UNIVERSITY OF MINNESOTA

ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 581

Monitoring an Iron-Enhanced Sand Filter for Phosphorus Capture from Agricultural Tile Drainage

Final Report for the Project:
Performance of an Agricultural Drainage Tile Filter

by

Andrew J. Erickson[1], John S. Gulliver[1], and Peter T. Weiss[2]

[1]St. Anthony Falls Laboratory, University of Minnesota, 2 Third Avenue SE Minneapolis, MN 55455
[2]Valparaiso University, Valparaiso, IN 46383

Prepared for
U.S. Environmental Protection Agency Section 319 Program
and
Minnesota Pollution Control Agency
520 Lafayette Road North.
St. Paul, MN 55155

June 2017
Minneapolis, Minnesota

Grant Project Summary

Project title: Performance of an Agricultural Drainage Tile Filter

Organization (Grantee): University of Minnesota

Project start date: 7/1/2014 Project end date: 6/30/2017 Report submittal date: 6/30/2017

Grantee contact name: John Gulliver Title: Professor

Address: 2 Third Ave SE

City: Minneapolis State: MN Zip: 55414

Phone number: 612-625-4080 Fax: Email: gulli003@umn.edu

Basin (Red, Minnesota, St. Croix, etc.) /Watershed & 8 digit HUC:: Crow / 070102040605 County: Wright

Project type (check one):

☐ Clean Water Partnership
☐ Total Maximum Daily Load (TMDL)/Watershed Restoration or Protection Strategy (WRAPS) Development
☐ 319 Implementation
☒ 319 Demonstration, Education, Research
☐ TMDL/WRAPS Implementation

Grant funding

Final grant amount: $256,464.84 Final total project costs: $471,024.44

Matching funds: Final cash: $0 Final in-kind: $214,559.60 Final Loan: $0

MPCA project manager: David Wall

For TMDL/WRAPS development or TMDL/WRAPS implementation projects only

Impaired reach name(s):

AUID or DNR Lake ID(s):

Listed pollutant(s):

303(d) List scheduled start date: Scheduled completion date:

AUID = Assessment Unit ID
DNR = Minnesota Department of Natural Resources

Executive summary of project

The purpose of this project was to measure the total phosphorus and soluble phosphorus capture performance of an iron enhanced sand filter (IESF) in Wright County, Minnesota, near the cities of Buffalo and Rockford. This IESF was installed in 2012 to treat water from approximately 18.4 acres of farmland (crop and pasture) that drains towards a shallow wetland and into a tile drainage system. Before 2012, the tile drain discharged into a ditch that carried the water a few hundred yards to Martha Lake. Though Martha Lake is not listed on Minnesota's 303(d) List of Impaired Waters, it is managed for protection from becoming impaired. Thus, the watershed draining to Martha Lake is managed to reduce excessive phosphorus loading.

Overall, for natural rainfall/discharge events that were monitored during 2015-2016, the IESF captured 66% ± 7% ($\alpha = 0.05$, $n = 20$) of the total phosphorus mass load and 64% ± 8% ($\alpha = 0.05$, $n = 31$) of the influent soluble reactive phosphorus (phosphate) mass load. Total phosphorus and phosphate capture was approximately uniform for large and small rainfall events and varied from approximately 40% to 90%. Approximately 50% of the total phosphorus and phosphate load was contributed by only 20% and 15% of the rainfall events with the largest mass load, respectively. This performance is specific to this IESF and this contributing area, which may not be applicable to other sites and designs. Routine and non-routine maintenance was performed throughout the project to ensure adequate flow through the IESF and adequate performance. Detailed results, maintenance activities, design and operating & maintenance recommendations, and lessons learned are given within this report.

Problem

This monitoring project was performed on an iron enhanced sand filter (IESF) in the Wright County, MN. Water from the IESF discharges into a wetland that ultimately drains into Upper Prior Lake. This IESF was installed in 2012 to treat drain tile flow from approximately 18.4 acres of farmland (crop and pasture) that drains toward a shallow wetland and into tile drainage system upstream of Martha Lake. Martha Lake is managed to protect it from being added to the impaired list; thus, reducing phosphorus loading is one of the goals of the management strategy.

Waterbody improved

Though Martha Lake is not currently listed on Minnesota's 303(d) List of Impaired Waters, it is managed for protection from becoming impaired. Thus, the watershed draining to Martha Lake is managed to reduce excessive phosphorus loading. One management strategy that targets a reduction in phosphorus loading to Martha Lake was the installation of an iron enhanced sand filter (IESF) that intercepts a tributary ditch to Martha Lake and captures total and soluble reactive phosphorus (phosphate). Although the quality of the effluent from the IESF was substantially improved, the impact of this IESF on the overall water quality of Martha Lake was not directly evaluated.

Project highlights

Natural rainfall/discharge events were monitored during summer and fall months (June through November) in 2015 and 2016 to assess the performance of an IESF near Buffalo and Rockford, MN. This stormwater treatment practice is designed to capture soluble reactive phosphorus (phosphate) and total phosphorus, thereby reducing the phosphorus load to Martha Lake. This project was funded with US EPA 319 funds through the Minnesota Pollution Control Agency (MPCA), and was a combined effort between St. Anthony Falls Laboratory, University of Minnesota and the Wright Soil and Water Conservation District.

Results

Overall, for natural rainfall/discharge events that were monitored during 2015 and 2016, the IESF captured (66% ± 7% ($\alpha = 0.05$, $n = 20$ events) of the total phosphorus mass load and 64% ± 8% ($\alpha = 0.05$, $n = 31$ events) of the influent soluble reactive phosphorus (phosphate) mass load. Approximately 0.955 kg (2.11 lbs) of total phosphorus and 0.688 kg (1.52 lb) of phosphate was captured by the IESF during the study (2015 and 2016). Total phosphorus and phosphate capture was approximately uniform for large and small rainfall events and varied from approximately 40% to 90%. Approximately 50% of the total phosphorus and phosphate load was contributed by only 20% and 15% of the rainfall events with the largest mass load, respectively. This performance is specific to this IESF and this contributing area, which may not be applicable to other sites and designs. Routine and non-routine maintenance, which are discussed in detail within this report, was performed throughout the project to ensure adequate flow through the IESF and adequate performance.

Partnerships

This project, which was funded with US EPA 319 funds through the Minnesota Pollution Control Agency (MPCA), was a combined effort between St. Anthony Falls Laboratory, University of Minnesota and the Wright Soil and Water

Conservation District. The US EPA provided funding while the MPCA provided project oversight and reporting. The University of Minnesota's St. Anthony Falls Laboratory performed the majority of the research effort. Wright Soil and Water Conservation District provided in-kind match via the project location in coordination with the local property owner, maintenance of the IESF, and grab sampling throughout the project duration.

Pictures

Pictures are provided throughout the report and will will be attached as separate files to the final report.

Acknowledgements

This project was a contract between the University of Minnesota and the Minnesota Pollution Control Agency, who funded the project through the Federal Clean Water Act Section 319 grant program, SWIFT Contract No. 66692; Award No. 44095, with David Wall as Project Manager. David's assistance and support throughout this project is greatly appreciated. The Wright Soil and Water Conservation District provided in-kind match and assistance throughout the project.

Support from the Wright Soil and Water Conservation District including Joe Jacobs, Dan Nadeau, Alicia O'Hare, Kerry Saxton, and summer support staff is greatly appreciated. In addition, the assistance and support from St. Anthony Falls Laboratory (SAFL) staff and students including Peter Corkery, Jenni Snyder, David Liddell, Tyler Olsen, Poornima Natarajan, Rob Gabrielson, Ben Erickson, Dick Christopher, Seth Strelow, and Raphael Martins is appreciated.

Participation by the following volunteer industry professionals as members of the Technical Advisory Panel is greatly appreciated: David Wall, Erin Anderson Wenz, Mark Deutschman, Mike Isensee, Al Kean, Rhonda Rae, Kerry Saxton, and Bill VanRyswyk.

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

ASTM = American Society of Testing and Materials
C.I. = Confidence Interval
DFM = Discovery Farms Minnesota
EMC = Event mean concentration
FW Average = Flow-weighted Average
IESF = Iron enhanced sand filter
IN = Influent
KCFE = Buffalo (MN) Municipal Airport
MN = Minnesota
MPCA = Minnesota Pollution Control Agency
OUT = Effluent
PVC = Polyvinyl Chloride
RMSE = Root Mean Square Error
SAFL = St. Anthony Falls Laboratory
SCM = Stormwater control measures
SRP = Soluble reactive phosphorus or phosphate
SWCD = Soil and Water Conservation District
TAP = Technical advisory panel
TKN = Total Kjeldahl Nitrogen
TSS = Total Suspended Solids
US EPA = United States Environmental Protection Agency

Section I – Work Plan Review

Approved changes: There was one change order and one amendment approved to reflect changes in staff and required materials that occurred during the project.

Task 1. Technical Advisory Panel

A technical advisory panel (TAP) was established and meetings were held on April 13, 2016 and April 26, 2017. During these meetings, data from the project were presented and questions were asked and answered by both the TAP members and project staff. During the meeting on April 26, 2017, TAP members were asked to provide comment on the draft Final Report. TAP Members that attended meetings included David Wall, Erin Anderson Wenz, Mark Deutschman, Mike Isensee, Al Kean, Rhonda Rae, Kerry Saxton, and Bill VanRyswyk.

Development of the Technical Advisory Panel was completed as scheduled.

Task 2. Install monitoring equipment

Uncertainty in field site conditions led to changes in the planned flow measurement methods, equipment, and devices. These changes prevented installation of equipment during the rainy season of 2014. Alternatives were developed, tested, and calibrated at St. Anthony Falls Laboratory and installed in Spring 2015.

Monitoring equipment was installed in at the field site from June through November 2015 and again from June through November 2016. The equipment that was installed included a tipping bucket rain gauge, air temperature sensor, data logger, automatic water samplers, water pressure transducers, solar panels, and deep cycle marine batteries.

Installation of monitoring equipment was completed as scheduled.

Task 3. Monitor Water Quality Performance of Enhanced Filter.

The performance of the iron enhanced sand filter (IESF) was monitored during natural rainfall/discharge events for two rainy seasons in 2015 and 2016. Monitoring began in June and continued through November of each year. Challenges with equipment occurred throughout the project and included faulty equipment (requiring replacement), interference from amphibious species (requiring screens to be installed), and vehicular collision with research equipment (requiring purchase of new equipment).

