Real Time Control Schemes for Improving Water Quality From Bioretention Cells

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Abstract

Extreme weather and the proliferation of impervious areas in urban watersheds increases the frequency of flood events and deepens water quality concerns. Bioretention is a type of green infrastructure practice developed to mitigate these impacts by reducing peak flows, runoff volume, and nutrient loads in stormwater. However, studies have shown inconsistency in the ability of bioretention to manage some pollutants, particularly some forms of nitrogen. Innovative sensor and control technologies are being tested to actively manage urban stormwater, primarily in open water stormwater systems such as wet ponds. Through these cyber-physical controls, it may be possible to optimize storage time and/or soil moisture dynamics within bioretention cells to create more favorable conditions for water quality improvements. A column study testing the influence of active control on bioretention system performance was conducted over a nine-week period. Active control columns were regulated based on either maintaining a specific water level or soil moisture content and were compared to free draining and internal water storage standards. Actively controlled bioretention columns performed similarly, with the soil moisture-based control showing the best performance with over 86% removal of metals and TSS while also exhibiting the highest ammonium removal (43%) and second highest nitrate removal (74%). While all column types showed mostly similar TSS and metal removal trends (median 94 and 98%, respectively), traditionally free draining and internal water storage configurations promoted aerobic and anaerobic processes, respectively, which suggests that actively controlled systems have greater potential for targeting both processes. The results suggest that active controls can improve upon standard bioretention designs, but further optimization is required to balance the water quality benefits gained by retention time against storage needs for impending storms.

Keywords: stormwater, bioretention, biofilter, real time control, water quality

Introduction

Degradation of urban waterways has caused poor water quality and a decline in ecosystem services worldwide. Stormwater is one major source of impairment for urban systems, leading watershed managers to seek mitigation strategies (USEPA, 2016). As such, the use of green infrastructure (a principal component of Water Sensitive Urban Design) has become more prevalent for treating stormwater runoff before its release into larger stream systems due to its holistic social, ecological, and hydrological benefits (Fletcher et al., 2015; Larsen et al., 2016). In particular, bioretention cells (also known as bioretention areas or biofilters) have shown promise for reducing the effects of stormwater pollution on urban waterways. Bioretention cells are designed to replicate natural environmental processing. Using permeable soil media and native plant species, they incorporate infiltration and various pollution removal mechanisms to reduce both the volume and pollutant concentrations in stormwater runoff. Bioretention practices have shown the ability to significantly reduce nutrient, metal, and pathogenic bacteria concentrations in urban runoff. (Henderson et al., 2007; Hunt et al., 2008; B. E. Hatt et al., 2009; Hathaway & Hunt, 2012).

The interactions between media, plants, and microbes are a primary source of research in literature when seeking to understand bioretention function (Hunt et al., 2012; Glaister et al., 2017; Yan et al., 2017). Variations in bioretention design have been used to optimize functionality of these systems by changing these interactions. Free draining (FD) bioretention systems, a common first-generation design, have shown good success, but often are dominated by aerobic conditions and lack the ability to consistently perform both nitrification and denitrification (other than in internal microsites)(Hunt et al., 2012; Laurenson et al., 2013; Tang & Tian, 2016; McPhillips et al., 2018). Implementation of internal water storage (IWS) zones have been used in an attempt to allow both aerobic and anaerobic environments to promote nitrification and denitrification processes, however, there is the potential for lost storage capacity with these systems depending on the underlying soil infiltration rate (Dietz & Clausen, 2005; Li et al., 2014; Waller et al., 2018). Both designs, while generally successful, are static. That is, they cannot adapt to changing conditions, or switch between storing and releasing water to optimize runoff reduction and water quality performance.

The optimal operation of bioretention systems is largely site-specific because no two areas are under the same environmental stressors. Further, extreme weather events may necessitate occasional deviations in operation to accommodate large volumes of water. Active control systems have been recently studied to manage stormwater systems using networks of valves and sensors (Mullapudi et al., 2017; Mullapudi et al., 2018). They direct stormwater flows in and out of a watershed network to mitigate flood effects in cities (Parolari et al., 2018), however, research has typically focused on ponds and other storage systems. The effects of active controls on bioretention cells have only recently been considered for the purposes of water harvesting with a focus on indicator bacteria reduction (Shen et al., submitted). Using active control systems to optimize bioretention function has the potential to allow consideration of sometimes conflicting objectives, but also creates a dynamic environment for soils, plants, and microbes that is unexplored in this cyber-physical context and may have unintended consequences.

Adding active control to the already dynamic bioretention environment poses some challenges, but also provides opportunities. Drying and wetting cycles are an unavoidable and highly influential component of bioretention cell function and can lead to inefficiencies in performance (Manka et al., 2016). Drying periods affect soil structure and biological processes which can lead to metals export, microbial dormancy, and lowered water holding capacity of a soil (Blecken et al., 2009; Laurenson et al., 2013). When dry periods end and a storm event channels stormwater into a treatment area, a flushing effect is observed. Drying periods cause mineralization and exposure of previously unavailable organic matter in soils which cannot be sufficiently processed by microbes due to their inactivity in dry periods; although some microbial communities have developed resistances to dry climate conditions (Zhou et al., 2016; Salazar et al., 2018). The result is a nutrient export once wet conditions arise (Vangestel et al., 1993; Pulleman & Tietema, 1999). Drying and wetting cycles also alter soil respiration rates which can increase or decrease depending on soil type (Fierer & Schimel, 2002). Lowered soil respiration occurs once a bioretention media is constantly inundated with moisture which prohibits plant root access to oxygen or facilitation of nutrient uptake, and leads to die off (Colmer, 2003; Payne et al., 2014). This further reduces the efficiency of bioretention areas. Active controls can both exacerbate these effects, for instance if water is released based on forecasted rainfall that doesn't occur or can improve these conditions if the outlet is managed to maintain a more consistent soil moisture regime.

This research aims to improve the understanding of how the performance of bioretention systems can be improved using active control to regulate operating conditions. This work highlights the benefits and tradeoffs of active controls in comparison to traditional bioretention designs. By comparing two standard passive bioretention designs to two active control strategies, the objectives are to (1) quantify and examine metal and nutrient removal from the four treatments, and (2) investigate and compare the performance of the two active control schemes.

