Does Biochar Improve Stormwater Pollutant Removal?

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Abstract

This paper summarizes initial findings from a monitoring study evaluating the potential for a Biochar additive to improve pollutant removal in bioretention practices. The results are from an ongoing monitoring study, and the goal to both draw initial conclusions and identify potential issues with the monitoring design in order to guide the remaining data collection. Bioretention practices remove pollutants from stormwater runoff by filtering pollutants and by reducing the volume of stormwater runoff by promoting infiltration into the soil surface, and this study is attempting to evaluate the impact of a Biochar additive on the filtering ability of the practices. The pollutants of focus in this study include Suspended Solids (TSS), Total Phosphorus (TP) and Nitrate-Nitrite Nitrogen (NOx). Data collected include the concentrations of these pollutants at both the inflow and outflow of each practice as well as a total flow measurement (in m^3) at the inflow and outflow.

Initial results are somewhat surprising, in that they suggest that the concentrations at the outlet of the Biochar practice are actually higher for two pollutants (NOx and TP), and that biochar has no effect on TSS. Closer inspection suggests that there may be a correlation between flow volume and outflow concentration for TP. Due to an issue in the study design, a greater flow volume is directed to this practice. The positive correlation between the TP concentration and flow volume may partially explain why we are seeing higher TP concentrations at the Biochar outlet.

Another interesting finding related to the ability of the practices to reduce the volume of runoff by promoting infiltration. Although the median flow reduction was negligible, and the practices appeared to actually export flows for many storm events, a closer look at the data suggests that flow reductions are significant for larger runoff events.

Introduction

Stormwater runoff from urban land is a significant contributor of pollution from urban areas. In the Chesapeake Bay Watershed, nutrients (i.e., nitrogen and phosphorus) and sediment have caused degradation of this resource. Nutrients act as a food source for algae which then degrade and cause oxygen to be depleted from the water column, resulting in a dead zone where fish and other aquatic life cannot survive. Sediment, which is measured as Total Suspended Solids, causes degradation by physically altering habitat in the Chesapeake Bay and its tributaries. In addition, sediment in the water column often transports other pollutants that can harm aquatic ecosystems.

The most recent data from the USGS suggest that, while the amount of nutrients and sediment generated by urban land has decreased on a unit basis (i.e., pounds per acre of urban land), this reduction has not kept pace with the rate of development in the watershed. Thus, it is critically important to find measures to improve treatment of runoff from urban lands.
Stormwater Bioretention (Figure 1) is a common and highly effective method of treating stormwater runoff. The practice is essentially a depressed landscaping area, which allows runoff to percolate and be filtered through the engineered soil layer. Some of the water enters the natural soil beneath the practice, but often a perforated pipe captures the remainder of the filtered stormwater, which is then piped to the storm drain system, and ultimately to a stream or other natural water.

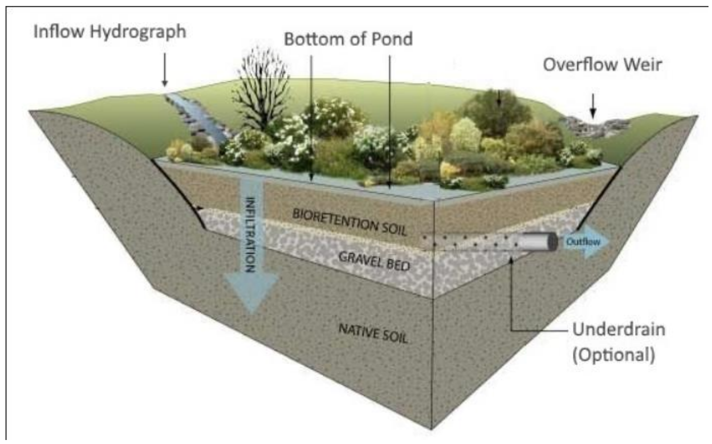

Figure 1. Stormwater Bioretention Schematic

These practices are effective at removing nutrients and other pollutants from stormwater runoff, but their performance can be highly variable depending on the design. Modifying the soil layer by incorporating certain additives is one potential method to improve the soil's ability to absorb pollutants. Biochar, which is a form of charcoal formed by a process known as pyrolysis is currently being investigated as a potential soil additive. Initial laboratory studies show promise for removing a wide range of stormwater contaminants (Reddy at al., 2014), and some field tests have shown potential for removing selected pollutants. For example, an initial field study in the Pacific Northwest shows some promise for removing zinc in a highly contaminated boatyard environment (PPRC, 2014).

