Slag Filter BMP Performance in the Macatawa Watershed

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1. Overview

Lake Macatawa and its watershed suffer from excess phosphorus (P) (Walterhouse 1999). The TMDL (total maximum daily load) for the lake calls for a P reduction of 55,000 lb/yr from the estimated load of 138,500 lb/yr (1997), with the majority of that load reduction coming from nonpoint sources (Walterhouse 1999). If fully implemented, the model results indicate that the water column total phosphorus (TP) concentration will be reduced to 50 µg/L, thereby meeting the TMDL goal.

Previous research has demonstrated that agriculture is a major source of nonpoint P in this watershed (Steinman et al. 2018). Although overland flow is generally considered the major transport mechanism for P, there are situations when significant P transport occurs through agricultural tile drainage (King et al. 2015). It is currently uncertain how much P enters Lake Macatawa from surface runoff vs. subsurface runoff, but very high concentrations of both TP and bioavailable P were measured in tile drain effluent from agricultural fields in the watershed (Clement and Steinman 2017). Similar findings have been reported for agricultural areas in the western basin of Lake Erie (Calhoun et al. 2002; Smith et al. 2015), which has been subject to devastating harmful algal blooms the past few decades (Michalak et al. 2013; Wynne and Stumpf 2015).

Various best management practices (BMPs) have been implemented in the Macatawa watershed to reduce P loading, including among others, grassed waterways, cover crop plantings, gypsum application, and wetland restoration, although their effectiveness has been questioned (Steinman et al. 2018). Iron slag, a waste product from the steel industry, can chemically bind P and has been implemented previously in agricultural settings (Roychand et al. 2020; Hua et al. 2016). Interest was expressed as to whether iron slag filters may be an effective management practice in the Macatawa watershed. To that end, the Outdoor Discovery Center (ODC) Network, along with Dykhuis Farms and Plant Tuff, Inc., committed to install up to six iron slag filters at the end of agricultural tile lines in the watershed. To date, three of the six have been constructed. Our goal was to evaluate the efficiency of these systems in removing P, while also monitoring for the presence of potentially toxic chemicals leaching from the slag, which may be released into surface waterways. It is our understanding that these filters are the first application of their kind within Michigan.

2. Methods

2.1 Overall site description

The deployment of iron slag filters (Figs. 1, 2) was proposed in the Macatawa watershed in 2018 and three sites were selected as of 12/31/19 for installation. Several additional sites were considered for installation in 2020. Multiple sites throughout the watershed were sampled prior to installation to determine which locations were best suited for iron slag filter installation. Of the three currently constructed filters, two were completed in April 2019 (Behind Mill 1 and Oak Grove 2) and the third (Fillmore Flex; Fig. 3) in September 2019. We present the data related only to the completed iron slag filters. Due to the COVID-19 pandemic, sampling was not permitted for several months in spring 2020 due to the state of Michigan's "stay-at-home" executive order. Sampling resumed once the order was lifted.

Filters are designed to work passively, receiving water after it infiltrates through soils into subsurface tiled drains (Fig. 1). Water moves up and through the iron slag gravel in large concrete tank(s), where the slag binds with and removes the P from the water before it passively releases to adjacent surface waterways (Figs. 1, 2). A layer of calcium carbonate particulate was applied within the treatment tank to help balance tile drain water pH. A control box allows for the slag filter to be bypassed if too much water is moving through the tile drains (indicated by standing water on the farm field), and serves as the inflow access point for water collection for most sites. Outflow water can be sampled either from the outflow pipe, or via access points in the top of the tank with a hose and hand pump (Fig. 4).

