Centre for Alternative Wastewater Treatment

Phosphorus Removal Performance of Bioretention Soil Mix Amended with Imbrium® Systems Sorbtive® Media

Gordon C. Balch, Heather Broadbent, Brent C. Wootton, and Stephanie L. Collins

February 2013

In association with Fleming College

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EXECUTIVE SUMMARY

A pilot study was undertaken by researchers at Fleming College in Ontario, Canada to assess the phosphorus removal performance of bioretention soil mix amended with Imbrium® Systems Sorbtive® Media AI 28x48. Five bioretention cells were constructed and filled with a soil mix comprised of sand, peat moss, and various percentages of the phosphorus adsorbent Sorbtive® Media. One cell was a control with no amendment, and four cells were amended with the additive blended in at 3%, 5%, 10%, and 17% volume basis, respectively.

Batches of artificial stormwater were spiked with potassium dihydrogen phosphate (KH_2PO_4) at target concentrations of 0.2, 0.4, 0.6, and 0.8 mg/L (P-basis). Starting with the artificial stormwater containing the lowest concentration of phosphorus, each bioretention cell was subjected to a series of daily simulated storm events of controlled water volume for five consecutive days. This five-day simulated storm series was undertaken five times for each of the four phosphorus concentrations. The total volume of spiked artificial stormwater applied to each cell was representative of two years of regional cumulative urban runoff for a drainage area five times the size of a bioretention cell.

Influent and effluent samples were collected for each cell and analyzed for total phosphorus and total dissolved phosphorus. Study results demonstrated a very substantial improvement in phosphorus removal with the amended bioretention soil compared to the control. Over the course of the study, the control cell's total phosphorus removal efficiency decreased from approximately 60% to 25%, while each of the amended cells maintained removal efficiency of up to 99% and at least 84% for the duration of the study. These results suggest that Sorbtive® Media, even when blended into the soil mix at only 3 - 5% volume basis, would be highly effective for improving phosphorus removal in bioretention installations. A similar benefit would be expected when using the amendment in bioswale, rain garden, green roof, and sand filter installations.

1 INTRODUCTION

1.1 Overview

An increasing focus of stormwater regulators and researchers is the impairment of water bodies due to nutrient loads transported in stormwater runoff. Regional authorities for watersheds in the U.S. and Canada have targeted phosphorus as a primary pollutant of concern. The widespread adoption of bioretention as a low-impact stormwater treatment practice has produced some well-documented water quality benefits, however, an increasing number of monitoring studies have detected substantial leaching of phosphorus from compost-containing bioretention installations.

The focus of this pilot study was to assess the phosphorus removal performance of bioretention soil mix amended with Imbrium® Systems Sorbtive® Media AI 28x48, an engineered granular media containing aluminum oxide and iron oxide that demonstrates substantial capacity for adsorption of dissolved phosphorus from stormwater runoff. In order to simulate natural stormwater runoff, this study utilized artificial stormwater spiked with various concentrations of potassium dihydrogen phosphate (KH_2PO_4). Spiked stormwater was applied to constructed bioretention cells containing a sand/peat soil mix amended with varying percentages of the additive.

Five bioretention cells were constructed and filled with soil mix and vegetated with a grass and wildflower mix. One cell was a control with no amendment, and four cells were amended with the additive blended in at 3%, 5%, 10%, and 17% volume basis, respectively. Batches of artificial stormwater were spiked with KH_2PO_4 at target concentrations of 0.2, 0.4, 0.6, and 0.8 mg/L (P-basis). Starting with the artificial stormwater containing the lowest concentration of phosphorus, each bioretention cell was subjected to a series of daily simulated storm events of controlled water volume for five consecutive days through an irrigation system. This five-day simulated storm series was undertaken five times for each of the four phosphorus concentrations, therefore each cell was subjected to 25 storm events at each phosphorus concentration, for a total of 100 storm events for each cell. The volume of water applied during each storm event was 990 liters. The total volume of spiked artificial stormwater applied to each cell was representative of two years of regional cumulative urban runoff for a drainage area five times the size of a bioretention cell.

The cells were located outdoors, and therefore were additionally subjected to actual rainfall precipitation; however, no exterior runoff from such rain events could enter the cells. Since the only phosphorus possibly present in such rainfall was from atmospheric sources, it was considered negligible for the purposes of this study and was not measured.

Influent and effluent samples were collected for each cell and analyzed for total phosphorus and total dissolved phosphorus. Phosphorus removal performance was examined as a function of Sorbtive® Media percentage in the soil mix, phosphorus concentration in the artificial stormwater, and cumulative phosphorus load. This information is useful in assessing the practicality of using Sorbtive® Media as a bioretention soil amendment to achieve regulatory phosphorus treatment benchmarks as well as media longevity in such applications.

1.2 Phosphorus and Stormwater Management

Increasing stormwater runoff, as a result of urbanization and consequent increase in landscape imperviousness, contributes to increased contaminant loadings that degrade receiving water quality and negatively affect aquatic ecosystems. A significant stormwater pollutant of concern is phosphorus due to the correlation of increased phosphorus concentrations in surface waters and eutrophication, toxic algae blooms and reduced dissolved oxygen concentrations (Fried et al, 2003). Phosphorus is a naturally occurring element found within rock, sediment, soil, and organic matter. Phosphorus is essential for life as it is a component of adenosine triphosphate (ATP), the energy transfer molecule needed for cellular processes carried out within all living matter (Darnell et al., 1990).

In stormwater phosphorus is generally present both in a dissolved phase and in a particulate-bound phase. The measurement of phosphorus in water samples is commonly quantified in two manners; Total Phosphorus (TP) and Total Dissolved Phosphorus (TDP). The quantification of Total Phosphorus includes the total of both particulate-bound and dissolved phase phosphorus, while Total Dissolved Phosphorus refers to the dissolved phase only. The separation of particulate-bound and dissolved phase phosphorus is conducted through filtration utilizing 0.45 micron membrane filters. Dissolved phosphorus may also be referred to as Total Filterable Phosphorus (TFP) and is represented by dissolved soluble reactive phosphorus (SRP) (orthophosphate) and hydrolysable phosphorus (DHP). Soluble reactive phosphorus is the fraction of phosphorus in surface water that readily contributes to eutrophication through the availability of phosphorus for excessive aquatic plant and algae growth.

Quantification of typical stormwater runoff quality by land use has found that particulate-bound phosphorus and dissolved phosphorus each contribute approximately 50% of the total phosphorus load in runoff from residential and commercial properties (Perry, Garbon, Lee). Phosphorus inputs to stormwater runoff may be from a variety of sources including lawn fertilizers, animal wastes and detergents (Hsieh et al, 2007).

Due to the concerns associated with stormwater impacts to aquatic and terrestrial ecosystems local governments, agencies, regulators and land developers seek cost-effective methods to manage stormwater. Many jurisdictions publish stormwater literature related to best management practices and methods to control stormwater impacts. In addition, many jurisdictions maintain surface water quality guidelines or policies that outline water quality criteria for many pollutants, including total phosphorus.

Structural stormwater best management practices (BMPs) are designed and constructed to attenuate peak stormwater flow, capture and treat runoff to improve water quality, contribute to groundwater recharge through infiltration, and facilitate Low Impact Development (LID) applications which are generally preferred by local governments, agencies and/or regulators to limit aquatic ecosystem impacts. Phosphorus removal performance varies depending on the BMP design. The widespread adoption of bioretention as a low-impact stormwater treatment practice has produced some well-documented water quality benefits, however, an increasing number of monitoring studies have detected substantial leaching of phosphorus from compost-containing bioretention installations (Hunt, Davis, Gulliver, Pitt, et al).

2 MATERIALS AND METHODS

2.1 Study Summary

The experimental design entailed passing simulated stormwater enriched with phosphorus through bioretention cells containing sand/peat soil mix amended with known concentrations of Sorbtive® Media AI 28x48. Stormwater exiting the bioretention cells was measured for phosphorus concentration (both as dissolved phosphorus and total phosphorus) to determine the percentage of phosphorus retained by each cell. The testing facility consisted of five individual bioretention cells, four of which had different concentrations of Sorbtive® Media (3%, 5%, 10% and 17% by volume). The fifth cell contained only the sand/peat soil mix and no amendment, and therefore represented a control that provided the ability to determine how much phosphorus was retained by the sand/peat mix alone.