Although adding biochar to a soil matrix appears may improve pollutant removal by stormwater Best Management Practices (BMPs), including bioretention, from contaminated stormwater runoff, there has been very little study to date to quantify these impacts. Furthermore, studies to date have either been laboratory bench studies rather than field studies, and have not focused on nutrients (i.e., nitrogen and phosphorus) or sediment removal.

Although the primary focus of this study is to quantify the benefits of biochar, an ongoing debate in the stormwater field is how the performance of any stormwater BMPs should be measured. Most state standards and regulations require practices to meet a specific *efficiency* such as an 80% removal of a specific pollutant. However, some researchers suggest that pollutant concentrations at the outlet of any practice have no relationship to the inflow concentration. Thus, they suggest that practices should be characterized by the concentration at the outflow alone, and not expressed as a % removal. In 2004, a large-scale analysis of available studies found that the raw outflow and inflow concentration data was much less variable than the combination of these data into percentages (Strecker et al., 2004). Thus, this study attempted to evaluate practices both in terms of the removal (%) and the raw differences in outflow concentrations.

Finally, the overall goal of these practices is to reduce the total amount of pollutant load (in kilograms) reaching our waterways. Thus, a practice that reduces outflow concentrations for large storm events (with corresponding large runoff volumes), will have a greater impact than one that is effective only for small runoff volumes. This study also attempted to measure stormwater flows, so that the effectiveness at reducing total pollutant loads (measured as flows times concentration) could be better understood.

The analysis reported in this report is part of an ongoing study designed to monitor stormwater practices at two locations. Key questions we seek to address include the following:

1) Does adding biochar to a bioretention practice change its ability to reduce pollutant concentrations?
2) Is the concentration at the inlet of the practice a good predictor of the flow at the outlet? This will help us understand if expressing practice performance as a percent removal is appropriate.
3) Is the concentration influenced by the flow at the outlet? If the concentration is not constant, and not directly related to inflow concentrations, there could be an effect of “flushing” pollutants from the practice during large storm events.
4) When we combine flow and concentration data (i.e., multiply these factors), do we see a different load reduction at the biochar site?

Methods

Study Design and Site Selection

This study uses a “matched pairs” design. In this case, the pairs are bioretention practices of identical design, except that the “Biochar” practice has a biochar additive to the soil media, while the “Control” practice does not have this additive. In addition, each practice in the treatment pair treats runoff from the same parking lot. This pairing is designed to reduce the sources of difference between the control and the treatment (i.e., biochar) practices.

In the overall study, two sites were selected in Howard County, Maryland. Both sites are parking lots, and both the biochar and the control practices were designed to capture a similar area from the parking lot. The two sites, Bethel and Diamond Hills, are at different stages in the monitoring process, and consequently are discussed separately here. While paired monitoring has been conducted for 17 storms at the Bethel site, monitoring at the Diamond Hills site has just begun on the control practice. Thus, we discuss the data collected to date at the Diamond Hills site, but focus on the Bethel site when evaluating the effects of biochar.

Monitoring Methods and Challenges

Monitoring data collected at these sites included rainfall, and both flow and pollutant concentrations at the inflows and outflows of the practices (See Table 1 for a summary). At the outset of the study, the goal was to collect a minimum of 30 paired samples at each site to include the data described in Table 1, and the Maryland Department of the Environment (MDE) requires a minimum of twenty samples to consider new technologies for approval as a stormwater management technology. Issues with monitoring equipment and a very long dry period in 2017 has created some challenges in collecting paired data. Some of these challenges included the following:

