Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-018-3267-5

RESEARCH ARTICLE

Design parameters and treatment efficiency of a retrofit bioretention system on runoff nitrogen removal

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Received: 4 March 2018 / Accepted: 17 September 2018

Abstract

Mixed media design is key factor that affects the operation of bioretention systems. In this study, four types of modifiers, namely, water treatment residual (WTR), green zeolite, fly ash, and coconut bran, were mixed with traditional bioretention soil (65% sand + 30% soil + 5% sawdust, by mass). Consequently, four kinds of modified media were obtained. Ten pilot-scale bioretention basins were constructed by setting different configurations. The steady infiltration rates of the modified packing bioretention systems were 3.25~62.78 times that of plant soil, which was 2.88~55.75 m/day. Results showed that the average concentration removal (ACR) of both mixed and layered fly ash and WTR were better than those of the other media, and the effects could reach over 61.92%. In the bioretention basins with WTR as the modifier, the treatment efficiency of nitrogen under the submerged zone height of 150 mm was relatively optimal, and ACR could reach 65.46%. Outflow total nitrogen (TN) load was most influenced by inflow load, and the correlation coefficient was above 0.765. Relative to the change of inflow concentration (IC), the change of recurrence interval (RI) and discharge ratio (DR) was more sensitive to TN load reduction. The reduction rate of TN load decreased by approximately 15% when the recurrence interval increased from 0.5 to 3 years. It decreased by approximately 12% when the discharge ratio increased from 10 to 20. This study will provide additional insights into the treatment performance of retrofit bioretention systems, and thus, can guide media and configuration design, effect evaluation, and related processes.

Keywords Bioretention · Modified media · Recurrence interval · Discharge ratio · Inflow concentration

Introduction

Rapid urbanization worldwide is a major contributor to changes in runoff quantity and quality, such as increase in runoff volume and rates, reduction in runoff lag time and groundwater recharge, and degradation of water quality (Liu et al. 2017; Pumo et al. 2017). Several rainstorm management concepts have been proposed and developed internationally to reduce runoff and rainwater pollution load. Representative concepts include low-impact development (LID) in the USA, water-sensitive urban design in Australia, and sustainable drainage systems in the UK and other European countries (Zhang et al. 2016; Wang et al. 2015a). LID or green infrastructure practices have been extensively adopted and proven successful in addressing hydrologic and water quality issues (Eckart et al. 2017).

In recent years, China has emphasized the importance of the integrated management of water-related issues in urban areas. In December 2013, the Central Urbanization Working Conference spearheaded the proposal of the concept of a sponge city, which asserts that accumulation, penetration, and purification should be performed naturally. A LID bioretention system is an important measure in sponge city construction. The existing combination of media for bioretention facilities is mainly composed of a layered packing of 30–70 cm planting layer, 20–50 cm artificial packing layer, 15–30 cm gravel drainage layer, or mixed media composed of planting soil with organic matter and sand. The upper layer mainly captures suspended solids, dissolved metals, and hydrophobic organic substances by adding organic matter. The middle layer increases the adsorption of phosphorus by adding iron/aluminum oxide and a saturated anoxic zone with e-donors to promote denitrification for nitrogen removal; an upturned elbow drainpipe creates an internal water storage

Responsible editor: Philippe Garrigues

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Published online: 26 September 2018

zone to promote saturation or anoxia (LeFevre et al. 2015). Studies have also shown that a layered combination of media with different permeability levels contributes to the formation of aerobic–anaerobic reaction conditions. The filtration column of a highly permeable media layer on a lower permeable packing layer achieves better ammonia (NH_3) removal than the reverse packing order (Hsieh et al. 2007). Researchers also have added a certain proportion of modifiers, e.g., water treatment residual (WTR), perlite, peat soil, vermiculite, cinder, volcanic rock, zeolite, and ceramsite, to enhance the operation of facilities (Gao 2014; O'Neill and Davis 2012).

Bioretention systems attenuate runoff peak flow and reduce runoff volume through detention and retention. The water quality treatment performance of bioretention basins relies heavily on different design parameters, such as rainfall intensity, rainfall patterns, and inflow pollutant characteristics. Davis (2008) conducted a hydrographic study of two outdoor bioretention cells at the University of Maryland; the results showed that bioretention cells effectively reduced stormwater runoff in 49 rainfall events and that peak flow decreased by 49 to 59%. The average peak flow time was also delayed 5.8–7.2 times. Hatt et al. (2009) demonstrated that bioretention systems could reduce 80% of peak flow and 33% of runoff volume mainly through packing retention and plant evapotranspiration. However, most studies on bioretention systems for runoff quantity regulation have not considered the refinement of design parameters. Inflow pollutant concentrations, antecedent dry time (ADT), recurrence interval, packing factor, and submerged zone height are among the main internal and external factors that affect nitrogen treatment efficiency. Studies have shown that bioretention systems can effectively remove suspended solids, phosphorus, and heavy metals. However, nitrogen removal performance is highly variable (Yang et al. 2013). Setting submerged areas to promote denitrification and carbon sources to provide electron donors, optimize plant selection, and improve the biological microenvironment is key method for removing nitrogen pollutants (Li et al. 2016; Wang et al. 2015b).

The composition and ratio of filter media play a critical role in bioretention functions. An optimization method for the design and structural combination of bioretention media is developed to achieve runoff flow control and non-point source pollution control, particularly efficient nitrogen pollution control. In the current study, 10 bioretention systems were constructed by (1) mixing efficient modifiers with traditional bioretention soil to form four modified media for bioretention and (2) setting different configurations (i.e., layered or mixing media, different submergence area heights). These procedures were undertaken to (i) develop modified media for improving bioretention performance; (ii) confirm the superior bioretention media configuration for runoff volume control and pollutant removal; and (iii) identify the relationship between the load reduction rate of total nitrogen and hydrologic/hydraulic elements (e.g., recurrence interval, discharge ratio, steady infiltration rate).