Batches of artificial stormwater were spiked with KH_2PO_4 at target concentrations of 0.2, 0.4, 0.6, and 0.8 mg/L (P-basis). Starting with the artificial stormwater containing the lowest concentration of phosphorus, each bioretention cell was subjected to a series of daily simulated storm events of controlled water volume for five consecutive days, Monday through Friday, through an irrigation system. This five-day simulated storm series was undertaken five times (weekly over a 5-week period) for each of the four phosphorus concentrations. Progressing from the lowest concentration to the highest concentration, after 20 weeks each cell had been subjected to 25 storm events at each phosphorus concentration, for a total of 100 storm events for each cell. The volume of water applied during each storm event was 990 liters. The total volume of spiked artificial stormwater applied to each cell approximated the volume of cumulative runoff generated in this region over a two-year period by a drainage area five times the size of a bioretention cell.

The experiment utilized five 1000 L plastic totes installed as header tanks to supply the simulated stormwater to the bioretention cells (Figure 2-1). The desired stormwater application flow rate of approximately 7.6 L/min was pumped from each header tank through a series of perforated pipes running the length of each cell. Stormwater was applied to the surface of each cell through the irrigation system. Water collected in the underdrain piping of each cell drained into a common collection tank located below grade of the exit ports. Effluent samples were collected from each cell's drain pipe as the effluent exited into the collection tank. Treated water from the common collection tank was passively directed to an existing pond.

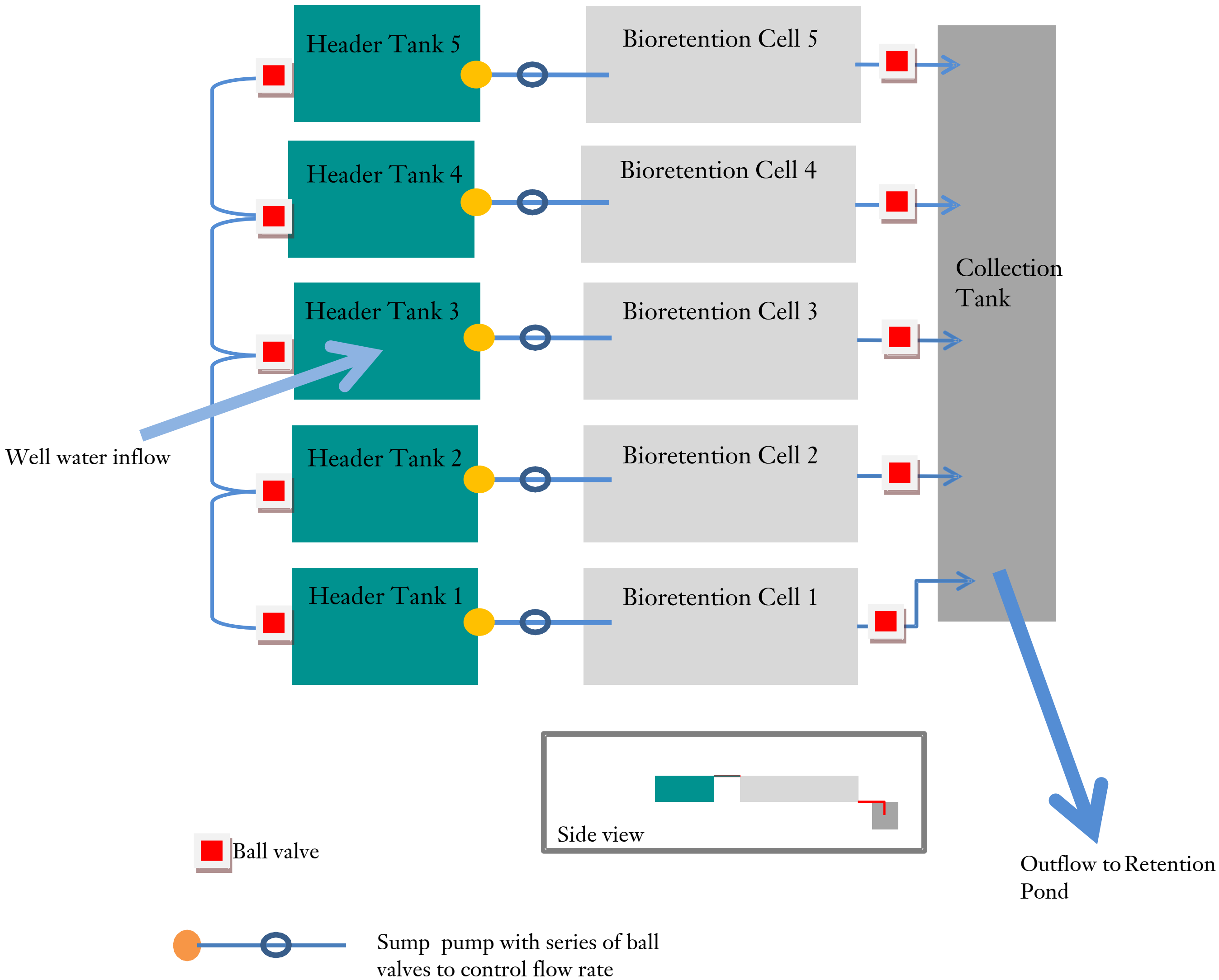

Figure 2-1 A schematic overview of the study site.

2.2 Bioretention cell construction

The five bioretention cells were constructed with identical configurations from prefabricated fibreglass reinforced plywood (FRP) troughs lined with rubberized pond liner to ensure the units were watertight. Each trough had an internal dimension of approximately 4.8 m (long) X 0.75 m (wide) X 0.75 m (high) for a total volume of approximately 2.7 m^3 and was placed on grade with earth banked around the sides of the trough to provide extra support. The underdrain pipe was a 4.6 meter length of 3-inch diameter PVC drainage pipe with 2 rows of predrilled holes. The underdrain pipe was covered with window screen to prevent clogging from fines and centrally placed in the bottom of the trough for the collection of filtered storm water (Figure 2-2). The underdrain pipe was fitted to a two inch bulkhead connection. A 2-inch PVC effluent pipe, fitted with a ball valve for potential effluent flow restriction, ran from the trough to the common collection tank located below grade of the exit port. Piping was positioned to allow for sample collection ease and ensure that each cell drained completely between simulated rain events (Figure 2-3).

Figure 2-2 Fibreglass reinforced plywood trough lined with pond liner with 3 inch PVC underdrain pipe running the length of the bioretention cell

Figure 2-3 Effluent collection pipes exiting the bioretention cells and directed to a sub grade collection tank

The bottom of each cell was lined with a 15 cm depth of half-inch granite stone to surround the underdrain pipe. The next layer was 3 cm of sand, topped by a 50 cm layer of soil. The sand was utilized to separate the bioretention soil mix from the coarse stone. The soil mix of the control cell (designated Bioretention Cell 1) contained only sand and peat moss. The other four cells (Bioretention Cells 2 through 5) contained soil mix comprised of sand/peat amended with various percentages of Sorbtive® Media AI 28x48. Front end loaders were used in the soil blending process. The appropriate amounts of sand, peat, and amendment were measured by hand using 23L plastic pails which were then poured into the bucket of a front end loader. The material was passed from bucket to bucket of two loaders to ensure uniform mixing. After the soil mix was thoroughly blended, the material was dumped into the cell using the front end loader (See Figure 2-4).

Figure 2-4 **Mixing of bioretention soil between the buckets of two front end loaders and dumping of soil mix into the cell**

The soil mix composition for each bioretention cell is summarized in Table 2-1.

Table 2-1 **Bioretention Soil Mix Composition**

Cell Number	Soil Mix Composition (% by volume)		
	Sand	Peat Moss	Sorbtive® Media
Bioretention Cell 1	85%	15%	0%
Bioretention Cell 2	82%	15%	3%
Bioretention Cell 3	80%	15%	5%
Bioretention Cell 4	75%	15%	10%
Bioretention Cell 5	68%	15%	17%

Each bioretention cell was vegetated with a mix consisting of commercially available Scotts® Premium Sun™ grass seed, MacKenzie® brand native grass and wildflower mix, and MacKenzie® brand low-growing wildflowers.