1) The rain gages at both sites malfunctioned for a very long period in 2017, resulting in very few samples that include both rainfall depth and flow measurements. In this paper, we will not discuss rainfall depth, but future monitoring at these sites should continue to collect rainfall data.
2) Due to site constraints at the Bethel site, one of the practices (the Biochar practice) receives more runoff than the control practice. We attempt to address this issue by considering how flow volumes affect outflow concentrations.
3) There were some storms for which the flow monitoring devices malfunctioned. Thus, there are some storms for which we have concentration data but do not have corresponding flow or volume data.
4) At the Diamond Hills site, the Control practice was started later, and thus these data are not yet available.
5) Some of the forms of nitrogen and phosphorus monitored fell below the detection limit for a large number of storms. Consequently, this analysis focuses on one measure of each pollutant: Total Phosphorus (TP) for Phosphorus, Nitrate-Nitrite Nitrogen (NOx) for Nitrogen and Total Suspended Solids (TSS) for Sediment.

Statistical Methods

This analysis was completed using classical statistical methods and the generalized linear model. We used the following specific analyses:

1) Linear regression using log transformed variables, quadratic variables, and Boolean Variables
2) ANOVA to compare the significance of specific factors in understanding outflow data.

Although multiple data points were collected from each practice, each storm event was treated as discrete and independent. Concentrations and flows at the outflow were uncorrelated to previous events, and we were unable to detect any trend or autocorrelation in the data.

Results

Data Overview

A brief overview of the data (N, median value) is provided in Table 1. Although a total of 17 storms were monitored at the Bethel location, fewer data points are available for each pollutant, due to issues with sample collection or laboratory methods. In particular, the TSS laboratory monitoring protocol required sufficient volume and a preserved sample.

Table 1. Summary Statistics for All Storm Events

Parameter	Bethel Biochar	Location	N	Median
NOx (mg/L)	Bethel Biochar	Inflow	16	0.42
		Outflow		0.29
	Bethel Control	Inflow	13	0.40
		Outflow		0.26
	Diamond Hills	Inflow	14	0.31
		Outflow		1.25
TP (mg/L)	Bethel Biochar	Inflow	16	0.05
		Outflow		0.08
	Bethel Control	Inflow	13	0.05
		Outflow		0.07
	Diamond Hills	Inflow	13	0.12
		Outflow		0.05
TSS (mg/L)	Bethel Biochar	Inflow	7	4
		Outflow		6
	Bethel Control	Inflow	9	3
		Outflow		5
	Diamond Hills	Inflow	9	4
		Outflow		2
Flow Volume (m^3)	Bethel Biochar	Inflow	11	0.73
		Outflow		0.76
	Bethel Control	Inflow	11	0.07
		Outflow		0.14
	Diamond Hills	Inflow	NA	NA
		Outflow		NA

Part 1: Review of Concentration Data

In this section, we review the concentration data alone, addressing the following two questions:

1) Does adding biochar to a bioretention practice change its ability to reduce pollutant concentrations?
2) Is the concentration at the inlet of the practice a good predictor of the flow at the outlet?

To begin with, we developed box plots of Inflow and Outflow concentrations for each parameter. The initial results were quite surprising. At the Bethel Site, which has both a biochar and a control site, the biochar appears to have higher outflow concentrations for both TP and TSS (Figure 2). In addition, the inflow concentrations for both of these parameters appeared to be slightly higher at the outflow than at the inflow. The results for NOx are not as clear from this box plot, but there is no obvious reduction at first glance. At the Diamond Hills Site, which currently has no control data, the results are also not what was expected (Figure 3). While the median TSS concentration does appear lower at the outfall, the median NOx concentration appears higher at the outlet. These data also seem to indicate that there are a few outlier values that may need to be addressed, either by using nonparametric statistical methods, transforming variables, or possibly removing values from analysis.

