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SUSTAINABLE DEVELOPMENT OF ENERGY, WATER AND ENVIRONMENT SYSTEMS

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The influence of extensive green roofs on rainwater runoff quality: a field-scale study in southwest China

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Abstract
Green roofs of young age (≤ 5 years old) have boomed in China since the Sponge City Construction initiative was implemented. To use green roofs for better urban stormwater management, it is necessary to investigate the runoff quality of field-scale young green roofs as well as to examine common plant-media combination in green roof projects of China. The influence of two *Sedum*-vegetated extensive green roofs of different designs at the early stage of operation on runoff water quality was investigated by a field-scale study in Chengdu, southwest China. The water quality parameters of pH, suspended solids (SS), chemical oxygen demand (COD), total phosphorus (TP), and total nitrogen (TN) of rainwater (that is, input water for roofs), runoff from the two green roofs, and runoff from a conventional concrete control roof were compared. The results indicate that both green roofs mainly act as pollutant sources with greater concentrations of SS, COD, and TP when compared with rainwater quality. When compared with runoff quality from the control roof, greater TP concentrations in runoff from one green roof with commercially available substrate were observed. Attention should be paid to TP leaching in runoff for retrofitted green roofs with imported commercial substrates in that region. Adoption of pre-cultivated *S. lineare* mats of low fertility and localized soils may reduce nutrient leaching in green roof runoff. A nitrogen-rich substrate is not recommended for a plant community of a single species. Investigation of the effect of green roofs on water quality involving various pollutants in the long run is recommended.

Keywords Green roofs · *Sedum* · Stormwater · Runoff quality · Nutrients · Sponge City

Introduction

Green roofs have become increasingly popular in recent years (Carson et al. 2013; Dvorak and Volder 2010) due to numerous environmental, economic, and esthetic benefits (Getter and Rowe 2006). A green roof is a rooftop treatment involving the addition of plants, growing media, and other functional layers (e.g., filter layer and drainage layer). Based on the thickness of the growing media, green roofs can be divided into extensive or intensive category. Extensive green roofs

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have a shallow growing media layer (≤ 15 cm) and low maintenance plants, which are mainly constructed for environmental benefits. Intensive green roofs are thicker and emphasize esthetic considerations. One notable environmental benefit of green roofs is stormwater management (Fassman-Beck et al. 2013; Moran and Jennings 2003). Runoff quantity from extensive green roofs can be notably less than rainfall, specifically 34 to 83% of rainfall according to various studies (Carpenter and Kaluvakolanu 2011; Carter and Rasmussen 2006; Fassman-Beck et al. 2013; Gregoire and Clausen 2011; Mentens et al. 2006; Stovin 2010; Vanwoert et al. 2005). When water flows through various layers in green roofs, the initiation of stormwater runoff is delayed and the peak runoff is also attenuated compared with that from a conventional impervious roof (Czemiel Berndtsson 2010).

Runoff quality from green roofs, however, is less studied compared to runoff quantity, though it is an important aspect in stormwater management. Pilot-scale green roof experiments are widely used for water quality research (Chai et al. 2018; Chen et al. 2018; Monteiro et al. 2017; Wang et al. 2017; Zhang et al. 2014), while field-scale green roofs are investigated to a lesser extent (Buffam et al. 2016; Carpenter et al. 2016; Mitchell et al. 2017; Todorov et al. 2018). It should be noted that conditions experienced by full-sized green roofs cannot be reproduced strictly by pot experiments (Dusza et al. 2017). Water quality performances of full-scale green roofs in urban watersheds, especially in developing countries (Vijayaraghavan 2016) are needed to be quantified. Green roofs may be either a source or a sink of runoff pollutants (Buffam and Mitchell 2015; Czemiel Berndtsson et al. 2006; Czemiel Berndtsson 2010; Gregoire and Clausen 2011; Hathaway et al. 2008; Moran et al. 2005; Teemusk and Mander 2011), as various factors, such as substrate composition (Toland et al. 2012), dynamics of rainfall (Teemusk and Mander 2011), and maintenance (Buffam et al. 2016), roof age (Mitchell et al. 2017) may all influence runoff quality of green roofs. Newly constructed green roofs (e.g., ≤ 5 years old) tend to release nutrients of high levels (Harper et al. 2015; Mitchell et al. 2017; Todorov et al. 2018), potentially posing a threat to water bodies in cities. Harper et al. (2015) observed initial TP and TN concentrations in runoff from several month-old green roof plots can be beyond 30 mg/L and 60 mg/L, respectively. Todorov et al. (2018) found that averaged annual TP and TN runoff concentrates of 0–4 year-old green roofs in the field were 1.46 ± 1.02 mg/L and 2.87 ± 2.62 mg/L, respectively. More studies should be conducted for green roofs at the early stage of operation which may have the nutrient leaching issue.