2.3 Water Volume and Flow Rates

The calculations for the storm flow rates and volumes were based on the following criteria:

- Average rainfall of 55 mm/month
- Drainage area treated is 5 times greater than the area of the bioretention cell
- Rainfall intensity of 25.4 mm/hr
- Bioretention cell area of 3.6 m^2

Based on these criteria, each simulated storm event would have volume of 990 L (262 gal.) and flow rate of 7.62 L/min (2.01 gpm) with a duration of 130 minutes.

2.4 Artificial Stormwater Composition

The recipe for the artificial stormwater used in testing is shown in Table 2-2, and based on a 990 L volume of potable well water.

Table 2-2 Quantity of salts added to 990 L of well water to create artificial stormwater

Salt Compound	Quantity of Salt per 990 L (g)
Sodium Chloride (NaCl)	123.81
Calcium Chloride ($CaCl_2$)	24.50
Sodium Sulphate (Na_2SO_4)	23.35
Sodium Nitrate ($NaNO_3$)	2.81
Potassium Chloride (KCl)	2.59
Magnesium Chloride Hexahydrate ($MgCl_2.6H_2O$)	5.66

Target phosphorus concentrations in the artificial stormwater were varied between 0.2 mg/L and 0.8 mg/L P-basis. The mass of KH_2PO_4 added to each 990 L of artificial stormwater is shown in Table 2-3.

Table 2-3 Target phosphorus concentrations and respective quantities of KH_2PO_4 added to 990 L of artificial stormwater

Target P-basis concentration (mg/L)	Quantity of KH_2PO_4 per 990 L (g)
0.2	0.87
0.4	1.74
0.6	2.61
0.8	3.48

2.5 Artificial Stormwater Preparation, Storage, and Metering

The header tanks consisted of graduated 1000 L plastic totes. Tank 3 was a central fill location where the outflow from the potable well was attached. Tanks were plumbed together in series through the use of the outlet port on each tank and were filled overnight via a timer with final volumes adjusted manually the following morning. Tanks were then isolated by valve before the artificial stormwater was prepared (See Figure 2-5). After addition of salts, the tanks were mixed for 1 hour before the simulated storm events were initiated.

Figure 2-5 **Individual 1000 L header tanks plumbed in series to fill simultaneously and then isolated for addition of salts, mixing, and distribution of artificial stormwater to each bioretention cell.**

Artificial stormwater was pumped from each header tank with a 1/6 HP sump pump and through an irrigation system comprised of ¾-inch PVC pipe. Two solid pipes ran to the midpoint of each cell, and then split off to two equal length perforated pipes. Flow exiting the perforations naturally distributed across the full length and width of each cell (See Figure 2-6). Some water re-circulated back to the header tank. The target flow rate of 7.6 L/min was established to each cell by adjusting ball valves and measuring influent and effluent flows by means of bucket and stopwatch.

Figure 2-6 Artificial stormwater irrigation system

2.6 Stormwater Application Frequency, Sample Collection, and Sample Analysis

2.6.1 Frequency of dosing

Starting with the artificial stormwater containing the lowest concentration of phosphorus, each bioretention cell was subjected to a series of daily simulated storm events of controlled water volume for five consecutive days, Monday through Friday, through an irrigation system. This five-day simulated storm series was undertaken five times (weekly over a 5-week period) for each of the four phosphorus concentrations. Progressing from the lowest concentration to the highest concentration, after 20 weeks each cell had been subjected to 25 storm events at each phosphorus concentration, for a total of 100 storm events for each cell. The volume of water applied during each storm event was 990 liters. The total volume of spiked artificial stormwater applied to each cell approximated the volume of cumulative runoff generated in this region over a two-year period by a drainage area five times the size of a bioretention cell.

Natural rainfall events were recorded using rain gauges located in bioretention cells 1 and 5, as well as a SCADA recorded tipping bucket located on site at Fleming College.

2.6.2 Sample Collection and Analysis

Once per week, samples were taken from each header tank and from the corresponding exit port of each bioretention cell, midway through the simulated stormwater event. Potable well water and water from the collection pond was sampled as well. Samples were tested for total phosphorus (TP) and total dissolved phosphorus (TDP). Total phosphorus samples were digested in acid with potassium persulfate followed by reaction with molybdate to create a blue colour change that could be detected using a discrete auto-analyser (SM 4500-P). Total dissolved phosphorus concentrations were determined in the same fashion as above, after filtration of the sample with a 0.45 micron filter.

The pH of artificial stormwater in each header tank and effluent from each bioretention cell was monitored on a daily basis.

3 RESULTS

3.1 Phosphorus Removal Performance

Measured values of total dissolved phosphorus and total phosphorus concentrations in the artificial stormwater (header tank samples) were consistently lower than the target phosphorus concentrations (See Table 3-1). The deviations between measured and target values decreased as the target concentration increased. In addition, dissolved phosphorus concentrations were consistently lower than total phosphorus concentrations. These results suggest that within the header tanks a portion of the phosphorus partitioned from the dissolved phase to a filterable colloidal or particulate-bound phase, with some precipitating out of solution or adsorbing to the vessel surfaces. For the purposes of determining the phosphorus removal performance of each bioretention cell, the measured values of total dissolved phosphorus and total phosphorus in the header tanks are used as the influent basis.

Table 3-1 Measured dissolved and total phosphorus expressed as a percentage of the target concentrations in artificial stormwater within header tank samples

Target P-basis concentration (mg/L)	Average TDP measured value (mg/L)	% of target	Average TP measured value (mg/L)	% of target
0.2	0.11	56	0.16	78
0.4	0.28	70	0.36	89
0.6	0.46	76	0.54	90
0.8	0.65	82	0.72	90

The mass of phosphorus, both dissolved and total, retained by a bioretention cell was determined by measuring the phosphorus concentration of the header tank sample and subtracting from this value the measured phosphorus concentration in the effluent from each cell. The influent volume was factored in. The mass of phosphorus retained by the cell for the sampled simulated storm event for a given week was multiplied by five to estimate the phosphorus mass retained for the week's total of five simulated storm events. The other four simulated storm events for a given week were not sampled. Retained phosphorus mass was summed for all twenty weeks to determine the estimated cumulative retained phosphorus mass.

The cumulative retained phosphorus mass for each cell is shown in Figure 3-1 (dissolved phosphorus) and Figure 3-2 (total phosphorus). The data represented in these figures illustrate that although the cells retained less dissolved phosphorus compared to total phosphorus, overall the trends remained the same. All the cells amended with Sorbtive® Media demonstrated nearly 3 times greater retained dissolved phosphorus mass, and nearly 2.5 times greater retained total phosphorus mass, compared to the control cell with no Sorbtive® Media. Results for the 3% and 5% amendments were similar to each other, although slightly lower than the 10% and 17% amendments, which were also similar to each other.

The percentage of phosphorus removed by each bioretention cell for each for each the four phosphorus concentrations tested is illustrated in Figure 3-3 (dissolved phosphorus) and Figure 3-4 (total phosphorus). Once again, the trends for dissolved phosphorus are similar to those for total phosphorus. At every phosphorus concentration, all the cells amended with Sorbtive® Media demonstrated much higher percent removal of phosphorus compared to the control cell with no Sorbtive® Media. The performance gap between the amended cells and the control cell widened as the phosphorus concentration increased. At the 0.2% target phosphorus concentration, mean dissolved phosphorus removal ranged 79-92% for the amended cells compared to 54% for the control cell. At the 0.8% target phosphorus concentration, mean dissolved phosphorus removal ranged 86-98% for the amended cells compared to 20% for the control cell. In the final week of the study, with 0.8% target phosphorus concentration in the artificial stormwater, percent removal of dissolved phosphorus was 82% for the 3% amendment, 97-98% for the 5%, 10%, and 17% amendments, and 11% for the control. These results demonstrate that the Sorbtive® Media maintained high phosphorus adsorptive capacity throughout the study, especially at the 5% and greater amendment levels.

