A laboratory study to determine the use of polluted river sediment as a substrate for extensive green roofs

Wei Zhang, Xing Zhong, Wu Che, Huichao Sun and Hailong Zhang

ABSTRACT

In this study, laboratory-scale green (e.g. living) roof platforms were established to assess the potential use of polluted river sediment in their substrate mixture. The mean runoff retention of the green roof platforms, which contained peat and/or river sediment, after 11 artificial rainfall events was >72%, significantly higher than traditional roofs. However, green roof platforms that had been filled with peat soil showed chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) leaching. Green roofs that had used river sediment showed good leaching control for COD, TN and TP. The cumulative leaching masses from the green roofs contained 30% (COD), 42% (TN) and 47% (TP) as much as the total leaching mass from traditional roofs, and the Cu, Zn, Cd and Pb leaching risk from green roofs when river sediments are used as part of a substrate mixture was relatively low. Despite some nutrient leaching in the initial phase of runoff from the green roofs, river sediment has the potential to be used as a substrate for extensive green roofs.

Key words | extensive green roof, heavy metals, leaching, river sediment, substrate

Wei Zhang (corresponding author)
Xing Zhong
Wu Che
Huichao Sun
Beijing Engineering Research Center of Sustainable Urban Sewage System Construction and Risk Control,
Beijing University of Civil Engineering and Architecture,
100044 Beijing, China
E-mail: *zhangwei@bucea.edu.cn*

Wei Zhang
Wu Che
Key Laboratory of Urban Stormwater System and Water Environment, Ministry of Education,
Beijing University of Civil Engineering and Architecture,
Beijing 100044, China
and
Beijing Advanced Innovation Center for Future Urban Design,
100044 Beijing, China

Hailong Zhang
Zhuanghe Urban-Rural Planning and Development Bureau,
Zhuanghe 116400, China

INTRODUCTION

Green roofs are one of numerous technical practices for urban storm water management; they are also referred to as living or vegetated roofs (Berndtsson 2010). In addition to mitigating urban storm water runoff, there are several environmental and social benefits, including providing insulation, creating habitat for wildlife, helping to lower urban air temperatures and combating the heat island effect (Dunnett & Kingsbury 2004; Berndtsson 2010). With rapid urbanization, green roofs are growing in popularity globally. There are two typical types of green roof, intensive and extensive. Green roofs with thin substrate layer (<15 cm) are considered to be extensive green roofs. On the other hand, if the substrate is thicker (20–200 cm), they are considered to be intensive green roofs. The intensive green roof is thicker and can support heavier plants (Morakinyo *et al.* 2017). Intensive green roofs are suitable to grow large herbaceous vegetation, shrubs as well as small trees, and extensive green roofs are favorable for growing smaller, slow growing plants (Gourdji 2018). Several codes of practice for extensive green roofs exist in many countries (FLL 2002; GRO 2011; MOHURD 2013).

The thermal benefits of green roofs have been widely investigated (Wong *et al.* 2003; Clark *et al.* 2008) as has their reduction of the urban heat island effect (Santamouris 2014; Kuronuma *et al.* 2018); both have yielded positive results. Moreover, the hydrological performance of green roofs has been investigated through experimental plot scales (Stovin 2010; Gregoire & Clausen 2011; Stovin *et al.* 2012; Andrés-Doménech *et al.* 2018), field studies (Bengtsson *et al.* 2005; Teemusk & Mander 2011; Ouldboukhitine *et al.* 2012; Shafique *et al.* 2018) and mathematical modeling (Locatelli *et al.* 2014; Peng & Stovin 2017). Previous research has indicated that green roofs can effectively capture storm water by reducing peak runoff and decreasing annual runoff volume (Soulis *et al.* 2017; Stovin *et al.* 2017; Li *et al.* 2018).

doi: 10.2166/wst.2018.501

While green roofs can control storm water volume, their impact on the quality of infiltrating water can be either positive or negative (Gnecco *et al.* 2013; Malcolm *et al.* 2014; Harper *et al.* 2015; Vijayaraghavan 2016). A green roof has the ability to retain pollution from atmospheric wet deposition, while the pollutants retained in substrates have the potential to leach into runoff, increasing the runoff pollution load (Berndtsson *et al.* 2009; Berndtsson 2010). Therefore, several modified substrates, which have been used to improve the water quality of green roof runoff, have gradually begun to be investigated. The potential use of recycled inert construction waste materials in the substrate mixture for extensive green roofs has initially been investigated in laboratory studies. The substrate mixture was shown to support plant growth, be resistant to erosion and slippage, and capable of providing good drainage (Mickovski *et al.* 2013). Seaweed can be used as a substrate additive in green roofs to enhance water retention and sorption capacity (Vijayaraghavan & Joshi 2015). Sargassum biomass has also been used as an additive to improve runoff quality of green roofs (Vijayaraghavan & Raja 2015), and biochar has been used as an amendment substrate to improve water quality (Kuoppamäki *et al.* 2016; Kuoppamäki & Lehvävirta 2016). In recent years, the use of modified substrate mixtures in green roofs to improve runoff quality has become a topic of increasing interest (Hashemi *et al.* 2015; Vijayaraghavan 2016; Kazemi & Mohorko 2017; Akther *et al.* 2018).

