DEPARTMENT OF TRANSPORTATION

Continued Monitoring of Stormwater Effluents from Filter Media in Two Bioslope Sites

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16. Abstract (Limit: 250 words)

Over the last thirty years, the Minnesota Department of Transportation (MnDOT) has implemented biofilters along roadways as a stormwater control measure. The state and national regulations require that the biofilters must be able to infiltrate and treat the first inch of rainfall onsite. However, the performance of the biofilters after installation has rarely been studied. An early phase of this project monitored two newly constructed biofilter sites for two years and for three months, respectively. This study extended the monitoring of soil moisture changes and infiltration water quality for another two years (2019-2020). Over the four-year monitoring period, both salvage peat and compost materials showed the capacity to retain the first inch of runoff, and this retention capacity did not change over the study period. The drainage water quality showed significantly temporal trends, particularly phosphorus concentrations, which were declining significantly for both compost and salvage peat. The application of tailing with compost can reduce the phosphorus release. The leachate from salvage peat has similar metal concentrations but much lower phosphorus concentrations (below 100 ppb) than the compost. The lowest chemical concentrations were achieved when the soil mixture contained 10% compost and 10% salvage peat, implying the best stormwater control practice is to limit the organic ratio to around 20%. Findings from this work determined the validity of using peat and compost for future biofilters and can aid in future design.

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CONTINUED MONITORING OF STORMWATER EFFLUENTS FROM FILTER MEDIA IN TWO BIOSLOPE SITES

FINAL REPORT

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EXECUTIVE SUMMARY

Two bioslopes using salvage materials were monitored as part of two previous MnDOT-funded projects (MnDOT project 99008 work order 189; and project 1003325 work order 31). One experimental site, comprised of three compost + natural soil (1:1) plots and three salvage peat + natural soil (1:1) plots, was constructed in the Natural Resources Research Institute (NRRI) parking lot in late 2016 and monitored from 2017. Another site was located at the Highway 169 Eagle's Nest and monitored for moisture and water quality from late 2018.

Because of the short monitoring period, data from the previous two projects did not give any clear temporal trend to estimate aging effects of infiltration media. Therefore, extended monitoring was performed for another two years (August 2019 – June 2021) to assist in the understanding of long-term retention and stormwater treatment capacity by salvage materials. The monitoring results, together with data from previous projects, can provide information for the future design and application of salvage materials in stormwater treatment in bioslope/bioswale as well as a soil amendment. Data gathered will assist in evaluating the volume of materials to be used in a mix and the lifetime of the application.

WATER RETENTION CAPACITY

Water retention capacity was determined through changes in water content. Each site was instrumented with water content sensors as well as temperature gauges and rain gauges. Changes in water content were related to water retained in the soil through weight-volume relationships and were compared to measured rain to determine whether the bioslopes retained the first inch of runoff during rainfalls.

At both sites, the biofiltration system proved effective at capturing the first inch of runoff. In lower rainfall events, the systems were extremely effective, capturing a volume equal to or greater than the rainfall. The system could catch a greater volume of rain due to its proximity to impermeable surfaces. In some high-volume rain events following previous rain events, the system did not catch the first inch of rainfall.

The NRRI site allowed for comparison between the use of *in situ* peat and commercial compost in biofiltration systems. The *in situ* organic material performed as well as commercial peat, demonstrating its potential for wider use along Minnesota's roads. The use of this material would represent both a cost-saving measure and provide a beneficial reuse for material that is currently waste. The conclusion of this study is that engineered soil is effective in meeting the biofiltration system's purpose of capturing the first inch of precipitation events.

WATER QUALITY

Water infiltrated through soil was collected by lysimeters and perforated pipe under the soil immediately after every major rain event. The samples were brought back the laboratory and analyzed for pH and metals (copper, lead, and zinc) using atomic absorption spectroscopy and phosphorus by spectrophotometric method.

From the monitoring conducted over the past four years (2017-2020) at the NRRI site, compost released a significant amount of phosphorus, but the concentrations declined rapidly from 5,000 ppb in 2017 to 2,000 ppb in 2020. The high phosphorus concentrations indicated the applications of compost must be limited to a small ratio, such as 20% or less. When the compost ratio in the mixture is reduced to 10% in the Eagle's Nest site, the leachate phosphorus concentrations could be below 10 ppb. This declining trend was also observed for the peat soil, but the phosphorus concentrations were typically below 100 ppb. The concentration difference in these two materials and declining temporal trends indicated that salvage peat could be a good alternative to compost for treating phosphorus.

When the organic ratio was 50% for the soil mixture, the median metal concentrations were between 40 and 85 ppb for copper and zinc, but the concentrations were reduced to below 20 ppb when organic ratio in the soil mixture was reduced to 20%. This finding further verified that the organic ratio should be controlled at 20% and below. Tailing materials reduced phosphorus release from compost, but additional metals were released when they were mixed with compost. As a result, the tailing materials should be controlled under a small ratio during the application.

CHAPTER 1: INTRODUCTION

Drainage from highways, particularly the first flush of runoff, contains high levels of contaminants such as suspended solids, metals, and organics. To restrict the discharge of polluted stormwater, the National Pollutant Discharge Elimination System (NPDES) State Disposal System (SDS) General Permit issued by the Minnesota Pollution Control Agency (MPCA) in 2013 requires that the first inch of stormwater runoff from new impervious should be held onsite through infiltration, harvesting, or reuse (MPCA, 2013). The onsite retention of the first inch of runoff could reduce contaminant contents by adsorption and plant uptake to meet water-quality standards.

The performance of water retention capacity and contaminant removal properties are highly dependent on the media used in the soil and are affected by the number of years applied. Multiple types of infiltration materials have been studied in the laboratory and the field, but few studies have considered the application of local materials for best management practices (BMP), particularly changes from field applications over time. The project team evaluated the stormwater treatment properties of salvage peat, muck, taconite tailing and compost, including absorption, infiltration, filtration, and pollutant capture by laboratory tests (Johnson et al., 2017). The salvage material was defined as a good alternative to the compost because of the similar infiltration capacities and lower phosphorus release. Taconite tailing was exchangeable with sand in hydraulic conductivity property and showed the potential to remove phosphorus.

Based on the laboratory test results, the project team constructed one experimental site at the Natural Resources Research Institute (NRRI) parking lot. Bioslope test plots were constructed on October 27, 2016, on a 1:5 slope (22% grade) in silty or clayey sand. The soil moisture and the water quality were monitored from 2017. Another field site on the Eagle’s Nest roadside was monitored from August 2018 (Johnson et al., 2019).

The objective of this project was to extend the monitoring for another two years (2019-2020). The new monitoring data were compiled with previous data to investigate the potential temporal trends of the soil moisture changes and the pollutant-retention capacity. Based on the monitoring results, suggestions for the life term of the soil application will be developed for bioslopes.

CHAPTER 2: SITE DESCRIPTION AND SAMPLE ANALYSES

2.1 FIELD SITES

Two field bioslope sites include one experimental site located in the NRRI parking lot and one roadside site (Eagle's Nest site) at Highway 169 reference (mile) post 270 close to Tower, MN (Figure 2.1).

The NRRI experiment site was constructed in late 2016 and was monitored from spring 2017. On this site, media mixtures were blended by volume of a 1:1 mixture of native soil and compost for three plots, and a 1:1 mixture of native soil and peat for another three plots. Once media was mixed in proper ratios, six square media beds approximately 36 inches x 36 inches in size were prepared by placing six inches of treatment media over four inches of gravel. The gravel layer was included to promote drainage via an underdrain (Figure 2.2) to collection vessels, which allowed for determination of water quality effects. The plan was to seed the plots with the same seed mix used for the surrounding area. Due to the late installation date and snowfall occurring soon after, the field monitoring could not be started in 2016. In spring 2017, instrumentation that monitors rainfall, soil moisture content and temperature were installed for long-term field monitoring. Plots were seeded in July 2017. Water samples started to be collected at the same time.

In addition to the six experimental plots, another plot (the white plot in Figure 2.1) of the same size was constructed in 2018 using the mixture of compost and tailings (1:1), funded by University of Minnesota internal funding. The water quality data of this plot are included in this report to evaluate the pollutant removal efficiencies by different soil material blends.

