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TECHNICAL MEMORANDUM

SUBJECT: Task 3.1.7 – Water Treatment Residuals as an Additive to Bioretention Soil Media

Date: September 25, 2020

To: Shanti Colwell, Seattle Public Utilities

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INTRODUCTION

Purpose

The purpose of this white paper is to summarize research findings and evaluate the effectiveness and potential consequences of using Water Treatment Residuals (WTRs) as a component in bioretention soil media (BSM) for improved phosphorus and copper removal.

Background Information

Bioretention systems are shallow earthen depressions, composed of engineered soils (BSM) and plants, that provide water quality treatment and flow attenuation for stormwater runoff. These systems remove target pollutants from stormwater runoff through filtration and infiltration. Typical targeted pollutants for bioretention include:

- Sand, silt, and other suspended solids
- Heavy metals such as copper, lead, and zinc
- Nutrients such as nitrogen and phosphorus
- Bacteria and viruses
- Organic contaminants such as hydrocarbons, pesticides, and herbicides

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The current City of Seattle specification for BSM consists of 60 percent mineral aggregate and 40 percent fine compost by volume (Seattle 2017, Volume 3, Section 5.4.4.5). Compost consists of organic matter that is rich in nutrients such as nitrogen and phosphorus, and metals such as copper (Lopes et al. 2011). Because of this, sand/compost filter media has been shown to export variable amounts of phosphorus, copper, and nitrogen to downstream receiving waters (Mullane et al. 2015; Herrera 2016a). Many studies have been conducted to refine the specification for typical BSM to reduce export of these pollutants (Herrera 2016a; Taylor et al. 2018; Xu et al. 2020).

For recent Seattle capital projects, the BSM blend has been adjusted to 70 percent mineral aggregate and 30 percent fine compost with an intent to reduce phosphorus export by reducing the compost fraction. Facilities constructed with the modified blend have not yet been monitored to evaluate performance.

A 2020 report entitled *Bioretention Media Blends to Improve Stormwater Treatment: Final Phase of Study to Develop New Specifications* (Herrera 2020) summarized the selection and leaching potential of a broad range of BSM components as well as pollutant export and capture characteristics of new BSM blends for water quality treatment. The study resulted in an improved BSM that supports plant growth and does not export nutrients or copper. The new media, deemed High Performance Bioretention Soil Media (HPBSM), consists of the following components:

- 2-inch mulch layer
- 18-inch primary layer consisting of:
    - 60 percent sand
    - 20 percent coconut coir
    - 10 percent high-carbon wood ash (biochar)
- An optional 12-inch polishing layer consisting of:
    - 90 percent sand
    - 7.5 percent activated alumina
    - 2.5 percent iron filings

While this improved BSM offers a higher performance than typical bioretention media, the report acknowledged the anticipated challenges of sustainably sourcing coconut coir, iron filings, and activated alumina. Water treatment residuals (WTRs) are one option to assess as an additive to the existing 70 percent sand/30 percent compost blend to mitigate the export of nutrients and obviate the need for less environmentally sustainable BSM components such as coir, iron, and activated alumina.

Water Treatment Residuals for Stormwater Treatment

WTRs are a byproduct generated from the addition of alum or ferric salts used in the coagulation process during drinking water treatment (Xu et al. 2020). Depending on the primary coagulant used, the residual material is typically characterized as either Al-WTR (aluminum-based) or Fe-WTR (iron-based). WTRs are composed of sediment from the initial drinking water source influent and coagulant hydroxide precipitates (Kates 2019). Approximately 2 million tons of WTRs are generated every year in the USA, the majority of which is dried on site and then disposed in landfills (Xu et al. 2020). However, dried WTRs still contain a high concentration of reactive iron or aluminum and, consequently, could potentially be reused in filtration applications where the reactive properties of these materials could improve pollutant removal performance. The use of WTRs for BSM can potentially further reduce costs for stormwater treatment and provide a typically wasted resource with a new application, making the system more economically competitive in the market and finding a sustainable approach to the waste originally disposed through landfilling (Deng 2020).

