An exploration in constructed wetlands and EAF steel slag filters:

Combining constructed wetlands and EAF steel slag filters to remove E. coli from a stormwater/wastewater mix

and

Does the type of flow make a difference? Horizontal vs. vertical flow in aerated constructed wetlands

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Abstract

Excess phosphorus inputs to Lake Champlain are causing unwanted algal growth resulting in decreased lake water transparency, odor, and reduced dissolved oxygen levels, while the presence of pathogen-indicating bacteria in the lake cause occasional beach closings. This has implications for both recreational and drinking water uses of the lake. It has been determined that non-point sources of phosphorus, mostly from surface runoff, are responsible for 80% of the phosphorus inputs to Lake Champlain, mostly from agricultural runoff. Pathogenic bacteria are also associated with agricultural runoff – particularly from livestock operations. Simple, low-cost technologies for phosphorus and pathogen removal from stormwater and agricultural wastewater are needed. One such technology is an on-site, combined constructed wetland-EAF steel slag filter system.

This experiment had two levels. In the first level, aerated horizontal flow, aerated vertical flow, and unaerated vertical flow constructed wetlands were evaluated for their pollutant removal efficiencies. In the second level, constructed wetlands in series were compared to constructed wetlands paired with EAF steel slag filters for their E. coli removal efficiencies.

In the first level of treatment, aeration significantly increased removal of DRP, E. coli, NH_3, and BOD. Furthermore, horizontal flow cells removed significantly more TSS than vertical flow cells. In the second level of treatment, wetland-slag systems removed significantly more DRP and E. coli than wetland-wetland systems.

1. Background

1.1 Introduction

Cultural eutrophication and anthropogenic increases in pathogen loading are threats to the health of freshwater bodies and the people that rely on them. In the Lake Champlain basin, urban and agricultural stormwater along with agricultural wastewater have been implicated in this threat (LCBP 2003).

The Lake Champlain Basin, which crosses the borders of Vermont, New York, and Québec, is home to more than 600,000 people, 4000 of which draw drinking water directly from the lake (LCBP 2003). Overloading of phosphorus to Lake Champlain is causing excessive algal growth resulting in reduced water transparency, odor, and reduced dissolved oxygen levels upon algal death and decomposition (LCBP 2003) (Meals and Budd 1998). Furthermore, the presence of pathogen-indicating bacteria in the lake occasionally results in beach closings (LCBP 2003). This has implications for both recreational and drinking water uses of the 1,124 km^2 Lake Champlain (LCBP 2003) (Meals and Budd 1998).

Non-point sources of phosphorus are responsible for 80% of the phosphorus entering Lake Champlain (LCBP 2003). Of the nonpoint sources, agricultural activities contribute 55% of the annual load, even though they use only 15% of the basin's land area (LCBP 2003). A common agricultural activity in the region is dairy farming and pathogen-indicating bacteria have been found in dairy wastewater (Cullor 1995 as in Karpiscak et al. 2001).

A report by the Lake Champlain Basin Program predicted that even after implementing agricultural Best Management Practices on the farms in the Vermont and Québec portions of the basin, the phosphorus loads will still exceed the twenty-year non-point source target for certain portions of the basin (LCBP 2000). The report suggests that meeting reduction targets will require new phosphorus reduction techniques (LCBP 2000). In order to be adopted, these new techniques will need to be both low-cost and low-maintenance so that they will be practical for individual land owners to implement. If a technology could provide the dual service of both phosphorus and pathogen removal, it may reduce wastewater and stormwater treatment steps, increasing cost-effectiveness. Onsite treatment systems combining constructed wetlands with electric arc furnace (EAF) steel slag filters have the potential to become one of these technologies.

1.2 Constructed wetlands

Constructed wetlands are on-site stormwater and/or wastewater treatment systems. They are used in urban areas to treat stormwater runoff while on farms they intercept and treat wastewaters (Knight et al. 2000). Low-cost and low-maintenance, they are easily adopted by agricultural operations (Knight et al. 2000). The major phosphorus removal mechanism within constructed wetlands is by binding to the substratum, since plant uptake contributes to only a small portion of total phosphorus removal (Gottschall et al. 2007) (Drizo et al. 2008). Constructed wetlands have also been found to remove pathogen-indicating bacteria, such as E. coli (Decamp and Warren 2000, Mantovi et al. 2003, Green et al. 1997).