In total, over 30 natural rainfall/discharge events were monitored. Water samples were analyzed at St. Anthony Falls Laboratory (SAFL) for soluble reactive phosphorus (SRP, phosphate) and total phosphorus.

Field monitoring was completed as scheduled.

Task 4. Data Analysis

Monitoring results were analyzed by concentration-based, load-based, and percent exceedance methods (Erickson, et al., 2013) for both total phosphorus (2016) and soluble reactive phosphorus (2015 and 2016). Event, annual, and cumulative phosphate influent and effluent mass loads and event mean concentrations were determined along with the percent capture of these loads by the IESF.

Data Analysis was completed as scheduled.

Task 5. Dissemination of Results

Project results were disseminated at two meetings of the Technical Advisory Panel (April 13, 2016 and April 26, 2017). An article on the results was published in an UPDATES email newsletter (October 2016; http://stormwater.safl.umn.edu/updates-october-2016). A manuscript is in press and is expected to be published in 2017 in the Journal of Environmental Engineering, for a Special Issue on Environment and Sustainable Systems: A Global Overview. A second manuscript is in preparation and is expected to be published in 2017 in the Journal of Water for a Special Issue on Additives in Stormwater Filters for Enhanced Pollutant Removal. The draft final report was prepared and shared with project team members and the TAP Panel prior to revision into the Final Report. The Final Report of this project will be posted on the University of Minnesota's Digital Conservancy (http://conservancy.umn.edu/) and linked on St. Anthony Falls Laboratory's Stormwater Research website (http://stormwater.safl.umn.edu/).

In addition to the reports, journal publications, and email newsletter articles described above, the project or results have been, or will be, disseminated at 12 or more presentations. It is estimated that these efforts have reached over 1,000 participants, including watershed planners, municipal engineers, and consulting environmental or stormwater engineers.

Results were, and will continue to be incorporated into Stormwater 'U' and Stormwater Management and Erosion Control Certification courses and workshops. Results have already been included in senior and/or graduate urban hydrology classes at the University of Minnesota and Valparaiso University, Valparaiso, IN.

Research dissemination was completed as scheduled.

Section II – Grant Results

Introduction

Rainfall and snowmelt on urban or agricultural landscapes typically produces enough water to generate flow over the surface of the landscape, which is called stormwater runoff. In agricultural watersheds, there are also buried perforated pipes called drain tiles that collect soil moisture and discharge it downstream, allowing soils to be farmed. This drain tile flow has quantitative characteristics such as volume and flow rate as well as qualitative characteristics such as temperature, pH, and pollutant concentrations. One such pollutant of concern is phosphorus, which can be either particulate (> 0.45 μm in size) or soluble (< 0.45 μm). Stormwater runoff from nationwide highways and urban areas, on average, has 30 – 45% soluble and 55 – 75% particulate phosphorus (Kayhanian, et al. 2007; Pitt et al. 2005), but the soluble fraction ranges from 3 – 100% (Erickson et al. 2007). Total phosphorus is a measure of the combined particulate and soluble phases of phosphorus. In stormwater runoff, drain tile flow, and surface water bodies, soluble phosphorus is most often in the form of phosphate (PO_4^{3-}) (Stumm and Morgan 1981). Though phosphate is often also known as dissolved phosphorus, soluble reactive phosphorus, and ortho-phosphorus, this report will use the term "phosphate" to describe the soluble reactive phase of phosphorus.

Sources of phosphate in urban stormwater runoff include lawn fertilizers (although in some states such as Minnesota, these are phosphate-free), leaf litter, grass clippings, unfertilized soils, detergents, and rainfall, among others (American Public Health Association, 1998; US EPA, 1999). In agricultural watersheds, phosphate sources include natural organic matter, crop biodegradation, natural and synthetic fertilizers, livestock waste, among others. Phosphate is more bioavailable than particulate phosphorus (Sharpley et al., 1992), and thus typically limits biological growth in temperate non-marine surface water ecosystems (Aldridge and Ganf 2003, US EPA 1999, Schindler 1977). When in excess, phosphorus often generates nuisance algae blooms and eutrophic conditions in surface water bodies.

Sedimentation (i.e., particle settling) and filtration are two mechanisms used by common stormwater control measures (SCM) such as wet ponds, dry ponds, and filters to capture particulate forms of phosphorus. Phosphate, however, is often not captured by most SCMs because a chemical or biological process is necessary to do so. For example, sand filters can capture approximately 80% of total suspended solids (Weiss et al. 2007), which primarily consists of particulates that can be captured by filtration. Sand filters also typically capture approximately 80% of total suspended solids, but typically capture only about 45% of the total phosphorus (Weiss et al. 2007) because phosphate passes through the sand filter with the water.

Stormwater control measures can be improved to capture soluble pollutants such as phosphate. Erickson et al. (2007, 2012) found that adding metals such as steel wool or elemental iron to sand filter media resulted in the capture of a significant amount of phosphate. As stormwater passes through the filter media, the elemental iron rusts to form iron oxides, which bind with phosphate via surface adsorption to remove phosphate from the stormwater.

To limit the phosphate load moving from the landscape into surface water bodies, Wright Soil and Water Conservation District (SWCD) of Minnesota installed an iron-enhanced sand filter (IESF) based on previous studies (Erickson et al. 2007, 2012, 2015). A drain tile from an agricultural field was re-routed away from an existing ditch system and into the new IESF. The St. Anthony Falls Laboratory at the University of Minnesota and Wright SWCD then sought funding from the Minnesota Pollution Control Agency (MPCA) to assess the performance of the IESF to capture total phosphorus and phosphate from agricultural drain tile flow and to investigate maintenance requirements. Thus, a main objective of this study was to determine phosphate capture of the IESF by monitoring natural rainfall/discharge events for two rainy seasons.

Site Location

This monitoring project was performed in Wright County, near the cities of Buffalo and Rockford, Minnesota. The 2011 Amendment (Wright SWCD 2011) of the Wright SWCD Water Management Plan (Wright SWCD 2015) identifies Martha Lake and Charlotte Lake as Protection Lakes due to their low phosphorus concentrations. To protect the water quality of these lakes, an IESF was installed in 2012 to treat water from approximately 18.4 acres of farmland (crop and pasture) that drains towards a shallow wetland and into tile drainage system. Before 2012, the tile drain discharged into a ditch that carried the water a few hundred yards to Martha Lake. The project location in relation to Martha Lake and nearby roadways in shown in Figure 1.

Figure 1. Martha Lake and iron enhanced sand filter (IESF) location (courtesy Wright SWCD).

The subwatershed that drains to the IESF is approximately 18.4 acres of mostly row crop (corn & soybean) agriculture with ~10% pasture for grazing dairy cows. An unknown portion of this 18.4 acres has random clay tile drainage (not patterned) with no surface inlets. The extent and quality of the clay tile is unknown. The extent to which the shallow wetland interacts with the tile drainage system is also unknown, and thus it is not known how the wetland hydrology and water quality may have affected the results of this study. The wetland is identified as a Palustrine, Emergent, Persistent, Temporary Flooded, and Farmed (PEM1Af) according to the Minnesota Department of Natural Resources National Wetland Inventory. A description of these characteristics is provided below:

- P: System PALUSTRINE: The Palustrine System includes all nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses or lichens, and all such wetlands that occur in tidal areas where salinity due to ocean-derived salts is below 0.5 ppt. It also includes wetlands lacking such vegetation, but with all of the following four characteristics: (1) area less than 8 ha (20 acres); (2) active wave-formed or bedrock shoreline features lacking; (3) water depth in the deepest part of basin less than 2.5 m (8.2 ft) at low water; and (4) salinity due to ocean-derived salts less than 0.5 ppt.

- EM: Class EMERGENT: Characterized by erect, rooted, herbaceous hydrophytes, excluding mosses and lichens. This vegetation is present for most of the growing season in most years. These wetlands are usually dominated by perennial plants.
- 1: Subclass Persistent: Dominated by species that normally remain standing at least until the beginning of the next growing season. This subclass is found only in the Estuarine and Palustrine systems.
- A: Water Regime Temporary Flooded: Surface water is present for brief periods (from a few days to a few weeks) during the growing season, but the water table usually lies well below the ground surface for most of the season.
- f: SPECIAL MODIFIER Farmed: Farmed wetlands occur where the soil surface has been mechanically or physically altered for production of crops, but where hydrophytes would become reestablished if the farming were discontinued. Farmed wetlands should be classified as Palustrine-Farmed. Cultivated cranberry bogs may be classified Palustrine-Farmed or Palustrine Scrub-Shrub Wetland-Farmed.

The area contributing drainage to the tile drainage system was estimated by the Wright SWCD and Minnesota Department of Agriculture using Stream Power Index (SPI), surface topography, and other Geographic Information System (GIS) tools. While these methods are robust, the exact area contributing to the tile drainage system is still uncertain. The outline of the subwatershed is shown in Figure 2, and contours are shown in Figure 3. Despite the uncertainty of the contributing area and the tile drainage system extent and quality, the site was selected because it provided enough elevation change to allow installation of the filter, was easily accessible from nearby roadways, and the ditch and tile drainage system were identified as sources of phosphorus that could potentially impair Martha Lake.