Various studies have been conducted to research the effectiveness of WTRs in removing target pollutants. Research methodologies typically consist of either spiking influent water with pollutants to simulate stormwater or collecting stormwater from the field for experimentation. Spiked or collected stormwater is then dosed onto the BSM (with the addition of WTRs), and the treated stormwater, or leachate, is analyzed. Typical testing includes the use of:

- Column testing (laboratory controlled);
- Mesocosm container testing (large drums filled with media);
- Small bioretention cell testing; or
- Incubation testing (i.e., jar testing).

The remainder of this section focuses on two pollutants of concern: total phosphorus (TP) and total/dissolved copper (Cu). The *Phosphorus and Copper in Bioretention Soil Media – Kates (2019) Incubation Study* section focuses on a batch incubation study performed at the University of Washington by Norah Kates (2019). This study is particularly relevant because Kates incorporated both a local iron-based WTR from Seattle, as well as several organic composts sourced from the King County area. The *Column Studies* and *Mesocosm Studies* sections document the methodologies and results from column and mesocosm container studies, respectively.

Phosphorus and Copper in Bioretention Soil Media – Kates (2019) Incubation Study

Methodology

In Kates (2019), a total of four different WTRs and eight different organic materials were used to investigate phosphorus and copper export in BSMs (see Table 1). WTRs were provided as screw-pressed wet material: one Fe-based from Seattle, Washington (Fe-WTR), one Al-based from Tacoma, Washington (Al-WTR1), and another Al-based from Vancouver, British Columbia (Al-WTR2). A fourth Ca-based WTR from Chicago was used in preliminary tests (Ca-WTR), but it was eliminated early in the study due to poor TP sorption.

Table 1. Total Copper and Phosphorus Measured in Organics and WTRs.[a]

Media Name	Description	Total Cu (mg/kg)	TP (g/kg)
WTR			
Al-WTR1	Al-based WTR from Tacoma	30.7	147
Al-WTR2	Al-based WTR from Vancouver	69.5	0.543
Fe-WTR	Fe-based WTR from Seattle	119	0.846
Organic Components			
BioFe	Biosolids from San Francisco (Fe added)	485	26.5
BioPot	Sawdust/bark/biosolids potting soil (Tagro)	60.3	3.93
BioKC1	Biosolids from King County's South Plant	318	29.9
BioKC2	Biosolids from King County's Brightwater Plant	233	15.8
BioKC3	Biosolids from King County's West Point Plant	349	23.7
ComBS	Sawdust/biosolids compost (Groco)	161	8.1
ComFY	Food/yard waste compost (Cedar Grove)	57.2	2.98
ComY	Yard waste compost (LRI)	32.2	2.19

Notes

[a] Kates (2019).

Abbreviations

Al = Aluminum

Cu = Copper

Fe = Iron

g/kg = gram per kilogram

mg/kg = milligram per kilogram

P = Phosphorus

WTRs = Water Treatment Residuals

Organic components and WTRs were incubated with dionized water to assess leaching potential. WTRs and organic components were also incubated with controlled synthetic solutions of TP and Cu to test their sorption capacity. Batches were incubated for 24 hours, shaken to facilitate chemical release and sorption, and then filtered to separate particulate and dissolved constituents. The supernatant was then tested for TP and Cu (Table 2).

Table 2. Phosphorus and Total Copper Mean Reduction Results for Sorption Testing.[a]

Media Name	Phosphorus Mean Reduction[b]	Total Copper Removal – All Solutions	Total Copper Removal – High Cu Solutions Only[c]
WTR	**(percent)**	**(percent)**	**(percent)**
Al-WTR1	98 ± 0.28	-95 ± 28	88 ± 0.72
Al-WTR2	93 ± 0.90	-77 ± 31	86 ± 0.80
Fe-WTR	86 ± 2.0	-2,100 ± 380	3.8 ± 9.6
Ca-WTR	75 ± 2.4	8.6 ± 14	94 ± 0.19

Notes

[a] Results from Kates (2019)

[b] Starting solution contained a minimum of 2.78 mg/L TP.