Artificial aeration has been introduced in constructed wetlands to enhance removal of several pollutants, including nitrogen and phosphorus (Jamieson et al. 2003, Tang et al. 2008, Platzer 2000, Ouellett-Plamodon et al. 2006). However, removal of pollutants by aerated horizontal flow versus aerated vertical flow wetlands has not been directly compared.

1.3 EAF steel slag filters

EAF steel slag is a byproduct of steel production. Use of an EAF steel slag filter following a constructed wetland has been shown to significantly increase phosphorus removal when compared with two constructed wetlands used in series (Lee et al. 2009). In addition to simple physical filtration, EAF steel slag filters have physicochemical properties that facilitate phosphorus removal (Drizo et al. 2002, Drizo et al., 2006, Shilton et al. 2005, Weber et al. 2007, Shi 2004). Among a range of materials that have been examined for their phosphorus removal abilities (Mann 1997, Drizo et al, 1999; Johansson 1999, Brooks et al. 2000, Arias et al. 2001, Drizo et al. 2002, Arias et al. 2003, Del Bubba et al. 2003, Forbes et al. 2004, Molle et al. 2005), those best suited for use in phosphorus removal were found to be materials with reactive iron or aluminum hydroxide or oxide groups on their surfaces that adsorb phosphorus, or calcareous materials which can promote Ca phosphate precipitation (Drizo et al. 1997, Johansson 1997, Zhu et al. 1997)**.** EAF steel slag has been found to be rich in both iron and calcium oxides, promoting phosphorus removal (Drizo et al. 2006). Although few potential phosphorus filter materials have been included in a large number of tests of varying character, slag materials have undergone a battery of tests (Westholm-Johansson 2006). In studies of 57 different filter media, EAF steel slag was found to have the highest phosphorus retention capacity (Drizo et al. 2002). In Drizo et al. (2006), EAF steel slag demonstrated a nearly 100% phosphorus removal efficiency over a period of 180 days through the processes of specific adsorption onto metal hydroxides and precipitation as hydroxyapatite.

Furthermore, tests of the effect of EAF steel slag filters on a pathogen-indicating bacteria, E. coli (Bach et al. 2002, Crump et al. 2003, Lynn et al. 1998), at the University of Vermont's Constructed Wetlands Research Center demonstrated an average E.coli removal efficiency of 87.8% during the first 350 days of operation; after a resting period, 78.1% E. coli removal efficiency was demonstrated over 100 days of operation (Drizo, ongoing). No direct comparison of EAF steel slag filters and constructed wetlands in E. coli removal efficiency has yet been carried out.

1.4 Research questions addressed in this study

1) Is there a difference between wetland-wetland systems and wetland-slag systems in E. coli removal?
2) Is there a difference in DRP, E. coli, NH3, TSS, and BOD removal in aerated horizontal flow constructed wetlands compared against to aerated vertical flow constructed wetlands?
3) Can this study replicate previous findings of higher DRP, E. coli, NH3, and BOD removal in aerated constructed wetlands when compared to unaerated constructed wetlands?
4) Can this study replicate previous findings of higher DRP removal in wetland-slag systems when compared to wetland-wetland systems?

1.5 Hypotheses

I hypothesized that:

1) wetland-slag systems would remove more E. coli than wetland-wetland systems
2) there would be no difference in removal of any of the parameters of interest between aerated vertical flow and aerated horizontal flow cells
3) this study would replicate previous findings of higher DRP, E. coli, NH3, and BOD removal in aerated constructed wetlands when compared to unaerated constructed wetlands
4) this study would replicate previous findings of higher DRP removal in wetland-slag systems when compared to wetland-wetland systems

2. Methods

2.1 Experimental design

This study was conducted at the University of Vermont's Constructed Wetlands Research Center in South Burlington, VT. The twelve research cells used in this study (see Figure 1) had a length, width, and depth of 1.7 m, 1.1 m, and 0.5 m, respectively. Cells 1-9 operated as gravel-bed constructed wetlands (porosity = 0.4) with river bulrush (*Schoenoplectus fluviatilis*) growing on 3 cm. of organic soil (Lee et al. 2009). Cells 10-12 operated as EAF steel slag (20-50 mm diameter) filters with a porosity of 0.42 (Lee et al. 2009; Drizo et al., 2006).

