Slag Filter BMP Preliminary Performance in the Macatawa Watershed, Monitoring Year 2

Prepared for:

Travis Williams and Dan Callam, Outdoor Discovery Center Network
and
Jim Johnson, Michigan Department of Agriculture and Rural Development

Prepared by:

Michael Hassett, Scientific Technician
Alan Steinman, Ph.D., Director and Professor

Annis Water Resources Institute, Grand Valley State University
740 W. Shoreline Dr., Muskegon, MI 49441

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1. Overview

Excess phosphorus is resulting in the eutrophication of water bodies throughout the world (Paerl et al., 2016), often resulting in harmful algal blooms in both freshwater and marine systems (Boesch, 2019; Wurtsbaugh et al., 2019). Agricultural runoff is one of the main sources of excess nutrient loading to aquatic systems (Carpenter et al., 1998; Mrdjen et al., 2018); controlling this runoff, through either structural or non-structural Best Management Practices (BMPs), is the conventional means to reduce eutrophication. Implementing and enforcing regulatory measures is far less common, although litigation to enforce numeric nutrient standards is known to occur (Fumero and Rizzardi, 2000).

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), 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.

It is well established that land use, and especially hydrologic connectivity in the watershed, plays a major role in nutrient loading to lakes (Soranno et al., 2015). Previous research has demonstrated that agriculture is a major source of nonpoint P in the Macatawa watershed (Steinman et al., 2018; Iavorivska et al., 2021). 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; Michaud et al., 2019), which provides direct input to surface drains via outfalls. 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 other parts of the Midwest, including central Ohio (Mrdjen et al., 2018) and the western basin of Lake Erie (Calhoun et al., 2002; Smith et al., 2015), which in both cases led to harmful algal blooms (Michalak et al., 2013; Wynne and Stumpf, 2015; Mrdjen et al., 2018).

Various BMPs have been implemented in the Macatawa watershed to reduce P loading, including among others, grassed waterways, cover crop plantings, gypsum application, two-stage ditches, and wetland restoration, although their effectiveness has been questioned (Steinman et al., 2018; Kindervater and Steinman, 2019). Iron slag, a waste product from the steel industry, can chemically bind P and has been implemented previously in agricultural settings (Hua et al., 2016; Roychand et al., 2020). Interest was expressed as to whether iron slag filters may be an effective management practice in the Macatawa watershed. To that end, various public and private entities involved in Project Clarity (https://outdoordiscovery.org/project-clarity/) committed to install a series of iron slag filters at the end of agricultural tile lines in the watershed. Our goal has been to evaluate the efficiency of these systems in removing P, while also monitoring for the presence of potentially toxic chemicals leaching from the iron slag, which may be released into surface waterways. Although these filters have been installed in Ohio, to our knowledge, this is their first usage in Michigan.

2. Materials and Methods

2.1 Study Area

The Macatawa watershed (464 km^2) is located in Ottawa and Allegan Counties (MI) and drains into Lake Macatawa (Figure 1). Land use is dominated by agriculture (46%) and developed (33%), which has contributed to the loss of 86% of the watershed's natural wetlands (MWP, 2012). The watershed includes the cities of Holland and Zeeland and parts of 13 townships. Lake surface area is 7.2 km^2. This drowned river mouth lake is relatively shallow, with an average depth of 3.6 m and a maximum depth of 12 m in the western basin. The Macatawa River, the main tributary to the lake, flows into the lake's shallow eastern basin. A navigation channel at the western end of the lake connects Lake Macatawa with Lake Michigan.

This 2021 report builds upon previous pre- and post-installation monitoring in 2019-2020. Water quality monitoring continued at three existing iron slag filter sites (Behind Mill 1 and Oak Grove 2 constructed in April 2019; Fillmore Flex constructed in September 2019) and new sampling began at one freshly installed iron slag filter (Joe's House, constructed in April 2021). Due to the COVID-19 pandemic, sampling was halted 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. Additional sites in the watershed were sampled for consideration for slag filter installation; however, we present data in this report only for the completed slag filters.