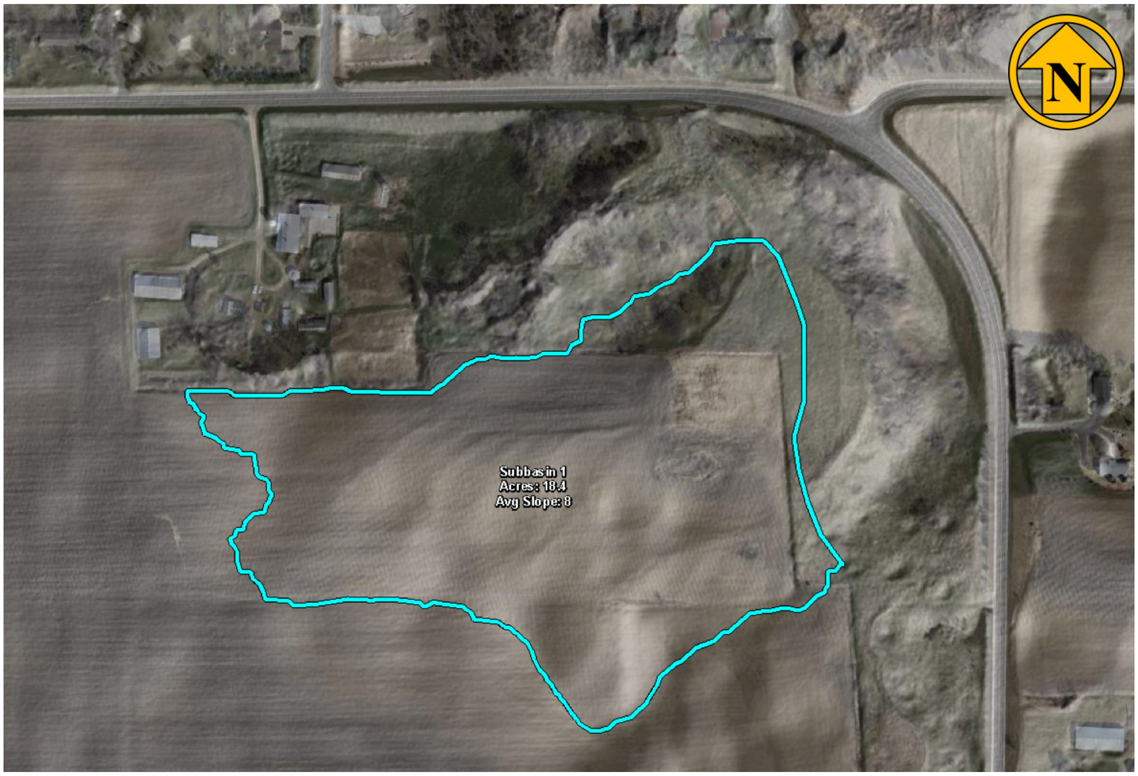

Figure 2. Subwatershed draining to iron enhanced sand filter (IESF) outlined in blue (courtesy Minnesota Department of Agriculture).

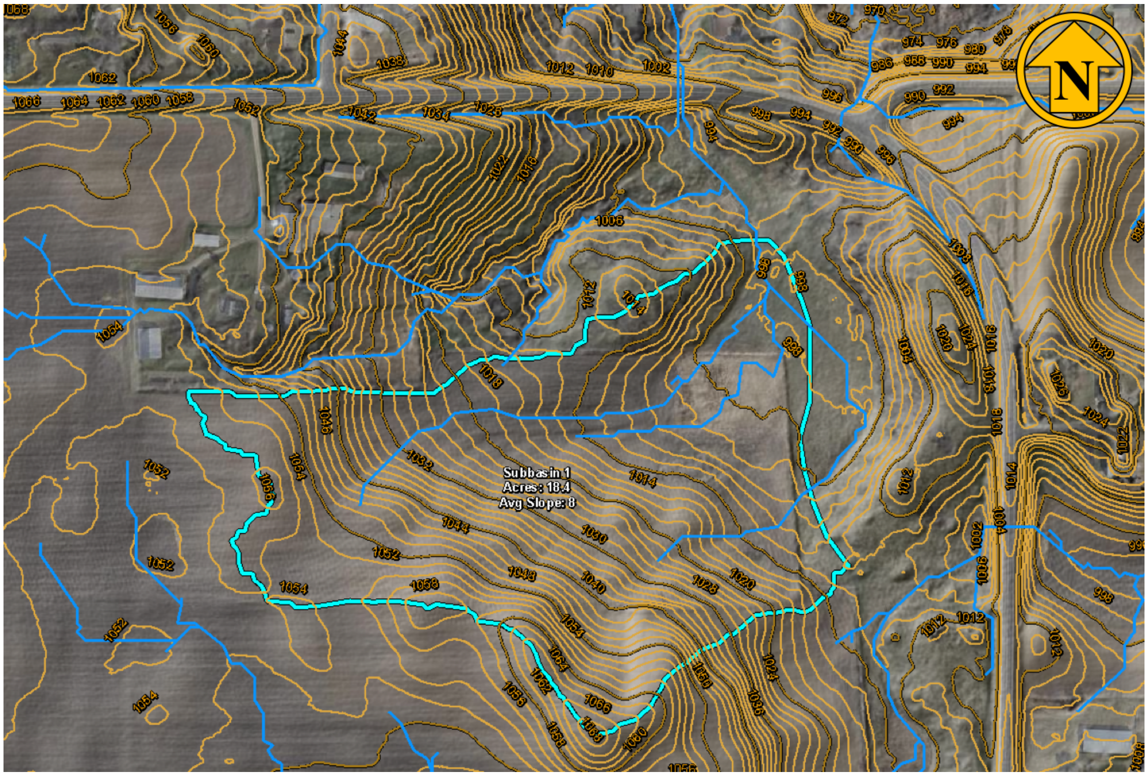

Figure 3. Surface contours (orange lines) around iron enhanced sand filter (IESF) location. Subwatershed draining to IESF shown in light blue, approximate location of surface channels shown in blue (courtesy Minnesota Department of Agriculture).

To protect the water quality of Martha and Charlotte Lakes, an iron-enhanced sand filter (IESF) was installed in 2012 to treat tile drainage from the contributing watershed. The IESF was installed just south of 10th St. SE and west of Hamlin Ave SE, 3.7 miles (5.95 km) north of Rockford, MN (T119N/R24W/S8; N 45.136412, W 93.740104), as shown in Figure 1. The locations of the IESF, the ditch, the Agri Drain (to be discussed later), and the re-routed flow path are shown in Figure 4.

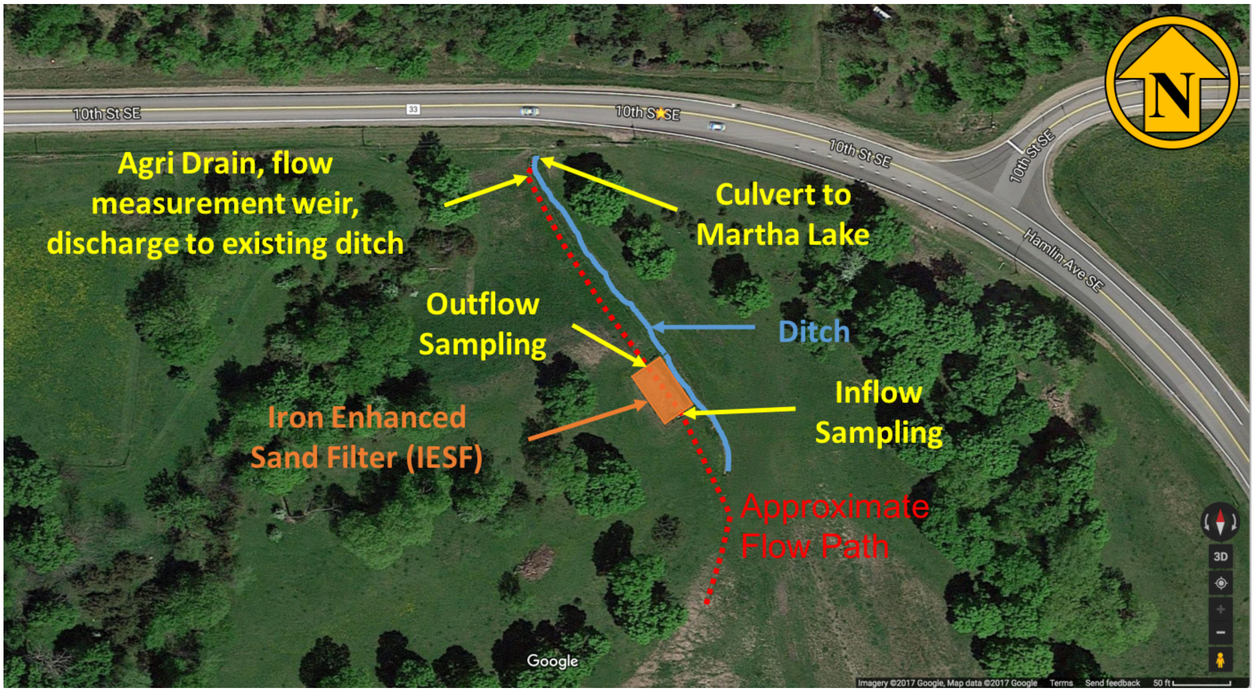

Figure 4. Iron enhanced sand filter (IESF) with flow path, location of Agri Drain, adjacent ditch, and culvert towards Martha Lake (courtesy Google Maps).

Iron-Enhanced Sand Filter Design

The iron enhanced sand filter (IESF) was designed with the filter surface just below the natural topography. An existing drain tile from the upstream agricultural area was intercepted upstream of its discharge into a nearby ditch, and re-routed towards the IESF. The drain tile discharges on the surface of the IESF, and berms were installed around the IESF to provide storage volume above the filter surface and prevent overland flow from around the filter to enter. These berms also prevented flow onto the surface of the IESF when the nearby ditch became flooded due to downstream water level backups. A photo of the IESF shortly after construction is provided in Figure 5.

Figure 5. Site photo of Iron Enhanced Sand Filter (IESF) shortly after construction.

The IESF is approximately 20 feet (6.1 m) wide, 50 feet (15.2 m) long, 1 foot (30 cm) thick and comprises 95% ASTM C-33 concrete sand (ASTM 2002) and 5% iron filings by weight. Below the sand/iron filter media is a layer of approximately 6 inches (15 cm) of pea gravel encompassing a 6-inch (10 cm) diameter PVC perforated pipe underdrain system designed to collect water after it filters through the media. This underdrain system consists of two longitudinally oriented pipes along the length of the IESF (from influent to effluent). This system connects to a single 8-inch (20 cm) outlet pipe, with a connection to the surface of the filter to allow for cleanout access and sample collection (see Figure 6). The IESF is lined with an impermeable liner such that only water that has been filtered by the filter enters the drain tile and water only enters the IESF through the top surface. After water is filtered by the media and collected by the underdrain system, it is routed through an 8-inch (20 cm) solid pipe roughly 200 feet (61 m) long to a culvert that flows north under 10th St. SE towards Martha Lake.