Methods

Bioretention Column Design

The experiment was designed to mimic traditional operational conditions of bioretention in the United States whereby impermeable liners are uncommon, thus captured runoff is allowed to exfiltrate the system (i.e. seepage) at a rate consistent with the in-situ soil infiltration capacity. The columns were constructed using 30 cm diameter gray PVC with both a small valve to mimic seepage (seepage outlet) and an underdrain on the bottom of each column to allow drainage. Seepage outlets were adjusted to mimic an infiltration rate of 0.20 cm/hr (in the range of a clay soil type) and were frequently maintained to avoid biological fouling. The interior of each column was sanded to minimize the effects of preferential flow. Columns were filled using layers of gravel (washed #57 stone), washed pea gravel, sand, bioretention media and mulch with a 10-centimeter ponding zone (Figure 1). The composition of the bioretention media was 85-88% sand, 10% clay/fines, and 2-3% organic matter, consistent with design suggestions in the United States for Tennessee and North Carolina (TSM, 2015; NCDEQ, 2018). Each column contained one *Echinacea purpurea* (purple coneflower) and one *Juncus effuses* (common rush). Bioretention columns were kept in a climate-controlled greenhouse where temperatures were maintained at seasonal averages (15-27°C).

Four outlet configurations were tested with five replicates being used for each configuration, a total of 20 columns (Figure 1). Configuration one was traditional free drainage (FD), where the underdrain provided unobstructed drainage from the column (i.e. drained via gravity). The second configuration was internal water storage (IWS, also known as a Submerged Zone), where a submerged zone of 45 centimeters was present in the bottom of the column and regulated by an upturned elbow in the piping. The remaining two configurations were actively managed using automated, remotely controlled, ball valves based on two experimental active control schemes. Both configurations relied on historic rainfall data and historic rainfall predictions as described in the Experimental Procedure.

For configuration three (SM, Soil Moisture), the system valve was opened and closed as needed to maintain, to the degree possible, field capacity in the column soils based on real time monitoring data and rainfall predictions (See Monitoring Description below). Field capacity was used as a target in this study because it is the optimal moisture level to facilitate microbial activity (Barros et al., 1995). Finally, configuration four (VC, Volume Control) involved use of a level controller to maintain water storage levels at 30 centimeters based on continuous monitoring and rainfall predictions as further described in the Experimental Procedure. A lower water storage level allowed the opportunity to test the ability of the active control to achieve similar water quality performance to IWS despite the smaller internal storage depth.

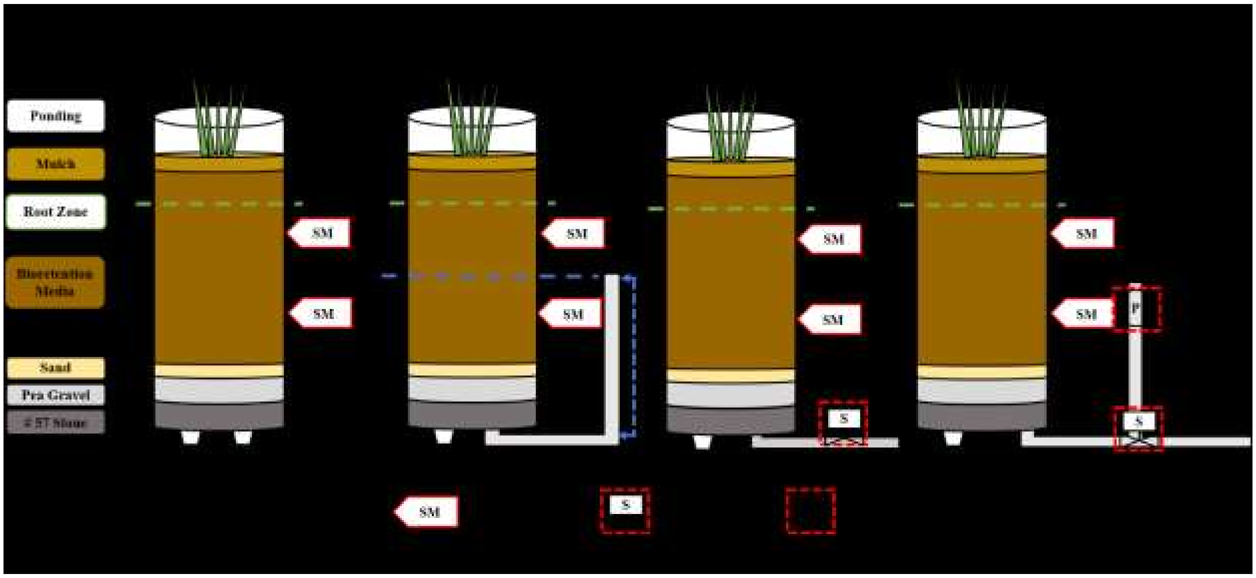

Figure 1. Column design configurations

Bioretention Column Monitoring

Decagon GS1 soil moisture sensors were buried in each column at depths of 30.5 and 61 cm from the top of the media. The sensors were calibrated in the Department of Civil and Environmental Engineering hydraulics laboratory by incrementally saturating a known volume of bioretention media and recording raw sensor readings (a method consistent with manufacturer suggestions for calibration). Water storage levels were measured in the fourth configuration (VC) using a Stevens pressure transducer. Error estimates for the soil moisture sensors and pressure transducers were +/- 0.03 m^3/m^3 and +/- 0.02% respectively. Continuous monitoring for each column were stored on an InfluxDB database and visualized using Grafana, including soil moisture readings, pressure transducer depths (configurations 3 and 4), and when active control valves opened or closed. Active control was achieved using photon microcontrollers to trigger valves to drain or retain water consistent with the corresponding management scheme.