Filters are designed to work passively, receiving water after it infiltrates through soils into subsurface tiled drains (Figure 2). Water moves up and through the iron slag in large concrete tank(s), where the iron slag binds with and removes the P from the water before the water passively releases to adjacent surface waterways (Figures 2, 3). A layer of calcium carbonate particulate was applied within the treatment tank on top of the iron slag 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 (see below).

2.2 Field and Laboratory Processes

Prior to installation, grab samples were taken monthly at 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 (Figure 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 1 (Figure 4A) and through a control box at Oak Grove 2, Fillmore Flex, and Joe's House (Figures 1, 4B). Outflow was sampled at the original outflow pipe (Figure 4E; which remained after installation) for all sites; however, when the outflow pipe was inaccessible due to being underwater (the surface drains are very flashy and water levels can rise quickly after a rain event [Steinman et al., 2018], submerging the outflow pipes), 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 (Figures 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], and turbidity). Grab samples were collected for analysis of TP and soluble reactive P (SRP). All samples were placed in a cooler on ice and brought back to the 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 1-week post-installation and then every 6-months post-installation, for up to 2.5 years post-installation as of this reporting 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. Reporting detection limits for chromium improved (i.e., became better at detecting smaller concentrations) between pre-construction and 1-week post-construction sampling at Behind Mill 1 and Oak Grove 2 sites, changing the limit from <0.050 mg/L to <0.0050 mg/L.

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, and the 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 either paired t-tests or Wilcoxon signed rank tests, depending on normality. Normality assumptions were tested using Shapiro-Wilk tests. Significance was set at $\alpha = 0.05$. Data analysis was conducted using SigmaPlot (v14.0). Percent reductions were calculated for the paired mean inflow and mean outflow measurements post-installation for SRP and TP by calculating the difference between each nutrient's respective 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

3.1 Water Quality Sampling

Sampling events in 2021 occurred with similar frequency and seasonality at Behind Mill 1, Oak Grove 2, and Fillmore Flex. Across all sites, mean water temperatures increased ~0.5-2 °C from inflow to outflow (Table 1). Mean DO correspondingly decreased at each site between flow sampling locations and the lowest mean DO of 4.7 (±1.9) mg/L was measured at Joe's House (Table 1). Mean inflow pH was generally circumneutral at all sites and mean outflow was higher than inflow (i.e., more basic; Table 1). Behind Mill 1 outflow pH (mean 9.82±0.79) was consistently higher than corresponding inflows (mean 7.26±0.61) throughout the year (Table 1) and reached a maximum of 11.3 in June 2021. Mean SpCond ranged 613-1083 µS/cm among sites and flows, with Fillmore Flex being the lowest and Oak Grove 2 being the highest, although variability among all sites overlapped (Table 1). Mean ORP was steady between flows at each site (Table 1). Mean turbidity decreased at each site's outflow and never exceeded <29 NTU regardless of whether it was inflow or outflow (Table 1).

Iron slag filters continued to result in reduced P concentrations in 2021. At the older three sites (Behind Mill 1, Oak Grove 2, Fillmore Flex), mean TP inflow ranged 332-750 µg/L and outflows were reduced by 97.5%, 35.8%, and 35.3% respectively; all reductions were statistically significant ($P<0.05$; Table 2). Differences in mean SRP were more variable between sites with Behind Mill1 showing a strong ($P<0.001$) 98.7% reduction, while Oak Grove 2 and Fillmore Flex had similar SRP concentrations in the inflows and outflows (Table 2). Mean turbidity followed the same trends as TP and showed large reductions in the outflow (60%-84%; $P<0.05$; Table 2).

The newly installed iron slag filter at Joe's House experienced very low flow volumes throughout the year and there were only two instances through the year when we had usable paired inflow-outflow data.

Given the limited number of observations, statistical results should be interpreted cautiously. That stated, mean TP at Joe's House mean inflow (868 µg/L) was much higher than the mean outflow (150 µg/L), showing 82.7% reduction in TP and the paired t-test indicated this difference was statistically significant (P=0.029; Table 2). Both mean SRP and turbidity declined in the outflow at this site, but the differences were not statistically significant due to limited statistical power and high variance (Table 2).