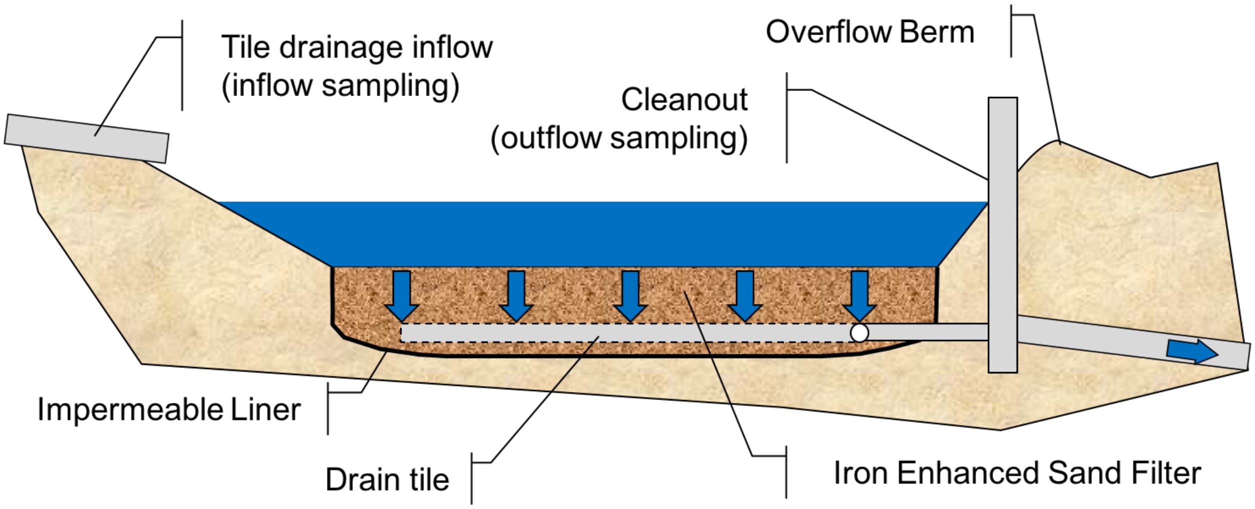

Figure 6. Iron enhanced sand filter (IESF) schematic.

It should be noted that the filter media of an IESF must dry out between flow events to allow for continuous rusting of the iron particles, which creates more sorption sites (Erickson et al. 2007, 2012). For this site, this is achieved because the underdrain outlet is rarely submerged from downstream; allowing water to freely drain out by gravity and oxygen in the air to reach the bottom of the IESF media through the underdrain. When water is not standing on top of the IESF filter during or shortly after a rainfall event, air can also reach the surface of the IESF. In addition, the impermeable liner prevents adjacent groundwater from keeping the media saturated between flow events.

Measurements

The total phosphorus and phosphate capture performance of the IESF was determined by monitoring natural rainfall events in 2015 and 2016. The parameters measured during the study included rainfall at the site, total flow volume, and flow rate through the filter. For each monitored event, water samples were collected where drain tile flow entered and exited the filter. All parameters that were measured on-site were collected remotely and stored on a Campbell Scientific CR1000 data logger. Samples were collected manually as grab samples or by ISCO automatic samplers (described below). Data were sometimes downloaded directly from the data logger and otherwise were transmitted by cellular modem (Sierra Wireless Raven XT model V2227-VD). All equipment was powered by two, 12-volt deep cycle marine batteries located on site. Two Renogy 50-Watt, 12-Volt Polycrystalline Solar Panels and two Renogy Wanderer 30A PWM Charge Controllers sufficiently recharged the deep cycle marine batteries between flow events.

Rainfall and Air Temperature Measurement

Rainfall was measured by a Texas Electronics model TR-525I tipping bucket rain gauge located at the site. Air temperature was measured by an RM Young shielded air temperature sensor located at the site.

Flow Rate Measurement

Influent flow rate measurement was cost prohibitive due to minimal elevation change, (i.e. low available head) that prevented the use of a weir or flume, and low velocity and flow rate values that prevented the use of a flow meter. Because the IESF has an impermeable liner, however, it was assumed that all water that entered the IESF from the surface would also exit through the underdrain collection system. Thus, effluent of the IESF was measured and assumed to be similar to the influent.

The effluent flow rate was measured near the discharge from the 8-inch (20 cm) pipe at the culvert that flows north under 10th St. SE. An Agri Drain was installed at the end of the pipe (8" pipe connection, 2 feet tall, 11 5/8 inches wide by 12 inches long; https://www.agridrain.com/) and a custom weir was fabricated, calibrated, and placed within the Agri Drain. Measuring near the discharge location allowed the maximum possible drop in elevation between the underdrains within the IESF and the Agri Drain weir crest. This minimized the potential for backup of water into the underdrains and maximized the allowable water depth over the weir. Because backwater from the downstream culvert could extend to the weir, the water level upstream and downstream of the weir was measured using two separate Campbell Scientific CS450 pressure sensors. These sensors were fixed in elevation and protected from debris by placing them within a 1-inch (2.5 cm) PVC pipe. A photo of the weir in operation with the pressure sensors is shown in Figure 7.

Figure 7. Custom V-notch weir with upstream and downstream pressure sensors (inside white PVC pipes).

The water level upstream and downstream of the weir was used to calculate the flow. When the water level downstream of the weir was below the vertex (i.e., lowest point) of the weir, the standard V-notch equation was used to calculate flow rate as given by Equation 1.

$$Q_1 = \frac{8}{15} \mathrm{C_{dv}} \left[\tan\left(\frac{\Theta}{2}\right)\right] \left(\sqrt{2\mathrm{g}}\right) H_1^{2.5} \tag{1}$$

where Q_1 = discharge (cfs), C_{dv} = weir discharge coefficient (C_{dv} = 0.601), Θ = angle of V-notch (41.1°), and g = acceleration of gravity (32.2 ft/s^2), and H_1 = total upstream head (i.e., water depth) above the vertex of the V-notch (feet) (Franzini and Finnemore 1997).

When the downstream water level was above the vertex of the V-notch weir, an adjustment to Equation 1 was necessary to estimate the correct flow rate (Villemonte 1947), as given by Equation 2.

$$Q_2 = Q_1 \left(1 - \left(\frac{H_2}{H_1}\right)^{1.5}\right)^{0.385} \tag{2}$$

where Q_2 = adjusted discharge (cfs), Q_1 = discharge (cfs) from Equation 1, H_1 = total upstream head above the vertex of the V-notch (feet), H_2 = total downstream head (i.e., water depth) above the vertex of the V-notch (feet) (Villemonte 1947).

The accuracy of Equation (2) was tested at SAFL by measuring flow rate and comparing the measured value to the predicted flow rate based on Equation 2, as shown in Figure 8. The Root Mean Square Error (RMSE) for the use of Equation 2 to predict the measured flow data shown in Figure 8, up to a maximum of ~0.2 cfs, is 0.0077 cfs for 636 flow calibration measurements collected at SAFL. It can be noted that Equation 2 collapses to simply Q_1 (Equation 1) when the downstream head (H_2) becomes very small, which allowed the use of Equation 2 for all flow calculations.

In total, 10,070 non-zero flow rate measurements were collected at the field site during the monitoring periods. Of these non-zero measurements, 30 measurements (0.3%) exhibited a downstream water level greater than zero such that $Q_2 \neq Q_1$. These measurements accounted for approximately 3.93% of the total non-zero flow measurements. In addition, all field measurements were less than 0.174 cfs and thus within the range of the calibration curve shown in Figure 8.

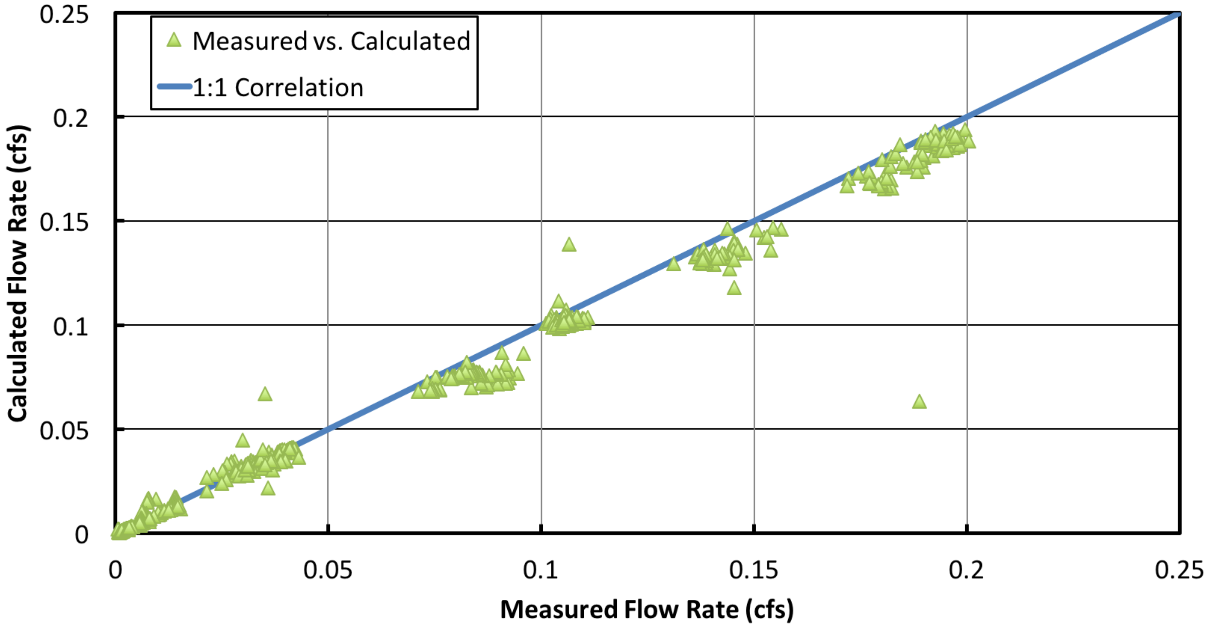

Figure 8. Weir Calibration: Measured flow data (SAFL) vs. Calculated flow data (Equation 2).

Water Sample Collection and Storage

Water samples were collected from within the pipe that discharged tile drainage water from the agricultural watershed onto the surface of the IESF, and were called influent samples. Water samples were also collected from a cleanout on the downstream end of the IESF where the underdrain system below the IESF connected to the effluent pipe, and were called effluent samples. Because the IESF has an impermeable liner, it is assumed that water can only enter the IESF from the surface and can only leave through the underdrain system.

Wright SWCD irregularly collected grab samples from the influent and effluent sampling locations from March through November of each year since the installation of the IESF. These samples were collected and stored in 500 mL plastic bottles supplied by the analytical laboratory (RMB Laboratories, Inc.).

Two ISCO 6712 automatic water samplers were used to collect two, single flow-weighted composite samples, one from the influent and one from the effluent, for each monitored rainfall event. Sample collection began when rainfall exceeded a minimum threshold of 0.02 inches (0.05 cm) and flow rate exceeded 0.01 cfs (0.28 L/s). For the calibrated weir equation provided in Equation 2, a flow rate of 0.01 cfs over the V-notch weir corresponds to a water depth of approximately 0.165 ft (5 cm). Sampling continued until the flow rate decreased to below 0.01 cfs (0.28 L/s). During sampling, the automatic water samplers collected a subsample of 90 mL for every 200 ft^3 (5.66 m^3) of flow over the downstream weir, and added the 90-mL subsample to the composite sample bottle stored within the sampler.