Weather Data

Nine weeks of rainfall data recorded by the National Oceanic and Atmospheric Administration (NOAA) from June to July 2017, in Knoxville TN, were mimicked in this study, that is, were used to inform the number and size of applications to the columns. Although this study was carried out in the autumn of 2018, data for the months of June and July 2017 were used due to high density and variety of precipitation events observed over that period. A total of 18 events occurred during this period ranging from 0.18 to 3.81 cm, with a median size of 0.56 cm. In addition, the precipitation forecast preceding each storm event (at 12 hours before a given event) was obtained to inform the active control treatments (configurations SM and VC). These historic quantitative precipitation forecasts and events for 2017 were obtained from the National Oceanic and Atmospheric Administration (NOAA). The weather station at the McGhee-Tyson airport in Alcoa, Tennessee, was used as a reference location when obtaining forecast data.

Experimental Procedure

Pre-Event

During each day of the study, weather predictions for the next day of the rainfall time series were observed to determine if a rain event was projected to occur. If so, the predicted rainfall depth was sent out that night via wireless communication to signal the release, if necessary, of stored water from actively controlled columns in accordance with their respective schemes. For treatment three, the runoff produced as a result of the predicted rainfall was quantified and considered along with the current soil moisture conditions at the 30 cm sensor. The amount of predicted runoff that could be captured given the existing soil moisture, without exceeding field capacity, was calculated and any amount in excess of this value was preemptively released from the valve to provide the necessary additional storage. Drainage from the system was still possible despite the system being at field capacity as (1) our measurement of field capacity was likely an overestimate as it was calculated in a laboratory setting (Kirkham, 2005), (2) water was released from deeper in the profile where water was stored in places such as the gravel layer, and (3) opening of the drainage port created a new equilibrium in the system. For treatment four, the amount of predicted runoff that could be captured without exceeding the targeted internal water storage depth was determined, and any excess amount was preemptively released to make room for the predicted event. The influence of weather uncertainty in the control scheme meant that a predicted storm event did not always occur even though the valve opened and released water in preparation. In the same respect, storm events sometimes occurred when there was no forecasted event. Although this type of forecast error added complexity to the experimental method, it was necessary to realistically reflect the function of actively controlled bioretention which are subject to weather uncertainty.

During Event

During the event, columns three and four were actively managed to maintain targeted conditions. For instance, during an event for treatment three, once soil moisture readings exceeded field capacity the active control valve drained until field capacity was reached. Likewise, for treatment four, the column was triggered to open as needed to maintain the 30-cm depth. These schemes thus provided both a preemptive and adaptive control to manage internal conditions.

Stormwater Application

Storm events smaller than 1mm were excluded from this study as runoff would not be produced from a typical urban catchment for these storms (Guo & Adams, 1998; Le Coustumer et al., 2012). Previous work researching bioretention systems have used local climate data to determine dosing volumes. Chandrasena et al. (2017) reports using a storm size of 5.75 mm per event while Glaister et al. (2017) and Morse et al. (2018) used a local yearly average of 540 mm. Each storm event was applied based on 20:1 sizing ratio for each column (TSM, 2015). Columns were dosed with synthetic stormwater following procedures outlined by Bratieres et al. (2008). In short, tap water in the greenhouse was used to make the stormwater mixture which was supplemented with various chemicals to meet, to the extent possible, target concentrations shown in Table **1**. Sediment added to the stormwater mixture was collected from a local concrete-lined detention pond and sieved to 300 μm to remove larger particles and meet a target total suspended solids (TSS) concentration of 150 ppm. The nutrient contributions from the sediment were analyzed prior to mixing and were considered when preparing the final mixture. The stormwater mixture was continuously and vigorously mixed as columns were dosed with the prescribed amount of stormwater for a given event. Each dose was applied in three passes to ensure consistency in the stormwater concentrations received by each column. In the event that a column reached capacity, as evidenced by the column filling to the top and no longer receding, the application was ceased.

Table 1. Sediment contributions and stormwater target concentrations

Constituent	Sediment Contribution (mg/L)	Target Concentration (mg/L)
NO_x - N	0.01879	0.75
NH_4^+-N	0.00335	0.27
TDP	0.002	0.04
Cu^{2+}	0.0055	0.05
Zn^{2+}	0.0043	0.25
Pb^{2+}	0.0045	0.14
Cr^{6+}	0.0026	0.025
Mn^{2+}	0.0012	0.25
Fe^{3+}	0.0151	1
Ni^{2+}	0.0003	0.03
Cd^{2+}	0.0006	0.0045

Water Quality Sampling

Water samples of column discharge were collected 24 hours after each event, allowing completion of free drainage. An initial water quality sample of the inflow was also taken when semi-artificial stormwater was applied. Because rainfall predictions signaled opening of active control valves in preparation for anticipated rainfall events, samples were also occasionally collected of column discharge due to predicted precipitation that did not occur. That is, the columns were actively controlled and discharged for an impending event that did not happen. Samples were analyzed for TSS using standard methods (SM 2540 D), for nutrients (NO_2-N, NO_3-N, and NH_4^+-N) using ion chromatography, and for dissolved metals (Cu^{2+}, Zn^{2+}, and Mn^{2+}) using inductively coupled plasma mass spectrometry (ICP-MS). Prior to sampling for nutrients and metals, samples were filtered through 0.45 μm Whatman disposable filters. They were also acidified using a 1% dilution with concentrated nitric acid prior to ICP-MS analysis. Samples were stored in refrigeration after filtration awaiting analysis.

Statistical Analysis

Statistical analysis for this research was conducted using MATLAB R2018a. Percent reduction for each pollutant was calculated by subtracting the outflow from inflow Event Mean Concentration (EMC) then dividing by the inflow EMC. First, a Kolmogorov-Smirnov test was used to confirm the presence or absence of normality on raw data. Data was found to be non-normally distributed, necessitating non-parametric statistical analysis. The Wilcoxon signed-rank test was used to determine statistical differences among the treatments and antecedent rainfall effects on water quality were measured using a Spearman's Rank correlation coefficient. A 0.05 significance level was used to indicate statistical significance.