Cells 1, 3, 5, and 6 were subsurface vertical flow constructed wetlands; cells 2, 4, 7, 8, and 9 were subsurface horizontal flow constructed wetlands; cells 10, 11, and 12 were subsurface horizontal flow steel slag filters. The horizontal flow constructed cells received an evenly distributed inflow of water across the width of the cell on the inlet side. The vertical flow cells received an inflow of water at the center of the inlet side of the wetland (Lee et al. 2009).

There were two levels of treatment in this experiment, denoted by the two rows in Figure 1. In the first row, the treatments were horizontal flow + aeration (HA), vertical flow + aeration (VA), or vertical flow + no aeration (VNA); the first row contained only constructed wetlands. In the second row, the treatments were either an unaerated horizontal flow constructed wetland (W) or an EAF steel slag filter (S). See Figure 1 below for a schematic of the configuration. This is the same system that was under study in 2007 and 2008 by Lee et al. (2009).

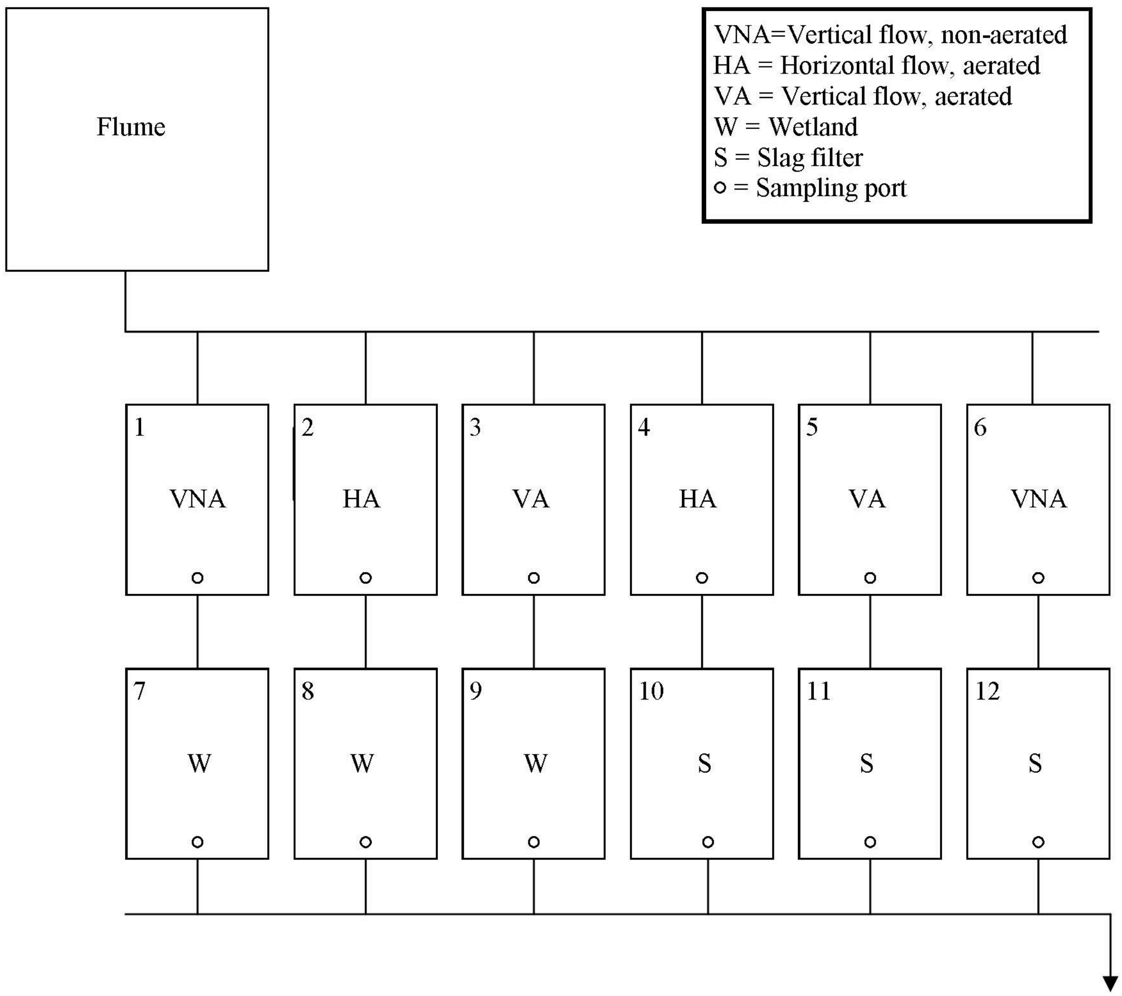

Figure 1. Schematic of the research site. (Not to scale.)

A mixture of dairy barn and milkhouse wastewater along with stormwater runoff collected in a settling pit before passing to the flume. Flow of wastewater from the flume into the research cells was controlled by six Little Giant pumps that were operated such that each cell received the wastewater/stormwater mixture in a pulse flow of .0748 m^3/day. The theoretical hydraulic residence time was 5 days. Pump malfunction was suspected during the last week of the sampling period, so it is possible that new effluent was not delivered to the system during some of that time, allowing an extended hydraulic residence time in the cells.

Aerated cells received air pumped by a GAST (DDL LINEAR HP80-101 115 VAC/60 Hz, 1.8A) pump through flexible plastic tubing that had been lined on the bottom of the cells. Aeration was monitored on-site by checking DO levels each time samples were taken using a Hach LDO HQ10 Portable Dissolved Oxygen Meter. Water temperatures were also measured on-site using the same tool. There were no significant differences in DO between the replicates of each treatment. Aeration had a significant effect on the DO of the cells with aerated cells averaging 0.1 mg O2/L and unaerated cells averaging 5.5 mg O2/L. Among aerated cells, there was a significant ($p=.0026$) difference between vertical flow (DO= 4.9 mg O2/L) and horizontal flow cells (DO=6.1 mg O2/L).

