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Phosphorus removal of retrofit bioretention systems on urban surface runoff

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ABSTRACT

Bioretention systems rely on mixtures of soil, sand, and organic materials to manage stormwater runoff. However, bioretention systems can also leach nutrients, and the media has unstable effect in infiltration rates and downstream pollution loads. In this study, 10 bioretention basins were constructed by setting different configurations with modified media which a mixture of water treatment residual (WTR), green zeolite, fly ash, and coconut bran and traditional bioretention soil media (BSM, 65% sand+30% soil+5% sawdust, by mass), respectively. The steady infiltration rates of the modified packing bioretention systems were 3.25–62.78 times that of undisturbed soil, which was 0.24–3.3 times that of traditional bioretention soil. Results showed that the removal rate of total phosphorus in bioretention basin with coconut bran as modifier was lower than others (79.14%), and the removal rates of total phosphorus were 86.22%–96.87% in other systems. The effluent concentrations of total phosphorus in 10 bioretention systems were basically better than Class IV limitation (0.3 mg/L) of Environmental Quality Standards for Surface Water in China. The probabilities of BSM and fly ash mixed (#7), BSM and fly ash layered (#8), BSM and zeolite mixed (#9), and BSM and coconut bran mixed (#10) bioretention basins outflow concentration inferior to Class II limitation (0.1mg/L) were relatively high, which were 93%, 94%, 40%, and 91%, respectively. The total phosphorus load reduction rate decreased by approximately 20% for #1, and 15% for #7 bioretention basin, when the design recurrence interval increased from 0.5 to 3 years, or the contribution area ratio increased from 10 to 20. In 10 simulated rainfall experiments, the total phosphorus load reached 4.8 kg in each bioretention basin, and the total phosphorus load reduction rate reached 82.39% (#1)–98.32% (#3).

Keywords: Bioretention; Modified media; Steady infiltration rates; Outflow concentration; Load reduction rate

1. Introduction

The increase in impervious surface accompanying urban development over recent decades has increased both the volume of stormwater runoff, and the amount of pollution flowing downstream to receiving waters [1,2]. The main pollutants in stormwater runoff can be divided into six categories: solid (sediment and suspended matter), heavy metals (zinc, copper, lead, and chromium), biodegradable organic pollutants (Chemical oxygen demand (COD), and biochemical oxygen demand (BOD)), nutrients (nitrogen and phosphorus), and microorganisms and organic micro-pollutants (polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and endocrine disruptors) [3]. Bioretention basins have better removal effect on pollutants such as suspended particles, heavy metals, lipids, and pathogenic bacteria in runoff, but it is not stable to the removal of nitrogen, phosphorus, and other nutrients [4,5]. In addition, nutrients have drawn much attention because of their significant role in the eutrophication of water bodies [6,7].

Research on this technology mainly involves the removal of pollutants, hydraulic properties of infiltration, the size of the system, the choice of media type and depth, the role of plants, and the hydrological effects of the system. In bioretention systems, media is a key factor in the function of the

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system [8]. It is getting more and more attention by scholars to develop bioretention mixed media with high water permeability, high water-holding capacity, and water purification capacity by adjusting the proportion of clay and sand in the soil, adding a certain proportion of organic matter, increasing the specific surface area and adsorption capacity of the media and so on [9]. O'Neill and Davis [10,11] mixed different proportions of water treatment residual (WTR), hardwood bark mulch, leaf and yard waste compost, and sand to form 14 mixed media for batch test and mini-column test. It was found that phosphorus mass was adsorbed by media when adding 4%–5% air-dried WTR to BSM, and that of media without WTR repair increased by 71.2%. Wang et al. [12] designed composite media bioretention systems though layered/mixed 7-type packing structure with soil, zeolite, activated carbon, and wood chips to study the runoff pollutants removal. The removal rate of total phosphorus (TP) can reached 70% for all systems. Nitrogen removal in the media with zeolite/activated carbon (40 cm) + wood chips (10 cm) was relatively high, reaching about 90%. In common modifiers, the characteristics of zeolite are adsorption, ion exchange, stability, acid heat resistance, and other properties, but it is expensive and not easy to recover. WTR contains a large amount of Al^{3+}, and it has a strong ability to absorb phosphorus. There are more active points and larger specific surface area of fly ash than general materials. However, material adsorbed by fly ash easily leached in the infiltration process and lead to secondary pollution. The inner part of the coconut substrate is sponge-like fibers, which is capable of absorbing water of eight times its own mass. The other features of coconut are moderate pH, good air permeability and water-holding capacity, natural environment protection, and no harmful substances, but without enough source.