Results and Discussion

Soil Moisture and Active Control

To explain the water quality results from this study, an understanding of how each treatment affects system hydrology is necessary. In particular, soil moisture dynamics are critical to biogeochemical processes in these systems. As noted above, soil moisture readings collected throughout this study were taken at 30 and 60 centimeters below the surface of the bioretention media. Field capacity of the bioretention media was measured to be 28% (v/v) and was used as the marker for active control in the SM treatment. The readings for one storm event are shown in Figure 2 while the average readings for each storm event are shown in Figures 3 and 4, which highlight trends in treatment types. The period for each storm (for the sake of soil moisture summary statistics) was defined as the 24 hours following the start of each storm event. As expected, the IWS treatment has a higher soil moisture content that the other treatments, in particular for the deeper sensor, while the FD was the driest system at the shallow (30 cm) reading. This is a result IWS creating internal storage and promoting wetter conditions, while FD being freely drained and retaining less moisture in the upper soil profile. Comparable soil moisture patterns were observed for the active control treatments. At the 30 cm sensor, both active control treatments operated between IWS and FD, while at the 60 cm depth, VC, SM, and FD all showed similar soil moisture readings and patterns. SM was slightly more wet than FD, while VC was slightly drier than FD at the deeper depth.

The difference in control scheme between VC and SM treatments was in the operation of the solenoid valve to store or release water. More sporadic open and close cycles were seen for the VC treatments while SM treatments exhibited a more stable open and close cycle for each storm event (over the course of the study opening an average of 693 and 50 times respectively). Because VC treatments were based on a target storage depth within the column, collection and reaction times between pressure transducer readings and solenoid valves to maintain a 30-centimeter storage depth caused more frequent opening and closing of the solenoid valve. This could be corrected in future studies by allowing depths ranging from 28 to 32 cm, for instance. On the other hand, the SM treatments required the maintenance of a specific soil moisture reading. Soil moisture sensors would trigger release only when field capacity was exceeded. The collection and reaction timing were slower, and solenoids were open and closed for longer periods of time while soil moisture changes occurred at the 30-cm sensor. Essentially, once the solenoid was open, there was a delay in soil moisture changes as water percolated out of the system.

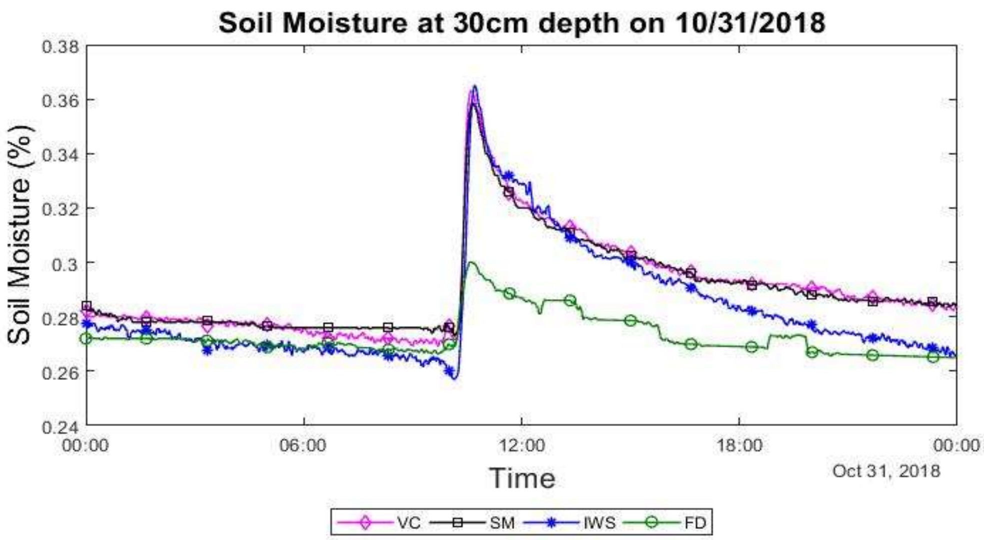

Figure 2. Soil moisture at 30-cm depth for storm on 10/31/2018

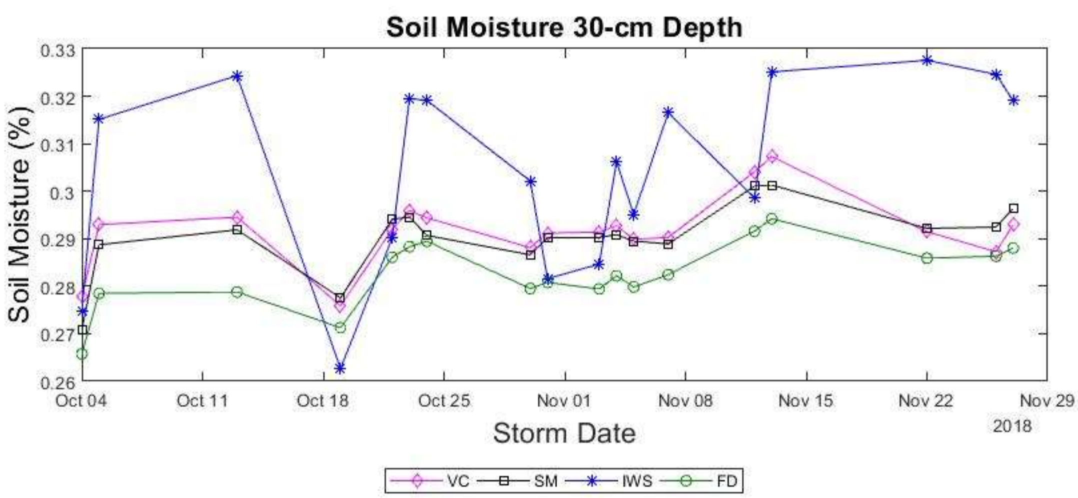

Figure 3. Average soil moisture at 30-cm depth for each storm.
Storms are defined as the 24-hr period following a storm event.

