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ADVANCING THE USE OF DWTR IN STORMWATER TREATMENT FEATURES TO ENHANCE PHOSPHORUS REMOVAL FOR TRANSPORTATION PROJECTS

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16. Abstract

Stormwater runoff from urban areas threatens water quality and ecosystems around the world. For freshwater ecosystems, phosphorus (P) is often a primary concern, as excess P loading can cause eutrophication, symptoms of which include harmful algal blooms and oxygen depletion. Dissolved P forms are taken up by primary producers and are therefore a particular concern for water quality. To mitigate these threats, stormwater control measures are often employed to reduce P loading. Sand filters are a type of stormwater management practice that primarily function to trap particulates and thereby reduce downstream sediment and P loads. However, sand filters typically exhibit a negligible capacity to retain dissolved P forms, due to low P sorption capacity of sand. To target both particulate and dissolved P species in stormwater, a P-sorbing material amendment can be added to sand filter media to increase P sorption capacity. This project examined the use of alum-based drinking water treatment residuals (DWTRs), a waste byproduct of drinking water treatment plants, to enhance P removal in sand filter media. The research centered on a field study to determine stormwater P load reductions provided by DWTR-amended sand filters in transportation projects under real-world conditions. Two stormwater sand filters enhanced with DWTRs (3-5% of the sand layer by volume) were monitored from Fall 2022 to Spring 2024 in Chittenden County, VT. One filter receives runoff from a small catchment (1.8 acres) at a residential site (A) and the other from a larger catchment (4.5 acres) in an industrial/commercial area (B). The composition of influent stormwater was markedly different between sites, dominated by dissolved P at the residential site, and mostly particulate P at the more industrial/commercial site. Due to this difference in influent water quality, >99% of the total P removed at the residential sand filter was in the form of dissolved P, while only 4% of the total P load removed at the industrial/commercial site was dissolved P. Because removal of dissolved P by sand filters tends to be negligible, the dissolved P load reductions observed at both sites are likely attributable to the DWTRs. Overall, the two systems reduced total P loads by 65-78% during the monitored events. This field study indicates that including DWTRs in sand filter media is an effective way to couple both physical and chemical P removal mechanisms and thereby enhance water quality improvement performance. We provide guidance on future use of DWTRs in stormwater infrastructure based on our

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ABSTRACT

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1. INTRODUCTION

An important focus in stormwater management is the mitigation of phosphorus (P) loading into aquatic ecosystems, which can negatively impact water quality and is rapidly cycled in urban environments (Reddy et al. 1999; Khan et al. 2021). One type of stormwater control measure used in urban areas is a sand filter, which filters out particles and particulate-bound nutrients and contaminants. Zarezadeh et al. (2018) found that an urban stormwater sand filter removed 94% of total suspended solids but exhibited a negligible removal of orthophosphate ions. This limitation has long been observed in stormwater sand filtration studies (Tofflemire & Chen 1977; Ament et al. 2021; Bolster 2021). Therefore, researchers have investigated potential use of various amendments with high P sorption capacity in sand filter media (Erickson et al. 2007; Fairbairn & Trojan 2023; Wang et al. 2021). Among the most promising of these amendments is drinking water treatment residuals (DWTRs), particularly aluminum-based materials. DWTRs are byproducts of the drinking water treatment process. They generally have greater surface areas than alternative P sorbing materials, allowing for greater P sorption capacity (Wang et al. 2021; Chiang et al. 2012). DWTRs are widely available, economical, and provide comparable P removal to other sorbents (Lin et al. 2014; Shen et al. 2019). For example, a study by Adhikari et al. (2016) found that alum sludge removed the greatest percentage of TP (99%) from synthetic stormwater when compared to other P-sorbing materials such as clay (~20%), fly ash (~15%), mulch (~15%), and dolomite (~25%).

It is estimated that 40% of DWTRs are trucked to a landfill in the United States, the most typical method for disposal (Turner et al. 2019). Additionally, DWTRs are often generated in urban areas (Pikaar et al. 2022; Turner et al. 2019), proximal to urban stormwater BMPs such as sand filters. Thus, use of DWTRs in engineered stormwater BMPs introduces opportunities for a circular economy within the water treatment sector to minimize impacts on the environment (Li et al. 2018).

However, DWTR performance can be variable due to material heterogeneity (Belzile & Chen 2024). This variability is driven by the nature of water sources, the coagulant added at the water treatment plant, storage and dewatering methods, and any additional processing (Li et al. 2019a; Ren et al. 2020, Wang et al. 2021, Li et al. 2022). For use in stormwater treatment applications, it is recommended to obtain samples from multiple sources and examine their

compatibility for P retention through laboratory batch tests and column experiments (Rahmati et al. 2022; Ament et al. 2021; Kubow 2022). Performance variability for DWTRs is evident across existing studies. For example, the DWTRs used in a column study by Kaspryzk et al. (2020) had a 50% PO_4-P adsorption efficiency, which is lower in comparison to Wang et al. (2021) who reported over 85% removal of PO_4-P. Similarly, Leader et al. (2008) studied twelve different DWTR sources and reported average P sorption rates from 66 to 990 mg P kg^{-1}. Both aluminum-based DWTRs (Al-DWTRs) and iron-based DWTRs (Fe-DWTRs) have promising kinetic performance for P removal, however, DWTRs derived from aluminum-based coagulants tend to perform better. In Makris et al. (2004), Al-DWTRs exhibited sorption rates of 7,700 mg P kg^{-1}, which was nearly four times greater than iron-based DWTRs (Fe-DWTRs). Similarly, Ippolito et al. (2011) reported total P sorption by Al-DWTRs as 2,157 mg P kg^{-1} compared to Fe-DWTR's 710 mg P kg^{-1}.

This VTrans-funded project builds on prior research at the University of Vermont (UVM) that examined DWTR characteristics and P sorption performance in both the lab and field (Ament et al. 2021, Ament et al. 2022, Kubow 2022). In Ament et al. (2021), column tests containing DWTRs were conducted to determine the impacts of layering media on P sorption. It was found that inclusion of DWTRs as a solid layer negatively impacts hydraulic conductivity, restricting water flow, whereas DWTRs that are mixed uniformly throughout the media do not impede flow and had nearly 100% P removal. Then, in Ament et al. (2022), this uniformly mixed design was applied to a bioretention study, where it was observed that 77-93% of the cumulative dissolved P load was removed from influent runoff. These researchers also noted that methods used to estimate P sorption capacity of DWTRs can also influence results (Ament et al. 2021). Along these lines, in a study of eleven Al-DWTRs sourced from drinking water treatment facilities in US EPA Region 1, Kubow (2022) observed mean P sorption capacities ranging from 1,347 to 18,160 mg P kg^{-1} and 421 to 9,576 mg P kg^{-1} for batch isotherms and low P/high flow column experiments, respectively. The latter method (low P/high flow columns) was designed to approximate field conditions (1 mg P L^{-1}, ~3 min contact time) and is therefore more likely to yield results appropriate for estimating field performance. Furthermore, Kubow (2022) found that DWTRs characterized by lower bulk density (<1.0 g cm^{-3}, especially <0.6 g cm^{-3}) and greater oxalate-extractable Al+Fe (>3,000 mmol kg^{-1}) tended to provide the greatest P sorption capacity in low P/high flow column experiments.

To date, no other published field studies on stormwater P reduction by sand filters enhanced with Al-DWTRs have been identified. Studies with Al-DWTR-enhanced sand filtration have not advanced from laboratory modeling (Erickson et al. 2007; Vu and Wu 2019; Codling and Isensee 2005) to field studies with inherently less predictable stormwater runoff characteristics and environmental conditions. Existing sand filter field studies include a conventional sand filter (Urbonas 1999), and those that contain different amendments such as iron filings (Erickson et al. 2017; Fairbairn and Trojan 2023), lime (Kuster et al. 2022), or bentonite (Wang et al. 2021).

Our study objectives were to: (1) Investigate the capacity of enhanced stormwater treatment systems incorporating Al-DWTRs to retain total P, soluble reactive P, dissolved organic P, particulate P, and chloride in field contexts, and (2) Translate research findings into actionable recommendations for DWTR use in VTrans projects.

2. MATERIALS AND METHODS

2.1. Site Description

This study was conducted with two newly constructed stormwater sand filter BMPs in Chittenden County, Vermont (VT), USA (**Table 1**). Sand filter A (44.487676, -73.090748) is in a residential cul-de-sac with a drainage area of 7,309 m^2. Sand filter B (44.458293, -73.135370) is along a heavily traveled four lane road adjacent to industrial/commercial businesses with a drainage area of 18,251 m^2.

Table 1. Sand filter site characteristics.

Sand Filter	Location	Site Area (ac)	Pervious Area (ac)	Impervious Area (%)	Dominant Hydrological Soil Group
A	Essex Junction, VT	1.806	1.102	39	A
B	South Burlington, VT	4.510	2.770	39	D

For sand filter A, water that passes through the system is conveyed to a plunge pool and disperses into a small stream, and water from site B is conveyed to a stone-lined slope before being discharged into a brook. Both have a sedimentation chamber that precedes filtration and an impermeable bottom that does not allow for infiltration into soil (**Fig. 1**). The structure of sand filter A measures 3.66 m x 1.83 m x 1.40 m (12' L x 6' W x 4.6' D) with its sand layer (0.3 m D) including 3% by volume Al-DWTRs mixed within the sand layer. The structure of sand filter B is larger at 16.15 m x 4.27 m x 3.05 m (53' L x 14' W x 10' D) with its sand layer including 5% by volume Al-DWTRs mixed within the sand layer. The construction of sand filters A and B by independent contractors was completed in Fall 2022 and 2023, respectively, under the jurisdiction of the Vermont Agency of Transportation. For additional site-specific information, refer to **Appendix A.**