Urban water pollution has been increasingly significant as a result of rapid urbanization in recent years, especially in China (Xia *et al.* 2017; Luo *et al.* 2018). Restoration of polluted urban water bodies is a key component to achieve sustainable urban water management (Barbosa *et al.* 2012). China has started a new nationwide initiative intended to deal with urban water pollution. As a commonly used technical practice, sludge dredging is currently used to reduce endogenous water source pollution in China. However, polluted river sediment disposal has become a new challenge. It was previously reported that river sediment was used as a raw material in producing building materials (Mezencevova *et al.* 2012). River sediment is rich in minerals, organic matter and nutrients, which are important for plant growth. It may also have potential to be used as an organic matter additive in extensive green roofs to replace the more commonly used peat soil and other organic matter additives. If proven feasible, it would be a low-cost green roof substrate, as well as an effective use of waste material (Rincón *et al.* 2014; Vijayaraghavan 2016). However, mixing in polluted river sediment to green roof substrates could contribute to pollutants being released into runoff. Therefore, the potential use of polluted river sediment in a substrate mixture for extensive green roofs should be assessed.

In this study, a pilot array of green roof platforms was established. The objectives of this study were: (1) to quantitatively assess the possibility of using polluted river sediment in green roof substrate; and (2) to evaluate nutrient leaching from extensive green roofs with polluted river sediment-mixed substrate. These objectives allowed us to determine the quality of green roof runoff and therefore the feasibility of using river sediment as part of green roof substrate in this study.

MATERIALS AND METHODS

Experimental set-up

The study included 10 green roof platforms (external dimensions: 13 cm wide × 42 cm long × 12 cm high) that were installed on a roof at Beijing University of Civil Engineering and Architecture, China. Platform size was not the main influential factor of the green roof experiment, and the small test beds made it easy to implement a batch experiment with different substrate compositions (Zhang *et al.* 2018).

The green roof platforms had a longitudinal slope of 5%, and the lower end of the device was provided with an outflow pipe. The diameter of the outlet pipe was 20 mm. An individual green roof platform consisted of four layers: the drainage layer (a concave-convex plastic drainage plate); filtration layer (a water-permeable, non-woven geotextile); substrate layer; and vegetation (*Sedum lineare Thunb*). The planting density was 240 strains/m^2. The green roof structure was determined according to the technical specifications for green roofs (JGJ 155-2013), which is a national standard in China (MOHURD 2013).

Native soil (NS) was taken from a green belt area. Two types of river sediments were chosen as potential additives, both of which were recovered from the Zhuanghe River located in Dalian, China. One type of sediment (RSU) was taken from the upstream section of the Zhuanghe River. Due to tidal effects, many seabed sediments migrate to the reach near the river mouth to form another type of sediment (RSS). The apparent difference between RSU and RSS is significant. The sediments and NS were shading dried, and screened over a 2-mm standard sieve.

The composition of simulated green roof substrates is shown in Table 1. Several main physical-chemical properties of the substrates are shown in Table 2. Platform C was filled with NS, and platform B represented a traditional roof with no substrate. Platforms PS1, PS2, PB1, PB2, PV and PP were filled with peat soil to increase the organic matter content and ensure vegetation growth. Platforms PS1, PB1, PV and PP were set up to investigate the capacity of inorganic lightweight materials to improve rainwater retention. The sediments RSU and RSS were used instead of peat soil in platforms PE and PH, respectively, to compare nutrient leaching and rainwater retention relative to platforms PV and PP.

The concentrations of metals in garden soil and river sediments are shown in Table 3. The Al, Fe, oxalate-extractable aluminum (Al_{ox}) and oxalate-extractable iron (Fe_{ox}) content in the two types of river sediments (RSU and RSS) were lower than water treatment residues (WTRs), but significantly higher than NS. The substrate composition of platforms PS2 and PB2 was based on platforms PS1 and PB1, but 5% RSU and 5% RSS were added in the substrate to assess phosphorus leaching control. Furthermore, the 16 polycyclic aromatic hydrocarbons (PAHs) of RSU and RSS have also been analyzed. According to Chinese national standards, Soil Environmental Quality: Risk Control Standard for Soil Contamination of Development Land (GB36600-2018) and Soil Environmental Quality: Risk Control Standard for Soil Contamination of Agricultural Land (GB15618-2018), there was low risk for PAHs leaching. Hence, the PAHs in the runoff from extensive green roof platforms was not analyzed in this experiment.

Table 1 | Composition of simulated green roof substrates

No.	Depth (cm)	Composition (volume ratio)
C	10	NS 100%
PS1	10	NS 40% + Peat soil 30% + Cinder 30%
PS2	10	NS 35% + Peat soil 30% + Cinder 30% + RSU 5%
PE	10	NS 40% + RSU 30% + Vermiculite 30%
PB1	10	NS 40% + Peat soil 30% + Brickbat 30%
PB2	10	NS 35% + Peat soil 30% + Brickbat 30% + RSS 5%
PH	10	NS 40% + RSS 30% + Perlite 30%
PV	10	NS 40% + Peat soil 30% + Vermiculite 30%
PP	10	NS 40% + Peat soil 30% + Perlite 30%
B	–	–