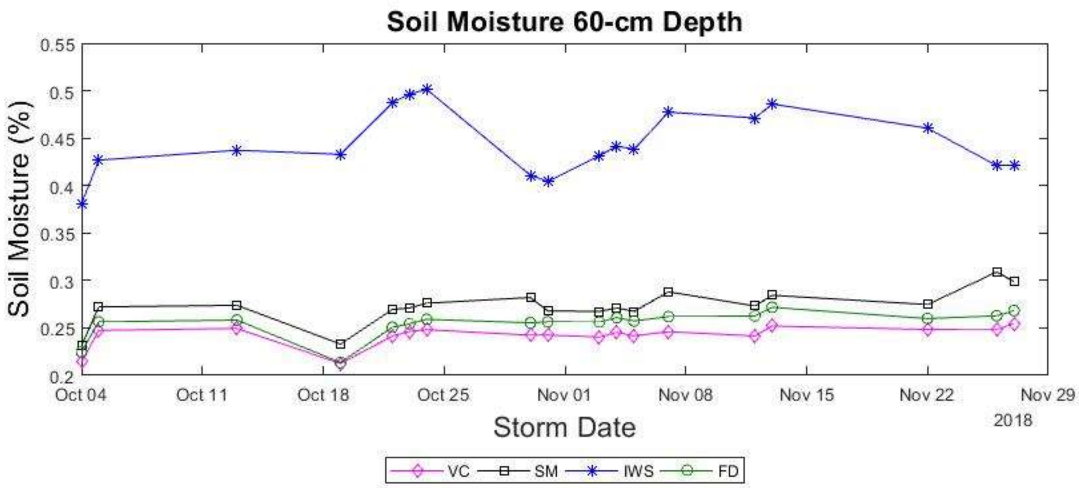

Figure 4. Average soil moisture at 60-cm depth for each storm. Storms are defined as the 24-hr period following a storm event.

TSS

TSS removal for all treatments was above 97%, which is unsurprising given that this parameter is typically removed by upper soil layers which are generally not influenced by treament type (Hunt et al., 2012). This is consistent with previous studies which report TSS reduction between 80% and 98% (E. Hatt et al., 2007; B. E. Hatt et al., 2009; Blecken et al., 2010). Median effluent TSS concentrations were between 1.1 and 1.7 mg/L among the treatments with FD having the highest (1.7 mg/L) and SM (1.1 mg/L) having the lowest values. Similar laboratory studies of biroetention by Blecken et al. (2010), and Bratieres et al. (2008) reported comparable TSS concentrations of 2 mg/L, and 0.9-7.2 mg/L respectively.

Table 2. Event Mean Concentration (EMC), Median Concentration, Standard Deviation (Std Dev) and Relative Standard Deviation (RSD) for each Treatment Type

Pollutant	Configuration	EMC (mg/L)	Median (mg/L)	Reduction %	Std Dev	RSD %
Cu^{2+}	VC [*a]	0.012	0.009	64.9	0.007	60.0
	SM [b]	0.004	0.004	86.6	0.001	20.7
	IWS [c]	0.003	0.003	90.4	0.001	23.6
	FD [b]	0.004	0.004	87.2	0.001	18.3
Mn^{2+}	VC [a]	0.008	0.005	95.2	0.008	96.3
	SM [a]	0.009	0.007	94.8	0.008	85.5
	IWS [b]	1.961	1.984	-995.6	0.445	22.7
	FD [a]	0.011	0.006	93.5	0.013	113.7
Zn^{2+}	VC [a]	0.010	0.006	95.3	0.007	69.1
	SM [b]	0.015	0.012	93.1	0.009	60.1
	IWS [a]	0.013	0.004	94.5	0.025	183.9
	FD [b]	0.014	0.011	93.5	0.007	50.9
NH_4^+-N	VC [a]	0.008	0.007	41.2	0.004	46.6
	SM [b]	0.013	0.009	43	0.013	107.4
	IWS [a]	0.026	0.028	26.3	0.017	65.0
	FD [b]	0.010	0.011	39.1	0.004	42.5
NO_2^--N	VC [a]	0.087	0.041	-19.9	0.167	192.6
	SM	0.100	0.046	-18.6	0.196	196.0
	IWS [b]	0.069	0.049	-87.9	0.102	146.9
	FD [a]	0.062	0.046	-14.7	0.116	185.9
NO_3^--N	VC [a]	0.824	0.743	73.6	0.545	66.2
	SM [b]	0.759	0.525	74.3	0.621	81.8
	IWS [c]	0.138	0.096	95.6	0.206	149.6
	FD [d]	1.007	0.977	67.2	0.524	52.1
TSS	VC	2.681	1.6	97.4	2.930	109.3
	SM	2.913	1.1	97	3.929	134.9
	IWS	1.940	1.2	98.2	2.353	121.3
	FD	1.749	1.7	98.1	2.985	170.7

* letters indicate significant difference (α =0.05) per Wilcoxon Sign-Rank test within each pollutant, if no letter is present, there is no significant difference for that configuration

Metals

Overall, effective removal of metals was observed across all treatment types, in particular for Zn^{2+} (Figure 5). This is consistent with observations seen in previous studies such as Laurenson et al. (2013) in which over 90% removal was reported for Zn^{2+}. When comparing Zn^{2+} to Cu^{2+} and Mn^{2+}, however, Zn^{2+} has over 93% removal for all treatment types, while more variability is noted for the other constituents. The more variable results for Cu^{2+} and Mn^{2+} are likely due to differences in treatment type and the variable conditions they provide. The overall magnitude of removal observed for Cu^{2+} is in line with previous studies from Blecken et al. (2009) and Laurenson et al. (2013) who showed 70% and >90% removal of Cu^{2+}, respectively, between treatments.

Removal of Cu^{2+} between SM, IWS, and FD treatments were all similar, ranging from approximately 87 to 90%. However, there was an observable difference in Cu^{2+} removal by the VC treatment, which could be a result of the more frequent, rapid, small water releases associated with this treatment type (as compared to SM). The more frequent storage and release by the VC scheme may alter the redox potentials within VC treatments by allowing oxygen into the system when active control valves open and close which limits Cu^{2+} sequestration through adsorption. Similar changes in redox potential have led to Cu^{2+} dissolution because of oxic and anoxic variability within a given system (HamiltonTaylor et al., 1996; Chaudry & Zwolsman, 2008). The other treatment types had more stability in transporting water through the columns and were able to remove Cu^{2+} from stormwater influent more effectively. As noted above, these frequent releases may have been mitigated to some degree by utilizing a scheme that allowed an acceptable range of storage depths as opposed to one singular objective (30 cm). This would allow active control systems to better maintain a consistently anaerobic zone by minimizing level fluctuations.