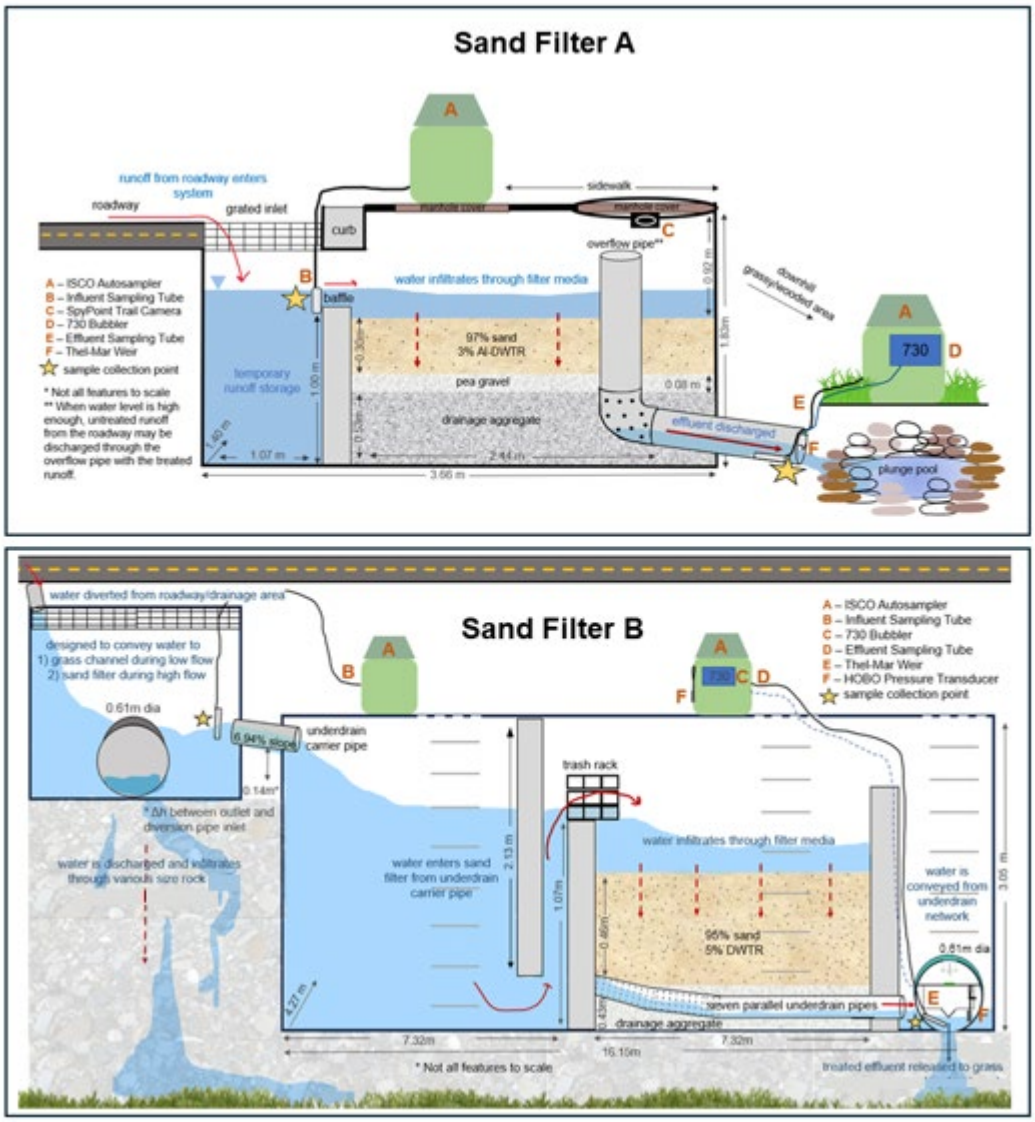

Figure 1. Sampling schematics of Sand Filters A and B show the design and equipment used for stormwater monitoring.

2.2. DWTR Characterization

DWTRs used in the field study were obtained from Champlain Water District (CWD), a regional water treatment plant (WTP) that supplies drinking water to twelve municipal water systems in Northern Vermont (Champlain Water District 2016). A 5-gallon bucket of DWTRs was collected during this study to re-examine key characteristics deemed most indicative of P sorption capacity (Kubow 2022, Bai et al. 2014): bulk density, porosity, oxalate-extractable Al, Fe, and P, and bulk chemistry (Al, Fe, and Ca). A triplicate sample of the material (~750g each) was dried in an oven at 80°C for over 12 hours, cooled, weighed, and returned to the oven until masses were within 1% of the previous weight. Then, bulk density was determined by calculating the dry weight to bulk volume ratio of the media (Drizo et al. 1999). Porosity was measured gravimetrically as the amount of water needed to saturate the mass of media used to determine bulk density (Brix et al. 2001).

The bulk chemical composition of the DWTRs collected from the visit to CWD was obtained through acid digestion, lithium borate fusion, and ICP-MS analysis by an external laboratory (ALS Geochemistry, Reno, NV). Amorphous aluminum and iron oxides were determined at the University of Vermont on 0.40g of sieved and ground DWTR using 0.2 M acid ammonium oxalate (1:100 solid:solution extraction ratio) followed by ICP-AES analysis in triplicate (AETL, Burlington, VT) (Dayton and Basta 2005). The P Saturation Ratio (PSR) was then calculated as [$P_{ox}/(0.5 \times Al_{ox} + Fe_{ox})$)) x 100] with P_{ox}, Al_{ox}, and Fe_{ox} expressed in mmol/kg (Nair and Harris 2004; Ament et al. 2021).

2.3. Stormwater Sampling

Stormwater runoff was monitored at inflow and outflow points with two separate autosamplers (Teledyne ISCO 6712, Lincoln, NE) at each sand filter. A 90° V-Notch compound weir (Thel-Mar, LLC, Lima, OH) was installed into the outflow pipe (which discharges the treated effluent from the sand filters) at both sites, in addition to a flow module (Teledyne 730 Bubbler, Lincoln NE), which was used to determine the stage height and therefore volume for nutrient load estimates. The weir for sand filter A was 38.1cm (15") in diameter and the weir for sand filter B was a 38.1cm (15") weir adapted to 61cm (24"), maintaining its V-notch shape. An additional two pressure transducers (Onset, HOBO U20L, Bourne, MA) were submerged at the outflow to gather information about ambient pressure and stage height for 24-hour flow monitoring. At sand filter A, untreated runoff entering an overflow pipe also discharges where treated effluent samples were collected. Therefore, results from site A may underestimate the performance of the sand filter media as the effluent could have been diluted with untreated water in higher flow events. To address this issue, a camera (SpyPoint, FORCE-20, Québec, CA) was installed on the inside of the manhole cover above the overflow pipe to visually identify events during which runoff bypasses the filter media and may affect the filter's estimated performance (events where bypass likely occurred are marked with an asterisk in **Table 2**). These results were not removed from the study. At sand filter B, the design allows some runoff to be discharged directly into a stone-lined slope instead of flowing into the sand filter structure. This is due to the pipe into the sand filter being slightly higher in elevation than the pipe diverting water directly to the stone-lined slope. Based on visual inspection, there was a constant flow of water conveyed directly to the stone-lined slope in both wet and dry periods. This effluent not treated by the sand filter was not monitored during this study.

Inflow volumes to the sand filters were assumed to be equal to the outflow amounts because there is no opportunity for infiltration through the concrete base. At the discharge pipe, the flow modules measured the height at 1-minute intervals and were adjusted to determine the height above the V-notch. These stage height measurements were converted to flow rates using the following equation (Teledyne 2016):

$$Q(t) = L/s = 1380\ H^{2.50} \qquad \textbf{(Equation 1)}$$

Time-based sampling was used to monitor inflow and outflow stormwater quality simultaneously for precipitation events greater than 2 mm. Samples were collected in standard 1-L PE bottles. Each bottle represented 1 hour of sampling with 3-100 mL samples taken in 20-minute intervals. At the end of the event, samples were composited into three inflow and three outflow samples and prepped for analysis within 24 hours of the first sample taken. If the event was longer than 24 hours (n=3 events at Site A, n = 0 events at Site B), samples were retrieved and prepped for analysis, and the sampling program was restarted for an additional set of six samples. Rainfall amounts were recorded from Burlington International Airport retroactively, which is within a 5 km radius of both sites.

Table 2. Summary of Monitored Precipitation Events. Events with evidence of observed overflow via trail camera are indicated with an asterisk (*).

Event	Date(s)	Estimated Duration (hr)	Estimated Precipitation (mm)	Event Type	Intensity Classification	Antecedent Dry Days (d)
Site A (7309 m^2 drainage area)						
1	11/30/2022 - 12/1/2022	6 hr 30 min	17.8	Rain, Snow	Moderate	1
2	12/3/2022	2 hr 30 min	2.5	Rain	Light	2
3	12/7/2022	17 hr 50 min	17.8	Rain	Moderate	9
4	5/2/2023	14 hr 30 min	7.6	Rain	Light	9
5	5/20/2023 - 5/21/2023	3 hr 10 min	15.2	Rain	Heavy	3
6	5/24/2023	6 hr 10 min	7.6	Rain	Light	2
7	6/6/2024	7 hr	10.2	Rain	Light	11

8	6/13/2024	7 hr 10 min	7.6	Rain	Heavy	4
9*	6/14/2024	7 hr 40 min	22.9	Rain	Moderate	0
10	6/16/2024	7 hr 5 min	12.7	Rain	Light	1
11	6/17/2024	12 hr 30 min	12.7	Rain	Light	0
12*	6/24/2024	8 hr 10 min	63.5	Rain	Heavy	6
13	6/26/2024	7 hr	2.0	Rain	Light	0
14*	6/28/2024	4 hr 40 min	20.3	Rain	Light	0
15	7/1/2024 - 7/2/2024	15 hr 30 min	2.3	Rain	Moderate	2
16	7/7/2024	3 hr 40 min	2.3	Rain	Light	4
17	7/9/2023 - 7/11/2023	38 hr 55 min	58.4	Rain	Moderate	1
18	7/16/2023	14 hr 40 min	50.8	Rain	Moderate	1
19	7/18/2023	2 hr 35 min	3.0	Rain	Light	2
20*	7/21/2023	5 hr	30.5	Rain	Moderate	2
21	7/27/2023	12 hr	30.5	Rain	Moderate	2
22	8/7/2023 - 8/8/2023	24 hr 30 min	36.3	Rain	Moderate	0
23*	8/10/2023	5 hr 30 min	35.6	Rain	Moderate	0
24	8/18/2023	11 hr 50 min	5.1	Rain	Moderate	0
25	8/25/2023	4 hr 40 min	17.8	Rain	Light	0
26*	9/7/2023	2 hr 10 min	5.1	Rain	Light	7
27	9/19/2023	10 hr	10.2	Rain	Moderate	4
28*	10/7/2023 - 10/8/2023	21 hr 20 min	74.9	Rain	Heavy	17
29	10/15/2023 - 10/16/2023	4 hr 30 min	9.1	Rain	Light	4
30*	10/21/2023 - 10/22/2023	26 hr 30 min	21.8	Rain	Moderate	5
Site B (18,251 m^2 drainage area)						
1	10/30/2023	12 hr 45 min	7.6	Rain	Light	1
2	11/7/2023 - 11/8/2023	4 hr 20 min	2.5	Rain	Light	5
3	11/9/2023	7 hr 10 min	12.7	Rain, Snow	Moderate	1
4	11/17/2023 - 11/18/2023	9 hr 20 min	22.9	Rain	Moderate	2
5	11/26/2023 - 11/27/2023	9 hr 10 min	53.3	Rain, Snow	Heavy	1
6	12/1/2023 - 12/2/2023	9 hr 40 min	7.6	Rain	Light	3
7	12/10/2023 - 12/11/2023	30 hr 5 min	30.5	Rain	Moderate	4
8	3/6/2024 - 3/7/2024	18 hr	29.2	Rain	Light	0
9	3/9/2024 - 3/10/2024	12 hr 30 min	19.1	Rain	Moderate	1
10	3/14/2024 - 3/15/2024	16 hr	16.5	Rain	Moderate	4
11	3/25/2024 - 3/26/2024	18 hr	16.0	Snow Melt	Light	1
12	4/5/2024 - 4/6/2024	20 hr 30 min	19.5	Snow Melt	Light	0
13	4/10/2024	6 hr	2.0	Rain	Light	3
14	4/12/2024	6 hr 10 min	17.5	Rain	Moderate	0
15	4/18/2024	12 hr	4.3	Rain	Light	2
16	4/24/2024	4 hr 50 min	3.0	Rain	Light	5
17	4/28/2024	5 hr 10 min	6.0	Rain	Light	0

