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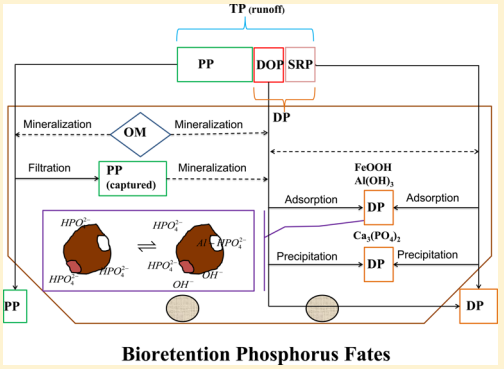
Phosphorus Speciation and Treatment Using Enhanced Phosphorus Removal Bioretention

Jiayu Liu and Allen P. Davis*

Department of Civil and Environmental Engineering, University of Maryland, College Park, College Park, Maryland 20742

ABSTRACT: This field research investigated the water quality performance of a traditional bioretention cell retrofitted with 5% (by mass) water treatment residual (WTR) for enhanced phosphorus removal. Results indicate that WTR incorporation into the bioretention media does not negatively influence the infiltration mechanism of the bioretention system. Total suspended solids (TSS), total phosphorus (TP), and particulate phosphorus (PP) concentrations in runoff inflow were significantly reduced compared to outflow due to filtration of particulate matter. TP concentrations were significantly reduced by the bioretention cell; before WTR retrofit TP export occurred. Although net removal of soluble reactive phosphorus (SRP) and dissolved organic phosphorus (DOP) from incoming runoff was not found, leaching of dissolved phosphorus (DP) was prevented not only from incoming runoff, but also from the media and captured PP. Near constant outflow SRP and DOP concentrations suggest an equilibrium adsorption treatment mechanism. Both event mean concentrations and mass loads were reduced for TSS and all P species. Pollutant mass removals were higher than the event mean concentration removals due to the attenuation of volume by the bioretention media.



Bioretention Phosphorus Fates

INTRODUCTION

Phosphorus (P) in urban stormwater results from fertilizers, automobile exhaust, living and decaying plants, animal remains, and detergents.[1] Although P is an essential nutrient for plant growth, excessive input to water bodies is a common cause of eutrophication and algal blooms in surface water, leading to poor water quality and loss of biodiversity.[2]

Bioretention is a low-impact development stormwater control measure (SCM) which has been proven as a technology to successfully manage flows and volume, and to mitigate a multitude of pollutants.[3−9] However, since P removal is complicated by possible leaching from the media and vegetation within various SCMs,[10] the removal efficiency is highly variable, and the pollutant load reduction commonly results primarily from volume reduction.[3]

Total phosphorus (TP) transported by stormwater runoff is composed of particulate phosphorus (PP) and dissolved phosphorus (DP). Since traditional bioretention relies on physical removal mechanisms such as sedimentation and filtration, bioretention is highly effective at removing PP, but is less successful at addressing DP. The effectiveness of the overall treatment is additionally complicated by the fact that P partitioning between particulate and dissolved phases is variable, depending on site-specific conditions, with the particulate fraction ranging from 20% to >90% of the total load.[11,12] DP removal in bioretention depends on chemical phosphorus sorption, complexation mechanisms to immobilize P species, and the geometry of the flow system.[6]

Novel technologies, therefore, are necessary for enhanced P removal. Amendment of soil with iron (Fe-) or aluminum (Al-) based water treatment residuals (WTRs) is a suggested way to mitigate P leaching from agriculture soils with limited P sorption capacity.[13−16] WTRs coapplied with manures and biosolids can mitigate excess P loss from soil to surface water or groundwater.[17] WTRs are byproducts from the coagulation process in drinking water treatment. P adsorption occurs at WTR-hydrous iron/aluminum oxide interfaces; phosphate replaces hydroxyl (OH^-) groups or water molecules (H_2O) and then reorganizes into a very stable binuclear bridge through mono ligand and/or bidentate ligand exchange mechanisms.[18]

Pilot and laboratory studies have demonstrated that WTR incorporation can greatly enhance P bioretention treatment. After the equivalent of over three decades of urban runoff loads, PO_4−P retention ranged from 95% to 99% of the input load, whereas the traditional bioretention systems with sandy media appeared ineffective for even a decade of urban runoff loads.[19] With an input of 0.12 mg/L DP, discharges from a 5% WTR bioretention media column were less than 0.01 mg/L.[20] Nonetheless, enhanced P performance information for field research is sparse. In the present work, an existing traditional bioretention cell was retrofit with 5% (recommended by ref 20) WTR incorporation in order to enhance P removal. Total suspended solid (TSS) and phosphorus species TP, DP, and soluble reactive phosphorus (SRP) were monitored during rainfall events. The cell was first installed in 2004 and

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demonstrated excellent treatment performance for TSS and other water quality parameters, but less-effective performance for TP control.[3] Ultimately, this work was undertaken to (i) assess discharge water quality and the efficacy of the WTR retrofit cell compared to previous performance for removing TSS and TP and (ii) clarify the mechanisms of P species removal in field application of WTR incorporation within a traditional bioretention system.