In Figure 7, Mn^{2+} is exported from IWS treatments while all other columns showed similar removal trends to other metals. Media descriptions from the bioretention media manufacturer showed high levels of manganese in the media mix (Manganese Index =175). Furthermore, anaerobic heterotrophs within the IWS systems use manganese compounds within soils as electron donors and the reduced metal ions then leach out of the system (Nealson & Saffarini, 1994; Lee et al., 2001; Lovley et al., 2004). Because Mn^{2+} is soluble and mobile it can be transported readily, effectively flushing from the system. The IWS treatment appeared to facilitate anaerobic processing more than the other treatments (which is logical based on the soil moisture data) which likely explains the Mn^{2+} leaching. It should be noted that manganese concentrations are not typically a criterion in design manuals for bioretention media mixtures.

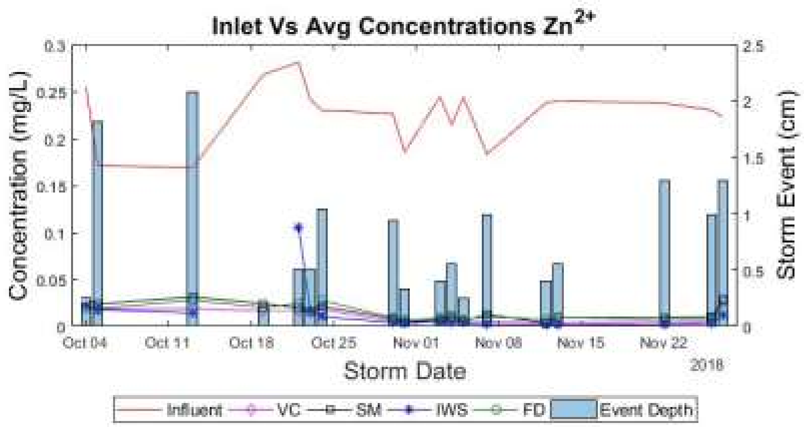

Figure 5. Zn^{2+} outlet concentrations for all treatment types

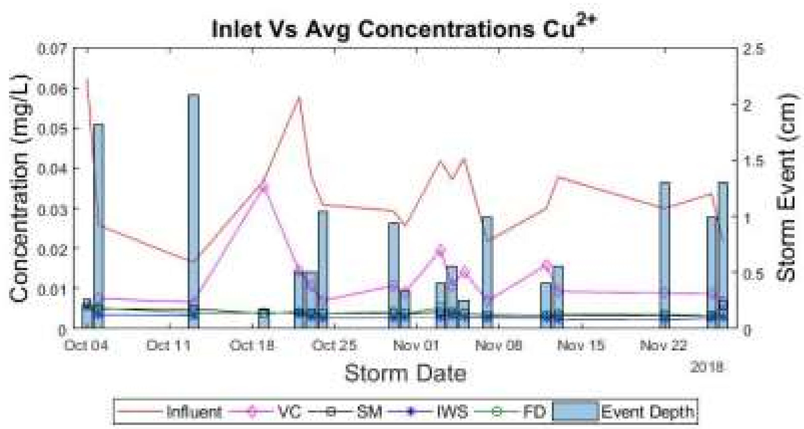

Figure 6. Cu^{2+}outlet concentrations for all treatment types

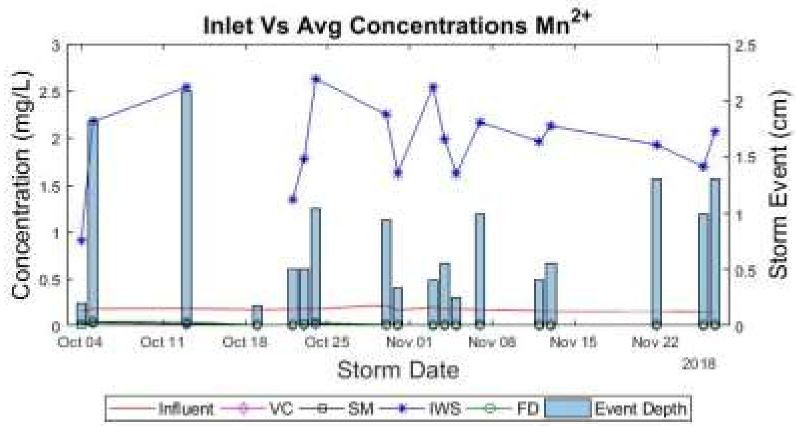

Figure 7. Mn^{2+} outlet concentrations for all treatment types

Nutrients

Nitrogen processing within bioretention systems was a focal point of this study, because export of nitrogen (NO_3^--N) has been observed in previous studies after long periods of dry conditions and due to a presumed lack of the necessary anaerobic conditions in some bioretention designs, a required condition for denitrification (E. Hatt et al., 2007; Hsieh et al., 2007; Blecken et al., 2010; Manka et al., 2016). As noted above, the SM active control treatment was designed to target field capacity to bolster microbial activity, specifically aerobic and anaerobic microbial processes, in an attempt to meet multiple nitrogen processing objectives (Barros et al., 1995; Schimel, 2018). Nutrient dynamics are described through the lense of microbial activity, which should be considered as influencing nutrient processing.

NO_3^--N showed high variability in performance between treatment types with mean effluent concentrations ranging from 0.14 to 1.01 mg/L for the IWS and FD treatments, respectively (Figure 8). The FD treatment showed the least NO_3^--N removal (67.2%), which is not surprisng as it is the treatment considered to primarily foster an aerobic environment, resulting in the most limited conditions to facilitate dentirification (Collins et al., 2010). FD has no designated anaerobic zones to allow conversion, so any denitrification would have to be facilitated within the micropores of the bioretention media. The lack of denitrification as a result of the aerobic environment promoted by FD systems has been noted in studies such as Davis et al. (2006) and Li et al. (2014). IWS shows the greatest removal of all treatments (95.6% removal). This is attributed to a constant anaerobic zone in the IWS columns which facilitates denitrification. The VC and SM treatments showed similar performance with removal percentages between that of FD and IWS (73% and 74% removal, respectively).The VC treatment has a more shallow anaerobic zone than IWS and more frequent release which allows more aerobic processing than the IWS systems. At the same time, SM treatments allow a more stable release and are not dictated by a particular storage depth, but still retain more water than the FD treatment, resulting in aerobic and anaerobic processing.