2.2 Sampling

Samples were collected approximately once a week between June 23, 2009 and August 18, 2009, with a total of 11 sample collections. There were seven days between the first and second sampling days and nine days between the second and third sampling days; all other samples were taken five days apart.

The following parameters were measured: dissolved reactive phosphorus (DRP), E. coli, dissolved oxygen (DO), NOx (nitrate + nitrite), ammonia (NH3), total suspended solids (TSS), biological oxygen demand (BOD_5), pH, water temperature, and total phosphorus (TP).

Between sampling and laboratory analysis, samples were stored in plastic bottles in coolers for transport and then they were refrigerated until analysis. All samples were analyzed at the University of Vermont.

2.3 Laboratory Analysis

E.coli bacteria concentration was determined using Colilert reagent and Idexx QuantiTrays (method by Idexx Laboratories Inc.). Samples analyzed for phosphorus were filtered through a 0.45-µm pore size membrane (DRP) or digested (TP) prior to the molybdate - reactive P method (Eaton et al. 2005); the spectrometer used was a Genesys 10vis ThermoSpectronic with Spectronic Unicam. Samples analyzed for NOx and NH3 were analyzed on a Lachat flow meter. BOD_5 analysis was performed according to standard methods (Eaton et al. 2005). TSS was determined by filtering samples through a glass fiber filter and drying at 103-105^{o}C (Eaton et al. 2005). pH was measured in the lab with a standard pH probe.

The data for NOx and TP were discarded due to suspected inaccuracy.

2.4 Statistical Analysis

A one-way ANOVA was used to compare the various treatment combinations. Comparisons were made among first-row cells and between the six systems (system =

first row cell + second row cell). See Appendix A for further discussion of the data preparation for statistical analysis.

3. Results and Discussion

Flume concentrations of all parameters were highly variable (see Table 1). The variability in flume concentrations can be explained by the fact that it receives a mix of milkhouse and dairy barnyard wastewater in addition to stormwater. During periods of higher precipitation, the wastewater is more dilute than during times of low precipitation. Additionally, the herd of cows at the dairy farm decreased from approximately 200 to 30 during the course of the sampling period which is thought to have affected the wastewater concentration.