2.2 Field and Laboratory Processes

Prior to installation, grab samples were taken monthly at only the outflow pipe, which at that time was a direct open connection from the tile drain pipes to adjacent surface waters. Pre-installation sampling dates are provided in Table 1. Post-installation samples were collected bimonthly; sampling approaches varied among sites due to differences in filter design and implementation (Fig. 4). Post-installation sampling occurred at the inflow using a hand pump and hose to siphon water accessed through an inflow pipe at Behind Mill (Fig. 4A) and through the control box at Oak Grove 2 and Fillmore Flex (Figs. 1, 4B). Outflow was sampled at the original outflow pipe (Fig. 4E; which remained after installation) for all sites; however, when the outflow pipe was inaccessible due to being underwater, samples were taken via one of the access points on top of the tank using a hand pump and hose without disturbing the calcium carbonate top layer (Figs. 4C-D).

General water quality was monitored with a YSI 6600 data sonde (temperature, dissolved oxygen [DO], pH, specific conductivity [SpCond], total dissolved solids [TDS], redox potential [ORP: oxidation-reduction potential – the degree to which a substance is capable of oxidizing or reducing another substance], and turbidity). Grab samples were collected for analysis of TP and soluble reactive P (SRP). All samples were placed in a cooler on ice until received by the AWRI lab, usually within 4 hours, where they were stored and processed appropriately. Water for SRP analyses was syringe-filtered through 0.45-µm membrane filters into scintillation vials and refrigerated until analysis. TP and SRP were analyzed on a SEAL AQ2 discrete automated analyzer (U.S. EPA 1993). Any values below detection were calculated as ½ the detection limit.

2.3 Metals and PAHs

Chemical analysis sampling for metals (mercury, arsenic, barium, cadmium, chromium, cobalt, copper, lead, molybdenum, nickel, selenium, silver and zinc), low-level mercury, Polycyclic Aromatic Hydrocarbons ([PAHs] 2-Methylonaphthalene, Acenaphthene, Acenaphthylene, Anthracene, Benzo (a) anthracene, Benzo (a) pyrene, Benzo (b) fluoranthene, Benzo (g,h,i) perylene, Benzo (k) fluoranthene, Chrysene, Dibenz (a,h) anthracene, Fluoranthene, Fluorene, Indeno (1,2,3-cd) pyrene, Naphthalene, Phenanthrene, and Pyrene) and available cyanide was conducted three times post-installation (1-week, 6-months and 1-year). Analyses were conducted at TRACE Analytical Laboratories, Inc. (Muskegon, MI) using Standard Methods (US EPA 1993). Any values below analytical detection methods were calculated as ½ their detection limits.

2.4 Data analysis

The water residence time in the reservoir depends on the rate at which the water enters the slag filter, determined by rain, irrigation, or a control box. This means that water during baseflow conditions can spend much longer in the reservoir than water during stormflow conditions, especially in dry summer months. Therefore, for statistical purposes, the inflow and outflow values were paired for each sampling event rather than using grand means. SRP, TP, and turbidity samples were analyzed using paired t-tests or Wilcoxon tests, depending on normality. Normality assumptions were tested using Shapiro-Wilk tests. Significance was set at $\alpha = 0.05$. Data analysis was conducted using R (version 3.4.2 R core Team, Vienna, Austria). Percent reductions were calculated for the paired mean inflow and mean outflow measurements post-installation for SRP and TP by calculating the difference between mean inflow and mean outflow concentrations, dividing that number by the mean inflow concentration, and multiplying it by 100. Negative percent reduction values indicated an increase in P concentration.

3. Results and Discussion

3.1 Pre-Installation Sampling

Pre-installation mean water temperatures varied between sites and ranged from 8.61 – 13.89 °C, with lower mean temperatures associated with Behind Mill 1 and Oak Grove 2 likely due to the majority of sampling occurring primarily in the winter months, whereas most of Fillmore Flex sampling occurred during warmer months (Table 1). Mean DO ranged from 7.86 – 11.30 mg/L with the lowest mean DO found at Fillmore Flex (Table 1). All sites had similarly neutral pH (Table 1). Mean SpCond ranged 676 – 894 µS/cm, the lowest being at Oak Grove 2, while Behind Mill 1 and Fillmore Flex were similar (Table 1). Mean ORP prior to installation was similar among all sites (Table 1). Mean turbidity was lower at Behind Mill 1 and Oak Grove 2 than at Fillmore Flex, with all sites <25 NTU (Table 1).