Table 2 | Selected physicochemical properties of the substrates

No.	Particle density g/cm³	Organic matter content %	Alkali solution nitrogen mg/kg	Available phosphorus mg/kg
C	1.22	0.3	7.35	1.79
PS1	0.81	3.8	109.20	11.30
PS2	0.88	3.6	168.00	10.79
PE	0.93	1.2	39.20	12.84
PB1	0.81	3.0	161.00	11.2
PB2	0.73	2.1	310.80	19.43
PH	0.90	4.7	215.60	35.27
PV	0.61	2.7	219.80	9.20
PP	0.61	2.6	221.20	8.64

Sampling and laboratory testing

Rainfall simulation tests were performed with a peristaltic pump to control the simulated rainfall intensity, and water sprayed on to the platform surfaces simulated actual rainfall. Tap water has frequently been used to simulate rain in similar research (Bus et al. 2016; Kuoppamäki et al. 2016). Local tap water was used to simulate rainwater; the TN, NO_3^--N, NH_4^+-N, TP and COD of the tap water was 2.78 mg/L, 1.79 mg/L, 0.04 mg/L, 0.01 mg/L and 6.0 mg/L, respectively. The pH of tap water used in experiments was 7.20 ± 0.02.

A total of 11 rainfall events were simulated in this study. The rainfall amount of the first seven rainfall events was 30 mm, which corresponded to 82% volume capture ratio of annual rainfall in Beijing. The rainfall of events 8 to 11 was 35 mm (85% volume capture ratio of annual rainfall). It was assumed that rainfall has a uniform intensity (15 mm/h), but this may differ with actual rainfall. The antecedent dry period in this study was 7 days because the mean antecedent dry period in Beijing in the rainy season (June to September) is 7.3 days.

The total rainfall amount was approximately 350 mm. A drain with polyvinyl chloride piping was installed at the lower end of each test plot to collect runoff from individual platforms. The runoff was sampled manually over a fixed time interval (20 mins). Runoff samples were tested for turbidity (NTU), chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) using standard methods (APHA 2012). The Al_{ox} and Fe_{ox} content was analyzed according to O'Neill & Davis (2012). The metal concentrations in water samples and digested filter media samples were analyzed using inductively coupled plasma mass spectrometry (NexION^{TM} 300, PerkinElmer, USA).

Table 3 | Concentrations of metals in native soil (NS), river sediments (RSU and RSS), and water treatment residue (WTR)

	Cu g/kg	Cd mg/kg	Pb g/kg	Zn g/kg	Al g/kg	Fe g/kg	Al_{ox} g/kg	Fe_{ox} g/kg
NS	0.04	–	0.01	0.24	6.03	9.33	0.72	0.38
RSU	0.04	0.05	0.02	0.41	31.77	22.20	6.54	1.00
RSS	0.10	0.15	0.03	0.30	29.39	26.98	6.26	1.28
WTR[a]	–	–	–	–	–	–	155	3.67

[a]O'Neill & Davis 2012.

The pH of mixed samples of green roof runoff were analyzed. The pH of green roof runoff from platform PS1, PS2, PB1, PB2, PH, PV and PP was 9.04 ± 0.02, 9.03 ± 0.03, 9.00 ± 0.05, 9.4 ± 0.12, 9.21 ± 0.10, 9.11 ± 0.09 and 9.15 ± 0.11 respectively, during the experiment.

Data analysis

The runoff volume reduction rate (Q) was used to evaluate the water retention capacity of a green roof, as follows:

$$Q\% = \frac{Q_i - Q_e}{Q_i} \times 100\%$$

where Q_i is the total rainfall (L) and Q_e is the total runoff (L).

The statistics were performed with SPSS 19.0 (IBM Corp., Armonk, NY, USA). Mean values were checked with the Kolmogorov-Smirnov test and accepted at $P > 0.05$. The differences between mean effluent COD, TN, TP and other pollutants were analyzed by two-way analysis of variance.

RESULTS AND DISCUSSION

Runoff volume retention

The runoff volume reduction of green roof platforms over the 11 rainfall events are illustrated in Figure 1. Except for platform B (the traditional roof), the runoff volume reduction of all the green roof platforms varied significantly during the first six rainfall events (Figure 1(a)). However, from rainfall event 7 the rate of reduction in runoff volume tended to be stable, although a significant decrease occurred during event 4. This is because natural continuous rainfall occurred before the 4th artificial rainfall event. To prevent the influence of natural rainfall, plastic sheeting