Table 1. Mean flume concentration and standard deviation of monitored pollutants

	Flume				
	DRP (mg/L)	TSS (mg/L)	E. coli (cfu/100 ml)	NH3 (mg/L)	BOD (mg O2/L)
Average	45.5	318.0	1.6×10^7	69.9	1648.1
Standard Deviation	19.5	91.3	4.1×10^7	22.3	788.4

Table 2. Mean percent removal from flume of monitored pollutants by each cell or system[1,2]

		Mean percent removal (%)				
	Cell or System	DRP	TSS	E. coli	NH3	BOD
First row cell	1 (VNA)	3.8	19.2	-55.5	.2	88.3
		36.6	33.4	429.9	19.4	8.2
	2 (HA)	49.1	51.9	98.8	89.3	98.9
		27.4	30.3	2.4	3.4	.7
	3 (VA)	39.9	-81.2	95.0	88.5	97.5
		30.8	369.4	12.5	5.3	.9
	4 (HA)	60.6	59.5	99.4	93.4	99.5
		22.6	23.5	1.4	3.3	.5
	5 (VA)	39.9	-70.0	98.0	81.4	98.4
		22.6	285.7	2.9	8.4	1.4
	6 (VNA)	6.9	22.2	61.4	10.5	87.1
		28.3	39.3	84.0	28.0	19.6
System	1+7 (VNAW)	9.0	21.2	59.9	19.1	96.8
		33.1	40.1	68.8	24.0	3.7
	2+8 (HAW)	47.1	53.7	60.0	74.6	98.5
		15.9	24.1	75.4	21.5	1.0
		39.8	50.9	96.1	70.5	97.8

	3+9 (VAW)	19.2	27.3	5.1	10.6	2.5
	4+10 (HAS)	99.5	98.0	99.3	77.1	98.7
		.9	2.8	.3	18.3	1.6
	5+11 (VAS)	99.3	97.7	100.0	59.4	95.7
		1.0	97.7	0	23.1	4.2
	6+12 (VNAS)	99.6	97.9	100.0	18.5	97.2
		.4	3.3	0	35.2	1.4

[1]Second row for each cell is the standard deviation
[2]A negative number means that the concentration of the pollutant increased in the cell/system.

3.1 E. coli

Evaluating first row cells, there was not a significant difference in E. coli removal between the replicates for any of the treatments. Among aerated first row cells, the type of flow did not significantly affect E. coli removal (VA = 96.5%, HA=99.1%, p=.965). Among all first row cells, there was a significant (p=.0442) difference in E. coli removal by aerated (97.8% removed) cells when compared with unaerated (2.95% removed) cells.

Assessing system performance, there were no significant differences in E. coli removal among the three wetland-wetland systems or among the three wetland-slag systems. There was a significant (p= .0097) difference between the E. coli removal of the wetland-wetland systems (72% removal) when compared with the wetland-slag systems (99.8% removal). None of the systems seem to be particularly sensitive to the influent concentration in their removal efficiencies (Figure 2). The wetland-slag systems exhibited less variability in E. coli removal than the wetland-wetland systems (Figure 3).

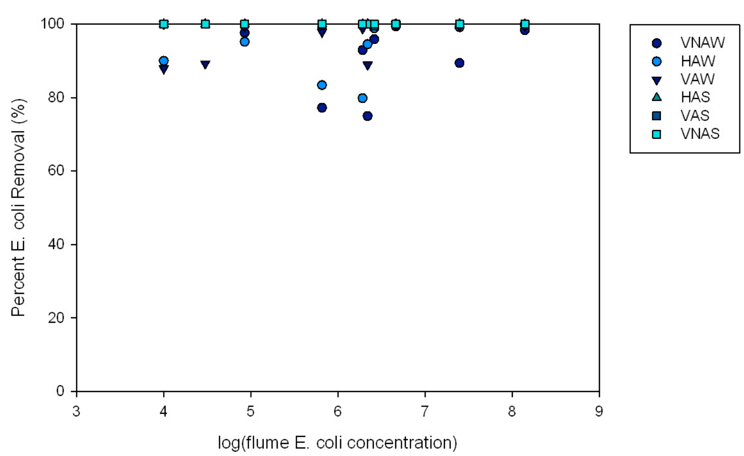

Figure 2. Percent E. coli removal as a function of influent E. coli concentration