Mean pre-installation SRP concentrations ranged from 135 to 283 µg/L (Table 2); these particular sites were selected for installation due to their relatively high initial concentrations. Mean TP concentrations ranged from 167 to 721 µg/L (Table 2). Among site variance was high, reflecting differences in field management, drainage, and time of year sampled. The highest mean P concentrations were measured at Fillmore Flex (Table 2).

3.2 Post-Installation Sampling

Following installation, mean DO, conductivity, TDS, and ORP showed modest declines in the outflow compared to the inflow (Table 1). In contrast, pH increased in the outflow, presumably due to buffering from the calcium carbonate layer. Whereas turbidity declined significantly at Behind Mill 1 and Oak Grove 2, it increased slightly at Fillmore Flex (Table 1). Reduction in turbidity between inflow and outflow was anticipated as water velocity decreases when water enters the iron slag filter, allowing sediment particles to settle out of the solution before the water reaches the surface waters. The Fillmore Flex outflow pipe is angled and below grade (not pictured). It has been observed to experience back flow from the drainage ditch into the outflow pipe if water levels are sufficiently high. This could result in back flow into the slag filter, which may explain the higher levels of turbidity in the outflow than inflow and general variability (Table 1). We did not measure sediment load within the pipes pre-or post-installation. It is unclear if the sediment will impact the longevity of the slag filter’s P trapping effectiveness.

After installation of the slag filters, both SRP and TP decreased in the tile drain effluent: percent reductions of SRP ranged from 57.3% (Oak Grove 2) to 7.4% (Fillmore Flex); percent reductions of TP ranged from 76.5% (Oak Grove) to 59.5% (Behind Mill 1) (Table 2). Analysis of paired inflow and outflow samples at each of the sampling sites revealed significant reductions of TP at Behind Mill 1 and Oak Grove 2 ($p = 0.0011$ and $p = 0.0001$, respectively) and of SRP ($p = 0.0028$ and $p = 0.0004$, respectively; Table 3). Fillmore Flex had a marginally significant reduction of SRP ($p = 0.0825$) and a statistically significant reduction of TP ($p = 0.0002$) (Table 3).

These slag filters function by the binding of phosphorus to iron, similar to what happens under oxic conditions in lake sediments (Mortimer 1941; Orihel et al. 2017). Therefore, their ability to reduce P is not surprising, and they should remain effective as long as conditions within the reservoir remain oxic and the binding sites do not become saturated. Prior studies have confirmed the ability of iron slag to bind phosphorus, with phosphate percent removals of 95% in metal-free and mixed-metal solutions of synthetic stormwater (Okochi and McMartin 2011) and a TP removal percentage of 77% (Shilton et al. 2006) at a treatment plant, although P removal effectiveness dropped off after 5 years.

Although TP reductions of ~60 to 75% are certainly helpful, mean outflowing concentrations of 100 to 329 µg/L are still far above the 50 µg/L goal for Lake Macatawa. There will likely be additional removal of P due to biotic uptake and abiotic adsorption as the nutrient flows downstream to the lake, although it is uncertain to what degree this removal will be offset by additional P sources entering the drainage system. Hence, while iron slag filters clearly can reduce P, their installation is only part of the solution, and will need to be complemented by other BMPs, and perhaps ultimately, a more holistic public works project.

3.3 Metals and PAHs

Metals were measured during pre-installation and 1-week, 6-months and 1-year post installation at all sites. Behind Mill 1 and Oak Grove 2 were sampled a few months past the 1-year mark because of COVID-19 restrictions. All metals, PAH compounds, and available cyanide were below U.S. Environmental Protection Agency (EPA; source: https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals) and World Health Organization (WHO; source: https://www.wqa.org/learn-about-water/common-contaminants) standards for drinking water. Recreational water standards are unavailable.

