DEPARTMENT OF TRANSPORTATION

Iron-Enhanced Swale Ditch Checks for Phosphorus Retention

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16. Abstract (Limit: 250 words)

Iron-enhanced ditch checks in roadside swales were developed specifically for capturing dissolved phosphorus and dissolved metals from roadway runoff in both urban and agricultural environments. One iron-enhanced ditch check constructed along CR 15 (formerly TH 5) in Stillwater, Minnesota, was monitored during 40 storm events from 2016 to 2018. The iron-enhanced sand filter insert generally captured phosphate, yielding lower phosphate concentrations and mass load reductions that varied between 22% and 50% during several events. However, the cumulative phosphate retention in the filter insert decreased from 42% in 2015 to 30% in 2016, 25% in 2017, and 23% in 2018. The filter insert was not an effective retention device for dissolved copper and zinc. The overall ditch check's performance, although unexceptional in 2016 and 2017, appeared to improve in 2018. Sampling issues likely contributed to the low performance measured until 2017. The 2018 water sample collection method provided a better estimate of the ditch check's performance and roughly matched that of the filter insert. Synthetic runoff testing supported the level of treatment achieved during storm events. Phosphate load from the degrading topsoil and the overutilization of the bottom filter media most likely affected overall treatment performance. Design improvements and recommended maintenance actions were developed based on the lessons learned from field monitoring. The iron-enhanced ditch check can improve net phosphate retention through roadside swales, as long as the recommended maintenance actions are performed as scheduled.

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IRON-ENHANCED SWALE DITCH CHECKS FOR PHOSPHORUS RETENTION

FINAL REPORT

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EXECUTIVE SUMMARY

Dissolved phosphorus load introduced by stormwater runoff is impairing the water quality of lakes and streams in several locations in Minnesota. Iron-enhanced ditch checks in roadside swales have been developed specifically to capture dissolved phosphorus (phosphate) and dissolved metals from stormwater runoff in both urban and agricultural environments. The horizontal-flow ditch check design incorporates an iron-enhanced sand filter insert that has the ability to retain phosphate and dissolved metals by sorption to iron in the filter media. The main goals of this project are to investigate the long-term effectiveness of the iron-enhanced ditch check in retaining pollutants and develop recommended maintenance actions.

This project involved monitoring an iron-enhanced ditch check, located along CR 15 (formerly TH 5) in Stillwater, Minnesota, from 2016 to 2018. As part of a previous project, this ditch check was monitored in 2015. During the 40 rainfall events sampled between 2016 and 2018, the filter insert section captured phosphate in the runoff inflow and lowered phosphate concentrations in the discharge from the filter during a majority of the events. The phosphate mass load reductions varied between 22% and 54%, although low phosphate mass retention (<15%) and export of phosphate mass were observed for six events. Input total phosphorus (TP) mass decreased from 11% to 30% in the outflow when mass reduction was observed. However, the cumulative phosphate retention in the filter insert decreased from 42% in 2015, to 30% in 2016, 25% in 2017, and 23% in 2018. Synthetic runoff testing in 2017 and 2018 supported the decreasing treatment efficiency trend. It was estimated that the filter insert area that filtered most of the inflow volume (bottom 10 cm or 3.9 in) treated about 1322 m (4337 ft) of runoff from 2015 to 2018. Batch tests on filter media cores collected in 2018 confirmed the decreased phosphorus sorption capacity of the bottom ~10 cm (3.9 in) of the sand-iron media. The passage of most of the runoff load through the filter's bottom area diminished its sorption capacity and was likely the reason for the overall reduction in phosphate retention ability over time.

Performance of the entire ditch check, assessed by comparing water quality at the upstream and downstream toes of the entire ditch check, was lower than that of the filter insert. The cumulative phosphate retention in the ditch check was -10% in 2016, 13% in 2017, and 17% in 2018. Sampling issues likely contributed to the low performance measured until 2017. The 2018 sampling method provided a better estimate of the ditch check's performance, which was marginally below that of the filter insert. Phosphate leaching from the degrading topsoil and sod covering the entire ditch check could have affected the overall performance of the ditch check and filter insert.

The entire ditch check and filter insert were not as effective in retaining dissolved copper and zinc. Mass reductions were mixed, with reductions ranging between -36% to 61% for copper and -86% to 64% for zinc. However, copper and zinc concentrations in the inflow and treated runoff were generally lower than typical concentrations in highway runoff.

For future applications of iron-enhanced ditch checks, it is recommended that topsoil and sod cover over the filter insert section be avoided. If possible, topsoil and sod must not be applied over the remaining areas of the ditch check (i.e., upstream and downstream slopes). If a given application requires the upstream and downstream slopes to be covered by sod, a phosphorus-lean topsoil (for example, 60% sand, 30% topsoil, 10% peat moss by volume) should be used to reduce the release of phosphate from degrading topsoil and sod into water flowing through the ditch check. Construction of ditch checks with a lower overall height (0.30 m or 1 ft instead of the current design of 0.61 m or 2 ft) is recommended to mainly target medium- and low-flow events and maximize the filter insert area subject to runoff filtration, although an increase in the width of the filter insert (current design of 0.40 m or 16 in) is not necessary. Lastly, the installation of a series of iron-enhanced ditch checks can improve net pollutant retention; the treatment performance data from the current project suggest three to four ditch checks built in series would provide cost-effective phosphate removal. Still, selection of the number of ditch checks will depend on the application, stormwater management goals, and the balance of treatment levels and cost. As part of routine maintenance, removal of organic material upstream of the ditch check at least once during the growing season is recommended to minimize external phosphorus input. Mixing of the iron-sand media every other year to partially restore sorption capacity and eliminate macropores in the media and replacing the entire filter media approximately every six years are recommended as part of the non-routine maintenance at the iron-enhanced ditch check.

CHAPTER 1: INTRODUCTION

Swales and drainage ditches for linear road projects have excellent potential for stormwater treatment. They can infiltrate water into the soil, filter sediments and associated pollutants out of the water, and settle solids to the bottom of the swale. Riprap check dams or ditch checks are commonly installed erosion-control structures in grassed channels and help increase storage and infiltration of runoff. In Minnesota, riprap check dams are currently one type of stormwater control measure that can be installed to help meet permit requirements.

Dissolved phosphorus loads introduced by runoff are impairing the water quality of lakes and streams in several locations in Minnesota. Iron-enhanced ditch checks in roadside swales are a novel stormwater treatment system developed specifically to capture dissolved phosphorus (phosphate) from roadway runoff in both urban and agricultural environments. The horizontal-flow ditch check design incorporates an iron-enhanced sand filter insert with the ability to retain phosphate and dissolved metals by sorption to iron in the filter media. Also, a fraction of the particulates is filtered out as runoff flows through the gravel/riprap and sand-iron media in the ditch check.

Permeable check dams enhanced with iron filings were developed and tested in the laboratory (Ahmed et al. 2014), and iron-enhanced ditch checks were constructed by the Minnesota Department of Transportation (MnDOT) in 2014 (Natarajan and Gulliver 2015). One iron-enhanced ditch check, located along CR 15 (formerly TH 5) in Stillwater, was monitored in 2015 and found to retain 36% of the phosphate mass in road runoff, but it did not consistently reduce the dissolved zinc and copper concentrations in runoff.

This project was undertaken to continue the performance monitoring of the CR 15 (formerly TH 5) iron-enhanced ditch check for three additional years. The main goals were to investigate the long-term effectiveness of the iron-enhanced ditch check in retaining pollutants and to develop recommended maintenance actions. The objectives were to 1) determine the reduction of phosphate, dissolved copper, and dissolved zinc in the sand-iron filter insert section and in the entire ditch check for three years, 2) determine whether the treatment performances varied with time and determine the controlling factors, and 3) identify maintenance actions necessary for effective performance. The pollutant retention performance of the iron-enhanced ditch check was monitored during storm events and tested using synthetic runoff from 2016 to 2018. The data obtained was used to identify the general level of phosphate and dissolved metal reduction that can be expected and identify any problems with the technology that needed to be solved, including maintenance needs.

CHAPTER 2: BACKGROUND

The iron-enhanced ditch check was developed as an application of the iron-enhanced sand filtration technology for roadside swales and drainage ditches. A prototype of permeable ditch check containing iron in the filter media was tested at the St. Anthony Falls Laboratory (SAFL) through a project funded by the Local Road Research Board (LRRB) (Ahmed et al. 2014). The full-scale design development and construction of iron-enhanced ditch checks in swales in the right-of-way of the MnDOT was completed through another project funded by the Minnesota Pollution Control Agency (MPCA) (Natarajan and Gulliver 2015). Two iron-enhanced ditch checks were constructed by MnDOT in a swale located along CR 15 (previously TH 5) in Stillwater, Washington County, in September 2014 (Figure 2.1). The iron-enhanced sand filter was incorporated as an insert in a riprap check dam such that, as runoff flows through the ditch check, a fraction of the particulates will be filtered out by riprap and sand media, and phosphates will be retained in the sand-iron media (Figure 2.2). In the CR15 Ditch Check 1, the sand-iron filter media was filled into several geotextile fabric socks and these socks were arranged inside a metal cage to form the filter insert. In the CR 15 Ditch Check 2, the filter media was filled into a single geotextile fabric sock placed inside the metal cage. Detailed design information and construction photos are available in Natarajan and Gulliver (2015).

Figure 2.1 Location of the two iron-enhanced ditch checks (Ditch Check 1 and Ditch Check 2) constructed by MnDOT along CR 15 (formerly TH 5) in Stillwater, Washington County, Minnesota. (Source: <maps.google.com>). Ditch Check 2 was monitored in this project.

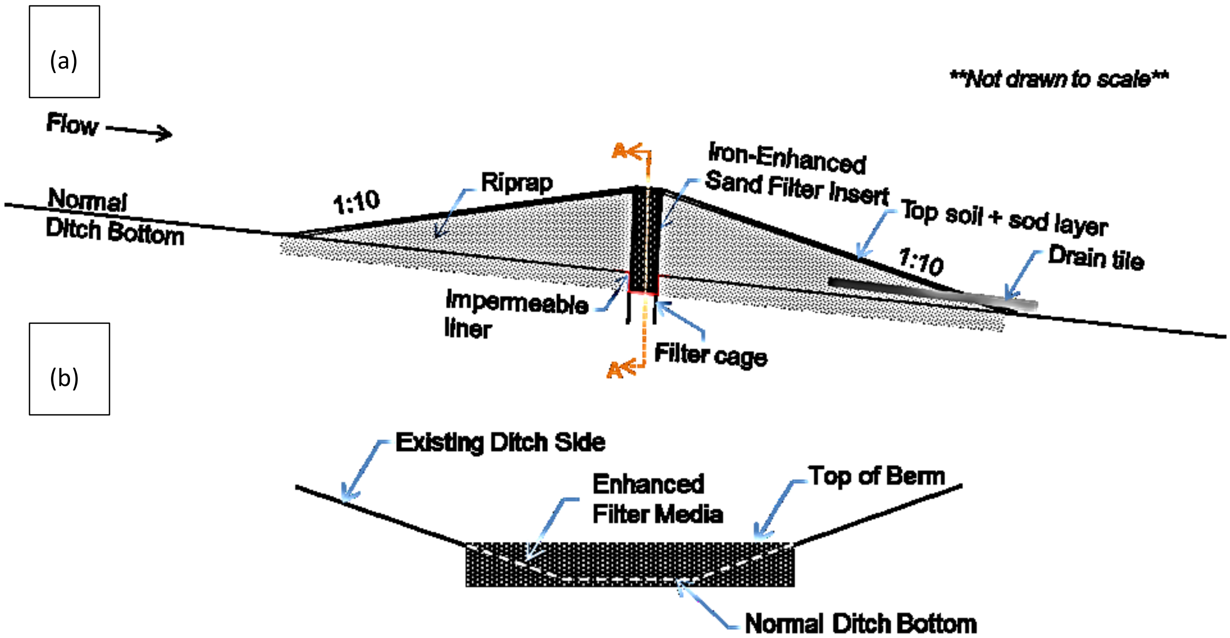


Figure 2.2 Schematic of the iron-enhanced ditch check designed and constructed by MnDOT in Stillwater. (a) Profile view and (b) Cross-sectional view (Section A-A). (Source: Natarajan and Gulliver 2015)

Ditch Check 1 appeared to have substantial untreated leakage likely due to the passage of water around the multiple filter socks arranged in the cage and was therefore not monitored. Ditch Check 2 was monitored during storm events between May and August 2015 (Figure 2.1 and

Figure 2.3 2.3). The drainage area to Ditch Check 2 is 0.29 ha (0.72 ac), consisting of 0.21 ha (0.52 ac) of swales and 0.08 ha (0.20 ac) of highway area. The iron-enhanced sand filter insert spans the entire width of the ditch (~3.81 m or 12.5 ft), and is 0.40 m (16 in) long in the direction of flow. The ditch check is approximately 0.61 m (2 ft) high and is fully covered by topsoil and sod (

Figure 2.3). The topsoil and sod cover was required for roadside clear zone safety since bare riprap was considered a hazard.

Figure 2.3. (a) Photograph of the iron-enhanced ditch check (Ditch Check 2) along CR 15 (formerly TH 5) in Stillwater, Washington County (Photograph by P. Natarajan, 2014). Approximate location of the filter insert in the ditch check is shown. (b) Photograph taken during construction in 2014 shows the placement of filter media into a single geotextile fabric that was wrapped to form the filter insert core inside the filter cage, and (c) Photograph shows the completed filter insert.

A water truck test was conducted in November 2014, two months after construction, and the pollutant retention by the filter insert was determined by measuring the phosphate and dissolved zinc concentrations in the flow-weighted composite water samples of the filter inflow and outflow collected throughout the two-hour testing duration. About 78% retention of the phosphate mass input (inflow EMC = 206 µg/L, outflow EMC = 45 µg/L) and 11% retention of the dissolved zinc mass input (inflow EMC = 70 µg/L, outflow EMC = 62 µg/L) was observed for the filter insert. Field monitoring during summer 2015 showed that, in general, the filter insert captured phosphate in road runoff resulting in lower effluent phosphate concentrations than the inflow. The cumulative phosphate mass load input from 16 storm events was reduced by 42%. The observed dissolved copper and zinc mass reductions were mostly negative, attributed to leaching of metals from the filter media or the surrounding filter cage, although the metal concentrations in the inflow runoff were much lower than the concentrations typically measured in roadway runoff. Since the 2015 monitoring provided only a short-term assessment of Ditch Check 2's performance, this project was undertaken to monitor Ditch Check 2 for three more years to evaluate its long-term treatment efficiency. The Ditch Check 2 will be referred to as iron-enhanced ditch check in the following sections of the report.

CHAPTER 3: 2016 TO 2018 PERFORMANCE MONITORING METHOD

The ditch check was monitored during the growing season until the air temperature dropped below 0 °C, typically by late October or early November. The treatment performance of the iron-enhanced ditch check was assessed by measuring the flow through the ditch check (and filter insert) and collecting water samples on the upstream and downstream points of the ditch check and the filter insert section during multiple storm events. Monitoring wells that had been installed at the filter insert during construction were utilized for flow and water quality monitoring. By determining the concentrations of the desired pollutants in the water samples, the pollutant mass load captured, and treatment efficiencies were calculated.