METHODOLOGY

Site Description. The enhanced-P site was created by retrofitting an existing bioretention cell (installed in 2004) on the campus of the University of Maryland, College Park, MD. It is trapezoidal in shape (length = 50.3 m, width = 2.4 to 4.8 m; area = 181 m^2), with the media depth between 0.5 and 0.8 m and manages stormwater runoff from a 2800 m^2 asphalt parking lot, roads, and concrete surfaces.[21] P sources in this site are expected to be the same as in most parking lots, such as soil/dust deposition and vegetation detritus.

Approximately 5% WTR (air-dry by mass) was employed to create enhanced-P removal media. WTR obtained from the Rockville drinking water treatment plant in Potomac, MD, were mixed with the top 40 cm of the media in the site. The small vegetation at this site was cleared off and then replanted after the WTR incorporation. The site was studied beginning July 2011 for 22 months.

Monitoring and Sampling Methodology. ISCO 6712FR refrigerated autosamplers equipped with a bubble flow meter (730 Bubbler) were assigned to both the influent channel and underdrain effluent for flow measurement and water sampling. A recording rain gauge (674 Rain Gauge) with 0.0254 cm sensitivity connects with one of the autosamplers to record rainfall depth. Discrete sampling was employed for both inputs and outputs. The sampling program was set to collect twelve samples per event with different sample timing to emphasize obtaining more samples in the early part of the runoff event. Samples were picked up within 24 h from the site and transported to the University of Maryland Environmental Engineering Laboratory for analysis. Samples for P analysis were acidified with H_2SO_4. All sample bottles were sealed, labeled, and then refrigerated (<4 °C) before testing. Parameters such as TSS and pH were tested immediately when samples were collected. Holding times for P species were <7 days.

Analytical Procedures. Water quality parameters analyzed included pH, total suspended solids (TSS), TP, DP, and SRP (considered equal to dissolved phosphate) using Standard Methods.[22] PP (PP = TP − DP) and dissolved organic phosphorus (DOP, DOP = DP− SRP) are calculated from direct P measurements. Sample pH was determined with a glass electrode pH meter (Mettler Toledo MA235, Greifensee, Switzerland). TSS was processed gravimetrically by Standard Method 2540 D. TP was analyzed using potassium persulfate digestion (4500-P B.5) and colorimetric determination by the ascorbic acid molybdenum blue method (4500-P E) at 880 nm (Shimadzu UV-160, Kyoto, Japan). DP and SRP samples were first filtered through a 0.22 μm membrane filter, then analyzed using methods identical to TP analysis, except without the digestion process for SRP. A 5-cm path length cuvette was employed to provide a detection limit of 0.01 mg/L P.

Data Handling and Statistical Analyses. Discrete rainfall events were identified if separated by a dry period greater than 6 h. Runoff volumes, V, were calculated based on simple numerical integration of flow measurements over time:

$$V = \sum Q(t)\,\Delta t \tag{1}$$

Overall cumulative input/output pollutant masses, M, were calculated by the following:

$$M = \sum Q(t)\,C(t)\,\Delta t \tag{2}$$

The Event Mean Concentration (EMC) is representative of the volume-weighted pollutant concentration throughout an entire event:

$$\mathrm{EMC} = \frac{\int_0^{t_d} Q(t)\,C(t)\,dt}{\int_0^{t_d} Q(t)\,dt} \approx \frac{\sum C_i Q_i\,\Delta t_i}{\sum Q_i\,\Delta t_i} \tag{3}$$

where $C(t)$ is the concentration; Q is the runoff flow rate; C_i is an individual concentration measurement; Q_i is the flow rate at the time concentration C_i was measured; Δt_i is the time interval associated with C_i.

Annual pollutant mass loads produced or discharged per unit drainage area (L, kg/ha-yr) were calculated by the following:

$$L = \frac{MP}{AD} \tag{4}$$

where M is overall cumulative input/output pollutant mass (kg) measured during this study; P is the average annual rainfall [107 cm/year for the State of Maryland; Maryland Department of the Environment (MDE) 2011]; A is the effective (runoff/rainfall) drainage area (ha) [0.6 × 0.28 ha for the site]; and D is the total rainfall depth (cm) measured during the study duration.