3.2 Metals and PAHs

New 2021 sampling events for metals and PAHs were conducted at 1.5, 2, and 2.5 years post-installation at Behind Mill 1 and Oak Grove 2; at 1, 1.5, and 2 years post-installation at Fillmore Flex; and at 6 months post-installation at Joe's House. Pre-installation and 1-week post-installation metals sampling did not occur at Joe's House. 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 14 ng/L at all sites, maintaining the trend from previous reporting years of concentrations being two orders of magnitude below EPA (2,000 ng/L) and WHO (6,000 ng/L) drinking water standards (Figure 5A). Behind Mill 1 concentrations consistently decreased from its 6-month post-installation peak and ended the monitoring year with concentrations lower than pre-installation. Oak Grove 2 and Fillmore Flex remained steady across both sampling years, although Fillmore Flex was generally higher and showed more variation in mercury concentrations. Joe's House 6-month measurement was the lowest value among all the sites for that given post-installation time period.

Arsenic was below detection at all sites in 2021 (Figure 5B). Barium at Behind Mill 1 in 2021 was consistently below detection, while other sites were more variable and had ranges similar to those seen during 2020 sampling (Figure 5C). Chromium was consistently below detection at all sites except for Fillmore Flex at 1-year post-installation, yet it remained one order of magnitude below drinking water guidelines (Figure 5D). Copper was measured at all sites and in slightly increased concentrations compared to last year with 2-years and 2.5-years post-installation measurements higher than pre-installation (Figure 5E). Zinc was found at all sites in 2021. Behind Mill 1, which had been consistently below detection in 2020, was the highest of all sites with 0.77 mg/L at 2-years post-installation (Figure 5F).

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).

4. Summary

The iron slag filters assessed as part of this study have shown that after one year of performance, they are effective at removing P from tile drain effluent. We observed considerable variation in the percent reduction among the 3 sites, indicating the importance of site selection and environmental context in their P reduction effectiveness, which is consistent with findings from other studies (Penn et al., 2017; Hauda et al., 2020). Although both the percent and absolute reductions in P were substantial, they were still well above the 50 µg/L TMDL goal. Encouragingly, there was no indication that the iron slag is releasing toxic metals, PAH compounds, or cyanide at levels that would cause concerns for drinking water standards.

To maximize performance effectiveness, we recommend that the installation of iron slag filters should be targeted to areas where tile drain effluent SRP levels exceed 250 µg/L. Continued monitoring will determine how long they remain effective at reducing P. While they are not a panacea, when installed in combination with other BMPs, iron slag filters can play an important localized role in reducing P in watersheds that are underlain with tile drains.

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. Data are shaded to improve readability. Dates of sampling range is provided below each Pre/Post. Data are shaded to improve readability. n= number of successful sampling events per site, N/A = not applicable, ND = no data, parameter 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 to 4/16/2019)	N/A	8	8.6 (5.5)	10.9 (2.0)	7.9 (0.5)	872 (130)	0.567 (0.085)	253.2 (103.0)	7.9 (16.8)
	Post (11/5/2020 to 10/20/2021)	Inflow	16	14.2 (6.1)	6.2 (2.7)	7.3 (0.6)	799 (319)	0.519 (0.208)	338.3 (127.9)	29.0 (44.8)
		Outflow	18	14.8 (5.6)	6.1 (2.4)	9.8 (0.8)	706 (127)	0.459 (0.083)	264.9 (149.4)	6.8 (14.9)
Oak Grove 2	Pre (9/20/2018 to 3/19/2019)	N/A	7	9.1 (7.2)	11.3 (2.6)	8.2 (0.3)	676 (132)	0.439 (0.086)	284.3 (72.6)	0.0 (5.4)
	Post (11/5/2020 to 10/20/2021)	Inflow	15	13.4 (5.9)	8.7 (2.9)	7.6 (0.8)	1074 (422)	0.698 (0.274)	310.3 (142.4)	19.0 (18.9)
		Outflow	18	15.2 (6.7)	7.6 (3.2)	8.1 (0.6)	1083 (531)	0.704 (0.345)	279.7 (140.5)	2.6 (3.6)
Fillmore Flex	Pre (3/26/2019 to 8/28/2019)	N/A	9	13.9 (5.7)	7.9 (1.6)	7.7 (1.8)	894 (1187)	0.581 (0.772)	221 (113.5)	20.0 (45.3)
	Post (11/5/2020 to 10/20/2021)	Inflow	13	14.4 (6.2)	8.0 (2.5)	7.1 (0.6)	765 (478)	0.497 (0.311)	286.9 (139.1)	12.1 (10.2)
		Outflow	17	16.2 (6.4)	7.2 (2.4)	8.1 (1.0)	613 (139)	0.398 (0.09)	273.1 (140.4)	3.3 (3.7)
Joe's House	Pre (1/16/2020 to 3/10/2020)	N/A	ND	ND	ND	ND	ND	ND	ND	ND
	Post (5/12/2021 to 10/20/2021)	Inflow	2	17.4 (5.2)	7.8 (3.5)	6.7 (0.6)	760 (274)	0.494 (0.178)	181.2 (333.4)	12.9 (8.5)
		Outflow	10	19.4 (2.9)	4.7 (1.9)	7.7 (0.7)	965 (834)	0.627 (0.542)	183.3 (151.1)	2.3 (1.3)