3.1 FLOW AND RAINFALL DEPTH MEASUREMENT

Pressure transducers (PS9105, Instrumentation Northwest, Kirkland, WA) installed in the monitoring wells measured the upstream and downstream water levels at the filter insert section (Figure 3.1). The pressure transducers tips were placed 3 cm (1.2 in) above the ditch bottom to avoid damage to the pressure sensor (this means that the minimum water level measurable at the filter insert was 3 cm or 1.2 in). The total water depth (including the 3-cm or 1.2-in offset) was used for flow rate computations in a CR1000 data logger (Campbell Scientific, Logan, UT). The flow through the filter insert was calculated using the Dupuit's equation (Freeze and Cherry 1979):

$$Q = \frac{K_{sat}}{2B}(h_0^2 - h_d^2) \times L \tag{1}$$

where, Q is flow through the filter (m^3/s), K_{sat} is the saturated hydraulic conductivity of the filter media (m/s), h_0 is the upstream head (m), h_d is the downstream head of water at the filter (m), B is the width of the filter in the direction of flow (m), and L is the length of the filter perpendicular to flow (m). For the filter insert in the ditch check site, K_{sat} = 0.046 cm/s (79 in/hr) (determined under laboratory conditions), B = 0.41 m (1.3 ft), and L = 3.8 m (12.5 ft). The treated runoff flow volume was computed by integrating the flow rate over 5-min time intervals throughout the sampling duration.

It was assumed that the infiltration within the ditch check is zero, and the runoff volumes passing through each sampling location at the ditch check were equal to each other. This means the inflow and outflow volumes are also equal at the ditch check. Water loss by infiltration directly below the filer insert was not expected to occur because of the impervious sheet installed under the filter at the time of construction (see Figure 2.2).

A tipping-bucket rain gauge (0.254-cm or 0.01-inch sensitivity) connected to the CR1000 data logger recorded rainfall depths at the site. The rain gauge was mounted on top of a cabinet located approximately 0.48 km (0.30 miles) from the monitoring site. The water levels, flow rate, flow volume, cumulative flow volume, and rainfall depth data are continuously recorded in the data logger at 5-min intervals.

3.2 WATER SAMPLE COLLECTION

Water samples were collected at four sampling points in the ditch check (Figure 3.1) using four automated ISCO 6700 samplers (Teledyne ISCO, Lincoln, NE) that were powered by four, 12-Volt deep-cycle marine batteries. The batteries were replaced periodically between runoff events. The four sampling points correspond to the runoff inflow to the ditch check (Ditch check_in), inflow to filter insert (Filter insert_in), outflow from the filter insert (Filter insert_out), and outflow from the entire ditch check (Ditch check_out).

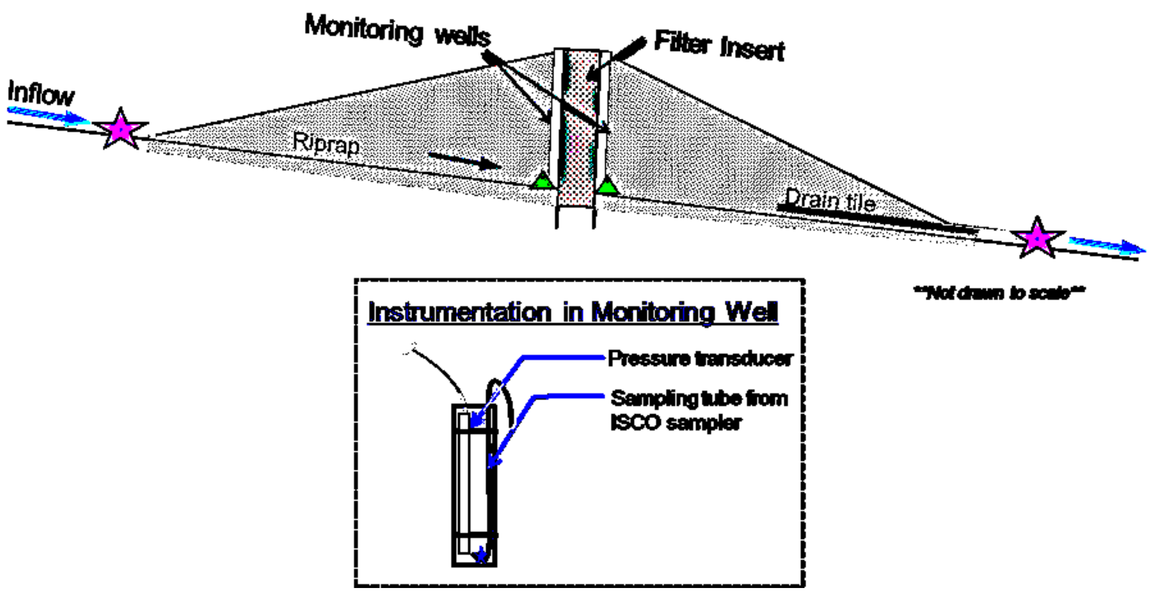


Figure 3.1 Schematic of the monitoring system at the iron-enhanced ditch check site.

At the ditch check inflow and outflow sampling points, the tubing from the ISCO sampler was secured to wooden stakes installed in the grass channel. Strainers attached to the tubing end prevented it from being clogged by debris during water sampling. Tubing placed inside the monitoring wells collected the filter insert inflow and filter insert outflow samples.

The sampling program was triggered when the flow rate through the filter insert was at least 0.02 L/s (0.32 gal/min) corresponding to a given elevation of water upstream. Flow volume-weighted composite samples were collected at flow volume increments of 100 L (~26 gal) or more, depending on the expected total rainfall depth. The data logger was programmed to pass a signal to the ISCO samplers every time the specified runoff volume increment (e.g. 100 L) passed through the filter insert, and this signal triggered the samplers to collect a water sample. The sample collection time was recorded by the data logger every time a sample was collected. The sample collection results are illustrated in Figure 3.2 for reference. A modem connected to the data logger allowed real-time remote access to the flow and sample collection data being recorded at the site.

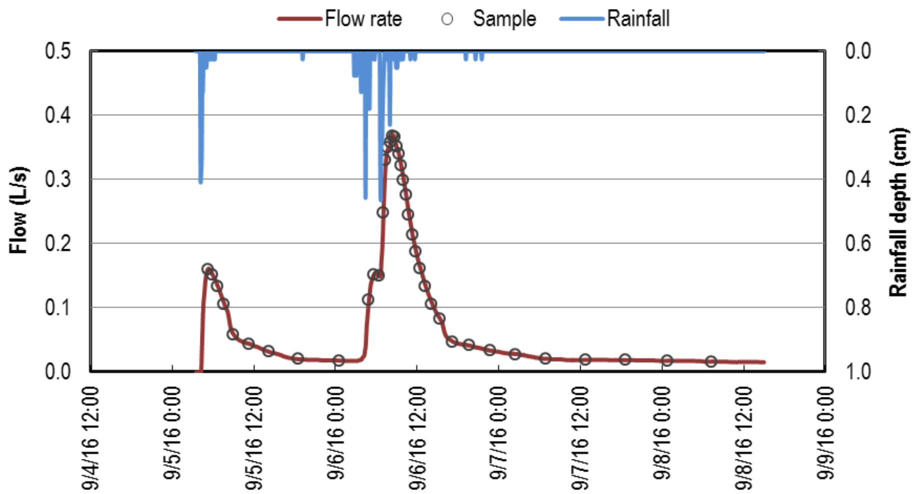


Figure 3.2 Sample storm event monitored at the iron-enhanced ditch check site in September 2016. The measured rainfall, runoff flow through the filter insert and water sample collection frequency are plotted. The circles (○) show the instances of flow volume-weigh

During the 2016 and 2017 monitoring, water samples were composited into 9 L glass containers in the ISCO samplers. However, fewer samples were collected in the 9 L containers on the outflow side than on the inflow side towards the end of the rainfall event ,which resulted in unequal number of samples (and hence unequal total volume) collected in the sample containers at the four sampling locations in the ditch check. Typically, the water volume collected at the ditch check outflow point was the lowest, but sometimes the sample container for the filter insert outflow contained less sample volume than the sample container for the filter insert inflow. Therefore, in 2018, the runoff sampling method was changed to collect flow volume-weighted samples in multiple bottles (i.e., 4 samples per bottle using 24 bottles total). The 2018 multiple-bottle sampling method is illustrated in Figure 3.3, which shows that 15 inflow samples and only 8 outflow samples were collected during a sampling event. Only the first 8 inflow sample concentrations were considered to calculate an inflow EMC to obtain a better comparison with the outflow EMC.

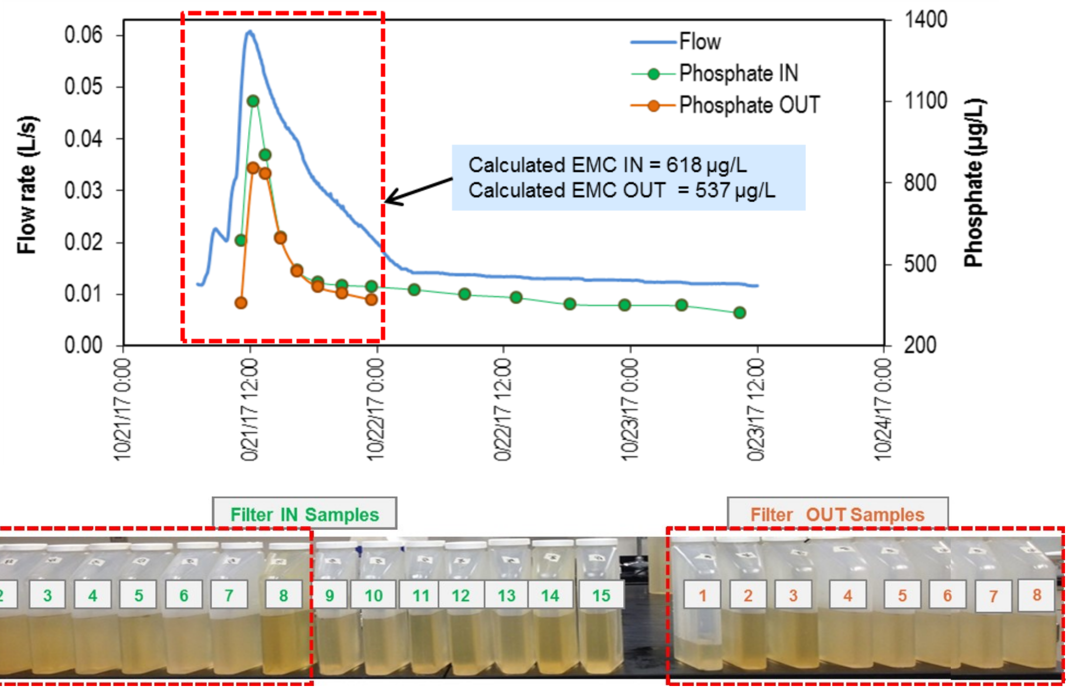


Figure 3.3. Sample event showing the composite water sample collection into multiple ISCO bottles at the iron-enhanced ditch check during the October 21, 2017, rainfall event. Phosphate concentrations in the sample bottles (15 inflow and 8 outflow) are plotted. Red-dashed window is the sampling window constructed to compute the inflow and outflow EMCs for the event. Photograph shows the inflow and outflow water samples collected during the event.

The water samples were retrieved and brought to the Wet Chemistry Laboratory at St. Anthony Falls Laboratory, typically within 24 hours of the end of the event. When sampling ended late Friday evening or the weekend, the water samples were collected Monday morning. The end of the event was typically characterized as <0.009 L/s (0.14 gal/min) flow rate through the filter, which is below the threshold for triggering water sampling. The 0.009 L/s (0.14 gal/min) mark was chosen based on observations from the first few events in 2016. When the downstream water level fell below the established 3-cm (1.2-in) datum at the site, the filter outflow could not be sampled because of the position of the sampling tubing in the monitoring wells. At very low rate of filtration through the filter insert, the interval at which a representative water sample is collected (conforming to the prescribed volume increment) was several hours. Therefore, the water samples were retrieved when the downstream water level was below 3 cm (1.2-in) or when the flow rate approached a low value to avoid long on-site holding time. Analysis of data from several storms indicated that the sampling duration established by this method covered 71 to 99% of the hydrograph.

3.3 WATER SAMPLE ANALYSIS

The water in the sample containers was mixed well prior to subsampling for chemical analysis. For the 2016 and 2017 monitoring, three separate 15 mL water samples were drawn from each 9 L container, filtered through a 0.45 micron membrane filter, and frozen until analysis for ortho-phosphate (soluble reactive phosphorus). One 15 mL water sample was filtered per bottle during the 2018 monitoring period. One 50 mL sample was drawn from each container and frozen until analysis for total phosphorus (TP). The ortho-phosphate determinations were performed by direct colorimetry using the ascorbic acid method at 880 nm wavelength in a spectrophotometer (Cole-Parmer, Vernon Hills, IL) (4500-P Standard Methods, APHA 1995). For total phosphorus analysis, 10 mL duplicate samples were digested by the persulfate digestion method followed by colorimetric analysis using ascorbic acid (4500-P Standard Methods, APHA 1995). The concentration of the replicate samples were averaged and reported as the sample concentration. The analytical limit of detection is 10 µg/L phosphorus. After the phosphate analysis was completed, the three subsamples were combined as one sample for dissolved metal analysis for the 2016 and 2017 samples. For the 2018 samples, water from individual bottles from an event was composited into a single sample for metal analysis. The metal analysis was performed by the ICP-MS method at the Research Analytical Laboratory (RAL), University of Minnesota. The analytical limit of detection is 1 µg/L for both copper and zinc.

3.4 DATA ANALYSIS

A rainfall event occurring six hours after the end of the previous event (i.e. last rain gauge tip record) was defined as a new rainfall event. On some occasions, a new rainfall event occurred while runoff from the previous event was still filtering through the ditch check and additional runoff was generated at the site. When this happened, water quality samples from the two events were composited at the same volume-weightage into the sample container on site (see sample event shown in Figure 3.4). The treated runoff volume and rainfall depth for the two events were added accordingly, and the data point analyzed as one water quality event.

Performance of the ditch check and the filter insert section were evaluated by comparing the water quality at the upstream and downstream toes of the ditch check (Ditch check_in vs. Ditch check_out), and that at the filter insert (Filter insert_in vs. Filter insert_out), respectively. The event mean concentrations (EMCs) at each sampling location, and the mass removals achieved through the filter insert and the entire ditch check were quantified.

Event mean concentration (EMC) was calculated as:

$$EMC = \frac{Total\ Pollutant\ Mass}{Total\ Volume} = \frac{M}{V} = \frac{\sum QCdt}{\sum Qdt} \qquad (2)$$

where, Q = flow rate (L/min), C = concentration (µg/L), dt = sample interval (min). For the multiple-bottle sample collection method a sampling window covering the paired inflow and outflow samples was constructed (as shown in Figure 3.4) and the corresponding EMCs calculated; this method yielded better representation of the filter insert's performance. The pollutant concentration in the composite water sample volume collected in 9 L containers directly represented the EMC.

The total mass of pollutant (*M*) is the product of the measured EMC and the total runoff volume (*V*) passing through the iron-enhanced filter insert section, i.e., the treated runoff volume. Pollutant mass reduction efficiency (%) was calculated as:

$$M_R = \frac{(Mass_{IN} - Mass_{OUT})}{Mass_{IN}} \times 100 \qquad (3)$$

where, $Mass_{IN}$ and $Mass_{OUT}$ are the pollutant masses in the inflow and outflow, respectively, of the filter insert section, or of the entire ditch check. Because infiltration of runoff into the ditch check is assumed to be zero and, therefore, inflow volume equals outflow volume, the percent reductions in pollutant mass load are identical to the reductions in EMCs for the inflow-outflow pair for the filter insert or the ditch check. The cumulative EMC was obtained by dividing the total pollutant mass load for the entire monitoring duration by the total runoff volume treated during that period.

Probability exceedance plots based on treated runoff volumes were developed to evaluate trends in treatment performance of the iron-enhanced ditch check. The treated flow volumes were ranked in increasing order and plotted against the percent of time the volume is exceeded as:

$$\%\ Exceedance = \left[1 - \frac{rank}{n}\right] \times 100\% \qquad (4)$$

where, *rank* is the numerical rank in order of increasing runoff volume, and *n* is the total number of values or storm events (Erickson et al. 2013). The inflow-outflow pollutant mass load data pairs (for example, EMC data from Figure 3.3) corresponding to the total treated runoff volume were then plotted as a function of percent flow volume exceedance for all monitored events.