Mercury was below 12 ng/L for all sites, which is orders of magnitude below the drinking water standards for 2,000 ng/L (US EPA) and 6,000 ng/L (WHO). Behind Mill 1 showed a slight increase in mercury between pre-installation and 6-month post-installation, although 1-year post installation was below pre-installation. Oak Grove and Fillmore Flex remained relatively steady with Fillmore Flex having the highest levels (Fig. 5A). Arsenic was found in detectable amounts only at Fillmore Flex pre-installation, and was below both the EPA and WHO standard of 0.010 mg/L (Fig. 5B). Barium was found below detection 1-week post installation at Behind Mill 1 and Oak Grove 2 and at 1 year at Fillmore Flex, although all samples were below drinking standards of 2.0 mg/L (EPA) and 0.7 mg/L (WHO). Behind Mill 1 and Oak Grove 2 had similar although reduced values, where Fillmore Flex saw a reduction from the highest value to below detection (Fig. 5C). Chromium was detected 1-week post installation at Oak Grove 2 and Fillmore Flex, 6-week post installation at Behind Mill 1 and Fillmore Flex and 1-year post installation only at Fillmore Flex, but all were below both the EPA (0.10 mg/L) and WHO (0.05 mg/L) standards (Fig. 5D). Copper increased at Behind Mill 1 and Oak Grove 2 from pre-installation to 1-year post installation, while Fillmore Flex Cu levels declined from pre- to 1-year post installation (Fig. 5E, 5F). Zinc was above the detection level only at Oak Grove at 6-month post installation (Fig. 5G, 5H).

Cadmium, cobalt, lead, molybdenum, nickel, selenium, silver, Naphthalene, 2-Methylnaphthalene, Acenaphthylene, Acenaphthene, Fluorene, Phenanthrene, Anthracene, Fluoranthene, Pyrene, Benzo (a) anthracene, Chrysene, Benzo (b) fluoranthene, Benzo (k) fluoranthene, Benzo (a) pyrene, Indeno (1,2,3-cd) pyrene, Dibenz (a,h) anthracene, Benzo (g,h,i) perylene, Nitrobenzene-d5, 2-Fluorobiphenyl, and Terphenyl-d14, were all below detection limits for all sites and sampling dates (data not shown). Cyanide (available) was detectable only at Fillmore Flex at 6-month post installation (0.0027 mg/L).

Prior work has shown that the presence of cadmium, lead, and zinc had minimal effect on P removal when using electrical arc furnace slag media; however, copper did significantly inhibit P removal (Okochi and McMillan 2011). Although metal concentrations were not measured in the slag media used in the present study, the copper levels in the leachate from our slag filters were extremely low (Fig. 5), and presumably, had minimal impact on P removal. Moreover, studies have shown that there are no detrimental effects to human health or to the environment as a result of leaching from steel slags, and that due to the very high temperatures applied in their formation, heavy metals are bound tightly together within the slag matrix (Proctor et al. 2002; Johansson Westholm 2010; Shilton et al. 2006), which is consistent with our data.

4. Summary

The iron slag filters have been installed for a minimum of 1 year and the current data indicate they are effective at removing P from tile drain effluent. There is considerable variation in the percent reduction among the 3 sites, but this is not unexpected. The percent reductions in P are significant but still well above the 50 µg/L goal. Encouragingly, there is no indication that the iron slag is releasing toxic metals, PAH compounds, or cyanide at levels that would cause concerns for drinking water standards.

We conclude that the installation of these filters should be targeted to areas where tile drain effluent P levels are very high (SRP > 250 µg/L) to obtain an optimal cost/benefit ratio. While they are not a panacea, when installed in combination with other best management practices, iron slag filters can play an important localized role in reducing P to Lake Macatawa.

5. Acknowledgements

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Table 1. Mean (1 standard deviation [SD]) values of selected water quality parameters for tile drain in/outflow iron slag pre- and post-installation monitoring. Date of first sampling is provided below each Pre/Post. Data are shaded to improve readability. n= number of successful sampling events per site, abbreviations in main text.