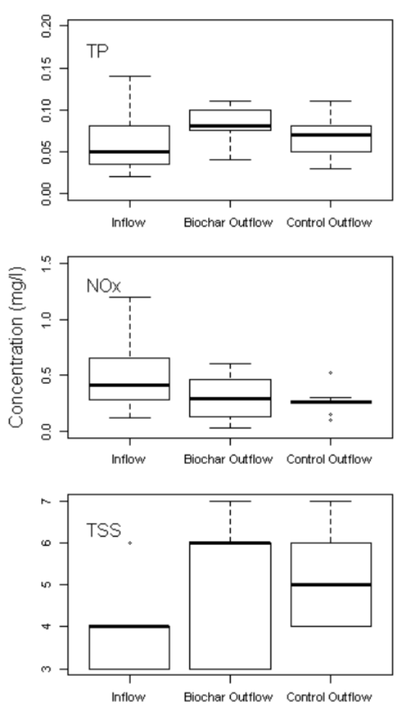

Figure 2. Concentrations at Bethel with Some Outliers Removed

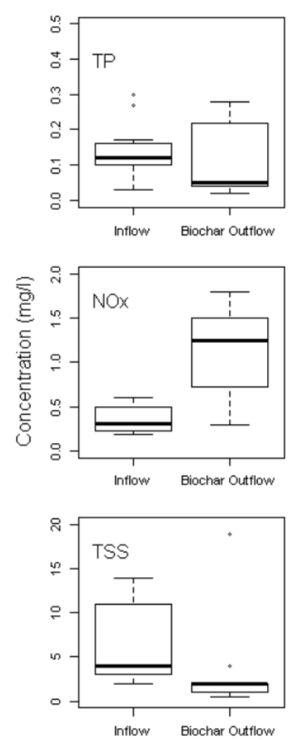

Figure 3. Concentrations: Diamond Hills with Some Outliers Removed

Statistical Analysis: Comparison of Outflow Concentrations for Paired Data at the Bethel Site

As Table 1 indicates, the number of storms recorded for the control practice is not the same as the number of storms for the biochar practice. This discrepancy occurred due to issues such as problems collecting a sample, or insufficient flow volume at one practice. In order to directly compare the outlet concentrations, we completed a paired t-test comparing the biochar and control outlet concentrations. Using the Anderson-Darling test of normality, we concluded that the difference between biochar and control is normally distributed for each parameter (p=0.07 for TP, and 0.38 for NOx. For TSS, the sample size was small (only 5), so we were not able to use the Anderson-Darling test of normality. Instead, we used the Shapiro-Franklin test of normality, with a resulting p-value of almost 1.0. Consequently, we decided to use the paired t-test to compare outflow concentrations for the Control versus the Biochar practice. The results (See Table 2), suggest that, while the outflow concentrations are higher for the Biochar practice, the differences are not statistically significant at the 5% significance level. However, the TP concentration *is* significant at the 10% significance level.

Table 2. Paired t-test Results for Biochar versus Control

Parameter	Mean Difference (Biochar-Control)	DF	t-value	p-value
NOx	0.03	11	0.54	0.60
TP	0.02	11	1.90	0.08
TSS	0.2	4	0.19	0.86

Although these initial results are not encouraging since biochar appears to be performing slightly worse than the control practice and the inflow concentrations are on average lower than outflow concentrations, one potential issue may be that these sites have quite low concentrations for these pollutants. For example, a typical phosphorus concentration in urban runoff is about 0.3 mg/L (Pitt et al., 2004), but the median inflow concentration at the Bethel site is much lower (almost 0.05). It is possible that these concentrations are so low that the filters cannot remove the pollutants.

To give some insight into how inflows and outflows are related, we plotted inflow versus outflow concentrations (Figure 4). Since monitoring has just begun at the Diamond Hills site, and there are some very high outlier values that could possibly be attributed to a construction issue, we focused on data from the Bethel Site for the remainder of the analyses of concentration data.