The removal of phosphorus is closely related to the operating life of the bioretention facility and the initial level of phosphorus in the media. The bioretention facility with higher initial phosphorus content or longer operation life has the phenomenon of phosphorus re-release in the media. Appropriately increasing the content of Al, Fe and Ca in the media can increase the removal effect of phosphorus [13,14]. In addition, the higher clay content has a better adsorption for phosphorus [15]. However, clay content is too high to affect the permeability of the system. The United States and New Zealand required infiltration rate at least 12.5mm/h, Austria required 36–360mm/h, and Australia required 50–200mm/h [16]. The Facility for Advancing Water Biofiltration (FAWB) guidelines prescribed that hydraulic conductivity will generally be between 100 and 300 mm/h in order to meet best practice targets, biofiltration systems with a hydraulic conductivity greater than 600 mm/h are unlikely to support plant growth due to poor water retention, and this may also result in leaching of pollutants [17]. If a system does not perform adequately with this hydraulic conductivity, then the ponding depth should be increased. The infiltration capacity of the biofiltration system will initially decline during the establishment phase as the filter media settles and compacts, but this will level out and then start to increase as the plant community establishes itself and the rooting depth increases [18].

The composition and ratio of filter media and hydrologic performance play critical roles in bioretention functions. In this study, 10 bioretention systems were constructed through media design and structural combination to achieve runoff flow control and non-point source pollution control, particularly efficient phosphorus pollution control. These procedures were undertaken (i) to improve media infiltration capacity and phosphorus event mean concentration (EMC) removal; (ii) confirm the characteristics of outflow phosphorus concentration for retrofit bioretention systems, and (iii) identify the relationship between phosphorus removal and the design parameters of the bioretention system (e.g., recurrence interval, contribution area ratio, steady infiltration rate, and inflow concentration).

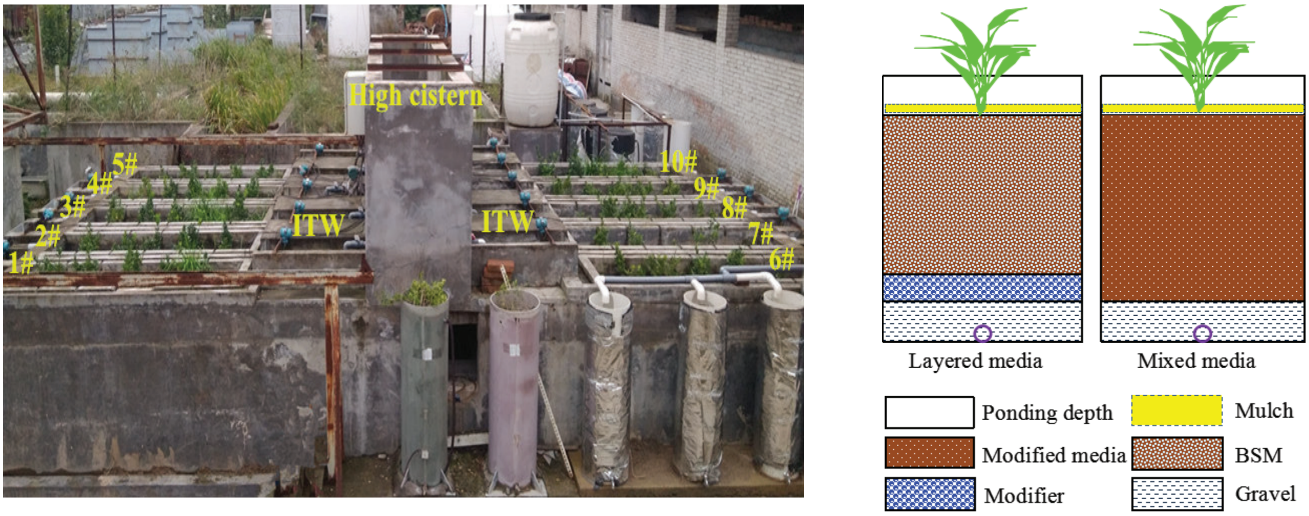
2. Materials and methods

2.1. Device setting and media preparation

Ten pilot-scale bioretention systems were constructed in the outdoor field of Xi'an University of Technology. The structure and site photos are shown in Fig. 1. Each tank 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. Permeable geotextile was laid between the media and the gravel layers. A perforated drain (DN75) was placed on the bottom of the system. 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 soil, and we defined that as BSM (sand:soil:wood chips = 6.5:3:5, by mass) in this study. WTR, zeolite, coconut bran, and fly ash were used as modifiers and mixed with BSM in different proportions to form modified mixed media (Table 1). BSM and WTR, fly ash, and zeolite were mixed at a ratio 9:1 by mass, respectively, and the ratio of BSM and coconut was 19:1.