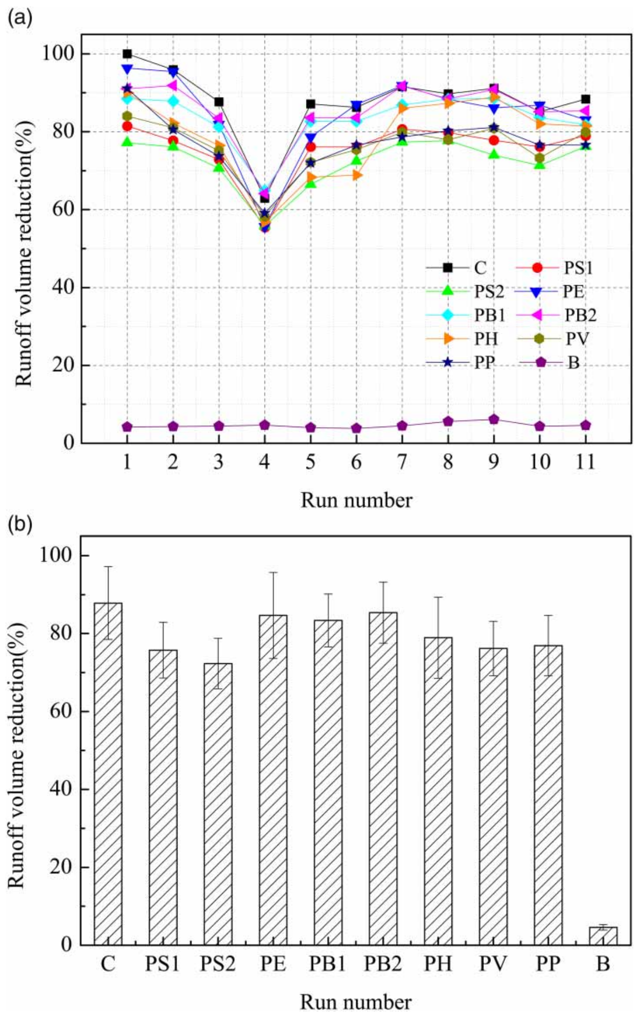

Figure 1 | Runoff volume reduction from the green roof platforms. (a) Rainfall event reduction, (b) mean reduction.

was used to cover the green roof platforms. However, this affected water evaporation off the green roof platforms, and as a result the runoff volume was reduced significantly (Figure 1(a)).

The runoff volume from platform C, containing only NS, presented the highest reduction (87.80 ± 9.34%) over the 11 rainfall events. Platform B showed the lowest runoff volume reduction (4.6 ± 0.69%). In general, the mean runoff retention of green roof platforms over the 11 rainfall events was greater than 72%. Although previous studies reported that the addition of porous materials can effectively improve water retention performance (Berndtsson 2010), the green roof platforms filled with porous media did not show greater water volume reduction in this experiment. Furthermore, there was no significant difference in runoff reduction among green roof platforms filled with various substrates.

COD and nutrition leaching

The mean concentrations and cumulative leaching masses of COD, TN and TP from green roof platforms are illustrated in Figure 2. The mean effluent COD concentration of platform C was 140.10 ± 33.31 mg/L, which was 3.34 times higher than the COD concentration of platform B (41.91 ± 27.76 mg/L). The effluent COD concentration of the seven platforms filled with peat soil or river sediment (PS1, PS2, PB1, PB2, PH, PV and PP) was significantly higher than platform C because of the high organic matter content in peat soil or river sediment.

Although the effluent COD concentration for platform C was higher than platform B, the COD cumulative leaching mass from platform C was only 30% of platform B. Compared with platform B, platform C presented better COD control. The plant growth was observed by visual inspection in this study. During the experiment, plant growth on platform C was obviously inferior to other green roof devices because of the overall insufficient organic matter in the substrate. No obvious difference was observed for the plant growth for other platforms.

Platform PH (30% RSS) showed significant COD leaching. The cumulative leaching mass from platform PH was 5.96 times higher than platform C, which is even higher than platform B. The COD cumulative leaching mass from platform PE (30% RSU) was 210.58 mg after 11 rainfall events, which was similar to platform C. Thus, the use of RSU can effectively control COD leaching pollution. The low COD leaching may relate to the low organic matter content of PE substrate. Additionally, the relative high particle