The Eagle's Nest site was constructed in 2018 during the Minnesota Department of Transportation (MnDOT) Highway 169 reconstruction project. This site contained biofilter amendments throughout the 5.7 miles of new road construction. Peat that was excavated from sections of the site, shown in Figure 2.3, was placed on slopes adjacent to roads at a depth of four inches and seeded. An infiltration bench was placed at the toe or cutoffs of sloped sections along the roadways. The swales contained an 80:10:10 by volume mixture of sand, peat, and compost. A perforated pipe underdrain system was also placed under the swale trench to promote drainage. The monitoring of soil moisture changes and the collection of water samples from bioslope and bioswale started from August 2018.

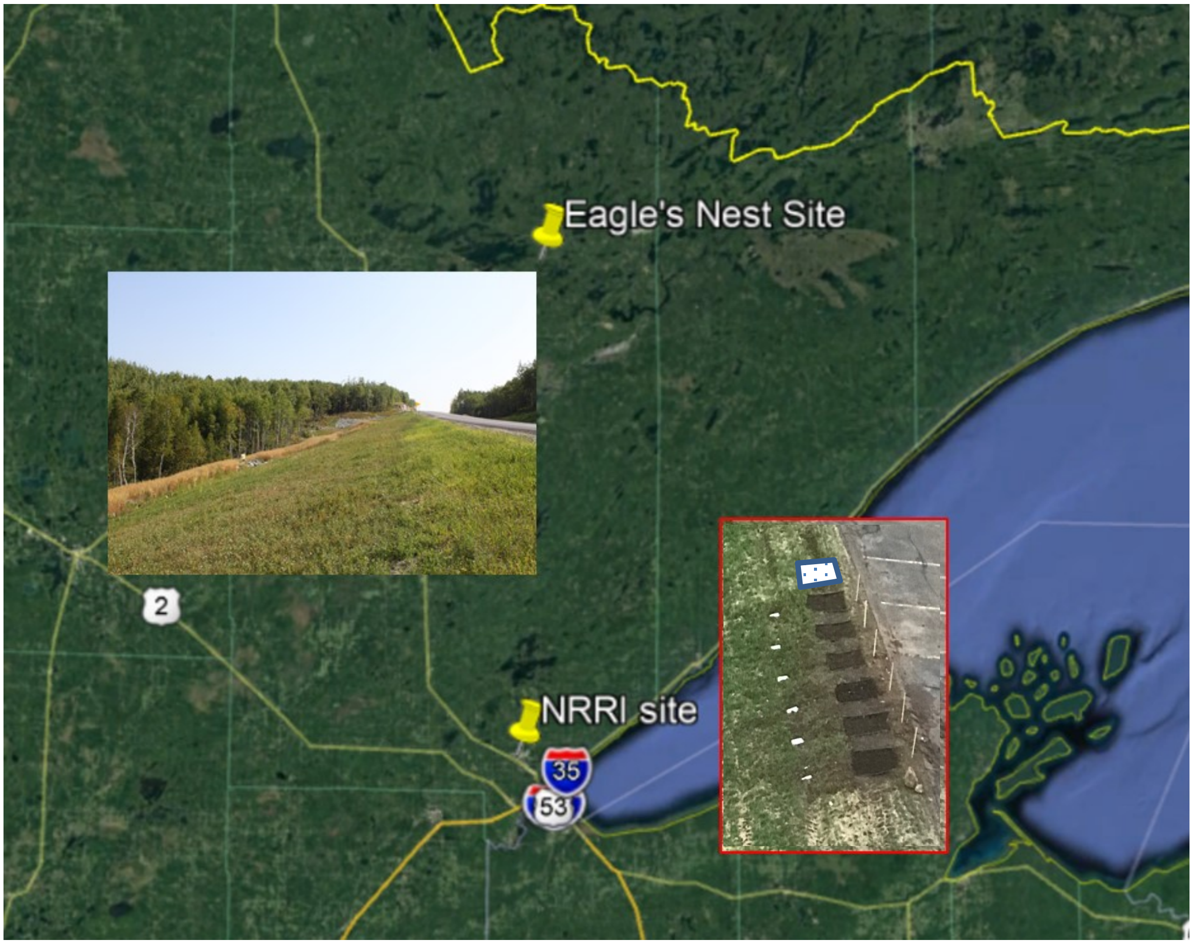

Figure 2.1 Two field sites in northeastern Minnesota.

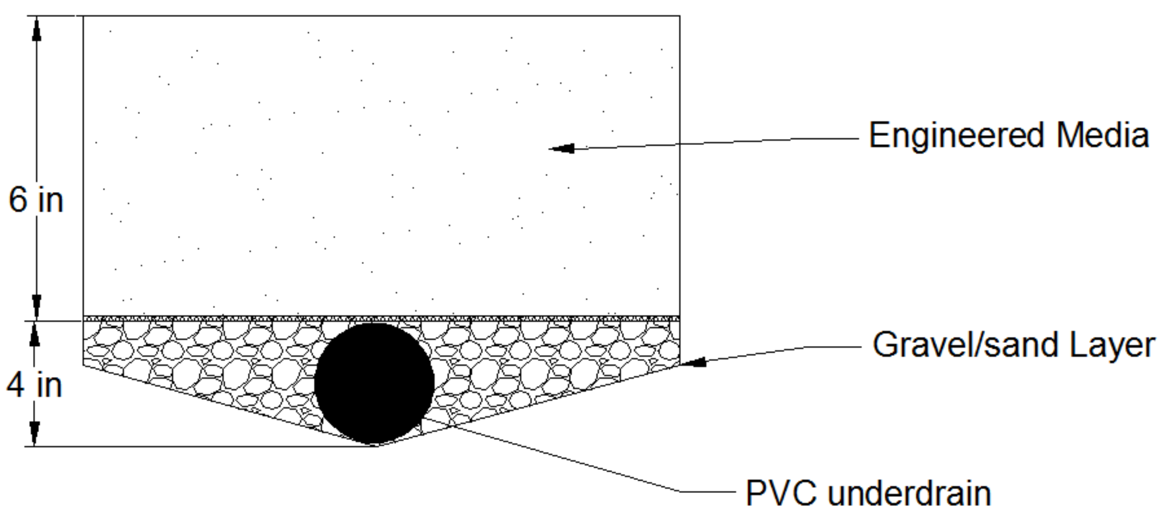

Figure 2.2 Cross section of mixed media pilot.

Figure 2.3 Bioslope and bioswale construction on Eagle’s Nest site in 2018.

2.2 IN-SITU MOISTURE MONITORING

Soil moisture changes were monitored by moisture sensors (Figure 2.4), which were connected to a data logger. The tip ends of the moisture sensors were inserted into soil at a depth around 9 cm. A solar panel was installed to provide a trickle charge for the 10 amp/hour battery and extend battery life.

For the NRRI site, one sensor was used for each of six experimental plots from May 7 to November 14, 2019. The sensors were temporality removed from the site between July 20 and 21 due to the Duluth air show’s use of the adjacent parking area. Three sensors stopped working and were replaced during the 2019 monitoring period. In addition to one sensor for each of the six experimental plots, two sensors were installed in 2020 for the compost and tailing mixture plot and the background natural soil, respectively. The moisture monitoring was performed at NRRI from May 26 to November 4, 2020.

At the Eagle’s Nest site, nine moisture sensors were installed in 2019, with six on the slope and three sensors on the trench. Due to the miscommunication of this task, these sensors were installed on October 22 and removed on November 14, 2019. In 2020, 36 moisture sensors were installed, with 27 on the slope and 9 sensors on the trench (Figure 2.5). These sensors were installed on May 20 and removed on October 31, 2020. However, one set of moisture sensors (labels begging with S2) on the slope did not have data collected since late July due to the malfunctioned or broken logging box.

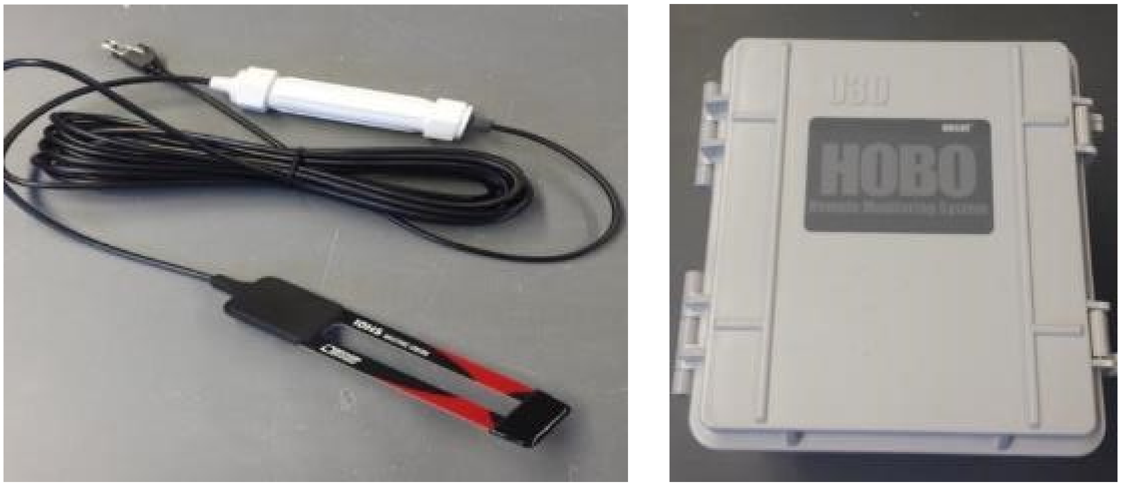

Figure 2.4 The moisture sensor (left) and data logger (right) used for in-situ moisture measurement.