Exceedance probability plots were used to compare the cell performance. They were created by ranking the measured values from largest to smallest, and plotted on a log scale implying their log-normal distribution nature, as described by Li and Davis.[3] Pollutant duration curves based on time-scheduled samples were created by plotting individual sorted concentration values corresponding with the duration time to investigate concentrations performance with time. The Wilcoxon sum-rank test was used to determine if the improvements in water quality were statistically significant.

RESULTS AND DISCUSSION

From July 2011 through April 2013, 31 storm events were collected and analyzed for water quality performance.

General Trend of a Storm Event. Sample input and output pollutant concentrations for TSS and P species on Aug. 10th, 2012 are presented in Figure 1 as an example to show general trends during a storm event. The onset of the effluent sampling was delayed about 3 h because it was a "multiple peaks" event. Since minimal underdrain discharge occurred from the first peak of rainfall, the sampling program was triggered by the second peak, which was about 2 h later than the first.

Significant reductions in TSS concentrations were noted in the event [Figure 1(a)]. The influent TSS was as high as 340 mg/L and the input EMC was 200 mg/L. Effluent TSS peak and EMC were 18 and 6.2 mg/L, respectively. TP and PP concentration reductions are also obvious [Figure 1(b)]: the peak decreased from 0.66 mg/L in influent to 0.12 mg/L in effluent for TP, and from 0.61 mg/L to 0.06 mg/L for PP. The

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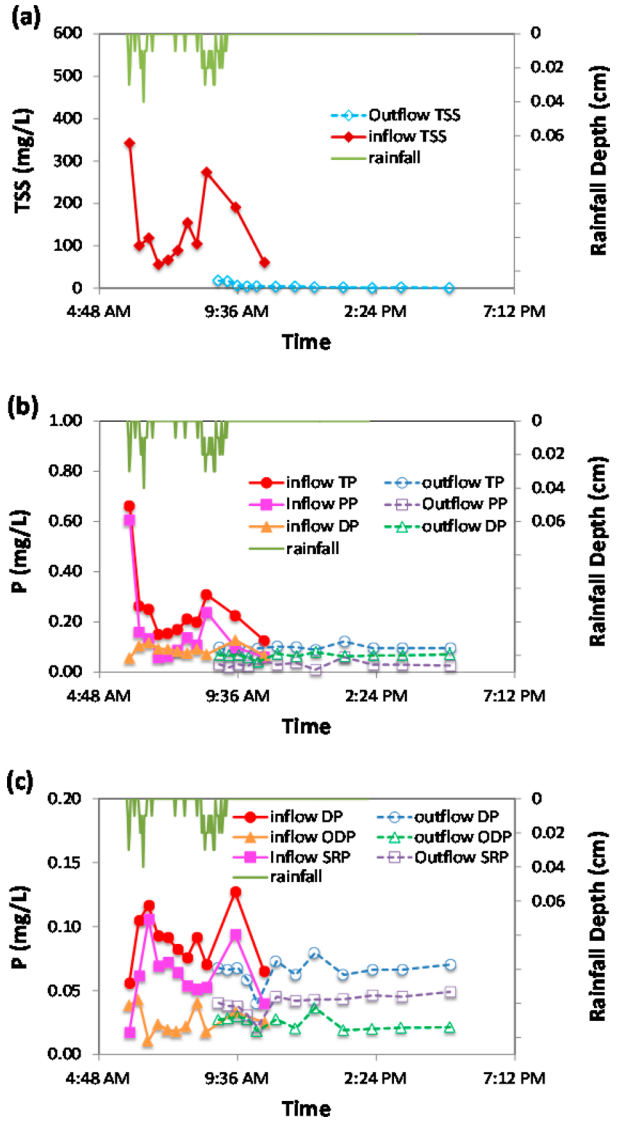

Figure 1. Water quality monitored at enhanced-P bioretention site, August 10th, 2012. (a) TSS concentrations. (b) P species (TP, PP, DP); and (c) P species (DP, SRP, ODP).

effluent concentrations were not as variable as influent concentrations, due to an effective treatment and "buffering" of the incoming runoff by the bioretention system.[23] From Figure 1(c), the DOP was not significantly removed for this storm event. Both the influent and effluent EMC were 0.03 mg/L. For SRP, the influent and effluent EMC were 0.07 and 0.04 mg/L, respectively, indicating some removal. The influent SRP concentrations varied significantly, ranging from 0.02 to 0.11 mg/L. After the first several points, output concentrations of SRP and DOP remained constant, both at 0.04 mg/L. Data from the other events were generally similar, but differ in details.