2.2. Experimental design

Pilot-scale experiments were designed for a preliminary experiment (Test 0) and nine standard orthogonal tests (Test 1–Test 9), including the design of rainfall intensity, contribution area, and inflow concentration, to determine the appropriate design parameters for the bioretention facilities. In addition, three submerged zone heights (0, 150, and 350 mm) were set for the bioretention cells with BSM + 10% WTR as the media. Table 2 shows the test schedule. Water volume 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 Xi'an, China. The preparation reagents of COD, nitrate (NO_3–N), ammonia (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. Among them, the high, medium, and low concentrations of TP were 2.5, 1.5, and 1.0 mg/L, respectively. In rainstorm design, the Pilgrim and Cordery (PC) method is insignificantly affected by rainfall duration and only



(a) (b)

Fig. 1. Pilot-scale bioretention device site photos (a) and structures (b).

Table 1
Pilot plant structure

No.	1	2	3	4	5	6	7	8	9	10
Ponding	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm
Mulch	Pine bark	Pine bark	Pine bark	Pine bark	Pine bark	Pine bark	Pine bark	Pine bark	Pine bark	Pine bark
Media	Soil 70 cm	BSM 70 cm	BSM + WTR 70 cm	BSM + WTR 70 cm	BSM + WTR 70 cm	BSM + WTR 70 cm	BSM + fly ash 70 cm	BSM + fly ash 70 cm	BSM + zeolite 70 cm	BSM + coconut bran 70 cm
CF	–	–	Mixed	Mixed	Mixed	Layered	Mixed	Layered	Mixed	Mixed
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

CF, combination form; SZH, submerged zone height; GDL, gravel drainage layer.

Table 2
Test schedule for the pilot-scale bioretention systems

Test number	Precipitation/mm, Factor $A_{(\text{Level 1, 2, 3})}$	Catchment ratio, Factor $B_{(\text{Level 1, 2, 3})}$	Inflow concentration, Factor $C_{(\text{Level 1, 2, 3})}$	Antecedent dry time	Test conditions
0	11.47(A_1)	10(B_1)	High(C_1)	6 d	$A_1B_1C_1$
1	11.47(A_1)	15(B_2)	Medium(C_2)	6 d	$A_1B_2C_2$
2	11.47(A_1)	20(B_3)	Low(C_3)	6 d	$A_1B_3C_3$
3	23.88(A_2)	10(B_1)	Medium(C_2)	6 d	$A_2B_1C_2$
4	23.88(A_2)	15(B_2)	Low(C_3)	6 d	$A_2B_2C_3$
5	23.88(A_2)	20(B_3)	High(C_1)	6 d	$A_2B_3C_1$
6	27.51(A_3)	10(B_1)	Low(C_3)	6 d	$A_3B_1C_3$
7	27.51(A_3)	15(B_2)	High(C_1)	6 d	$A_3B_2C_1$
8	27.51(A_3)	20(B_3)	Medium(C_2)	6 d	$A_3B_3C_2$
9	11.47(A_1)	10(B_1)	High(C_1)	6 d	$A_1B_1C_1$

Note: Catchment ratio is the catchment area/bioretention surface area.

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 this study for the short-term rainfall data of 60 min from 1961 to 2014 in Xi’an [19]. The sampling was set as follows: (i) inflow sampling at 0, 30, and 60 min after the start of the experiment; and (ii) overflow/outflow water sampling during overflow/outflow at 0, 15, 30, 45, and 60 min.

2.3. Analysis methods

The parameters for the water quality analysis were pH, electrical conductivity, dissolved oxygen (DO), TP, and soluble reactive phosphorus (SRP). The first three parameters were used in the instrumental measurement with HACH HQ40d two-circuit input, multi-parameter numerical analysis (The manufacturer is HACH water quality analysis instrument (Shanghai) co. LTD). TP was determined using potassium persulfate oxidation and the molybdenum antimony anti-spectrophotometric method [20]. SRP was determined using a 0.45-μm membrane filter and the molybdenum antimony anti-spectrophotometric method. Water outflow rate (R_o), pollutant removal rate (R_c), and load reduction rate (R_L) were determined using Eqs. (1)–(3). Data from 10 simulated rainfall events about #1–#10 bioretention basins were introduced into Eq. (4), and the reduction of pollutant load for 10 bioretention basins during the test period was obtained.

$$R_o = V_{\text{out}} / V_{\text{in}} \times 100\% \tag{1}$$

$$R_c = (\text{EMC}_{\text{in}} - \text{EMC}_{\text{out}}) / \text{EMC}_{\text{in}} \times 100\% \tag{2}$$

$$R_L = (T_{\text{in}} - T_{\text{out}} - T_{\text{over}}) / T_{\text{in}} \times 100\% \tag{3}$$

$$R_{L(\text{total})} = \left(\sum_{i=1}^{10} L_{i(\text{inflow})} - \sum_{i=1}^{10} L_{i(\text{outflow})} \right) / \sum_{i=1}^{10} L_{i(\text{inflow})} \times 100\% \tag{4}$$

where $V_{\text{in/out/over}}$ is the inflow, outflow, and overflow volume, L; $\text{EMC}_{\text{in/out}}$ is the mean concentration in a single rainfall event for inflow or outflow, mg/L; and $T_{\text{in/out/over}}$ is the inflow, outflow, and outflow pollutant load, mg.