Materials and methods

Media preparation

Soil was collected from local topsoil by using a 2 mm sieve. The sieved soil contained 16.68% sand, 8.30% clay, and 75.02% silt and was classified as silt loam according to the soil texture classification of the United States Department of Agriculture. To improve soil infiltration capacity, water retention capacity, and organic quality, sand and wood chips were separately added to form traditional bioretention media (BSM). The test local river sand and soil were mixed at a ratio of 7:3 (by mass). The mixture contained 49.0% sand, 5.5% clay, and 45.5% silt; then, 5% (by mass) wood chips were added to the mixture to increase the organic content and water-holding capacity of the media. The ratio of test local river sand, soil, and wood chips was 65:30:5(by mass), and we defined that as BSM in this study. WTR, zeolite, coco peat, and fly ash were used as modifiers and mixed with BSM in

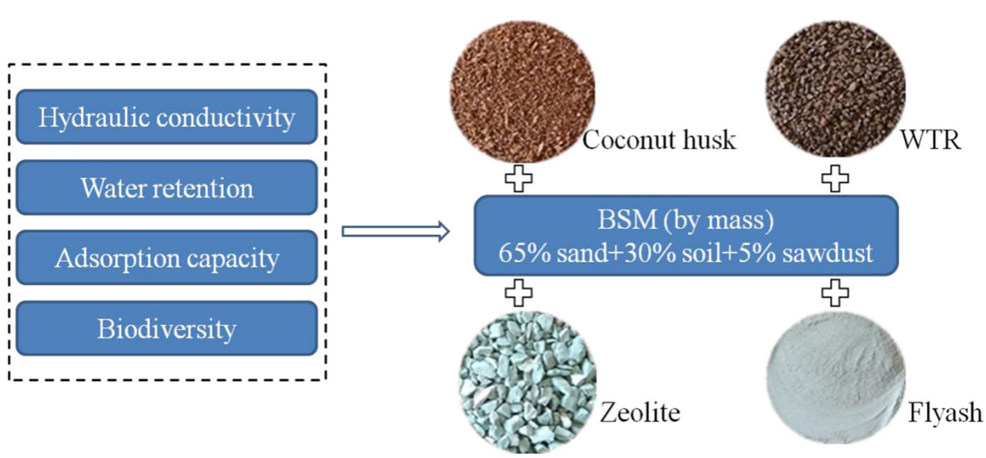

Fig. 1 Composition of the modified mixed media

Table 1 Component characteristics of the media

No.	Media	pH	ρ (g/mL)	BET (m^2/g)	CEC (cmol/kg)	OM (%)	Porosity (cm^3/g)
1	Soil	8.4	1.121	20.837	19.44	0.03	0.0300
2	BSM	7.9	1.116	4.991	34.45	7.55	0.0096
3	WTR	7.8	0.953	28.433	9.31	10.3	0.0215
4	Green zeolite	8.0	1.054	16.871	27.50	6.98	0.0510
5	Fly ash	10.7	1.008	1.381	23.23	2.66	0.0066
6	Coconut bran	a	0.092	0.811	13.62	4.65	0.0026

[a] Data not collected; ρ is the filling density for particles; BET is the specific surface area, m^2/g; CEC represents the cation exchange capacity; pH was used with an air-dried media:water ratio of 1:2.5 (*W/V*)

different proportions to form modified mixed media (Fig. 1). The particle sizes were as follows: zeolite (3–6 mm), BSM and WTR (< 6 mm), and fly ash and coconut bran (< 1 mm). Table 1 shows the component characteristics of the media.

Device setting

Ten pilot-scale bioretention systems were constructed in the outdoor field of Xi'an University of Technology. Each basin has the following dimensions: length 2.0 m × width 0.5 m × depth 1.05 m. The construction involved 15 cm ponding depth, 5 cm mulch, 70 cm media, and 15 cm gravel layer from top to bottom. The mulch was pine bark, and *Buxus sinica* and *Lolium perenne* L. were planted. Geotextile was laid between the media and the gravel layers. A perforated drain (DN75) was placed on the bottom of the system (Fig. 2; Table 2).

Experimental design

Pilot-scale experiments were designed for 10 orthogonal experiments, including the design of rainfall intensity, contribution area, inflow concentration, and submerged zone heights, to determine the appropriate design parameters for the bioretention facilities. The ponding height of the pilot-scale bioretention system was 15 cm, and water was injected into the device until overflow occurred (water injection time was as short as possible); the changes in water level were observed over time. The infiltration rate tended to stabilize, and the infiltration capacity represented by the slope of the fitted line