Rainfall during the testing period was sporadic and the total weekly volume of rainwater added to individual bioretention cells was insignificant. The heaviest weekly rainfall generated approximately 68 L of extra water for each cell, compared to 4950 L of artificial stormwater applied to each cell each week.

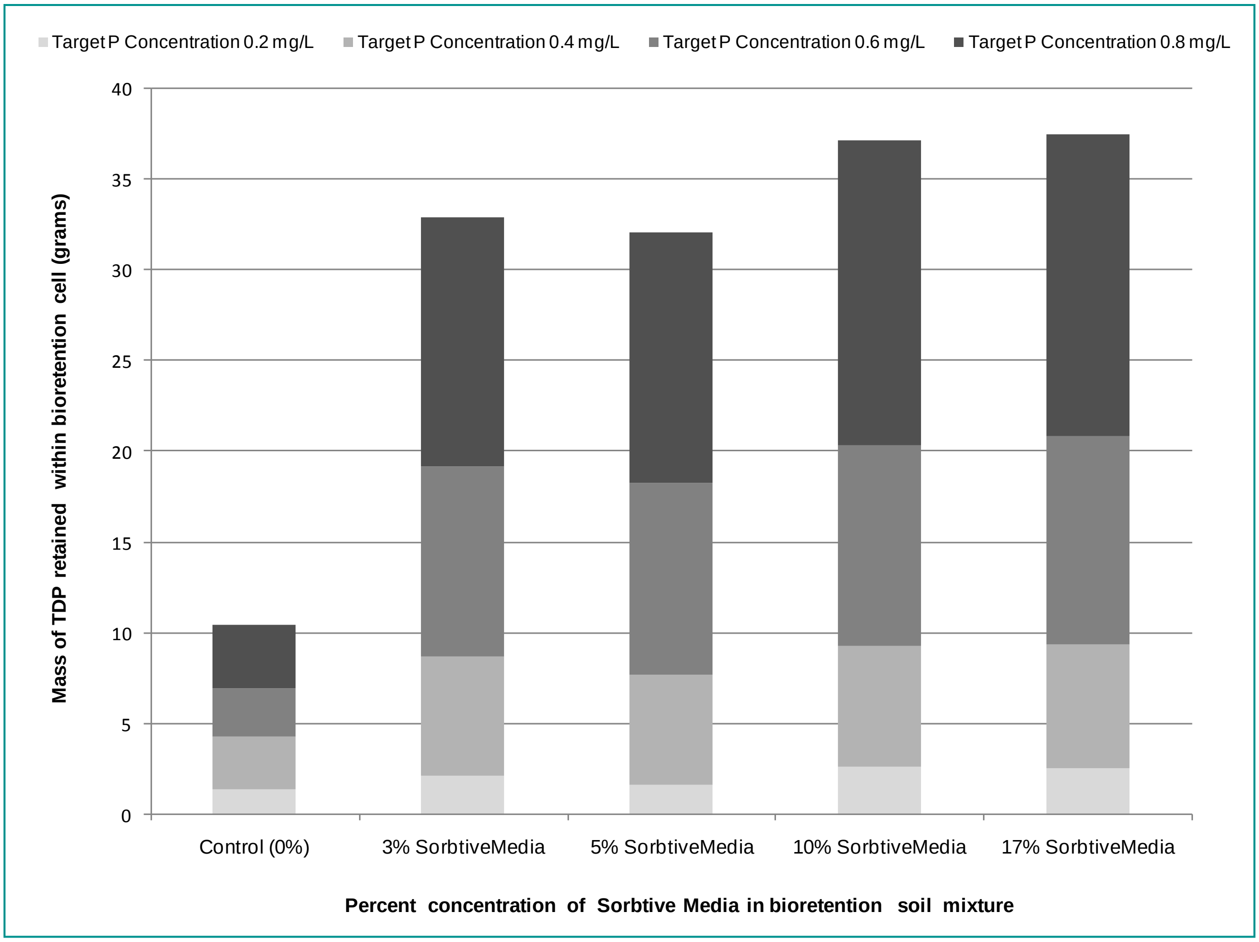

Figure 3-1 Cumulative mass of total dissolved phosphorus retained in each bioretention cell.

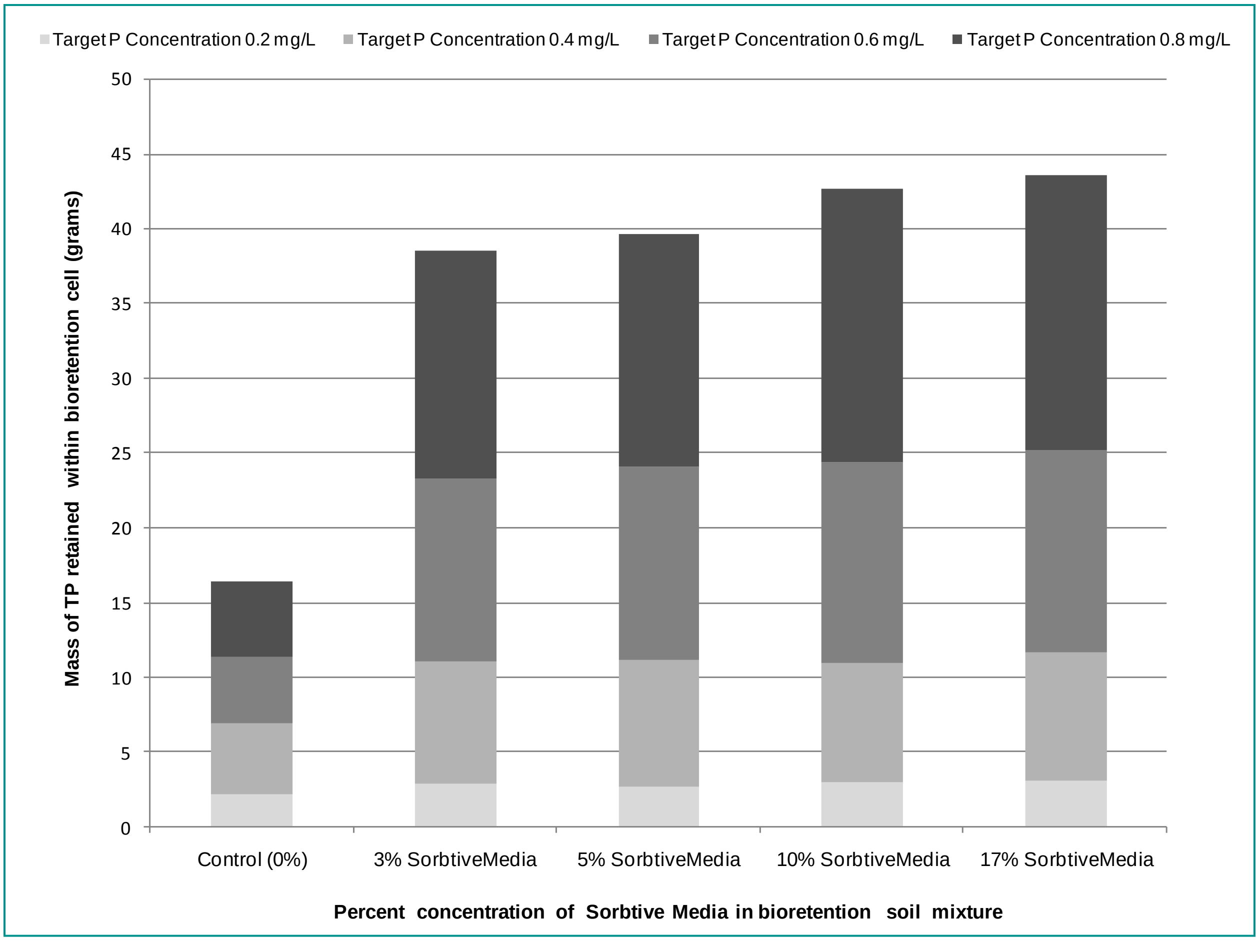

Figure 3-2 Cumulative mass of total phosphorus retained in each bioretention cell.

