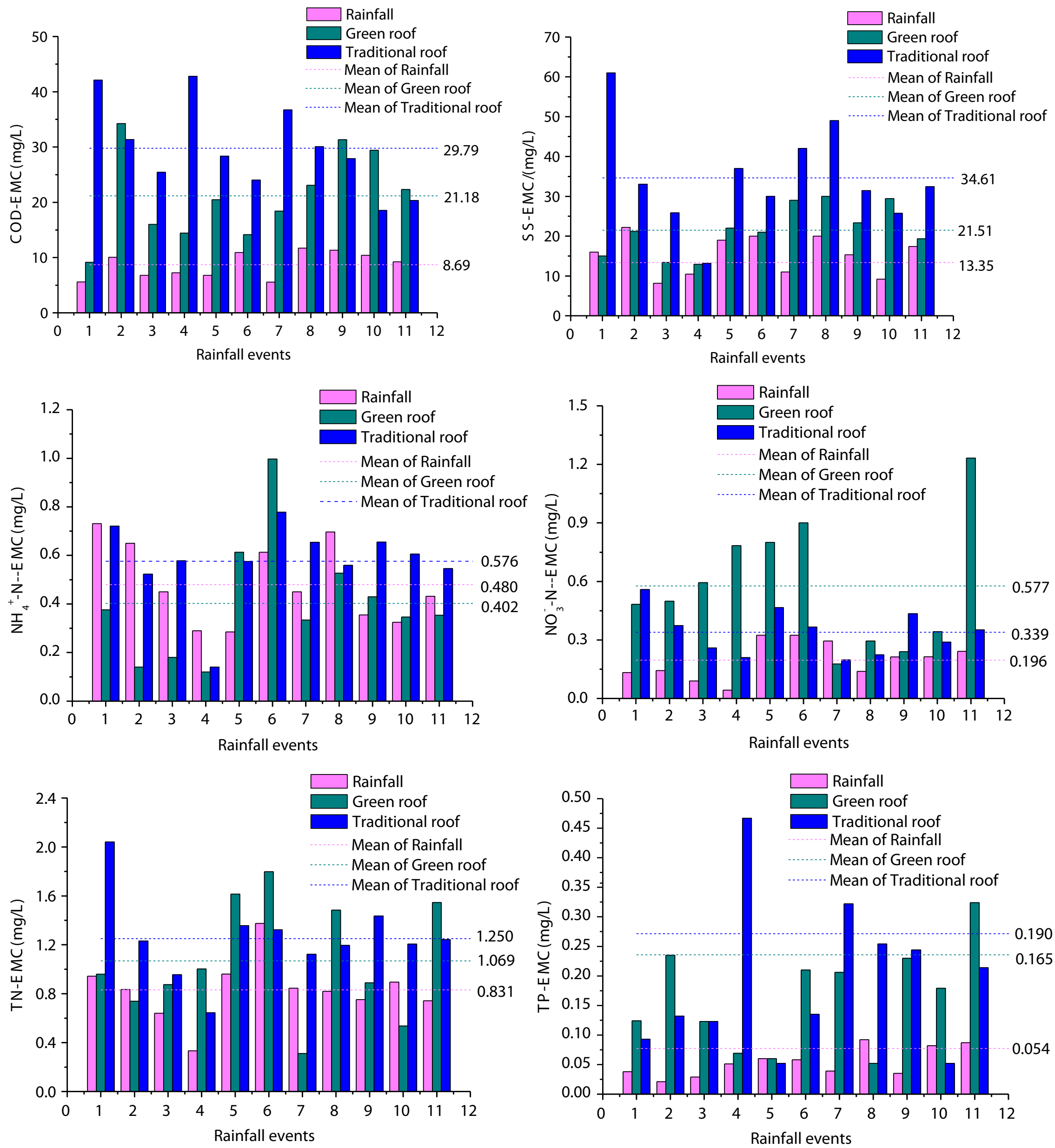

Fig. 6 Comparison of 2# green roof, precipitation, and traditional roof runoff quality