2.4. Water Quality Analysis

All water samples were transferred immediately from the field sites to the Aiken Forestry Lab at UVM within 24 hours of the start of the first sample collected. Samples were analyzed for total phosphorus (TP), total dissolved phosphorus (TDP), and soluble reactive phosphorus (SRP). TP and TDP samples were stored in a closed box at room temperature until analyzed at the Agricultural and Environmental Laboratory (AETL) at UVM by a persulfate digestion using the autoclave method (APHA Method 4500-P). Samples for TDP and SRP analyses were filtered using a 0.45-µm filter prior to storage. The samples designated for SRP analysis were frozen for storage and thawed before being analyzed in house at the Aiken Forestry Lab using a malachite green method on a standard curve running from 0.01 to 1 mg PO_4-P L^{-1} (D'Angelo et al. 2001; Ruhatomo et al. 2019). Dissolved organic phosphorus (DOP) was calculated as the difference between TDP and SRP. Similarly, particulate P (PP) was calculated as the difference between TP and TDP. Small measurement errors may produce negative DOP or PP values. TP values were replaced with TDP values when TP < TDP and TDP values were replaced with SRP values when TDP < SRP (Ament et al. 2022).

2.5. Hydrologic and Water Quality Calculations

The total volume of water (V_{tot}) that passed through the system during each precipitation event was calculated piecewise by multiplying the average flow rate (Q(t) (L/s)) (**Equation 1**) by the associated time t (sec) corresponding to the range of discharge from the system (**Equation 2**) for each of the three composite outflow samples.

$$V_{tot} = \sum (Q(t)\,\Delta t)_1 + \sum (Q(t)\,\Delta t)_2 + \sum (Q(t)\,\Delta t)_3 \quad \textbf{(Equation 2)}$$

Similarly, the total mass of P (M_{tot}) that passed through the system for each precipitation event was calculated as the sum of the P loads corresponding to the three inflow composite samples, where P load is the product of the sample's P concentration (mg/L) and the volume of water that passed through the system (L). The inflow volumes (V) of each composite sample were assumed to be equal to their corresponding outflow sample's volume. Thus, the mass of P discharged from the outflow was determined similarly to the total volume (**Equation 3**).

$$M_{tot} = \sum C_1V_1 + C_2V_2 + C_3V_3 \quad \textbf{(Equation 3)}$$

The event mean concentration (EMC) was then calculated by dividing the total P influent mass load by the total flow volume for each event using the following calculation:

$$EMC = M_{tot}/V \quad \textbf{(Equation 4)}$$

The P removal efficiency was then determined by using the equation:

$$\text{Removal efficiency (\%)} = [(M_{influent}\text{-}M_{effluent})/(M_{influent})] \times 100 \quad \textbf{(Equation 5)}$$

2.6. Statistical Methods

Statistical analyses were performed to assess the differences in water quality between the paired influent and effluent data within each site. The paired data failed parametric tests for normality, thus the nonparametric test, Wilcoxon Signed Rank test, was used to evaluate the differences between influent and effluent concentrations and loads. Because there are significant differences in sand filter design, sites A and B are not compared statistically; rather influents and effluents for multiple storms are compared within the individual sites.

3. RESULTS AND DISCUSSION

3.1. DWTR Physical and Chemical Properties

The bulk density and porosity of the DWTR material was found to be 0.99 g/cm^3 and 0.52, respectively (**Table 3**). The oxalate-extractable Al, Fe, and P were 1892±117, 41±3, and 28±2 mmol kg^{-1}, yielding a phosphorus saturation ratio of 2.9%. This indicates substantial available P sorption sites as only 2.9% of the DWTR sorption sites are occupied (**Table 3**). See **Table 4** for metal concentrations in the DWTR sample.

Table 3. Summary of Select Physical and Chemical Properties of Al-DWTRs from CWD.

Physical Properties							
bulk density (g cm^{-3}) [a]		porosity (cm^3 water cm^{-3} DWTR) [a]					
0.99 ± 0.01		0.52 ± 0.02					
Chemical Properties				oxalate-extractable (mmol kg^{-1}) [a]			Phosphorus Saturation
Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Al_{ox}	Fe_{ox}	P_{ox}	% [b]
14.90	3.51	1.28	0.68	1892±117	41±3	28±2	2.9

[a] Values are reported as means with ±1 standard deviation (n=3).
[b] Calculated as $[(P_{ox}/(0.5 \times (Al_{ox} + Fe_{ox}))) \times 100]$

Table 4. DWTR sample metal concentrations (ppm). Results are shown as an average of three samples submitted to the laboratory (ALS Geochemistry, Reno, NV).

Ag	As	Cd	Co	Cu	Li	Mo	Ni	Pb	Tl	Zn
< 0.5	17.3	< 0.5	7	52.7	20	1	25.7	12	< 10	103.7
Ba	**Ce**	**Cr**	**Cs**	**Dy**	**Er**	**Eu**	**Ga**	**Gd**	**Hf**	**Ho**
333	33.7	48	1.06	3.3	1.9	0.7	10.4	3.2	10.7	0.7
La	**Lu**	**Nb**	**Nd**	**Pr**	**Rb**	**Sc**	**Sm**	**Sn**	**Sr**	**Ta**
16.8	0.3	11.2	16.7	4.4	31.1	7.6	3.5	1.2	107	0.7
Tb	**Th**	**Ti**	**Tm**	**U**	**V**	**W**	**Y**	**Yb**	**Zr**	
0.5	3.5	0.5	0.3	7.5	57	3.7	18.9	1.9	490	

3.2. Monitored Precipitation Events

There were 30 monitored precipitation events at Site A (Acorn Circle) from November 30, 2022 to October 22, 2023 having cumulative estimated rainfall of ~620 mm corresponding to 864,056 L of stormwater. At Site A, the filter performance determined here is reflective only of the duration of sampling and includes events where some runoff bypassed the sand filter and mixed with treated water prior to sample collection at the effluent. There were 15 precipitation events and two (2) large snowmelt events monitored at Site B (Williston) from October 30, 2023 to April 28, 2024 having a cumulative estimated rainfall of ~270 mm corresponding to 1,346,698 L of treated stormwater fully monitored. At Site B, the filter performance determined here is reflective only of the duration of sampling and does not include water that bypassed the sand filter or persistent low flow through the sand filter between rain/snowmelt events. For event-specific details, see **Table 2**.

3.3. Stormwater P Composition

The concentration and load of each P species in the influent water received by the systems differed markedly between the two sites as shown by **Fig. 2** and **Table 5**. The cumulative influent TP loads were comprised of 16% PP, 79% SRP, and 5% DOP at site (A), the smaller, more residential sand filter, and 91% PP, 8% SRP, and 1% DOP at site (B), the larger, industrial/commercial sand filter.

The composition of the influent water received at both sites differed from what is generally expected in urban runoff, as half of TP present in stormwater runoff is typically found in its dissolved forms (45-65%) (Pamuru et al. 2022; Wei et al. 2011; Maestre and Pitt 2005; Erickson et al. 2012). However, studies by Yang and Toor (2018) that found SRP concentrations that dominated nearly all the storms they sampled in an urban residual area, and Erickson et al. (2007) found TDP concentrations comprising up to 90% of TP. Zhou et al. (2013) observed the reverse scenario, where dissolved P comprised only 10-30% of TP loads.

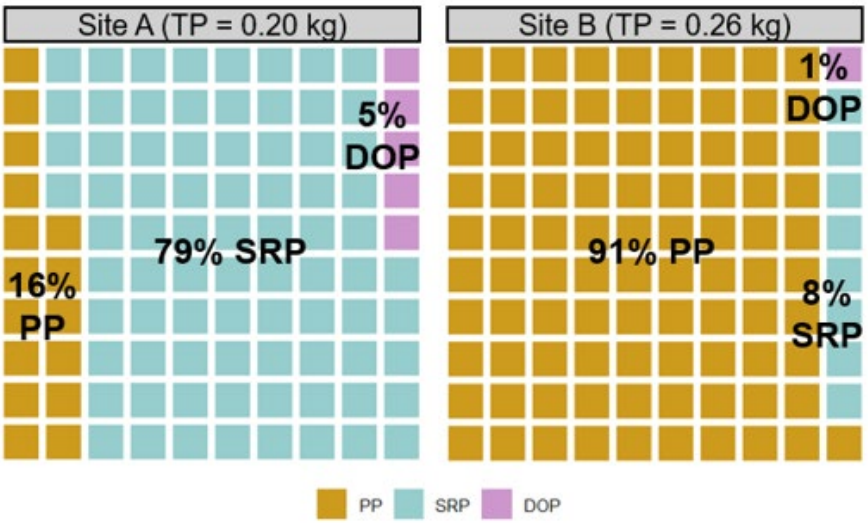

Figure 2. Fraction of the total mass of P (kg) in influent runoff received at sites A (n = 30 events) and B (n = 17 events). Each unit represents 1% of the site's respective total influent load (kg) and is further classified into particulate phosphorus (PP), soluble reactive phosphorus (SRP), and dissolved organic phosphorus (DOP).

Table 5. Summary of P loads and removal by sand filters A (n = 30 events) and B (n = 17 events) during the study.

		Parameter				
Sand Filter	**Performance Metric**[a,b]	**TP**	**TDP**	**PP**	**SRP**	**DOP**
A (smaller, residential)	Total Influent Load (kg)	0.20	0.17	0.03	0.16	0.01
	Total Effluent Load (kg)	0.07	0.04	0.03	0.03	0.01
	Total Influent Conc. (mg/L)	0.24	0.20	0.04	0.19	0.01
	Total Effluent Conc. (mg/L)	0.08	0.04	0.04	0.04	0.01
	Removal Efficiency (%)	65	78	0	80	34
B (larger, commercial)	Total Influent Load (kg)	0.26	0.02	0.24	0.02	0.00
	Total Effluent Load (kg)	0.06	0.02	0.04	0.02	0.00
	Total Influent Conc. (mg/L)	0.19	0.02	0.18	0.02	0.00
	Total Effluent Conc. (mg/L)	0.04	0.01	0.03	0.01	0.00
	Removal Efficiency (%)	78	32	83	29	61

[a] Total Influent Load (kg) and Total Effluent Load (kg) are reported as the sum of P loads from all events.