3. Results and discussion

3.1. Media characteristics

In this study, the media of bioretention cells were a mixture of BSM and WTR, green zeolite, fly ash, and coco peat. Table 3 showed the component characteristics of the media. Scanning Electron Microscope (SEM) images of WTR, zeolite, coco peat, and fly ash are shown in Fig. 2.

The hydraulic conductivity of the media depends on the size of conducting pores primarily. Therefore, a sandy media is favored and high-clay contents can decrease infiltration ability. Because fine fractions in soils tend to be the most chemically active, however, a balance needs to be developed between the permeability of the media and pollutant-removal characteristics. Consequently, design of the media profile is critical to determining bioretention performance characteristics [21]. The media particle size was as follows: zeolite (3–6 mm), BSM and WTR (<6 mm), and fly ash and coconut bran (<1 mm). Fill media selection is critical for TP removal. The ability of a soil to adsorb a significant amount of P can be related to the amorphous iron oxide + aluminum oxide contents $(\text{Fe} + \text{Al})_{\text{am}}$ [22]. The higher the $(\text{Fe} + \text{Al})_{\text{am}}$, the greater the capacity of the soil for P adsorption. Hunt and Jarrett [23] found that as fill media with a low P index and relatively high cation-exchange capacity (CEC) appear to remove phosphorus much more readily. There is little difference between the modifier and the traditional BSM in iron content in this study, and the WTR has high aluminum ion content. Comparing the properties of these media, specific surface areas of WTR and green zeolite were relatively large, and BSM, green zeolite, and flyash CEC is relatively high.

3.2. Improvement of infiltration capacity and EMC removal

In order to study the effect of the packing adsorption capacity, infiltration capacity, water retention capacity, and organic quality on the regulation of rainwater runoff by bioretention cells, tests 1–9 simulated the precipitation in the 10 bioretention systems, and 90 infiltration scenarios were simulated. The design inflow volumes were affected by recurrence periods (included 0.5, 2, and 3 years; three recurrence periods under 1-h rainfall duration) and confluence ratio (included 10:1, 15:1, and 20:1; three levels). A total of 38 scenarios demonstrated different ponding degrees, and overflow occurred in 8 scenarios. Five scenarios caused overflow in system #1 (soil only), and three scenarios caused overflow in system #7 (BSM with mixed fly ash) (Fig. 3).

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 [24]. However, as infiltration capacity increases, the contact time between the media and runoff water decreases, and poor water retention

Table 3
Media characteristics

No.	Media	ρ (g/mL)	BET (m²/g)	CEC (cmol/kg)	Porosity (cm³/g)	Ca (g/kg)	Mg (g/kg)	Fe (g/kg)	Al (g/kg)
1	Soil	1.121	20.837	19.44	0.0300	a	a	a	a
2	BSM	1.116	4.991	34.45	0.0096	25.78	7.79	12.47	8.56
3	WTR	0.953	28.433	9.31	0.0215	0.02	0.30	9.33	122.04
4	Gz	1.054	16.871	27.50	0.0510	1.92	5.63	11.49	67.72
5	Flyash	1.008	1.381	23.23	0.0066	21.51	3.49	13.78	13.34
6	Cb	0.092	0.811	13.62	0.0026	a	a	a	a

[a] Data not collected.

ρ, filling density for particles.

BET, specific surface area, m²/g; CEC, cation exchange capacity; Gz, green zeolite; Cb, the coconut bran.