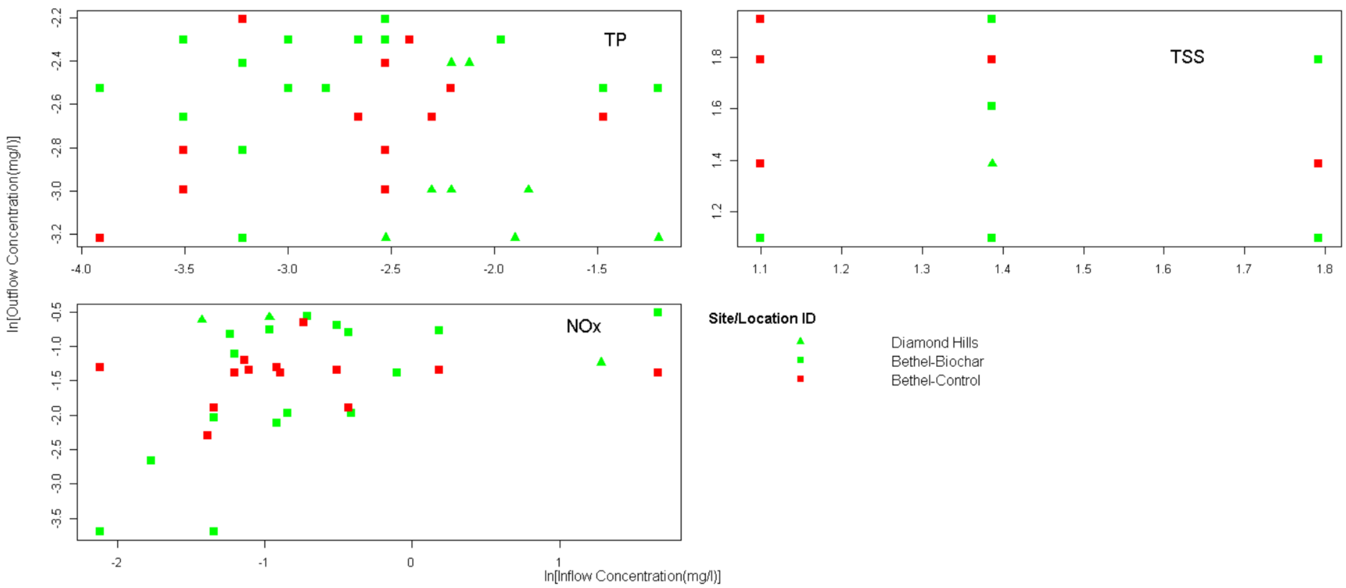

Figure 4. Log-Transformed Concentration Data (Inflow vs. Outfall) at Bethel.

We used the data plotted in Figure 4 to test the following two hypotheses for each pollutant:

1) Is there a significant relationship between Inflow and Outflow Concentration at 10% confidence level?
2) Is there a significant difference between the Control Biochar practice, after controlling for the influence of the inflow concentration at the 10% confidence level?

In order understand these relationships, developed a linear regression of the log-transformed variables for each parameter. We tried several model options for each parameter, starting with a model that included variables for both the practice type (Biochar vs. Control) and the Inflow Concentration, as well as an interaction term between the two. We then used Stepwise Backward Regression to select the best model for each parameter. Summary Data of Each model (from R) are presented in Table 3.

Table 3. Models of Log-Transformed Outflow Concentration Data and ANOVA

Outflow Parameter	***Factor***	***Coefficient***	***F-Value***	***DF (residuals)***	***p-value***
ln(TP)	ln(Inflow)	0.156	1.95	26	0.075
	Control[1]	-0.2444	-2.20		0.037
Ln(TSS)	No Significant Relationships Found				
Ln(NOx)	Ln(Inflow)	0.754	8.36	25	0.008
	Control	-0.374	0.368		0.549
	Ln(Inflow)*Control	-0.697	5.49		0.027
1: The “Control” factor is a dummy variable that identifies the Control Practice					

These results suggest the following conclusions:

1) For this experimental set-up, we find a significant positive relationship between inflow and outflow concentrations for both Total Phosphorus (TP) and Nitrate-Nitrite(NOx).
2) For both TP and NOx, it appears that the Control practice (no biochar) actually has a lower concentration than the Biochar practice at better than the 5% significance level, once we control for inflow concentrations.
3) For NOx, there is also a significant interaction term between the Inflow Concentration and the BMP Type. This term implies that, for the Control BMP, the slope between the Inflow Concentration and the Outflow Concentration is smaller.
4) For TSS, we can find no relationship between the inflow and outflow concentrations, and can also find no significant difference between the Biochar and Control practice.