Figure 2.5 The layout of the sensors placed on the Eagle's Nest site in 2020 for the moisture measurement.

2.3 WATER SAMPLE COLLECTION

Seven pipes to capture runoff were installed at the NRRI site and two were used at the Eagle's Nest trench (Figure 2.6). These pipes were installed when the experimental site was constructed in 2016 at the NRRI site and when Highway 169 was reconstructed in 2018. No additional construction was completed for this project. Water samples were collected from both the NRRI and Eagle's Nest sites by perforated pipe installed under modified soil media and are connected to the collectors.

Figure 2.6 Perforated pipe to collect water samples in the NRRI site (left) and Eagle's Nest trench site (right).

For the bioslope at the Eagle's Nest site, water samples were collected by six suction lysimeters, which were installed after spring snow melted and removed after the first fall snow in 2019 (Figure 2.7). In 2020, water samples were collected by a stainless pan lysimeters, which were newly manufactured this year because the suction lysimeters used in 2019 were damaged by grass mowing and animal activities.

Figure 2.7 The suction lysimeter (left) used in 2019 and the 1-ft pan lysimeter (middle and right) used in 2020 at the Eagle's Nest slope.

After water samples were collected from the field, they were filtered through 0.45 µm membrane. Filtered samples collected for metals analyses were acidified to pH <2 and stored at room temperature. Samples for phosphorus measurement were preserved in a 4°C cooling room immediately after filtration. Concentrations of metals (copper, lead and zinc) in water samples were measured by graphite atomic absorption spectrometry, and phosphorus was measured by the colorimetric method. The detection limits of metals and phosphorus are 1µg/L.

In 2019, some field monitoring equipment on the Eagle's Nest site became non-functional by natural or human activities. In September, one trench pipe outlet was observed to be cut, possibly by an animal's chewing (Figure 2.8). The sample collection jar was pushed away from the site. The tube was reconnected at that time. However, a fallen tree, together with some rock debris, buried that site in October. Now the entire site and its equipment are completely destroyed and covered by the fallen tree.

Figure 2.8 The same trench water collection point. The picture on the left was taken on September 10, 2019. The tube connection to the sample collection bottle was cut, probably by an animal. The same site was destroyed by fallen trees, as shown in the picture on the right taken on October 22, 2019.

All six lysimeters on the Eagle's Nest slope were destroyed between September 13 and October 11, 2019 (Figure 2.9). These lysimeters may have been cut by grass mowing. Therefore, no sample was collected from the slope after September 13 in 2019.

Figure 2.9 Pictures of destroyed lysimeters taken on October 11, 2019. The picture of a working lysimter is shown on the left in Figure 2.7.

CHAPTER 3: SOIL MOISTURE DATA

Soil moisture was monitored for NRRI's experimental sites from 2017 to 2020 and the Eagle's Nest site for late 2018, late 2019, and 2020.

3.1 SOIL MOISTURE CHANGES IN NRRI SITE

From 2017 to 2020, the maximum soil moisture changes were typically below 30% (Figure 3.1), implying the maximum water retention capacity of the soils was 30%. Soil moisture changes showed significantly seasonal patterns, with large variations during spring and summer and relatively small changes in fall. Even though there were no high-volume rain storm events in fall, the soil moisture remained in high content of around 30-40% for all four years, probably due to the reduced evaporation rates at low temperature or multiple small rain events in fall. Within the four years, the soil moisture was relatively lower in the later two years, probably because 2019 and 2020 were drier than 2017 and 2018. Moisture data did not show a clear difference between compost and peat over the four-year observations. In 2020, the moisture of background natural soil was typically at the high end but not significantly different from other soil types.

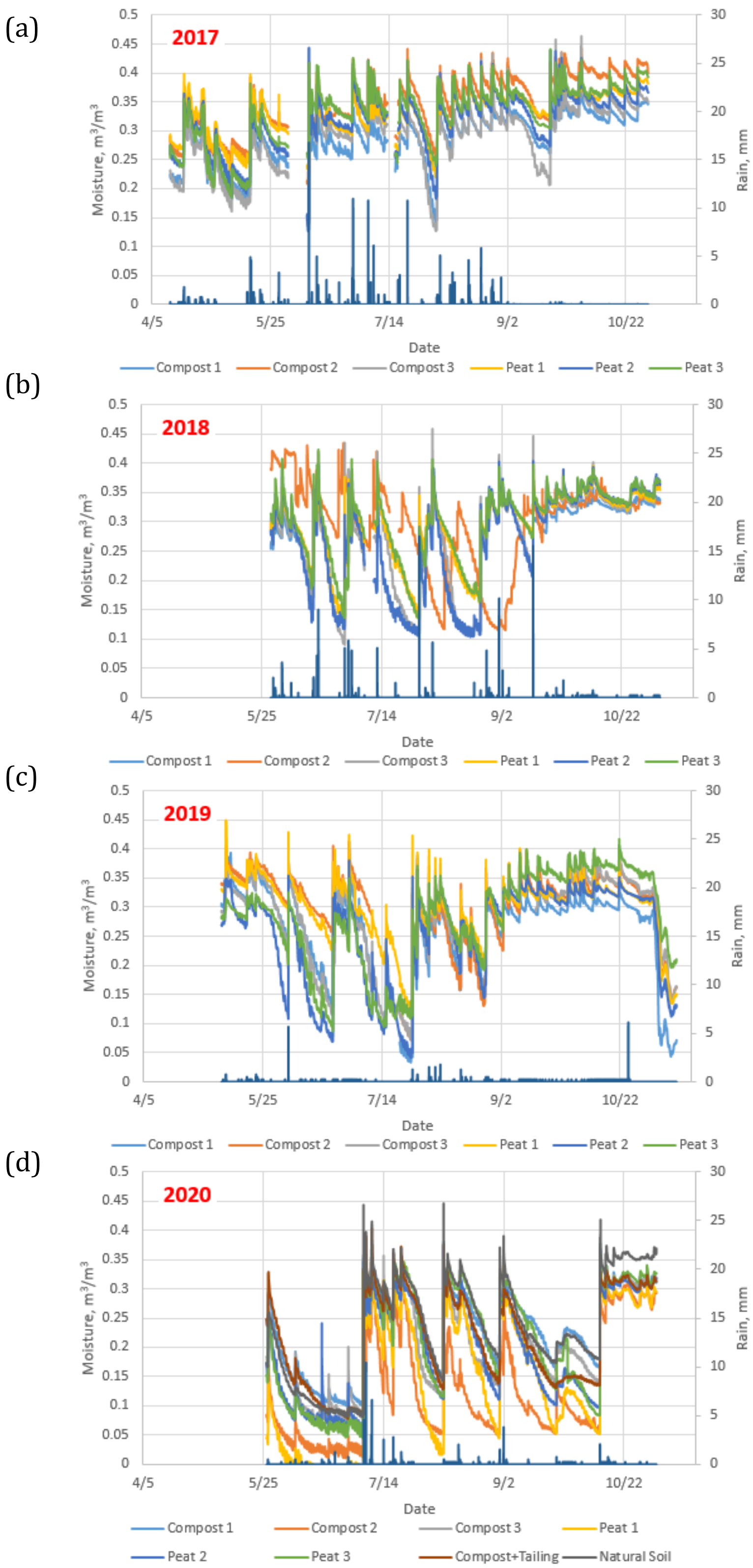

Figure 3.1 Soil moisture changes and in-situ rain records for six experimental plots at NRRI's parking lot for four years: (a) 2017, (b) 2018, (c) 2019, and (d) 2020. In 2020, two additional plots (compost + tailing plot and background natural soil plot) were added into the monitoring.