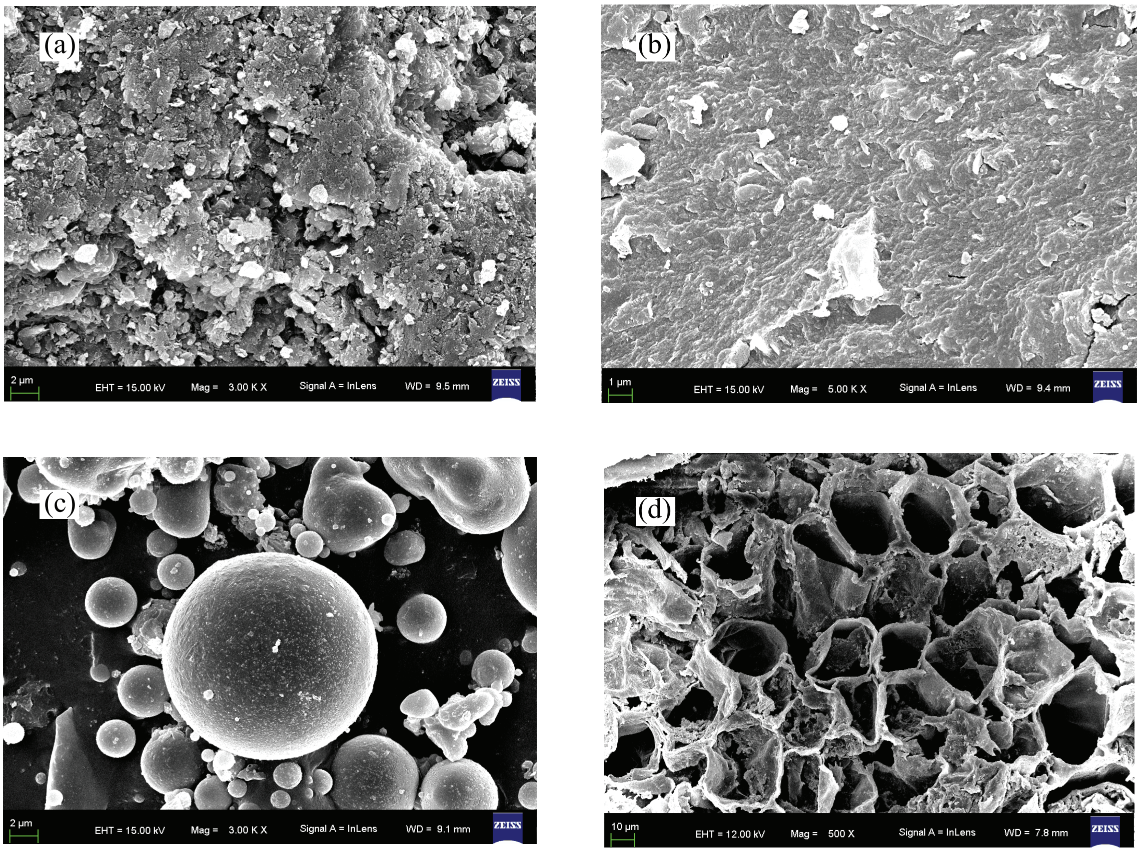


Fig. 2. SEM images of modifier (a) green zeolite, (b) WTR, (c) flyash, and (d) coconut bran.

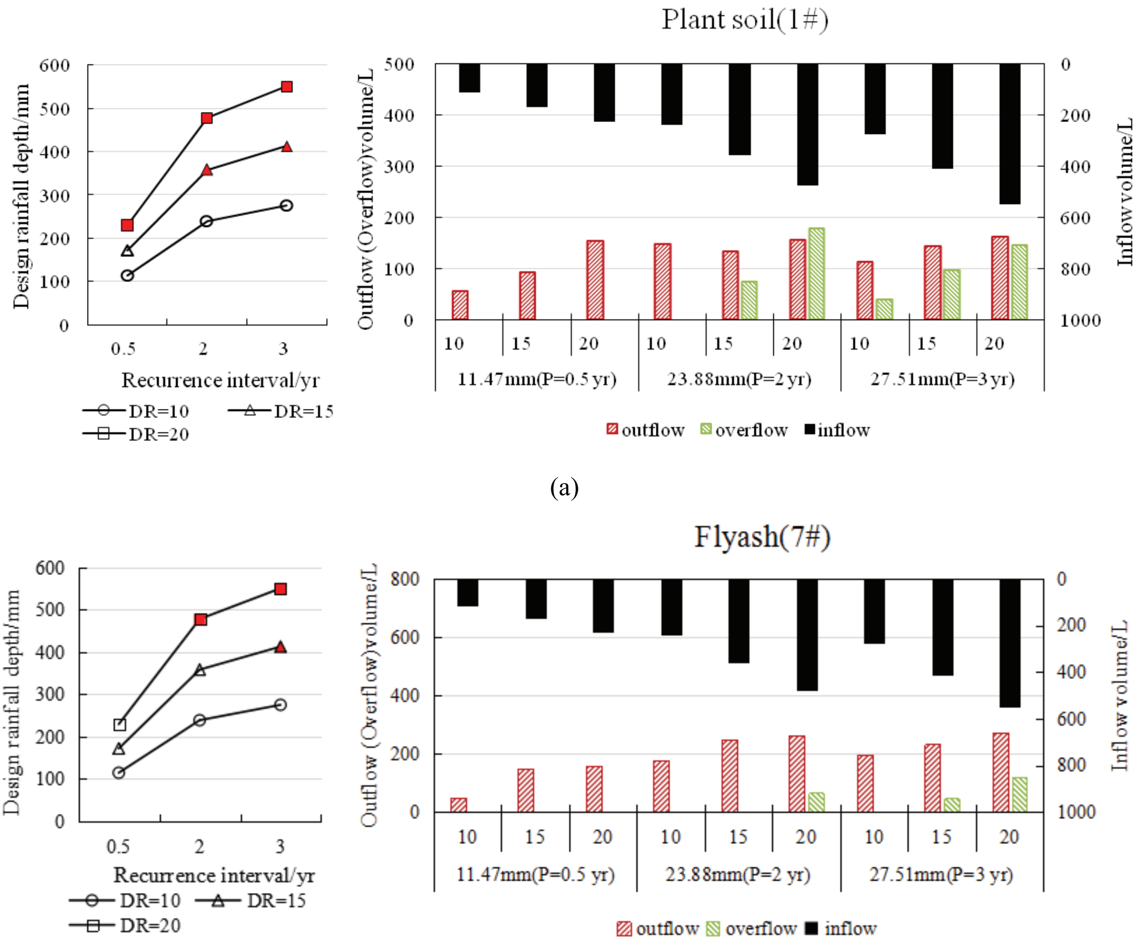
may result in the leaching of pollutants. A side wall flow or partial preferential flow might have occurred to a certain extent, which led to a high infiltration rate. Hsieh and Davis [21] constructed 18 bioretention columns which the runoff infiltration rate through different media mixtures ranged from 0.28 to 8.15 cm/min at a fixed 15-cm head. The removal efficiency of TP ranged widely from 4% to 99% in the 3mg/L inflow phosphorus concentration condition, apparently due to preferential flow patterns. The experimental results showed that the infiltration capacity of undisturbed soil in this study was relatively low, and the steady infiltration rates of the modified media were 0.9–55.8 m/d, 3.25–62.78 times that of undisturbed soil, and significant ponding of #1 and #7 was observed. 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 across all bioretention systems and all scenarios, respectively. The removal rate of TP in bioretention basin with coco peat as modifier was lower (79.14%) and the removal rates of TP were 86.22%–96.87% in other systems (Table 4).