[c] Low Total Cu solutions contained between approximately 1 and 8 ug/L Cu. High Total Cu solutions contained between approximately 30 and 92 ug/L Cu (Kates 2019).

Abbreviations

Al = Aluminum

Ca = Calcium

Cu = Copper

Fe = Iron

WTR = Water Treatment Residual

Results and Discussion

Table 1 summarizes the leachable total Cu and TP as measured in each organic component and WTR used in Kates' study. Total Cu in WTRs ranged from 30.7 to 119 mg/kg, and TP ranged from 0.543 to 147 g/kg (Table 1). Organic component total Cu composition ranged from 32.2 to 485 mg/kg, while TP ranged from 2.19 to 29.9 g/kg. Prior studies (Mullane et al. 2015; Herrera 2020) have shown copper export from BSMs that contain compost. In Table 1 ComFY (organic compost sourced from Seattle) has a leachable total Cu concentration of 57.2 mg/kg and two of the three WTRs have total Cu concentrations that exceed this value, 69.5 mg/kg for Al-WTR2 and 119 mg/kg for Fe-WTR. This would indicate that the Fe-WTR material in particular may be a source of copper when used in bioretention. This result was further supported by the sorption testing results.

Table 2 summarizes mean reduction and removal rates for WTRs spiked with synthetic stormwater solutions. Removal of TP varied by WTR, with the highest TP removal provided by the Al-WTR1 and Al-WTR2. Starting solution TP concentrations were never lower than 2.78 mg/L. Typical stormwater in western Washington averages between 0.1 to 0.23 mg/L, depending on the land use (Ecology 2011), so the concentrations used in this study are not comparable to those which would be encountered in typical stormwater. This makes extrapolation of these results to the field difficult. However, the relative comparison between the WTRs is still informative.

Two separate total Cu solutions were used in the sorption assessment. A low concentration solution (ranging from 1 to 8 ug/L) and a high concentration solution, ranging from 30 to 92 ug/L. Total Cu in stormwater in western Washington averages 3.1 to 28.4 ug/L depending on land use (Ecology 2011), so the lower concentration test is a more accurate analog for potential performance in the field. In the low concentration test total Cu export occurred for each WTR, with the highest total Cu export coming from Fe-WTR. This was expected since Fe-WTR contained significantly more initial copper than the other three WTRs (see Table 1). This is an important finding because this WTR is local to Seattle and thus is a prefered source for potential use in the City; however, these results indicate that the material could be a potential source of Cu when influent stormwater concentrations are at or below 8 ug/L.

Column Studies

As discussed above, several methods have been used for examining how WTRs as a BSM additive affect TP and Cu removal. These methods include column testing, mesocosm testing, full scale bioretention cell testing, and incubation testing. This section focuses on results from column studies.

Methodology

Column studies typically consist of injecting a collected or spiked stormwater solution into a column containing 18 inches or more of BSM. The effluent from the bottom of the column is collected and the chemistry is compared with influent chemistry. Results from two relevant column studies are discussed herein.

A recent local study by Jay et al. (2018) used stormwater from a major Seattle highway bridge to dose columns containing BSMs with various combinations of sawdust, oyster shells, sand, and WTRs. The WTRs used for this study were the same Fe-based WTRs from Seattle that were used in Kates (2019), so the results, discussed in the next section, are of particular interest. Stormwater was applied to the columns to simulate Seattle storm events with a return interval of 0.2 years or 1 year. Fourteen events in total were run, but only results from the last four events (after the columns were flushed) were presented in the findings.