Nitrification is being promoted within all treatment types but most noteably the FD treatment. As discussed above, this is expected based on the primarily aerobic environment provided by FD designs. Conversely, the IWS NH_4^+-N effluent concentrations are indicative of more limited aerobic processing, which is similar to results show in Tang and Tian (2016) where IWS had less NH_4^+-N reduction than the traditionally free draining column (63% and 71% respectively). The NH_4^+-N remaining in the IWS system and being exported indicates the issue of incomplete aerobic processing. As noted above, VC and SM treatments both allow for more of an anaerobic zone than the FD treatments and less than that of the IWS treatment. They perform similarly to the FD treatment in regard to NH_4^+-N reduction because of their presumed greater depth of aerobic zone but perform better than FD in regard to NO_3^- removal. This shows that there is more anaerobic processing facilitated in the actively controlled treatments, and that these systems may allow a balance between the conditions observed in FD and IWS designs.

Although NO_2^--N is a less frequently reported and discussed parameter, it is often lumped with NO_3^--N and reported as NO_x-N, it provides some insight into the denitrification process in the treatments. Overall, there is a consistent export of NO_2^--N from all treatments (Figure 9). When coupled with data observed for NO_3^--N and NH_4^+-N, NO_2^--N trends suggest the possibility of incomplete dentrification in the columns. That is, NO_3^--N is converted to NO_2^--—N and produces N_2O gas (a greenhouse gas of major concern), but full conversion to N_2 gas is not occurring. This is potentially due to an inadequately deep saturated zone (lack of substantial anaerobic conditions) within these systems. This is worthy of further study, as completing the denitrification cycle is of critical importance for nitrogen management in biofilters.

A period of particular interest is the storm events and subsequent treatment that occurred in mid-October. Export of NO_2^--N was noted, and to a smaller degree an increase in NO_3^--N for some treatments, which follows the largest event during the study period and occurred during the smallest stormwater application of the study. It should also be noted that the upper soil layers for all columns were relatively dry during this event compared to the rest of the study. While the exact cause of this export is unknown, it is likely the result of large shifts in soil moisture between the two events and the subsequent impacts to biogeochemical processes (i.e. Manka et al. 2016). It should be noted that the IWS treatment was able to completely capture this event due to available storage.

Although unintentional, this spike in NO_2^--N does act as a sort of chemical tracer for the system, allowing an understanding of the differences in recovery times for each treatment type, that is, the amount of time required to bring the system back to producing typical NO_2^--N effluent concentrations. This was generally linked to the amount of flushing provided by each treatment type. The FD treatment recovers after the next applied storm while other treatments required additional storm events before effluent NO_2^--N concentrations return to a baseline in the system. This observation is likely due to the speed with which water moves through each treatment type. The FD treatment has the fastest flow through the system because it freely drains, with the VC, SM and IWS following in decreasing flow speed and increased water storage. The rate of flushing also infers differences in detention times between the systems, which likely also influences performance.