CHAPTER 4: RESULTS OF FIELD MONITORING

4.1 2016 PERFORMANCE

The iron-enhanced ditch check was monitored during 18 rainfall events from August to October 2016. After combining events with overlapping runoff flows, the total number of events monitored was reduced to 14. The total rainfall depth of the smallest storm event monitored was 0.86 cm (0.34 in) and that of the largest event 8.36 cm (3.29 in). The ditch check treated 115,720 L (30,570 gal) of stormwater runoff generated from these 14 events. The 2016 phosphate and total phosphorus (TP) data are summarized in Table 1 and Table 2. Ditch check outflow samples were not collected during some smaller rainfall events because the outflow from the filter insert did record flow at the ditch check outflow sampling point, likely due to a diffused flow pattern downstream and the 3 cm datum at which the pressure transducer was located (data for these events are indicated as n/a in Table 1 and Table 2).

4.1.1 Phosphorus Retention by the Filter Insert

At the filter insert, the inflow phosphate EMCs ranged between 85 and 227 µg/L (mean = 151 µg/L; median = 131 µg/L) and the outflow EMCs ranged between 58 and 159 µg/L (mean = 104 µg/L; median = 94 µg/L). The average outflow phosphate concentrations were always lower than the inflow, suggesting phosphate was retained by the filter insert during all events. Combining all events, the cumulative phosphate EMCs in the filter inflow and outflow were 154 and 108 µg/L, respectively.

On a mass load-basis, the reductions ranged between 26% and 42% (mean = 31%; median = 30%) during the events. The average mass reduction was 30% for the four largest events (rainfall depth > 4.34 cm or 1.71 in) that contributed 48% of the total runoff volume and 56% of the total phosphate mass load input in 2016 (9.83 g of 17.5 g). The remaining 10 medium and small events contributed 7.67 g phosphate load in total, and 25% of this mass was retained in the filter (average mass reduction was 31% for the 10 individual events). Overall, the total phosphate mass input and output for 14 events were 17.8 g and 12.4 g respectively, which amounts to 30% cumulative reduction through the filter insert.

On average, 61% of the total phosphorus (TP) mass in the filter inflow was in the form of phosphate, and 44% of the TP mass was phosphate in the filter outflow. The TP reduction by the filter insert was similar to that of phosphate. While the inflow contained 154 to 378 µg/L TP (mean = 247 µg/L; median = 223 µg/L), the outflow TP concentrations were between 126 and 290 µg/L (mean = 188 µg/L; median = 167 µg/L), with outflow concentrations lower than the inflow during all monitored events. Considering all 14 events together, the filter insert reduced the cumulative inflow EMC of 253 µg/L TP to 191 µg/L in the outflow. The TP mass reduction ranged between 15 and 36% during the events (mean = 23%; median = 23%), and the cumulative mass reduction was 25% for the 2016 period (29.3 g TP in inflow reduced to 22.1 g TP in outflow).

Table 1. Phosphate water quality at the iron-enhanced ditch check during storm events monitored in 2016.

Event Date	Rainfall Depth (cm)	Treated Runoff Volume (L)	Phosphate EMC (µg/L)				Phosphate Mass (g)				Phosphate Mass Reduction (%)	
			Ditch _in	Ditch _out	Filter _in	Filter _out	Ditch _in	Ditch _out	Filter _in	Filter_ out	Filter Insert Section	Entire Ditch Check
08/04/16	3.35	5263	253	n/a	227	155	1.33	n/a	1.19	0.817	31.6%	n/a
08/10/16	8.36	17,318	172	193	170	126	2.97	3.33	2.95	2.18	25.9%	-12.3%
08/16/16	2.59	6765	116	107	125	91	0.784	0.724	0.844	0.614	27.2%	7.61%
08/19/16 *	2.46	7003	75	n/a	85	58	0.522	n/a	0.593	0.408	31.2%	n/a
08/23/16	2.51	6210	126	112	123	81	0.782	0.695	0.766	0.501	34.6%	11.1%
08/29/16	5.02	11,853	247	229	214	159	2.93	2.71	2.54	1.88	25.8%	7.45%
09/05/16 *	5.73	15,618	124	120	133	97	1.94	1.87	2.08	1.52	26.9%	3.80%
09/15/16 *	4.34	10,509	189	257	213	129	1.98	2.70	2.24	1.35	39.6%	-36.1%

09/21/16	3.60	7605	98	136	119	84	0.746	1.03	0.907	0.635	30.0%	-38.5%
09/23/16 *	1.13	5701	88	n/a	85	64	0.504	n/a	0.487	0.363	25.6%	n/a
10/05/16	1.32	3002	176	n/a	194	132	0.528	n/a	0.581	0.396	31.9%	n/a
10/06/16	2.64	8864	132	152	129	91	1.17	1.34	1.14	0.804	29.6%	-14.9%
10/17/16	1.87	4805	105	163	123	71	0.507	0.785	0.592	0.342	42.2%	-54.9%
10/25/16	2.10	5203	143	n/a	169	120	0.745	n/a	0.877	0.622	29.1%	n/a

n/a: Data not available

Table 2. Total phosphorus (TP) water quality at the iron-enhanced ditch check during storm events monitored in 2016.

Event Date	Total Phosphorus EMC (µg/L)				TP Mass (g)				TP Mass Reduction (%)	
	Ditch _in	Ditch _out	Filter _in	Filter _out	Ditch _in	Ditch _out	Filter _in	Filter_ out	Filter Insert Section	Entire Ditch Check
08/04/16	n/a	n/a	378	284	n/a	n/a	1.99	1.49	24.9%	n/a
08/10/16	284	282	300	210	4.92	4.89	5.19	3.64	29.8%	0.74%
08/16/16	215	178	235	167	1.45	1.20	1.59	1.13	29.0%	17.0%
08/19/16	n/a	n/a	158	133	n/a	n/a	1.11	0.93	15.4%	n/a
08/23/16	218	196	208	166	n/a	n/a	1.29	1.03	20.1%	9.9%
08/29/16	424	343	346	290	5.03	4.07	4.10	3.44	16.3%	19.1%

09/05/16	247	194	225	167	n/a	n/a	3.51	2.61	25.5%	21.3%
09/15/16	247	294	295	190	2.60	3.09	3.10	2.00	35.6%	-18.7%
09/21/16	212	214	221	163	1.61	1.63	1.68	1.24	26.1%	-1.0%
09/23/16	n/a	n/a	154	126	n/a	n/a	0.88	0.72	18.0%	n/a
10/05/16	n/a	n/a	312	250	n/a	n/a	0.94	0.75	20.0%	n/a
10/06/16	214	244	207	165	1.89	2.16	1.84	1.46	20.5%	-14.1%
10/17/16	186	174	191	145	0.90	0.83	0.92	0.69	24.5%	6.9%
10/25/16	n/a	n/a	221	177	n/a	n/a	1.15	0.92	19.7%	n/a

n/a: Data not available

4.1.2 Phosphorus Retention by the Ditch Check

There were nine events when both inflow to and discharge from the ditch check were sampled. The phosphate levels ranged from 98 to 247 µg/L in the inflow (mean = 145 µg/L; median = 126 µg/L), and 107 to 257 µg/L in the discharge (mean = 163 µg/L; median = 152 µg/L). The mass reduction was low (3.8 to 11%) for four events, and negative (-55% to -2.5%) during the remaining five events, suggesting phosphate retention did not always occur through the ditch check. In fact, about 10% more phosphate mass load was discharged than the 13.8 g phosphate received from nine events, indicating export of phosphate from the entire ditch check for the 2016 monitoring period.

The TP mass reductions were between -19% and 21% during the storm events (mean = 4.6%; median = 6.9%). The discharge TP was higher than the inflow during three out of the nine events, as observed for phosphate during some events. The average TP concentrations were 250 µg/L in the inflow and 235 µg/L in the discharge. The TP mass load reduction for the nine events combined was 2.9% (18.4 g in vs. 17.9 g out).

Reasons for the low or negative removals of phosphorus species were hypothesized. First, if the sheet flow from adjoining roadway/shoulder was draining directly to the ditch check outflow sampling point and mixing with the treated water, it could elevate the phosphate level in the water. The phosphorus concentrations in the ditch check discharge were higher than the filter insert outflow during nine events (i.e. ditch check_out > filter insert_out by up to 129 µg/L phosphate and 103 µg/L TP). Second, the presence of a phosphorus source within the ditch check itself was considered. If the topsoil-sod cover over the ditch check is leaching phosphate, it could influence the measured phosphate concentrations. For these two reasons, installation of lawn edging as a means to divert runoff away from the ditch check along its entire length, and removal of the topsoil layer over the filter insert section were proposed before the 2017 monitoring season.

4.1.3 Dissolved Metal Retention

Filter inflow and outflow samples from eight events were analyzed for dissolved metal analysis. The EMC and mass data are provided in Table 3. Since the quality of the ditch check discharge samples collected were possibly affected (due to mixing with road runoff), the ditch check inflow and outflow samples were not analyzed.

Table 3. Dissolved copper and dissolved zinc water quality at the iron-enhanced ditch check during selected storm events monitored in 2016.

Event Date	Dissolved copper					Dissolved zinc				
	EMC (µg/L)		Mass (g)		Mass removal (%)	EMC (µg/L)		Mass (g)		Mass removal (%)
	Filter in	Filter out	Filter in	Filter out		Filter in	Filter out	Filter in	Filter out	
08/04/16	9.25	9.49	0.049	0.050	-2.53%	34.0	22.4	0.179	0.118	34.3%
08/10/16	6.78	7.61	0.117	0.132	-12.2%	39.7	53.3	0.687	0.922	-34.2%
08/29/16	12.1	6.79	0.144	0.080	44.3%	55.5	36.1	0.657	0.428	34.9%
09/05/16	18.6	8.13	0.290	0.127	56.2%	41.6	40.2	0.650	0.628	3.38%
09/15/16	7.42	8.33	0.078	0.088	-12.2%	98.3	48.3	1.03	0.508	50.9%
10/05/16	9.83	9.53	0.030	0.029	3.09%	52.8	31.3	0.159	0.094	40.8%
10/06/16	5.29	5.72	0.047	0.051	-8.30%	42.7	32.5	0.379	0.288	24.1%
10/17/16	16.7	6.98	0.080	0.034	58.1%	38.8	27.3	0.187	0.131	29.8%

In general, inflow to the filter insert contained dissolved copper and zinc at concentrations lower than the national median concentrations in road runoff (11 µg/L copper and 51 µg/L zinc; Maestre and Pitt 2005). The copper EMCs were reduced during four out of the eight events sampled. Although the net removal was negative for the remaining four events, the effluent EMC levels were very low (<9.5 µg/L) and only marginally higher than the inflow EMCs. Positive reductions in inflow zinc EMC and mass ranging between 24 and 51% occurred during most events, except for one event. The mean mass reductions were 16% for copper and 23% for zinc during the eight events. On a cumulative mass load basis, the removals were 29% for copper and 21% for zinc in 2016. The mass reductions achieved during the eight events did not appear to exhibit a particular trend associated with treated runoff volumes.

4.2 2017 PERFORMANCE

In May 2017, the sod and topsoil covering the filter insert section was removed and replaced with washed river rock (~2.54 cm or 1 inch size) (Figure 4.1a, b). The sod cover on the remaining surface of the ditch check was not disturbed. Second, lawn edging was installed along the entire length of the ditch check feature on the roadway side (in-slope) and the back-slope to divert sheet flow away from the ditch check (Figure 4.1c). Monitoring began after these maintenance actions.

Figure 4.1. Maintenance performed at the ditch check site in May 2017. The topsoil and sod covering the filter insert section were removed (a & b), and lawn edging (highlighted by white dashed line) was installed along the ditch check (c).

There were 19 sample events in the 2017 season, after combining events with overlapping flow among the 27 events monitored from May through October 2017. The first two events in May 2017 showed large negative mass reduction of phosphate by the filter insert (-29%), most likely because topsoil spilled into the monitoring wells during the maintenance exercise. These two events were eliminated from data analysis, and the remaining 17 events were considered for the 2017 performance assessment. The total rainfall depth of the smallest storm event monitored was 0.68 cm (0.27 in) and that of the largest event was 4.71 cm (1.86 in). The 17 storm events totaled 30.9 cm (12.1 in) rainfall, and the ditch check treated 72,453 L (19,140 gal) of runoff from these events. The phosphate and total phosphorus (TP) data are summarized in Table 4 and Table 5.

Table 4. Phosphate water quality at the iron-enhanced ditch check during storm events monitored in 2017.

Event Date	Rainfall Depth (cm)	Treated Runoff Volume (L)	Phosphate EMC (µg/L)				Phosphate Mass (g)				Phosphate Mass Reduction (%)	
			Ditch in	Ditch out	Filter in	Filter out	Ditch in	Ditch out	Filter in	Filter out	Filter Insert Section	Entire Ditch Check
06/11/2017	2.02*	3301	662	n/a	310	235	2.185	n/a	1.023	0.777	24.0%	n/a
06/28/2017	2.05	3501	146	142	122	85	0.511	0.498	0.427	0.298	30.1%	2.64%
06/30/2017	0.68	5001	380	117	111	90	1.903	0.585	0.556	0.450	19.1%	69.2%
07/17/2017	2.44	3602	473	451	466	238	1.705	1.626	1.677	0.856	48.9%	4.67%
07/26/2017	1.40	2401	96	133	149	111	0.231	0.319	0.358	0.266	25.8%	-37.9%
08/03/2017	1.98	2903	1056	1054	1078	817	3.065	3.059	3.128	2.371	24.2%	0.18%
08/06/2017	1.14	2043	152	281	303	212	0.311	0.574	0.619	0.432	30.2%	-84.5%
08/09/2017	1.82	4655	129	150	148	107	0.599	0.696	0.687	0.496	27.8%	-16.3%
08/13/2017	2.26	4808	215	140	131	80	1.031	0.672	0.630	0.386	38.8%	34.9%

08/16/2017 *	4.71	9766	194	82	87	65	1.899	0.803	0.850	0.636	25.1%	57.7%
08/25/2017	1.89	5206	216	115	111	73	1.126	0.597	0.577	0.379	34.3%	47.0%
10/02/2017	0.91	1401	196	n/a	277	139	0.274	n/a	0.388	0.195	49.7%	n/a
10/03/2017	3.88	7423	112	n/a	102	73	0.828	n/a	0.758	0.538	29.0%	n/a
10/06/2017	1.76	5505	59	73	69	61	0.326	0.399	0.378	0.336	11.1%	-22.6%
10/14/2017	0.78	3203	92	n/a	135	138	0.294	n/a	0.432	0.441	-2.1%	n/a
10/21/2017	0.98	3604	705	799	618	537	2.540	2.880	2.228	1.936	13.1%	-13.4%
10/27/2017 +	0.15	4129	184	307	191	187	0.760	1.269	0.788	0.774	1.8%	-67.0%

n/a: Data not available

*Data combined for two overlapping storm events

+snow-rain mixed event

Table 5. Total phosphorus (TP) water quality at the iron-enhanced ditch check during storm events monitored in 2017.