In most cases water samples were retrieved from the site within 24-48 hours of the end of the sampling event and returned to SAFL, where a portion of each sample (typically three separate ~45 mL sub-samples) was immediately separated and labeled for total phosphorus analysis and another portion (typically one ~45 mL sub-sample) was immediately filtered through a 0.45-micron filter in preparation for analysis of phosphate (soluble reactive phosphorus). Samples were frozen immediately after subsampling and 0.45-micron filtering if they could not be analyzed immediately.

Water Sample Analysis

Grab samples were analyzed by RMB Laboratories, Inc. in Detroit Lakes, MN. The analytes and associated analysis methods were as follows:

- Total Kjeldahl Nitrogen (EPA 351.2 Rev 2.0
- Orthophosphate, as P (dissolved) (EPA 365.3)
- Phosphorus, Total as P (EPA 365.3)
- Residue- Nonfilterable (TSS) (SM 2540 D-2011)
- Iron (EPA 200.7)

Flow-weighted composite samples were analyzed at SAFL. Total phosphorus analysis of water samples followed standard methods section 4500-P B5 - Persulfate Digestion method (American Public Health Association, 1998) and phosphate concentrations of water samples were measured according to standard methods section 4500-P E - Ascorbic Acid (American Public Health Association, 1998) with a minimum detection level of 10 μg P/L.

Results and Discussion

The performance of the IESF for capturing total phosphorus and phosphate from agricultural drain tile flow was assessed by monitoring natural rainfall/discharge events during 2015 and 2016. In addition, grab samples were collected from 2012 through 2017 to record the influent and effluent pollutant concentrations, though grab samples were not used to calculate performance. The results of grab sample collection and performance of the IESF based on monitoring is discussed in the following sections.

Grab Sampling Results

Grab samples were collected by Wright SWCD beginning when the IESF was installed through the duration of the project. Several parameters were analyzed in the grab samples, as shown in Figures 9 – 13. Influent iron concentration (Figure 9) varied from below 0.2 mg/L to approximately 1.5 mg/L, though two samples had substantially larger concentrations (4.64 mg/L on 6/22/15; 8.1 mg/L on 9/15/16). It is unclear why these two samples had concentrations of this magnitude. One effluent sample concentration was substantially larger than the other samples (35.2 mg/L on 9/15/16), which coincides with one of the influent samples of substantially larger concentration. In general, the iron concentration decreased when moving through the IESF, with effluent concentrations varying from below detection (0.05 mg/L; reported at 0.025 mg/L) to approximately 0.4 mg/L. It is possible that iron is captured by the IESF because an ionic double layer develops. In this process, iron particles within the IESF would attract ions of opposing charge (negative charge, including phosphate), which would alter the surface charge of the iron particles. Iron ions in the influent water would then be attracted to these negatively charged ions, forming a double layer.

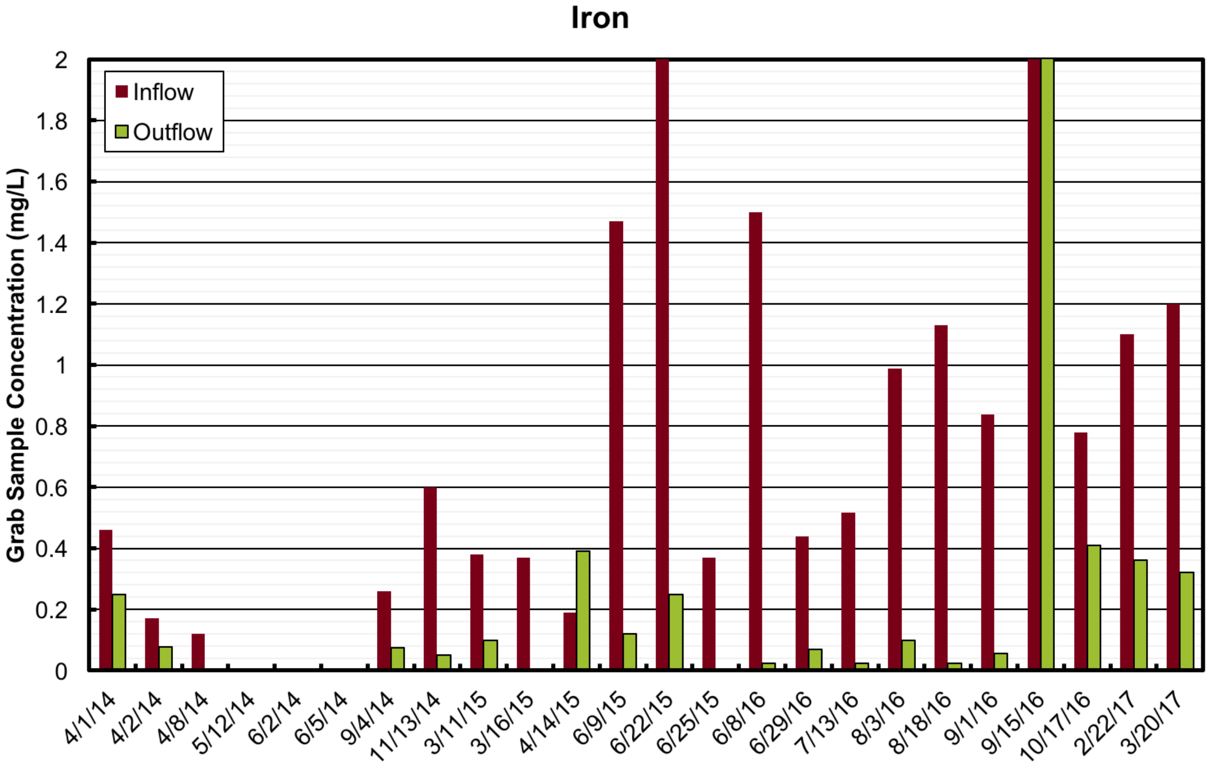

Figure 9. Grab sample data for iron

Though Total Kjeldahl Nitrogen (TKN) was measured in the grab samples, this project was not tasked with measuring performance for nitrogen capture. The grab samples, however, indicate that TKN concentrations often decreased from influent concentrations of approximately 0.7 to 1.7 mg/L down to effluent concentrations of approximately 0.4 to 1.6 mg/L (Figure 10). It is unclear why TKN is reduced through the IESF, but it is likely that particulate organic nitrogen is captured on the surface of the IESF. In addition, nitrification may have converted organic nitrogen or ammonia to nitrate or denitrification may have converted nitrate to nitrogen gas.

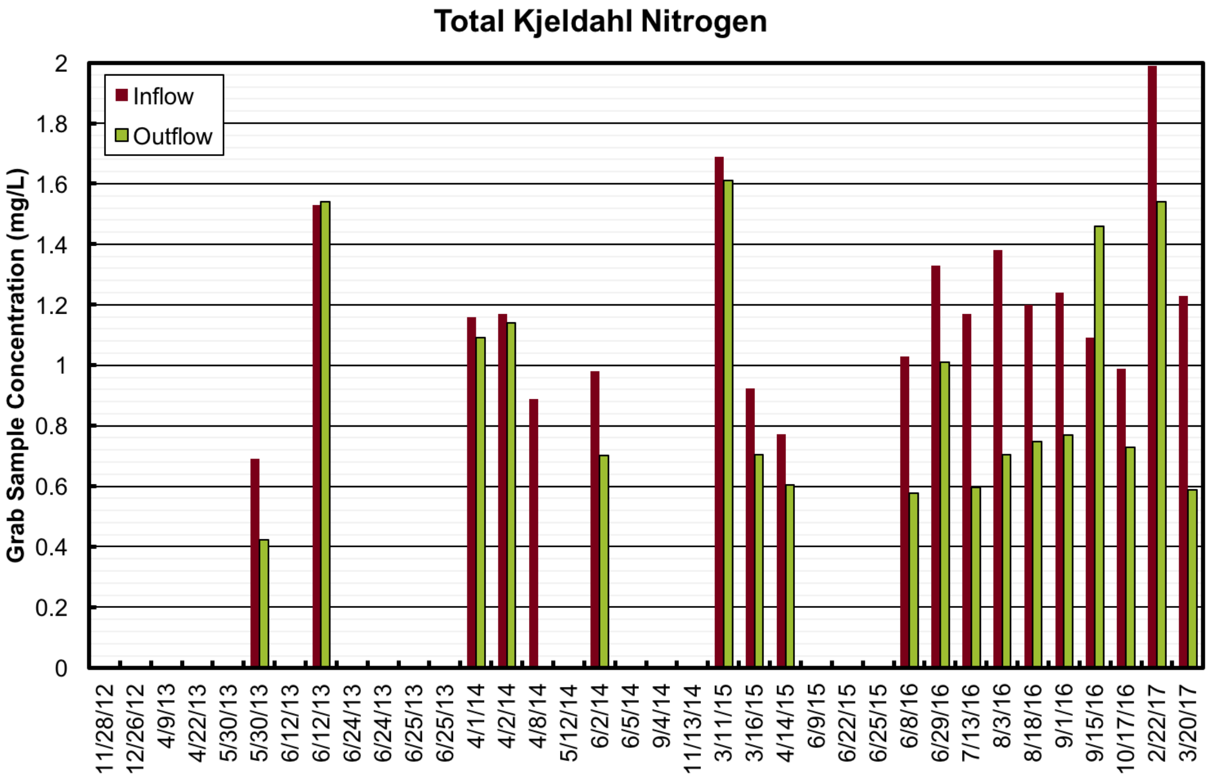

Figure 10. Grab sample data for Total Kjeldahl Nitrogen (TKN)

Grab samples for phosphate (Figure 11) and total phosphorus (Figure 12) show that nearly all sample pairs exhibited a reduction in concentration from influent to effluent through the IESF. Influent phosphate samples varied from 0.03 to 0.33 mg/L and were reduced to between 0.004 and 0.214 mg/L from 2012 to early 2017. Total phosphorus also decreased from an influent of 0.073 to 0.58 mg/L down to an effluent of 0.006 to 0.293 mg/L. One total phosphorus sample had a concentration substantially larger than the other samples (3.12 mg/L on 9/15/16), which coincides with one sample exhibiting high iron influent and effluent concentrations. It is unclear why this sample had a concentration of this magnitude.