Water Quality Data Comparison and P Speciation. Pollutant duration curves shown in Figure 2 are created to focus on the performance of discrete sample concentrations. Exceedance probability plots (Figure 3) are used to present water quality data in order to emphasize the treatment outcome and subsequent ecological impact of the discharge.[5] In addition to results from this study, comparisons of TSS and TP in both influent and effluent were made between the current data

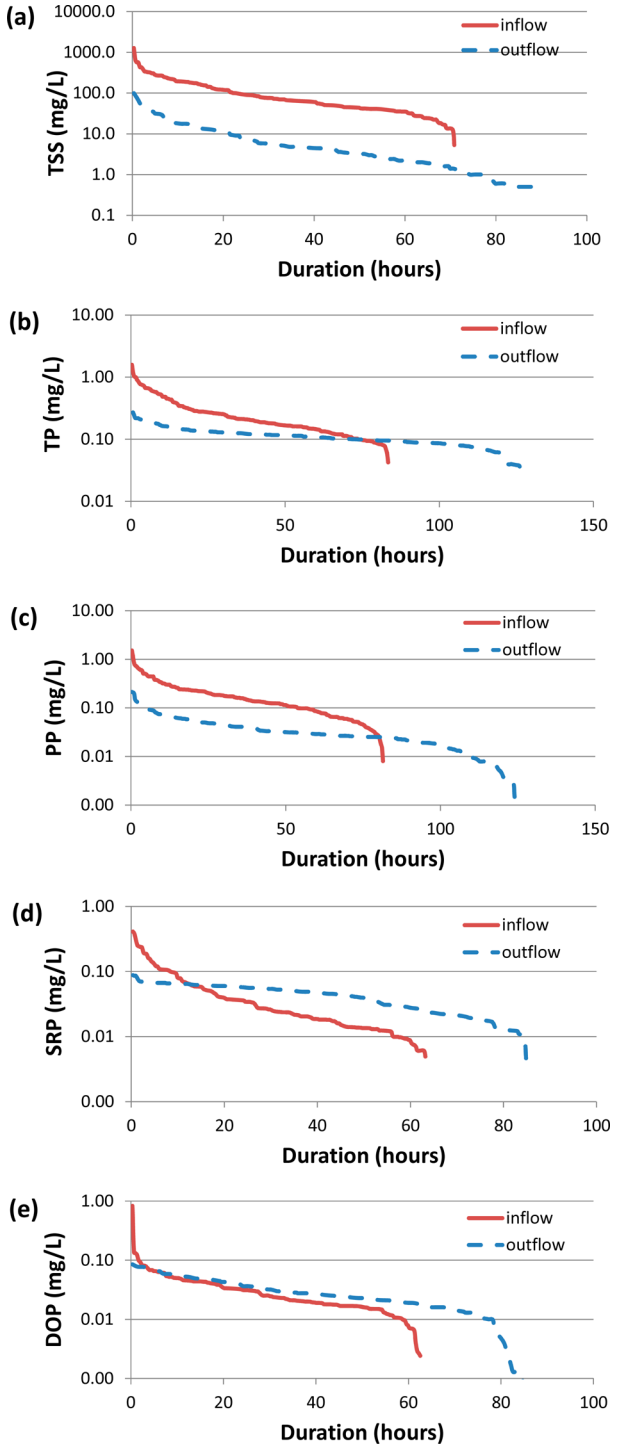

Figure 2. Pollutant duration curves for enhanced-P bioretention site (a) TSS; (b) TP; (c) PP; (d) SRP; and (e) DOP.

collected during 2011−2013 and that collected during 2006−2007.

Total Suspended Solids. TSS demonstrated very good treatment performance and effluent quality for both sample-based tests [pollutant duration curve, Figure 2(a)] and event-based tests [EMC exceedence probability plot, Figure 3(a)], which agree with previous studies on this site.[3] From Figure 2(a), input discrete runoff TSS concentrations ranged from 5.3 to 1274 mg/L (median = 76 mg/L), whereas discharge TSS ranged from 0.5 to 99 mg/L (median = 4.6 mg/L).