For each major rain event, the moisture changes of four soil types were computed by using the peak moisture minus the base moisture. The moisture changes over four years did not show significant difference between compost and peat soil from 2017 to 2020 (Figure 3.2). Relatively, the moisture changes of background natural soil had the largest variations while the mixture of compost and tailing soil had the smallest variations in 2020.

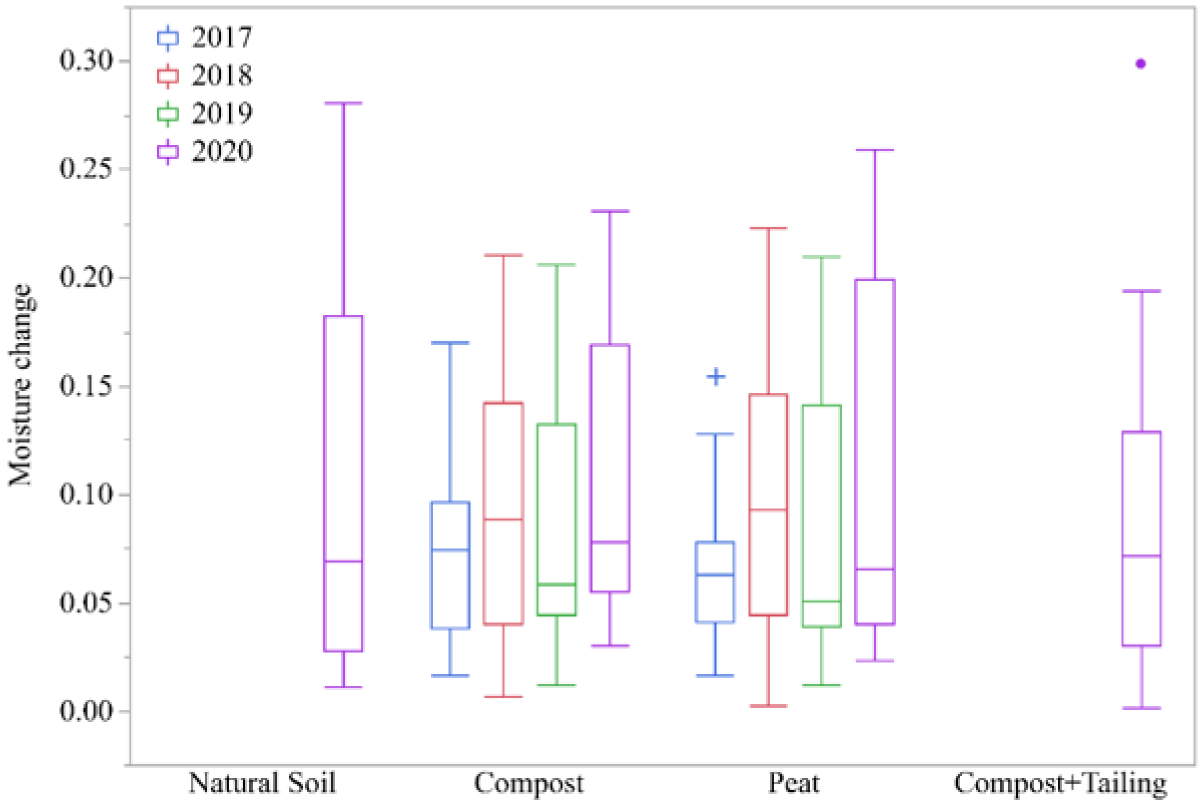

Figure 3.2. The box plots of moisture changes for four soil types over four-year observations.

Figures 3.3 and 3.4 show total rainfall in 2019 and 2020, respectively, as compared with water captured by the NRRI biofilters. The water captured by the biofilters was calculated using weight-volume relationships. Given changes in water content and the biofilters' known unit weight, the authors calculated the change in water for a unit area of biofilter. The resulting change in volume of water could then be related to a height of water captured in the filtration system.

The data indicate a near one-to-one relationship during smaller rainfall events where the biofilters were able to efficiently infiltrate rainfall. The data becomes less grouped as rainfall intensity increases. The higher rainfall events do not have the same linear relationship that the smaller events have. The larger-event data appears to experience a limited infiltration rate, which is potentially linked to the saturated hydraulic conductivity of the media. During lower-intensity events, there are points that indicate a height of water caught that is greater than the event rainfall intensity. There are two likely explanations. First, there is a large impermeable area near the test area, and additional runoff likely entered the filtration systems. Additionally, since the biofiltration systems are more permeable than the native soil surrounding the relatively small test areas, there is the potential that moisture was absorbed from the surrounding soil. The data demonstrates that the biofiltration systems are efficiently capturing the first inch of runoff.

As seen in Figures 3.3 and 3.4, peat and compost performed comparably at NRRI, with neither demonstrating better performance. Therefore, the results of this study demonstrate peat's ability to act as a substitute for commercial compost in biofiltration systems.

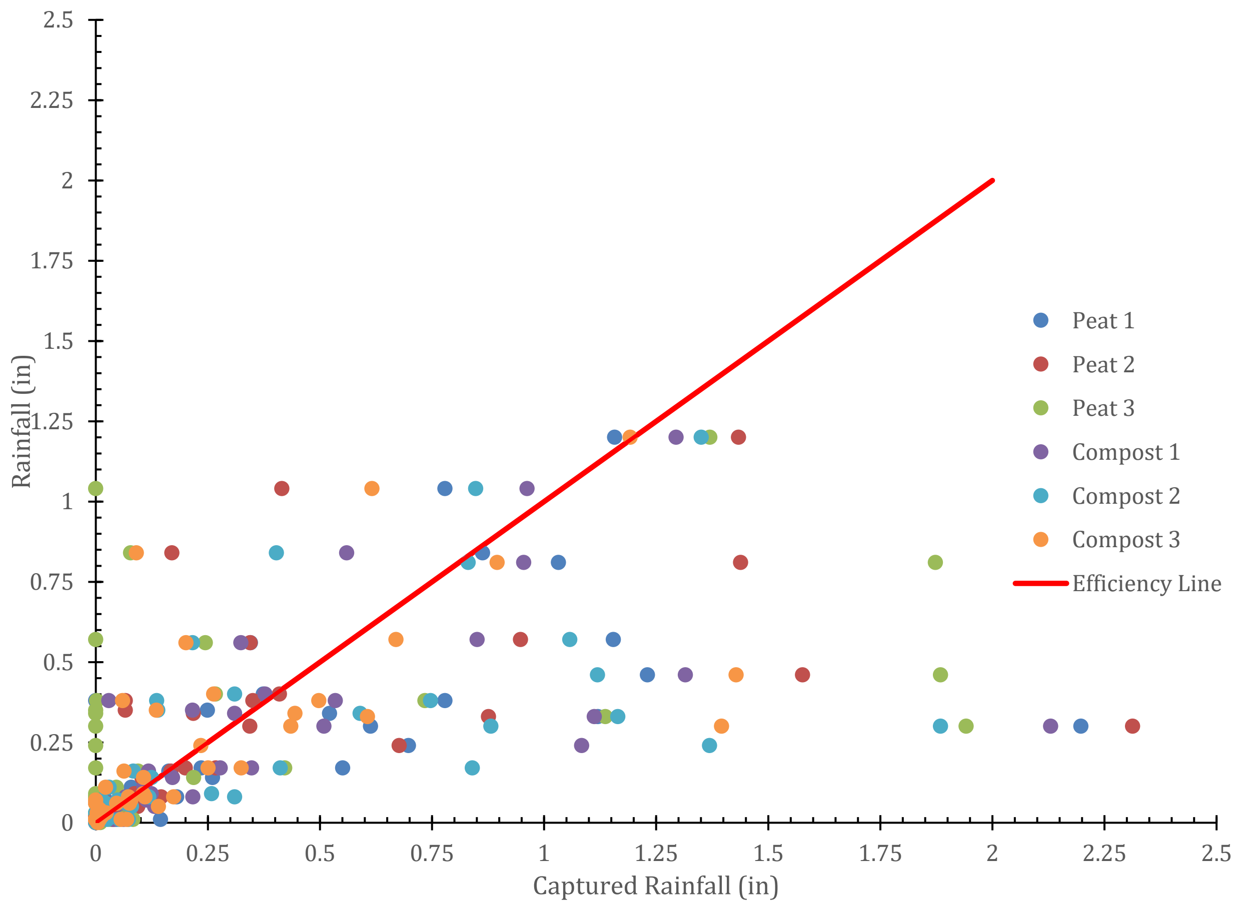

Figure 3.3. Rainfall vs. water captured by the biofilters at NRRI in 2019.