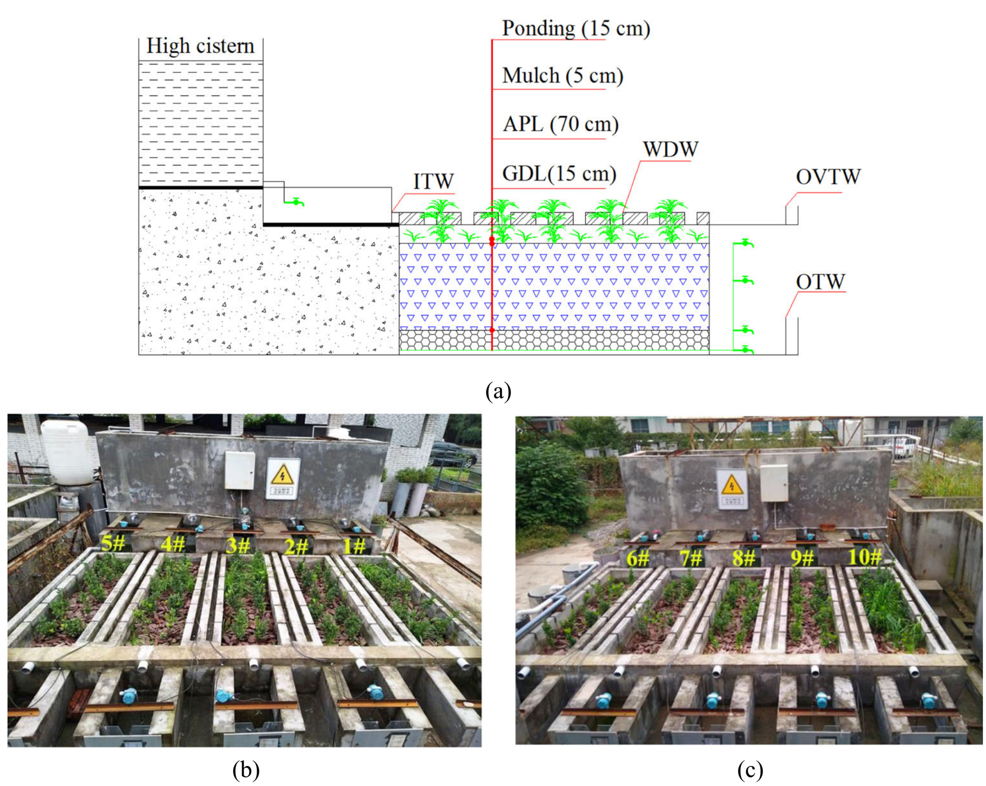

Fig. 2 Pilot plant structure and site photos. Each bioretention basin includes an ponding, mulch, artificial packing layer(APL), and gravel drainage layer(GDL) from top to bottom; ITW for inflow triangle weir, OTW for outflow triangle weir, OVTW for over triangle weir, WDW for water distribution weir.

Table 2 Pilot plant structure

No.	1	2	3	4	5	6	7	8	9	10
Plants	B. and L.	B. and L.	B. and L.	B. and L.	B. and L.	B. and L.	B. and L.	B. and L.	B. and L.	B. and L.
Ponding	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm
Mulch	Pine bark 5 cm	Pine bark 5 cm	Pine bark 5 cm	Pine bark 5 cm	Pine bark 5 cm	Pine bark 5 cm	Pine bark 5 cm	Pine bark 5 cm	Pine bark 5 cm	Pine bark 5 cm
Media	Soil 70 cm	BSM 70 cm	BSM + WTR mixing 70 cm	BSM + WTR mixing 70 cm	BSM + WTR mixing 70 cm	BSM + WTR layering 70 cm	BSM + fly ash mixing 70 cm	BSM + fly ash layering 70 cm	BSM + zeolite mixing 70 cm	BSM + coir mixing 70 cm
GDL	10 cm	10 cm	10 cm	10 cm	10 cm	10 cm	10 cm	10 cm	10 cm	10 cm
SZH	0	0	0	150	350	0	0	0	0	0

SZH, submerged zone height; *GDL*, gravel drainage layer

indicated the permeability of the bioretention system under saturated water condition. The steady infiltration rates of the 10 pilot systems were tested firstly.

Inflow volume under 60 min was calculated in three recurrence intervals, namely, 0.5, 2, and 3 years. Pollutant concentrations were determined by comparing the results of water quality assessment with urban road surface runoff in northwest China. Tables 3 and 4 show the test schedule and inflow pollutant concentrations, respectively. In rainstorm design, the Pilgrim and Cordery (PC) method is insignificantly affected by rainfall duration and only increases or reduces the rain tail part when duration increases or decreases; consequently, the calculated peak flow is stable. The PC method was adopted in the rainstorm pattern calculation in the present study for the short-term rainfall data of 60 min (Zhou 2015; Cen et al. 1998). The rainfall pattern is shown in Fig. 3. The inflow, outflow, and overflow weirs are installed with level monitoring gauges (*XMTJ3246R*). Their record frequency is 1 s to determine the water volume after calculation. The sampling was set as follows: (i) inflow sampling at 0, 30, and 60 min after the start of the experiment; (ii) overflow water sampling during overflow at 0, 15, 30, 45, and 60 min; and (iii) effluent water sampling during outflow at 0, 15, 30, 45, and 60 min.

Analysis methods

The parameters for the water quality analysis were pH, electrical conductivity, dissolved oxygen (DO), total nitrogen (TN), nitrate nitrogen (NO_3–N), and ammonia nitrogen (NH_3–N). The first three parameters were used in the instrumental measurement with HACH HQ40d two-circuit input, multi-parameter numerical analysis. Water sample was filtered with a 0.45-μm filterable membrane, and the original water sample was oxidized with potassium persulfate. Ultraviolet spectrophotometry was performed to determine TN. Phenol disulfonic acid spectrophotometry was conducted to determine NO_3–N content. Nessler's reagent colorimetric method was adopted to analyze NH_3–N content. Water reduction rate ($R_{\text{retention}}$), peak flow cutting rate (R_p), pollutant removal rate (R_c), and load reduction rate (R_L) were determined using Eqs. (1)–(4), as follows:

$$R_{\text{retention}} = (V_{\text{in}} - V_{\text{out}} - V_{\text{over}})/V_{\text{in}} \times 100\% \tag{1}$$

$$R_p = \left(Q_{p-\text{in}} - Q_{p-\text{out}}\right)/Q_{p-\text{in}} \times 100\% \tag{2}$$

$$R_c = (EMC_{in} - EMC_{out})/EMC_{in} \times 100\% \tag{3}$$

$$R_L = (L_{\text{in}} - L_{\text{out}} - L_{\text{over}})/L_{\text{in}} \times 100\%, \tag{4}$$