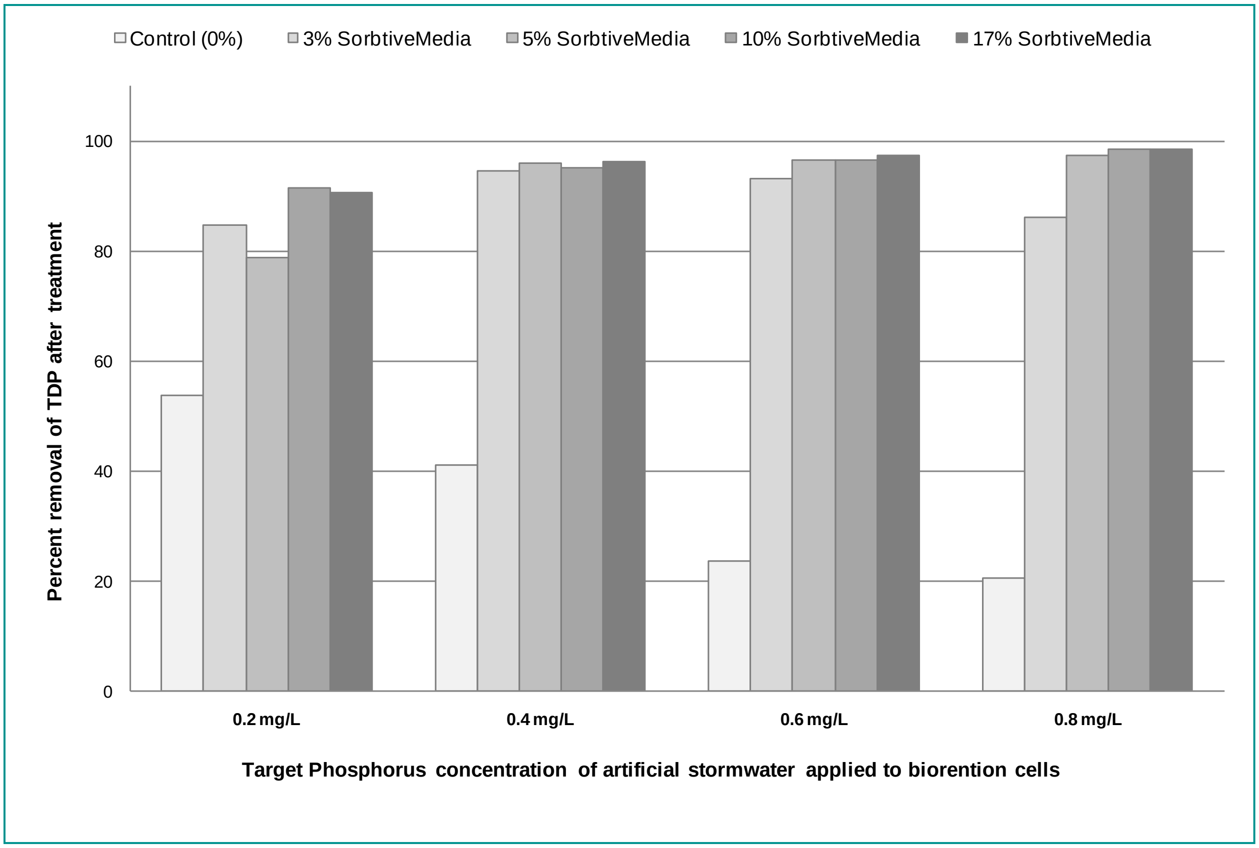

Figure 3-3 Percent removal of total dissolved phosphorus for each bioretention cell at each of four different target phosphorus concentrations

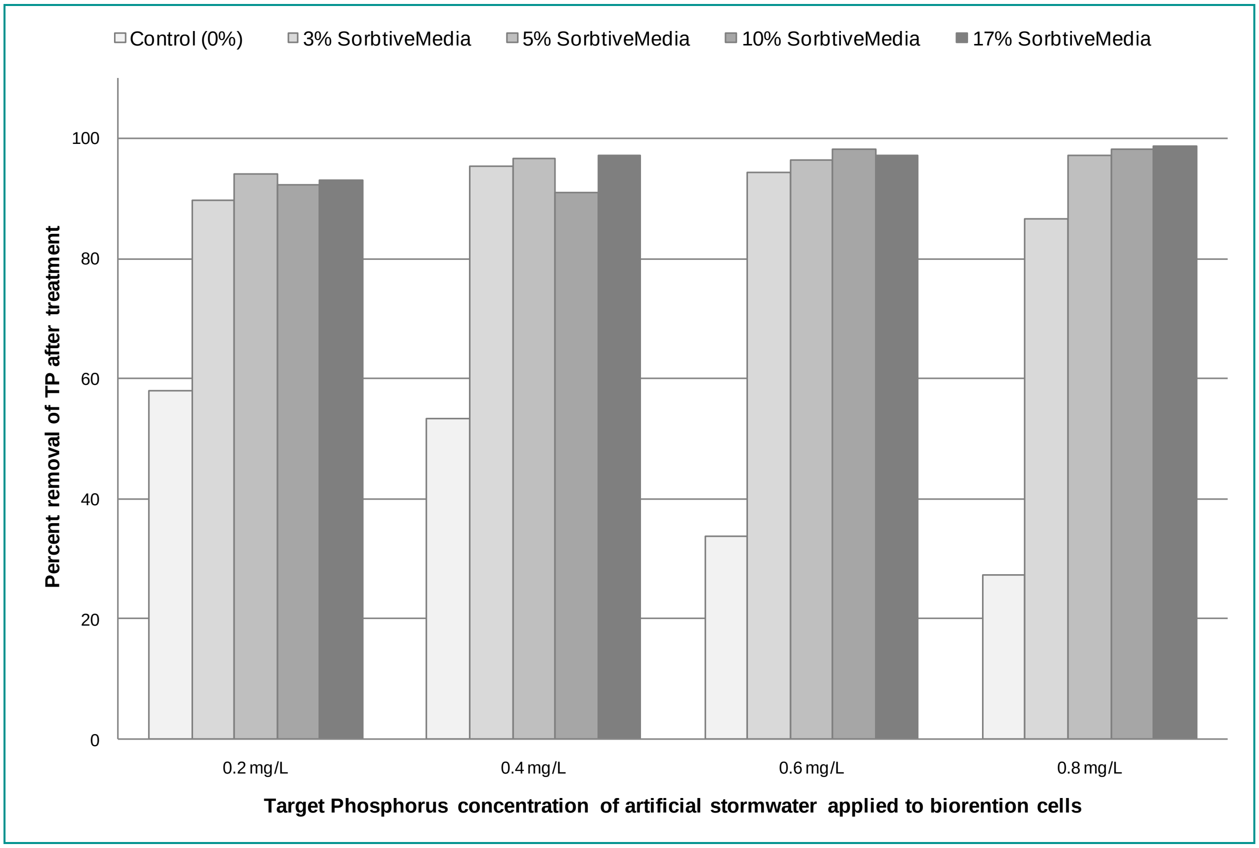

Figure 3-4 Percent removal of total phosphorus for each bioretention cell at each of four different target phosphorus concentrations

3.2 Effect on Effluent pH

The pH of artificial stormwater in each header tank and effluent from each bioretention cell was monitored on a daily basis. The data in Table 3-2 illustrates that minimal change in pH occurred as artificial stormwater was treated by each of the bioretention cells, and effluent pH remained well within regulatory discharge limits.

Table 3-2 pH measurements for influent and effluent of each bioretention cell

Target Phosphorus Conc	Control (0%)		3% Sorbtive® Media		5% Sorbtive® Media		10% Sorbtive® Media		17% Sorbtive® Media	
(mg/L)	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
0.2	7.29	7.57	7.28	7.52	7.21	7.32	7.30	7.29	7.33	7.02
0.4	7.30	7.72	7.31	7.80	7.28	7.73	7.31	7.67	7.31	7.35
0.6	7.40	7.81	7.38	7.86	7.33	7.79	7.39	7.79	7.38	7.61
0.8	7.50	7.81	7.41	7.84	7.33	7.88	7.38	7.78	7.39	7.67

4 CONCLUSIONS

The removal of phosphorus from stormwater using bioretention BMPs with a sand/peat soil mix can be greatly enhanced by amendment of the soil with Sorbtive® Media AI 28x48. Compared to a control with no Sorbtive® Media, amended bioretention cells demonstrated much greater removal of dissolved and total phosphorus on both a mass and percent removal basis. Over the course of this study, the control cell's total phosphorus removal efficiency decreased from approximately 60% to 25%, while each of the amended cells maintained removal efficiency of up to 99% and at least 84% for the duration of the study. These results suggest that Sorbtive® Media, even when blended into the soil mix at only 3 - 5% volume basis, would be highly effective for improving phosphorus removal in bioretention installations. A similar benefit would be expected when using the amendment in bioswale, rain garden, green roof, and sand filter installations.