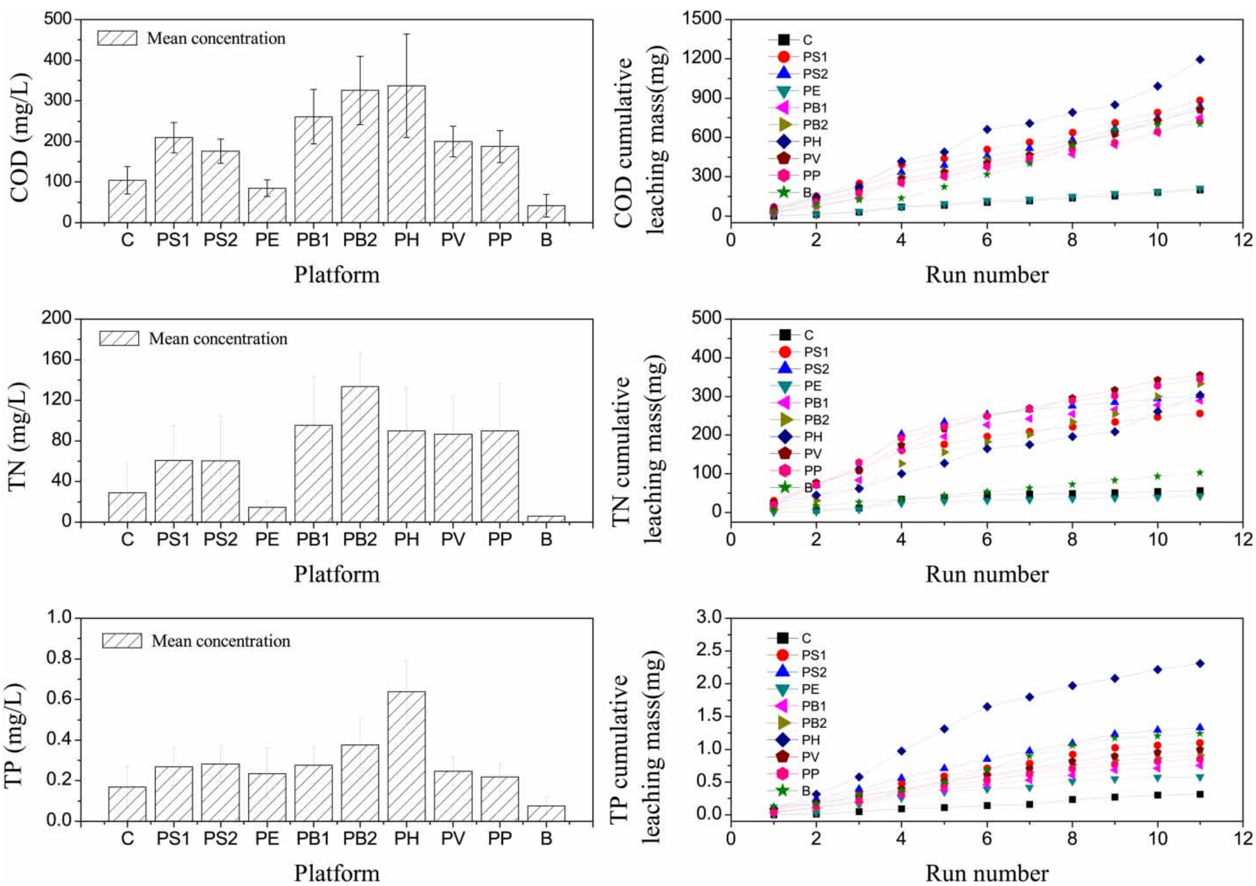

Figure 2 | The mean concentration and cumulative leaching mass of COD, TN and TP for the green roof platforms over 11 rainfall events.

density and high proportion of fine particles may help to increase the COD adsorption of the matrix by providing a higher adsorption surface area. The COD leaching and removal mechanisms need further research.

The mean effluent TN concentration for platform C was 28.97 ± 28.50 mg/L, which was 4.73 times higher than platform B (6.12 ± 0.44 mg/L). However, the effluent TN concentration for seven platforms (PS1, PS2, PB1, PB2, PH, PV and PP) was significantly higher than platform C, which can be attributed to highly alkaline solutions containing nitrogen in the peat soil or river sediment (Table 2). The green roof that contained substrate with 30% peat soil or RSS indicated serious TN leaching. The TN cumulative leaching mass from platform PE (30% RSU) was 38.40 mg after 11 rainfall events, which was 0.85 times higher than platform C and 0.42 times higher than platform B. The use of RSU in substrate (PE) can also effectively control TN leaching.

The mean effluent TP concentration for platform C was 0.17 ± 0.10 mg/L, which was 2.13 times higher than platform B (0.08 ± 0.04 mg/L). The effluent TP concentrations were higher in all of the platforms containing peat soil, RSU and RSS. However, only the platforms containing RSS (PS2 and PH) had higher cumulative leaching masses than platform B. Other types of green roof showed better TP discharge control. Platform PE, which demonstrated good COD and TN leaching control, also showed relatively better control of TP leaching. The TP cumulative leaching mass from platform PE is 0.58 mg, which was only 0.47 times higher than platform B.

It is significant that TP leaching control of platforms PS2 and PB2 did not exhibit better performance compared with PS1 and PB1, although RSU and RSS were added to the substrates of the former. In general, higher content of Al_{ox} and Fe_{ox} in substrate tends to indicate better TP absorption (Elliott *et al.* 2002; Maguire & Sims 2002). The content of Al_{ox} and Fe_{ox} in RSU and RSS was much lower than WTR, which could be a possible cause of insignificant TP leaching control. Additionally, the unsatisfactory effect on TP leaching control may be due to the high content of available phosphorus in RSU and RSS (Zhong *et al.* 2018).

Heavy metal leaching

To evaluate the heavy metal leaching risk of the green roof platforms with river sediment and other media, the concentrations of Cu, Zn, Cd and Pb in effluent were monitored during the experiment. The concentrations of As, Co, Ni, Mn, Sb, Bi, Cr in effluent have also been surveyed and were very low or below detection limit. These four metals (Cu, Zn, Cd and Pb) are typical heavy metal pollutants in urban storm water runoff (Sansalone & Buchberger 1997). The mean concentrations of Cu, Cd, Pb and Zn in the outflow of the green roof platforms are illustrated in Figure 3. Platform PE showed relatively minimal metal leaching and