Table 2. Mean water quality parameters (1 standard deviation [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. N/A = not applicable. Note that negative reduction % values indicate an increasing change from inflow to outflow.

Site	Analysis	n	Mean Inflow		Mean Outflow	Reduction (%)	Stats
Behind Mill 1	Pre-installation	8	TP = 167 (161) SRP = 135 (131)			N/A	N/A
	TP (µg/L)	17	750 (485)	>	19 (21)	97.5	**P < 0.001**
	SRP (µg/L)	17	478 (341)	>	6 (10)	98.7	**P < 0.001**
	Turbidity (NTU)	16	29 (45)	>	8 (16)	72.4	**P = 0.018**
Oak Grove 2	Pre-installation	7	TP = 254 (328) SRP = 229 (328)			N/A	N/A
	TP (µg/L)	14	332 (322)	>	213 (209)	35.8	**P = 0.042**
	SRP (µg/L)	14	111 (103)	≈	114 (48)	-2.7	P = 0.464
	Turbidity (NTU)	15	19 (19)	>	3 (3)	84.2	**P < 0.001**
Fillmore Flex	Pre-installation	9	TP = 721 (699) SRP = 267 (201)			N/A	N/A
	TP (µg/L)	12	702 (368)	>	454 (218)	35.3	**P = 0.045**
	SRP (µg/L)	12	338 (136)	≈	308 (124)	8.9	P = 0.544
	Turbidity (NTU)	11	10 (5)	>	4 (4)	60.0	**P = 0.017**
Joe's House	Pre-installation	5	TP = 261 (52) SRP = 216 (43)			N/A	N/A
	TP (µg/L)	2	868 (48)	>	150 (94)	82.7	**P = 0.029**
	SRP (µg/L)	2	194 (121)	≈	56 (21)	71.1	P = 0.303
	Turbidity (NTU)	2	13 (8)	≈	1 (1)	92.3	P = 0.312