Young extensive green roofs, typically ranging from 0 to 5 years old in China, as well as other low-impact development technologies, have boomed nationwide since the Sponge City Construction initiative was implemented in 2014 (Jia et al. 2017). More existing roofs are expected to be retrofitted as green roofs along with the Sponge City Construction, aiming for a healthy urban water cycle. However, as green roof industry is still in its infancy in China, selections of plant and growing media for green roofs are quite limited. The plant *Sedum lineare* and local soils are frequently used for green roof projects, without considering imported green roof components due to cost and/or non-compatibility issues (Vijayaraghavan 2016). The role of *Sedum* plants on green roof runoff quality is not clear. Aitkenhead-Peterson et al. (2011) observed that *Sedum kamtschatium* led to higher nitrate-N concentrations in leachate, compared with two other succulent species *Delosperma cooperi* and *Talinum calycinum*. Similarly, Monterusso et al. (2004) found nitrate-N concentrations from *Sedum*s were higher than herbaceous perennials. On the contrary, Beck et al. (2011) found green roof trays with *Sedum hispaniucum* released much less nutrients compared to green roof trays with grass *Lolium perenne*. Chen et al. (2018) examined the effects of three substrates and three types of plants on leachate quality and noticed the lowest nitrate-N concentration was from the plant *Sedum nussbaumerianum* regardless of the substrate type. The type and depth of growing media can also influence leachate quality of green roofs. Dusza et al. (2017) investigated natural sandy-loam soil and commercial artificial substrate at different depths and observed different NO_3-N leaching patterns when they were planted with the same Crassulaceae species (*Sedum album*, *Sedum acre*, *Hylotelephium telephium*, and *Hylotelephium maximum*). When the depth was fixed at 10 cm, there was no significant difference between the two growing media regardless of their quite different nitrogen contents. However, when the depth was fixed at 30 cm, a much less NO_3-N concentrate was observed in leachate from the natural soil in relative to the artificial substrate. As leachate quality is also influenced by interactions between plants and growing media (Chen et al. 2018; Dusza et al. 2017), it is hard to predict water quality performance of a green roof with a specific plant-media combination. So far in China, field studies regarding water quality performance of green roofs with imported/localized components are needed to inform prospective developers as well as policy makers who have an interest in green roof installations.

The purpose of this study is to qualify water quality performances of two field-scale extensive green roofs of different designs adopting localized/imported components, in the city of Chengdu, a "Sponge City" undergoing construction in southwest China. The physicochemical characteristics of runoff from the two young green roofs and a concrete control roof as well as rainwater (input water for roofs) were examined for 6 months during the first installation year. Water quality parameters of concern were pH, suspended solids (SS), chemical oxygen demand (COD), total phosphorus (TP), and total nitrogen (TN). There are several questions of interests: whether extensive green roofs at a very young age act as a sink for contaminants? what are runoff pollutant levels from extensive green roofs with localized/imported components in urban settings? Is there any suggestion on green roof technology for better stormwater management?

Materials and methods

Experimental setup

The monitoring site involved two multistory buildings of similar height located at the State Key Laboratory of Hydraulics and Mountain River Engineering in Chengdu city (30.634 N, 104.081 E), Sichuan Province in southwest China. The two buildings were approximately 25 m apart and one of smaller size was retrofitted as extensive green roofs whereas the other one remained a bare concrete roof, a common roof type in the region.

The retrofitted green roofs were constructed into two plots, each with a size of 4.5 m × 20 m according to different design guidelines. One plot was constructed according to local guidelines (Government of Chengdu City 2005), referred to as Green Roof A, consisting of a 50-mm carbon residue drainage layer, a geotextile mat, a 60-mm topsoil layer, and a *Sedum lineare* mat. The other plot was constructed according to well-recognized literature guidelines (e.g., FLL (2002)), referred to as Green Roof B, consisting of a root barrier, a protection moisture mat, a 25-mm drainage board, a filter sheet, a 60-mm artificial soil (or called substrate) layer, and a *Sedum lineare* mat. Figure 1 shows the cross-section designs of the two green roofs. The concrete roof of the nearby building was chosen as the control roof, referred to as Control Roof C.