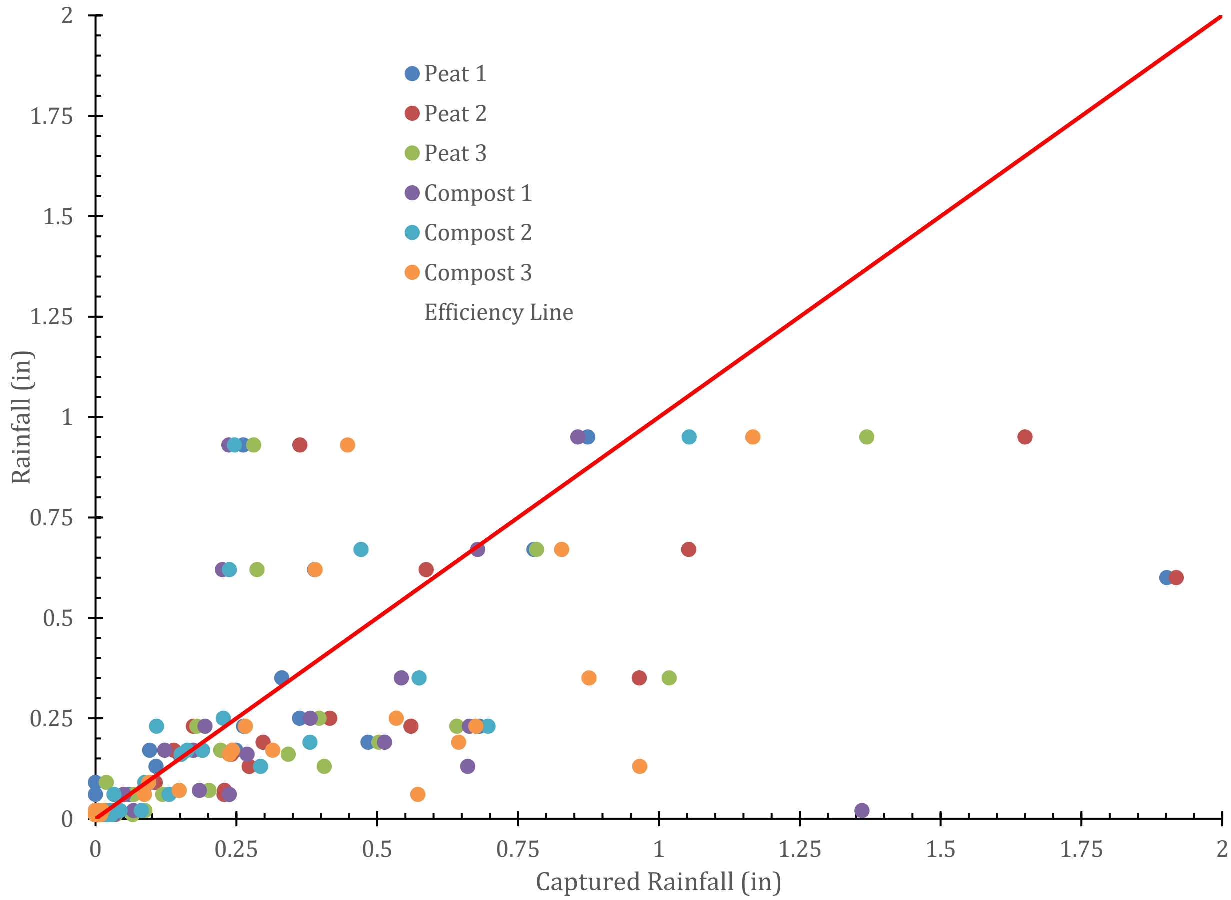

Figure 3.4. Rainfall vs. water captured by the biofilters at NRRI in 2020.

3.2 SOIL MOISTURE CHANGES AT EAGLE'S NEST SITE

In 2018, 36 moisture sensors were placed at the Eagle's Nest site, including 27 sensors on the slope and 9 sensors in the trench (Figure 3.5). Because there was no significant difference among sensors on the slope or on the trench, only nine sensors were installed in 2019, with six sensors on the slope and three sensors on the trench. In 2020, 36 moisture sensors were placed again to evaluate the changes over time.

The moisture content on the slope and the trench remained relatively high values, around 40% to 60% for 2018, but was reduced to around 10% to 30% for 2019 and 2020. The clear reduction of moisture content from the first year to the other years is probably attributed to the reduction of porosity because of the soil compaction over time. However, the compaction does not change the magnitude of moisture change after any major rain events; typically, the moisture changes could be as high as 20%. Similar to the moisture changes at the NRRI site, soil appears to hold more water in fall than other seasons.

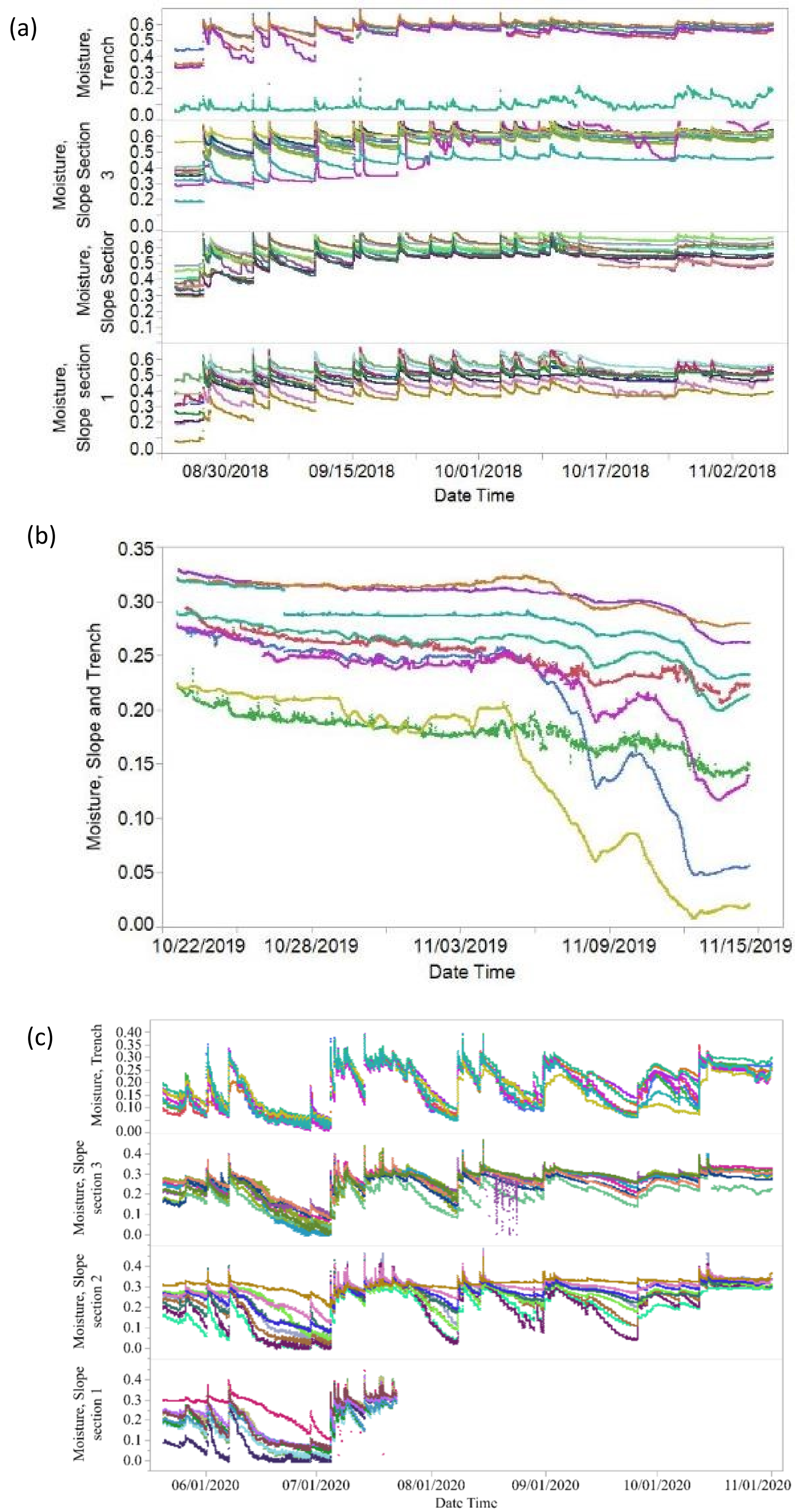

Figure 3.5 Soil moisture changes for the slope and trench at Eagle's Nest roadside (Highway 169) for (a) late 2018, (b) late 2019, and (c) 2020.