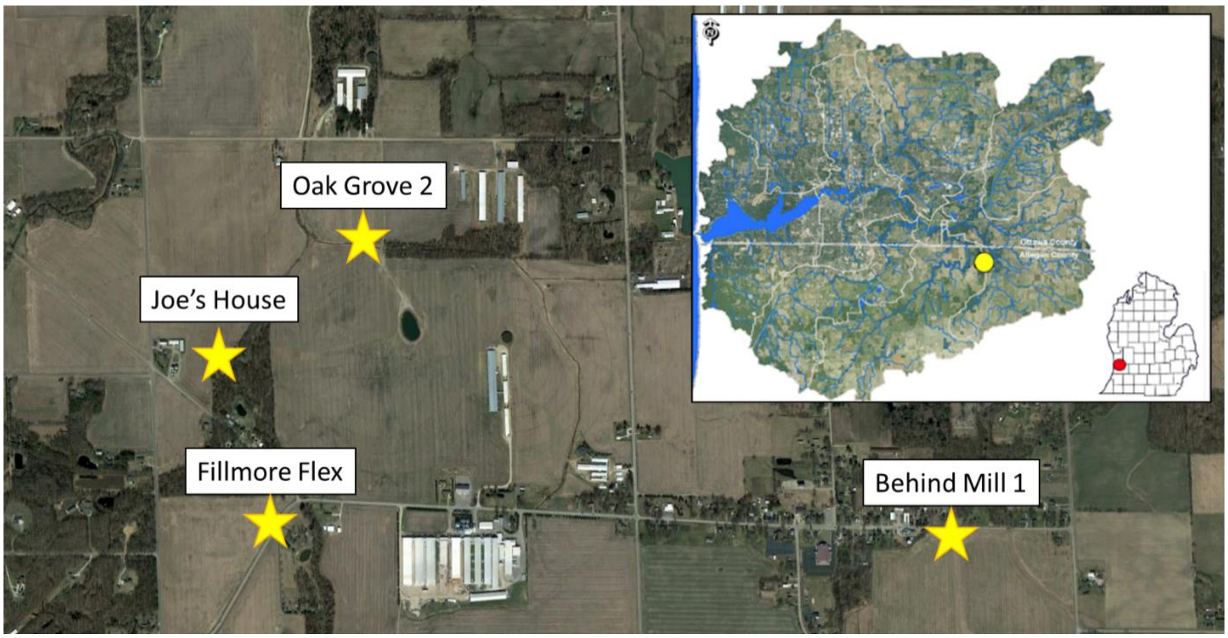

Figure 1. Completed iron slag filter sites are indicated by yellow stars, each draining approximately 30 acres. Fillmore Flex, Joe’s House, and Oak Grove 2 sites flow into the south branch of the Macatawa River, which later joins the main branch of the Macatawa River. Behind Mill 1 flows into Peter’s Creek. Insert: location of sites within the Macatawa watershed (yellow circle) and location within the lower peninsula of Michigan (red circle).

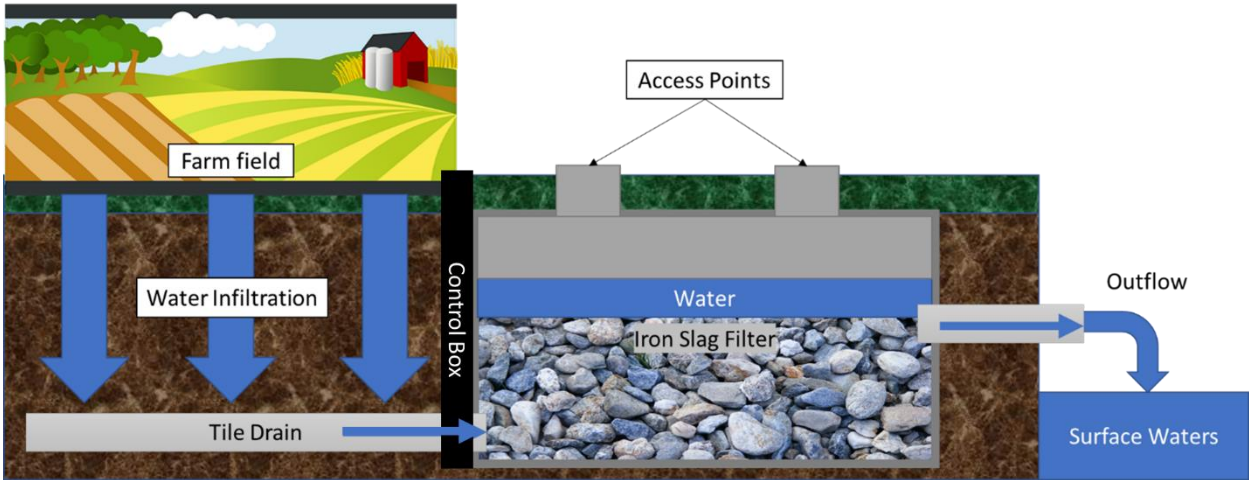

Figure 2. Stylized cross-section of iron slag filters design/function. Figure is not to scale as iron slag filter size is dependent on multiple factors (e.g. size of the tiled field, water velocity from the tile drains, soil type). See text for more detail on how the filters function. Image credit: Maggie Oudsema.