Effluent pH is relatively unaffected by amendment of bioretention soil mix with Sorbtive® Media.

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6 APPENDICES

The following contains the data used to generate the Tables and Figures embedded within the body of the report

Appendix 1

Raw Data for Table 3-1; Measured dissolved and total phosphorus expressed as a percentage of the target concentrations in artificial stormwater within header tank samples.

Target P Concentration in Artificial Stormwater	Header Tank corresponding to Percent Sorbtive®Media Within Bioretention Cell	Week	TDP (mg/L)	% of Target Concentration	TP (mg/L)	% of Target Concentration
0.2 mg/L	Control (0%)	1	0.12	58.71	n.m.	n.m.
	3%		0.11	54.73	n.m.	n.m.
	5%		0.08	40.72	n.m.	n.m.
	10%		0.12	60.23	n.m.	n.m.
	17%		0.14	68.75	n.m.	n.m.
	Control (0%)	2	0.13	64.81	n.m.	n.m.
	3%		0.16	79.62	n.m.	n.m.
	5%		0.12	60.98	n.m.	n.m.
	10%		0.13	65.85	n.m.	n.m.
	17%		0.13	66.03	n.m.	n.m.
	Control (0%)	3	0.11	55.31	0.12	59.49
	3%		0.10	47.65	0.09	43.80
	5%		0.11	56.41	0.15	75.91
	10%		0.11	55.86	0.09	44.16
	17%		0.11	54.76	0.10	52.01
	Control (0%)	4	0.09	42.60	0.17	83.39
	3%		0.08	41.15	0.17	87.04
	5%		0.06	31.36	0.18	88.87
	10%		0.11	56.74	0.15	77.19
	17%		0.09	46.95	0.17	85.04
	Control (0%)	5	n.m.	n.m.	0.20	99.48
	3%		n.m.	n.m.	0.19	93.64
	5%		n.m.	n.m.	0.18	90.38
	10%		n.m.	n.m.	0.19	93.81
	17%		n.m.	n.m.	0.18	89.52
	mean		***0.11***	***55.46***	***0.16***	***77.58***
	SD		***0.02***	***11.32***	***0.04***	***18.63***

- ***n.m. = not measured***

Target P Concentration in Artificial Stormwater	Header Tank corresponding to Percent Sorbtive® Media Within Bioretention Cell	Week	TDP (mg/L)	% of Target Concentration	TP (mg/L)	% of Target Concentration
0.4 mg/L	Control (0%)	1	0.29	73.32	0.37	92.16
	3%		0.29	72.67	0.37	91.70
	5%		0.29	71.55	0.36	91.14
	10%		0.28	69.78	0.37	91.51
	17%		0.29	73.04	0.38	95.06
	Control (0%)	2	0.24	60.97	0.35	87.23
	3%		0.24	60.43	0.35	87.23
	5%		0.20	49.52	0.35	87.32
	10%		0.25	62.15	0.34	84.25
	17%		0.24	61.24	0.35	88.40
	Control (0%)	3	0.31	78.68	0.37	93.01
	3%		0.31	77.05	0.37	91.83
	5%		0.31	78.14	0.36	90.20
	10%		0.31	78.68	0.37	93.28
	17%		0.31	77.86	0.37	92.01
	Control (0%)	4	0.27	67.03	0.35	88.19
	3%		0.28	68.77	0.30	75.64
	5%		0.20	50.09	0.35	87.18
	10%		0.28	68.77	0.33	83.52
	17%		0.29	72.25	0.34	85.26
	Control (0%)	5	0.30	75.21	0.36	89.99
	3%		0.29	71.65	0.34	85.24
	5%		0.28	69.10	0.36	89.99
	10%		0.29	73.57	0.36	89.80
	17%		0.30	75.39	0.36	89.16
	mean		***0.28***	***69.48***	***0.36***	***88.81***
	SD		***0.03***	***8.08***	***0.02***	***4.04***

Target P Concentration in Artificial Stormwater	Header Tank corresponding to Percent Sorbtive® Media Within Bioretention Cell	Week	TDP (mg/L)	% of Target Concentration	TP (mg/L)	% of Target Concentration
0.6 mg/L	Control (0%)	1	0.45	74.49	0.54	90.27
	3%		0.43	72.47	0.53	87.64
	5%		0.42	69.36	0.56	92.53
	10%		0.45	74.68	0.53	88.37
	17%		0.46	77.18	0.54	90.57
	Control (0%)	2	0.47	78.46	0.55	91.23
	3%		0.47	78.58	0.53	88.83
	5%		0.48	80.12	0.56	93.58
	10%		0.48	79.44	0.55	92.41
	17%		0.48	79.88	0.57	94.88
	Control (0%)	3	0.43	71.86	0.52	86.36
	3%		0.42	69.35	0.52	87.14
	5%		0.43	71.03	0.52	87.38
	10%		0.44	73.72	0.63	104.44
	17%		0.46	76.78	0.53	87.56
	Control (0%)	4	0.50	82.66	0.53	88.17
	3%		0.50	83.74	0.52	86.62
	5%		0.49	80.92	0.53	87.93
	10%		0.49	81.46	0.54	89.67
	17%		0.51	84.52	0.54	90.21
	Control (0%)	5	0.45	75.31	0.53	87.78
	3%		0.44	73.57	0.51	84.74
	5%		0.39	64.45	0.55	90.95
	10%		0.45	75.74	0.51	85.24
	17%		0.46	77.23	0.63	104.66
	mean		***0.46***	***76.28***	***0.54***	***90.37***
	SD		***0.03***	***4.92***	***0.03***	***4.96***

Target P Concentration in Artificial Stormwater	Header Tank corresponding to Percent Sorbtive® Media Within Bioretention Cell	Week	TDP (mg/L)	% of Target Concentration	TP (mg/L)	% of Target Concentration
0.8 mg/L	Control (0%)	1	0.74	92.07	0.82	102.92
	3%		0.72	90.52	0.81	101.78
	5%		0.30	37.60	0.39	48.23
	10%		0.77	95.90	0.83	103.79
	17%		0.76	94.44	0.82	102.56
	Control (0%)	2	0.68	84.76	0.74	92.43
	3%		0.66	82.72	0.71	88.76
	5%		0.63	78.73	0.72	90.39
	10%		0.69	86.81	0.75	93.70
	17%		0.67	83.54	0.74	92.34
	Control (0%)	3	0.69	86.29	0.72	90.16
	3%		0.64	80.41	0.68	85.04
	5%		0.69	85.86	0.70	87.29
	10%		0.69	85.76	0.73	90.78
	17%		0.68	84.81	0.74	92.02
	Control (0%)	4	0.70	87.89	0.75	93.68
	3%		0.62	76.91	0.68	84.61
	5%		0.66	82.30	0.69	86.62
	10%		0.68	85.44	0.74	92.40
	17%		0.71	88.63	0.76	95.39
	Control (0%)	5	0.60	75.10	0.71	88.67
	3%		0.57	71.38	0.69	86.60
	5%		0.59	73.31	0.72	90.13
	10%		0.62	77.17	0.72	90.55
	17%		0.61	76.61	0.70	87.77
	mean		***0.65***	***81.80***	***0.72***	***90.34***
	SD		***0.09***	***11.18***	***0.08***	***10.34***

Appendix 2

Raw Data for Figure 3-1; Cumulative mass of total dissolved phosphorus retained in each bioretention cell.