Part 2: Review of Flow and Concentration Data

Here, we evaluated both Flow and Concentration Data to answer the remaining research questions, including:

3) Is the concentration influenced by the flow at the outlet? If the concentration is not constant, and not directly related to inflow concentrations, there could be an effect of “flushing” pollutants from the practice during large storm events.
4) When we combine flow and concentration data (i.e., multiply these factors), do we see a different load reduction for the biochar practice?

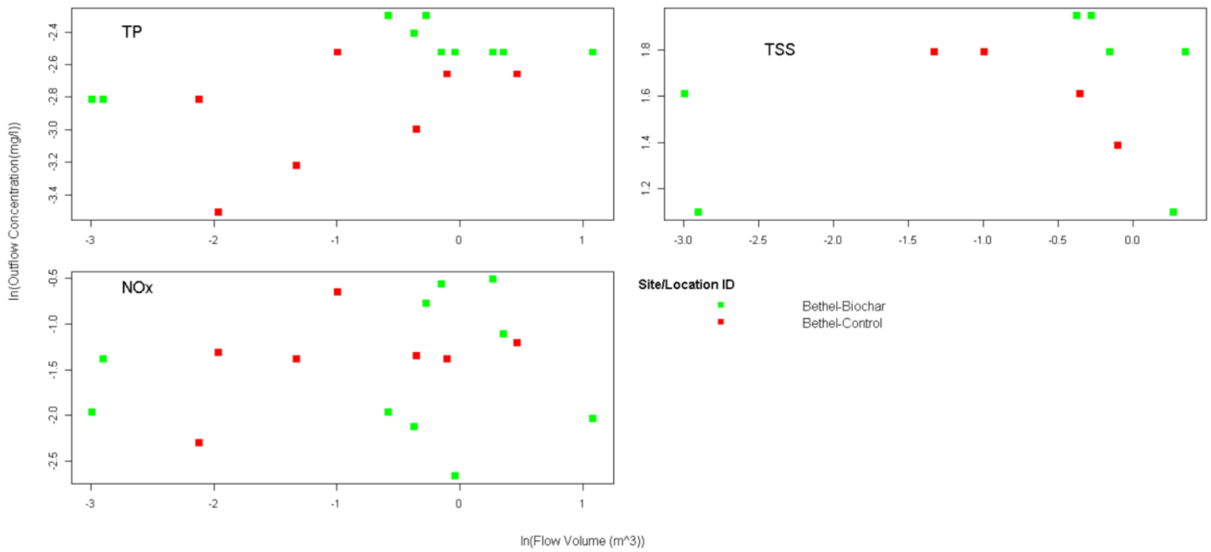

Figure 5. Outflow Flow Volume vs Outflow Concentration

The plots seem to indicate that there may be a correlation between TP Concentration and Flow at the outlet. Interestingly, this is one parameter for which we found a significant difference between the Control and the Biochar practice. We also find in this figure that the Biochar concentration appears to be higher at every comparable level of outflow. Another interesting note in this plot is that the flow volumes for the Control site are generally lower than those for the Biochar Site. Note that the two low flow values observed at the Biochar site coincide with events for which there was no outflow at the Control site. This difference resulted from a construction issue, which resulted in a larger volume of water being diverted to the Biochar practice. Another important observation here is that the number of events where both flow and concentration are observed much lower than the number of events where concentration alone is observed.

We did not find any relationship between outflow volume and concentration for TSS, but did find a relationship for TP (See Figure 6) We also found that (when accounting for outflow volumes), we continue to find a statistically significant difference between the control and biochar practice for TP.

```
Call:
lm(formula = logTP ~ logVolume + BMP)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.47156 -0.10622 -0.01149  0.15645  0.39508 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept) -2.46112    0.07662 -32.121 1.62e-14 ***
logVolume    0.11750    0.04849   2.423  0.02953 *  
BMPControl  -0.34286    0.11298  -3.035  0.00891 ** 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2266 on 14 degrees of freedom
Multiple R-squared:  0.5587,	Adjusted R-squared:  0.4956 
F-statistic: 8.861 on 2 and 14 DF,  p-value: 0.003262
```

Figure 6. Relationship between Log (TP) and Log (Outflow Volume)

The final question, which relates to the combination of inflow volumes and concentrations, is not possible to answer given both the amount of data currently available and the difference in flows reaching the Control versus the Biochar site. However, in order to answer this question, we also need to understand if either of the practices (Control or Biochar) is successfully reducing the flow volume between the inflow and the outflow. Thus, we simply compare the volume of flow at the inflow and outflow. The boxplot of the associated flow reduction (Figure 7) shows a median flow reduction of almost 0.