Site	Pre/Post	Outflow/ Inflow	n	Temp. (°C)	DO (mg/L)	pH	SpCond (µS/cm)	TDS (g/L)	ORP (mV)	Turbidity (NTU)
Behind Mill 1	Pre (9/20/2018 thru 4/16/2019)		8	8.61 (5.54)	10.93 (2.00)	7.91 (0.46)	872 (130)	0.567 (0.085)	253.2 (103.0)	7.9 (16.8)
	Post (4/25/2019 thru 5/27/2020)	Inflow	22	13.56 (5.97)	8.34 (1.73)	7.18 (0.38)	905 (506)	0.588 (0.329)	321.5 (66.7)	46.9 (62.4)
		Outflow	22	13.36 (5.21)	7.23 (1.97)	7.91 (0.82)	820 (169)	0.533 (0.110)	301.2 (80.5)	9.3 (11.6)
Oak Grove 2	Pre (9/20/2018 thru 3/19/2019)		7	9.13 (7.20)	11.30 (2.64)	8.19 (0.25)	676 (132)	0.439 (0.086)	284.3 (72.6)	0.0 (5.4)
	Post (5/7/2019 thru 5/27/2020)	Inflow	18	13.15 (7.10)	8.68 (2.16)	7.58 (1.07)	724 (175)	0.471 (0.114)	325.2 (63.6)	26.9 (30.5)
		Outflow	17	12.62 (7.14)	8.49 (1.98)	8.08 (1.23)	711 (139)	0.462 (0.090)	305.0 (64.6)	6.2 (9.0)
Fillmore Flex	Pre (3/26/2019 thru 8/28/2019)		9	13.89 (5.69)	7.86 (1.55)	7.65 (1.81)	894 (1187)	0.581 (0.772)	221.0 (113.5)	20.0 (45.3)
	Post (9/18/2019 thru 9/24/2020)	Inflow	19	14.23 (7.77)	7.34 (2.43)	7.81 (0.73)	537 (164)	0.349 (0.106)	315.5 (87.5)	28.2 (66.8)
		Outflow	19	14.65 (7.95)	7.13 (2.68)	8.33 (1.54)	453 (158)	0.294 (0.102)	288.7 (101.7)	33.7 (68.1)

Table 2. Mean (1 SD) values of soluble reactive phosphorus (SRP) and total phosphorus (TP) for tile drain in/outflow iron slag pre- and post-installation monitoring. Percent reduction was calculated by finding the difference between inflow and outflow values divided by inflow x100. Data are shaded to improve readability. n= number of successful sampling events per site. N/A = not applicable.

Site	Pre/Post	Outflow/Inflow	n	SRP (µg/L)	TP (µg/L)	% Reduction SRP	% Reduction TP
Behind Mill 1	Pre		8	135 (131)	167 (161)	N/A	
	Post	Inflow	25	365 (357)	598 (652)	52.3	59.5
		Outflow	25	174 (122)	242 (199)		
Oak Grove 2	Pre		7	229 (328)	254 (328)	N/A	
	Post	Inflow	23	157 (167)	426 (634)	57.3	76.5
		Outflow	22	67 (57)	100 (87)		
Fillmore Flex	Pre		9	267 (201)	721 (699)	N/A	
	Post	Inflow	23	283 (192)	907 (1368)	7.4	63.7
		Outflow	22	262 (170)	329 (148)		

Table 3. Mean water quality parameters (1 SD) for paired inflow and outflow at each site for TP, SRP and Turbidity. Data are shaded to improve readability. n= number of successful sampling events per site. α = 0.05. V = Wilcoxon test statistic; t = test statistic for the t-test.