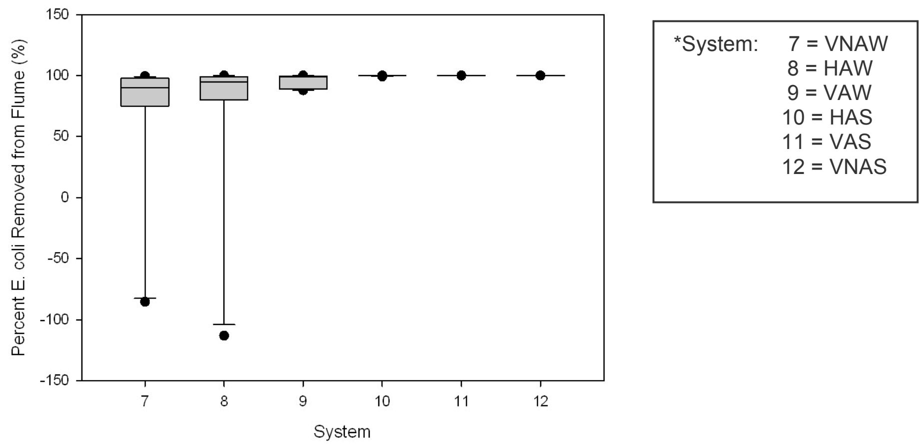

Figure 3. Variability in E. coli Removal by the Six Systems*

The high E. coli removal of wetland-slag filters is attributed to the elevated pH levels in the slag cells (See section 3.6 for further discussion). Further pairwise comparisons of individual wetland-wetland and wetland-slag systems revealed that the difference between HAW (60%) and HAS (99.3%) was significant (p=.0298), the difference between VNAW (59.9%) and VNAS (100%) was significant (p=.0333), but the difference between VAW (96.1%) vs. VAS (100%) was not significant (p=.8284). So, overall, wetland-slag systems removed approximately 25% more E. coli than wetland-wetland systems however those systems which had an aerated vertical flow cell in the first row removed similar amounts of E. coli regardless of whether the second-row cell was a constructed wetland or a slag filter.

3.2 DRP

The effluent from cells 1, 6, and 7 sometimes exhibited a higher DRP concentration than the flume – so there must be a source of phosphorus in the wetlands that is mobilized, perhaps through the process of desorption from sediments or gravel within the cell.

In evaluating the first-row cells, there was not a significant difference in the DRP reduction between the two replicates of any of the treatments (HA, VA, VNA). Among the first-row cells, there was not a significant (p=.0909) difference in DRP reduction between VA (39.9% removal) and HA cells (54.9% removal). In a comparison of all aerated with all unaerated cells, aeration made a significant (p< .0001) difference in DRP reduction with aerated cells removing 47.4% DRP and unaerated cells removing 5.4% DRP. So, evaluating first row wetland cells individually, aeration significantly increased DRP removal while the type of flow (horizontal vs. vertical) did not.

Assessing system performance, there was a significant (p< .0001) difference in DRP removal between the three wetland-wetland systems (32.0% removal) compared against the three wetland-slag systems (99.5% removal). So, wetland-slag systems exhibited a removal efficiency that was greater than three times that of wetland-wetland systems.

3.3 TSS

Looking at the first-row cells, there was not a significant difference in TSS reduction between the replicates for each treatment. Additionally, aeration did not create a significant difference in TSS reduction among first row cells. However, among aerated cells, the type of flow significantly ($p=.0376$) affected TSS reduction with horizontal flow cells removing more TSS than vertical flow cells. On average, HA cells removed 55.7% TSS while VA cells removed -75.6% TSS (meaning that TSS was generated in the cell).

Considering system performance, wetland-slag systems removed significantly ($p< .0001$) more TSS than wetland-wetland systems (97.9% and 41.9% removal respectively).