Table 3 Test schedule for the pilot-scale bioretention systems

Test number (date)	Precipitation/mm, factor $A_{(\text{Level } 1,\, 2,\, 3)}$	Discharge ratio, factor $B_{(\text{Level } 1,\, 2,\, 3)}$	Inflow concentration, factor $C_{(\text{Level } 1,\, 2,\, 3)}$	Test conditions
0 (1 Aug., 2017)	11.47 (A_1)	10 (B_1)	High (C_1)	$A_1B_1C_1$
1 (7 Aug., 2017)	11.47 (A_1)	15 (B_2)	Medium (C_2)	$A_1B_2C_2$
2 (13 Aug., 2017)	11.47 (A_1)	20 (B_3)	Low (C_3)	$A_1B_3C_3$
3 (19 Aug., 2017)	23.88 (A_2)	10 (B_1)	Medium (C_2)	$A_2B_1C_2$
4 (25 Aug., 2017)	23.88 (A_2)	15 (B_2)	Low (C_3)	$A_2B_2C_3$
5 (31 Aug., 2017)	23.88 (A_2)	20 (B_3)	High (C_1)	$A_2B_3C_1$
6 (6 Sept., 2017)	27.51 (A_3)	10 (B_1)	Low (C_3)	$A_3B_1C_3$
7 (12 Sept., 2017)	27.51 (A_3)	15 (B_2)	High (C_1)	$A_3B_2C_1$
8 (18 Sept., 2017)	27.51 (A_3)	20 (B_3)	Medium (C_2)	$A_3B_3C_2$
9 (24 Sept., 2017)	11.47 (A_1)	10 (B_1)	High (C_1)	$A_1B_1C_1$

Discharge ratio is the catchment area/bioretention surface area

$$R_{L(\text{total})} = \left(\sum_{i=1}^{10} L_{i(\text{inflow})} - \sum_{i=1}^{10} L_{i(\text{outflow})} \right) \Big/ \sum_{i=1}^{10} L_{i(\text{inflow})} \times 100\% \tag{5}$$

where, $V_{\text{in/out/over}}$ is the inflow, outflow, and overflow volume, L; $Q_{p\text{-in}}$ and $Q_{p\text{-out}}$ are the inflow and outflow peak flows, respectively; $L_{\text{in/out/over}}$ is the inflow, outflow, and outflow pollutant load, mg; and $EMC_{\text{in/out}}$ is the mean concentration in a single rainfall event for inflow or outflow, mg/L.

Results and discussion

Hydraulic characteristics of the bioretention system

Permeability in the bioretention system is a crucial design consideration for water quality and quantity regulation. Sun et al. (2011) analyzed the sensitivity of bioretention cell design elements to their hydrologic performances, and the results showed that the permeability of native soil and underdrain size were the two most sensitive design elements for bioretention cells with underdrain. Media texture, hydrophobicity, and water content are critical factors that affect hydraulic conductivity (Wang et al. 2000; Hsieh and Davis 2005). The steady infiltration rates of the 10 pilot systems are shown in Fig. 4.

When rainfall runoff flowed into the bioretention system, the bioretention media should go through the moist stage, seepage stage, and saturation steady flow from unsaturated to saturated infiltration. The rain infiltration velocity in the packing was equal to the saturated hydraulic conductivity (Ks) in saturated infiltration. When Ks was less than the rainfall intensity, the bioretention basin appeared to be ponding. If V_{ponding} exceeds the water volume of the facility, then overflow will occur. Tests 1 to 9 simulated the precipitation in the 10 bioretention systems, and 90 infiltration scenarios were simulated. A total of 38 scenarios demonstrated different ponding degrees, and overflow occurred in 8 scenarios. The overflow scenarios in bioretention basin no. 1 were $A_2B_2C_3$, $A_2B_3C_1$, $A_3B_1C_3$, $A_3B_2C_1$, and $A_3B_3C_2$. The overflow scenarios in bioretention basin no. 7 were $A_2B_3C_1$, $A_3B_2C_1$, and $A_3B_3C_2$, as shown in Table 3. Trowsdale and Simcock (2011) found that a bioretention system smoothed the hydrograph by reducing peak flow and volume for all 12 events monitored in detail, and overflow occurred in 10 events. Thereby indicating that the increased permeability did not fully compensate for the undersized volume; the subsoil infiltration rates during construction were high, with a mean of 224 mm/h (103–405 mm/h). The flow process line is shown in Fig. 5.

When infiltration technology is used to treat rainwater to recharge groundwater, the permeability coefficient is generally not less than 1×10^{-6} m/s. When infiltration technology is used to treat rainwater for harvest, the permeability coefficient is not less than 1×10^{-5} m/s (Che and Li 2006). However, as permeability coefficient increases, the contact time between the media and runoff water decreases, and poor water retention may result in the leaching of pollutants. Infiltration velocities were relatively high during construction. A side wall flow or partial preferential flow might have occurred to a certain extent, which led to a high infiltration rate. The experimental results showed that the infiltration capacity of plant soil in this

Table 4 Concentrations of inflow pollutants

Pollutants	COD	NO_3–N	NH_3–N	TP	Cu	Zn	Cd
High	600	12	6	2.5	1.0	1.5	0.5
Medium	300	6	3	1.5	0.5	1.0	0.3
Low	100	3	1.5	1.0	0.3	0.5	0.1

The preparation reagents of COD, NO_3–N, NH_3–N, TP, Cu, Zn, and Cd are glucose, potassium nitrate, ammonium chloride, potassium dihydrogen phosphate, copper chloride, zinc sulfate, and cadmium chloride, respectively

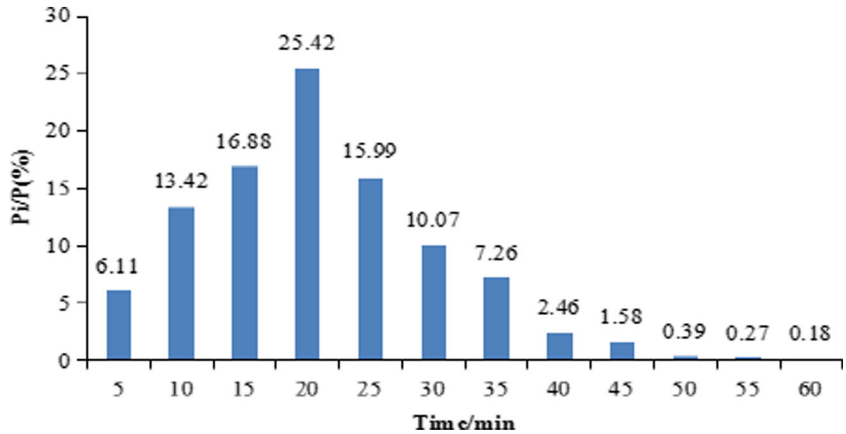

Fig. 3 Rainfall pattern

study was relatively low, and the steady infiltration rates of the modified media were 3.25–62.78 times that of plant soil. Because of the high steady infiltration rate, bioretention basin no. 2–9 has a higher outflow rate than planted soil (29.38–66.30%). The water-holding capacities of the modified media were slightly lower than that of plant soil, and the median value of the modified media was 19.89~40.99%, which was 0.84–1.73 times that of the traditional BSM, most of the values were higher than that of the traditional BSM. The peak flow median reduction rates of bioretention basin nos. 1 and 7 were significantly high, which were 86.52% and 93.62%, but significant ponding was observed. The peak flow control rates of the other bioretention basins were approximately 60% (Table 5).