Site	Analysis	n	Mean Inflow		Mean Outflow	Stats
Behind Mill 1	TP (µg/L)	25	595 (653)	>	242 (199)	p = 0.0011 V = 278
	SRP (µg/L)	25	364 (355)	>	174 (122)	p = 0.0028 V = 270
	Turbidity (NTU)	19	49 (61)	>	9 (12)	p = 0.0002, t = 4.6
Oak Grove 2	TP (µg/L)	21	438 (664)	>	104 (86)	p = 0.0001 V = 217
	SRP (µg/L)	21	164 (188)	>	69 (57)	p = 0.0004 V = 210
	Turbidity (NTU)	10	27 (29)	≈	5 (8)	p = 0.0063 t = 3.3
Fillmore Flex	TP (µg/L)	17	997 (1451)	>	304 (126)	p = 0.0002 V = 210
	SRP (µg/L)	17	285 (208)	≈	234 (149)	p = 0.0825 V = 152
	Turbidity (NTU)	15	26 (66)	≈	12 (19)	p = 0.6819 t = 0.4

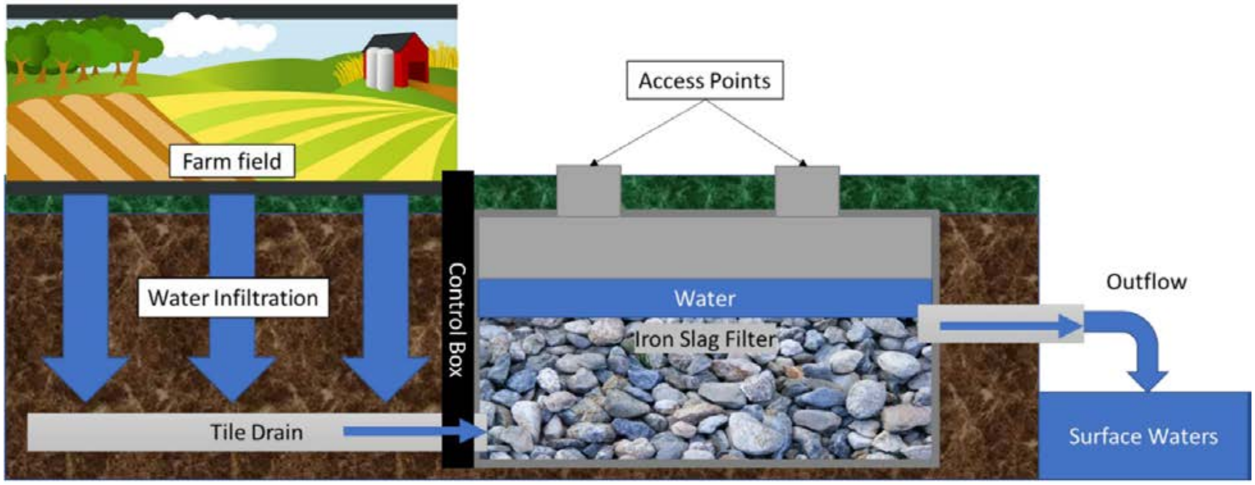

Figure 1. Stylized cross-section of iron slag filters design/function. Figure is not to scale as iron slag filter size is dependent on multiple factors (e.g. size of the tiled field, water velocity from the tile drains, soil type). See text for more detail on how the filters function. Image credit: Maggie Oudsema

Figure 2. Inlet pipes being laid in the bottom of an iron slag filter. Drainage water enters at the bottom, moves up through the iron slag material (not yet installed) and leaves out a pipe near the top (not pictured) that leads to a nearby surface drain (not pictured). Photo credit: Macatawa Area Coordinating Council.