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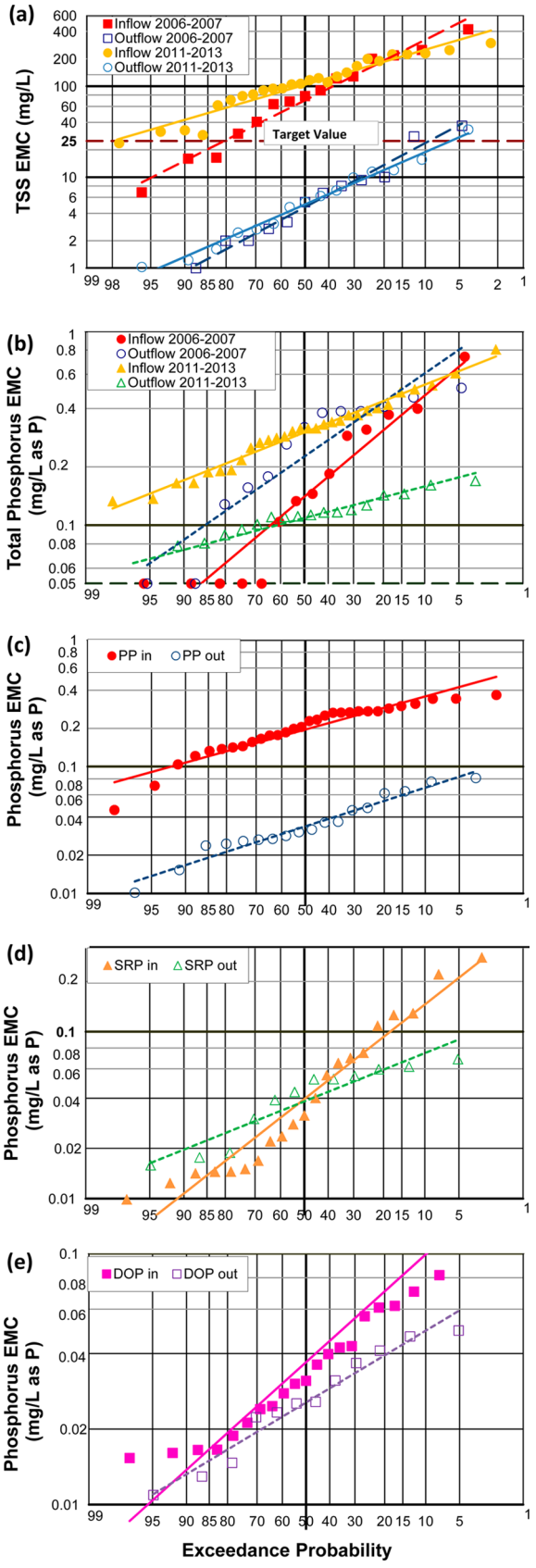

Figure 3. Exceedance probability plots (a) TSS; (b) TP; (c) PP; (d) SRP; and (e) DOP. (Data in 2006–2007 were collected at the same site before enhanced P retrofit[3,21]).

Bioretention discharge met the 25 mg/L TSS target level criterion[24] for 92% (83.6 h out of 90.5 h) of the discharge time comparing to only 9% (6.61 h out of 70.84 h) for influent.

TSS removal is dominated by settling and filtration by the bioretention media.[25,26] Steady state particulate matter removal (C/Co) is predicted by the fundamental filtration model:[27,28]

$$\frac{C}{C_0} = \exp\left(-\frac{3}{2}\frac{(1-\varepsilon)}{d_c}\alpha\eta_o L\right) \quad (5)$$

where ε is the filter porosity; α is sticking coefficient; d_c is the collector diameter; and d_p is particle diameter. The parameter η_o is the overall collector efficiency, which is the sum of three individual collector efficiencies: sedimentation ($\eta_s = ((\rho_s - \rho)gd_p^2)/(18\ \mu V)$), interception ($\eta_I = (3/2)((d_p)/(d_c))^2$) and diffusion $\eta_D = 0.9((kT)/(\mu d_p d_c V))^{2/3}$. Employing realistic bioretention values for the parameters of eq 5 (ε = 0.4, α = 0.1, d_c = 0.2, d_p = 0.05),[24] a predicted removal of 96% is found, supporting an effective filtration mechanism in bioretention. Intermittent, variable, heterogeneous nonsteady state urban particle loadings in stormwater runoff can account for the slightly higher than predicted effluent TSS concentrations.[25]

Figure 3(a) presents TSS EMCs of the influent compared with the corresponding effluent for events with both inflow and outflow during 2006–2007 (before WTR retrofit) and 2011–2013 (after retrofit). Inflow TSS EMCs ranged from 6.8 to 422 mg/L before, and from 23.6 to 298 mg/L in the current study. Outflow TSS concentrations were low during both monitoring periods. All except one of the events met the 25 mg/L target level criterion after WTR incorporation.

The Wilcoxon rank-sum test evaluation found that TSS concentrations were significantly (α = 1%) reduced by the bioretention cell for both current and previous data periods. Both inflow and outflow concentrations showed no dissimilar behavior between the two monitoring periods at α = 1%. The results demonstrate that WTR incorporation did not harm bioretention media filtration performance.