Figures 3.6 shows total rainfall before July 2020 as compared with water captured by the Eagle's Nest bioslopes and bioswale. The rain gage was damaged in July, and the rainfall data shown in Figure 3.7 is based on historic rainfall data, not data measured at the site; therefore, the authors' analysis prioritized the data shown in Figure 3.5. Additionally, instrumentation issues prevented collection of data in the spring and early summer of 2019 at the Eagle's Nest site. In the late summer and fall, there were no significant rain events while temperatures were above freezing. Therefore, no rainfall versus captured water data is presented for 2019.

Similar to the NRRI data, smaller rainfall events are effectively captured by the biofiltration systems. At the Eagle's Nest site, the biofiltration system extends across the entire site, rather than the discrete plots at NRRI. Therefore, the higher volume of water captured is likely due to additional runoff from the impermeable surface rather than infiltration from surrounding soil. The cases where the biofiltration system failure to capture the first inch of rain were relatively limited and were largely high-intensity events following previous rainfall. The data demonstrates that the biofiltration systems are efficiently capturing the first inch of runoff. As seen in Figures 3.6 and 3.7, there are no significant differences between the bioslopes and bioswale at the Eagle's Nest site.

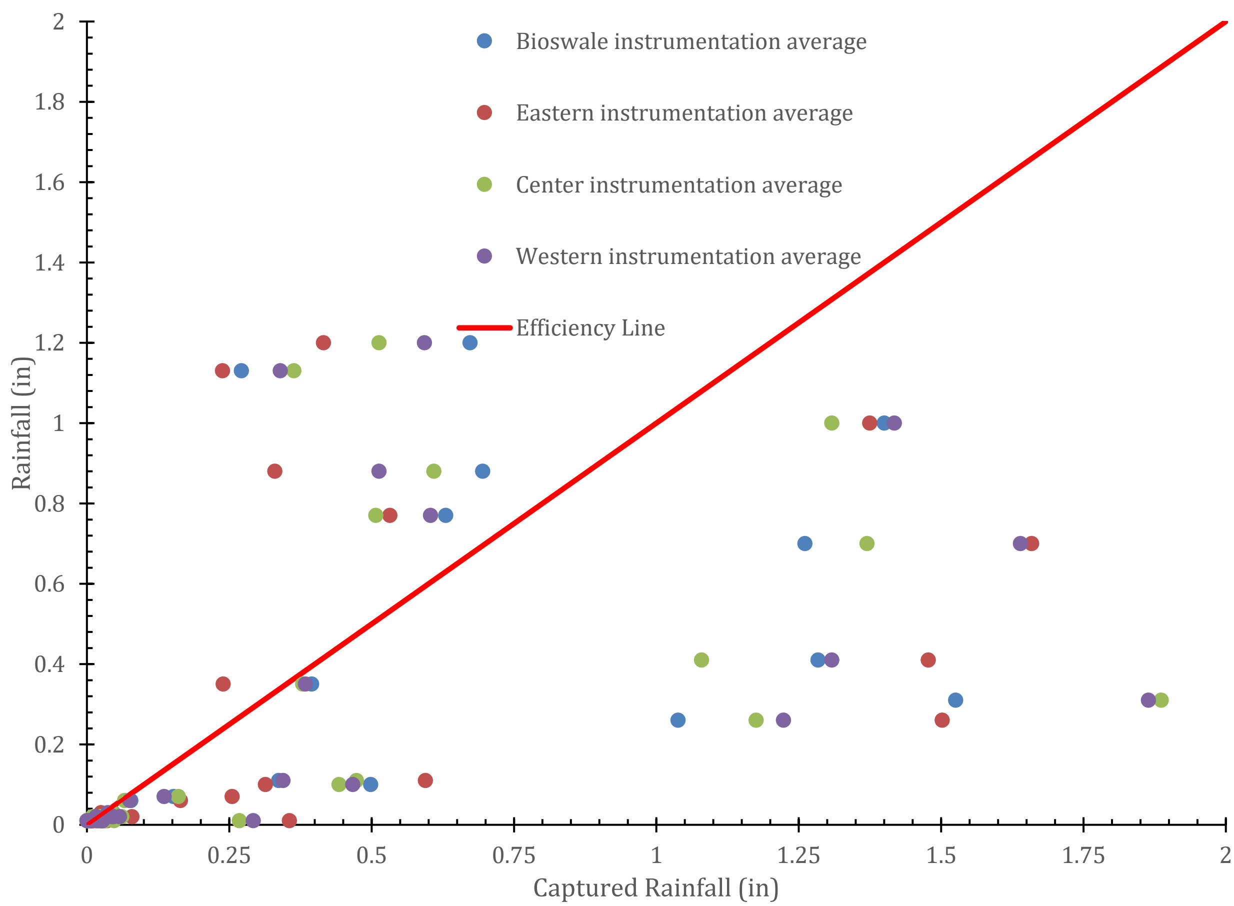

Figure 3.6. Measured rainfall vs. water captured by the biofilters at Eagle's Nest before July 21, 2020.

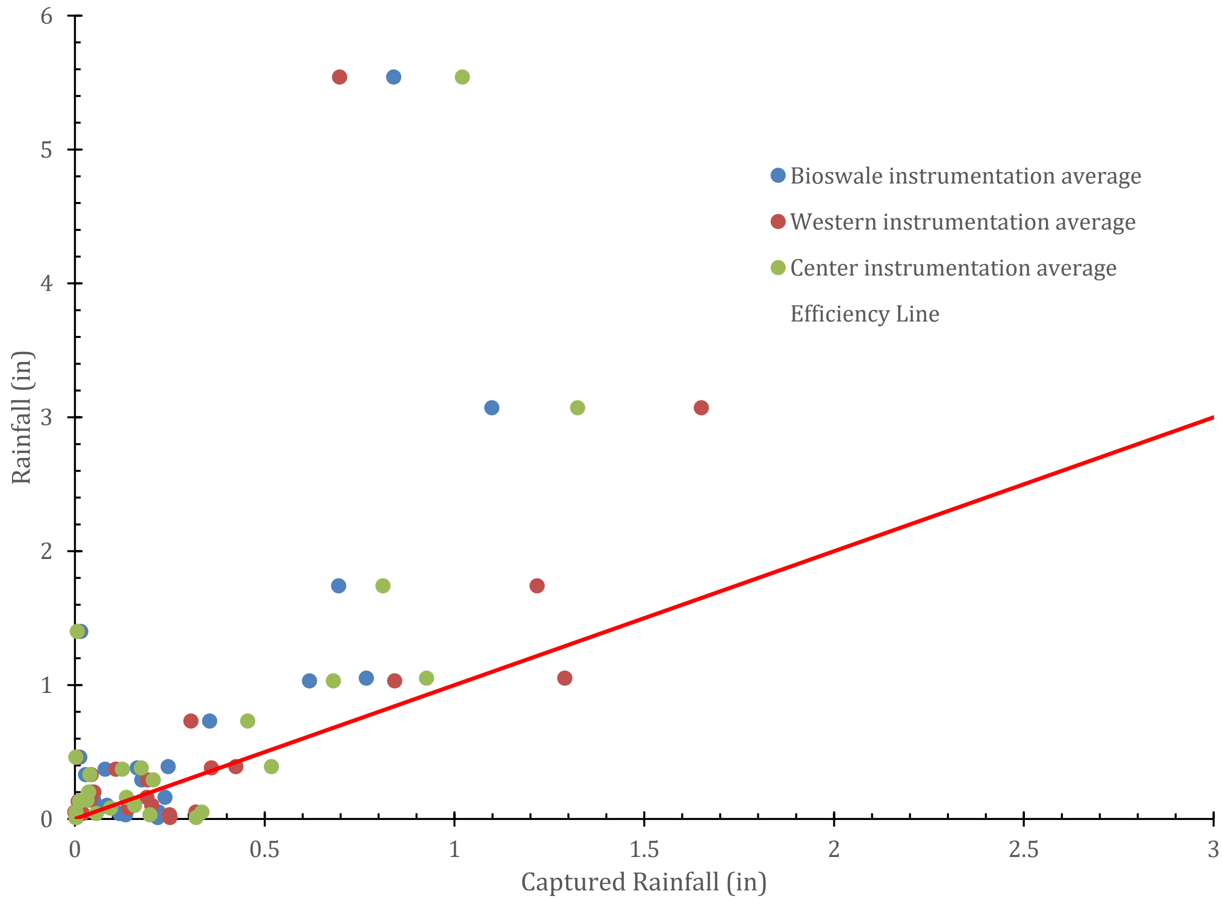

Figure 3.7. Historic rainfall vs. water captured by the biofilters at Eagle's Nest after July 21, 2020.