Figure 3. 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.

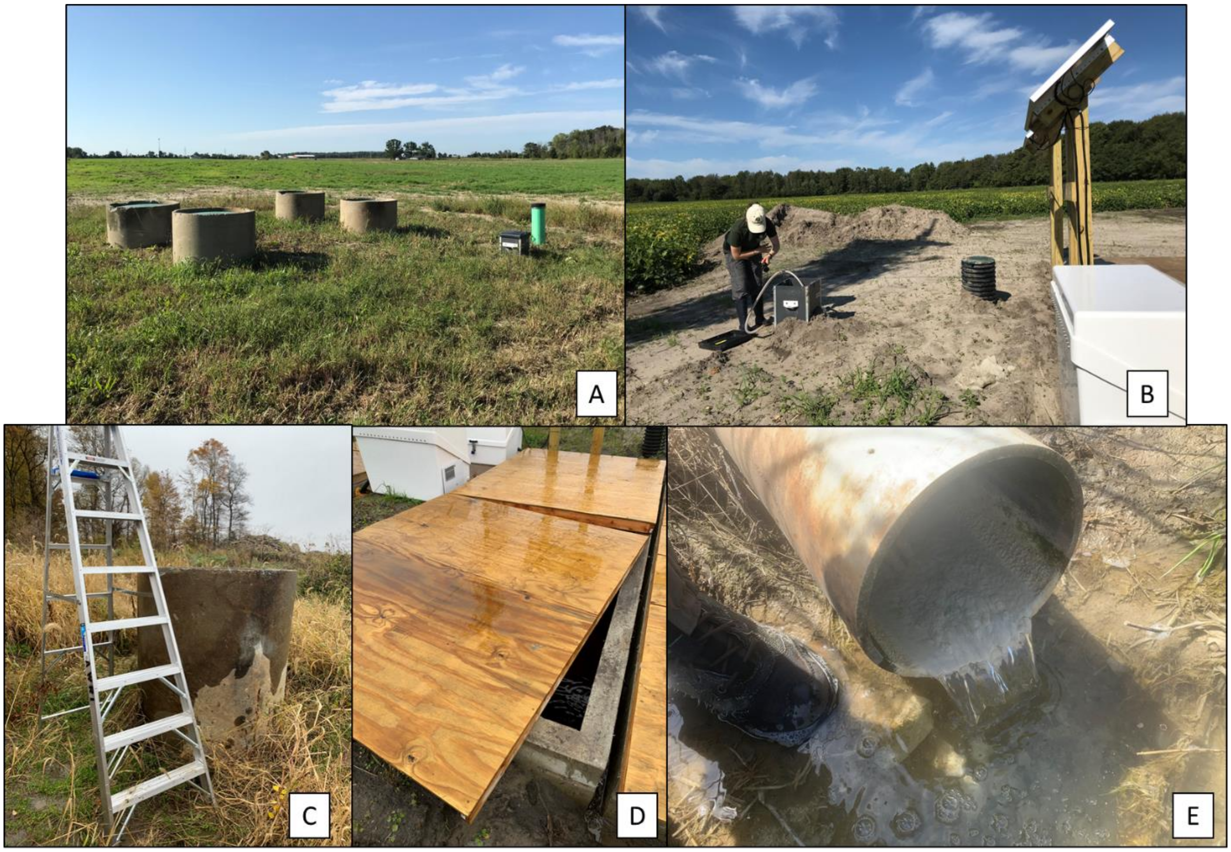

Figure 4. Photos of different sampling locations. A) Behind Mill 1 with completed iron slag filters in place. The green tube (far right) is an inflow sampling port that was installed only at this location. Access ports (for cement upright tubes) are for two slag filter basins (considered to be one slag filter site) that receive tile drain water from the adjoining field (in background) and are used to sample outflow. B) Sampling via 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. Photo credit: Maggie Oudsema.