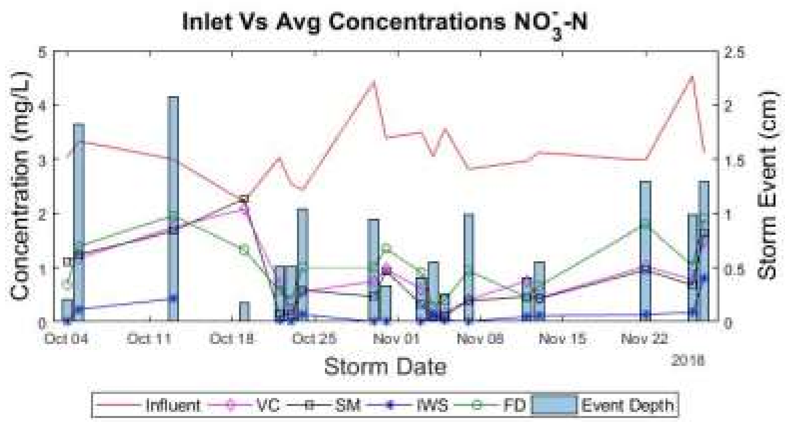

Figure 8. NO_3^--N outlet concentrations for all treatment types

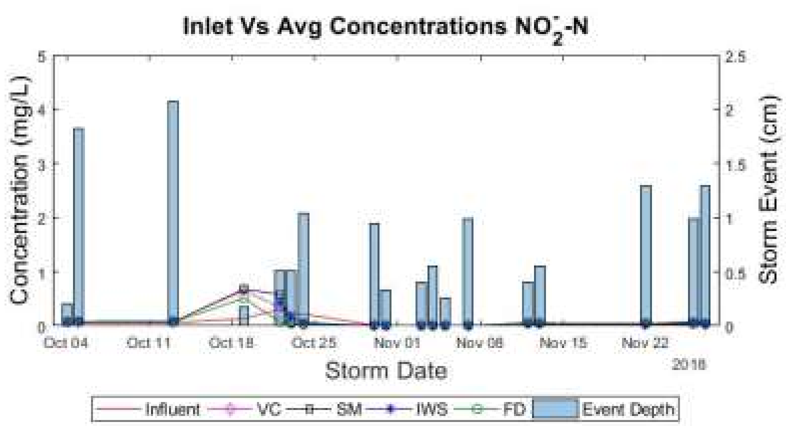

Figure 9. NO_2^--N outlet concentrations for all treatment types

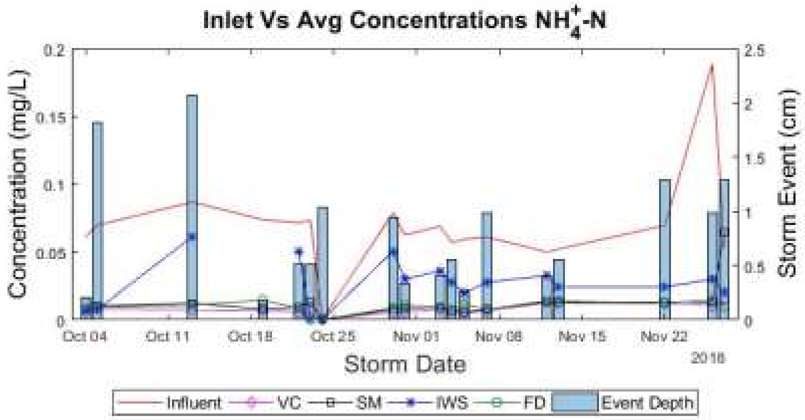

Figure 10. NH_4^+-N outlet concentrations for all treatment types

Influence of Antecedent Conditions

Correlations between both 5-day antecedent rainfall and pollutant removal, and the antecedent number of dry days and pollutant removal (for all pollutants) were analyzed to determine the influence that wet and dry conditions have on water quality (which has been shown in studies such as E. Hatt et al. (2007) and Tang and Tian (2016)). Nutrient processing through physical and microbial interactions have the potential to be overloaded when a system is tasked with managing frequent storm events. Likewise, periods of drought can affect biogeochemical processes, causing leaching from bioretention cells during subsequent storms (as was proposed for the mid-October event).

Contrary to results found by Manka et al. (2016) and Hatt et. al (2007), there was typically no significant correlation between removal and either measure of antecedent conditions. The one exception was a slightly negative correlation between NO_3-N removal by IWS treatment and the 5-day antecedent rainfall (Spearman Rank Correlation Coefficient = -0.54). Thus, there is minimal influence of wetting and drying periods on water quality. However, this study exhibited shorter dry periods (longest dry period of 9 days) and the lack of correlation is consistent with work done by Blecken et al. (2009) in which no effects were seen for dry periods shorter than 3 weeks. Work done by E. Hatt et al. (2007) also utilized longer dry and wet periods in examining removal performance. Further study on long term hydrologic implications of active control systems should be conducted to determine further correlations between treatment and removal. It is possible that active controls could be used to manage soil moisture more effectively during dry conditions, but this is an untested hypothesis.

Overall Comparison of Treatments

Traditional FD and IWS treatments can be considered controls to compare the efficacy of VC and SM treatments. FD and IWS represent the extremes of bioretention function, promoting aerobic and anaerobic conditions, respectively, and differential detention times. VC and SM treatments were actively controlled, leading to more variable patterns of water release compared to FD and IWS, and subsequent differences in storage times and soil moisture patterns. These trends were found to influence water quality, being an explanatory factor for dissimilarities in metal and nutrient effluent concentrations from the treatments.

Overall, deeper water storage zones lead to better anaerobic nutrient processing of nitrate (denitrification), while shallower water storage zones allow for greater aerobic treatment and conversion of NH_4^+-N to NO_3^--N . In this study, this understanding played out by the FD treatments more effective at performing nitrification (i.e. NH_4^+-N concentration reductions were accomplished), while the IWS treatment showed the most reduction in NO_3^--N concentrations, indicating more denitrification when compared to other treatments. The VC and SM treatments were found to be better at performing nitrification than the FD treatment but not better at performing denitrification than the IWS treatment, that is, they were able to provide both nitrification and denitrification in moderation (compared to other treatments). This provides some hope that continued scheme development for actively controlled bioretention may lead to systems that can balance the conflicting aerobic and anaerobic environments needed for fully processing nitrogen.

In terms of metals, the treatments largely performed similarly other than the IWS treatment exported Mn^{2+}, and the VC treatment removing Cu^{2+} with less efficiency. This resulted in a few notable observations as to how active controls could influence metal concentrations (e.g. by effecting redox potential). Similar results are evident with TSS removal being over 97%.

Although not a focus of this study, it should be noted that the IWS treatment was able to store runoff from smaller rain events which would result in total runoff reduction. For fewer storms, SM and VC treatments were also able to do the same as the threshold for active release was not reached. The hydrologic implications of the various treatment types should be further studied to understand how active controls can be used to balance volume reduction and water quality improvement. We hypothesize that active controls will be able to meet these multiple objectives more effectively than static systems.

Conclusions

This column study tested the use of active control systems, as compared to static designs, over a 9-week period by observing water quality improvements provided by each treatment. Historic weather predictions were coupled with observed precipitation events to replicate weather conditions from June and July 2017, which amounted to a total of 18 storm events. Most notable was the influence of the treatments on nutrients. For nutrients in the static systems, the largely aerobic free draining performed best for NH_4^+-N, while the more anaerobic environment provided by the internal water storage led to the best performance for NO_3^--N. Deeper media depths could remedy this issue in future implementation of IWS treatment, that is, a larger aerobic zone above the IWS could be provided. As the optimum IWS depth for water quality has not been explored in literature, these data suggest that balancing nitrification and denitrification is critical and more scientifically informed IWS design is possible. The soil moisture and volume control treatments were able to balance these two environments, removing NH_4^+-N by more than 40% and NO_3^--N by more than 73%. Differences between soil moisture and volume control were minimal for nutrients. This suggests that active controlled systems may strike a balance between traditional free draining and internal water storage systems.

Numerous factors influenced the results of this research and should be considered in future research. First, using one scheme per configuration targets only one control objective but having multiple control objectives could further improve the effectiveness of active control. Second, having a seepage port allows the columns to better mimic field conditions in a laboratory setting, but also results in biofouling and should be carefully monitored. Finally, Eastern Tennessee is subject to frequent, hard to predict thunderstorms in summer months which could have affected the rainfall forecast data used herein. Using rainfall data from easier to predict seasons may affect the results of the study.

Future research into actively controlled bioretention systems should include more hydrologic quantification of bioretention systems outfitted with this technology in both laboratory and field-scale studies. This should be coupled with further development of active control schemes to balance water quality and hydrologic objectives using soil moisture readings at variable media depths and by incorporating depth sensor measurements. The use of weather predictions in designing schemes for active control systems is critical, and additional study should be performed to compare preemptive control based on weather predictions to more adaptive control during storm events able. That is, if retention time is a critical treatment consideration, can it be further optimized by considering uncertainties in weather prediction? Despite these questions, active control systems show promise for the future of designing more efficient bioretention systems that are adaptive to external and internal environmental processes.

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