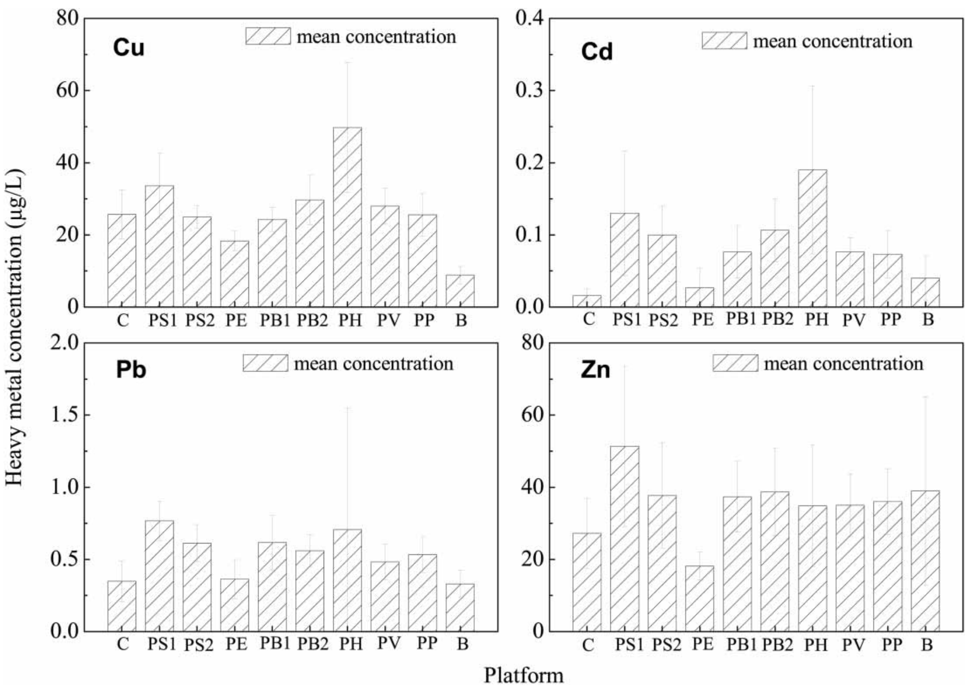

Figure 3 | Heavy metal (Cu, Cd, Pb and Zn) concentrations in the outflow of the green roof platforms.

better COD, TN and TP leaching control than the other platforms PS1, PS2, PB1, PB2, PH, PV and PP. In general, the metal leaching control of green roof platforms was higher than a traditional roof.

The concentrations of the four heavy metals in this experiment were similar to those in previous studies (Alsup *et al.* 2011; Speak *et al.* 2014). It is worth noting that the heavy metal concentrations in the outflow of the green roof platforms during the entire experiment were much lower than in Class II surface water, which is a high quality drinking water source classified by the Chinese national water quality standards (Environmental Quality Standards for Surface Water, GB 3838-2002). The standard concentrations for Class II water are $Cu \leq 1{,}000\ \mu g/L$, $Zn \leq 1{,}000\ \mu g/L$, $Cd \leq 5\ \mu g/L$ and $Pb \leq 10\ \mu g/L$. Based on the data from this study, the Cu, Zn, Cd and Pb leaching risk from green roofs when river sediments are used as part of a substrate mixture was relatively low. The heavy metal leaching depends of the quality of sediments. Hence, the types of river sediment and composition need to be fully studied to avoid contaminant leaching.

CONCLUSIONS

In this study, a pilot array of extensive green roof platforms was established to assess the performance of extensive green roofs that contained substrate with polluted river sediments from the Zhuanghe River (China).

After simulating 11 rainfall events, the average runoff retention of the extensive green roof platforms was assessed and found to be higher than 72%. This was significantly higher than a traditional roof. Contrary to previous research, the green roof platforms with porous media did not show a reduction in water volume in this experiment.

The extensive green roof platforms that contained peat soil and one type of river sediment (RSS) showed obvious COD, TN and TP leaching, indicated by the effluent concentrations and/or cumulative leaching masses. However, the green roofs containing the river sediment type (RSU) showed good leaching control for COD, TN and TP. In total, the cumulative leaching masses were only 30% (COD), 42% (TN) and 47% (TP) of the mass leached from a traditional roof, which is a significant improvement. Additionally, the COD and TN cumulative leaching masses from the green roofs containing the river sediment (platform PE) were like green roof platform C (filled only with NS), and TP cumulative leaching masses were slightly higher than platform C. However, plant growth on platform C was obviously inferior to other green roof devices because of the overall insufficient nutrients in the substrate, and green roof filled with only NS as a substrate is not a typical green roof practice. Furthermore, when the river sediments were mixed into the substrate, the Cu, Zn, Cd and Pb leaching risk from green roofs was relatively low.

Based on this pilot research, polluted river sediments overall have the potential to be used as substrate for extensive green roofs with a low heavy metal leaching risk, although some nutrient leaching (TN and TP) was found in the initial phase of bioretention. However, it is worth noting that the feasibility of using river sediment as part of green roof substrate depends of the quality of sediments. Before using river sediment as green roof substrate, the characteristics of local river sediment should be widely investigated to avoid contaminant leaching. Further research efforts are thus required to better understand pollutant leaching and removal mechanisms. Furthermore, pilot and field study of extensive and intensive green roofs filled with other types river sediments are also needed to validate the finding in this study.

ACKNOWLEDGEMENTS

This study was financially supported by the National Natural Science Foundation of China (No. 51608026), Beijing Advanced Innovation Center for Future Urban Design Projects (No. UDC2016040100), the Beijing Municipal Science and Technology Project (No. D161100005916004) the Fundamental Research Funds for Beijing University of Civil Engineering and Architecture (No. X18035, X18118). The authors thank the research team members for their enthusiastic support. We also thank Kara Bogus, PhD, from Liwen Bianji, Edanz Editing China (www.liwen-bianji.cn/ac), for editing the English text of a draft of this manuscript.

REFERENCES

Alsup, S. E., Ebbs, S. D., Battaglia, L. L. & Retzlaff, W. A. 2011 Heavy metals in leachate from simulated green roof systems. *Ecol. Eng.* **37** (11), 1709–1717.