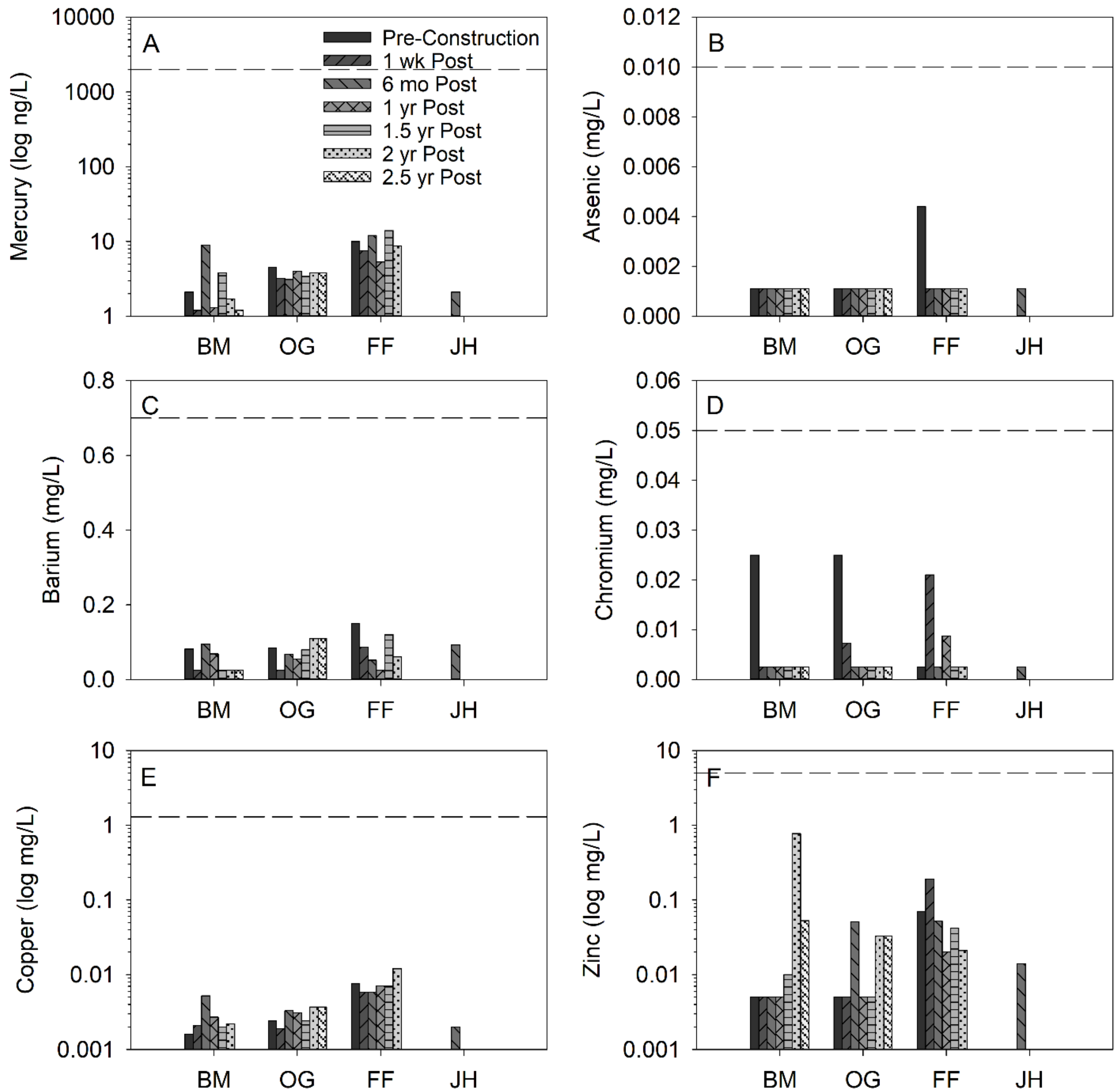

Figure 5. Metals for pre-installation, 1-week, every 6-months following post-installation at Behind Mill 1 (BM), Oak Grove 2 (OG), and Fillmore Flex (FF), and Joe's House (JH). The black dashed line represents the drinking water standard from either the EPA or WHO, which ever was the smaller of the two standards for the given analyte. The legend in panel A applies to panels B-F. Note that y-axes for panels A, E, and F have logarithmic scales.

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