[b] Total Influent and Total Effluent Concentrations (mg/L) are reported as the ratio of the total influent and effluent P loads and volumes that passed through the system during the sampling period ($\Sigma M_1+M_2+\ldots M_n / \Sigma V_1+V_2+\ldots V_n$). For event mean concentration information (EMC), see Fig. 3.

* Removal efficiency (%) was calculated prior to rounding as (total influent mass (kg) – total effluent mass (kg) / total influent mass (kg)) x 100.

* TP = Total Phosphorus; TDP = Total Dissolved Phosphorus; PP = Particulate Phosphorus; SRP = Soluble Reactive Phosphorus; DOP = Dissolved Organic Phosphorus

We hypothesize that the majority of P was found in dissolved forms in the inflow/influent at site A because of the neighborhood having low vehicle traffic and instead receiving P from abundant sources of organic matter, such as leaf litter, mown grass clippings, compost in home gardens, and animal waste, as well as potentially lawn fertilizer (Yang and Poor 2018; Finlay et al. 2017; Riemersma et al. 2006). Conversely, the dominance of particulate P received by sand filter B is likely due to the ongoing road work, traffic activities, and land-disturbing construction activity (Kim et al. 2008) upstream of the structure in addition to the influence of seasonality. Site B was sampled exclusively during colder months, which are associated with lower concentrations of dissolved inorganic P because there is less biological activity (Porter 2022). It is possible that the ratio of PP:TP may change from what was observed in future warmer months. In the spring, it is likely that seeds, blossoms, and pollen could contribute additional P (Selbig 2016; Dorney 1986). Fall is characterized by greater amounts of leaf litter, grass clippings, and decomposing natural organic matter, which can serve as significant contributors of dissolved P to urban stormwater (Selbig 2016; Yang and Toor 2018).

3.4. P Removal Performance

3.4.1. P Concentrations

The flow-weighted event mean concentration (EMC) of TP in influent to sand filter A ranged from 0.05 mg P/L to 0.65 mg P/L, with a median value of 0.12 mg P/L (**Fig. 3**). The median effluent TP concentration at site A was 0.07 mg P/L (**Fig. 3**). Details on EMCs for individual P species at site A are shown in **Figure 3**.

The EMC of TP in influent to sand filter B ranged from 0.02 mg P/L to 0.41 mg P/L, with a median value at 0.13 mg P/L. The median effluent TP concentration at site B was 0.03 mg P/L (**Fig. 3**). Details on EMCs for individual P species at site B are also shown in **Figure 3**.

The median influent TP EMCs of both sand filters were on the lower end compared to the median urban/residential TP concentration recorded in previous review papers and databases. An analysis by Pamuru et al. (2022) found that between the International Stormwater Best Management Practices Database (Clary et al. 2020) and the National Stormwater Quality Database (Pitt et al. 2018), the median TP concentration was 0.21 mg P/L for decades of stormwater data in the United States. Additionally, Drapper et al. (2022) found median TP concentration of 0.50 mg P/L from 143 international studies.

The treated effluent concentration results are in line with the recommendation by Perry et al. (2009), which suggests that a high P-sorbing material (e.g. alum-based media) should be considered in BMP design to achieve effluent a TP concentration of 0.10 mg/L or lower. Research suggests total P effluent concentrations below a limit of 0.10 mg/L can help control eutrophication in critical regions (Litke 1999; WRF 2019).

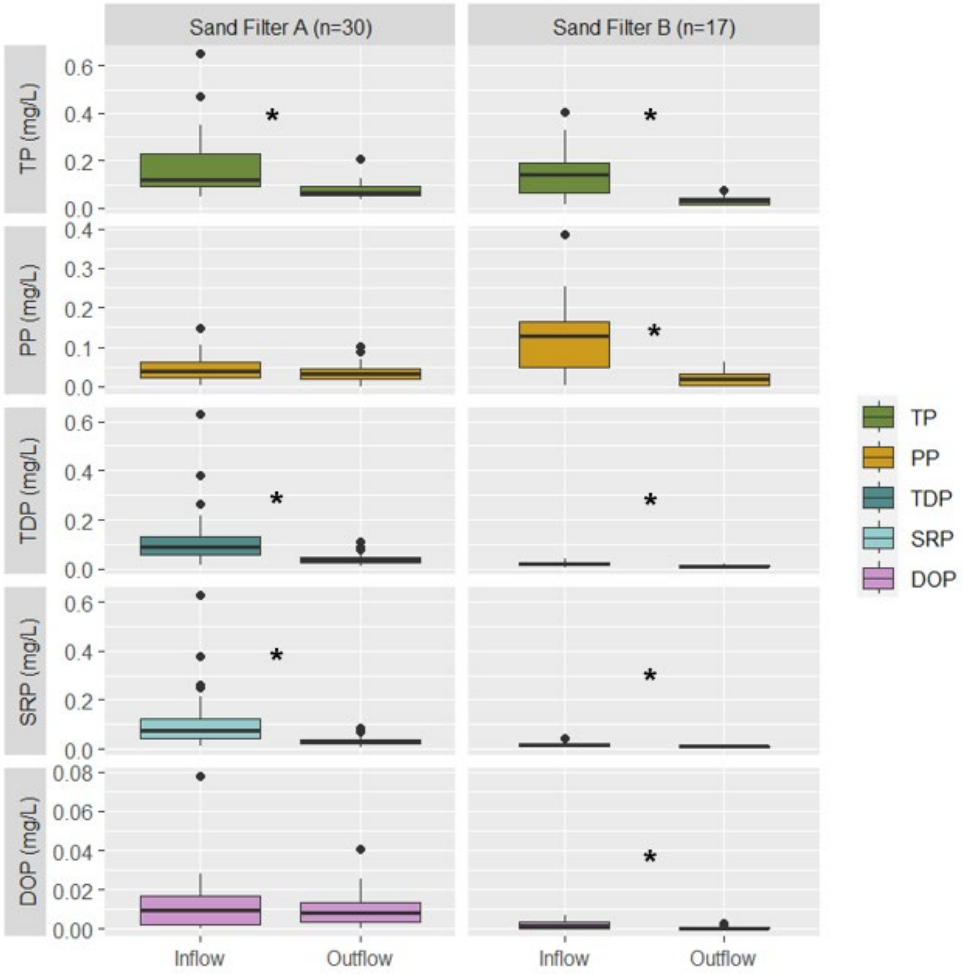

Figure 3. Phosphorus (P) event mean concentrations (EMC) for sand filters A and B. The box and whisker plots represent the distribution of flow-weighted EMC of inflow and outflow data for n=30 events (sand filter A) and n=17 events (sand filter B) for total phosphorus (TP), particulate phosphorus (PP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), and dissolved organic phosphorus (DOP). Asterisks (*) between the boxes indicate significant differences ($\alpha = 0.05$, Wilcoxon Signed Rank Test) between inflow and outflow EMCs. Note that the y-axes differ across P species. For p-values, see **Appendix B**.

3.4.2. P Loads

At sand filter A, the total P load removed varied greatly between events monitored, with a minimum, maximum, and median of -60%, 82%, and 45% of TP removed on a per storm basis. A cumulative 65% of the influent TP load was removed during the 30 studied events at site A (**Table 1, Fig. 4**). Generally, TP removal increased as the ratio of TDP:TP increased, however, some deviations occurred when influent TP concentrations were lower than 0.1 mg P/L or when untreated influent water discharged from the overflow pipe mixed with the treated effluent, as evidenced by trail camera imaging. The event with -60% TP removal was an anomaly in the dataset and was characterized by untreated overflow mixing with sand filter effluent prior to sample collection, which obscures the effects of the sand filter.

At sand filter B, the total P load removed varied greatly between storms, with a minimum of 26% TP removed. The maximum TP load removed was 94%, with a median 73% TP removed on a per event basis. A cumulative 78% of the influent TP load was removed during the monitored events (**Table 1, Fig. 4**).

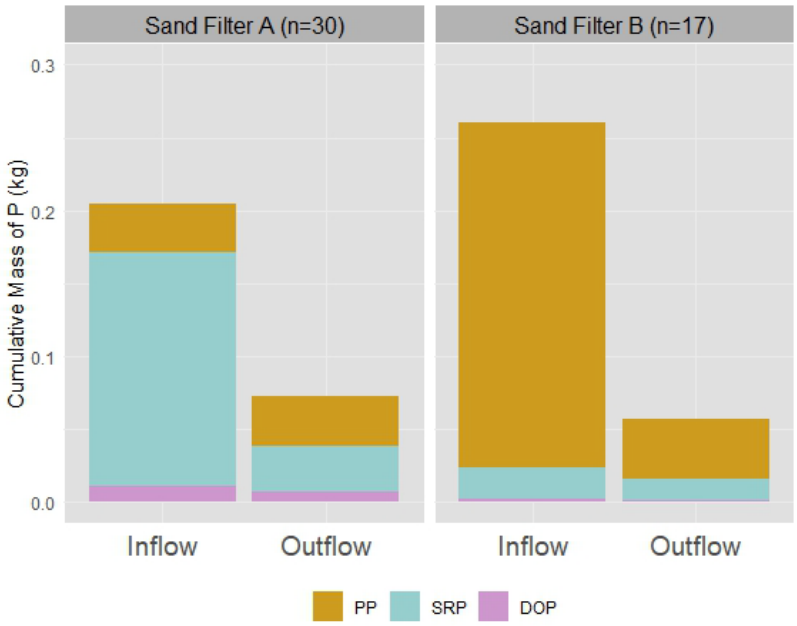

Figure 4. Cumulative phosphorus (P) inflow and outflow mass loads (kg) for each sand filter and P species during monitored storm events. The bars represent the total mass of each P species for n=30 events (sand filter A) and n=17 events (sand filter B) for particulate phosphorus (PP), soluble reactive phosphorus (SRP), and dissolved organic phosphorus (DOP). Masses are reported in **Table 5**.

3.5. Influent Concentration as a Driver for P Removal

For both sites, the percentage of TP removed generally increased with increasing influent TP EMC (**Fig. 5**). Higher concentrations of P correspond to greater potential for the systems to adsorb dissolved P and filter out greater amounts of material, thus yielding greater EMC reduction and P mass retention (Penn et al. 2017).