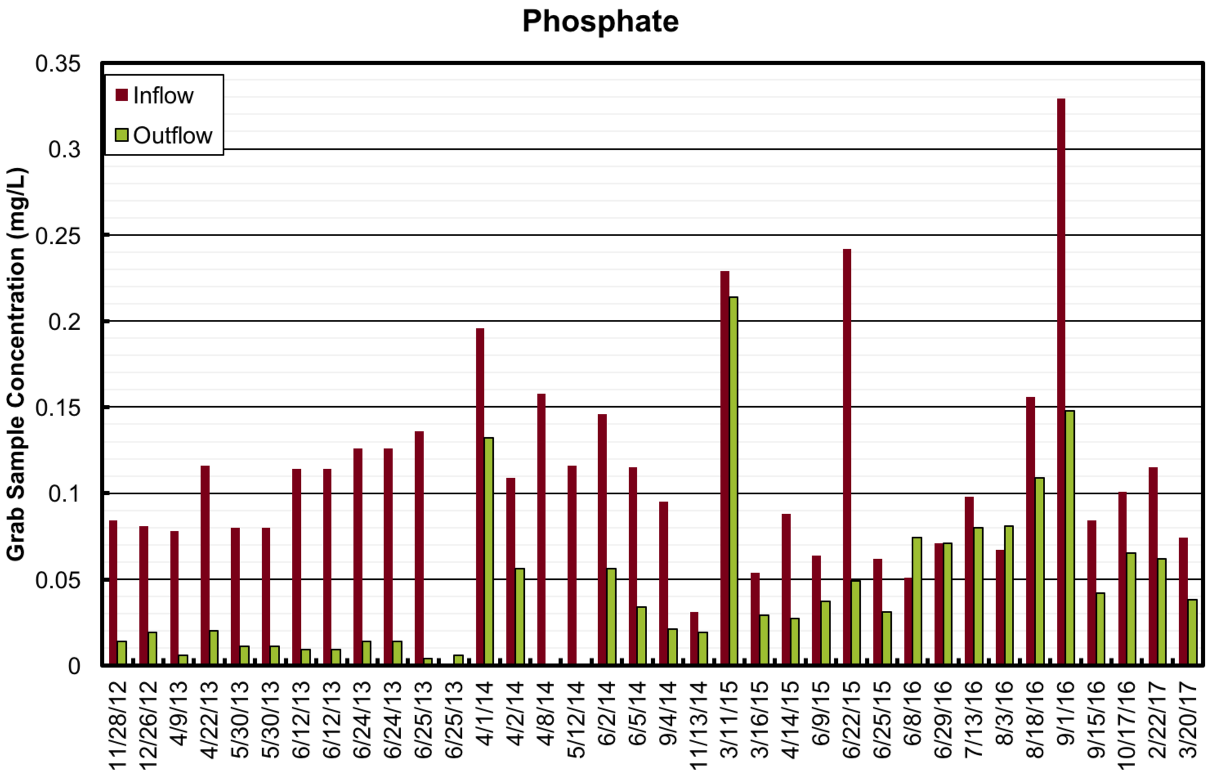

Figure 11. Grab sample data for phosphate

From Figure 11 it is apparent that the effluent phosphate concentration increased beginning with samples in 2014. In 2012 and 2013 the effluent concentration varied from 0.004 to 0.02 mg/L but the effluent samples in 2014 to 2017 varied from 0.019 to 0.214 mg/L. The influent concentrations were similar in each period: 0.078 to 0.136 mg/L in 2012 to 2013 and 0.031 to 0.329 mg/L in 2014 to 2017. It is possible that the increase in effluent concentration is due to any one or more of the following possible explanations:

1) changes in the laboratory operating procedure or equipment used for analysis of the grab samples,
2) application of manure fertilizer,
3) short-circuiting because of vegetation that create macropores from the surface to the underdrains,
4) the capacity of the IESF to capture phosphate had decreased.

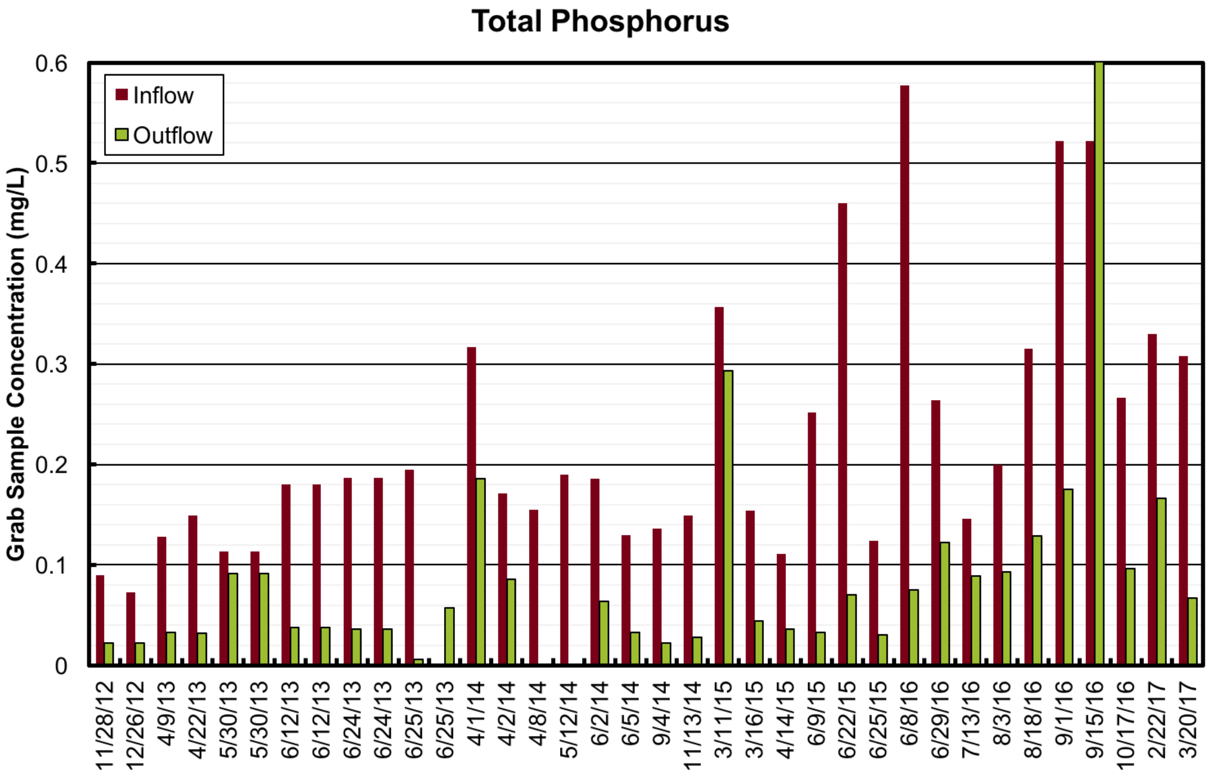

Figure 12. Grab sample data for total phosphorus

Total suspended solids (Figure 13) concentrations for grab samples varied from 1 to 25 mg/L in the influent and from below detection (1 mg/L; reported as 0.5 mg/L) to 5 mg/L in the effluent. The water coming into the IESF (influent) is from tile drainage of an agricultural field, and thus low concentrations of TSS are expected if the tile system is intact and functioning properly without the use of above-ground open inlets. The grab samples appear to verify this condition. In addition, the grab samples show that TSS is generally captured by the IESF, likely due to physical sieving of particulates by the filter media.

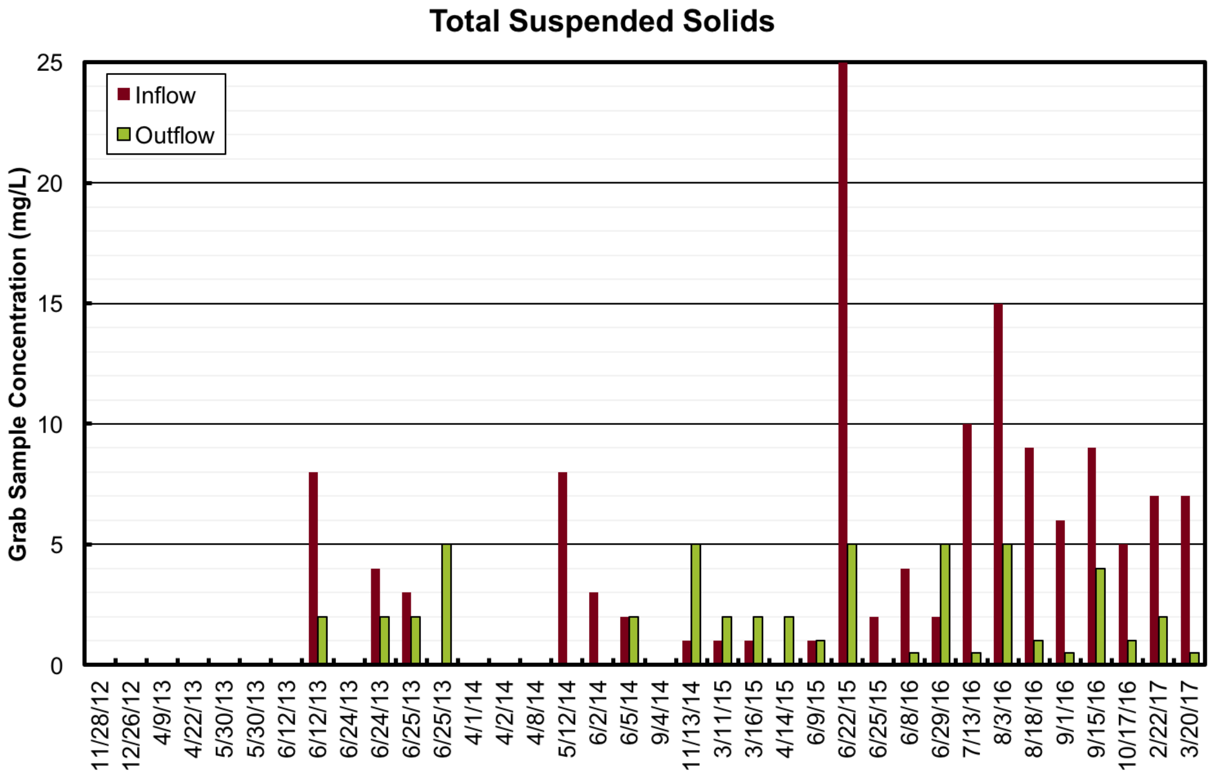

Figure 13. Grab Sample data for Total Suspended Solids (TSS)

Rainfall Event Performance

Monitoring natural rainfall events began in late June 2015 and continued until mid-late November 2015. Monitoring equipment was removed for the winter and reinstalled in May 2016 where it remained until early November 2016. It is important to note that several precipitation events occurred during December through May, outside the periods when monitoring equipment was installed, and are not discussed in this report.