Event Date	Total Phosphorus EMC (µg/L)				TP Mass (g)				TP Mass Reduction (%)		Phosphate:TP	
	Ditch in	Ditch out	Filter in	Filter out	Ditch in	Ditch out	Filter in	Filter out	Filter Insert Section	Entire Ditch Check	Filter in	Filter out
06/11/2017	1291	n/a	632	694	4.26	n/a	2.09	2.29	-9.79%	n/a	0.49	0.34
06/28/2017	733	381	346	242	2.57	1.33	1.21	0.85	30.1%	48.0%	0.35	0.35
06/30/2017	604	229	207	148	3.02	1.15	1.04	0.74	28.9%	62.1%	0.54	0.61
07/17/2017	729	576	667	297	2.63	2.08	2.40	1.07	55.5%	20.9%	0.70	0.80
07/26/2017	267	332	574	578	0.64	0.80	1.38	1.39	-0.60%	-24.4%	0.26	0.19
08/03/2017	1384	1390	1393	1105	4.02	4.04	4.04	3.21	20.6%	-0.44%	0.77	0.74
08/06/2017	327	454	461	372	0.67	0.93	0.94	0.76	19.5%	-39.0%	0.66	0.57
08/09/2017	228	223	343	207	1.06	1.04	1.60	0.96	39.7%	2.29%	0.43	0.52
08/13/2017	353	222	236	176	1.69	1.07	1.13	0.84	25.5%	36.9%	0.56	0.46

08/16/2017	386	174	183	173	3.77	1.70	1.79	1.69	5.67%	54.9%	0.48	0.38
08/25/2017	393	201	244	178	2.04	1.05	1.27	0.93	26.9%	48.7%	0.45	0.41
10/02/2017	350	n/a	396	323	0.49	n/a	0.55	0.45	18.4%	n/a	0.70	0.43
10/03/2017	246	n/a	173	137	1.82	n/a	1.28	1.02	20.6%	n/a	0.59	0.53
10/06/2017	135	332	131	139	0.75	1.83	0.72	0.76	-5.59%	-145%	0.52	0.44
10/14/2017	207	n/a	201	225	0.66	n/a	0.64	0.72	-12.3%	n/a	0.67	0.61
10/21/2017	975	1110	855	777	3.52	4.00	3.08	2.80	9.20%	-13.8%	0.72	0.69
10/27/2017	244	343	219	220	1.01	1.42	0.90	0.91	-0.35%	-40.3%	0.87	0.85

n/a: Data not available

4.2.1 Phosphorus Retention by the Filter Insert

At the filter insert, the inflow phosphate EMCs ranged between 69 and 1078 µg/L (mean = 259 µg/L; median = 148 µg/L) and the outflow EMCs ranged between 61 and 817 µg/L (mean = 191 µg/L; median = 111 µg/L). The high (>1 mg/L) inflow phosphate concentration measured for the 8/3/17 event was most likely because the swale was mowed before this event. The filter outflow concentrations were mostly lower than the inflow concentrations, suggesting phosphate removal occurred in the filter insert section during those events (Table 4). The cumulative phosphate EMCs in the filter inflow and outflow were 214 and 160 µg/L, respectively, for the 2017 period.

The mass reductions ranged between -2.1% and 50% during the 17 events (mean = 25%; median = 26%). For the five largest events sampled (rainfall depth 1.76 to 4.71 cm or 0.69 to 1.86 in; runoff volumes >5000 L) that produced 45% of the total runoff volume to the filter in 2017, the filter captured nearly 13% of the phosphate mass input from these events. The phosphate mass load contributed by the remaining medium and small events was 12.4 g, and 25% of this mass was captured by the filter. The total mass input and output for the 17 events were 15.5 g and 11.6 g phosphate respectively, which amounts to 25% reduction in the cumulative phosphate mass load.

The TP concentrations in the filter inflow ranged from 131 to 1393 µg/L (mean = 427 µg/L; median = 343 µg/L), while the filter outflow contained 137 to 1105 µg/L TP (mean = 352 µg/L; median = 225 µg/L). On average, 57% of the TP mass in the filter inflow was in the form of phosphate, and this TP:phosphate ratio was 52% in the filter outflow. Considering all 17 events together, the cumulative inflow EMC of 360 µg/L TP was reduced to 295 µg/L in the outflow. The TP mass removals ranged between -12 and 56% (mean = 16%; median = 20%), and the filter insert yielded a cumulative TP mass load reduction of 18% for the 2017 period (26.1 g TP inflow vs. 21.4 g TP outflow).

4.2.2 Phosphorus Retention by the Entire Ditch Check

There were 13 events when both inflow to and discharge from the ditch check were sampled. The phosphate levels were between 59 and 1056 µg/L in the inflow (mean = 308 µg/L; median = 194 µg/L), and between 73 and 1054 µg/L in the discharge (mean = 296 µg/L; median = 142 µg/L). The net phosphate mass removal was negative (-85% to -13%) for six events when the outflow EMCs were higher than the inflow EMCs. The mass reduction was between 0.18 to 58% for the remaining seven events. As observed during the 2016 events, phosphate reduction did not always occur through the ditch check. Overall, 13% of the 16.0 g total inflow phosphate mass load was reduced by ditch check for the 2017 monitoring period.

The TP mass removals were between -145% and 62%. The large negative removal (-145%) was observed for one event, during which the ditch check out sampler collected very few samples than the remaining ISCO samplers (likely due to a diffused outflow pattern at the ditch check out sampling point). Neglecting this event, the TP removal ranged between -40% and 62% (mean = 13%; median = 12%). The discharge TP was higher than the inflow during five out of the 12 events, as observed for phosphate during some events. The average TP concentrations were 552 µg/L in the inflow and 470 µg/L in the discharge. The TP mass load reduction for the 12 events combined was 23% (26.6 g in vs. 20.6 g out).

The entire ditch check did not perform as well in phosphate removal as the filter insert. As hypothesized after 2016 monitoring, it is possible that the sod and the topsoil placed on the ditch check caused a reduction in performance. Also, the total number of samples collected at the ditch out sampling point was often less than the other sampling points; this means the composite volume collected for ditch check outflow was not fully representative of the event when compared to the volumes collected at the remaining locations. The diffused pattern of outflow from the ditch check, especially as the storm progressed, resulted in fewer samples to be collected. If it is assumed that the ditch check inflow sample was diluted due to more samples being collected than at the ditch check outflow point, and that phosphate concentrations in the latter part of the event were lower than that during early part of the storm, it is possible that the actual removal of phosphate was higher than that measured in 2016 and 2017. However, the impact of different sample volumes collected on the phosphate concentration and actual phosphate reduction was not quantified. The sampling strategy of collecting single composite sample was therefore modified to collecting water samples in multiple bottles over the course of a storm in 2018 (see Methods section for description of the water sample collection method).

4.2.3 Dissolved Metal Retention

The inflow to the filter insert contained metal concentrations higher than the national median concentrations in road runoff during several events (11 µg/L copper and 51 µg/L zinc; Maestre and Pitt 2005) (Table 6). The filter insert decreased the copper concentrations during eight out of nine events, and decreased the zinc levels during seven events. Metal mass load reduction by the entire ditch check was, however, more variable. The mean mass reduction by the filter insert was 15% for copper and 25% for zinc during the nine events. On a cumulative mass load basis, the filter removed 19% copper mass input (0.58 g in vs. 0.47 g out), and 17% zinc mass input (4.4 g in vs. 3.7 g out) in 2017.

Table 6. Dissolved copper and zinc water quality at the iron-enhanced ditch check during storm events monitored in 2017.

Event Date	Dissolved Copper EMC (µg/L)				Dissolved Copper Mass (g)				Mass Reduction (%)	
	Ditch in	Ditch out	Filter in	Filter out	Ditch in	Ditch out	Filter in	Filter out	Filter Insert Section	Entire Ditch Check
06/28/2017	26	25	23	15	0.090	0.088	0.080	0.052	34.4%	3.01%
06/30/2017	31	19	12	12	0.157	0.096	0.059	0.058	1.56%	38.5%
07/17/2017	39	15	25	14	0.141	0.056	0.089	0.050	44.4%	60.6%
07/26/2017	39	20	16	13	0.094	0.049	0.038	0.031	18.6%	48.4%
08/03/2017	27	19	17	19	0.077	0.056	0.049	0.055	-13.6%	27.2%
08/09/2017	16	16	12	12	0.072	0.073	0.056	0.056	0.00%	-0.43%
08/13/2017	17	9	6	6	0.081	0.042	0.030	0.029	1.55%	48.1%
08/16/2017	11	9	9	7	0.110	0.085	0.092	0.066	27.7%	22.7%
10/06/2017	10	11	9	7	0.058	0.063	0.050	0.040	20.8%	-9.65%
Event Date	Dissolved Zinc EMC (µg/L)				Dissolved Zinc Mass (g)				Mass Reduction (%)	
	Ditch in	Ditch out	Filter in	Filter out	Ditch in	Ditch out	Filter in	Filter out	Filter Insert Section	Entire Ditch Check
06/28/2017	60	123	92	118	0.211	0.432	0.321	0.413	-28.5%	-105%
06/30/2017	67	130	116	119	0.334	0.652	0.580	0.597	-2.86%	-95.1%
07/17/2017	58	105	134	97	0.208	0.377	0.483	0.349	27.7%	-81.5%

07/26/2017	46	30	149	54	0.110	0.072	0.357	0.129	63.9%	34.5%
08/03/2017	84	99	218	102	0.245	0.288	0.633	0.296	53.2%	-17.5%
08/09/2017	36	50	62	56	0.168	0.232	0.290	0.262	9.65%	-38.0%
08/13/2017	15	17	44	36	0.071	0.082	0.214	0.171	19.9%	-14.3%
08/16/2017	45	87	101	75	0.437	0.853	0.984	0.733	25.6%	-95.3%
10/06/2017	136	42	75	34	0.751	0.230	0.411	0.188	54.3%	69.4%

4.3 2018 PERFORMANCE

Thirteen rainfall events were sampled from May through November 2018. The total rainfall depth of the smallest storm event monitored was 0.65 cm (0.26 in) and that of the largest event 5.11 cm (2.01 in). The 13 storm events totaled 39.1 cm (15.4 in) rainfall, and the ditch check treated 57,197 L (15,110 gal) of runoff generated from these events. However, sampler control cable malfunctioned causing a battery charge issue, which prevented sample collection at the ditch check outflow and filter outflow sampling locations during four events. Therefore, paired inflow and outflow samples were collected for nine events at the filter insert, and nine events at the ditch check, although some of these events did not overlap with the paired sampling at the filter insert. The phosphorus water quality data for the 2018 monitoring are provided in Table 7 and Table 8.

Table 7. Phosphate water quality at the iron-enhanced ditch check during storm events monitored in 2018.

Event Date	Rainfall Depth (cm)	Treated Runoff Volume (L)	Phosphate EMC (µg/L)				Phosphate Mass (g)				Phosphate Mass Reduction (%)	
			Ditch in	Ditch out	Filter in	Filter out	Ditch in	Ditch out	Filter in	Filter out	Filter Insert Section	Entire Ditch Check
5/30/2018	1.45	1801	296	235	n/a	226	0.533	0.422	n/a	0.408	n/a	20.7%
6/16/2018	5.06	4425	226	128	175	154	1.000	0.565	0.774	0.683	11.8%	43.5%
6/26/2018	2.08	2201	183	146	171	n/a	0.403	0.322	0.376	n/a	n/a	20.1%
7/1/2018	1.82	1201	n/a	n/a	168	120	n/a	n/a	0.202	0.144	28.5%	n/a
7/4/2018	1.70	2337	n/a	n/a	91	71	n/a	n/a	0.213	0.166	22.3%	n/a
7/12/2018	4.29	5636	n/a	n/a	442	334	n/a	n/a	2.491	1.883	24.4%	n/a
8/24/2018	4.74	6823	404	346	361	n/a	2.760	2.359	2.466	n/a	n/a	14.5%
8/27/2018	2.81	5409	207	n/a	193	120	1.117	n/a	1.046	0.648	38.1%	n/a
9/2/2018	4.75	5604	205	166	176	141	1.146	0.929	0.987	0.789	20.1%	18.9%
9/20/2018	5.11	9016	221	174	193	n/a	1.989	1.569	1.736	n/a	n/a	21.1%

10/1/2018	3.76	8017	158	121	169	129	1.266	0.967	1.358	1.036	23.8%	23.6%
10/27/2018	0.65	1600	263	397	317	267	0.421	0.636	0.507	0.427	15.8%	-51.1%
11/4/2018	0.83	1926	224	260	190	177	0.431	0.501	0.365	0.341	6.8%	-16.3%

Table 8. Total phosphorus (TP) water quality at the iron-enhanced ditch check during storm events monitored in 2018.

Event Date	Total Phosphorus EMC (µg/L)				TP Mass (g)				TP Mass Reduction (%)		Phosphate:TP	
	Ditch in	Ditch out	Filter in	Filter out	Ditch in	Ditch out	Filter in	Filter out	Filter Insert Section	Entire Ditch Check	Filter in	Filter out
5/30/2018	493	394	n/a	498	0.89	0.71	n/a	0.90	n/a	20.1%	n/a	0.45
6/16/2018	387	239	320	328	1.71	1.06	1.41	1.45	-2.8%	38.3%	0.55	0.47
6/26/2018	294	255	301	n/a	0.65	0.56	0.66	n/a	n/a	13.1%	0.63	n/a
7/1/2018	n/a	n/a	285	249	n/a	n/a	0.34	0.30	12.6%	n/a	0.59	0.48
7/4/2018	n/a	n/a	141	112	n/a	n/a	0.33	0.26	20.8%	n/a	0.65	0.64
7/12/2018	n/a	n/a	513	407	n/a	n/a	2.89	2.29	20.7%	n/a	0.86	0.82

8/27/2018	n/a	n/a	239	213	n/a	n/a	1.29	1.15	10.8%	n/a	0.81	0.56
9/2/2018	326	290	310	227	1.83	1.62	1.74	1.27	27.0%	11.3%	0.57	0.62
10/1/2018	193	110	163	128	1.55	0.88	1.31	1.02	21.8%	45.1%	1.04	1.01
10/27/2018	317	465	355	325	0.51	0.74	0.57	0.52	8.4%	-46.6%	0.89	0.82
11/4/2018	216	259	195	172	0.42	0.50	0.37	0.33	11.7%	-19.9%	1.04	1.01

n/a: Data not available

4.3.1 Phosphorus Retention by the Filter Insert

At the filter insert, equal number of inflow and outflow samples that covered the entire rainfall event was collected for six events. For the remaining three events, the number of outflow samples collected was less than the inflow samples. As an example, Figure 4.2 shows the sampling window, which excludes the last two inflow phosphorus concentrations, considered for the calculation of EMC for that event. The inflow and outflow EMCs calculated using this method were 169 µg/L and 129 µg/L, respectively, which is a 24% reduction in phosphate for the event. Otherwise (i.e., considering all inflow samples), the inflow EMC would be 161 µg/L, producing 20% phosphate reduction for the event. It is believed that constructing a sampling window and calculating the corresponding EMCs during 2018 yielded better representation of the filter insert's performance. The EMCs for each event (Table 7 and Table 8) were calculated by this method. Figure 4.2 also shows the variation in the inflow and outflow phosphate concentrations during the course of the event, and that the phosphate in the inflow was captured as water passed through the filter insert.

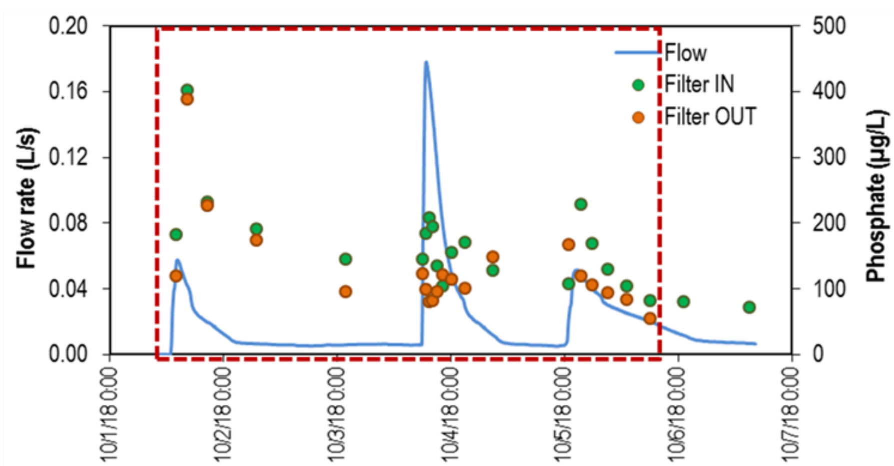


Figure 4.2. Inflow and outflow phosphorus concentrations measured at the filter insert during the October 1-6, 2018, rainfall event. Red dashed box represents the sampling window considered for the EMC calculation.