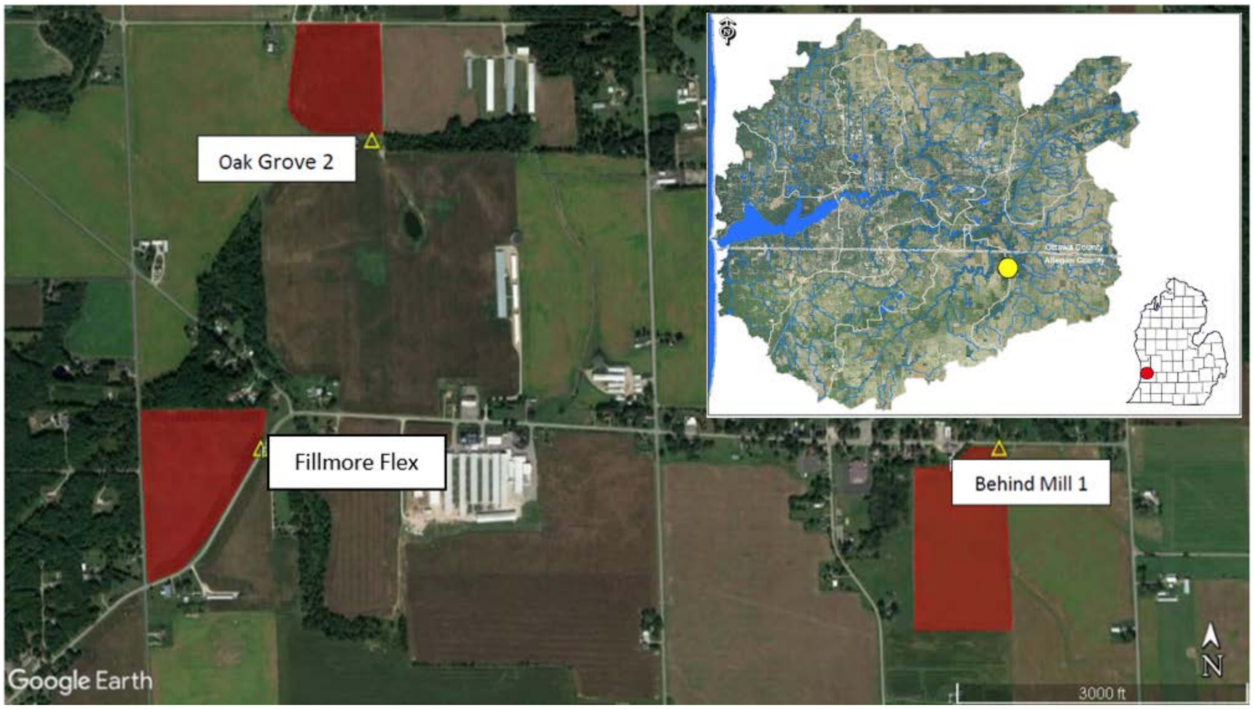

Figure 3. Completed iron slag filter sites are indicated by yellow triangles, the red polygons represent the adjoining fields being drained, each approximately 30 acres. Fillmore Flex and Oak Grove 2 sites flow into the south branch of the Macatawa River, which later joins the main branch of the Macatawa River. Behind Mill 1 flows into Peter's Creek. The insert shows the location within the Macatawa watershed by the yellow circle, and within the lower peninsula of Michigan by the red circle.

Figure 4. Photos of different sampling locations. A) Behind Mill 1 with completed iron slag filters in place. The green tube (far right) is an inflow sampling port that was installed only at this location. Access ports (for cement upright tubes) are for two slag filter basins (considered to be one slag filter site) that receive tile drain water from the adjoining field (in background) and are used to sample outflow. B) Research Assistant, Emily Kindervater, using a hand pump siphon to sample from a below-ground control box (inflow) at Fillmore Flex; Oak Grove 2 has a similar constructed inflow access (not shown). C) Slag filter outflow access point for Oak Grove 2, which required a ladder to remove the large plastic cap to sample outflow water. D) Slag filter outflow access point at Fillmore Flex, which is covered with large plywood lids. E) Outflow pipe at Behind Mill 1 directly after installation; the white particulate residue inside the tube is from the calcium carbonate layer placed on top of the iron slag inside the tanks to balance pH.