Total Phosphorus. The cumulative pollutant duration curve for TP is shown in Figure 2(b). Concentrations for inflow ranged from 0.04 to 1.58 mg/L (median = 0.21 mg/L), whereas outflow ranged from 0.03 to 0.27 mg/L (median = 0.11 mg/L), indicating effective treatment. A total of 42% (53.4 h out of 126.3 h) of the discharge time for effluent met the 0.1 mg/L target level criterion[29] compared to only 12% (9.61 h out of 83.4 h) for influent.

TP EMC data for the two monitoring periods are compared and shown in Figure 3(b). Influent EMC values for TP during the previous and current study ranged from 0.05 to 0.74 mg/L (median = 0.14 mg/L) and 0.13 to 0.81 mg/L (median = 0.31 mg/L), respectively. Corresponding effluent concentrations ranged from less than 0.05 to 0.51 mg/L (median = 0.32 mg/L) before retrofit and 0.05 to 0.17 mg/L (median = 0.11 mg/L) after retrofit. Comparing data sets using Wilcoxon rank-sum test indicates that (i) TP leaching occurred before the WTR incorporation (output > input); (ii) although the TP input is higher (α = 1%) compared to the 2006–2007 period, TP concentrations were significantly reduced (α = 1%) after treatment through the WTR bioretention media; and (iii) the effluent TP concentrations are much lower (α = 1%) than before WTR retrofit.

The bioretention cell was not effective for TP removal during the previous study, where it was concluded that the media had high phosphorus content, causing TP export.[3] TP export from

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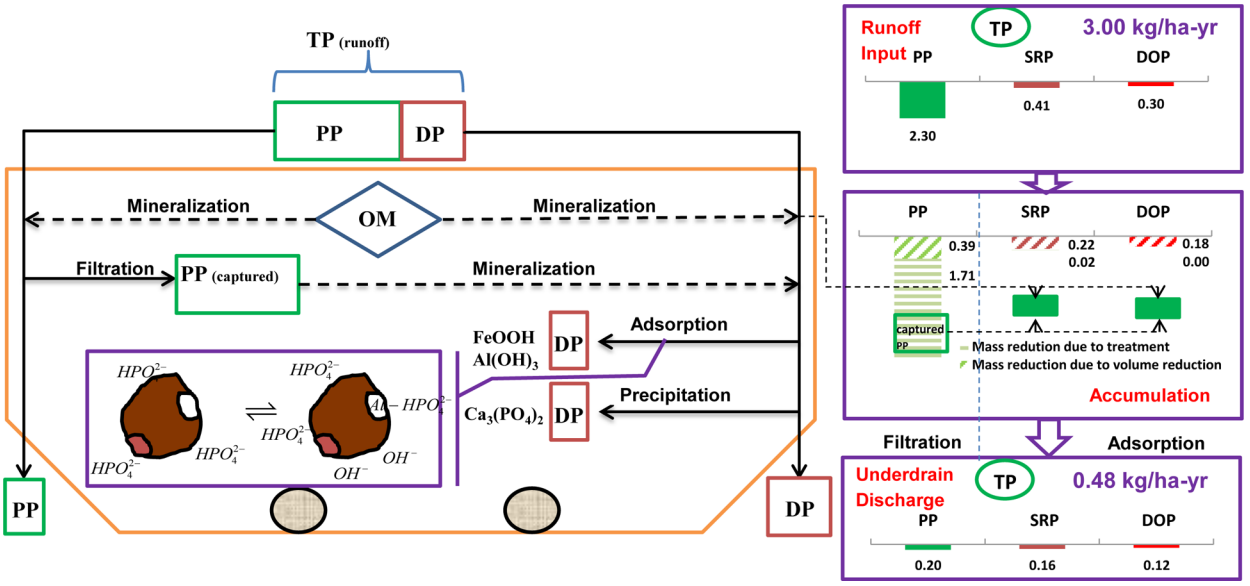

Figure 4. P fate in bioretention systems and pollutant mass loads comparison between influent and effluent. (OM: organic matter).

traditional bioretention media has also been noted by others.[30,31] However, after WTR incorporation the media is now shown to be effective at treating TP, which is attributed to the increase of P adsorption capacity contributed by the WTR[15,20,32,33]

Phosphorus Speciation. Sample-based pollutant duration curves for PP are presented in Figure 2(c), indicating excellent removal. PP concentrations in the inflow varied significantly, ranging from 0.01 to 1.51 mg/L; the median value was 0.15 mg/L. However, PP decreased significantly after the runoff passed though the bioretention media, lowered to values less than 0.01 to only 0.21 mg/L (median = 0.03 mg/L). For more than 96% (119.1 h/124.7 h) of the time, effluent concentrations were lower than 0.1 mg/L, whereas influent met this criterion for only 34% (27.5 h/81.4 h) of the time. The exceedance probability plot for PP [Figure 3(c)] also shows very good treatment performance. The median EMC of inflow and outflow for all collected events was 0.22 mg/L and 0.03 mg/L, respectively, which were close to the sample-based results.