The EMCs of SS, COD, NO_3^--N, TN, and TP in the runoff from the 2# green roof increased by 28.65%, 58.96%, 65.92%, 22.27%, and 67.44%, respectively, compared to the precipitation. However, the EMCs of NH_4^+ decreased by 19.42%. The fixation ability of the plants roots was difficult to resist the scouring of rainstorm, resulting in the EMCs of SS in the green roof effluent significantly higher than that in the precipitation. A small part of the organic matter in the effluent came from precipitation, and most of it came from substrate. The structure of green roofs directly connected to the storage layer under the filter layer, inevitably leading to organic matter in the substrate layer penetrating to the effluent and increasing the COD concentration in the effluent. After rainwater seep through the green roof, the NH_4^+-N concentration decreased because NH_4^+ is a water-soluble cation that can exchange ion with organic matter in the soil or be adsorbed by negatively charged clay, thereby reducing the effluent NH_4^+-N concentration (Hsieh et al. 2007). The high oxygen content in the substrate layer and temperature is suitable for nitrifying bacteria growth, resulting in strong nitrification. Therefore, the NO_3^--N concentration increased from 0.20 mg/L to 0.58 mg/L after rainwater seeping through the green roof. The NH_4^+ adsorbed by the substrate layer nitrated to NO_3^--N during the dry period, so that the NO_3^--N concentration in the next rainfall runoff increased significantly. The NH_4^+-N concentration in green roof effluent was lower than precipitation, while NO_3^--N was higher compared with precipitation. That means the increased nitrogen is mainly from the scouring of the substrate layer. In addition, the organic nitrogen source added to maintain plant growth inevitably increased the TN concentration in effluent. Some research reported that the TP concentration may be higher in green roof through flow than precipitation, although it was lower than in runoff (Gregoire and Clausen 2011; Teemusk and Mander 2011). In this study, after the rainwater seep through the green roof, the TP concentration in the effluent obviously increased which means that green roof releases TP. Similar to the scouring mechanism of nitrogen, the increased TP concentration in the effluent mainly from the substrate layer. The modified perlite adsorbs a little phosphorus, and *Ophiopogon japonicus* intake phosphorus is not much as well. As a result, the phosphorus retention ability of substrate layer is weak.

After 3 years, the EMCs of SS, COD, NH_4^+-N, TN and TP in the runoff from the 2# green roof decreased by 37.85%, 28.89%, 30.25%, 14.52%, and 12.93%, respectively, compared to the traditional roof. But the EMCs of NO_3^--N increased by 69.91%. Due to the nitrification of nitrifying bacteria, NO_3^--N concentration in green roof is higher than traditional roof.

Conclusion

According to the analysis of the green roofs runoff quality during the monitoring period, the following conclusions could be drawn.

Vegetation type had a significant effect on the COD concentration of runoff. *Ophiopogon japonicus* had a better COD control than the Yulong grass because of its good environmental adaptability. The substrate type and substrate thickness had significant effects on the NH_4^+-N concentration. The good ventilation condition of modified perlite promoted the progress of nitrification. At the same time, the increase of substrate thickness was conducive to absorb more NH_4^+, thereby reducing the NH_4^+-N concentration of runoff. Therefore, the optimal green roof was obtained: *Ophiopogon japonicus* and 200 mm thick modified perlite substrate (2# roof).

The interannual variations of the water quality indexes of the green roofs are different. With the growth of vegetation, the fixed ability of the plants roots increased, and the EMCs of SS and COD decreased with years. Due to the stability of the green roof substrate, the ability of adsorbing NH_4^+ by the negatively charged substrate gradually increased. As a result, the EMCs of NH_4^+-N decreased with years. With the proliferation and stability of nitrifying bacteria, nitrification gradually enhanced. The EMCs of NO_3^--N increased over time. However, as the EMCs of NH_4^+-N decreased, but NO_3^--N increased, the interannual variations of TN were not significant, showing a certain degree of volatility. TP is mainly affected by the leaching of the substrate. The EMCs of TP remained stable.

After 3 years, although the runoff quality of the green roofs effluent has improved, the green roofs are still a source of pollutants. The concentrations of these water quality indexes of runoff were higher than precipitation except NH_4^+-N. However, the effluent quality of the green roof was generally better than that of the traditional roof. Compared with the traditional roof, the EMCs of SS, COD, NH_4^+-N, TN, and TP were reduced by 37.85%, 28.89%, 30.25%, 14.52%, and 12.93%, respectively. But the EMCs of NO_3^--N increased by 69.91%. Green roofs have a certain ability to control the pollution, but the control of NO_3^--N needs to be further strengthened. A long-term process may be necessary to make the green roof runoff quality basically equal to or better than that of precipitation.

To improve the water quality of green roof effluent, for one thing, optimize controllable factors artificially, such as substrate and vegetation. For example, at present, more work is required to find a more efficient local substrate for the green roof, which can reduce the water quality problems from green roof runoff. Reducing the cost of green roofs and improving maintenance management are also critical to the development of green roofs. For another, reducing the release of pollutants from the human activities into the environment is the most fundamental way to reduce water pollution.

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References

Archer NA, Quinton JN, Hess TM (2002) Below-ground relationships of soil texture, roots and hydraulic conductivity in two-phase mosaic vegetation in South-east Spain. J Arid Environ 52:535–553

APHA (2005) Standard methods for the examination of water and wastewater. American Public Health Association (APHA), Washington, DC, USA

Berndtsson JC (2010) Green roof performance towards management of runoff water quantity and quality: a review. Ecol Eng 36:351–360

Berndtsson JC, Bengtsson L, Jinno K (2009) Runoff water quality from intensive and extensive vegetated roofs. Ecol Eng 35:369–380

Berndtsson JC, Emilsson T, Bengtsson L (2006) The influence of extensive vegetated roofs on runoff water quality. Sci Total Environ 355:48–63