For the periods in which monitoring equipment was installed, flow data were compiled and separated or grouped into "events" and "baseflow." As previously described in the Water Sample Collection and Storage section of this report, events occurred when rainfall and flow rate exceeded preset thresholds. Any flow that occurred between events was considered baseflow. In addition, equipment failure occurred during some events and thus samples were not collected properly. For these events, the flow rate was considered "non-sampled rainfall event flow." For other events, equipment malfunction or extreme flow conditions resulted in flow rate data that was unreliable. These events are not reported and considered "missed." Finally, total phosphorus was not measured in samples collected in 2015. With this grouping of events, the performance of the IESF was assessed for a total of 33 flow events (13 in 2015 and 20 in 2016). Of these events, rainfall was measured for 30 events (11 in 2015 and 19 in 2016), total phosphorus performance for 20 events (all in 2016), and phosphate performance for 31 events (13 in 2015 and 18 in 2016).

Figure 14 and Table 1 provide summary statistics of rainfall and flow volume for the entire monitoring periods in 2015 and 2016. As shown in Figure 14 and Table 1, rainfall depth varied from 0.02 to 2.88 inches (0.05 to 7.32 cm) per event with an average of 0.88 inches (2.24 cm) for 30 events. Because the events measured during this study are only a small sample of the total number of events that have occurred and continue to occur at the site, there is uncertainty associated with any statistical calculations. The 95% confidence interval (C.I.) on the average is approximately 0.28 inches (Figure 14), and thus there is 95% confidence that the average rainfall for this site is 0.88 ± 0.28 inches ($\alpha = 0.05$). The average is greater than the median (0.72 in) for the rainfall depth, rainfall duration, average rainfall intensity and flow volume because several large rainfall events skew the average towards larger values (See Figure 14). Also, many small events skew the median towards smaller values as reflected by the 25th – 50th quartiles being smaller than the 50th – 75th quartiles (See Figure 14).

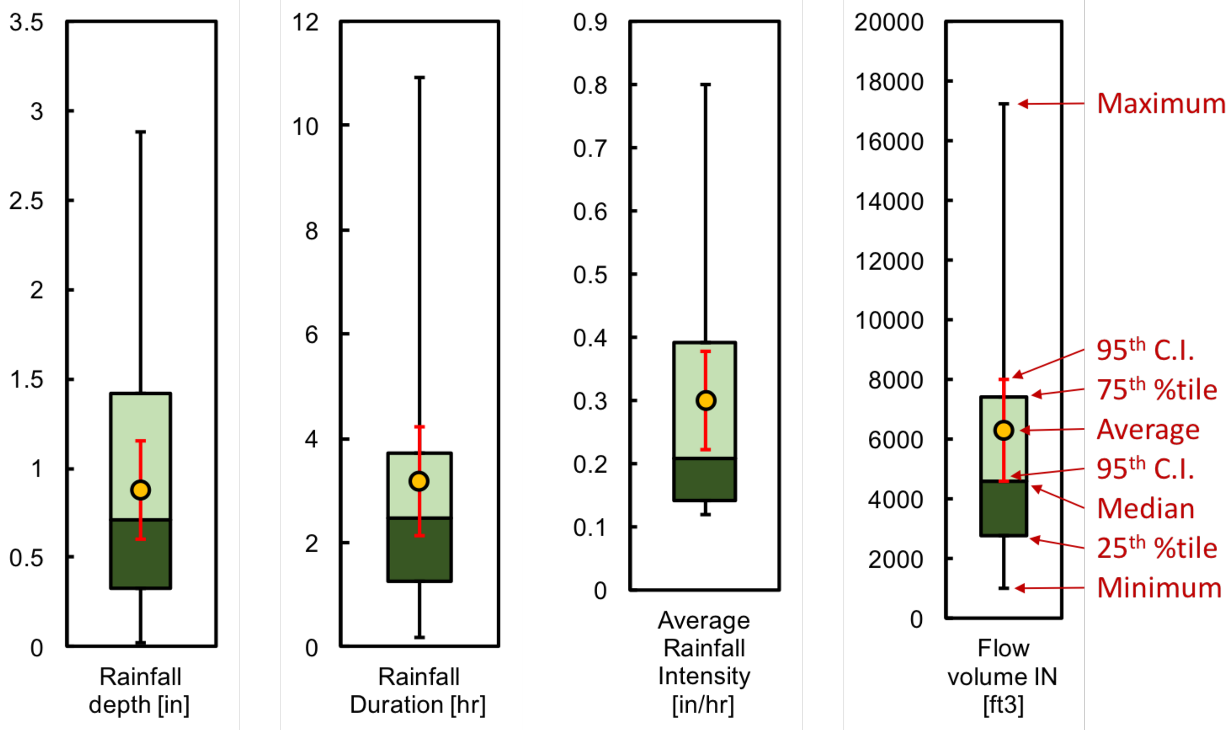

Figure 14. Rainfall depth, duration, average intensity, and flow volume statistics. Note: %tile = Percentile and C.I. = Confidence Interval

Table 1. Monitoring Results Summary Statistics for 2015 and 2016.

			Phosphate					**Total Phosphorus**				
	Rainfall depth [in]	**Flow Volume IN [ft^3]**	**EMC IN [µg/L]**	**EMC OUT [µg/L]**	**Load IN [g]**	**Load OUT [g]**	**Load Capture [%]**	**EMC IN [µg/L]**	**EMC OUT [µg/L]**	**Load IN [g]**	**Load OUT [g]**	**Load Capture [%]**
Minimum[1] =	0.02	1,000	18.3	8.1	2.8	0.4	9%	138.4	56.4	6.3	2.6	42%
Arithmetic Average =	0.88	6,304			42.3	15.6				74.3	26.4	
Flow-Weighted Average =			162.3	58.6				370.3	124.7			
Maximum[1] =	2.88	17,211	358.3	126.6	157.0	61.7	87%	1,516.4	342.5	178.3	86.0	95%
Count =	30	33	31	31	31	31	31	20	20	20	20	20
Totals =	26.4	208,041			956.1	345.1				1,273.6	429.0	
Load Capture Efficiency ± 95% Confidence Interval							**63.9% ± 7.7%**					**66.3% ± 6.7%**

[1] *NOTE: Minimum and maximum values were calculated for all rainfall events, and are independent of min and max values for other parameters. For example, the minimum Phosphate Load IN for all events was 2.8 g (occurred on 10/8/15); the minimum Phosphate Load OUT was 0.4 g (also occurred on 10/8/15), and the minimum Phosphate Load Capture for all events was 9% (occurred on 5/27/16).*

The total measured rainfall depth measured from July 6 until November 15, 2015 was 11.8 inches, and was 14.6 inches for May 23 through October 18, 2016. These values are approximately 50% less than the average annual precipitation for south central Minnesota because it excludes precipitation that occurred during non-sampled rainfall events (see Figures 28 & 29). In addition, several snowmelt and rainfall events occurred during March, April, and May but were not measured as part of this project. Snowmelt and early spring flow can be substantial portions of the annual water budget in some tile drainage systems. Annual rainfall is measured, however, at a municipal airport (Buffalo, MN; KCFE) approximately 5.4 miles (8.7 km) northwest of the IESF. The annual precipitation reported at KCFE was 21.14 in (53.7 cm) for the 2015 water year (October 1, 2014 - September 30, 2015) and 32.45 in (82.4 cm) for the 2016 water year (Oct 1, 2015 - Sept 30, 2016).

Flow volume varied from 1,000 to 17,211 ft^3 (28.2 to 487 m^3) with an average of 6,304 ft^3 (178.5 m^3) per event. The total rainfall for 2015 and 2016 was 26.36 inches (66.95 cm) which produced a total drain tile flow volume of 208,041 ft^3 (5,891 m^3). Distributing this flow volume over the contributing watershed (~18.4 acres of crop and pasture) results in a drain tile flow of approximately 3.11 inches (7.91 cm), which corresponds to a drain tile flow "runoff coefficient" of approximately 0.12. This drain tile flow "runoff coefficient" simply represents the approximate ratio of drain file flow volume to rainfall volume (rainfall depth X watershed area = rainfall volume).

The total flow volume for the monitoring period in 2015 was 86,567 ft^3, which corresponds to approximately 1.3 inches of drain tile flow and a "runoff coefficient" of 0.11. As reported in Table 2, these values can be compared to values from the IESF in 2016 and several sites that are part of the Discovery Farms Minnesota program (https://discoveryfarmsmn.org/). For this comparison, monthly data from the Discovery Farms sites were summed to estimate total rainfall depth, drain tile flow depth, and "runoff coefficient" for June through November in each year reported by Discovery Farms Minnesota (DFM). One site in the Discovery Farms program is located in Wright County and is approximately 22 miles (35.4 km) southwest of the IESF studied in this project. Discovery Farms data reported in Table 2 are average values from six years of measurements at nine different sites, including the site in Wright County. In addition, drain tile flow depth is plotted as a function of rainfall depth in Figure 15 for the IESF site, DFM sites, and the DFM site in Wright County.

Table 2. Rainfall Depth, Drain Tile Flow, and "Runoff Coefficient" for June through November. IESF is the iron enhanced sand filter studied in this report. Measurements at IESF in 2015 and 2016. Measurements at Discovery Farms Sites averaged over six years (2011 - 2016).