CHAPTER 4: WATER QUALITY DATA

The year 2020 was a relatively dry year with few major rain events. Because of this, fewer water samples were collected in comparing with other monitoring years. Water samples were collected for eight rain events at the NRRI site and four events at Eagle's Nest, even though the sample collectors were installed on site in late May. Three metals (Cu, Pb, and Zn) and one nutrient (PO_4) parameters were monitored in the samples. However, lead concentrations were usually under the detection limit (1 µg/L) for all samples; therefore, lead concentrations are not reported.

Data from 2019-2020 NRRI samples were combined with records from historical monitoring data of 2017 and 2018 to examine for potential temporal trends (Figure 3.4). Compost is known to leach phosphorus, but the leaching rates were decreasing over time from the median value of around 5,000 ppb in 2017 to around 2,000 in 2020, probably because plant uptake of phosphorus is depleting this chemical from compost material. When the compost material was mixed with tailing material, the leachate phosphorus concentrations were reduced to around 1,000 ppb. In contrast, the leachate phosphorus concentrations from peat materials were much lower, usually below 100 ppb with a median value of 60 ppb for the first three years, but the concentrations significantly dropped to around 20 ppb in 2020. This drop probably is implying the depletion of phosphorus, but this conclusion is not confirmed because the reduction was observed for this year only. Copper concentrations had significantly high values in 2019 for both peat and compost mixture soils. This increasing trend is particularly significant for compost soil from below 100 ppb to close 1,000 ppb at the maximum but drops to less than 200 ppb in 2020. Instead, zinc concentrations did not show a clear temporal trend over the years, probably because the soil affinity to zinc is stronger than it is to copper. Along with increasing copper concentrations, leachate pHs did not show a significant temporal trend.

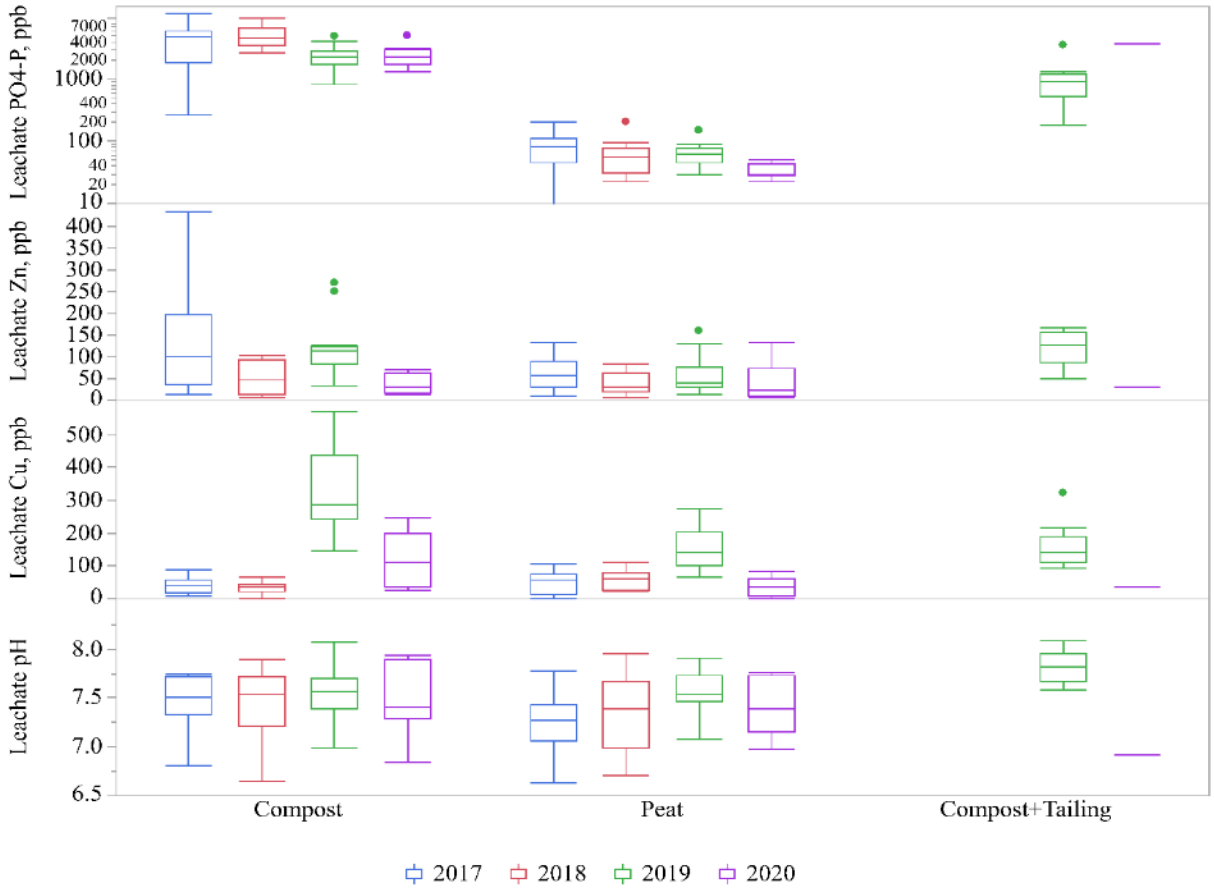

Figure 4.1. The concentrations of PO4-P, copper, zinc, and pH for leachate collected from the NRRI experimental site from 2017 to fall 2020.

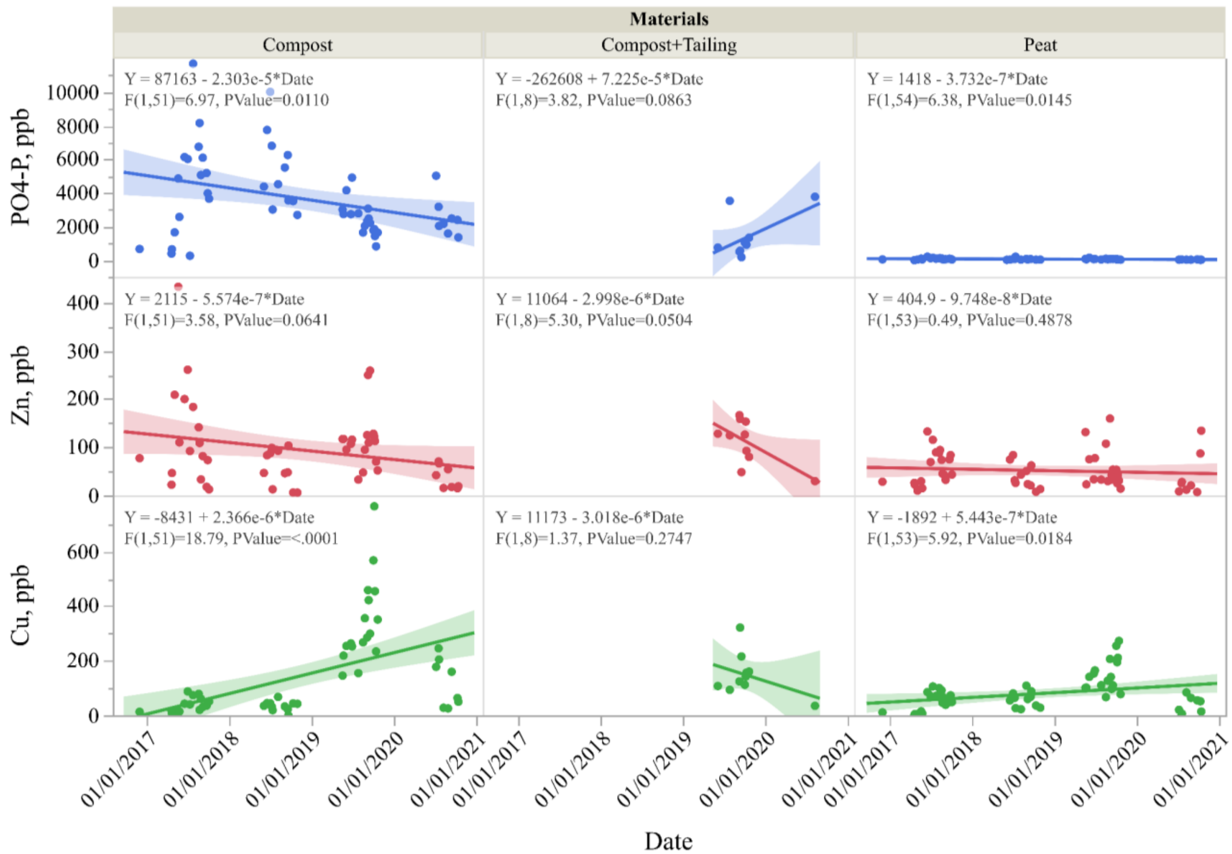

Figure 4.2 The linear regression fit between the effluent concentrations and the date. Any linear fit with PValue<0.05 indicates a significant temporal trend is defined.