The mean and median event-based dissolved fractions (f_d = (DP/TP)) are 0.31 and 0.28, illustrating that PP is the dominant species in surface runoff, which is in accordance with research by Berretta and Sansalone[34]. After passage through the bioretention media, the mean and median f_d in discharge increased to 0.67 and 0.68, indicating that PP removal is better than that of DP.

The Wilcoxon rank-sum test indicated that PP concentrations were significantly reduced (α = 1%) by the enhanced bioretention system. The PP is managed with the TSS, settling and becoming filtered from the influent.[5] Although no PP and DP data were collected in the prior study (2006−2007), it can be assumed that PP removal performance should have been good before retrofit because TSS removal was very good. As a result, the leaching of TP that was noted at this site[3] may be attributed to the leaching of DP, likely from organic matter in the media.

SRP and DOP. The Wilcoxon rank-sum tests indicated neither net removal of SRP nor DOP from incoming runoff [Figure 3(d) and Figure 3(e)]. The influent EMCs for SRP and DOP ranged from approximately 0.01 to 0.28 mg/L and 0.02 to 0.61 mg/L, respectively, and the effluent EMCs were consistently between 0.02 to 0.07 mg/L and 0.01 to 0.05 mg/L. The pollutant-duration curves [Figure 2(d), Figure 2(e)] show that the inflow concentrations for both SRP (less than 0.01 mg/L to 0.41 mg/L, median = 0.03 mg/L) and DOP (less than 0.01 to 0.83 mg/L, median = 0.03 mg/L) varied over more than an order of magnitude, yet the outflow concentrations were relatively stable. Concentrations ranged from less than 0.01 to 0.09 mg/L for both, and the median value is less than 0.03 mg/L for DOP and 0.04 mg/L for SRP. These data agree with the trend presented in Figure 1(c) for a single event. After the first several points (about 2 h), output concentrations of SRP and DOP remained essentially constant.

Previous research has shown that PP filtered and accumulated from urban stormwater may potentially partition back to the aqueous phase in long-term scenarios[35−37] and biological processing may cause DOP export.[19] Although this study of the enhanced-P treatment system examines and finds no DP loss from input, no leaching of DP was noted also, indicating that any release of DP from media organic constituents and from vegetation litter was not leached from the system.

The major mechanisms of P retention in the bioretention media include adsorption and/or precipitation, since microbial and plant uptake account for only small fraction of P retained.[19,38] Phosphorus retention mechanisms can be considered as a combination of a fast reversible true sorption process on soil particle surfaces, plus various slower time-dependent processes, which have been described as "slow adsorption", "slow reaction", "deposition", "fixation", "precipitation", or "solid-state diffusion".[2,39,40] After being retained, inorganic phosphorus species, which are typically considered bioavailable, can be utilized by vegetation growth in the bioretention facility.[41] Hsieh, et al.[42] found that long-term phosphorus reactions regenerate active short-term sorption sites in repetitive bioretention columns. Most of the retained phosphorus in the media layers was available for vegetative uptake and environmental risk thresholds were not exceeded.

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Table 1. Comparison of the Influent and Effluent Water Quality and Pollutant Mass Loads for Water Quality Sampling Events at the Bioretention Site in 2006−2007 and 2011−2013[a]

pollutant	input EMC (mg/L)[b]	output EMC (mg/L)[b]	L_{in} (kg/ha year)	L_{out} (kg/ha year)	R_m	L_{vred} (kg/ha year)	R_{mv}
			2006−2007				
TSS[d]	137	8	890[c]	32[c]	96.4%		
TP[d]	0.41	0.27	2.7[c]	1.2[c]	55.1%		
			2011−2013				
TSS[e]	97	6	1090	47	95.7%	106	10.2%
TP[f]	0.300	0.111	3.0	0.48	84.0%	0.79	31.4%
DP[f]	0.070	0.065	0.70	0.28	59.9%	0.40	95.6%
PP[f]	0.230	0.046	2.3	0.20	91.3%	0.39	18.6%
SRP[f]	0.041	0.037	0.41	0.16	60.3%	0.22	91.1%
DOP[f]	0.030	0.028	0.30	0.12	59.3%	0.18	∼100%

[a]Data in 2006−2007 were collected at the same site before retrofit[3,21]. [b]On the basis of the cumulative mass divided by the cumulative volume for all collected samples. [c]Calculated using eq 4. [d]12 events. [e]20 events. [f]17 events.