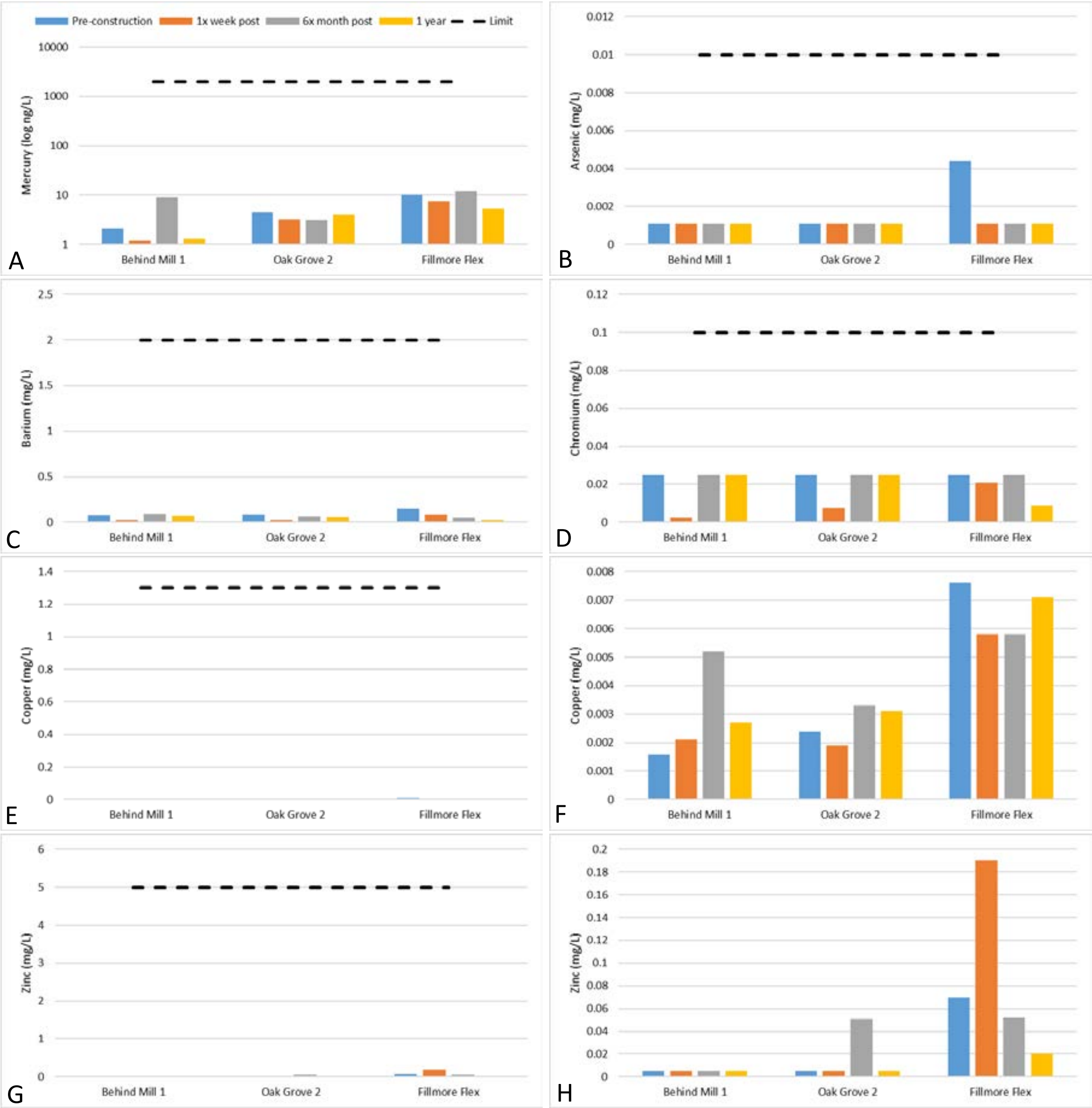

Figure 5. Metals for pre-installation, 1-week, 6-month and 1-year post installation. Blue is pre-installation, orange is 1-week post installation, grey is 6-month post installation, and yellow is for 1-year post installation. The black dotted line represents the drinking water standard from either the EPA or WHO, which ever was the smaller of the two standards for the given chemical. The legend in A applies to B-H. F and H are enlarged versions of E and G respectively. Note: y-axis for panel A is logarithmic scale.