3.4 NH3

There was no significant difference in NH3 reduction among the replicates for each treatment. There was no significant difference in NH3 reduction between HA and VA cells ($p=.2185$). Among all first-row cells, aerated cells (88.2% removal) removed significantly ($p< .0001$) more NH3 than unaerated cells (5.4% removal).

In evaluating system performance, there was a significant ($p=.048$) difference between the wetland-wetland systems (54.7%) when compared with the wetland-slag systems (51.7%). However, although this difference was statistically significant, it is so small (3%) that it may not be operationally relevant.

3.5 BOD

When looking at the first-row cells, there was not a significant difference in BOD removal between the two replicates for each treatment. Among aerated first-row cells, there was no significant difference between horizontal and vertical flow cells in BOD removal ($p=.6339$). Among all first row cells, aeration significantly ($p=.0001$) increased BOD removal with aerated cells averaging 98.6% removal and unaerated cells averaging 87.7% removal.

In evaluating system performance, there was no significant difference between wetland-wetland and wetland-slag systems.

3.6 pH

In evaluating the first-row cells, there were no significant differences in pH among the replicates for each treatment. Among aerated cells, the type of flow – vertical (pH=7.6) or horizontal (pH=8.0) – made a significant difference in pH ($p= < .0001$). Among vertical flow cells, aeration made a significant difference ($p= < .0001$) with an average pH of 7.6 for the aerated cells and 6.9 for the unaerated cells.

In looking at system pH, wetland-slag systems (pH=11.5) had a significantly ($p < .0001$) higher pH than wetland-wetland systems (pH=7.1). The elevated pH in the wetland-slag systems is attributed to the release of hydroxide ions during the reaction of the orthophosphate in the dairy wastewater with the calcium oxides in the EAF steel slag (Lee et al. 2009).

4. Conclusions

This study found that EAF steel slag filters can be used as a secondary level of treatment after constructed wetlands to significantly increase E. coli removal.

This study also found that the type of flow (horizontal vs. vertical) does not significantly affect DRP, E. coli, NH3, and BOD removal in aerated constructed wetland cells. Unexpectedly, this study found that aerated horizontal flow constructed wetlands remove significantly more TSS than aerated vertical flow constructed wetlands.

This study confirmed that wetland-slag systems remove significantly more DRP than wetland-wetland systems. Surprisingly, this study found that wetland-slag systems remove significantly more TSS than wetland-wetland systems.

This study also confirmed that DRP, NH3, and BOD removal is significantly higher in aerated than unaerated constructed wetlands. Aeration did not affect TSS removal in constructed wetlands.

Although this study focused on a dairy farm application of constructed wetlands and EAF steel slag filters in the Lake Champlain basin, these technologies can be adapted outside of the Lake Champlain basin and outside of dairy farm applications. Urban stormwater filtration is one such application. One challenge in urban areas will be designing systems with the necessary hydraulic residence time for filtration to occur even during flashy, higher intensity storms. Furthermore, with the growth of urban farming, these technologies may find an application treating agricultural wastewater within an urban setting.

5. Future Study

In the long-term, any EAF steel slag filter will not be sustainable for phosphorus removal without the exchange of the slag material upon reaching P retention capacity (Weber et al. 2007). Thus, wide-spread use of EAF steel slag systems will be dependent on the ability to reuse or dispose of the phosphorus-rich, spent EAF slag in an environmentally appropriate manner (Weber et al. 2007). Bird and Drizo (2008) recently investigated the re-use potential of saturated EAF steel slag material and showed not only that phosphorus adsorbed by slag is bio-available, but also that adsorbed phosphorus does not leach to the environment.

Drizo et al. (2008) recently showed that initiating a resting period prior to the filter reaching phosphorus saturation can increase the filter’s phosphorus retention capacity by between 40 and 50 percent. Similarly, in an 18-month box experiment conducted in part of a full-scale horizontal flow constructed wetland, resting periods regenerated the material's phosphorus sorption capacity by 22-53% (Adam et al. 2005). It has been suggested that filter rejuvenation could prolong life expectancy and increase cost efficiency, making full-scale applications of EAF steel slag filters a more feasible option for land managers (Drizo et al. 2008). There have not been any studies on the E. coli removal limits of EAF steel slag filters. Further study is needed in both these areas.