Qiu et al. (2019) describes another column study conducted using a WTR as an amendment to a sandy loam BSM to determine TP and Cu removal efficiency. The WTR used in their study was collected from a surface water treatment plant in Beijing, China. The coagulant used at the treatment plant was polyaluminum chloride (PAC). Synthetic stormwater was introduced into the columns in a sequential batch mode, and columns were tested under conditions simulating a bioretention system capturing stormwater from an impervious catchment whose area was 20 times that of the bioretention area. Columns were tested for 10 runs without a water storage zone, and then for an additional 10 runs with a water storage zone of 40 centimeters. Sandy loam with no additives was tested as a control in this study, and sandy loam with 15 percent WTR by weight was tested to analyze the effects of WTRs as an additive in BSMs. The BSMs in this study did not contain compost. Results are discussed in the next section.

Results and Discussion

Phosphorus Results

In the column study conducted by Jay et al. (2018), it was determined that all compost-based BSMs were a source of TP (even after flushing with 10 events); however, BSMs with WTRs (see C BY 17.5 WTR 2.5 and C BY 35 WTR 5 in Table 3 reduced TP export when compared to BSMs without WTRs. As seen in Table 3, TP in effluent from BSMs containing WTRs ranged from 4.0 to 4.7 mg/L, while TP in effluent from BSMs containing no WTRs averaged a higher concentration of 13.1 mg/L. Since influent TP concentrations (0.08 mg/L) in the study were close to the range of concentrations found in western Washington stormwater (Table 3), these results indicate that WTRs may be helpful in reducing TP export from BSMs that contain compost, but will still not result in a net TP removal from the influent stormwater.

In Qiu et al. (2019), influent TP concentrations in the spiked stormwater solution (2.5 to 7.0 mg/L) were much higher than concentrations typically found in western Washington stormwater (0.1 to 0.23 mg/L, Ecology 2011). Despite these high influent concentration, effluent concentrations from the treatment with WTRs were very low, averaging only 0.015 mg/L As seen in Figure 1, the control column (C1, no WTR) had very limited TP removal capacity, and the effluent concentration increased immediately after the first test run. By the sixth test run, effluent TP concencrations were very close to influent TP concentrations. The average TP reduction for C1 was only 22 percent. Conversely, C2, the column containing 15 percent WTR by weight, showed highly effective removal of TP, with an average TP removal of 99.6 percent. These results indicate the potential for effective TP removal when WTRs are added to BSMs that do not contain compost.

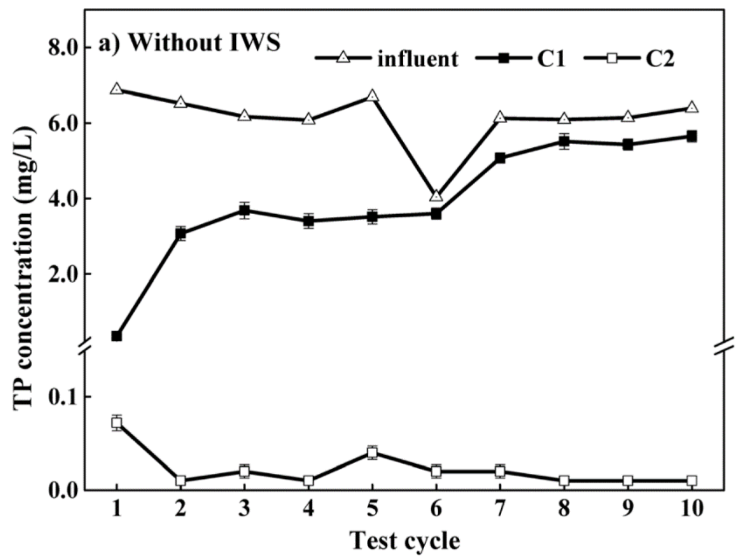

Figure 1. Total P Removal by Bioretention Columns Without a Water Storage Zone (from Qiu et al. [2019]).

Table 3. Phosphorus Performance for Various BSMs With and Without WTRs.