Blecken GT, Zinger Y, Deletic' A, Fletcher TD, Hedstrm A, Viklander M (2010) Laboratory study on stormwater biofiltration: nutrient and sediment removal in cold temperatures. J Hydrol 394:507–514

Buffam I, Mitchell ME, Durtsche RD (2016) Environmental drivers of seasonal variation in green roof runoff water quality. Ecol Eng 91:506–514

Carlson C, Barreteau O, Kirshen P, Foltz K (2015) Storm water management as a public good provision problem: survey to understand perspectives of low-impact development for urban storm water management practices under climate change. J Water Resour Plan Manag 141:04014080

Carpenter CMG, Todorov D, Driscoll CT, Montesdeoca M (2016) Water quantity and quality response of a green roof to storm events: experimental and monitoring observations. Environ Pollut 218:664–672

Emilsson T (2008) Vegetation development on extensive vegetated green roofs: influence of substrate composition establishment method and species mix. Ecol Eng 33:265–277

Getter KL, Rowe DB, Robertson GP, Cregg BM, Andresen JA (2009) Carbon sequestration potential of extensive green roofs. Environ Sci Technol 43:7564–7570

Gregoire BG, Clausen JC (2011) Effect of a modular extensive green roof on stormwater runoff and water quality. Ecol Eng 37:963–969

Hsieh CH, Davis AP, Needelman BA (2007) Nitrogen removal from urban stormwater runoff through layered bioretention columns. Water Environ Res 79:2404–2411

Harper GE, Limmer MA, Showalter WE, Burken JG (2015) Nine-month evaluation of runoff quality and quantity from an experiential green roof in Missouri, USA. Ecol Eng 78:127–133

Kok KH, Sidek LM, Chow MF, Abidin MRZ, Basri H, Hayder G (2016) Evaluation of green roof performances for urban stormwater quantity and quality controls. Intl J River Basin Manage 14:1–7

Lucas WC, Greenway M (2008) Nutrient retention in vegetated and non-vegetated bioretention mesocosms. J Irrig Drain Eng 134:613–623

Le Coustumer S, Fletcher TD, Deletic A, Barraud S, Poelsma P (2012) The influence of design parameters on clogging of stormwater biofilters: a large-scale column study. Water Res 46:6743–6752

Liu H, Jia Y, Niu C (2017) “Sponge city” concept helps solve China’s urban water problems. J Environ Earth Sci 76:473

Mentens J, Raes D, Hermy M (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century. Landsc Urban Plan 77:217–226

MacAvoy SE, Plank K, Mucha S, Williamson G (2016) Effectiveness of foam-based green surfaces in reducing nitrogen and suspended solids in an urban installation. Ecol Eng 91:257–264

Mitchell ME, Matter SF, Durtsche RD, Buffam I (2017) Elevated phosphorus: dynamics during four years of green roof development. Urban Ecosyst 20:1121–1133

Nagase A, Dunnett N (2012) Amount of water runoff from different vegetation types on extensive green roofs: effects of plant species, diversity and plant structure. Landsc Urban Plan 104:356–363

Rowe DB (2010) Green roofs as a means of pollution abatement. Environ Pollut 159:2100–2110

Ren NQ, Wang Q, Wang QR, Huang H, Wang XH (2017) Upgrading to urban water system 3.0 through sponge city construction. Front Environ Sci Eng 11:9

SEPA (2002) Water and wastewater monitoring and analysis method, Fourth edn. China Environmental Science Press, Beijing

Susca T, Gaffin SR, Dell’Osso GR (2011) Positive effects of vegetation: urban heat island and green roofs. Environ Pollut 159:2119–2126

Teemusk A, Mander U (2006) The use of greenroofs for the mitigation of environmental problems in urban areas. 4th Int Conf on Urban Regeneration and Sustainability 93: 3–17

Teemusk A, Mander U (2011) The influence of green roofs on runoff water quality: a case study from Estonia. Water Resour Manag 25: 3699–3713

Vijayaraghavan K, Joshi UM, Balasubramanian R (2011) A field study to evaluate runoff quality from green roofs. Water Res 46:1337–1345

Wong NH, Cheong DKW, Yan H, Soh J, Ong CL, Sia A (2003) The effects of rooftop garden on energy consumption of a commercial building in Singapore. Energy Build 35:353–364

Xia J, Zhang YY, Xiong LH, He S, Wang LF, Yu ZB (2017) Opportunities and challenges of the Sponge city construction related to urban water issues in China. Sci China Earth Sci 60:652–658

Zhao JW, Shan BQ, Yin CQ (2007) Pollutant loads of surface runoff in Wuhan City Zoo, an urban tourist area. J Environ Sci 19:464–468

Zhang QQ, Miao LP, Wang XK, Liu DD, Zhu L, Zhou B, Sun JC, Liu JT (2015) The capacity of greening roof to reduce stormwater runoff and pollution. Landsc Urban Plan 144:142–150