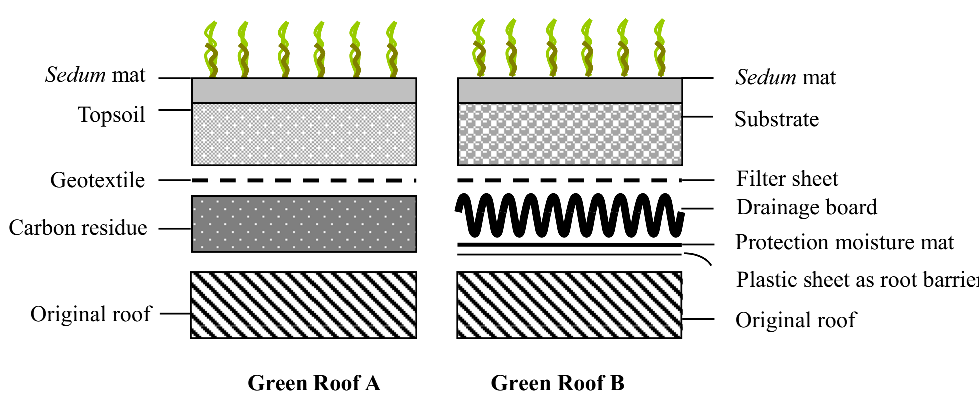
The same *S. lineare* mat on the top of each green roof (Fig. 1) was purchased in the local market, which was pre-cultivated in a rural area of Chengdu and transplanted onto the green roofs. However, growing media for the two green roofs (that is, topsoil in Green Roof A and substrate in Green Roof B) were quite different. Topsoil was a localized component, being transported from a nursery in Chengdu. Substrate was an imported commercial product from Beijing Greenlink Küsters Co., Ltd., using crushed brick as its aggregate. The dry bulk densities of topsoil and substrate were 1.47 g/cm^3 and 1.16 g/cm^3, respectively. The saturated hydraulic conductivity of natural topsoil (0.017 mm/s) was noticeably less than that of artificial substrate (≥ 1 mm/s, FLL compliant according to the supplier). Visually, particle sizes of topsoil were primarily less than those of substrate (Fig. 2).

Figure 3 shows a photograph of the two green roofs during the study period. No fertilizer was applied to either of the green roofs after establishment in January. It was suspected that different materials used for the two green roofs would result in differences in runoff quality. Therefore, samples of major materials from both green roofs were taken to a testing center of Sichuan Academy of Agricultural Sciences, Chengdu, for nutrient analysis in Feb, prior to a water quality monitoring program on-site. Materials were re-tested after several months of exposure when the monitoring program ended in Sep (Table 1). TN was measured by the modified Kjeldahl method and TP was measured by the NaOH melt-colorimetry method (Lu 1999). It can be seen from Table 1 that the *Sedum* mat soil of initial high nutrient contents (TP of 2.04 g/kg, TN of 1.56 g/kg) experienced noticeable decreases in TN and TP contents in both green roofs. While TP contents in both growing media remained stable, TN contents in topsoil and substrate underwent different changes. The material carbon residue was only used for Green Roof A, serving a function similar to the drainage board in Green Roof B (Fig. 1). This material was not tested for nutrients analysis in the beginning, since the material was believed to have no phosphorus/nitrogen compounds during a manufacturing process involving high-temperature incineration of coal-based materials. At the end of the study, TP and TN in the carbon residue were believed to increase to 0.56 g/kg and 0.82 g/kg, respectively.

Runoff quality analysis

Chengdu has a humid subtropical climate, receiving approximately 850 mm of rainfall per year on average. June through September are the wettest months in Chengdu, accounting for

Fig. 1 Cross-section structures of green roofs



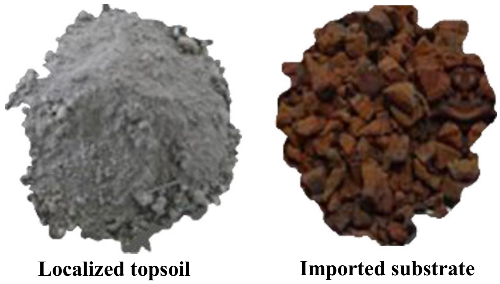


Fig. 2 Photograph of two growing media for green roofs

75% of the annual rainfall (Liu 2010). Thirteen rain events covering a wide range of rainfall depths occurring between April and September (Table 2) were monitored in a year receiving approximately 870 mm of rainfall. A rain event was considered to be any event which resulted in more than 0.5 mm of rain preceded and followed by a minimum of 6 h without measurable rainfall (Berghage et al. 2009). Since summer (June to August) in Chengdu was the rainy season, frequently zero antecedent dry day is presented in Table 2.