Target P concentration in artificial stormwater		0% Sorbtive® Media (Control) Average TDP Grams Retained/day	Average TDP Grams Retained/week
0.2 mg/L	Week 1	0.09	0.45
	Week 2	0.10	0.50
	Week 3	0.03	0.15
	Week 4	0.03	0.14
	Week 5	0.03	0.14
	Treatment Sum		**1.37**
0.4 mg/L	Week 1	0.14	0.71
	Week 2	0.10	0.49
	Week 3	0.14	0.70
	Week 4	0.10	0.50
	Week 5	0.11	0.53
	Treatment Sum		**2.94**
0.6 mg/L	Week 1	0.17	0.84
	Week 2	0.13	0.67
	Week 3	0.09	0.47
	Week 4	0.06	0.32
	Week 5	0.07	0.36
	Treatment Sum		**2.65**
0.8 mg/L	Week 1	0.18	0.91
	Week 2	0.16	0.77
	Week 3	0.17	0.83
	Week 4	0.14	0.69
	Week 5	0.06	0.31
	Treatment Sum		**3.51**
	Total sum		***10.47***

Target P concentration in artificial stormwater		3% Sorbtive® Media Average TDP Grams Retained/day	Average TDP Grams Retained/week
0.2 mg/L	Week 1	0.10	0.48
	Week 2	0.15	0.74
	Week 3	0.09	0.42
	Week 4	0.05	0.27
	Week 5	0.05	0.27
	Treatment Sum		**2.18**
0.4 mg/L	Week 1	0.28	1.37
	Week 2	0.23	1.14
	Week 3	0.29	1.45
	Week 4	0.26	1.29
	Week 5	0.27	1.33
	Treatment Sum		**6.58**
0.6 mg/L	Week 1	0.42	2.07
	Week 2	0.45	2.23
	Week 3	0.40	1.96
	Week 4	0.46	2.28
	Week 5	0.38	1.90
	Treatment Sum		**10.44**
0.8 mg/L	Week 1	0.65	3.22
	Week 2	0.59	2.90
	Week 3	0.55	2.71
	Week 4	0.52	2.58
	Week 5	0.47	2.31
	Treatment Sum		**13.73**
	Total sum		*32.93*

Target P concentration in artificial stormwater		5% Sorbtive® Media Average TDP Grams Retained/day	Average TDP Grams Retained/week
0.2 mg/L	Week 1	0.07	0.35
	Week 2	0.07	0.34
	Week 3	0.10	0.48
	Week 4	0.05	0.26
	Week 5	0.05	0.26
	Treatment Sum		**1.70**
0.4 mg/L	Week 1	0.28	1.37
	Week 2	0.19	0.93
	Week 3	0.30	1.50
	Week 4	0.19	0.94
	Week 5	0.27	1.32
	Treatment Sum		**6.06**
0.6 mg/L	Week 1	0.41	2.01
	Week 2	0.47	2.33
	Week 3	0.42	2.06
	Week 4	0.48	2.36
	Week 5	0.35	1.75
	Treatment Sum		**10.51**
0.8 mg/L	Week 1	0.29	1.41
	Week 2	0.62	3.07
	Week 3	0.67	3.33
	Week 4	0.65	3.20
	Week 5	0.57	2.83
	Treatment Sum		**13.84**
	Total sum		***32.11***

Target P concentration in artificial stormwater		10% Sorbtive® Media Average TDP Grams Retained/day	Average TDP Grams Retained/week
0.2 mg/L	Week 1	0.11	0.55
	Week 2	0.12	0.60
	Week 3	0.10	0.50
	Week 4	0.10	0.51
	Week 5	0.10	0.51
	Treatment Sum		**2.68**
0.4 mg/L	Week 1	0.27	1.33
	Week 2	0.23	1.11
	Week 3	0.30	1.50
	Week 4	0.27	1.31
	Week 5	0.28	1.40
	Treatment Sum		**6.65**
0.6 mg/L	Week 1	0.44	2.17
	Week 2	0.47	2.31
	Week 3	0.43	2.14
	Week 4	0.48	2.36
	Week 5	0.42	2.07
	Treatment Sum		**11.05**
0.8 mg/L	Week 1	0.76	3.74
	Week 2	0.68	3.39
	Week 3	0.67	3.34
	Week 4	0.67	3.33
	Week 5	0.61	3.01
	Treatment Sum		**16.81**
	Total sum		***37.19***

Target P concentration in artificial stormwater		17% Sorbtive® Media Average TDP Grams Retained/day	Average TDP Grams Retained/week
0.2 mg/L	Week 1	0.13	0.63
	Week 2	0.12	0.59
	Week 3	0.10	0.49
	Week 4	0.08	0.42
	Week 5	0.08	0.42
	Treatment Sum		**2.54**
0.4 mg/L	Week 1	0.28	1.40
	Week 2	0.23	1.16
	Week 3	0.30	1.48
	Week 4	0.28	1.38
	Week 5	0.29	1.44
	Treatment Sum		**6.86**
0.6 mg/L	Week 1	0.45	2.24
	Week 2	0.47	2.32
	Week 3	0.45	2.23
	Week 4	0.50	2.46
	Week 5	0.44	2.19
	Treatment Sum		**11.44**
0.8 mg/L	Week 1	0.74	3.68
	Week 2	0.66	3.26
	Week 3	0.67	3.31
	Week 4	0.70	3.46
	Week 5	0.60	2.98
	Treatment Sum		**16.69**
	Total sum		*37.54*

Appendix 3

Raw Data for Figure 3-2; Cumulative mass of total phosphorus retained in each bioretention cell.

Target P concentration in artificial stormwater		0% Sorbtive® Media (Control) Average TP Grams Retained/day	Average TP Grams Retained/week
0.2 mg/L	Week 1	0.07	0.33
	Week 2	0.07	0.33
	Week 3	0.05	0.27
	Week 4	0.10	0.51
	Week 5	0.13	0.66
	Treatment Sum		**2.10**
0.4 mg/L	Week 1	0.22	1.10
	Week 2	0.19	0.96
	Week 3	0.20	0.98
	Week 4	0.18	0.88
	Week 5	0.16	0.81
	Treatment Sum		**4.72**
0.6 mg/L	Week 1	0.26	1.29
	Week 2	0.21	1.06
	Week 3	0.18	0.91
	Week 4	0.09	0.47
	Week 5	0.15	0.75
	Treatment Sum		**4.47**
0.8 mg/L	Week 1	0.29	1.43
	Week 2	0.20	0.99
	Week 3	0.19	0.96
	Week 4	0.17	0.86
	Week 5	0.18	0.87
	Treatment Sum		**5.11**
	Total sum		***16.40***

Target P concentration in artificial stormwater		3% Sorbtive® Media Average TP Grams Retained/day	Average TP Grams Retained/week
0.2 mg/L	Week 1	0.08	0.41
	Week 2	0.08	0.41
	Week 3	0.07	0.35
	Week 4	0.16	0.81
	Week 5	0.18	0.88
	Treatment Sum		**2.86**
0.4 mg/L	Week 1	0.35	1.74
	Week 2	0.33	1.64
	Week 3	0.35	1.74
	Week 4	0.29	1.42
	Week 5	0.32	1.61
	Treatment Sum		**8.15**
0.6 mg/L	Week 1	0.50	2.47
	Week 2	0.51	2.55
	Week 3	0.50	2.50
	Week 4	0.48	2.37
	Week 5	0.46	2.30
	Treatment Sum		**12.19**
0.8 mg/L	Week 1	0.74	3.65
	Week 2	0.61	3.00
	Week 3	0.58	2.89
	Week 4	0.58	2.89
	Week 5	0.59	2.90
	Treatment Sum		**15.32**
	Total sum		*38.52*