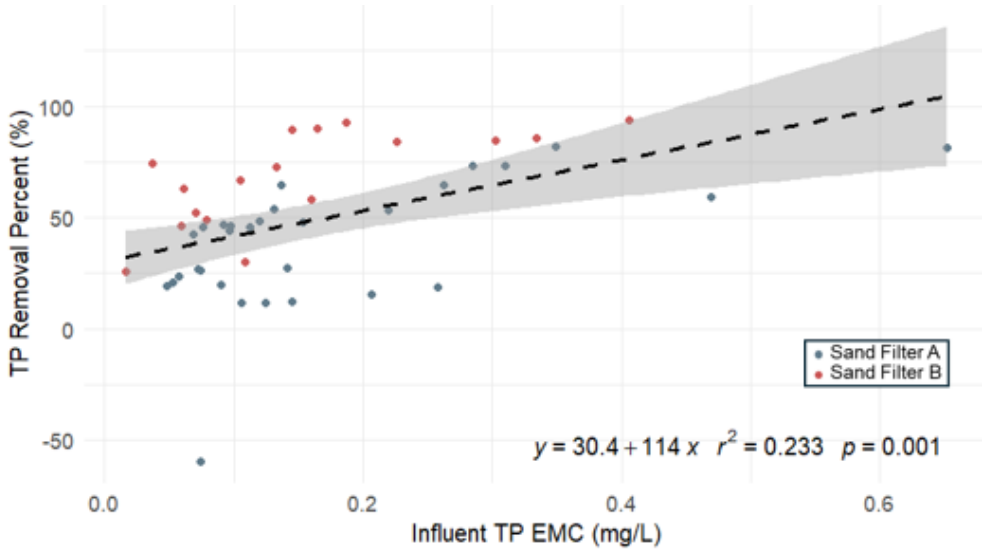

Figure 5. TP Load Removal % versus Influent TP EMC (mg/L) on an event-by-event basis for both sites. Blue points are indicative of removals observed by sand filter A (r^2 = 0.312), and red points are indicative of sand filter B (r^2 = 0.47) (individual regression lines not pictured). The equation y = 114x + 30.4, r^2 = 0.233, and p = 0.001 correspond to the fully combined data set of both sand filters.

3.6. Rainfall Impact on P Removal

Rainfall amount (mm) estimated from the Burington International Airport (< 5 km away from either site) was not correlated with event-specific percent load removals observed (**Fig. 6**). Performance was variable with no significant difference between larger (> 20 mm) and smaller storms (< 20 mm). This was also observed for the DWTR bioretention cells studied by Ament (2021). Other hydrological factors that could affect P removal include the duration and intensity of the storm (Munn et al. 1973; Ahn et al. 2017; Sønderup et al. 2018).

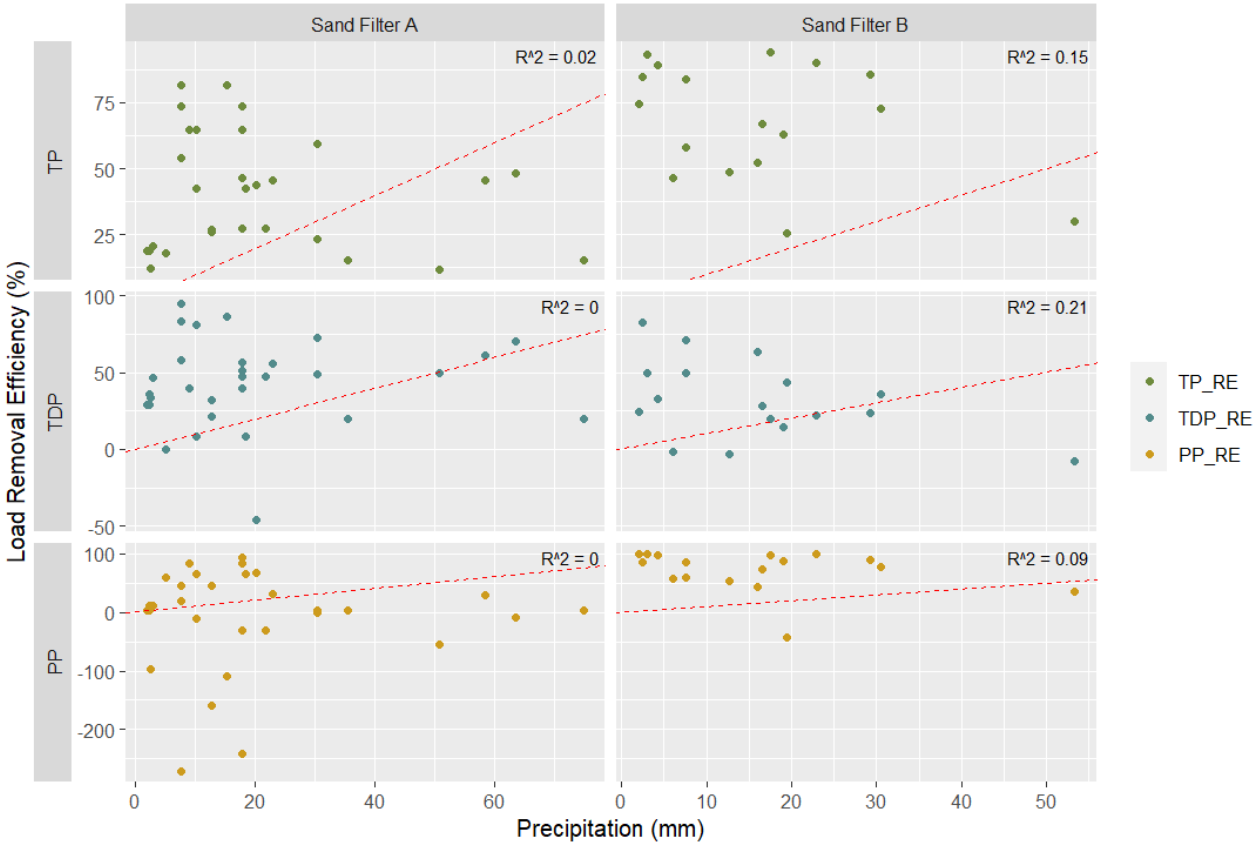

Figure 6. Load removal efficiency (%) versus precipitation amount (mm). The dashed red line indicates a slope = 1.

3.7. Chloride Monitoring Results

To protect aquatic biota, the Vermont Water Quality Standards include Cl^- limits for chronic and acute exposures of 0.230 g Cl^-/L and 0.860 g Cl^-/L, respectively. By design, sand filters are not expected to remove chloride from runoff. However, as chloride is a concern in aquatic systems, this study also gathered information about chloride content of stormwater entering the sand filters from the drainage areas (captured in influent samples), as well as the chloride discharged from each sand filter (captured in effluent samples).

At sand filter A, influent chloride EMC exceeded the chronic and acute exposure limits for 7 and 5 events, respectively, out of 30 total monitored storm events (range = 0.002 to 9.082 g Cl^-/L) (**Figure 7**). The median concentration of chloride in the effluent samples was 0.018 g Cl^-/L with a maximum of 0.766 g Cl^-/L.

At sand filter B, influent chloride EMC exceeded the chronic and acute exposure limits for 16 and 3 events, respectively, out of 17 total monitored storm events (range = 0.049 to 2.082 g Cl^-/L) (**Figure 7**). The median chloride concentration in the effluent samples was 0.648 g Cl^-/L with a maximum of 1.898 g Cl^-/L observed. As mentioned previously, all events monitored at site B were during cold weather periods which is likely why greater median chloride concentrations were observed in site B samples compared to site A, where events were mostly monitored during warmer months.

Lax et al. (2017) posits that during winter months, runoff from urban land use can experience a 20-fold increase in chloride concentration. Sonzogni et al. (1983) estimates that residential and commercial streets range in chloride from snow melt from 0.15 g/L to 8.51 g/L and 0.00 to 15.27 g/L, respectively. A study by Wilson et al. (2018) observed chloride concentrations from snowmelt events up to 26.33 g/L in a cold region.

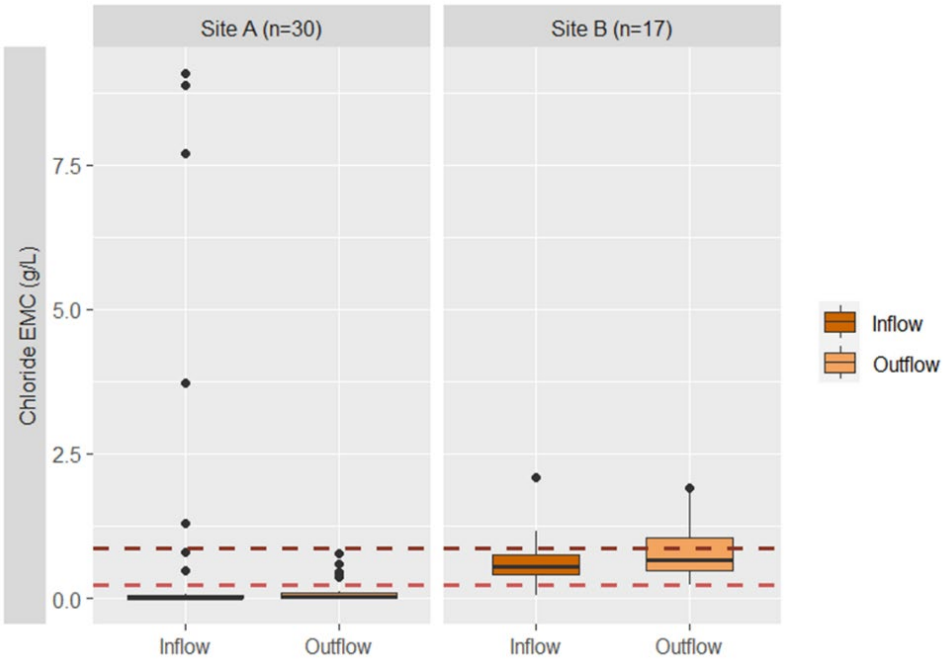

Figure 7. Chloride Event Mean Concentrations (EMC) of inflow and outflow water samples at sites A (Acorn) and B (Williston). The lower dashed line (0.230 g Cl^-/L) is the VTWQS chronic exposure limit, and the higher dashed line (0.860 g Cl^-/L) is the acute exposure limit for chloride exposure to aquatic biota.

3.8. Implications for stormwater BMP design

As engineers consider maximizing the potential of stormwater infrastructure, stormwater control measures, and best management practices, it is imperative to target both dissolved and particulate species of P (Clary et al. 2020) and avoid tradeoffs between the two (Roy et al. 2023). Even in cases where stormwater runoff is dominated by PP (e.g. site B), the particulate P that is retained in stormwater control measures can release dissolved P during decomposition of organic particles or desorption of P from the trapped sediment under anaerobic conditions that develop in the media (Duan et al. 2016). Similarly, it has been shown that dissolved P can adsorb to the surface area of particles and then rapidly desorb during stormflow in some cases (River & Richardson 2018; Wang et al. 2021; Al-Kanani and MacKenzie

1991). Thus, even when runoff compositions are dominated by PP, considerations for capturing dissolved P must be weighed. P can also desorb from DWTRs, reported to be generally <10% of P adsorbed by Wang et al. (2021) and Kubow (2022), but with appropriate percentages of DWTRs by volume, it may be possible for that P to re-adsorb elsewhere in the DWTR-enhanced filter media, limiting export. DWTR P sorption lifetime could surpass the lifetime of a sand filter (approx. 20 yrs according to EPA) depending on the properties of the material and influent P loads (Makris et al. 2004; Ament et al. 2021; Kubow 2022). See Section 5.3 for further discussion of P removal lifetime for the sites monitored in this study.