Rainfall characteristics were measured by a rain gauge (RG3-M, USA Onset Company) on the 5-story retrofitted roof (Fig. 3). Rainwater samples were collected during heavy rains to establish background concentrations of the pollutants of interest. Discharged green roof runoff from the 90-m^2 drainage area of each green roof was conveyed by the corresponding drainage pipe to the ground floor, where water sampling took place. Water grab samples were taken manually at a fixed time (i.e., 1 L every 20 min) for at least 3 h during a rainfall event. Dynamic flow process was recorded automatically by a water level logger (U20-001-04, USA Onset Company) installed in a weir-box where drainage water passed through. As for the control roof, one drainage pipe responsible for 300 m^2 of roof area was monitored at its outlet by the same methods for flow quantity and water quality. Grab samples in the same event from each roof site were then combined into one flow-weighted composite sample for water quality analysis. Sampling procedures followed those in the U.S. EPA NPDES Storm Water Sampling Guidance Document (USEPA 1992) and the Technology Acceptance Reciprocity Partnership (TARP 2003).

Fig. 3 Photograph of Green Roof A (in left) and Green Roof B (in right) during the monitoring period

Table 1 Analysis of phosphorus and nitrogen in green roof construction materials

Roof name	Material	Content in Feb (g/kg)	Content in Sep (g/kg)
Green Roof A	*Sedum* mat soil		
	TP	2.04	1.12
	TN	1.56	1.07
	Topsoil		
	TP	0.88	0.86
	TN	0.63	0.89
	Carbon residue		
	TP	ND	0.56
	TN	ND	0.82
Green Roof B	*Sedum* mat soil		
	TP	2.04	1.04
	TN	1.56	1.30
	substrate		
	TP	0.82	0.83
	TN	1.19	0.51

ND not determined, assumed zero because of the incineration method of manufacturing carbon residue

Composite samples were then analyzed for pH, SS, COD, TP, and TN. The preservation and analysis of the water samples followed standard methods specified by the Chinese State Environment Protection Agency (CSEPA 2002c). Specifically, the methods were method with portable pH meter for pH, gravimetric method for SS, dichromate method for

Table 2 Hydrologic characteristics of the thirteen monitored rainfall events

Event number	Date	Rainfall depth* (mm)	Rainfall duration (hours)	Antecedent dry weather period
1	4/6	9.2	17	17.6
2	5/8	22.8	14.6	27.4
3	5/10	1.0	5.2	14
4	5/26	7.2	9.2	11
5	5/30	> 11.4*	7.4	2.5
6	6/28	2.4	5.5	10.9
7	7/7	61.2	3.2	209.4
8	7/13	16.6	5.1	32.6
9	8/11	> 16.4*	< 2.5	120
10	8/13	> 27.0*	7	29.5
11	8/18	24.0	7.6	101
12	8/19	51.8	20	14.5
13	9/5	11.2	8.4	9.9

*Rainfall depth was unknown when the rain gauge fell down due to wind

COD, ammonium molybdate spectrophotometric method for TP, and alkaline potassium persulfate digestion-UV spectrophotometric method for TN. Not all the water parameters were tested for every single rain event.

The analysis of flow-weighted composite samples from different rainfall events provided the event mean concentrations (EMCs) of water quality parameters. The EMC distribution of each water quality parameter was checked for normality and data were log-transformed when needed. Data for each water quality parameter from different sources (i.e., rainfall, green roofs, control roof) were then subjected to analysis of variance (ANOVA; p = 0.05). Differences among sources were determined by the least significant difference (LSD) method.

Results

Table 3 shows the arithmetic mean EMCs with standard deviations (SD) of water quality parameters. The pH levels in runoff from different roofs were similar, from 7.61 (Green Roof B) to 7.79 (Green Roof A). There was no significant difference (F = 0.579, p = 0.567) detected among pH levels of roof runoff. However, compared to rainwater, the pH of roof runoff was significantly higher (F = 16.133, p = 0.000).

The rainwater was quite clean, with an SS value under the detection limit of 5 mg/L. On the other hand, the SS values varied from 8.42 mg/L in runoff from Green Roof A to 12.31 mg/L in runoff from Control Roof C. There was no significant difference (F = 0.933, p = 0.403) in SS between any pairs of roof runoff datasets.