EMC treatment efficiency

To thoroughly study the performance of bioretention treatment, the concentration removal and the pollutant load reduction were analyzed separately. Table 6 shows the DO, electric conductivity (δ), and concentration removal rates of TN, NO_3−N, and NH_3−N, along with the average concentration removal of TN, NO_3−N, and NH_3−N (ACR).

The average values of DO, conductivity, and pH were 7.6 mg/L, 283.7 μs/cm, and 7.4, and the standard deviations were 0.47, 50.45, and 0.09, respectively. DO in the effluent of mixed bioretention basins, except for bioretention basin no. 1, was 4.0–6.0 mg/L. The DO content decreased significantly. The average concentration removal (ACR) rates of BSM + fly ash (mixed and layered) and BSM + WTR (mixed and layered) were better than those of the other media, and the effects could reach over 61.92%. The removal rates of TN, NO_3−N, and NH_3–N in bioretention basins nos. 2 to 9 increased by 8.81–24.1%, 11.77–30.29%, and 5.22–12.57%, respectively, than planting soil (The removal rates of TN, NO_3−N, and NH_3–N were 50.67%, 42.28%, and 64.55%). Wang et al. (2017) operated 18 stepped bioretention systems from 2015 to 2016, and the results showed that all the systems provided satisfactory treatment for NH_3−N. Similarly, the removal effect of NH_3−N was relatively optimal and was greater than 62.97% in the present study. The TN and NO_3−N removal of the modified bioretention system with coconut bran as modifier was negative compared with other basins, the leaching rate for NO_3−N was 14.79%. Wan et al. (2017) developed a novel two-layered system with wood chips only in the upper layer, and the results indicated that the layered structure could