3.3. Concentration trends and phosphorus load treatment

3.3.1. Characteristics of outflow phosphorus concentration

The outflow pollutant concentration for 24 rainfall events data was analyzed with Class I–V in Environmental Quality Standards for Surface Water (GB3838—2002) of China taken as a benchmark. The limitations of Class I–V in environmental quality standards for TP are 0.02, 0.1, 0.2, 0.3, and 0.4 mg/L.

Field performance of bioretention basins found that TP median values for effluent EMCs and percent removals based on combined data sets (both cells) were 0.18 mg/L and 76% [25]. Liu and Davis [26] investigated the water quality performance of a traditional bioretention cell retrofitted with 5% (by mass) WTR for enhanced phosphorus removal. TP and particulate phosphorus concentration decreased from 0.66 mg/L in inflow to 0.12 mg/L in outflow for TP, and from 0.61 to 0.06 mg/L for particle phosphate. Effluent concentrations were not as variable as influent concentrations, due to an effective treatment and “buffering” of the incoming runoff by the bioretention system. In this study, the outflow concentration of each rainfall event was measured. The results show that the effluent concentrations of TP in 10 bioretention systems were basically better than those of Class IV limitation (0.3 mg/L) of Environmental Quality Standards for Surface Water in China (Fig. 4). Though the test of bioretention soil mixture of sand and compost enhanced with aluminum-based drinking WTRs to reduce nutrients from stormwater runoff, Palmer et al. [27] found that ortho-phosphate reduction was significantly better in the columns without a saturated zone (80%) compared with columns with 67%, and plants did not significantly improve removal [27]. In this study, when there is no submerged area, the TP effluent concentration of the bioretention cells with BSM + 10% WTR as the media was also better than that of the system when installed the submerged area. The probabilities of effluent for #3 (without submerged zone height),



(a)

(b)

Fig. 3. Design rainfall and overflow events (a) for plant soil, (b) for flyash. Note: Red solid marker is overflow simulated rainfall events.

Table 4
Infiltration rate, ponding depth, and pollutant removals for retrofit bioretention cell

No.	Ks (m/d)	h^a (cm)	R_o (%)	R_c-SRP(%)	R_c-TP (%)
#1	0.9	>15	44.91 ± 13.19	96.79 ± 1.33	96.87 ± 1.64
#2	12.2	10	76.81 ± 9.86	96.47 ± 1.26	94.04 ± 2.01
#3	33.3	5	60.65 ± 9.12	97.51 ± 0.81	96.32 ± 2.19
#4	40.3	2	68.38 ± 8.59	97.65 ± 0.87	92.95 ± 5.57
#5	38.8	3	70.07 ± 15.04	97.74 ± 0.92	93.75 ± 7.02
#6	20.4	5	61.9 ± 12.97	97.17 ± 0.87	95.57 ± 1.93
#7	2.9	>15	63.81 ± 13.70	90.50 ± 4.66	86.22 ± 5.64
#8	5.0	7	68.35 ± 13.05	90.27 ± 3.67	88.34 ± 3.56
#9	33.1	2	76.26 ± 11.78	93.99 ± 0.03	92.25 ± 3.37
#10	55.8	0	69.11 ± 12.05	86.76 ± 3.54	79.14 ± 5.73

[a] Maximum ponding depth.
Ks, Stable infiltration rate.