The COD values varied from the lowest value of 3.12 mg/L in rainwater to the highest value of 27.54 mg/L in the runoff from Green Roof B. Significant differences were difficult to detect when considering the high variability of COD in roof runoff. Results showed that while there was no significant difference (F = 1.658, p = 0.205) among COD values in runoff from different roofs, the COD concentrations in roof runoff were significantly greater (F = 10.215, p = 0.000) than those in rainwater.

The TP values varied from a low value of 0.03 mg/L in rainwater to a high value of 0.16 mg/L in the runoff from Green Roof B. The TP value of rainwater was significantly lower than those in runoff from different roofs (F = 16.672, p = 0.000). Significant differences were also detected for TP in runoff from different roofs (F = 13.859, p = 0.000). While TP values in runoff from Green Roof A and Control Roof C were not significantly different from each other (p = 0.071), these values were significantly lower than that in runoff from Green Roof B (p = 0.003 and 0.000).

The TN values varied from a low of 2.18 mg/L in rainwater to a high of 15.69 mg/L in the runoff from Green Roof B. Significant differences in TN not only existed between rainwater and roof runoff (F = 5.360, p = 0.003) but also among roof runoff (F = 5.737, p = 0.007). Significant differences came from TN of rainwater and Green Roof B runoff (p = 0.003) as well as from TN of runoff from two green roofs (p = 0.002).

Discussion

The pH value of 6.26 in the rainwater suggests that acid rainfall (pH ≤ 5.6) in Chengdu city is not an issue. Alkalescent values from two green roofs and the control roof may link to their roof materials containing basic oxides or base-forming cations (Wang et al. 2007; Zhang et al. 2014), such as Fe_2O_3 from crushed bricks and Ca^{2+} from concrete blocks. The fact that green roofs influence runoff water quality by increasing input rainwater pH in the study is consistent with other studies (Bliss et al. 2009; Buffam et al. 2016; Chen et al. 2018; Czemiel Berndtsson et al. 2009; Morgan et al. 2013; Razzaghmanesh et al. 2014; Teemusk and Mander 2007; Vijayaraghavan et al. 2012; Wang et al. 2017). Moreover, even when input rainwater shows alkalinity (pH > 7), green roofs are able to decrease pH. Beecham and Razzaghmanesh (2015) found that green roof systems turned input water pH value of 7.50 into runoff pH ranging from 6.70 to 6.98, which was attributed to relatively low pH values (between 5.5 and 6.5) of soil media and the existence of plants. The pH regulation ability demonstrated by green roofs is beneficial for urban areas with rainfall-runoff pollution issues related to rainfall pH values.

Table 3 shows that the SS concentration was hardly detected in sampled rainwater, indicating that both green roofs and the control roof act as SS sources. However, the range of SS concentration (8.42–12.31 mg/L) in runoff from these roofs in Chengdu city are relatively lower than pilot-scale green roof research conducted elsewhere. Chai et al. (2018) monitored pilot-scale green roofs for 24 events in three consecutive summers in Shenzhen city and found EMCs of SS in runoff from green roofs with 10-cm modified recycled bricks were 42.1 mg/L and 42.7 mg/L, with *Ophiopogonjaponicus* and Yulong grass combined, respectively. Chen et al. (2018) also investigated water quality of newly established pilot-scale green roofs configured with 3 substrate materials (10-cm depth) and 3 plants for 8 events during 6 months. The average SS concentrations ranged from 200 to 400 mg/L, due to a relatively high portion of fines (< 0.25 mm) in all substrates. The researchers noticed the role of plants on SS leaching, acknowledging that shrubs with long thick roots can compact coarse substrate better and contribute to less substrate loss, compared with *Sedum*s with shallow and thin roots. Differences in plant species and growing media characteristics, in addition to possible plant-media interaction (Dusza et al. 2017) and scale effect, lead to differences in SS concentrations among studies.

Concrete roof is one of the typical roof materials in China (Zhang et al. 2014) and it has been found that SS concentrations in this type of roof runoff can range widely (e.g., below detection limit − 82.9 mg/L (Liu et al. 2012)). The relatively low SS values in runoff from the concrete roof in this study may due to its better durability to weather and relatively low-level dust surrounding environment compared to other concrete roofs.