Source	WTR/ Control	Treatment Media	Typical PNW TP Influent Concentrations[a]	Average TP Influent Concentration	Average TP Effluent Concentration	Percent Reductio n
Column Studies						
Jay et al. (2018)	Control	"C BY 40": Biosolids/Yard Compost (40%), Sand (60%) by volume	0.1 to 0.23 mg/L	0.08 mg/L	13.1 mg/L	-16,275[b]
	WTR	"C BY 17.5 WTR 2.5": Biosolids/Yard Compost (17.5%), Sand (80%), WTR (2.5%) by volume	0.1 to 0.23 mg/L	0.08 mg/L	4.0 mg/L	-4,900[b]
	WTR	"C BY 35 WTR 5": Biosolids/Yard Compost (35%), Sand (80%), WTR (5%) by volume	0.1 to 0.23 mg/L	0.08 mg/L	4.7 mg/L	-5,775[b]
Qiu et al. (2019)	Control	Sandy Loam (100%) by weight	0.1 to 0.23 mg/L	2.5 to 7.0 mg/L	Not Provided	22
	WTR	Sandy Loam (85%), WTR (15%) by weight	0.1 to 0.23 mg/L	2.5 to 7.0 mg/L	0.015 mg/L[c]	99.6
Mesocosm Container Studies						
Knappenberger and Stark (2014)	Control	"Mix20": Sand (80%), Compost (20%)	0.1 to 0.23 mg/L	Not Provided	0.187 to 0.535 mg/L	28.1
	Control	"Mix40": Sand (60%), Compost (40%)	0.1 to 0.23 mg/L	Not Provided	0.202 to 0.377 mg/L	23.3
	WTR	"Mix15": Sand (60%), Compost (15%), Shredded Bark (10%), WTR (15%)	0.1 to 0.23 mg/L	Not Provided	0.1610.375 mg/L	39.6
	WTR	"Mix30": Sand (60%), Compost (30%), WTR (10%)	0.1 to 0.23 mg/L	Not Provided	0.257 to 0.680 mg/L	5.2
Liu et al (2014)	Control	"Biofilter": Saprolite (25%), Papermill Sludge (20%), Sand (55%) by volume	0.1 to 0.23 mg/L	0.10 to 1.0 mg/L	Not Provided	76.0
	WTR	"TerraSolve": Coir and Peat (15%), Shredded Hardwood Mulch (9%), WTR (12%), sand (58%) by volume	0.1 to 0.23 mg/L	0.10 to 1.0 mg/L	Not Provided	90.7
	WTR	"VT Mix": WTR (3%), Saprolite (15%), YWC (25%), Medium Sand (57%) by volume	0.1 to 0.23 mg/L	0.10 to 1.0 mg/L	Not Provided	78.5

Notes

[a] Values from Ecology (2011), Attachment A.

[b] Percent reductions calculated based on overall means reported in this table. Jay et al. (2018) did not independently calculate these values.

[c] After 10 test runs, total effluent P leveled out to an average value.

Abbreviations

BSMs = Bioretention Soil Mixes
TP = Total Phosphorus
PNW = Pacific Northwest
mg/L = milligrams per liter
ug/L = micrograms per liter
YWC = Yard Waste Compost

Copper Results

Jay et al. (2018) found that the addition of WTRs to compost-based BSMs resulted in improved total Cu removal; however, the results were highly variable; and the influent concentrations were higher than what would be encountered in typical stormwater in western Washington. As seen in Table 4, "C BY 40" (no WTRs) had a total Cu removal of approximately 67 percent, "C BY 17.5 WTR 2.5 (2.5 percent WTRs by volume) had a total Cu removal of approximately 80 percent, and "C BY 35 WTR 5" (5 percent WTRs by volume) had a total Cu removal of 51.5 percent. These numbers were statistically insignificant; therefore, no conclusion could be made about how the introduction of WTRs in BSMs affect total Cu performance. Dissolved Cu followed the same pattern wherein no obvious conclusion could be made.