Drinking water treatment residuals are an attractive amendment to enhance the chemical P removal mechanism (i.e., P sorption) in the substrate of sand filters. Other studies have also seen good results with use of DWTRs, such as Ament et al. (2021) with 77-97% load removal over 2 years and Kuster et al. (2022) observing a total 75% dissolved P load removal across 5-year study. While there have been concerns about DWTRs containing high concentrations of heavy metals, studies have found metal effluent concentrations like untreated stormwater or natural soil levels (Kuster et al. 2022; Kubow 2022; Ament et al. 2021). For example, arsenic (As) was detected at 17.3 ppm in the DWTR material sourced for this study, while natural levels of arsenic typically range from 1 to 40 ppm in soils in the US (USDHHS 2007a). Similarly, chromium (Cr) was reported below 0.5 ppm, which is lower than natural soil concentrations (1 to 2000 ppm, 37 ppm on average) (USDHHS 2007b) (**Table 4**). Ament et al. (2022) and Kubow (2022) found no evidence of concerning levels of heavy metal leaching in their respective DWTR studies.

Even though it was not the primary focus of the study, the presence of chloride in stormwater runoff is a significant issue. Monitoring during the study period (mostly during the growing season at site A, and with many winter sampling events at site B) showed high levels of chloride frequently exceeding chronic, and often acute water quality standards for biota. Sand filters, even those inclusive of DWTR, are not designed to, or able to, remove chloride due to it being a relatively conservative constituent that does not readily interact with media or undergo transformations (Burgis et al. 2020). Additional research suggests reduced-salt winter management practices can function as source controls to help limit chloride in stormwater in cold climates (Sparacino et al. 2022 and 2024).

4. CONCLUSIONS

The addition of DWTRs to traditional stormwater sand filters can improve observed TP and TDP removal. A traditional sand filter is limited in its ability to remove dissolved P, as it relies largely on physical removal mechanisms (i.e., gravity in the sedimentation chamber and filtration by the sand media). The addition of DWTRs to sand thus provides particle surfaces with a high affinity for phosphate ions. In this study, two DWTR-enhanced sand filters with different roadside placement, drainage area characteristics, filter size, percent DWTR by volume in the filter media, and runoff composition were evaluated for P removal efficiency. The residential, smaller watershed sand filter (Site A) had 65% TP removal efficiency, of which >99% of the cumulative P monitored during storm events removed was dissolved P. Similarly, 78% TP removal efficiency was observed at the larger, industrial/commercial watershed sand filter (Site B), where 9% of the cumulative influent TP load was in dissolved forms. Therefore, the addition of DWTRs to stormwater sand filter media can enhance P retention to help meet P load reduction goals and protect aquatic ecosystems. Chloride concentrations often exceeded Vermont Water Quality Standards during winter and post-winter thawing events at both sites and were in line with previous VT and cold-climate studies.

5. SUMMARY OF RECOMMENDATIONS TO VTRANS

5.1. Opportunities and Constraints related to DWTR use in Stormwater Management

Mixing DWTRs into sand media-based stormwater infrastructure can enhance P removal from stormwater. As the first field study of sand filters enhanced with DWTRs in VT, this study clarifies anticipated P load reductions for DWTR-amended sand filters and provides guidance for future stormwater treatment practices used in transportation projects. Anticipated benefits of this practice include: 1) no substantial additional cost, 2) reuse of local residual material that would otherwise be discarded/landfilled, and 3) increase in the longevity of P removal, targeting dissolved P that often passes through or is exported from stormwater treatment practices. Supply of quality DWTRs may eventually become a constraint if adoption of DWTR-enhanced sand media in stormwater infrastructure is widespread in the state and broader region.

5.2. DWTR Specifications

In our prior research at UVM investigating eleven DWTR materials from drinking water treatment facilities in US EPA Region 1, we found that DWTRs characterized by lower bulk density (<1.0 g cm^{-3}, especially <0.6 g cm^{-3}) and greater oxalate-extractable Al+Fe (>3,000 mmol kg^{-1}) tended to provide the greatest P sorption capacity in low P/high flow column experiments, which were designed to approximate field conditions (1 mg P L^{-1}, ~3 min contact time) (Kubow 2022). The CWD material used in this study (see **Table 2** for properties) did not entirely meet these optimal characteristics (bulk density = 0.99 g cm^{-3}, oxalate-extractable Al+Fe = 1,933 mmol kg^{-1}) but did perform very well in the field. Even the DWTRs evaluated in Kubow (2022) with the lowest P sorption capacity (approximately an order of magnitude lower than what was measured for the CWD DWTR in the past) were predicted to provide roughly 10 years of effective P removal in a bioretention context following the logic presented in Ament et al. (2021). If VTrans plans to use DWTRs from other drinking water facilities, we recommend checking with our team at UVM to determine if we have previously tested the material of interest and, if so, we will be able to provide information on whether it ranked on the lower or higher end of P sorption capacity. If it is a material that we have not tested, testing for bulk density and oxalate-extractable Al+Fe would be the most straightforward (albeit imperfect) way to gauge whether the material is likely to have relatively high P sorption capacity. Another key factor to consider is whether the DWTR has been dewatered (e.g., freeze-thaw cycling). DWTRs can exhibit a wet, congealed consistency that is undesirable prior to dewatering. Ideally the material should be like cat litter in terms of texture and have low moisture content. We also recommend considering testing for arsenic leaching and PFAS presence, depending on what is known about the source waters for the drinking water treatment facility (e.g., arsenic or PFAS contamination in source water). Finally, VTrans should work with the VT Agency of Natural Resources, and continue to collaborate with UVM researchers, to develop a specification for incorporation of DWTR amendments into sand filters for the VT Stormwater Management Manual.

5.3. Media Incorporation Methods

Our past research has shown that mixing DWTRs into sand is the best method of incorporation (as opposed to addition of DWTRs as a solid layer) (Ament et al. 2021 and 2022). This limits undesirable effects on hydraulics, while still allowing P sorption to occur (Ament et al. 2021). In this study, DWTRs were incorporated into the sand layer at 3-5% by volume, and results indicated effective P sorption with no obvious hydraulic impediment. We previously found that incorporating DWTRs into sand at 10% by volume was effective for bioretention cells (Ament et al. 2021 and 2022). We recommend adding DWTRs at no greater than 10% by volume to sand layers to help avoid clogging. Within the 3-10% by volume range, adding more DWTRs will likely lead to longer effective dissolved P removal. Ament et al. (2021) and Kubow (2022) reported predicted P removal longevity of DWTRs in bioretention systems (10% of sand layer, 5% of overall media layer above gravel) of 10-90 years. We estimate that the DWTRs incorporated into sand filters A and B in this study will continue to remove dissolved P for approximately <2 years at site A and >200 years at site B. These estimates should be considered rough approximations – assumptions and calculations are documented in **Appendix C**. The short lifespan of dissolved P removal predicted for site A is due to the relatively high TDP concentrations in influent and low incorporation rate of DWTRs (3% of sand layer by volume). If the incorporation rate was increased to 10% DWTR by volume in the sand layer at site A, then the effective lifetime of dissolved P removal would increase to ~5 years. Increasing the volume of the sand+DWTR layer, which would also increase the mass of DWTRs in the system, is another way to increase the duration of dissolved P removal. However, this would require a larger overall structure and increase cost. For site B, the 200+ year performance range is very high, but reasonable compared to past estimates. For example, Ament et al. (2021) estimated that bioretention cells with a 30.5 cm sand layer having DWTRs mixed in at 10% by volume (equivalent to 5% of total media volume above the pea stone layer) could provide ~90 years of dissolved P removal. Again, these are rough estimates based on lab experiments and coarse assumptions. Additional field monitoring in the future is needed to increase understanding of the efficacy of dissolved P removal by DWTRs over time in transportation projects.

5.4. Future Sampling Needs

Between this study and prior UVM research (Ament et al. 2021 and 2022, Kubow 2022), the general effectiveness of DWTRs for P removal in stormwater infrastructure is now well established. However, questions remain

about whether predictions of long-term P removal by DWTRs will hold up in field conditions. Therefore, we recommend reexamination of field performance for sites A and B in the future (e.g., 3-5 years after construction) to determine whether P load reduction performance changes over time compared to what was observed during this study immediately post-construction.

6. Acknowledgements

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Appendix A: DWTR and Site Characteristics

DWTR Source

A 5-gallon bucket of the DWTRs was obtained from CWD on February 15th, 2023, using a metal shovel from various spots of an accessible storage pile. This collection date was in between the construction of the two sites constructed in Fall 2022 and Fall 2023.

Figure A1. DWTR storage pile at CWD. Shows the pile from which a 5-gallon bucket sample of DWTRs were acquired from.

Site A

Site A was built as one of three cul-de-sac retrofits with infiltration or filtration systems and stabilized outfalls. The existing inlet structure was replaced with the media filter, pre-treatment chamber, and internal high flow bypass. Activities within the surrounding drainage area are largely suburban and residential, with single family detached dwelling units. The hydrologic soil groups of the drainage area and neighboring uphill land were estimated to be dominated by A (90.1%), B (8.8%), and A/D (1.1%) soils using the USDA's Web Soil Survey (USDA accessed 2024). The Site has a drainage area of 7,309 m^2 of which 39% is designated impervious. It was designed for a 53% P removal efficiency, or an estimated 0.55 kg/year P removal. The final structure interior volume measured 9.34 m^3 (330 ft^3). Water first enters a sedimentation chamber that can hold 1.93 m^3 (68.25 ft^3). Water from the sedimentation chamber overtops a weir wall and then flows over and downward through the filter substrate. The filter substrate (97% ASTM C-33 Coarse Sand: 3% Al-DWTR) is 0.30m (1 ft) deep in a 3.4 m^2 (~37 ft^2) area (volume = 1.02 m^3 = 37 ft^3), underlain by a 7.6 cm (3") layer of pea gravel and 53.3 cm (1.75') of drainage aggregate.

Figure A2. The pre and post development progress of Site A. A) Aerial cul-de-sac view (pre-development) is an arial image of the cul-de-sac branching from the neighborhood. B) Front-facing cul-de-sac view (pre-development) is the front-facing view to the end of the cul-de-sac before the sand filter was constructed. C) Drainage grate to subsurface sand filter shows the point from which runoff exits the landscape and enters the treatment system. D) Down-hill discharge point from sand filter shows the point from which treated water exits the system. E) Immediate drainage area (post-development) shows the immediate drainage area with the entry point in C) visible in the top center of the image. This grassed area was not in B). F) Plunge pool and landscape (post-development) shows the plunge pool and immediate drainage area into a wooded landscape. Images A and B were obtained from Google Earth. Images C-F were taken by M. Schambura.