Eagle's Nest site leachate solutions also showed lead concentrations for samples were under detection limit (1 µg/L) and are therefore not presented here. The concentrations of copper, zinc, and phosphorus varied significantly from 10 ppb to hundreds (Figure 4.3). Overall, the metal concentrations of copper and zinc for samples collected from the slope were higher than the samples collected from the trench. Because of the limited data, no clear spatial or temporal difference can be detected.

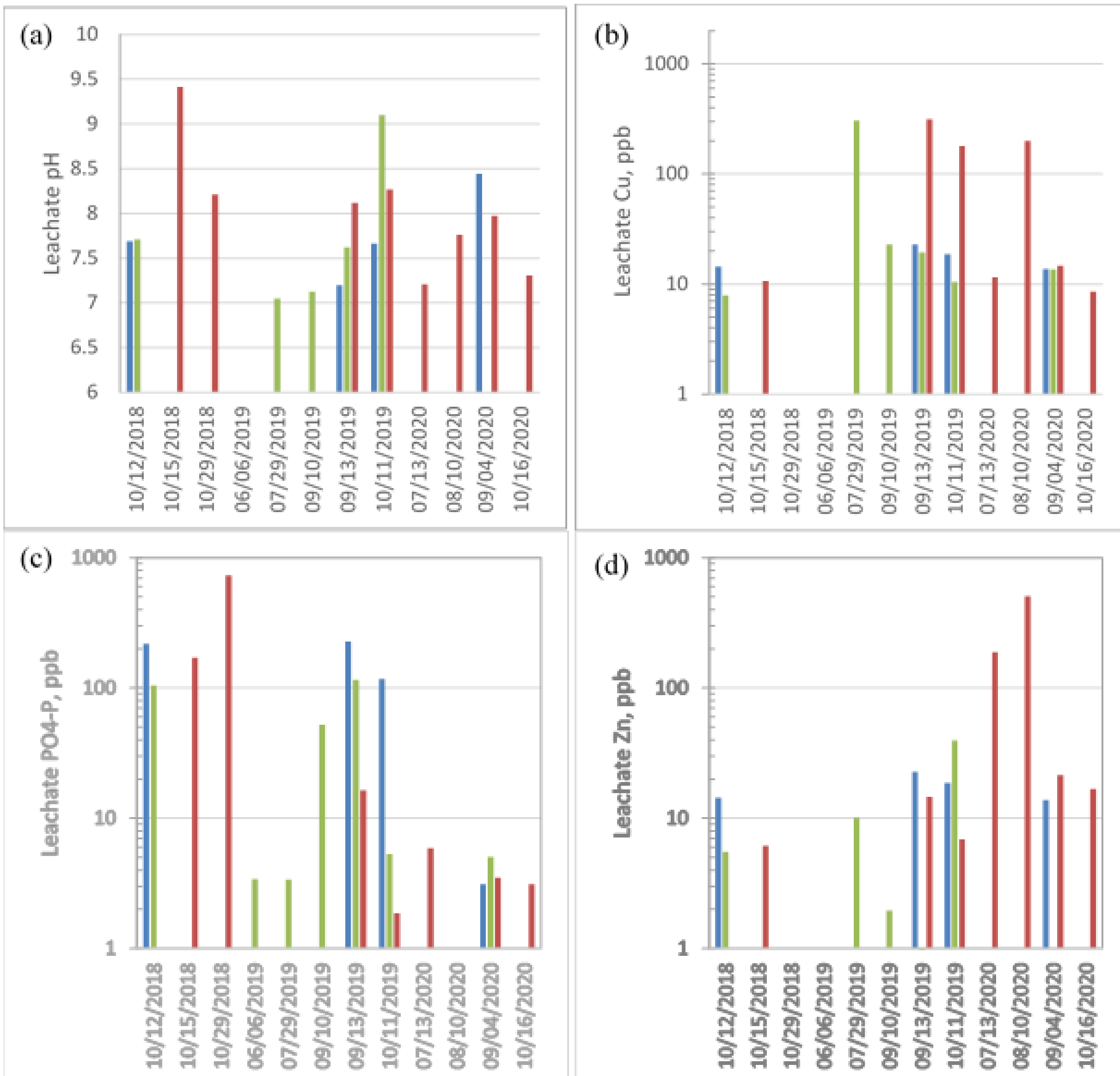

Figure 4.3. The concentrations of (a) pH, (b) copper, (c) PO4-P, and (d) Zn for leachate collected from the Eagle's Nest site from late 2018 to fall 2020. North and South are two sites for trench filtration water, and Slope are slope sites for lysimeters.

The performance of a biofilter is largely based on its compositions of the media to capture pollutants. With the different mix ratios of organics for the NRRI and Eagle's Nest sites, the median leachate chemical concentrations were compared to identify the optimal mix ratio (Table 4.1). The release of phosphorus from compost can be reduced by tailing materials, probably due the precipitation reactions between phosphorus and iron from tailing. However, the application of tailing needs to be limited to a small ratio because the tailing has the potential to release metals, including copper and zinc. The leachate from salvage peat had similar metal concentrations as compost but significantly low phosphorus contents. The lowest chemical concentrations were observed when the organic content of the soil mixture was reduced to 10% compost and 10% peat. In this soil mixture, the metal and phosphorus concentrations of the effluent were below 20 ppb. This low concentration level indicates that the optimal organic ratio in the field application should be limited to 20% or lower.

Table 4.1 The median concentrations of metals and phosphorus for the two field sites monitored in past 3 to 4 years.

Site	Compositions	Median Value, ppb			
		pH	Cu	Zn	PO4-P
NRRI	50% compost	7.6	61.0	83.3	3015.8
	50% peat	7.4	68.1	41.4	54.1
	50% compost + 50% tailing	7.8	133.7	125.6	969.6
Eagle's Nest	10% compost + 10% peat	7.7	14.7	6.9	5.9

CHAPTER 5: CONCLUSIONS

From four years of monitoring the NRRI experimental site and three years of monitoring the Highway 169 roadside site, water retention capacity did not exhibit a clear temporal trend or significant difference among materials for the NRRI site but dropped significantly from the first year to the other years on the Eagle's Nest site, probably due to the compaction of the soil. Unfortunately, the moisture monitoring for the NRRI site began in the second year, so the effect of soil compaction cannot be observed on this site. It has been verified that including applications of compost and peat in biofilters retains the first inch of runoff onsite.

The water quality of biofilter leachate showed significant temporal trends, particularly the phosphorus concentrations. The drainage phosphorus concentrations from compost and peat soils were decreasing over time for both sites because of plant update and the depletion of phosphorus from the materials. The mixture of compost and tailing released less phosphorus than the mixture of compost and natural soil. Compost released more copper in the recent two years than the previous two years, while the zinc concentrations in leachate remained stable.

Field monitoring equipment is sensitive to environmental and human activities. In 2020, we had to replace two moisture sensors because of the malfunction of the sensors. One data log box stopped working, leading to the loss of moisture data from nine sensors over three months. In 2019, six suction lysimeters were completely destroyed, probably during grass mowing. The use of a pan lysimeter worked well for this sampling season. This lysimeter was kept in the soil for future sample collection.

This research evaluated the performance of biofilters using compost and salvage peat in water retention capacity and pollutant removal. Continued monitoring of both the NRRI pilot test and the Eagles Nest biofilter is recommended to examine whether the performance changes over time. Moreover, it is suggested that the soil materials be characterized for five years following application to assist in life age estimate of the application.

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