Similarly, in Qiu et al. (2019), both the BSM containing WTRs and the BSM containing no WTRs had total Cu removal efficiencies between 96.8 and 99.9 percent (at both low and high initial Cu concentrations). These similar values are indicative that the addition of WTRs to BSMs has little to no effect on Cu removal in treated stormwater. See Table 4 for a summary of total and dissolved copper performance for these two studies.

Neither of these studies indicated a clear increase in copper concentration in the effluent after WTRs were added to the BSMs. So, unlike the Kates (2019) incubation results, Cu export from the WTRs was not observed. However, it should be noted that there may have been a copper flush in the Jay et al. (2018), but they did not report the chemistry of the first 10 runs.

Mesocosm Studies

Methodology

Mesocosm studies use large containers filled with media to simulate a bioretention facility. Similar to column studies, mesocosms are typically dosed with a collected or spiked stormwater solution and the effluent is collected and measured for water quality parameters. Liu et al. (2014) conducted a mesocosm study that consisted of multiple 256 L food-grade plastic storage drums filled with one of three media types: "Biofilter" containing no WTRs; "VT Mix" containing 3 percent WTRs by volume; and "TerraSolve" containing 12 percent WTRs by volume. Similarly, Knappenberger and Stark (2014) conducted a mesocosm container study at the LID Research Facility in Puyallup, Washington, using 60-inch-diameter containers. Four types of BSMs were analyzed in the study: "Mix20" and "Mix40" containing no WTRs (20 percent compost and 40 percent compost, respectively); and "Mix15" and "Mix30" containing 15 and 30 percent compost, and 15 and 10 percent WTRs, respectively. Results from these two mesocosm studies are discussed below.

Table 4. Copper Performance for Various BSMs With and Without WTRs.

Source	WTR/ Control	Treatment Media	Total Copper				Dissolved Copper			
			Typical PNW Influent Concentration[a]	Average Influent Concentration	Average Effluent Concentration	Percent Reduction	Typical PNW Influent Concentration[a]	Average Influent Concentration.	Average Effluent Concentration	Percent Reduction
Column Studies										
Jay et al. (2018)	Control	"C BY 40": Biosolids/Yard Compost (40%), Sand (60%) by volume	3.1 to 28.4 ug/L	39.8 ug/L	12.9 ug/L	67.6[b]	2.26 to 11.06 ug/L	18.2 ug/L	9.8 ug/L	46.1[b]
	WTR	"C BY 17.5 WTR 2.5": Biosolids/Yard Compost (17.5%), Sand (80%), WTR (2.5%) by volume	3.1 to 28.4 ug/L	39.8 ug/L	7.8 ug/L	80.4[b]	2.26 to 11.06 ug/L	18.2 ug/L	5.1	72.0[b]
	WTR	"C BY 35 WTR 5": Biosolids/Yard Compost (35%), Sand (80%), WTR (5%) by volume	3.1 to 28.4 ug/L	39.8 ug/L	19.3 ug/L	51.5[b]	2.26 to 11.06 ug/L	18.2 ug/L	12.8 ug/L	29.7[b]
Qiu et al. (2019)	Control	Sandy Loam (100%) by weight	3.1 to 28.4 ug/L	63.0 ug/L	2.0 ug/L	96.83	2.26 to 11.06 ug/L	Not Provided	Not Provided	N/A
	Control	Sandy Loam (100%) by weight	3.1 to 28.4 ug/L	1461 ug/L	9.0 ug/L	99.38	2.26 to 11.06 ug/L	Not Provided	Not Provided	N/A
	WTR	Sandy Loam (85%) WTR (15%) by weight	3.1 to 28.4 ug/L	63.0 ug/L	1.0 ug/L	98.41	2.26 to 11.06 ug/L	Not Provided	Not Provided	N/A
	1 WTR 0	Sandy Loam (85%) WTR (15%) by weight	3.1 to 28.4 ug/L	1461 ug/L	1.0 ug/L	99.93	2.26 to 11.06 ug/L	Not Provided	Not Provided	N/A
Mesocosm Container Studies										
Knappenberger and Stark (2014)	Control	"Mix20": Sand (80%), Compost (20%)	3.1 to 28.4 ug/L	Not Provided	2.4 to 14.5 ug/L	74.2	2.3 to 11.1 ug/L	Not Provided	2.0 to 9.2 ug/L	58.0
	Control	"Mix40": Sand (60%), Compost (40%)	3.1 to 28.4 ug/L	Not Provided	2.9 to 12.3 ug/L	72.1	2.3 to 11.1 ug/L	Not Provided	2.5 to 10.2 ug/L	43.2
	WTR	"Mix15": Sand (60%), Compost (15%), Shredded Bark (10%), WTR (15%)	3.1 to 28.4 ug/L	Not Provided	2.5 to 6.6 ug/L	69.5	2.3 to 11.1 ug/L	Not Provided	2.4 to 11.4 ug/L	48.8
	WTR	"Mix30": Sand (60%), Compost (30%), WTR (10%)	3.1 to 28.4 ug/L	Not Provided	2.7 to 21.1 ug/L	67.9	2.3 to 11.1 ug/L	Not Provided	2.5 to 14.5 ug/L	47.2