Site B

Site B was constructed next to U.S. Route 2 road in South Burlington, VT. The road is heavily traveled, and the segment of road adjacent to the site has on average an annual daily travel counts of 12,000 – 13,000 cars per day as reported by VTrans' Data Management System at Location D036 (VTrans accessed 2024). The sand filter is one component of a larger highway resurfacing project, consisting of the reconstruction and widening of the U.S. Route 2/Industrial Avenue intersection and additional traffic signaling. The drainage area is overall flat with gentle slopes, and the surrounding land in the watershed has several hills and steeper slopes. The site is dominated by Hydrologic Soil Group D (62.9%), followed by A (30%) and C (7.1%) according to Stormwater Discharge Permit #3-9015.

The site was designed to discharge stormwater runoff into the Muddy Brook at 73°8'8.90" W, 44°27'28.99" N. The sand filter structure was built in tandem with a stone-lined slope located at the exit of the filter structure. The underground sand filter is designed to store and treat runoff from higher flow events. Water treated from the underground sand filter is then secondarily treated by the stone-lined slope and vegetated riparian area upon exiting the structure.

The final structure has interior dimensions of 16.15m L, 4.27m W, and 2.74m D (189 m^3 = 6674 ft^3). The sand filter section includes substrate (95% ASTM C-33 Coarse Sand: 5% Al-DWTR) that is 0.46m (1.5 ft) deep in a 31 m^2 (336 ft^2) area (volume = 14 m^3 = 504 ft^3), underlain by 28 cm (11") of drainage aggregate. Within the drainage aggregate layer, an underdrain system of seven 15cm (6") diameter pipes collect and convey the filtered water to the chamber connected to the outlet pipe, where the treated effluent is discharged into the stone-lined slope. This 18,251 m^2 project (stone-lined slope and sand filter combined) was designed to achieve a 40% P load reduction, or an estimated 2.42 kg/year.

Fig A3. The pre and post development progress of Site B. A) Aerial view of STP location (early construction, Nov. 2021) shows the location for the sand filter and stone-lined slope after the project began. The Muddy Brook River is shown in the bottom left corner. B) Road view of STP location (pre-construction, July 2019) shows the view before construction began. C) Sand filter structure (during construction, Aug. 2023) shows the frame of the sand filter next to U.S Route 2. D) Stone-lined slope and vegetated riparian area (during construction, Aug. 2023) shows the treatment area, pre-seeded. E) Stormwater treatment site (post-construction, Oct 2023) shows the finished site with boxes for monitoring equipment atop the surface. F) Stone-lined slope that drains to a vegetated riparian area (post-construction, Oct 2023). Runoff exclusively conveyed by the stone-lined slope is discharged from the black pipe (left), and runoff treated by the sand filter during high flows is discharged from the blue pipe (right) and conveyed to the stone-lined slope/vegetated riparian area. Image A was obtained from Google Earth. Image B was obtained from Google Maps History. Images C-F were taken by M. Schambura.

Appendix B: Stormwater Quality Monitoring

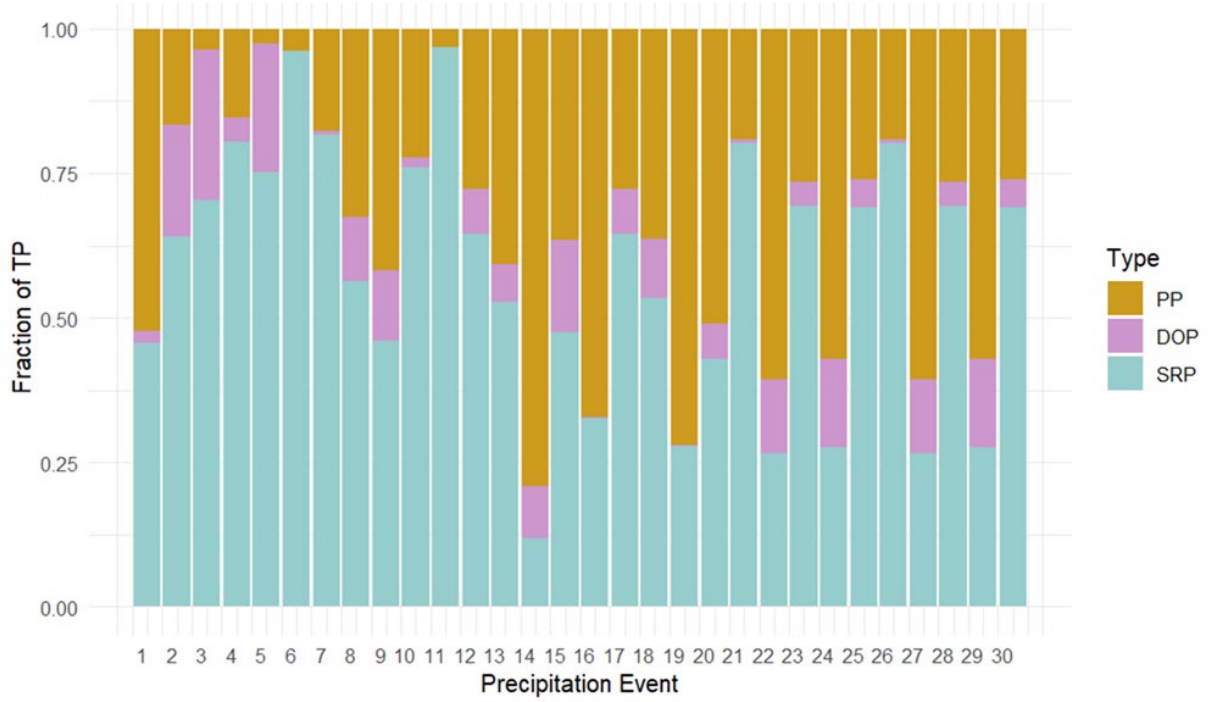

Figure B1. Fraction of TP Load by Event at Site A. PP = Particulate Phosphorus, SRP = Soluble Reactive Phosphorus, and DOP = Dissolved Organic Phosphorus.

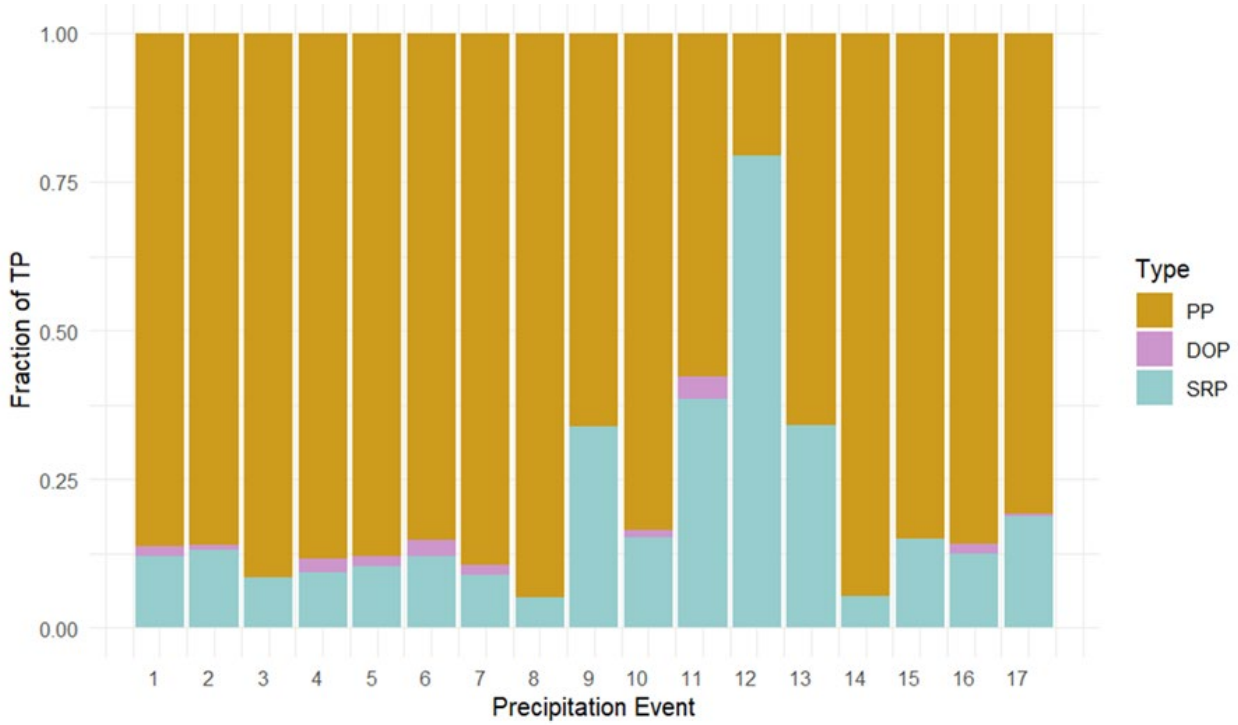

Figure B2. Fraction of TP Load by Event at Site B. PP = Particulate Phosphorus, SRP = Soluble Reactive Phosphorus, and DOP = Dissolved Organic Phosphorus.

Table B1. P-Values for P Influent and Effluent event mean concentrations (EMCs). The Wilcoxon Signed Rank Test with significance of α = 0.05 was used. Statistically significant values are bolded.