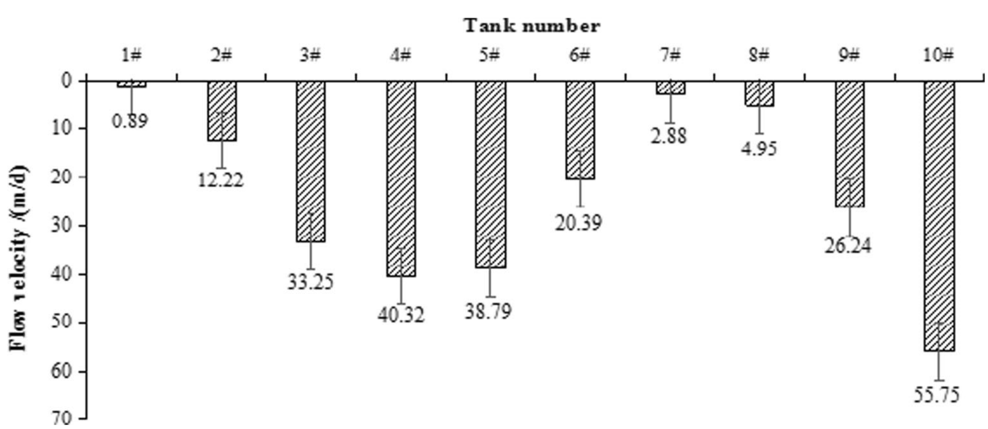

Fig. 4 Steady infiltration rates of the 10 bioretention basins

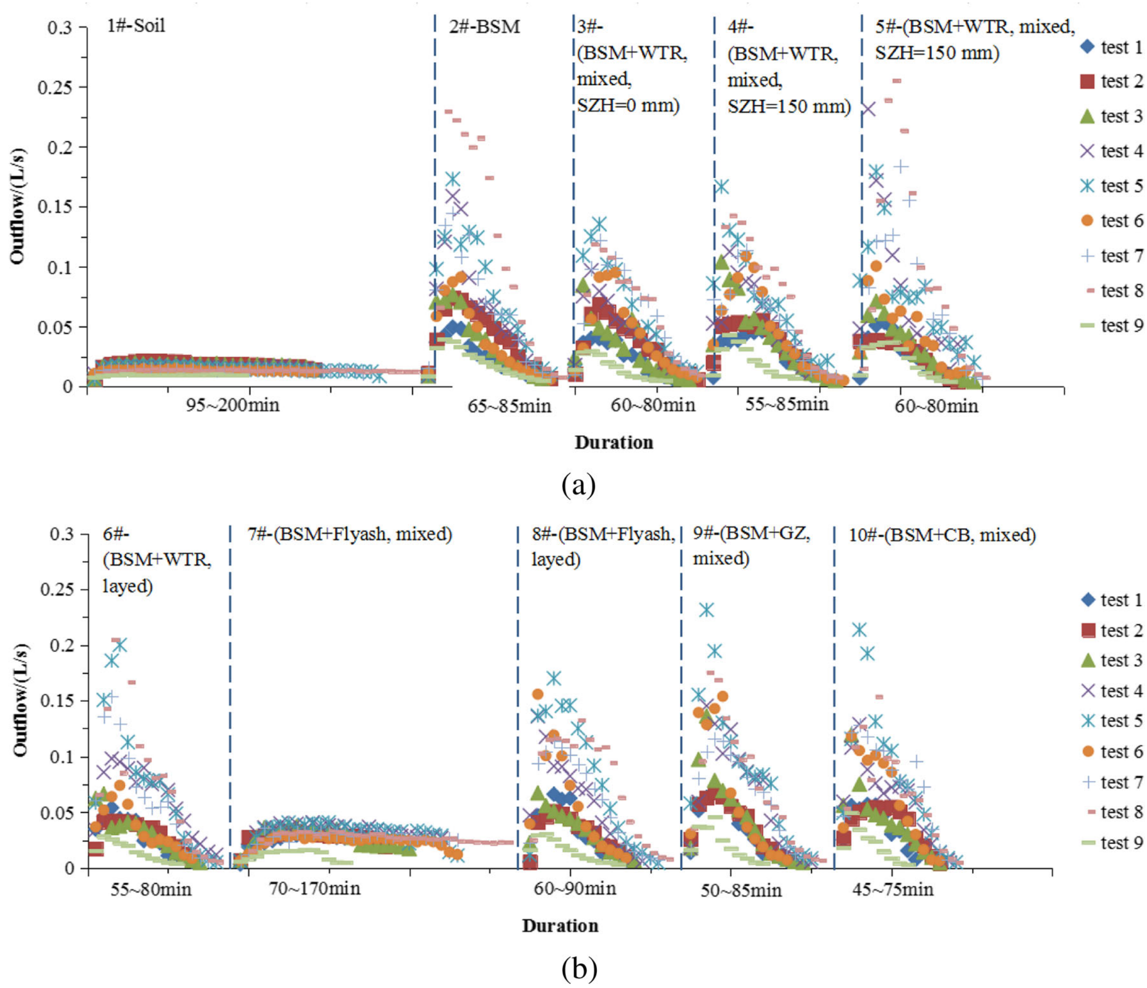

Fig. 5 Outflow process lines of different bioretention systems

effectively remove NO_3 by over 80%. Liu (2015) analyzed the effects of submerged zone height and the presence or absence of carbon sources on denitrification in bioretention basins. The results of Liu showed that as the submerged zone height increased, the removal rate of NH_3–N decreased, whereas those of NO_3–N and TN increased. When the submerged zone height was 450 mm and waste newspaper was added as the carbon source, the removal rates of NH_3–N, NO_3–N, and TN reached 73%, 68%, and 50%, respectively. In the bioretention basins with WTR as the modifier, the NO_3–N concentration removal rates were 54.05%, 59.95%, and 62.11% in the three submerged area

Table 5 Regulation effects of bioretention systems

No.	R_o (%) min–max (median)	$R_{retention}$ (%) min–max (median)	R_p (%) min–max (median)
1	29.38–66.30% (40.66%)	30.40–51.42% (42.38%)	88.01–96.85% (93.62%)
2	65.68–96.76% (76.36%)	13.24–34.32% (24.30%)	47.71–66.05% (59.15%)
3	47.85–72.14% (59.01%)	27.86–52.15% (40.99%)	58.12–74.59% (66.52%)
4	60.22–83.89% (66.92%)	16.11–39.78% (33.08%)	48.52–71.43% (62.90%)
5	45.20–89.20% (68.04%)	10.80–54.80% (31.96%)	23.74–80.22% (56.84%)
6	42.65–80.70% (65.44%)	19.30–57.35% (34.56%)	50.58–78.15% (67.19%)
7	43.37–86.25% (68.47%)	13.75–56.63% (30.14%)	78.09–92.91% (86.52%)
8	46.66–83.68% (72.60%)	16.32–53.34% (27.40%)	33.18–73.71% (66.75%)
9	54.85–89.78% (80.12%)	10.22–45.15% (19.89%)	32.67–66.82% (52.82%)
10	48.42–86.78% (69.09%)	13.22–51.58% (30.91%)	41.03–71.74% (57.55%)

Table 6 Outflow DO, electric conductivity, and the EMC removal rate of nitrogen

No.	DO (mg/L)	δ (μs/cm)	R_c-TN	R_c (NO_3−N)	R_c (NH_3−N)	ACR (N)
1	7.0 (0.44)	526.2 (63.35)	50.67% (0.10)	42.28% (0.06)	64.55% (0.19)	52.50%
2	5.4 (0.70)	632.8 (66.98)	65.78% (0.14)	64.63% (0.14)	75.11% (0.07)	68.51%
3	6.0 (0.31)	602.6 (44.75)	59.48% (0.11)	54.05% (0.12)	72.24% (0.10)	61.92%
4	4.4 (1.05)	633.2 (74.01)	63.06% (0.13)	59.95% (0.15)	73.36% (0.10)	65.46%
5	4.3 (0.88)	667.8 (80.16)	65.63% (0.14)	62.11% (0.19)	72.87% (0.09)	66.87%
6	5.8 (0.61)	561.5 (73.58)	62.17% (0.13)	54.14% (0.15)	76.43% (0.11)	64.25%
7	4.0 (1.03)	850.0 (116.31)	74.77% (0.11)	72.57% (0.13)	77.12% (0.09)	74.82%
8	5.3 (0.62)	595.6 (56.20)	69.83% (0.11)	67.23% (0.12)	72.13% (0.10)	69.73%
9	5.4 (0.47)	559.5 (54.60)	60.27% (0.12)	54.26% (0.12)	69.77% (0.11)	61.43%
10	5.1 (0.50)	558.4 (89.45)	− 1.91% (0.56)	− 14.79% (0.71)	62.97% (0.13)	15.42%

δ represents electric conductivity; values represent mean (standard deviation); ACR represents the average concentration rate of TN, NO_3−N, and NH_3−N

heights (0, 150, and 350 mm). Considering the concentration removal effect of TN, NH_3–N, and NO_3−N, the treatment efficiency of nitrogen under the submerged zone height of 150 mm was relatively optimal, and ACR could reach 65.46%.