COD data in Table 3 indicate that although two green roofs act as COD sources compared to rainwater, their pollutant levels are comparable to that of the conventional concrete roof. It should be noted the high variability of COD concentrations in roof runoff over the monitoring period may have made significant differences among different roofs difficult to detect. High variability in the study is mainly linked to a rapid decline in COD concentrations during the monitoring period. The initial COD concentrations from the first three rainfall events from all roofs were generally high, with the greatest values of 40.06 mg/L from Green Roof A, 69.40 mg/L from Green Roof B, and 84.10 mg/L from Control Roof C. In the literature, COD concentrations in runoff from plot-scale extensive green roofs range three orders of magnitudes (e.g. from 8 to 231 mg/L), with variabilities to different extents (Chai et al. 2018; Chen et al. 2018; Long et al. 2014; Wang et al. 2017; Zhang et al. 2014). Substrate type, plant species, and rainfall intensity are all shown to have an effect on COD from green roof systems (Chai et al. 2018; Chen et al. 2018; Teemusk and Mander 2007). Chen et al. (2018) concluded that substrate type, rather than plant species, determined the order of magnitude of COD. A substrate containing high organic matter of 63 g/L can produce leaching water with COD value up to 100 mg/L. On the contrary, Chai et al. (2018) proved that the use of plant *Ophiopogon japonicus* deteriorated the COD concentration, compared with the plant Yulong grass. Teemusk and Mander (2007) showed that while a heavy rain caused almost the same values from an extensive green roof and a bituminous roof, a moderate rain led to a lower COD concentration from the green roof. Like green roofs, concrete roofs also result in a variety of COD concentrations, ranging from 49.0 ± 30.7 mg/L in Nanjing city (Liu et al. 2012) and 77.0 ± 27 mg/L in Chongqing city (Long et al. 2014). Interestingly, a correlation between COD and TP in runoff from both green roofs was observed (Fig. 4), suggesting that the two pollutants may come from the same source.

The magnitude of TP concentrations (Table 3) in rainwater suggests that P inputs via atmospheric deposition to roofs in Chengdu city are relatively low. Still, all roofs acted as TP sources when compared to rainwater. The reason why both green roofs act as TP sources may be due to the materials used in their roof configurations (Fig. 1). Existing studies have found that green roof systems containing compost or fertilizer and green roofs being fertilized are generally TP sources (Bliss et al. 2009; Buffam and Mitchell 2015; Czemiel Berndtsson 2010; Monterusso et al. 2004; Teemusk and Mander 2007). Although no fertilizer has been applied since green roofs were established in this study, the prefabricated plant mat and/or growing media for plants are highly likely to contribute to nutrient leaching. Emilsson et al. (2007) claimed that plants of newly installed green roofs may bring fertilizers from the greenhouse/nursery. Mitchell et al. (2017) found that high P levels in engineered green roof "soil" (that is, substrate) was unnecessary relative to the P requirements of typical green roof plants and phosphate (PO_4^{3-}, primary P form of TP) leaching in runoff up to 3.85 mg/L during the second year after green roof installation in the field. Harper et al. (2015) investigated about 1-year-old green roof modules using two commercial media with high P levels of 60 mg/kg and 219 mg/kg, respectively. The P leaching in green roof runoff initially exceeded 30 mg/L, then declined to ~ 5 mg/L over a 9-month monitoring period. Chen et al. (2018) found differences in the P content of two substrates (20.1 mg/kg vs. 6.53 mg/kg)

Table 3 Summary of mean EMCs ±standard deviation of water quality parameters in rainwater, green roof runoff, and control roof runoff

Water parameter	Runoff						Rainwater	*n*
	Green Roof A	*n*	Green Roof B	*n*	Control Roof C	*n*		
pH	7.79 ± 0.41b (6.93–8.36)	11	7.61 ± 0.49b (6.83–8.22)	11	7.64 ± 0.31b (7.11–8.1)	11	6.26 ± 0.92a (4.81–7.44)	10
SS (mg/L)	8.42 ± 5.89a (2.5–17.5)	12	9.35 ± 3.96a (2.5–15)	13	12.31 ± 10.77a (2.5–36)	13	2.5 ± 0 (2.5–2.5)	6
COD*(mg/L)	16.85 ± 12.03b (2.5–40.06)	12	27.54 ± 19.86b (5.48–69.4)	13	22.47 ± 24.45b (2.5–84.1)	13	3.12 ± 1.34a (2.5–6.14)	10
TP*(mg/L)	0.09 ± 0.06b (0.03–0.23)	12	0.16 ± 0.07c (0.06–0.31)	13	0.05 ± 0.03b (0.005–0.11)	13	0.03 ± 0.02a (0.005–0.07)	12
TN*(mg/L)	2.55 ± 2.31a (0.14–7.14)	12	15.69 ± 17.51b (1.09–44.00)	13	4.10 ± 2.88ab (0.93–10.90)	13	2.18 ± 1.70a (0.57–5.27)	11