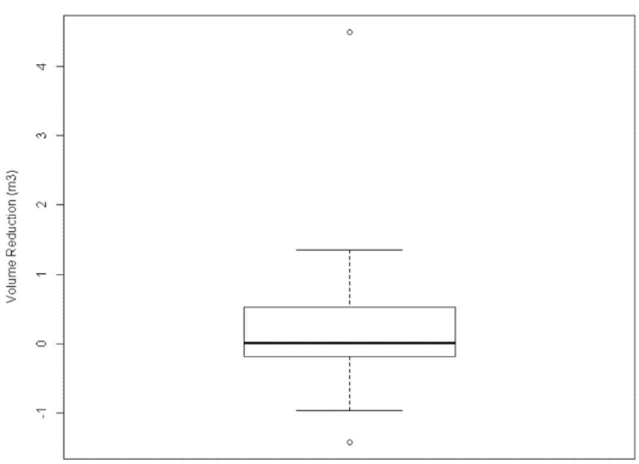

Figure 7. Box Plot for Volume Reduction

One potential issue that can explain this apparent failure to reduce flow volume is that flow monitoring equipment may not be very reliable for very small storm events. We were curious if the apparent *flow increase* data could be related to the difficulty in this measurement. In particular, we thought that perhaps the flow reduction was higher for the larger storm events. To test this hypothesis, we plotted the Flow Reduction Volume versus the Inflow Volume. The results suggest that the larger storm events had more volume reduction (Figure 8).

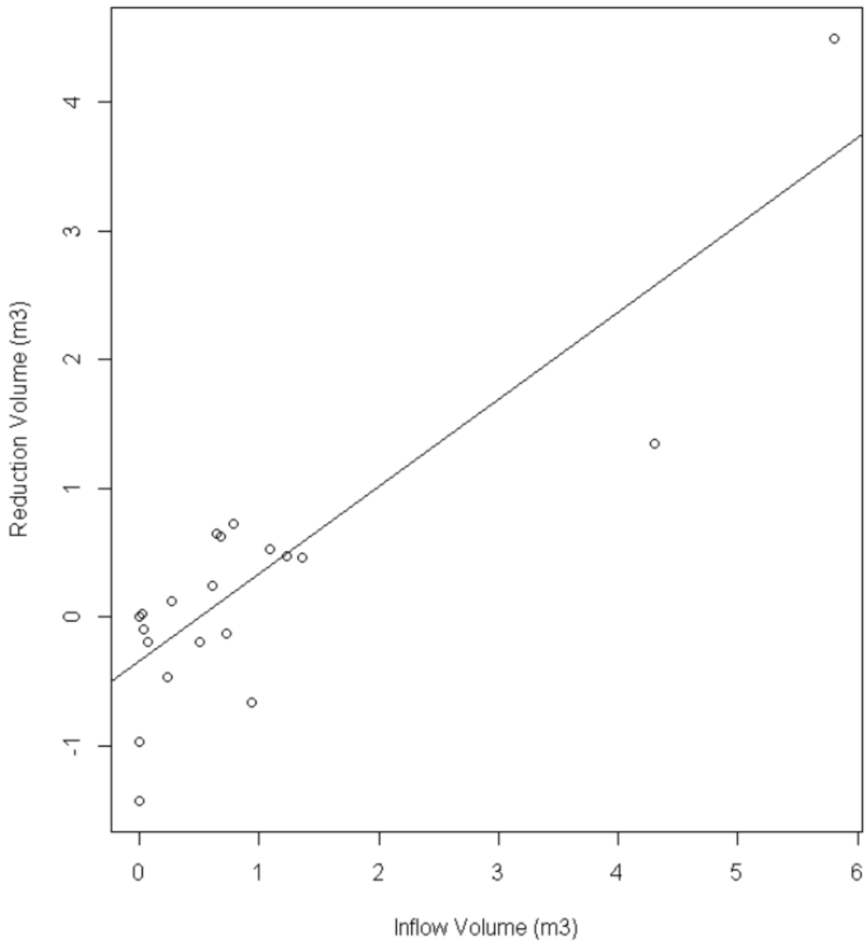

Figure 8. Inflow Versus Runoff Reduction at Bethel.

