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Nitrogen removal from urban stormwater runoff by stepped bioretention systems

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ABSTRACT

Nitrogen excess is a key trigger for the eutrophication of water bodies. Stormwater is an important nitrogen source in urban environments and thus requires effective treatment, especially in mountainous cities due to their stronger runoff flushing. However, the design method of bioretention systems focusing on mountainous cities is still rare in China and nitrogen is often released due to the lack of denitrification environments. In this study, the stepped bioretention systems were designed based on the terrain characteristics in mountainous cities by two columns in the stair-stepping connection. From 2015–2016, 18 replicates of stepped bioretention systems, which included a 400 mm deep planting layer, a 200 mm deep transition layer and a 200 mm gravel layer planted with *Radermachera hainanensis* (Merr.), *Juncus effusus* (L.), *Vetiveria zizanioides* (L.), *Ophiopogon japonicus* (Linn. f.) and *Medicago sativa* (L.)., respectively, were tested under certain operational conditions (e.g., the simulated rainfall intensity was 3.5, 5.3 and 14 mm/h, respectively.). The stepped columns planted with *Medicago sativa* (L.). showed poor nitrogen removal (e.g., the RRTN (removal rate of TN) was from – 29.8% to – 123.0%), while those planted with *Radermachera hainanensis* (Merr.), *Juncus effusus* (L.), *Ophiopogon japonicus* (Linn. f.) or *Vetiveria zizanioides* (L.) performed well without additional carbon sources (e.g., the RRTN was from 52.8% to 84.2%). Nitrogen would be released from the systems (e.g., the average RRTN was –178.0%) when peat soil was mixed in the planting layer at a ratio of 20%. After retrofitting the flow pattern within the stepped columns, U flow pattern was more advantageous for the improvement of nitrogen removal. In the 1st, 2nd, 4th, 5th, 10th and 11th systems, the average RRTN and RRNO_3—N (removal rate of NO_3—N) in the systems with U flow pattern were 1.2 – 7.0% and 5.0 – 5.8%, both higher than those with W flow pattern. Through leaching dynamics analysis, NH_3—N—C (NH_3—N Concentration) of all effluent samples was < 0.5 mg/L, but the concentrations of TN and NO_3—N were increased with the duration of rainfall events. Generally, RRTN was significantly correlated to TN—C (TN Concentration), NH_3—N—C, NO_3—N—C (NO_3—N Concentration) and D (Depth of saturated zone), while RRNH_3—N (Removal Rate of NH_3—N) was associated with ID (Interval Days between rainfall events). Our results suggested that the stepped bioretention systems should be recommended in mountainous cities if nitrogen discharges posed a potential threat to the receiving environments.

1. Introduction

With the increasing disposal rate of point source pollution, urban stormwater runoff has been the main cause of pollution for estuaries, lakes, and rivers in the recent years (Chahal et al., 2016). The current studies about stormwater runoff from urban impervious areas have indicated a higher nitrogen level in China than in developed countries (Lin et al., 2007; Taylor et al., 2005), especially in mountainous cities (Wang et al., 2013). The alleviation of nitrogen load from impervious areas has been paid greater attention than ever before.

Bioretention is an infiltration-based stormwater control measure widely installed for its capability to improve the water quality and enhance the hydrologic condition in the developed areas. Bioretention systems are effective in removing a variety of pollutants, such as suspended solids, heavy metals, phosphorus, oil,

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Table 1
Packing structures of the 18 bioretention systems.

Serial number of bioretention systems	Media of drainage layer	Media of plants growing	Plants
1–2	5–10 mm gravel in diameter	a mix of 20% local soil and 80% sand by volume	*Vetiveria zizanioides* (L.) (2015)
3	5–10 mm gravel in diameter	a mix of 20% peat soil, 20% local soil and 60% sand by volume	*Vetiveria zizanioides* (L.) (2015)
4–5	5–10 mm gravel in diameter	a mix of 20% local soil and 80% sand by volume	*Juncus effusus* (L.)
6	5–10 mm gravel in diameter	a mix of 20% peat soil, 20% local soil and 60% sand by volume	*Juncus effusus* (L.)
7–8	5–10 mm gravel in diameter	a mix of 20% local soil and 80% sand by volume	*Medicago sativa* (L.)
9	5–10 mm gravel in diameter	a mix of 20% peat soil, 20% local soil and 60% sand by volume	*Medicago sativa* (L.)
10–11	5–10 mm gravel in diameter	a mix of 20% local soil and 80% sand by volume	*Radermachera hainanensis* (Merr.)
12	5–10 mm gravel in diameter	a mix of 20% peat soil, 20% local soil and 60% sand by volume	*Radermachera hainanensis* (Merr.)
13	5–10 mm brick in diameter	a mix of 20% local soil and 80% sand by volume	*Vetiveria zizanioides* (L.) (2015)
14	5–10 mm sponge iron in diameter	a mix of 20% local soil and 80% sand by volume	*Vetiveria zizanioides* (L.) (2015)
15	5–10 mm volcanic rocks in diameter	a mix of 20% local soil and 80% sand by volume	*Vetiveria zizanioides* (L.) (2015)
16	5–10 mm gravel in diameter	a mix of 20% local soil and 80% sand by volume	*Vetiveria zizanioides* (L.) (2015)
17	5–10 mm volcanic rocks in diameter	a mix of 40% local soil and 60% sand by volume	*Radermachera hainanensis* (Merr.)
18	5–10 mm gravel in diameter	a mix of 40% local soil and 60% sand by volume	*Radermachera hainanensis* (Merr.)

grease, and so on. However, nitrogen removal performance is highly variable, with a figure ranging from as high as 60% to 0 nitrogen export (Li and Davis, 2014).