A barrier to widespread adoption of this technology is the elevated pH of the effluent from EAF steel slag filters. The pH was elevated not only in this study but also in Weber et al. (2007) in which effluent from EAF steel slag column tests had a pH of around 11 for the initial two months of operation before falling below 9. If high pH level were to persist in a full-scale application, a pH reducer unit may be necessary to keep the pH below the U.S. Environmental Protection Agency's effluent discharge limit of 9 (U.S. EPA 2006) (Weber et al. 2007). Naylor et al. (2003) demonstrated the pH reduction capability of a gravel and peat moss unit used in conjunction with a slag filter. Additionally, long term study conducted over a period of 850 days by Drizo et al. (2008) showed that aside from an initial two weeks of filter establishment – both at the beginning of filter use and after resting – pH levels remained below 9. Further study on the persistence of elevated pH levels is needed.

6. Appendix A

When analyzing pollutant removal efficiency in the research cells, it is important to consider that because filtration is not instant, the outlet samples from each research cell do not necessarily reflect the inlet (flume) samples of the same day but rather of several days prior (Kadlec 2000 as in Lee et al. 2009). The hydraulic residence time is a reflection of this time period. Pollutant removal efficiency analysis is further complicated because flow through a constructed wetland or steel slag filter can take multiple paths with varying retention times (Kadlec 2000 as in Lee et al. 2009), rendering the actual hydraulic residence time different from the theoretical hydraulic residence time.

Two methods of data preparation for statistical analysis were considered to deal with this difficulty. They are compared below. Method 1 (M1) was used in this paper. Statistical analysis using Method 2 (M2) will be completed in the spring 2010 semester.

Table 3. Mean percent removal (%) from flume: comparison of two methods[1] of calculation

Research cells	DRP		TSS		ECOLI		NH3		BOD	
	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2
1	3.8	20.7	19.2	83.7	-55.5	76.8	0.2	2.5	88.3	89.3
2	49.1	54.5	51.9	92.5	98.8	100.2	89.3	88.9	98.9	99.2

3	39.9	46.3	-81.2	-8.7	95.0	99.8	88.5	87.7	97.5	97.9
4	60.6	63.8	59.5	93.5	99.4	99.8	93.4	92.9	99.5	99.4
5	39.9	49.8	-70.0	87.3	98.0	98.9	81.4	80.6	98.4	98.9
6	6.9	15.1	22.2	87.3	61.4	88.5	10.5	14.5	87.1	97.1
7	9.0	19.1	21.2	86.6	59.9	96.6	19.1	24.7	96.8	98.0
8	47.1	50.3	53.7	92.7	60.0	99.4	74.6	74.9	98.5	98.9
9	39.8	45.3	50.9	92.3	96.1	99.3	70.5	71.1	97.8	98.6
10	99.5	99.6	98.0	98.9	99.3	100.0	77.1	77.9	98.7	99.0
11	99.3	99.5	97.7	98.7	100.0	100.0	59.4	61.4	95.7	97.0
12	99.6	99.6	97.9	98.7	100.0	100.0	18.5	25.7	97.2	97.8

[1]In Method 1, the assumption was that on each sampling day, the flume composition was representative of the flume composition that entered the research cells several days earlier. The analysis steps for each parameter involved:

- finding the difference between the flume concentration (as measured on the sampling day) and each research cell concentration
- calculating this "change from the flume" as a percent of the flume (as measured on the sampling day) for each sampling day (the one-way ANOVA was performed on these numbers)
- finding a mean cell removal (in Table 3) by averaging the percentages for all the sampling days for each cell

In Method 2, the assumption was that on the sampling day, the flume composition was NOT representative of the flume composition that entered the research cells several days earlier. The analysis steps for each parameter involved:

- averaging the concentrations of all the sampling days for the flume and for each research cell
- finding the difference in concentration between the mean flume concentration and the mean research cell concentration
- expressing this difference as a percentage (percent reduction from the flume); this is the mean cell removal (in Table 3)

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