The resulting equation is of the form:

Reduction= 0.676x(Inflow Volume)-0.340

This is a very strong regression with a p-value of almost 0 and an Adjusted R-SQ of 0.74.

Thus, while we are not able to draw conclusions at this point regarding whether the total pounds of reduction are different between the Biochar and the Control practices, we have identified a trend, wherein our greatest volume reduction will be achieved for larger storm events.

Discussion

This study is not able to draw definitive conclusions regarding the impact of biochar on pollutant removal in bioretention practices. An initial review of the data suggests that, accounting for inflow concentration alone, a practice amended with biochar has worse pollutant removal than a similar practice without the biochar amendment. However, this finding did not account for a difference between the Control and the Biochar site, which was that a greater flow volume was directed to the Biochar site. When we evaluated the impacts of the flow volume on outflow concentration, we found that there was a significant positive relationship between flow volume and concentration for Total Phosphorus. We could not find a similar relationship for other pollutants, however.

As a part of this evaluation, we investigated the relationship between the concentration at the inflow of each practice, and the resulting outflow concentration. While previous research has suggested that inflow and outflow concentrations may be unrelated, we found significant relationships between inflow and outflow concentrations for both TP and NOx. This finding is significant, as it helps us to understand how to describe the effectiveness of a practice (i.e., as a percent or by a single outflow concentration).

We also evaluated the ability of bioretention practices (both Biochar and Control taken together) to reduce the volume of flow by promoting infiltration. The initial result was quite surprising, as it suggested that the practices may actually be *exporting* additional flow for many of the runoff events. However, we found that the flow reduction is much more significant for larger storm events. It is unclear if this pattern is due to difficulties in monitoring very small storm events, particularly at the inlet, or if there is some unseen water source such as a spring that is resulting in this apparent export.

We also found that, overall, we did not see a concentration reduction by either the Control or Biochar sites for many pollutants. One possible explanation for this finding is that the concentrations found at the Bethel site were very low compared to typical urban runoff concentrations. One potential area for future research may be to develop a *rating curve* for stormwater practices that identifies how the performance of each practice varies with inflow concentration.

Perhaps the most important finding was regarding the amount of flow reduction occurring at each site. We would expect bioretention practices (either biochar or without biochar), by infiltrating water into the soil. However, our initial results suggested a median runoff reduction of almost zero. However, when we looked at the data more closely, we found that the negative runoff reduction volumes were estimated for very small inflow volumes, with a strong linear relationship between inflow volume and runoff reduction. This result suggests that there may be a difficulty in monitoring the inflow volume for very small storms. Also, it suggests that an important follow-up analysis will be to analyze the frequency of different sized storm events, to develop a curve that evaluates runoff reduction achieved in a typical year.

We recommend continuing monitoring at the Bethel site, but with the following modifications:

1) Evaluate the potential to divert the additional flow around the Biochar practice, as the differences in flow volume between the Control and the Biochar may be confounding the differences that can be explained by the Biochar additive.
2) Review the calibration of flow meters for very small storm events. If these events cannot be measured accurately, consider an alternative approach for measuring these events, or alternatively focus only on storms that can reliably be measured.
3) Complete an analysis of rainfall records to evaluate the amount of runoff reduction (and pollutant load reduction) that is achieved on an annual basis, accounting for the difference in performance between small storm events and large events.
4) At the Diamond Hills Site, commence monitoring both the Biochar and the Control practice, considering the findings from 1) and 2) above.

Although we did not evaluate these data extensively in this report, some anomalies in the data from the Diamond Hills site should be investigated. Some outflow concentrations were extremely high, and a more in-depth review of the data may point to potential reasons for these high concentrations.

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