Akther, M., He, J., Chu, A., Huang, J. & van Duin, B. 2018 A review of green roof applications for managing urban stormwater in different climatic zones. *Sustainability* **10** (8), 2864.

Andrés-Doménech, I., Perales-Momparler, S., Morales-Torres, A. & Escuder-Bueno, I. 2018 Hydrological performance of green

roofs at building and city scales under Mediterranean conditions. *Sustainability* **10** (9), 3105.
APHA, AWWA & WEF 2012 *Standard Methods for the Examination of Water and Wastewater*, 22nd edn. American Public Health Association, Washington, DC, USA.
Barbosa, A. E., Fernandes, J. N. & David, L. M. 2012 Key issues for sustainable urban stormwater management. *Water Res.* **46** (20), 6787–6798.
Bengtsson, L., Grahn, L. & Olsson, J. 2005 Hydrological function of a thin extensive green roof in southern Sweden. *Hydrol. Res.* **36** (3), 259–268.
Berndtsson, J. C. 2010 Green roof performance towards management of runoff water quantity and quality: a review. *Ecol. Eng.* **36** (4), 351–360.
Berndtsson, J. C., Bengtsson, L. & Jinno, K. 2009 Runoff water quality from intensive and extensive vegetated roofs. *Ecol. Eng.* **35** (3), 369–380.
Bus, A., Karczmarczyk, A. & Baryła, A. 2016 The use of reactive material for limiting P-leaching from green roof substrate. *Water Sci. Technol.* **73** (12), 3027–3032.
Clark, C., Adriaens, P. & Talbot, F. B. 2008 Green roof valuation: a probabilistic economic analysis of environmental benefits. *Environ. Sci. Technol.* **42** (6), 2155–2161.
Dunnett, N. & Kingsbury, N. 2004 *Planting Green Roofs and Living Walls*. TimberPress, Cambridge, UK.
Elliott, H. A., O'Connor, G. A., Lu, P. & Brinton, S. 2002 Influence of water treatment residuals on phosphorus solubility and leaching. *J. Environ. Qual.* **31** (4), 1362–1369.
FLL 2002 *Richtlinie für die Planung, Ausführung und Pflege von Dachbegrünungen* (in German) *(Guidelines for Planning Execution and Upkeep of Green Roof Sites)*. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau E.V, Bonn.
Gnecco, I., Palla, A., Lanza, L. G. & La Barbera, P. 2013 The role of green roofs as a source/sink of pollutants in storm water outflows. *Water Resour. Manag.* **27** (14), 4715–4730.
Gourdji, S. 2018 Review of plants to mitigate particulate matter, ozone as well as nitrogen dioxide air pollutants and applicable recommendations for green roofs in Montreal, Quebec. *Environ. Pollut.* **241**, 378–387.
Green Roof Organisation (GRO) 2011 *The GRO Green Roof Code: Green Roof Code for Best Practice for the UK 2011*. Groundwork, Sheffield, UK.
Gregoire, B. G. & Clausen, J. C. 2011 Effect of a modular extensive green roof on stormwater runoff and water quality. *Ecol. Eng.* **37** (6), 963–969.
Harper, G. E., Limmer, M. A., Showalter, W. E. & Burken, J. G. 2015 Nine-month evaluation of runoff quality and quantity from an experiential green roof in Missouri, USA. *Ecol. Eng.* **78**, 127–133.
Hashemi, S. S. G., Mahmud, H. B. & Ashraf, M. A. 2015 Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: a review. *Renewable and Sustainable Energy Reviews* **52**, 669–679.
Kazemi, F. & Mohorko, R. 2017 Review on the roles and effects of growing media on plant performance in green roofs in world climates. *Urban For. Urban Green.* **23**, 13–26.
Kuoppamäki, K. & Lehvävirta, S. 2016 Mitigating nutrient leaching from green roofs with biochar. *Landsc. Urban Plan.* **152**, 39–48.
Kuoppamäki, K., Hagner, M., Lehvävirta, S. & Setälä, H. 2016 Biochar amendment in the green roof substrate affects runoff quality and quantity. *Ecol. Eng.* **88**, 1–9.
Kuronuma, T., Watanabe, H., Ishihara, T., Kou, D., Toushima, K., Ando, M. & Shindo, S. 2018 CO_2 payoff of extensive green roofs with different vegetation species. *Sustainability* **10** (7), 2256.
Li, C., Liu, M., Hu, Y., Han, R., Shi, T., Qu, X. & Wu, Y. 2018 Evaluating the hydrologic performance of low impact development scenarios in a micro urban catchment. *Int. J. Environ. Res. Public Health* **15** (2), 273.
Locatelli, L., Mark, O., Mikkelsen, P. S., Arnbjerg-Nielsen, K., Jensen, M. B. & Binning, P. J. 2014 Modelling of green roof hydrological performance for urban drainage applications. *J. Hydrol.* **519**, 3237–3248.
Luo, K., Hu, X., He, Q., Wu, Z., Cheng, H., Hu, Z. & Mazumder, A. 2018 Impacts of rapid urbanization on the water quality and macroinvertebrate communities of streams: a case study in Liangjiang New Area, China. *Sci. Total Environ.* **621**, 1601–1614.
Maguire, R. O. & Sims, J. T. 2002 Soil testing to predict phosphorus leaching. *J. Environ. Qual.* **31** (5), 1601–1609.
Malcolm, E. G., Reese, M. L., Schaus, M. H., Ozmon, I. M. & Tran, L. M. 2014 Measurements of nutrients and mercury in green roof and gravel roof runoff. *Ecol. Eng.* **73**, 705–712.
Mezencevova, A., Yeboah, N. N., Burns, S. E., Kahn, L. F. & Kurtis, K. E. 2012 Utilization of Savannah Harbor river sediment as the primary raw material in production of fired brick. *J. Environ. Manage.* **113**, 128–136.
Mickovski, S. B., Buss, K., McKenzie, B. M. & Sökmener, B. 2013 Laboratory study on the potential use of recycled inert construction waste material in the substrate mix for extensive green roofs. *Ecol. Eng.* **61**, 706–714.
Ministry of Housing and Urban-Rural Development of People's Republic of China (MOHURD) 2013 *Technical Specification for Green Roof*. China Architecture & Building Press, Beijing, China.
Morakinyo, T. E., Dahanayake, K. K. C., Ng, E. & Chow, C. L. 2017 Temperature and cooling demand reduction by green-roof types in different climates and urban densities: a co-simulation parametric study. *Energy Build.* **145**, 226–237.
O'Neill, S. W. & Davis, A. P. 2012 Water treatment residual as a bioretention amendment for phosphorus. I: evaluation studies. *J. Environ. Eng.-ASCE* **138** (3), 318–327.
Ouldboukhitine, S. E., Belarbi, R. & Djedjig, R. 2012 Characterization of green roof components: measurements of thermal and hydrological properties. *Build. Environ.* **56**, 78–85.
Peng, Z. & Stovin, V. 2017 Independent validation of the SWMM green roof module. *J. Hydrol. Eng.* **22** (9), 04017037.
Rincón, L., Coma, J., Pérez, G., Castell, A., Boer, D. & Cabeza, L. F. 2014 Environmental performance of recycled rubber as drainage layer in extensive green roofs. A comparative Life Cycle Assessment. *Build. Environ.* **74**, 22–30.