Detection limits of SS, COD, TP, and TN were 5 mg/L, 5 mg/L, 0.01 mg/L and 0.05 mg/L respectively. One-half quantitation level substituted for data reported below the corresponding detection limit

n represents the sampled event number

*Data were logarithmic transformed for comparison

Different letters denote significant differences among sources

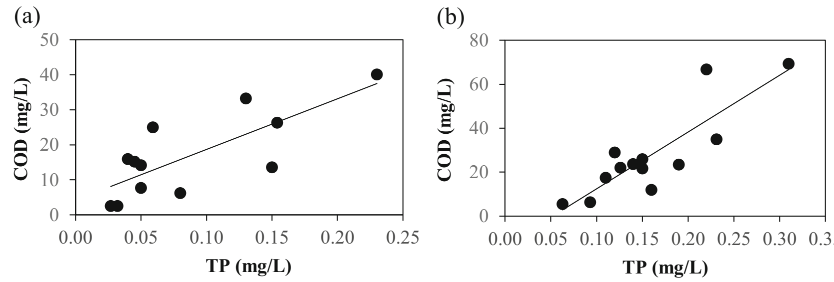


Fig. 4 Linear relationship between COD and TP in runoff from Green Roof A (**a**) and Green Roof B (**b**) with $R^2 > 0.55$

which resulted in PO_4^{3-} leaching (accounting for 97% of TP) of different orders of magnitude (3.86 mg/L vs. 0.11 mg/L). The relatively lower TP concentrations from green roofs in this study relative to those mentioned above are probably due to less TP mass losses from the vegetated and media layers over the monitoring period. Although *Sedum* mat soil in the vegetated layer for both green roofs underwent approximately a half reduction in TP content (Table 1), its shallow depth is unlikely to cause a massive nutrient export. On the other hand, the media layer, that is, topsoil in Green Roof A and substrate in Green Roof B, showed a negligible TP content change (Table 1), suggesting its little contribution to P leaching. Therefore, TP mass loss from the two green roofs would not be high as those found in other studies (Harper et al. 2015; Mitchell et al. 2017). TP concentrations in green roof runoff obtained in this study (i.e., 0.09 mg/L from Green Roof A and 0.16 mg/L from Green Roof B) fall in the wide range of 0.012–25 mg/L reported in the literature (as reviewed in (Li and Babcock 2014)). The lower P leaching from Green Roof A compared to that from Green Roof B may be attributable to the adsorption capacity of the carbon residue (Table 1) in the structure (Fig. 1a), which needs further investigation.

The TN concentrations (2.18 ± 1.70 mg/L) in rainwater demonstrate that N deposition from the atmosphere in Chengdu city is severe as conditions in developed cities (e.g., Fukuoka city, Malmö city, and Syracuse city (Czemiel Berndtsson et al. 2009; Todorov et al. 2018). Although different forms of N (e.g., NO_3-N and NH_4-N) have not been measured in this study, a local study characterizing rainfall chemistry indicates nitrate-nitrogen (NO_3-N), with concentrations varying from 1.46 to 1.64 mg/L, may account for a large portion of TN in rainwater. For TN leaching in green roof runoff, however, the major portion may be either in organic form (Gregoire and Clausen 2011; Todorov et al. 2018) or inorganic form (Aitkenhead-Peterson et al. 2011). With atmospheric N deposition being a pollutant source for the roofs, it is not surprising that TN concentrations in runoff from Green Roof A and Control Roof C were not significantly different from that in rainwater (Table 3). The particularly high TN concentration in runoff from Green Roof B, however, is highly likely due to the commercial substrate (Fig. 2b). The TN content of the 60-mm substrate decreased from an initial of 1.19 g/kg to 0.51 g/kg at the end of the study (Table 1), potentially as a substantial TN source. In the literature, there are also examples of TN leaching in green roof runoff (e.g., TN of 0.8–6.8 mg/L (Moran et al. 2005) and of 0.07-6.9 mg/L (Hathaway et al. 2008), as well as examples of negligible difference between green roof runoff and rainfall (Czemiel Berndtsson et al. 2009; Gregoire and Clausen 2011; Teemusk and Mander 2007). Many factors, such as plant species (Chen et al. 2018), media type, and depth (Akther et al. 2018; Chai et al. 2018), and meteorological factors like temperature and rainfall (Buffam et al. 2016; Carpenter et al. 2016), can influence N cycling in green roofs, which in return influence TN concentrations in green roof runoff. Initial high levels of N concentrations in runoff from newly installed green roofs tend to decrease rapidly with operation time. For example, Harper et al. (2015) observed a first-order decline of TN in the first few months of green roof operation. In this study, the initial TN concentrations in runoff from Green Roof B from the first five rainfall events were noticeably high, between 18 mg/L and 44 mg/L. Those values are comparable to the high ends of nitrate and ammonia nitrogen concentrations in non-fertilized green roofs with brick/scoria/organic mixes as growing media (Beecham and Razzaghmanesh 2015). Afterwards, the TN concentrations in runoff from Green Roof B and Green Roof A did not differ much, with low concentrations of 1.09 mg/L and 0.14 mg/L, respectively, at the end of the study.