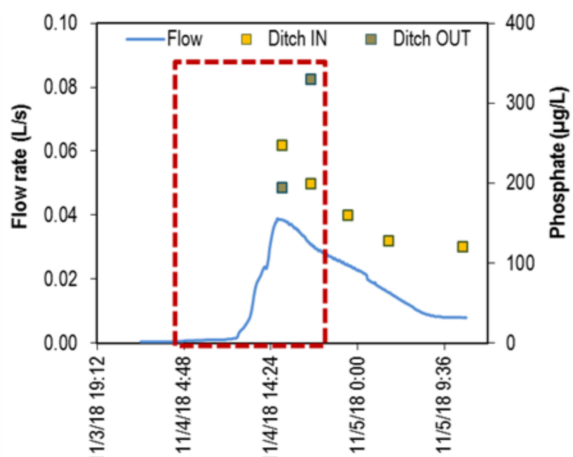
The inflow phosphate EMCs ranged between 91 and 442 µg/L (mean = 214 µg/L; median = 176 µg/L) and the outflow EMCs ranged between 71 and 334 µg/L (mean = 168 µg/L; median = 141 µg/L). The filter outflow concentrations were lower than the filter inflow concentrations during all sampled events, suggesting phosphate was retained within the filter insert section (Table 1). Phosphate mass reductions were between 7% and 38% (mean = 21%; median = 22%) during the nine events. From the three largest events sampled in 2018 (rainfall depth 3.76 to 4.75 cm; runoff volume >5600 L), average mass reduction was 23%. These three events together carried 61% of the total mass input in 2018 (4.8 g of 7.9 g), of which 1.1 g was captured by the filter. About 23% of the 3.1 g phosphate input from the remaining six medium and small events was captured by the filter. Combining all events, the cumulative phosphate

EMC for the 2018 period was 220 µg/L in the filter inflow and 169 µg/L in the outflow. The total phosphate mass input and output for 2018 were 7.9 g and 6.1 g, respectively, which amounts to 23% reduction in the total input mass load through the filter insert.

The TP concentrations in the filter inflow ranged from 141 to 513 µg/L (mean = 280 µg/L; median = 285 µg/L), while the filter outflow contained 112 to 407 µg/L TP (mean = 240 µg/L; median = 227 µg/L). Considering all events together, the cumulative inflow EMC of 284 µg/L TP was reduced to 238 µg/L in the outflow. On average, 81% of the TP mass in the filter inflow was in the form of phosphate, and this TP:phosphate ratio was 64% in the filter outflow. The TP mass removal ranged between -2.8 and 27% during the individual events (mean = 15%; median = 13%). The average TP mass removal was 23% for the three largest events, and 11% for the remaining events. The cumulative TP mass load reduction was 16% for the 2018 period (10.3 g TP inflow vs. 8.6 g TP outflow).

4.3.2 Phosphorus Retention by the Entire Ditch Check

At the ditch check, there were five events when fewer outflow samples were collected compared to the inflow samples, due to a diffuse pattern of discharge downstream of the filter insert. The EMC calculation for these events considered only the paired inflow and outflow concentrations (Figure 4.3a). When the number of samples was the same for the inflow and outflow (three events), all concentrations were included for the EMC calculation (Figure 3.2b).



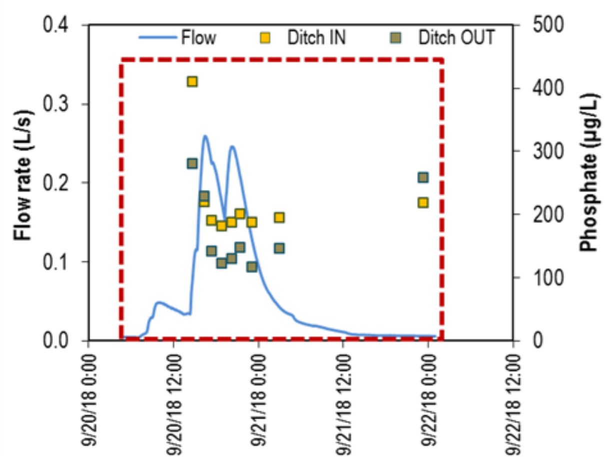


Figure 4.3. Inflow and outflow phosphorus concentrations at the ditch check during the (a) November 4, 2018, and (b) September 20, 2018, rainfall event. Red dashed box in each graph represents the sampling window considered for the EMC calculation.

The phosphate concentrations ranged between 158 and 404 µg/L (mean = 242 µg/L; median = 224 µg/L) in the inflow, and between 121 and 397 µg/L phosphate (mean = 219 µg/L; median = 174 µg/L) in the outflow. The ditch check outflow EMC was higher than the ditch inflow EMC during two events, and the net phosphate mass removal was thus negative for these events. The mass reduction was between 15 and 44% for the remaining events. Overall, the cumulative inflow phosphate mass load of 9.9 g was reduced by 17% through the entire ditch check for the monitoring period. The 2018 removal efficiencies of the ditch check appeared to relate well to that of the filter insert when compared to its performance during 2016 and 2017. It is possible that the new sampling strategy adopted in 2018 had an impact on the overall results. The TP mass removals were between -47% and 43% (mean = 8.5%; median = 13%). The discharge TP was higher than the inflow to the ditch check during two events. The average TP concentrations were 318 µg/L in the inflow and 287 µg/L in the discharge. The TP mass load reduction for all events combined is 20% (7.6 g in vs. 6.1 g out).

4.3.3 Dissolved Metal Retention

The filter insert inflow and outflow samples from nine events were analyzed for dissolved copper and dissolved zinc concentration. The EMCs, mass and mass removal data are provided in Table 9. While the inflow dissolved copper concentrations were mostly lower than the national median concentration of 11 µg/L in urban road runoff, zinc concentrations were higher than the 51 µg/L national median (Maestre and Pitt 2005). Metal treatment performance was mixed, with five out of nine events showing copper removal, and seven events showing zinc removal. However, the net cumulative mass load retention for the 2018 period was negative for both copper and zinc.

Table 9. Dissolved copper and zinc water quality at the iron-enhanced ditch check during storm events monitored in 2018.

Event Date	Dissolved copper					Dissolved zinc				
	EMC (µg/L)		Mass (g)		Mass removal (%)	EMC (µg/L)		Mass (g)		Mass removal (%)
	Filter in	Filter out	Filter in	Filter out		Filter in	Filter out	Filter in	Filter out	
6/4/2018	33.0	31.6	0.026	0.025	4.1%	277	202	0.221	0.161	27%
6/16/2018	17.0	20.3	0.075	0.090	-20%	86	141	0.381	0.623	-63%
7/4/2018	13.8	10.5	0.032	0.025	24%	246	137	0.575	0.320	44%
7/12/2018	8.6	11.7	0.048	0.066	-36%	118	220	0.667	1.242	-86%

8/27/2018	9.5	10.0	0.051	0.054	-5.5%	52	57	0.283	0.306	-8.1%
9/2/2018	9.0	8.5	0.051	0.047	6.2%	95	78	0.530	0.437	18%
10/1/2018	6.7	8.2	0.054	0.065	-22%	63	27	0.504	0.217	57%
10/27/2018	8.1	6.5	0.013	0.010	20%	37	36	0.059	0.058	1.5%
11/4/2018	7.8	6.3	0.015	0.012	20%	37	35	0.072	0.067	6.8%

CHAPTER 5: WATER TRUCK TESTING

Water truck testing was conducted at the iron-enhanced ditch check site to measure phosphorus capture from synthetic runoff under controlled conditions. In October 2017, approximately 19 m^3 (5000 gal) of synthetic runoff dosed with phosphate and metals was introduced upstream of the ditch check (equivalent to ~0.63 cm or ~0.25 in rainfall over the 0.29 ha or 0.72 ac drainage area), at nearly constant rate during the three-hour testing. Average concentrations in the composite water samples collected were 230 µg/L in the ditch check inflow, 172 µg/L in the filter insert inflow, 168 µg/L in the filter insert outflow, and 140 µg/L in the ditch check outflow. This corresponds to only 2.1% phosphate mass removal by the filter insert. The TP mass removal was 5.7%. The low phosphorus reduction was similar to the decreased performance observed during the October 2017 rainfall events. Copper EMCs of 5.88 µg/L in inflow and 5.59 µg/L in outflow, and zinc EMCs of 49.1 µg/L in inflow and 25.3 µg/L in outflow were measured at the filter insert; the corresponding mass removal is 4.83% for copper and 48.6% for zinc.

A second water truck testing was conducted in September 2018. The ditch check inflow and outflow phosphate EMCs were 299 µg/L and 230 µg/L, respectively, which is a 23% reduction in input phosphate. At the filter insert, the 267 µg/L inflow EMC and 188 µg/L outflow EMC correspond to 30% phosphate mass reduction. The TP EMCs measured were 319 µg/L in ditch check inflow, 282 µg/L in filter inflow, 221 µg/L in filter outflow and 252 µg/L in ditch check outflow. The corresponding mass reduction was 22% through the filter insert and 21% through the entire ditch check. Copper EMCs of 9.3 µg/L in the inflow and 17 µg/L in the outflow, and zinc EMCs of 50 µg/L in the inflow and 32 µg/L in the outflow were measured, which corresponds to mass removal of -82% for copper and 35% for zinc by the filter insert. These reductions in phosphate and metal were similar to the event-based performance of the filter insert in 2018.

The 2018 water truck test results were generally comparable to the ditch check's performance during sampling events, and indicative of the decreasing phosphorus retention capability of the filter insert since construction. In the 2014 water truck testing on the newly-installed filter, 78% of the phosphate mass input was captured by the filter insert (inflow and outflow EMCs were 206 µg/L and 45 µg/L, respectively). The water truck tests and storm event sampling showed the filter insert's diminishing treatment performance over the past four years.

CHAPTER 6: COMPARISON OF 2015 TO 2018 TREATMENT PERFORMANCE

6.1 FILTER INSERT PERFORMANCE FROM 2015 TO 2018

The filter insert's treatment performance from 2015 to 2018 is summarized in Table 10 (2015 data are from Natarajan and Gulliver 2015) and Table 11, and illustrated in Figure 6.1.

Table 10. Summary of 2015 to 2018 phosphate water quality at the filter insert in the iron-enhanced ditch check. The 2015 data are from Natarajan and Gulliver (2015).

Filter Insert Performance	2015	2016	2017	2018
Number of rainfall events sampled	16	14	17	9
Total rainfall depth	28.5 cm (11.2 in)	46.9 cm (18.5 in)	30.9 cm (12.1 in)	25.7 cm (10.1 in)
Phosphate EMC at Filter inflow (event-based)	Range: 114 – 1000 µg/L Mean: 398 µg/L	Range: 85 – 227 µg/L Mean: 150 µg/L	Range: 69 – 1078 µg/L Mean: 259 µg/L	Range: 91 – 442 µg/L Mean: 214 µg/L
Phosphate EMC at Filter outflow (event-based)	Range: 69 – 504 µg/L Mean: 238 µg/L	Range: 58 – 159 µg/L Mean: 104 µg/L	Range: 61 – 817 µg/L Mean: 191 µg/L	Range: 71 – 334 µg/L Mean: 168 µg/L
Phosphate mass reduction	Range: -8.7 – 54% Mean: 36%	Range: 26 – 42% Mean: 31%	Range: -2.1 – 50% Mean: 25%	Range: 6.8 – 38% Mean: 21%
Cumulative phosphate EMC (all events combined)[++]	Filter in = 353 µg/L Filter out = 205 µg/L	Filter in = 154 µg/L Filter out = 108 µg/L	Filter in = 214 µg/L Filter out = 160 µg/L	Filter in = 220 µg/L Filter out = 169 µg/L
Cumulative treated runoff volume	68,263 L	115,720 L	72,453 L	36,155 L

Cumulative phosphate mass	24.1 g	17.8 g	15.5 g	7.9 g
Cumulative phosphate mass	14.0 g	12.4 g	11.6 g	6.1 g
Cumulative phosphate mass	42%	30%	25%	23%

$^{+}$mean or median of mass reduction observed for individual events, for *n* events

$^{++}$calculated as the sum of P mass load from *n* events divided by cumulative treated volume

$^{+++}$cumulative EMC reduction is equal to cumulative mass reduction

Fewer events were sampled in 2018 compared to previous years, because of frequent dry periods in the summer of 2018. More large rainfall events were sampled in 2016 than other years. The phosphorus concentrations in the inflow to the filter insert varied each year, with the highest concentrations measured in 2015 (Figure 6.1c). In fact, the 2015 inflow phosphate EMCs were much higher than the median level of 120 µg/L dissolved phosphorus in stormwater runoff (Maestre and Pitt 2005). The total phosphate mass loading to the filter was also the highest in 2015 although the treated runoff volume was less than 2016 and 2017. Organic matter leaching from the topsoil and sod cover from the newly-constructed ditch check most likely contributed an additional phosphate loading in 2015 (Natarajan and Gulliver 2015). The phosphate mass load retention generally decreased since construction (Figure 6.1e and f). The cumulative phosphate retained decreased from 42% in 2015, to 30% in 2016, to 25% in 2017, and to 23% in 2018 (Table 10).

For dissolved copper and zinc, the filter insert generally exhibited a mixed removal performance since 2015 (Table 11). The inflow copper EMCs were generally much higher in 2015, but gradually decreased since then, with levels generally lower than that in typical road runoff (11 µg/L copper; Maestre and Pitt 2005) (Figure 6.1g). Zinc EMCs in 2017 and 2018 were much higher than the 2015 and 2016 measurements, and these concentrations were higher than the 51 µg/L level in typical road runoff. The reason for these observations is not clear, although general variability in runoff characteristics is a possibility. The cumulative mass load reduction by the filter insert indicates that the filter insert was not an effective retention device for copper and zinc during the 2015 to 2018 monitoring seasons.

Table 11. Summary of 2015 to 2018 dissolved copper and dissolved zinc water quality at the filter insert in the iron-enhanced ditch check. The 2015 data are from Natarajan and Gulliver (2015).