Target P concentration in artificial stormwater		5% Sorbtive® Media Average TP Grams Retained/day	Average TP Grams Retained/week
0.2 mg/L	Week 1	0.02	0.10
	Week 2	0.02	0.10
	Week 3	0.14	0.70
	Week 4	0.17	0.83
	Week 5	0.17	0.85
	Treatment Sum		**2.58**
0.4 mg/L	Week 1	0.35	1.74
	Week 2	0.33	1.65
	Week 3	0.35	1.74
	Week 4	0.34	1.68
	Week 5	0.35	1.73
	Treatment Sum		**8.53**
0.6 mg/L	Week 1	0.53	2.61
	Week 2	0.55	2.73
	Week 3	0.51	2.55
	Week 4	0.52	2.56
	Week 5	0.50	2.48
	Treatment Sum		**12.93**
0.8 mg/L	Week 1	0.36	1.77
	Week 2	0.71	3.52
	Week 3	0.69	3.41
	Week 4	0.68	3.38
	Week 5	0.70	3.49
	Treatment Sum		**15.56**
	Total sum		***39.59***

Target P concentration in artificial stormwater		10% Sorbtive® Media Average TP Grams Retained/day	Average TP Grams Retained/week
0.2 mg/L	Week 1	0.10	0.49
	Week 2	0.10	0.49
	Week 3	0.08	0.39
	Week 4	0.14	0.71
	Week 5	0.18	0.88
	Treatment Sum		**2.97**
0.4 mg/L	Week 1	0.25	1.22
	Week 2	0.32	1.61
	Week 3	0.36	1.80
	Week 4	0.32	1.60
	Week 5	0.35	1.73
	Treatment Sum		**7.95**
0.6 mg/L	Week 1	0.52	2.58
	Week 2	0.54	2.70
	Week 3	0.62	3.05
	Week 4	0.53	2.61
	Week 5	0.50	2.46
	Treatment Sum		**13.40**
0.8 mg/L	Week 1	0.82	4.04
	Week 2	0.73	3.59
	Week 3	0.72	3.55
	Week 4	0.73	3.61
	Week 5	0.71	3.53
	Treatment Sum		**18.32**
	Total sum		***42.64***

Target P concentration in artificial stormwater		17% Sorbtive® Media Average TP Grams Retained/day	Average TP Grams Retained/week
0.2 mg/L	Week 1	0.09	0.45
	Week 2	0.09	0.45
	Week 3	0.09	0.47
	Week 4	0.16	0.79
	Week 5	0.17	0.84
	Treatment Sum		**2.99**
0.4 mg/L	Week 1	0.37	1.83
	Week 2	0.34	1.70
	Week 3	0.36	1.77
	Week 4	0.33	1.64
	Week 5	0.35	1.72
	Treatment Sum		**8.66**
0.6 mg/L	Week 1	0.52	2.60
	Week 2	0.56	2.77
	Week 3	0.52	2.55
	Week 4	0.53	2.63
	Week 5	0.60	2.95
	Treatment Sum		**13.49**
0.8 mg/L	Week 1	0.81	4.01
	Week 2	0.73	3.61
	Week 3	0.73	3.59
	Week 4	0.75	3.73
	Week 5	0.69	3.43
	Treatment Sum		**18.37**
	Total sum		***43.51***

Appendix 4.

Raw Data for Figure 3-3; Percent removal of total dissolved phosphorus for each bioretention cell at each of four different target phosphorus concentrations

Percent Removal of Total Phosphorus

Sorbtive® Media Within Bioretention Cell (%)	Control (0%)	3%	5%	10%	17%
Target Concentration: 0.2mg/L TDP					
Week 1	76.56	88.70	87.72	91.70	92.73
Week 2	78.05	93.72	56.57	92.41	90.15
Week 3	27.61	89.51	86.73	91.05	90.87
Week 4	32.91	66.67	84.06	91.19	89.35
Week 5	n.m.	n.m.	n.m.	n.m.	n.m.
Average	**53.78**	**84.65**	**78.77**	**91.59**	**90.77**
Standard Deviation	27.25	12.19	14.88	0.61	1.44
Target Concentration: 0.4 mg/L TDP					
Week 1	49.11	95.25	96.51	96.42	96.58
Week 2	40.99	94.88	94.95	90.59	95.92
Week 3	44.78	94.93	96.80	96.82	95.91
Week 4	34.56	94.27	95.06	96.36	96.54
Week 5	35.48	94.09	96.38	95.86	96.68
Average	**40.98**	**94.68**	**95.94**	**95.21**	**96.33**
Standard Deviation	6.16	0.48	0.87	2.60	0.38
Target Concentration: 0.6 mg/L TDP					
Week 1	37.76	96.27	97.60	97.77	97.73
Week 2	28.55	95.66	97.92	97.90	97.91
Week 3	22.00	95.08	97.65	97.74	97.83
Week 4	12.84	91.58	98.37	97.61	98.03
Week 5	16.19	86.89	91.20	92.02	95.35
Average	**23.47**	**93.10**	**96.55**	**96.61**	**97.37**
Standard Deviation	9.98	3.92	3.01	2.57	1.14
Target Concentration: 0.8 mg/L TDP					
Week 1	24.90	89.90	94.98	98.48	98.31
Week 2	22.99	88.49	98.41	98.56	98.50
Week 3	24.25	85.04	97.95	98.28	98.53
Week 4	19.72	84.83	98.12	98.54	98.59
Week 5	10.51	81.87	97.35	98.38	98.37
Average	**20.47**	**86.03**	**97.36**	**98.45**	**98.46**
Standard Deviation	5.92	3.19	1.39	0.12	0.11

- *n.m. = not measured*

Appendix 5

Raw Data for Figure 3-4; Percent removal of total phosphorus for each bioretention cell at each of four different target phosphorus concentrations

Percent Removal of Total Phosphorus					
Sorbtive® Media Within Bioretention Cell (%)	Control (0%)	3%	5%	10%	17%
Target Concentration: 0.2 mg/L TP					
Week 1	n.m.	n.m.	n.m.	n.m.	n.m.
Week 2	n.m.	n.m.	n.m.	n.m.	n.m.
Week 3	45.09	80.28	93.41	88.68	90.39
Week 4	61.34	94.26	94.37	93.52	94.12
Week 5	67.24	94.66	94.47	94.67	94.41
Average	**57.89**	**89.73**	**94.08**	**92.29**	**92.97**
Standard Deviation	11.47	8.19	0.58	3.18	2.25
Target Concentration: 0.4 mg/L TP					
Week 1	60.05	95.90	96.38	67.14	97.45
Week 2	55.54	95.21	95.27	96.38	97.17
Week 3	53.29	95.50	97.23	97.32	97.28
Week 4	52.80	95.04	97.13	97.01	96.99
Week 5	45.27	95.19	96.92	97.22	97.20
Average	**53.39**	**95.37**	**96.59**	**91.01**	**97.22**
Standard Deviation	5.37	0.34	0.81	13.35	0.17
Target Concentration: 0.6 mg/L TP					
Week 1	48.20	95.00	94.83	98.19	96.54
Week 2	38.95	96.60	98.22	98.20	98.24
Week 3	35.51	96.53	98.09	98.40	98.10
Week 4	17.79	92.28	98.02	98.14	98.15
Week 5	28.60	91.37	91.95	97.20	94.79
Average	**33.81**	**94.35**	**96.22**	**98.03**	**97.16**
Standard Deviation	11.40	2.42	2.78	0.47	1.50
Target Concentration: 0.8 mg/L TP					
Week 1	35.06	90.55	92.77	98.27	98.78
Week 2	27.08	85.26	98.20	96.81	98.65
Week 3	26.78	85.85	98.53	98.62	98.64
Week 4	23.18	86.18	98.42	98.65	98.69
Week 5	24.89	84.48	97.69	98.48	98.58
Average	**27.40**	**86.47**	**97.12**	**98.17**	**98.67**
Standard Deviation	4.56	2.37	2.45	0.77	0.08

- *n.m. = not measured*

Centre for Alternative Wastewater Treatment

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The Centre for Alternative Wastewater Treatment (CAWT) at the School of Environmental and Natural Resource Sciences, Frost Campus, Fleming College is an internationally recognized research institute committed to excellence in research and education.

The CAWT conducts research in the areas of water and wastewater treatment science and communicates results in high quality publications. The Centre continues to expand research capacity and productivity over time.

The Centre fosters collaborative research partnerships with universities, government agencies, non-governmental organizations, and the private sector; and engages in opportunities to enhance student learning through the integration of applied research activities in student curricula.

The CAWT provides leadership to Fleming College in the expansion of research and innovation activities in other areas of the College.

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