#4 (150 mm), and #5 (350 mm) were greater than Class IV limitation, 0%, 2%, and 2%, respectively. The probabilities of effluent for #7, #8, #9, and #10 were relatively high, which were greater than Class II limitation (0.1 mg/L), 93%, 93%, 40%, and 91%, respectively. The probabilities of #7, #8, #9, and #10 exceeding the limits of Class III limitation (0.2mg/L) were 33%, 24%, 5%, and 64%. The probability of #10 greater than Class IV (0.3 mg/L) is 28.89%.

3.3.2. Phosphorus load treatment and hydrologic/hydraulic design parameters

Table 5 shows the effects of different packing combinations and structural designs on the TP load reduction of the 10 bioretention basins.

The system operated for about 8 weeks, and the hydraulic conductivity has not changed significantly in these tests. PO_4^{3-} and organic matter (OM) satisfied the recommended values for the systems. The effects of phosphorus control in this test were quantified under different recurrence intervals, contribution area ratios, and inflow concentrations. The TP load reduction rate decreased by approximately 20% for #1 bioretention cells and 15% for #7, when the design recurrence interval increased from 0.5 to 3 years, or when the contribution area ratio increased from 10 to 20. When the inflow concentration changed, the change in the TP load reduction rate was decreased by approximately 20% for #1 and 5% for #7. When the recurrence intervals, contribution area ratios, and inflow concentrations changed, the change in the TP load reduction rate was insignificant for cells except #1 and #7 (Fig. 5). The results of Liu and Davis [26] showed that the TP load infused into the bioretention system was 3.0 kg/(ha·y), and the particulate phosphorus, SRP, and dissolved organic phosphorus in the outflow of the bottom perforated tube were 0.2, 0.16, and 0.12 kg/(ha·y). Accumulation of TP load was 2.52 kg/(ha·y), accounting for 84% of inflow TP load, and the reduction of dissolved phosphorus load was mainly attributed to the reduction of runoff volume. In 10 simulated rainfall experiments, the bioretention basins load reduction rate was 82.39% (#1) to 98.32% (#3). In the #1 (plant soil) and #7 (BSM mixing fly ash) bioretention basins, the load reduction rate is lower due to the overflow events. The #10 bioretention basin is considered as a large hydraulic conductivity and loose voids with a low load reduction rate. The total load reduction rates of TP in other bioretention basins were greater than 92.6%. The total inflow loading capacity of each bioretention system was 4.8 kg, the outflow load was 0.052–0.62 kg, and overflow load of #1 and #7 was 0.79 and 0.40 kg, respectively.