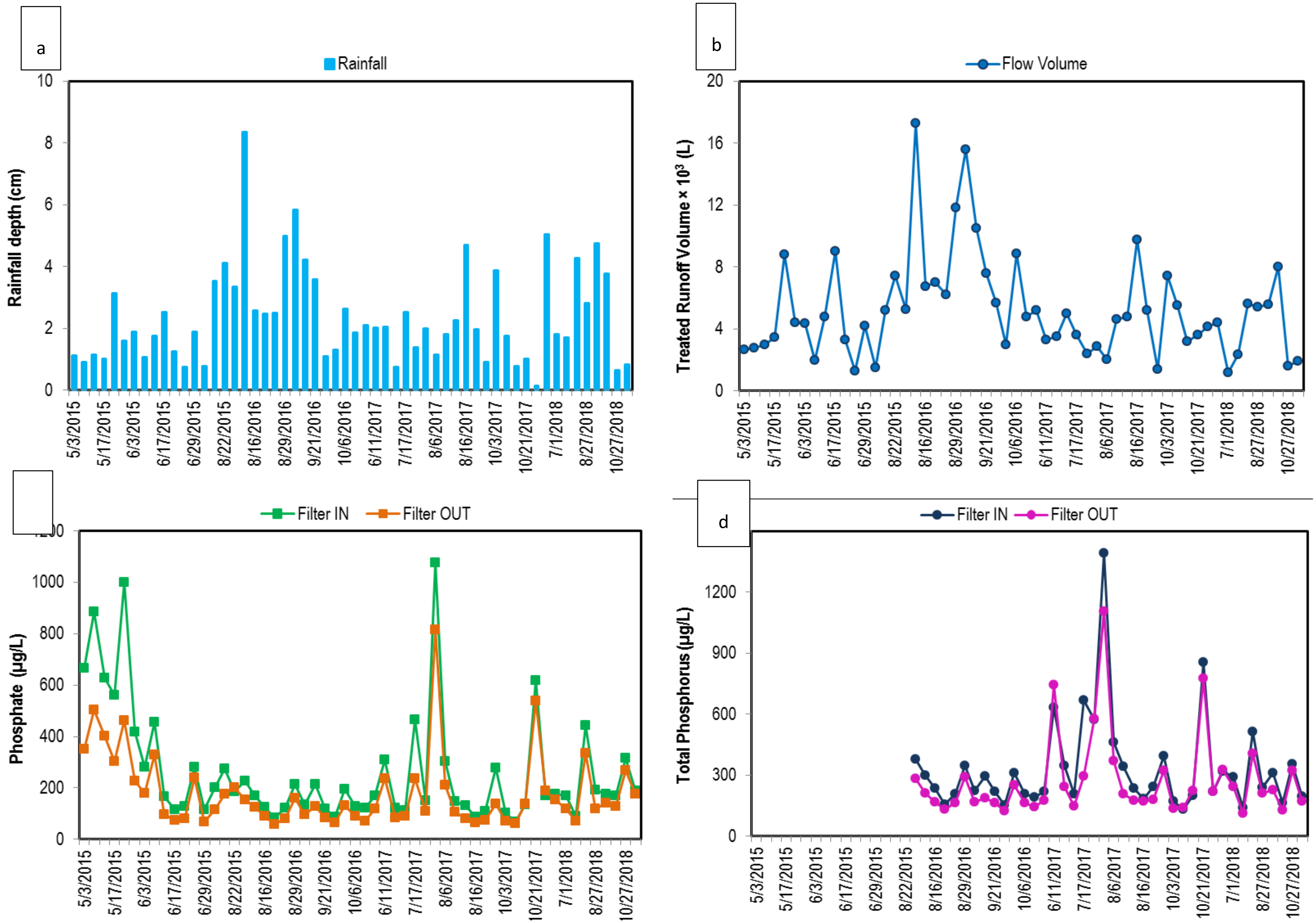
Filter Insert Performance	2015	2016	2017	2018
Number of rainfall events sampled	15	8	9	9
Copper EMC at Filter inflow (event-based)	Range: 9.8 – 103 µg/L Mean: 47 µg/L	Range: 5.3 – 19 µg/L Mean: 11 µg/L	Range: 6 – 25 µg/L Mean: 14 µg/L Median: 12 µg/L	Range: 7 – 33 µg/L Mean: 13 µg/L Median: 9.0 µg/L
Copper EMC at Filter outflow (event-based)	Range: 9.2 – 91 µg/L Mean: 63 µg/L	Range: 5.7 – 9.5 µg/L Mean: 7.8 µg/L	Range: 6 – 19 µg/L Mean: 12 µg/L	Range: 6 – 32 µg/L Mean: 13 µg/L
Copper mass reduction	Range: -511 – 34% Mean: -105%	Range: -12 – 58% Mean: 16%	Range: -9.6 – 61% Mean: 27%	Range: -36 – 24% Mean: -1.1%
Cumulative copper EMC	Filter in = 42 µg/L Filter out = 53 µg/L	Filter in = 11 µg/L Filter out = 8 µg/L	Filter in = 21 µg/L Filter out = 14 µg/L	Filter in = 94 µg/L Filter out = 97 µg/L
Cumulative copper mass load in	3.0	0.84 g	0.58 g	0.38
Cumulative copper mass load out	3.9	0.59 g	0.47 g	0.42
Cumulative copper mass reduction+++	-27%	30%	19%	-10%

Filter Insert Performance	2015	2016	2017	2018
Zinc EMC at Filter inflow (event-based)	Range: 13 – 77 µg/L Mean: 26 µg/L	Range: 34 – 98 µg/L Mean: 50 µg/L	Range: 44 – 218 µg/L Mean: 110 µg/L	Range: 37 – 277 µg/L Mean: 112 µg/L
Zinc EMC at Filter outflow (event-based)	Range: 14 – 112 µg/L Mean: 44 µg/L	Range: 22 – 53 µg/L Mean: 36 µg/L	Range: 34 – 119 µg/L Mean: 77 µg/L	Range: 27 – 220 µg/L Mean: 104 µg/L
Zinc mass reduction (event-based)+	Range: -624 – 10% Mean: -97%	Range: -34 – 51% Mean: 23%	Range: -29 – 64% Mean: -38%	Range: -86 – 57% Mean: -0.38%
Cumulative zinc EMC	Filter in = 22 µg/L Filter out = 33 µg/L	Filter in = 51 µg/L Filter out = 40	Filter in = 104 µg/L Filter out = 87 µg/L	Filter in = 94 µg/L Filter out = 97 µg/L
Cumulative zinc mass load in	1.61	3.93 g	4.40	3.35
Cumulative zinc mass load out	2.43	3.12 g	3.65	3.47
Cumulative zinc mass reduction+++	-51%	21%	17%	-3.5%

+mean or median of mass reduction observed for individual events, for *n* events

++calculated as the sum of metal mass load from *n* events divided by cumulative treated volume

+++cumulative EMC reduction is equal to cumulative mass reduction


a
Rainfall
Rainfall depth (cm)
b
Flow Volume
Treated Runoff Volume × 10³ (L)
Filter IN
Filter OUT
Phosphate (µg/L)
d
Filter IN
Filter OUT
Total Phosphorus (µg/L)
5/3/2015
5/17/2015
6/3/2015
6/17/2015
6/29/2015
8/22/2015
8/16/2016
8/29/2016
9/21/2016
10/6/2016
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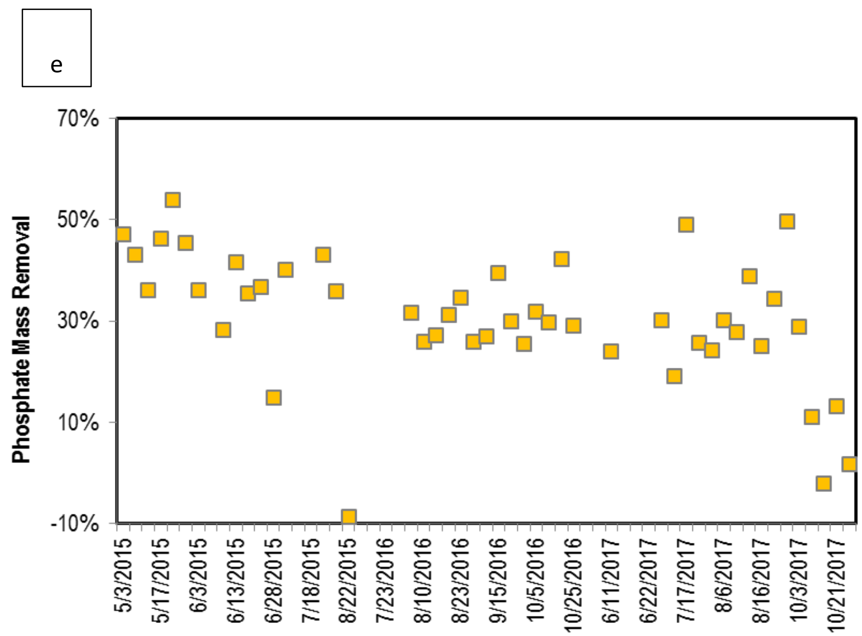
8/27/2018
10/27/2018


e
70%
50%
30%
10%
-10%
Phosphate Mass Removal
5/3/2015
5/17/2015
6/3/2015
6/13/2015
6/28/2015
7/18/2015
8/22/2015
7/23/2016
8/10/2016
8/23/2016
9/15/2016
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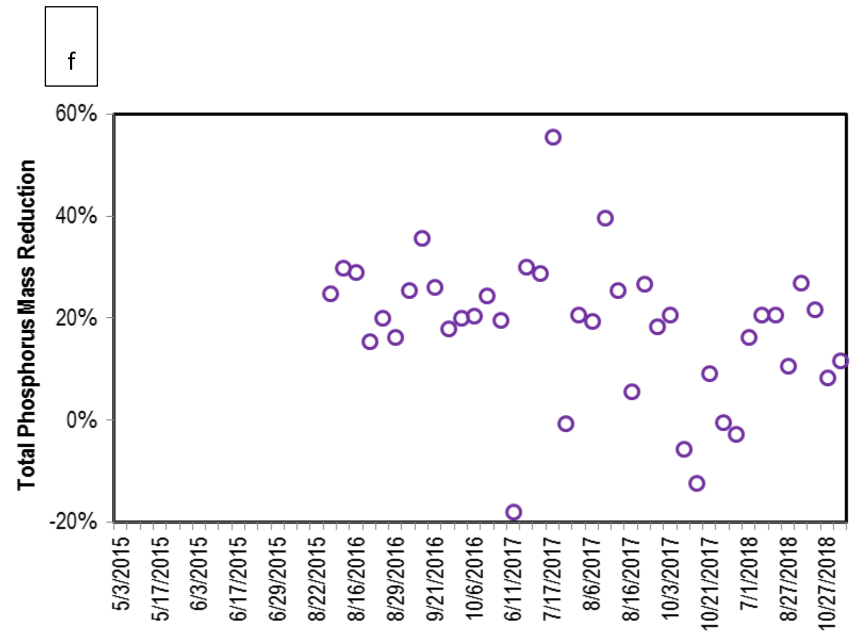
10/3/2017
10/21/2017


f
60%
40%
20%
0%
-20%
Total Phosphorus Mass Reduction
5/3/2015
5/17/2015
6/3/2015
6/17/2015
6/29/2015
8/22/2015
8/16/2016
8/29/2016
9/21/2016
10/6/2016
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8/27/2018
10/27/2018

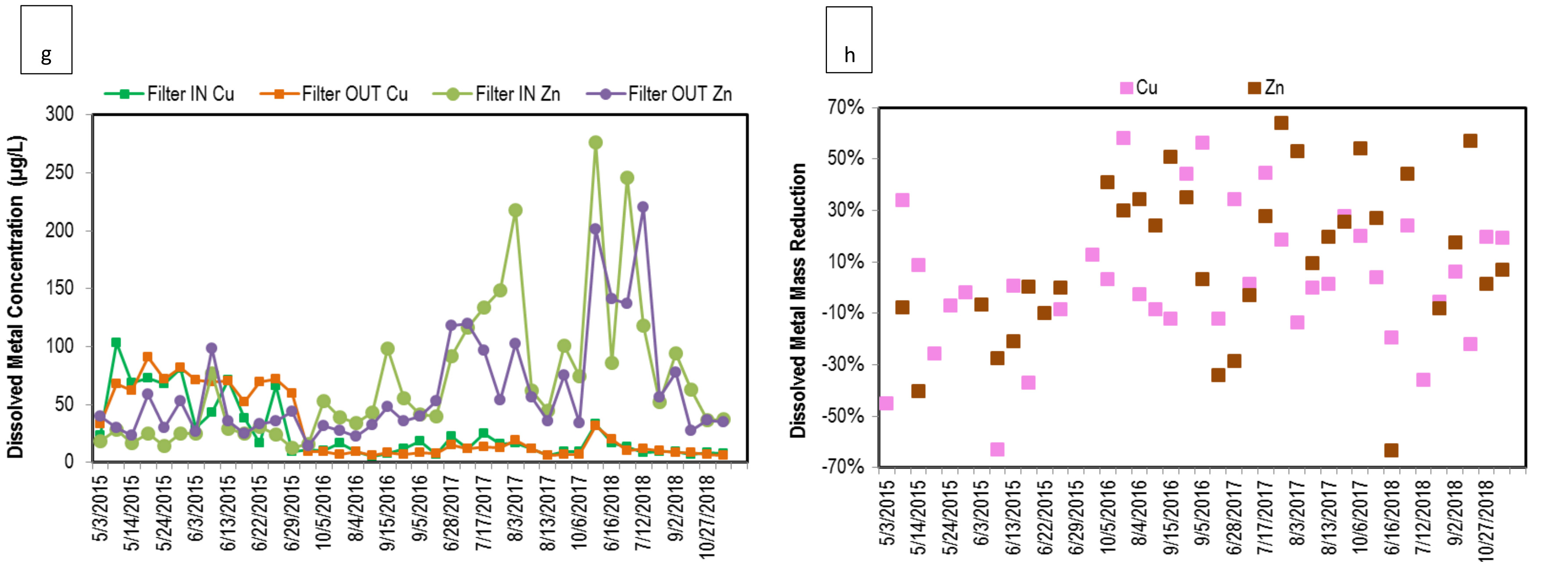

Figure 6.1. 2015-2018 treatment performance of the filter insert at the iron-enhanced ditch check. (a) rainfall; (b) treated flow volume; (c) phosphate concentrations; (d) total phosphorus (TP) concentrations; (e) phosphate mass removal; (f) TP mass removal; (g) dissolved copper and zinc concentrations; and (h) dissolved copper and zinc mass removal. The 2015 data are from Natarajan and Gulliver (2015).

The relationship between phosphorus retention and various independent parameters was considered to explain the differences in performance of the filter insert. The flow exceedance probability plot in Figure 6.2 shows the variation in event-based phosphate mass reductions by the filter insert as a function of the treated flow volumes from 2015 to 2018, to determine if a trend associated with removal during large storm event vis-à-vis small or medium storm event was possible. The scatter in the data indicates a lack of significant effect of treated volume on the phosphate reduction achieved by the filter insert for the entire monitoring duration. TP reduction also did not exhibit any trends for the flow volume exceedances (data not shown).

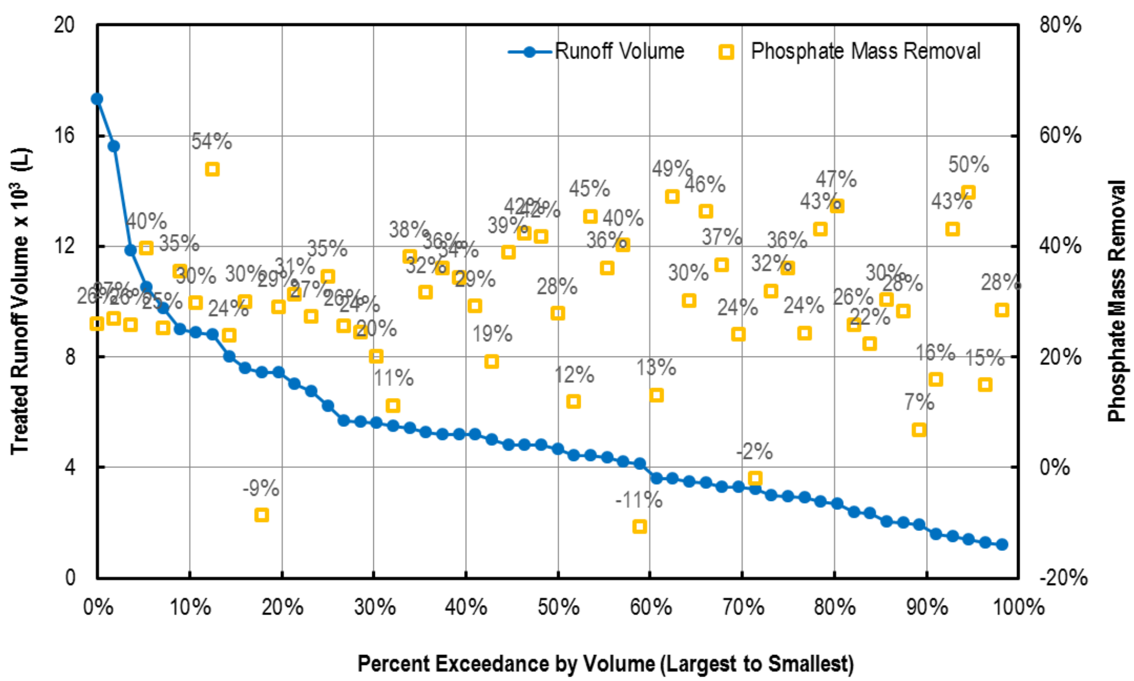

Figure 6.2. Phosphate mass reductions by the filter insert as a function of treated flow volume exceedances at the iron-enhanced ditch check from 2015 to 2018. The largest runoff volume (17,318 L) is plotted at 0% exceedance since this volume was not exceeded during the entire monitoring period. The 2015 data are from Natarajan and Gulliver (2015).