Notes

[a] Values from Ecology (2011), Attachment A.

b Percent reductions calculated based on overall means reported in this table. Jay et al. (2018) did not independently calculate these values.

Abbreviations

PNW = Pacific Northwest

WTR = Water Treatment Residual

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Results and Discussion

Phosphorus Results

In Knappenberger and Stark (2014), all four BSMs performed similarly in terms of TP reduction. As seen in Figure 2, “Mix20,” “Mix40,” and “Mix15” had similar TP effluent concentrations, while “Mix30” had slightly higher TP effluent concentrations. “Mix30” had an average TP reduction of 5.2 percent, less efficient than the other three BSMs with ranges from 23.3 to 39.6 percent. This difference was found to be statistically significant; however, the author of this study was unable to make any recommendations based on these results. These results again confirm that when compost is present in the BSM the addition of WTRs does not make the filter effective at reducing influent TP concentrations. See Table 3 for a summary of TP reduction results.

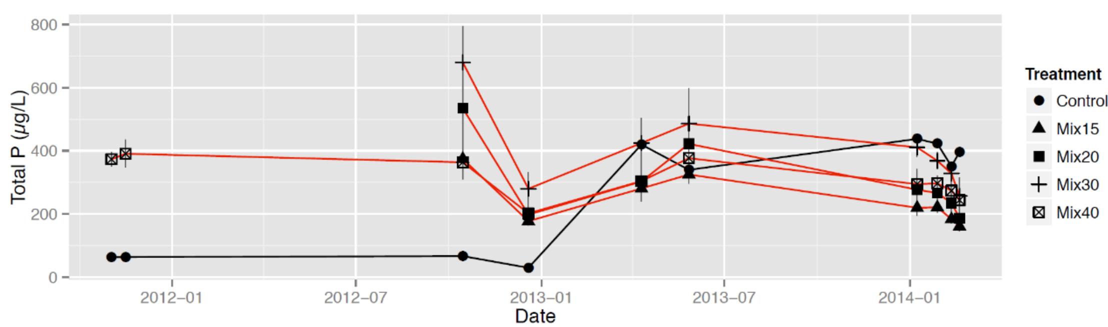

Figure 2. Total P Effluent Concentrations and Relative Values with Respect to Control (Knappenberger and Stark [2014], Figure 4.45).