Sansalone, J. J. & Buchberger, S. G. 1997 Partitioning and first flush of metals in urban roadway storm water. *J. Environ. Eng.-ASCE* **123** (2), 134–143.

Santamouris, M. 2014 Cooling the cities – a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* **103**, 682–703.

Shafique, M., Kim, R. & Kyung-Ho, K. 2018 Green roof for stormwater management in a highly urbanized area: the case of Seoul, Korea. *Sustainability* **10** (3), 584.

Speak, A. F., Rothwell, J. J., Lindley, S. J. & Smith, C. L. 2014 Metal and nutrient dynamics on an aged intensive green roof. *Environ. Pollut.* **184**, 33–43.

Soulis, K. X., Ntoulas, N., Nektarios, P. A. & Kargas, G. 2017 Runoff reduction from extensive green roofs having different substrate depth and plant cover. *Ecol. Eng.* **102**, 80–89.

Stovin, V. 2010 The potential of green roofs to manage urban stormwater. *Water Environ. J.* **24** (3), 192–199.

Stovin, V., Vesuviano, G. & Kasmin, H. 2012 The hydrological performance of a green roof test bed under UK climatic conditions. *J. Hydrol.* **414**, 148–161.

Stovin, V., Vesuviano, G. & De-Ville, S. 2017 Defining green roof detention performance. *Urban Water J.* **14** (6), 574–588.

Teemusk, A. & Mander, Ü. 2011 The influence of green roofs on runoff water quality: a case study from Estonia. *Water Resour. Manag.* **25** (14), 3699.

Vijayaraghavan, K. 2016 Green roofs: a critical review on the role of components, benefits, limitations and trends. *Renew. Sust. Energ. Rev.* **57**, 740–752.

Vijayaraghavan, K. & Joshi, U. M. 2015 Application of seaweed as substrate additive in green roofs: enhancement of water retention and sorption capacity. *Landsc. Urban Plan.* **143**, 25–32.

Vijayaraghavan, K. & Raja, F. D. 2015 Pilot-scale evaluation of green roofs with *Sargassum* biomass as an additive to improve runoff quality. *Ecol. Eng.* **75**, 70–78.

Wong, N. H., Chen, Y., Ong, C. L. & Sia, A. 2003 Investigation of thermal benefits of rooftop garden in the tropical environment. *Build. Environ.* **38** (2), 261–270.

Xia, J., Zhang, Y., Xiong, L., He, S., Wang, L. & Yu, Z. 2017 Opportunities and challenges of the Sponge City construction related to urban water issues in China. *Sci. China-Earth Sci.* **60** (4), 652–658.

Zhang, W., Zhong, X. & Che, W. 2018 Nutrient leaching from extensive green roofs with different substrate compositions: a laboratory study. *Water Sci. Technol.* **77** (4), 1007–1014.

Zhong, X., Zhang, W., Tian, X., Sun, C., Liu, Y., Che, W., Zhang, H. & Cui, X. 2018 Runoff pollutants purification effect of bioretention media improved by black-odorous river sediments. *Chinese Journal of Environmental Engineering* **12** (8), 2193–2201 (in Chinese).

First received 26 June 2018; accepted in revised form 1 December 2018. Available online 10 December 2018