The influence of factors such as rainfall depth, antecedent dry days, and inflow concentration on the filter effectiveness was also investigated. The hypotheses are that performance would be better for smaller rainfall events that generate less runoff, that longer dry period would allow the filter media to regenerate new sorption sites for phosphate capture during the subsequent flow period (Erickson et al. 2012), and that higher removal would be observed for higher concentrations (Erickson et al. 2015). Phosphate removal had a large scatter for <1.27 cm rainfall (0.50 in) and was generally positive (24 to 54%; except for two events) for <2.54 cm (1.0 in) and >2.54 cm rainfall events (Figure 6.3a). There is some indication of a slight decrease in phosphate removal at higher rainfall depths.

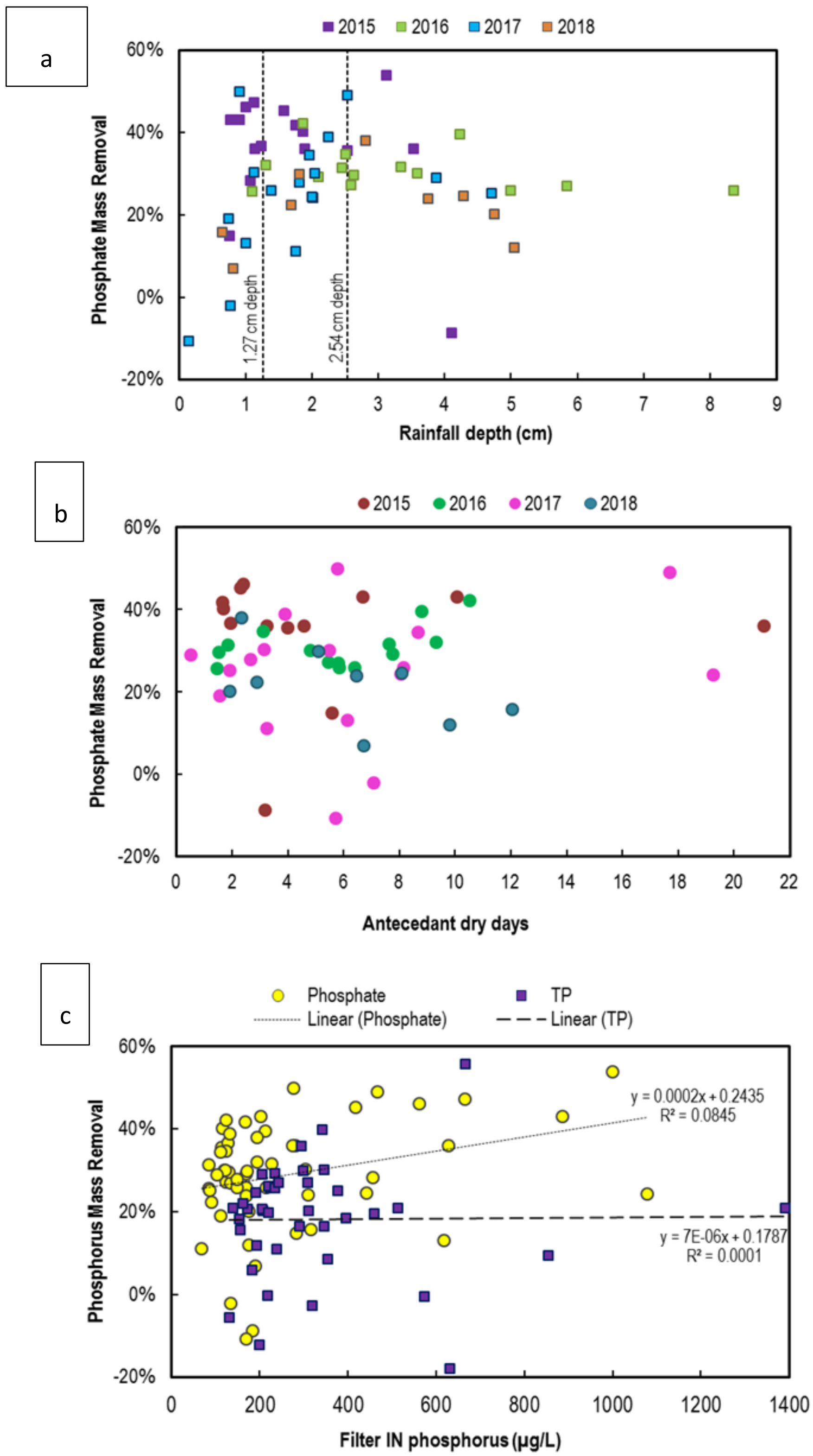

Figure 6.3. Relationship between (a) rainfall depth, (b) antecedent dry period, and (c) inflow concentration and phosphate mass removal by the filter insert for the 2015 to 2018 period. The 2015 data are from Natarajan and Gulliver (2015).

The inter-event duration was calculated as the time duration between cease of flow from one event and the beginning of flow from the following event. The inter-event dry days were between <1 day and 19 days in the three-year monitoring period. A trend between mass removal and the number of dry days between two consecutive events was not observed (Figure 6.3b), i.e., the improvement in phosphate removal efficiency was not consistent for longer dry periods. The relationship between inflow phosphate or TP concentrations and their respective mass removal was also not substantial (Figure 6.3c).

Two hypotheses are proposed for the change in filter insert's performance between 2015 and 2018:

a) The phosphate removal was affected due to an unaccounted phosphorus load input to the filter insert. The topsoil mix installed over the entire ditch check in 2014 contained 10% compost and 30% topsoil (by volume) (Natarajan and Gulliver 2015). Compost has been shown to release phosphate in laboratory experiments (Paus et al. 2014). The degradation of organic material in the topsoil and the sod could release phosphate into the water flowing through the filter insert and possibly through rain water seeping into the filter surface. This phosphate load from the soil and sod could affect the filter's apparent treatment effectiveness, especially in 2015.
b) There is a limited area of the filter area that is subject to runoff filtration on most occasions, and the phosphate-sorption capacity of the iron in that area of the filter can diminish or perhaps exhaust over time, and thus impact the treatment level achieved. Estimates of the treated runoff depth and filtration area are presented in the next section.

6.1.1 Treated Runoff Depth

The treated runoff depth, defined as runoff volume divided by wetted filter area, was calculated for all events from 2015 to 2018. The wetted area was calculated by multiplying the average water level (mean of upstream and downstream water levels) with the filter length transverse to the drainage ditch (3.8 m or 12.5 ft). Figure 6.4 shows the cumulative phosphate mass captured by the filter corresponding to the treated runoff depth, along with corresponding phosphate mass reduction, for the 2015 to 2018 period. The filter insert treated 364 m (1194 ft) runoff in 2015, 493 m (1618 ft) in 2016, 390 m (1280 ft) in 2017, and 121 m (397 ft) in 2018 (thus, cumulative depth = 1322 m or 4337 ft by the end of 2018). The percent phosphate mass reduction exhibits a general decreasing trend with increasing treated runoff depth (Figure 6.4). Laboratory column experiments with synthetic runoff indicated that an iron-enhanced sand filter containing 5% iron mass is able to capture an average of 88% phosphate for 200 m (656 ft) treated depth, and a 2% iron column's capacity is affected after 100 m (328 ft) treated depth (Erickson et al. 2012). On average, 8.1 cm (3.2 in) of the filter height was wet during storm flow periods (based on 12 cm (4.7 in) upstream and 4.5 cm (1.8 in) downstream mean water depths for 68 events), which means 0.31 m^2 (3.3 ft^2) is the wetted area of the filter. If this area of the filter insert is filtering most of the runoff phosphorus, it could lead to the filter's decreasing removal performance as the sorption sites are being used up.

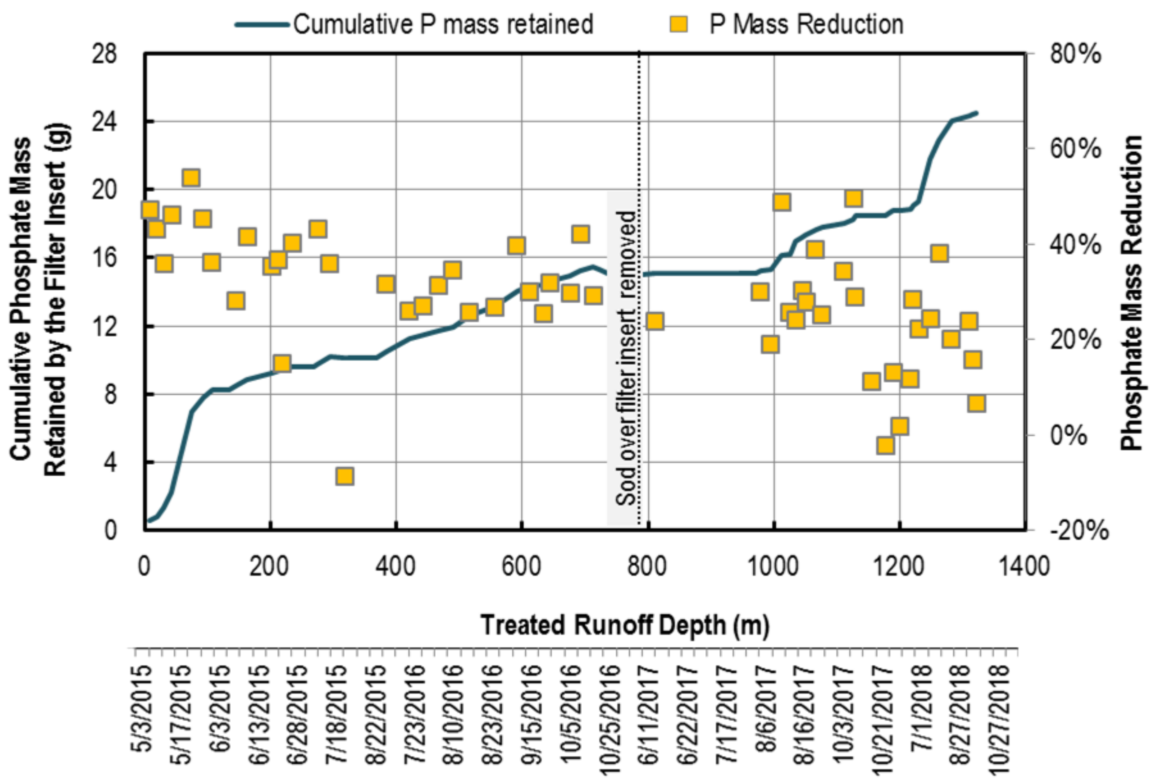

Figure 6.4. Cumulative phosphate mass retained in the filter insert (shown in primary y-axis) for the runoff depth treated by the filter insert along with the corresponding percent phosphate mass removal (shown in secondary y-axis) by the filter insert in the iron-enhanced ditch check from 2015 to 2018. The date axis shown is for the percent phosphate mass reduction during storm events from 2015 to 2018. The 2015 data are from Natarajan and Gulliver (2015).

6.1.2 Batch Test on Filter Media

To further investigate the hypothesis that the phosphorus sorption capacity of the media has diminished over time, the filter insert's sand-iron media was cored for testing. Three cores were collected in July 2018 with the help of MnDOT's Materials Group (Figure 6.5). After clearing the riprap, uncovering the geotextile fabric over the filter insert surface and using a Geoprobe®, two cores were taken ~0.61 m (2 ft) on either side of the approximate center of the filter insert (i.e., 0.61 m or 2 ft from the monitoring wells), and one core was taken ~1.5 m (5 ft) from the filter's center on the in-slope side. The geotextile fabric was closed and the riprap replaced on the filter surface afterwards.

Figure 6.5. Filter media core collection using a Geoprobe® at the iron-enhanced ditch check in July 2018.

The ~45 cm (18 in) long cores were sectioned at 5 cm (1.9 in) intervals (two cores) or 10 cm (3.9 in) intervals (one core). Media from each section was homogenized by hand mixing and then subsampled for the batch tests. The purpose of the batch tests was to measure the capacity of the media to capture phosphorus. The media samples (~4.5 g each) were added to containers containing stock phosphate solution (230 µg/L). The stock phosphate solution was prepared by dissolving standard phosphate solution (Ricca Chemicals) in deionized water (Milli-Q, 18.2 MΩ·cm). The containers were then gently mixed (~90 RPM) on an oribital shaker table for 1 min, 5 min, 10 min, 30 min, 60 min, and 24 hours. For comparison, the residence time of the filter insert is roughly 10 minutes. The solution withdrawn from the container after each mixing time (or contact time) was tested for phosphate concentration. Figure 6.6 summarizes the batch test results, where the reduction in the initial phosphate concentration (C_0) over a given contact time is shown for the entire filter core depth. A C/C_0 = 0.8 ratio means 20% removal of phosphorus was achieved during that contact time.

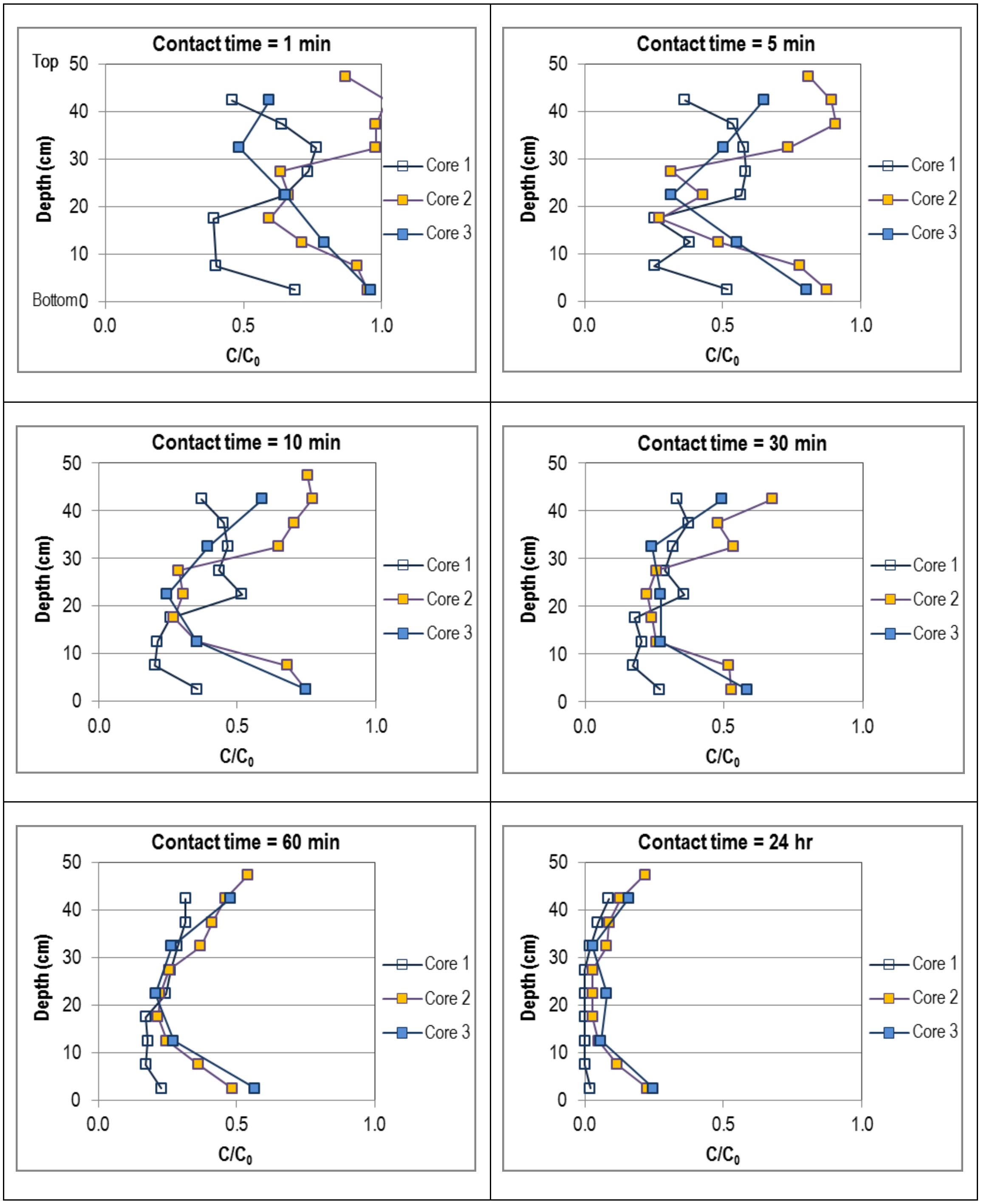

Figure 6.6. Results of batch tests on three filter media cores collected from the filter insert in 2018 to investigate phosphorus sorption capacity under contact times of 0 min, 5 min, 10 min, 30 min, 60 min and 24 hr. C/C_0 is the ratio of the concentration after a given mixing time (or contact time) and the initial phosphate concentration (230 µg/L). In y-axis, 0 cm is the bottom and 45 cm is the top of the filter core. The data are plotted at the midpoint of a given section (for example, at 2.5 cm for the 0-5 cm height of media).