In Lui et al. (2014), two of the three BSMs did not contain compost and exhibited increased TP reduction with increased hydraulic residence time as seen in Table 5; however, "TerraSolve," the BSM with the highest amount of WTRs by volume at 12 percent and no compost, had consistently high TP reduction rates when compared to "Biofilter" (no WTRs) and "VT Mix" (3 percent WTRs by volume). This study corroborates results from Qiu et al. (2019) indicating that when WTRs are added to BSMs that do not contain compost, the result is a filter that is quite effective at TP capture. See Table 3 for a summary of TP removal results from this study where TP removal results are reported for the 6-hour residence time (typical for bioretention with an underdrain) presented in Table 5.

Table 5. Bioretention Media P Reduction (Lui et al. [2014], Table 9).

HRT†	Bioretention media P reduction		
	Biofilter	TerraSolve	VT Mix
h	%		
1	54.1	90.8	58.2
6	76.0	90.7	78.5
12	82.4	95.1	94.0
24	93.7	97.9	97.9
48	96.0	98.9	98.2
Linear	0.0003‡	0.0012‡	<0.0001‡
Quadratic	0.0057‡	NS§	<0.0001‡

† Hydraulic retention time.

‡ *p* value or nonsignificant indicator as determined by linear and quadratic contrast.

§ Not significant.

Copper Results

Knappenberger and Stark (2014) found no statistically significant differences in Cu performance with the addition of WTRs to BSMs. The mesocosms exported total and dissolved copper for the first four events then acted as copper sinks for the last six events. The two mixes containing WTRs ("Mix30" and "Mix15") had the highest initial copper flush, but then performed similarly to the other BSMs for the remainder of the study. This may indicate a flushing pattern associated with WTRs, where copper removal improves after an initial flushing period. Lui et al. (2019) did not perform an analysis on the effects of WTRs on total and dissolved Cu performance.

Summary and Next Steps

Bioretention systems have been shown to be effective at removing a wide variety of target pollutants (Geosyntec and Wright Water 2014), however BSMs containing compost result in varying degrees of TP and Cu export (Mullane et al. 2015; Herrera 2020). The addition of WTRs in BSMs has been studied to determine the effect on TP and Cu export and/or removal. The goal of adding WTRs to BSM is to ameliorate export when compost is present or increase overall performance in non-compost BSMs. This literature review was conducted to assess if further study of WTR addition to compost-based BSMs is warranted.

The City of Seattle is particularly interested in the Fe-based WTRs, which are sourced locally. These Fe-based WTRs were used in two of the studies presented herein, Kates (2019) and Jay et al. (2018). These studies found that these WTRs are rich in copper, but that the copper likely flushes from the system within the first year of operation. After the copper has flushed from the system, there does not appear to be a net benefit to copper removal. These WTRs appear to be effective at sorbing TP, but the studies focused on compost-based BSMs and the WTRs were not effective enough to prevent the BSMs from exporting TP. This indicates that the addition of Fe-based WTRs to Seattle's 70 percent sand/30 percent standard BSM will not prevent the BSM from acting as a source of TP. This finding was corroborated by Knappenberger and Stark (2014) in their study at the LID research facility in Puyallup, Washington, which showed no net TP reduction benefit when WTRs were added to compost-based BSMs.

Two of the studies presented herein, Lui et al. (2014) and Qiu et al. (2019), found that the addition of WTRs to BSMs that did not contain compost improved TP removal by 14 to 77 percent. So, it appears that when compost is not present, the addition of WTRs can result in a significant TP reduction benefit.

It should be noted that Kates (2019) and Jay et al. (2018) did not look at layered systems where the compost-based BSM is underlain by a "polishing layer," which could consist of sand and WTRs with no compost. This configuration would likely result in better performance as has been demonstrated in another recent local study that showed an 89 percent TP reduction with the use of iron and activated alumina in a polishing layer beneath a compost-based BSM (Herrera 2016b). If, after reviewing these findings, the City remains interested in pursuing the use of WTRs in their compost-based BSMs, we suggest conducting a study with a WTR-based polishing layer configuration.

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