Nitrogen load treatment and hydrologic/hydraulic design parameters

The treatment performance of bioretention basins relies heavily on various factors, such as rainfall depth, ADT, and contribution area. Mangangka et al. (2015) assessed the hydraulic and hydrologic factors that influenced pollutant load removal by a bioretention basin under field conditions, and the results of them confirmed that ADT and retained volume were relatively important factors that influenced the performance of bioretention basin treatment in terms of pollutant load reduction. Table 7 shows the relationship between outflow TN load and inflow TN load for the 10 bioretention basins. In the present study, the correlation coefficients between outflow and inflow TN load were above 0.765, and outflow TN load was most influenced by inflow TN load.

Data from ten simulated rainfall events about 1~10# bioretention basins were introduced into Eq. (5), and inflow/outflow loads and load reduction rates of TN, NO_3−N, and NH_3−N for ten bioretention basins during the test period were obtained (Fig. 6). Variations in rainfall depths, ADTs, contribution areas, inflow concentrations, and other parameters will yield different operating results. In this experiment, ADT was 6 days, and the rainfall lasted 60 min. The main factors that influenced the design were rainfall recurrence interval, contribution area, and inflow concentration. Table 8 shows the effects of different packing combinations and structural designs on the TN load reduction of the 10 bioretention basins.

Li and Davis (2014) monitored the bioretention basins modified with 5% WTR. The results showed that the annual input nitrogen load was 14.0 kg/ha-year, whereas the annual output and infiltration nitrogen loads were 8.2 and 4.4 kg/ha-year, respectively. The annual net nitrogen mass retained by the bioretention cell was only 1.4 kg/ha-year. Studies have indicated that mass removals by bioretention are higher than concentrations due to water volume attenuation (Davis 2007; Lucke and Peter 2015). In the 10 bioretention basins, only bioretention basin nos. 1 and 7 overflowed. The difference between the outflow load and the overflow load for bioretention basin no. 1 was small, and they were approximately 19.7% of the inflow load. The load reduction rates of nitrogen pollutants in bioretention basin nos. 1 and 10 were relatively low, and the load reduction rates of TN, NO_3−N, and NH_3−N of the other bioretention basins were 66.28–75.49%, 61.47–73.83%, and 74.23–82.40%, respectively. The pore spaces and the loose structure allowed rapid movement of water through the basin, decreasing contact with the

Table 7 Correlation model between inflow and outflow TN loads

No.	Correlation model	No.	Correlation model
1	$L_{out} = 0.1763L_{in} + 0.0994$ ($R^2 = 0.981$)	6	$L_{out} = 0.3783L_{in} + 0.2967$ ($R^2 = 0.964$)
2	$L_{out} = 0.331L_{in} + 0.0998$ ($R^2 = 0.822$)	7	$L_{out} = 0.2189L_{in} + 0.1382$ ($R^2 = 0.980$)
3	$L_{out} = 0.3047\ L_{in} + 0.1155$ ($R^2 = 0.972$)	8	$L_{out} = 0.3287L_{in} + 0.2473$ ($R^2 = 0.950$)
4	$L_{out} = 0.331L_{in} + 0.1624$ ($R^2 = 0.957$)	9	$L_{out} = 0.4177L_{in} + 0.2402$ ($R^2 = 0.891$)
5	$L_{out} = 0.4203L_{in} + 0.3512$ ($R^2 = 0.949$)	10	$L_{out} = 0.3855L_{in} + 0.674$ ($R^2 = 0.765$)