The phosphorus sorption capacity was variable among the three cores and along the core height, especially for contact times less than 10 min. It was evident that the bottom section of the filter media (0 to 10 cm or 0 to 3.0 in core height) had the lowest phosphate removal capacity for all contact times tested. The phosphate capture generally improved with height of media, exhibiting 50 to 80% reduction for the 15 to 35 cm (5.9 to 14 in) height. However, the top section (35 to 45 cm or 14 to 18 in) displayed low phosphate removal. Visual examination of the cores showed accumulation of soil particles over the sand-iron media; these particles could be due to the movement of topsoil through the geotextile fabric and/or deposition of particulates in the inflow during large events that overtopped the filter insert. Because the topmost section of the core was primarily soil in nature, its phosphate removal capacity was low. As contact time increased from 30 min to 60 min, a significant increase in phosphate capture was measured across the 15 to 35 cm (5.9 to 14 in) height of media. Greater than 80% capture occurred across the 15 to 35 cm (5.9 to 14 in) height of media for 24 hour contact time.

The batch tests indicate that the filter still has the ability to retain phosphate, especially the middle section, given sufficient contact time of runoff with the filter. For contact time less than 10 min, which is typical for average-size rainfall event at the ditch check, the phosphate reduction was less than 40% in the bottom 10 cm (3.9 in) media. This level of removal is in agreement with the event-based phosphate removal efficiencies of the filter insert, and supports the hypothesis that the phosphate retention ability of the bottommost part of the filter insert is depressed. The results suggest that mixing of the media has the potential to partially restore the filter insert's phosphate retention ability and could likely to improve the filter performance.

6.2 DITCH CHECK PERFORMANCE FROM 2016 TO 2018

The phosphate treatment provided by the entire ditch check during 2016 to 2018 is provided in Table 12. The ditch check did not provide phosphate removal during several events during 2016 and 2017. Leaching of phosphate from the topsoil-sod cover is believed to have negatively impacted the overall performance of the ditch check. In addition, issues with collecting representative water samples at the ditch check outflow point could have affected the outflow EMC measured at the ditch check. It is possible that the actual phosphate reduction in 2016 and 2017 was higher than measured due to sampling issues. Nevertheless, the ditch check performance appears to have improved with better overall phosphate reductions in 2018. In fact, the phosphate reductions achieved in 2018 seem to roughly match with that of the filter insert. The possible explanation for the improved performance is that representative EMCs could be calculated using the multiple-bottle water sample collection method adopted in 2018.

Table 12. Summary of 2015 to 2018 phosphate water quality at the entire ditch check. The performance of the entire ditch check was not monitored in 2015, hence no data are available.

Entire Ditch Check Performance	2015	2016	2017	2018
Number of events sampled		9	13	9
Total rainfall depth		37 cm (14 in)	23 cm (9.1 in)	19 cm (9.3 in)
Phosphate EMC at ditch check inflow	No data	Range: 98 – 247 µg/L Mean: 145 µg/L	Range: 59 – 1056 µg/L Mean: 308 µg/L	Range: 158 – 404 µg/L Mean: 242 µg/L
Phosphate EMC at ditch check outflow (event-based)	No data	Range: 107 – 257 µg/L Mean: 163 µg/L Median: 152 µg/L	Range: 73 – 1054 µg/L Mean: 296 µg/L Median: 142 µg/L	Range: 121 – 397 µg/L Mean: 219 µg/L Median: 174 µg/L
Phosphate mass reduction (event-based)+	No data	Range: -55 – 11% Mean: -14% Median: -12%	Range: -85 – 69% Mean: -2.0% Median: 0.18%	Range: -51 – 44% Mean: 11% Median: 20%
Cumulative phosphate EMC (all events combined) ++	No data	Ditch in = 154 µg/L Ditch out = 170 µg/L	Ditch in = 280 µg/L Ditch out = 245 µg/L	Ditch in = 288 µg/L Ditch out = 239 µg/L
Cumulative treated runoff volume	No data	89,547 L	57,125 L	34,590 L
Cumulative phosphate mass load	No data	13.8 g	16.0 g	7.9 g
Cumulative phosphate mass load	No data	15.2 g	14.0 g	6.1 g
Cumulative phosphate mass	No data	-10%	13%	17%

+mean or median of mass reduction observed for individual events, for *n* events

++calculated as the sum of P mass load from *n* events divided by cumulative treated volume

+++cumulative EMC reduction is equal to cumulative mass reduction

CHAPTER 7: APPLICATION OF IRON-ENHANCED DITCH CHECKS IN SERIES

The cumulative phosphate mass load reduction by the filter insert can be put into perspective through an application of iron-enhanced ditch checks in series to illustrate how they can help reduce dissolved pollutant concentrations in runoff. This computation makes the following assumptions:

a) Equal lengths between the ditch checks,
b) Equal inflow off of the slope of the ditch into the ditch center, and
c) No infiltration in the center of the ditch (this assumption could be approximated by a high groundwater table or a clay-lined drainage ditch).

Then, the concentration coming out of the last ditch check is given as:

$$C_N = \sum_{i=1}^{N} (1-\eta)^i \frac{C_{in}}{N} \tag{5}$$

where C_N is the concentration of pollutant leaving ditch check N, η is the retention efficiency, and C_{in} is the inflow concentration upstream of the ditch checks and from the sides of the ditch.

We will assume that the material placed on top of the ditch check has been converted to one that does not release phosphate into the water (i.e., peat, for example). The performance of the filters would then be as given in Table 13. The advantage of having a number of ditch checks with filter inserts in series is apparent from Table 13. For example, five ditch checks in series, each removing 42% of the phosphate, would result in an overall removal of 74%. Five ditch checks in series, each removing 25% of the phosphate, would result in an overall removal of 54%. Based on the values in Table 13, between three and four iron-enhanced ditch checks would likely provide a cost-effective solution to phosphate removal. Nonetheless, selection of the number of ditch checks for an in-series installation would depend on the application, stormwater management goals, and the balance of treatment levels and cost.

Table 13. Assumed phosphate removal performance of iron-enhanced ditch checks in series without a contribution from the sod layer and with the assumptions given for equation 5.

Assumed Percent Phosphate Removal at Each Iron-Enhanced Ditch Check	Percent Phosphate Removal with a Number (N) of Iron-Enhanced Ditch Checks in Series				
	N = 5	N = 4	N = 3	N = 2	N = 1
42%	74%	70%	63%	54%	42%

30%	61%	56%	49%	41%	30%
25%	54%	49%	42%	34%	25%

CHAPTER 8: MAINTENANCE RECOMMENDATIONS

The exhaustion of the phosphorus retention capacity of the iron-sand media, physical clogging of the iron-sand media or the ditch check system, and the presence of macro-pores in the media are some of the mechanisms that can cause a drop in performance or life expectancy of the iron-enhanced swale ditch check system. As discussed earlier, the exhaustion of phosphorus retention capacity will eventually cause the system to retain phosphorus at unacceptably low levels. Physical clogging will cause water to pool upstream of the ditch check and/or bypass the iron-sand media. The presence of macro-pores can allow water to pass through the media too quickly, (i.e., effectively short-circuit the system), and reduce iron-water contact time and corresponding reduction in phosphorus retention. To reduce the impact of or prevent these mechanisms from occurring, routine maintenance actions at regular, planned intervals are recommended at the iron-enhanced ditch checks. Additional non-routine maintenance is recommended periodically on an as-needed basis when the system is not performing at acceptable levels.

8.1 ROUTINE MAINTENANCE ACTIONS

8.1.1 Routine Action 1: Weeding, removal of organics such as dead vegetation, leaves, grass clippings, and animal waste from the upstream slope of the ditch check.

Organics such as grass clippings, dead, dying, or wilting vegetation, animal feces, etc, left on the upstream slope of the ditch check can leach phosphorus that may be transported to the iron-sand media. This will have a similar effect in that it will provide additional phosphorus that would occupy adsorption sites and thereby decrease the performance and life of the system. Visual inspection, with removal of organics as necessary, of the ditch check system is recommended at least once a year between mid-summer and end of the growing season.

8.2 NON-ROUTINE MAINTENANCE ACTIONS

8.2.1 Non-Routine Action 1: Mixing of the iron-sand media; mixing should be done thoroughly from top to bottom.

Since ditch checks are horizontal flow systems with flow always passing through at lower levels, the lower portion of the iron-sand media treats more water than the media at or near the top of the filter. This causes the phosphorus retention capacity of the media near the bottom to be more quickly exhausted than that near the top. If influent and effluent sampling indicate that phosphorus retention has dropped to unacceptable levels, likely due to limited capacity of the iron, the iron at or near the top of the media will typically have a greater remaining capacity. Mixing of the media can transfer the higher capacity iron at the top to lower elevations where it can be utilized during low flow conditions, thereby increasing phosphorus retention performance and the life of the system. If sampling has not been performed it is recommended that, in the absence of clogging of the sand/iron media, mixing occur every other year. If the sand/iron media has been in service for six years it is recommended that the sand/iron media be replaced with new media. In this case it is recommended that the entire iron-sand media and geotextile fabric be removed and replaced.

Ditch checks can also become clogged with particles, which can lead to pooled water on the upstream side of the system for undesirable lengths of time. Based on field performance assessment, it appears that clogging occurs predominantly at the lower levels of the sand-iron mixture, where most of the flow passes through the system. Clogging may occur within the iron-sand media, on the upstream side of the geotextile fabric containing the sand, or at both locations. If clogging occurs in the iron-sand media, mixing the media can break apart clogged areas, disperse the clogging agents, and move cleaner, unclogged media to the lower levels. The result would be a restoration, at least partially, of hydraulic and phosphorus retention capacity.

If water pools on the upstream side of the ditch check and does not pass through in sufficient time, the system is likely clogged. Mixing of the iron-sand media may alleviate clogging and is recommended when pooled water exists for more than two days and when the media has not been previously mixed on two occasions.

Finally, if observations indicate that the system is passing water too quickly to provide adequate iron-water contact, mixing of the iron-sand media is recommended to collapse macro-pores that may be causing short-circuiting.

8.2.2 Non-Routine Action 2: Cleaning of the upstream side of the geotextile fabric on the upstream side of the ditch check.

If the system is clogged and not passing sufficient water and the iron-sand media has been recently thoroughly mixed, it is likely that fines collected on the upstream side of the geotextile fabric are causing the clogging. In this case it is recommended that the entire iron-sand media and geotextile fabric be removed and replaced.

This maintenance action should be performed when pooled water upstream of the ditch check exists for unacceptable lengths of time and when the iron-sand media has been previously and recently mixed, but hydraulic capacity has not been sufficiently restored.

8.2.3 Non-Routine Action 3: Removal of the entire iron-sand media bed and geotextile fabric and replacement with new media and new fabric.

If the ditch check is not performing at acceptable levels and applicable non-routine actions 1 and 2 have not sufficiently restored performance, replacement of the entire filtration mechanism (i.e., iron-sand media and geotextile fabric) is likely the only action that will sufficiently restore performance for an extended time.

CHAPTER 9: CONCLUSIONS AND FUTURE DESIGN RECOMMENDATIONS

1. Phosphorus reduction measured for the entire ditch check was unexceptional in 2016 and 2017, but it appeared to improve in 2018. Sampling issues likely contributed to the low performance measured until 2017. The 2018 sampling method provided a better estimate of the ditch check's performance, which roughly matched that of the filter insert.

2. In general, phosphate capture in the filter insert yielded lower concentrations and mass of phosphate discharged from the filter. Except for a few events, mass reductions varied between 22% and 50%. However, the phosphate treatment ability of the filter insert decreased from 2016 to 2018 (cumulative mass load reduction of 30% in 2016 to 23% in 2018). It was estimated that about 1322 m of runoff was treated by the filter from 2015 to 2018. Batch tests on filter media cores collected in 2018 confirmed the decreased phosphorus sorption capacity of the bottom ~10 cm of the sand-iron media. The passage of most of the runoff load through the filter's bottom area diminished its sorption capacity and **was** likely the reason for the overall reduction in phosphate retention over time.

3. The filter insert was not an effective retention device for copper and zinc during the 2016 to 2018 monitoring seasons. However, copper and zinc concentrations in the inflow and treated runoff were generally lower than typical concentrations in roadway runoff.

4. The constructed height of the filter insert in the ditch check was 0.61 m (2 ft). There were only two storm events during the 2015 to 2018 period when the ditch check was overtopped (total rainfall depth 6.25 cm (2.46 in) and 8.36 cm (3.29 in). Future design of a filter insert with a lower height of 0.30 m (1 ft) is recommended to improve the filter media area subject to runoff inflow. This means the purpose of the ditch check is to mainly treat low- and medium-flow events. An increase in the width of the filter insert from the current design of 0.40 m (16 in) (in the direction of flow) is not necessary.

5. To improve the net phosphate retention, a series of iron-enhanced ditch checks can be installed in the swale. The number of ditch checks to be constructed in series will depend on the application, stormwater management goals, and a balance between treatment level and cost. Data from the current project suggest three to four ditch checks in series would provide cost-effective phosphorus treatment.

6. The ditch check was covered with topsoil and sod due to clear zone requirements along the highway. Topsoil and sod are rich in phosphorus, and degradation of the organic material in these soils over time would release phosphate. If the soil is saturated with phosphorus, this phosphate would move with the water flowing through the sod and topsoil. Phosphate from the degrading topsoil could have affected the overall performance of the filter insert and ditch check, especially in

the first year after construction (2015). Topsoil and sod should be avoided over the filter insert. A phosphorus-lean topsoil and sod over the remaining area of the ditch check (i.e., upstream and downstream slopes) would reduce the release of phosphate into water flowing through the soil. Thus, a compost-free topsoil mix is recommended; for example, 60% sand, 30% topsoil, and 10% peat moss (by volume) is a possible topsoil mix composition. When possible, application of topsoil and sod over the ditch check should be avoided.

7. Like all structural stormwater management practices, iron-enhanced ditch checks require routine maintenance at regular, planned intervals to remain effective. Additional non-routine maintenance is required periodically on an as-needed basis. Without routine maintenance**,** the performance of the ditch check will decrease more rapidly and the life of the system will be shortened. Non-routine maintenance is required when the system has failed or is not performing at acceptable levels. Routine removal of organic material upstream of the ditch check is recommended to minimize external phosphorus input. Mixing of iron-sand media every other year to partially restore sorption capacity and eliminate macropores in the media and replacing the entire filter media approximately every six years are recommended as part of the non-routine maintenance.

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