	Form of P				
Sand Filter	TP	PP	TDP	SRP	DOP
A	**1.82 e-06**	0.434	**2.06 e-05**	**3.34 e-06**	0.388
B	**3.21 e-04**	**3.85 e-04**	**9.21 e-04**	**5.45 e-04**	**0.025**

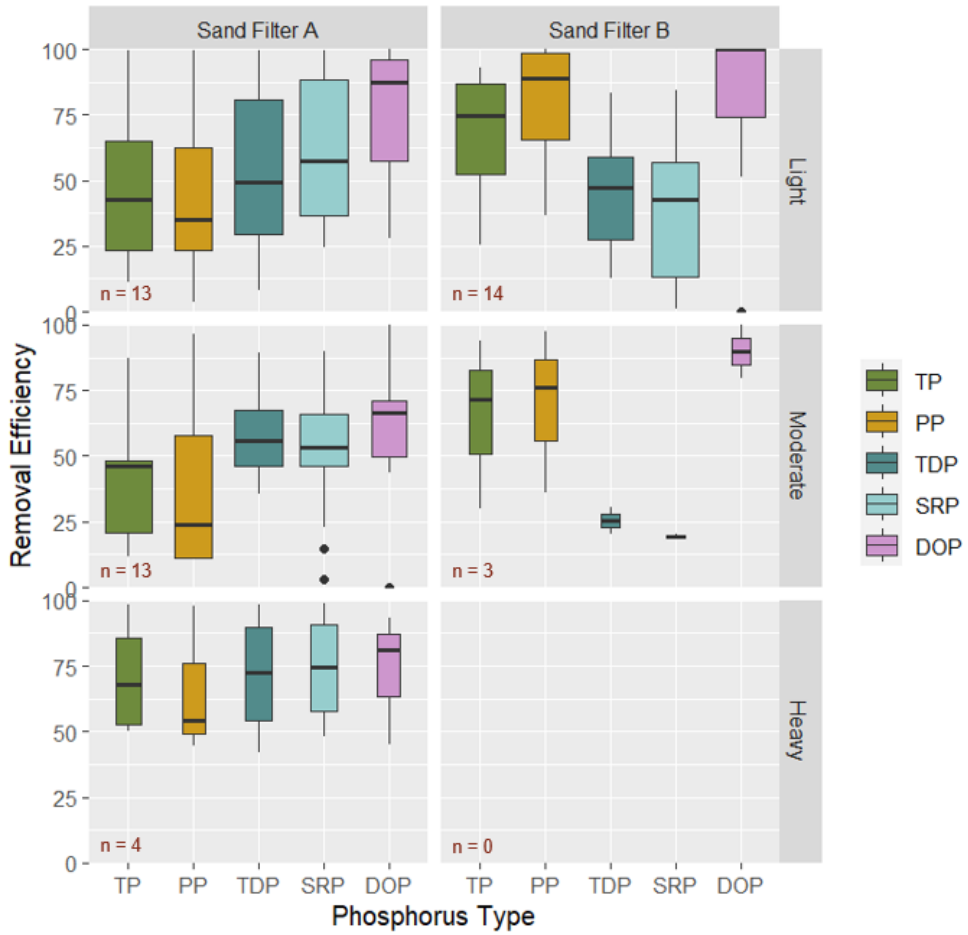

Figure B3. P removal by Storm Intensity (light, moderate, heavy). Intensities were deter using the Manual of Surface Weather Observation Standards, where < 2.5 mm/hr (<0.1”/hr) was deemed light, 2.5 to 7.5 mm/hr (0.1” to 0.3”) is moderate, and heavy is considered 7.5 mm/hr to 50 mm/hr (0.3” to 2”/hr) on average (MANOBS 2023).

At site A, median TP and TDP removals from highest to lowest were in the order of heavy storms > moderate storms > light storms. This is likely because in less intense storms water may follow preferential flow paths through the sand+DWTR media near the baffle instead of utilizing the full media bed (Maiyo et al. 2013). Similarly, less intense storms tended to be lower in TP concentration, which makes it more difficult to reduce the TP concentration (Wen et al. 2020).

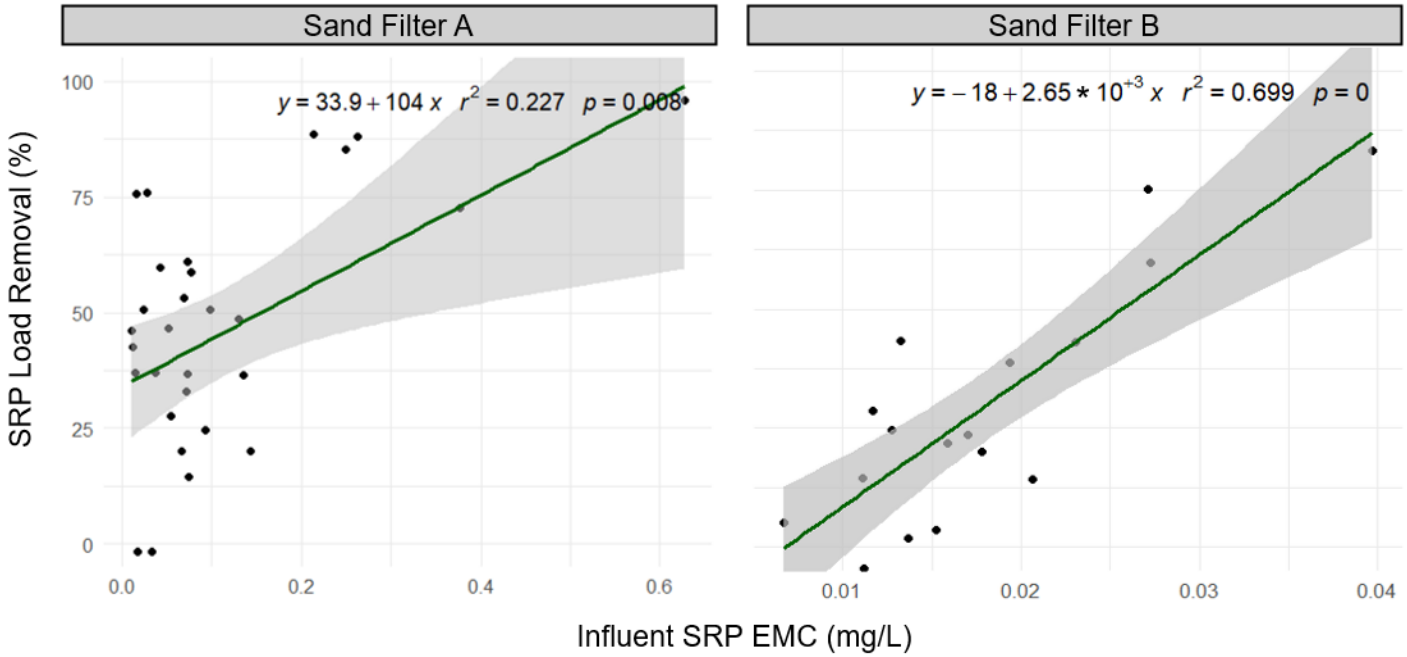

Figure B4. SRP Load Removal vs. Influent SRP EMC (mg/L) shows the mass removal of SRP vs. influent concentration separated by site.

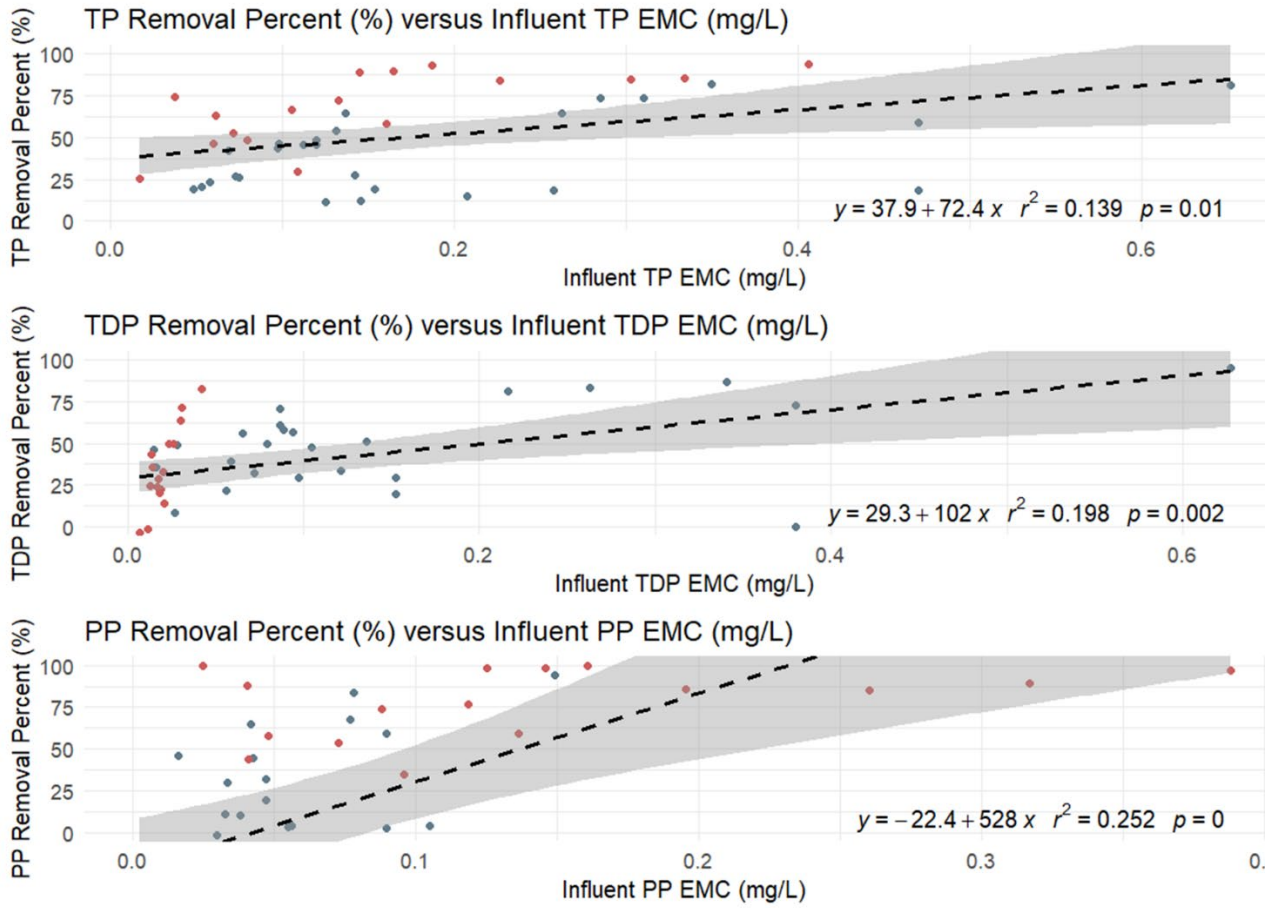

Figure B5. P Load Removal vs. Influent EMC (mg/L) shows the mass removal of TP, TDP, and PP vs. influent TP concentration (mg/L) for the combined datasets of each site.

Appendix C: Calculations for estimating longevity of dissolved P removal by DWTRs at each field site

DWTR Properties			
P sorption capacity	11363	mg P/kg DWTR	Source: Ament et al. (2021) - initial + additional P retained in low P/high flow experiment for CWD DWTR
bulk density	0.99	g DWTR/cm3 DWTR	
bulk density	28.03	kg DWTR/cubic ft DWTR	
Site	**A**	**B**	
TDP retained during events monitored	0.1331	0.0077	kg P
Precip for events monitored	620	270	mm
Annual precip	1148	1047	mm/yr
Predicted annual TDP removal	0.25	0.03	kg P/yr
Total sand+DWTR volume	37	504	cubic ft
DWTR incorporation rate	3	5	%
DWTR volume	1.10	25.20	cubic ft
DWTR mass	31	706	kg DWTR
Lifetime of TDP removal	**1.4**	**269**	**yrs @ DWTR incorporation rates used**
If 10% of sand volume is replaced with DWTRs at Site A, then:			
Lifetime of TDP removal (yrs)	**5**		