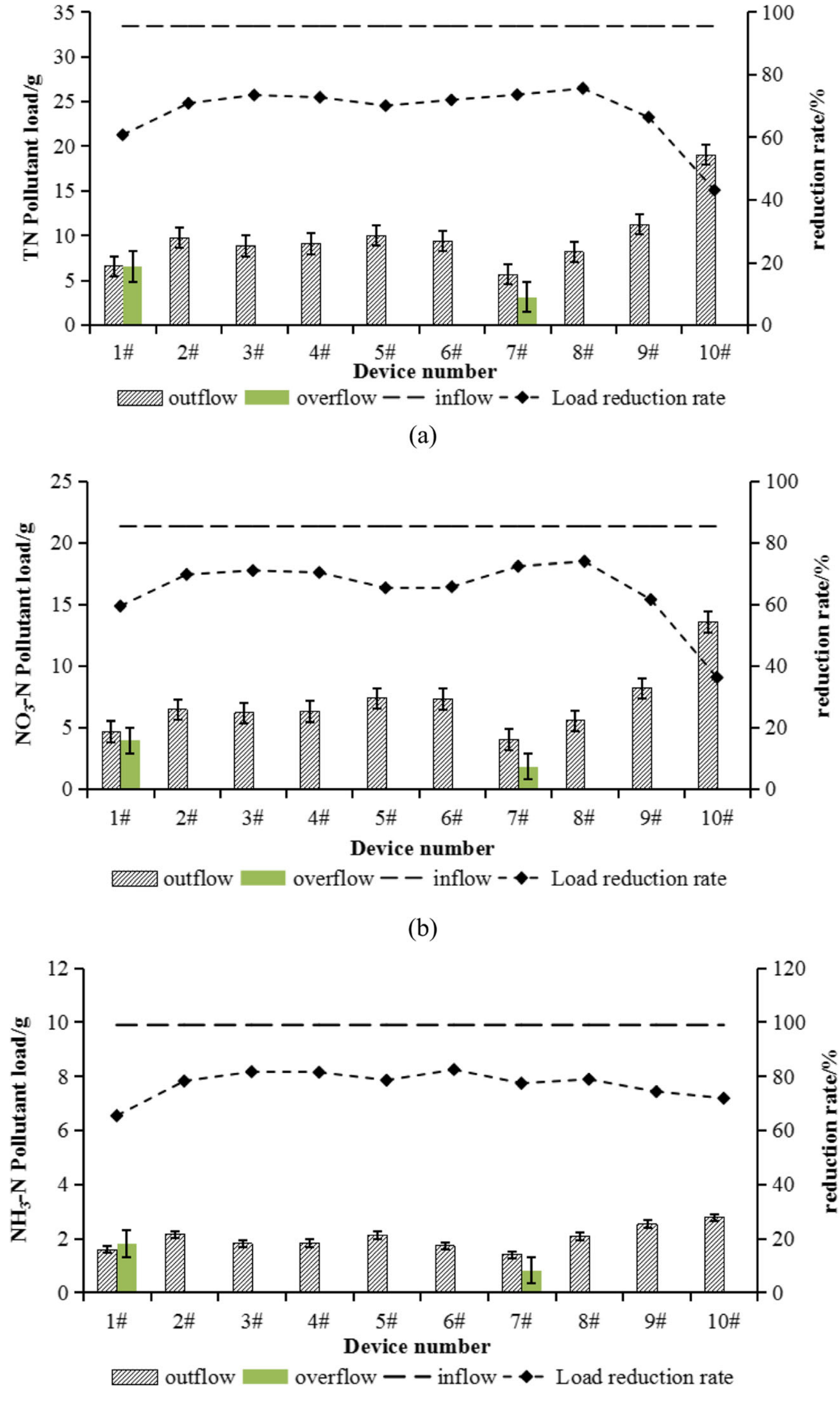

Fig. 6 Inflow/outflow loads and load reduction rates

coconut bran material and lowering bioretention basin no. 10 removal performance. Total load reduction rate of bioretention basin nos. 1 was affected by both the media adsorption capacity and overflowed events.

Recommendations for the hydraulic conductivity (*K*) of different media vary from one country to another. For example, guidelines for biofilter design require a *K* of at least 0.3 m/day in New Zealand and the USA and between 0.86 m/day and 8.64 m/day in Austria (Coustumer et al. 2009). The Facility for Advancing Water Biofiltration (FAWB) of the Australian Monash University recommends that 2.4–7.2 m/day hydraulic conductivity is temperate to meet optimal practice targets. In this test, bioretention basin no. 1 was below the recommended range of 2.4–7.2 m/day, bioretention basins nos. 7 and 8 were within the recommended range, and the other bioretention basins were above the recommended range.

Table 8 Total nitrogen load reduction in different design conditions

Index		FAWB	1	2	3	4	5	6	7	8	9	10
K (m/day)		2.4–7.2	0.89	12.22	33.25	40.32	38.79	20.39	2.88[a]	4.95[a]	26.24	55.75
TN (mg/kg)		< 1000	450[a]	790[a]	620[a]	620[a]	620[a]	620[a]	820[a]	820[a]	470[a]	2460
OM (%)		3~5	1.52	1.19	4.36[a]	4.36[a]	4.36[a]	4.36[a]	3.79[a]	3.79[a]	3.27[a]	9.13
R_{L}-$_{TN}$ (RI, year)	0.5	–	71.02	82.37	78.68	81.81	87.24	78.04	88.62	88.46	78.65	2.75
	2	–	62.11	74.29	76.09	72.07	73.02	74.11	78.97	75.54	58.41	30.61
	3	–	60.59	61.54	68.07	67.53	62.73	72.21	69.73	69.73	66.20	40.33
R_{L}-$_{TN}$ (DR)	10	–	73.48	77.28	77.32	77.08	83.52	85.87	87.45	81.42	72.86	38.45
	15	–	62.79	75.73	75.60	74.32	70.61	70.70	81.20	77.71	65.00	16.95
	20	–	57.44	65.19	69.92	70.00	68.86	67.80	68.67	74.59	65.40	18.29
R_{L}-$_{TN}$ (IC, mg/L)	C_H	–	59.59	76.08	76.90	77.41	73.62	75.77	76.30	78.48	71.16	60.16
	C_M	–	67.09	72.32	75.73	70.86	74.61	69.99	77.87	79.85	68.07	24.22
	C_L	–	67.03	69.79	70.20	73.13	74.77	78.60	83.15	75.40	64.03	10.69

[a] Means that the values are within the recommended range of FAWB; *K* is the hydraulic conductivity; *RI* is the recurrence interval; *DR* is the discharge ratio; *IC* is the inflow concentration

The biofilters clogged over time, with the average hydraulic conductivity decreasing by a factor of 3.6 over the 72 weeks of testing. The selection of plant species significantly affects the permeability reduction rate (Coustumer et al. 2012). TN and OM in ten pilot-scale systems met the recommended values by FAWB (TN < 1000 mg/kg, OM = 3~5%). The effects of nitrogen control in this test were quantified under different recurrence intervals, discharge ratios, and inflow concentrations. The TN load reduction rate decreased by approximately 15% when the design recurrence interval increased from 0.5 to 3 years and which decreased by approximately 12% when the discharge ratio increased from 10 to 20. When the inflow concentration changed, the change in the TN load reduction rate was insignificant. We can get that the design recurrence interval and the discharge area are more important factors for pollutant load control than inflow concentration.

Conclusions

The selection of appropriate internal and external influencing factors can increase the treated nitrogen load. In this study, the stable infiltration rate of modified packing was 2.88~55.75 m/day. The median value of the water-holding capacity of the modified media was 19.89%~40.99%, which was slightly lower than that of plant soil, and that was 0.84–1.73 times of traditional BSM, most of the values were higher than that of traditional BSM. The media of BSM + fly ash (mixed or layered) and BSM + WTR (mixed or layered) were recommended for reducing and purifying stormwater runoff and pollutants. Pollutant leaching influences the bioretention basin treatment performance of the modified media, such as coconut bran is used as bioretention media. The design rainfall recurrence interval and the discharge ratio are critical to pollutant load control. When the design recurrence interval increased from 0.5 to 3 years, TN load reduction rate decreased by approximately 15%. TN load reduction rate decreased by approximately 12% when the discharge ratio increased from 10 to 20.

Funding information This research was financially supported by the National Natural Science Foundation of China (51879215), the key research and development project of Shaanxi Province (2017ZDXM-SF-073), and the open foundation of Institute of Water Resources and Hydro-Electric Engineering of Xi’an University of Technology (2016ZZKTZ-30).

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