In order to improve the running efficiency of bioretention systems, many measurements have been conducted. For example, a saturated zone is designed to encourage denitrification for a higher total removal rate of nitrogen. Hsieh and Davis (2005) found that the design of a saturated zone was helpful for the removal of nitrate. Sometimes, the removal rate of nitrate could be as high as 71% (Palmer et al., 2013). But there are also some failed cases that the construction of a submerged zone in bioretention systems didn't lead to the significant promotion of nitrogen removal (Hunt et al., 2006). Besides, the layered bioretention systems, which contain the bottom media layer designed to be less permeable than the upper layers, are also found to be more potential in forming anoxic zones to promote nitrification/denitrification (Hsieh et al., 2007). At present, most of the published reports focus on the plain cities, and there are few studies concerning the mountainous cities. For the complex terrains and insufficient municipal land areas, developing the new methods is urgent to manage stormwater runoff in mountainous cities, especially to control nitrogen pollution efficiently. In the present study, 18 bioretention systems were used: 1) well-established conventional bioretention columns; 2) two constructed columns connected together to form a stepped bioretention system; and 3) the second bioretention column with a submerged zone.

2. Materials and methods

2.1. Bioretention column settings

Eighteen columns were constructed from a plexiglass pipe (diameter: 22 cm). Each column had a 20 cm extended ponding depth, a 80 cm medium (consisting of a 20 cm drainage layer in the bottom, a 20 cm filter layer and a 40 cm plant growing medium on the top), and a mix of 0 – 20% peat soil, 20 – 40% local soil and 60% sand by volume. From April 2015 to June 2015, the plant growing medium is mixed with 20% peat soil, 20% local soil and 60% sand in the 1st, 2nd, 4th, 5th, 7th, 8th, 10th, 11th, 13th, 14th, 15th and 16th bioretention systems; after June 2015, 20% local soil and 80% sand were used instead to detect the nitrogen release from peat soil (Table 1). The composition of packed media and plants were also shown in Table 1.

For every column, one outlet was set in every 20 cm from the bottom to the top. Two columns, which were installed on the platforms at an interval of 20 cm in height, were connected with the pipes to form the stepped bioretention systems (Fig. 1). The bottom outlet from the higher one was linked with different inlets in the lower one, thus developing sorts of flow patterns (e.g., "U" flow pattern and "W" flow pattern). The "U" flow pattern meant that the outlet on the bottom of the higher column was linked to inlet 1 on the bottom of the lower one and the effluent samples would be collected at outlet 1. Therefore, the rainfall runoff in the bioretention systems flowed downward firstly and then upward (Fig. 1). The "W" flow pattern meant that the outlet was connected to inlet 2 and the rainfall runoff would flow out from outlet 2. Therefore, the "downflow – upflow – downflow – upflow" would be formed within the bioretention systems and two saturated zones could also be shaped (Fig. 1). Four different plants were planted in the bioretention systems. *Radermachera hainanensis* (Merr.), *Juncus effusus* (L.), *Vetiveria zizanioides* (L.), and *Medicago sativa* (L.) were selected as test plants for observing their developed root systems in the 18 bioretention systems (Table 1). However, with a low capability of resistance to overwinter, *Vetiveria zizanioides* (L.) naturally withered in 2015, so *Ophiopogon japonicas* (Lf.) was used instead in 2016.

Table 2
Chemical constituents in the stormwater used in the experiment.

Constituent	Concentration/value[a]
pH	6–8
Dissolved organic carbon (mg/L) (without additional carbon)	13.31 ± 12.11
Dissolved organic carbon (mg/L)(with additional carbon)	244.89 ± 26.34
Total nitrogen (mg/L)	3.91 ± 3.92
Nitrate (mg/L)	2.13 ± 2.42
Ammonia nitrogen (mg/L)	1.31 ± 1.86
Total phosphorus (mg/L)	0.51 ± 0.48
Ortho-phosphorus (mg/L)	0.41 ± 0.13

[a] Values represent mean ± standard deviation. "–"means not given.

2.2. Semi-synthetic runoff

The semi-synthetic runoff was introduced to the bioretention systems during experiment. The sediment was collected from local soil, sieved using a 300 μm sieve and mixed with tap water to achieve the target TSS concentration. Other pollutants were made up by adding appropriate chemicals. Potassium nitrate, ammonium sulfate and potassium dihydrogen phosphate were used to imitate nitrate, ammonia nitrogen and ortho-phosphorus, and their concentrations were shown in Table 2. Glucose was added to tap water as additional carbon and 3 rainfall events were the introduced additional carbon. After the addition of glucose, TOC was increased from 13.31 ± 12.11 mg/L to 244.89 ± 26.34 mg/L. The semi-synthetic runoff was continuously mixed in a tank to ensure the dispersion of constituents before being introduced to the columns (Bratieres et al., 2008).