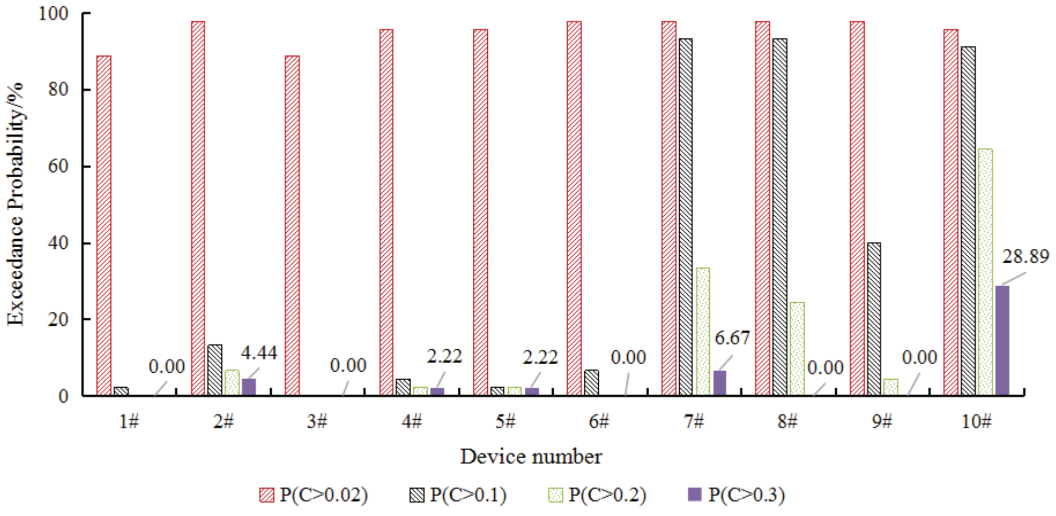


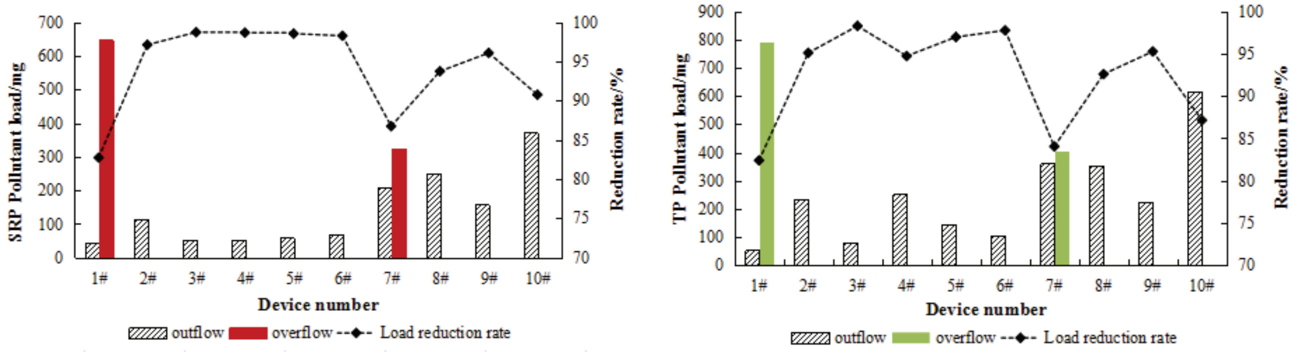
Fig. 4. Exceedance probability of outflow phosphorus concentration.

Table 5
Total phosphorus load reduction in different design conditions

Index		FAWB	1	2	3	4	5	6	7	8	9	10
PO_4^{3-} (mg/kg)		<80	120	43.08[a]	51.77[a]	51.77[a]	51.77[a]	51.77[a]	13.88[a]	13.88[a]	40.77[a]	63.50[a]
OM (%)		3~5	1.52[a]	1.19[a]	4.36[a]	4.36[a]	4.36[a]	4.36[a]	3.79[a]	3.79[a]	3.27[a]	9.13[a]
$R_{L\text{–}TP}$	0.5	–	97.82	96.21	97.19	96.77	97.66	97.32	90.57	93.49	93.28	85.84
(P, year)	2	–	79.74	96.03	98.08	93.31	97.02	97.44	86.48	91.92	94.04	86.00
	3	–	77.72	94.12	97.97	94.98	92.65	97.46	77.01	90.80	94.92	86.54
$R_{L\text{–}TP}$ (CAR)	10	–	94.57	96.78	97.49	93.65	92.59	97.63	92.34	92.72	94.18	84.57
	15	–	84.97	95.25	97.89	97.35	96.63	96.91	85.75	91.14	92.55	86.70
	20	–	75.74	94.34	97.87	94.07	98.11	97.67	75.97	92.35	95.51	87.12
$R_{L\text{–}TP}$	C_L	–	87.73	94.99	96.40	93.65	92.19	96.57	90.20	89.76	92.74	84.18
(C, mg/L)	C_M	–	88.36	95.78	97.97	96.82	97.32	97.30	78.52	92.09	92.78	88.95
	C_H	–	79.20	95.59	98.88	94.60	97.82	98.34	85.34	94.35	96.71	85.25

[a] The values are within the recommended range of FAWB.

P, the recurrence interval; *K*, the hydraulic conductivity; CAR, the contribution area ratio.



(a) (b)

Fig. 5. Inflow/outflow loads and load reduction rates: (a) total load of SRP and (b) total load of TP.

4. Conclusions

This study selected four kinds of modifiers, which were WTR, green zeolite, fly ash, and coconut bran, and ten bioretention basins were constructed with traditional bioretention soil. The steady infiltration rates of the modified media were 0.9–55.8 m/d, 3.25–62.78 times that of undisturbed soil, and significant ponding of #1 and #7 was observed. The removal rate of TP in bioretention basin with coco peat as modifier was lower (79.14 ± 5.73), and the removal rates of TP were 86.22%–96.87% in other systems. The effluent concentrations of TP in 10 bioretention systems were basically better than Class IV Environmental Quality Standards for Surface Water of China. The probabilities of effluent concentrations of #7, #8, #9, and #10 were 93.33%, 93.33%, 40.00%, and 91.11%, respectively, which is greater than Class II (0.1 mg/L). The probabilities of #7, #8, #9, and #10 were 33.33%, 24.44%, 4.44%, and 64.44 %, exceeding the limitation of Class III (0.2 mg/L). When the recurrence intervals, contribution area ratios, and inflow concentrations changed, the change in the TP load reduction rate was insignificant for cells except #1 and #7. In 10 simulated rainfall events, the total inflow TP loading of per bioretention system was 4.8 kg, the discharge loading were 0.052–0.62kg, and the load reduction rate was 82.39% (#1)–98.32% (#3).

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