The nearly constant outputs of SRP and DOP suggest an adsorption mechanism, in which a constant, equilibrium concentration would be discharged from the media. Given adequate time, P can find reactive sites in micropores, becoming more strongly adsorbed at individual surface sites.[13] Erickson et al. found similar results in the investigation of phosphate removal from synthetic stormwater by a sand filter amended with iron filings.[43,44] An adsorption equilibrium mechanism explains the steady state dissolved P concentrations observed in our study and others, including those higher than the influent concentrations. SRP and DOP exist at nearly equal fractions of DP in the incoming runoff, whereas SRP accounts for 59% of DP in the effluent. Moreover, as mentioned above, DOP can leach from captured PP and microbial processes occurring in the media.[35−37] This suggests that WTRs have the ability to sorb DOP. A schematic of various sources and fates of P species in bioretention is presented in Figure 4.

Pollutant Mass Load Reduction. Annual pollutant loads were calculated for individual storm events using eq 4. The pollutant mass reduction (or increase) ratio, R_m, was calculated by the following:

$$R_m = 1 - \frac{L_{out}}{L_{in}} \quad (6)$$

Pollutant load reduction for stormwater runoff passing through the bioretention system consists of reductions both in volume and pollutant concentration. This reduction can be envisioned as follows: (i) when water enters the cell, treatment/adsorption take place at the media surface[4,25] designated as system treatment and (ii) stormwater volume is reduced by percolation, storage, and/or evapotranspiration. Mass reductions in the latter case are based on the volume reduction.

The pollutant mass load reduction due to volume reduction, $L_{v\text{-}red}$, was estimated by summing the product of runoff volume reduction and discharge concentration for each storm. If zero discharge occurred, then the mass reduction was attributed entirely to volume reduction. The mass volume reduction ratio, R_{mv}, accounts for the fraction of $L_{v\text{-}red}$ responsible for the total mass reduction. The cumulative input and output pollutant EMCs and loads for the cell during 2006−2007 and 2011−2013 are listed in Table 1; the P species comparisons for overall pollutant mass loads between influent and effluent are shown in Figure 4.

Both EMCs and mass loads were reduced for TSS and all P species. Moreover, pollutant mass removals were higher than the EMCs removals due to the attenuation of volume by the bioretention media. TSS had pollutant mass removal of 95.7%, which was close to the value before WTR amendment (96.4%), again indicating that the bioretention filtration mechanism was not affected, but also that volume management was not compromised. The TP mass removal was improved by the retrofit. Before retrofit, the load was reduced from 2.7 to 1.2 kg/ha-yr; the new reduction, from 3.0 to 0.48 kg/ha-yr, supports the assertion that WTR incorporation enhanced P sorption capacity of the media, resulting in an effective TP treatment (Table 1).

The inflow PP mass proportion of TP is 76.6%, which reduces to about 41.5% in the outflow. The total runoff P reduction was dominated by PP (83.3%). SRP fractions of DP were similar in both inflow (57.8%) and outflow (57.2%), a bit higher than DOP. The enhanced bioretention system reduced the SRP mass by 60.3% and DOP by 59.3% (Table 1), which suggests that they were removed by similar (sorption) mechanisms. Although Table 1 indicates that DP mass reduction results almost entirely from the volume reduction (95.6%), this analysis does not consider any leaching of DP from media and from captured PP, which are expected to contribute to the P treated and accumulated by the media (Figure 4). Overall, amendment with Al-WTR decreased DP mass by approximately 60%.

■ ENVIRONMENTAL SIGNIFICANCE AND OUTLOOK

As population shifts to urban areas and more land is being developed, P is becoming a targeted pollutant in urban runoff. This project demonstrated the capacity of WTR incorporation within a traditional bioretention system to reduce stormwater P loads. The input EMCs for TP and DP are 0.30 and 0.07 mg/L, respectively, which are close to the mean values provided by USEPA[1] for runoff from mixed urban areas: 0.26 and 0.06 mg/L. Results indicate good performance for P removal and reveal information on the unit processes of P removal in WTR-amended bioretention systems: (i) filtration performance was not harmed by WTR incorporation; TSS, TP, and PP were significantly reduced compared to input; (ii) WTR incorporation can enhance the sorption capacity for both SRP and DOP, which can effectively prevent the leaching from incoming runoff and from media and captured PP. Enhanced P removal, using WTR appears to be an available option to reduce uncertainty in design, decision making, and applications to address P removal from urban stormwater.

AUTHOR INFORMATION

Corresponding Author

*Phone: 301-405-1958; fax: 301-405-2585; e-mail: apdavis@umd.edu.

Notes

The authors declare no competing financial interest.

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