Results showed that compared with rainwater quality, the green roofs elevated pH value and increased concentrations of SS, COD, and nutrients such as TP and TN, mainly acting as a pollutant source. The elevated pH in green roof runoff, however, can be regarded as a benefit to protect receiving water bodies from acidification. The mean EMCs of SS in runoff from the two green roofs were 8.42 mg/L and 9.35 mg/L (Table 3), respectively, with their greatest values below 20 mg/L, meeting the Standard A of the first class in "Discharge standard of pollutants for municipal wastewater treatment plant" (CSEPA 2002a). According to "Environmental quality standards for surface water" (CSEPA 2002b), runoff quality of both green roofs is worse than the grade V, with their greatest COD and TN concentrations exceeding than the corresponding standard limits of 40 mg/L and 2.0 mg/L, respectively. Nonetheless, when comparing with runoff quality from the concrete control roof, it was

TP that highlighted the worse condition of green roof runoff quality (Table 3). Therefore, for newly established green roofs, pre-treatment for COD and TN should be implemented before runoff discharge, and for retrofitted green roofs, attention should be paid to TP leaching, especially for green roofs with imported commercial substrates in areas where water bodies are phosphorus sensitive. Referring to "Standards of reclaimed water quality" (CMWR 2006), the possible utilization for green roof runoff could be agriculture/forestry consumptions and urban non-portable purposes.

The study also provides useful implications for green roof technology in China. The commercially available *S. lineare* mat is manufactured with initial high nutrient contents (i.e., TP of 2.04 g/kg and TN of 1.56 g/kg), which would be far beyond the requirements of *S. lineare*. As pointed out by Mitchell et al. (2017), a sedum is generally slow growing and adapted to nutrient poor conditions. Therefore, in order to prevent excessive nutrient loss in rainfalls, *S. lineare* mat should be pre-cultivated with soils of low nutrient contents (e.g., TP of 0.18 g/kg (Clark and Zheng 2013) and TN of 0.74 g/kg (Dusza et al. 2017)) and be fertilized according to its needs. Localized components like topsoil and carbon residue, showed an ability of anchoring or even retaining nutrients (Table 1). On the other hand, the imported commercial substrate experienced a substantial N loss which would deteriorate runoff quality. Such substrate of initial high N content (i.e., 1.19 g/kg) can be planted with a plant community of various species to increase N retention (Dusza et al. 2017), rather than with a single species which is a prevalent practice in green roof projects in China. It is possible that the native soil had stabilized its nutrients with respect to the local climate while the imported substrate did not. Thus, for a better stormwater management purpose, green roof construction may involve adopting localized components in preference to importing materials from other regions. Nonetheless, the use of the carbon residue should be cautious, as its adsorption ability for nutrients needs more solid evidence.

Conclusions

In this study, water quality of rainwater and runoff quality of two field-scale extensive green roofs at a young age and runoff quality of a control concrete roof were studied over a 6-month period in Chengdu, China. Comparing with rainwater quality, the green roofs in their first year of operation mainly acted as pollutant sources since elevated concentrations of SS, COD, and TP were found in roof runoff. When compared with runoff quality from the concrete control roof, TP was the water quality metric of greatest concern. For retrofitted green roofs, attention should be paid to TP leaching which may originate from pre-cultivated vegetation mats of high fertility. Green Roof A with localized components such as topsoil and carbon residue outperformed Green Roof B with imported components in terms of nutrient leaching in green roof runoff. For better stormwater management, commercially available *S. lineare* mats and substrate should be manufactured with appropriate nutrients in mind. A N-rich substrate can be considered for a plant community of different species, instead of a simple plant community of *S. lineare* only. Investigation of the effect of green roofs on water quality in the long term is recommended. Quantification of appropriate nutrients in vegetated and media layer for *Sedum*s is also needed.

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