	Rainfall Depth [in]	Drain Tile Flow [in]	"Runoff Coefficient"
IESF 2015	11.80	1.30	0.11
IESF 2016	14.60	1.82	0.125
Discovery Farms: 9 Sites	16.11	2.01	0.125
Discovery Farms: Wright County Site	18.44	1.20	0.065

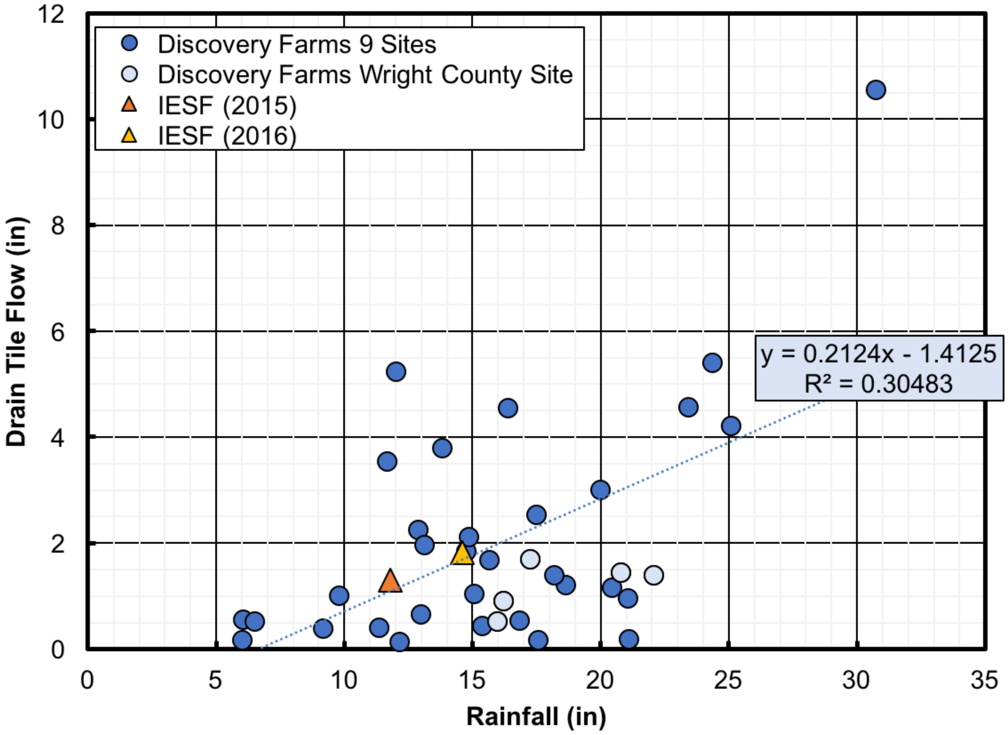

Figure 15. Total drain tile flow depth vs. total rainfall depth for June through November. IESF is the iron enhanced sand filter studied in this report. Measurements at IESF in 2015 and 2016. Measurements at Discovery Farms Sites averaged over six years (2011 - 2016).

The rainfall depth at the IESF site was less than the average rainfall measured at the DFM sites because equipment failure at the IESF site prevented measurement of some rainfall events during the monitoring period of June through November in both 2015 and 2016. The drain tile flow depth measured at the IESF was also less than the nine DFM sites, but approximately the same as the average drain tile flow depth reported by the Wright County DFM site. The "runoff coefficient" for the IESF was similar to the average "runoff coefficient" measured at the nine DFM sites, suggesting that episodic rainfall-induced tile flows at this IESF site were comparable to other locations in Minnesota. The rainfall depth and drain tile flow depth for the IESF site, nine DFM sites, and the Wright County DFM site for June through November are also shown in Figure 15. The IESF data are consistent with the best-fit linear regression of the DFM data, further suggesting that episodic rainfall-induced drain tile flow characteristics of the IESF site are consistent with other agricultural sites across Minnesota. When compared directly to the Wright County DFM site, the IESF site exhibited similar drain tile flow depth but less rainfall depth and thus a larger "runoff coefficient" as shown in Figure 15 and Table 2.

Figures 16 and 17, and Tables 3 and 4 provide statistics and summaries of 2015 and 2016 events, respectively, in which the iron enhanced sand filter (IESF) was monitored for total phosphorus and phosphate capture performance. By definition, the concentration of a flow-weighted composite sample is equivalent to the EMC (Erickson et al. 2013). For this project, flow-weighted composite samples were analyzed and the influent EMC was found to vary from 18.3 to 358 µg/L. The flow-weighted average phosphate EMC was 162.3 µg/L for 31 events. The flow-weighted average EMC is equivalent to the total load (e.g., 956.1 g) divided by the total flow volume (208,041 ft^3 = 5,891,065 L) for all the rainfall events. For comparison, the EMC in the effluent samples varied from 8.1 to 126.6 µg/L with a flow-weighted average of 58.6 µg/L. All events exhibited positive capture (i.e., effluent EMC < influent EMC) of phosphate, likely due to chemical reactions between the iron oxide surfaces in the IESF and phosphate in the water. As the iron rusts and becomes iron oxide, phosphate can sorb to the surface of the iron oxide and become captured within the IESF.

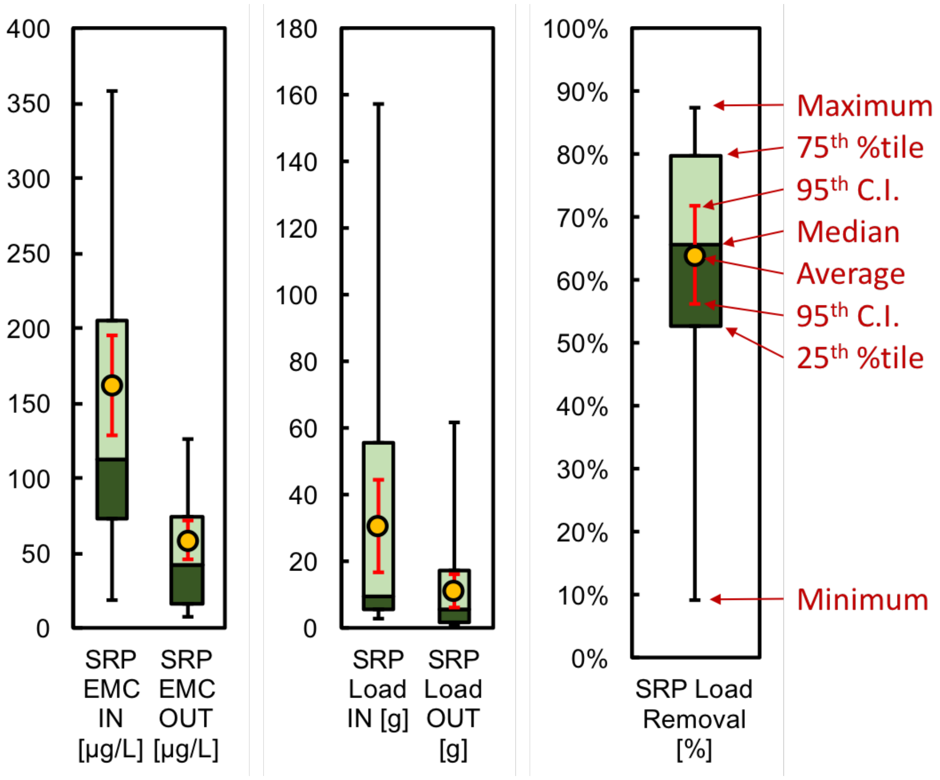

Figure 16. Phosphate (SRP) EMC, load, and load capture (%) statistics. Note: %tile = Percentile and C.I. = Confidence Interval

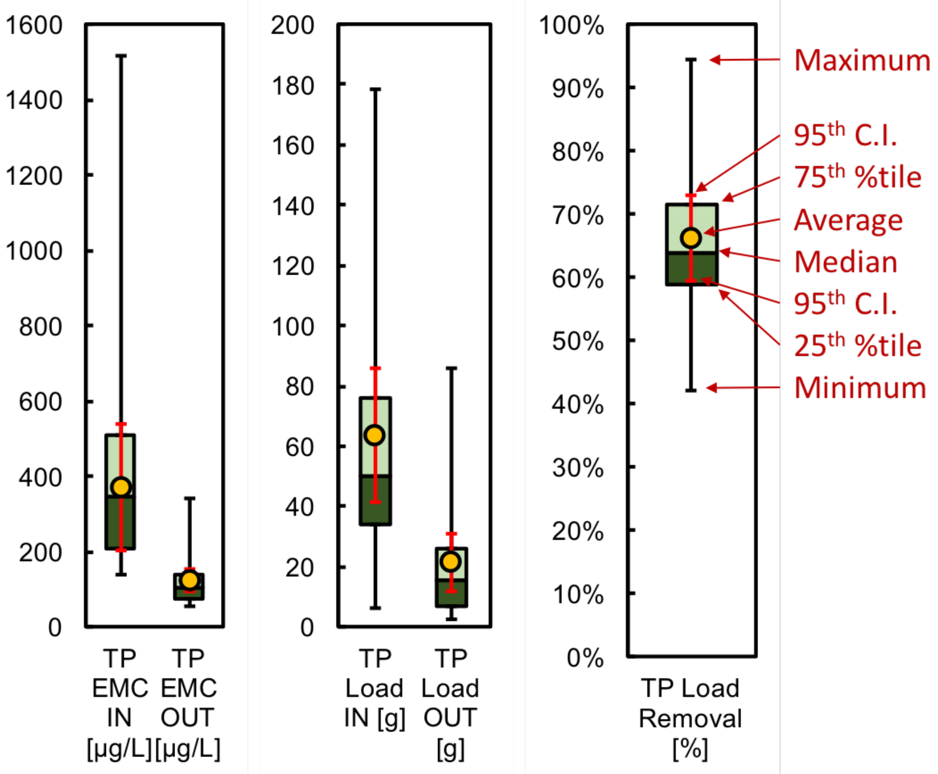

Figure 17. Total phosphorus (TP) EMC, load, and load capture (%) statistics. Note: %tile = Percentile and C.I. = Confidence Interval

Table 3. Monitoring Results Summary for 2015. N/D = No Data.

				Phosphate				
Rainfall Start	**Rainfall depth [in]**	**Flow Volume IN [ft^3]**	**Percent Exceedance by Filtered Volume**	**EMC IN [µg/L]**	**EMC OUT [µg/L]**	**Load IN [g]**	**Load OUT [g]**	**Load Capture [%]**
7/6/15	1.54	4,803	47%	68.0	13.9	9.2	1.9	**80%**
7/16/15	1.9	17,019	3%	238.3	42.0	114.8	20.2	**82%**
7/24/15	0.78	2,801	75%	54.1	8.1	4.3	0.6	**85%**
7/28/15	0.73	3,601	66%	55.6	11.8	5.7	1.2	**79%**
10/8/15	0.7	1,000	100%	100.2	15.1	2.8	0.4	**85%**
10/23/15	1.29	3,715	63%	68.4	16.7	7.2	1.8	**76%**
10/27/15	1.46	11,408	16%	211.8	96.5	68.4	31.2	**54%**
10/30/15	0.39	10,204	22%	201.9	88.8	58.3	25.7	**56%**
11/2/15	N/D	5,601	41%	145.1	55.6	23.0	8.8	**62%**
11/6/15	N/D	2,000	88%	102.3	53.4	5.8	3.0	**48%**
11/11/15	0.81	3,801	56%	122.7	52.7	13.2	5.7	**57%**
11/13/15	0.4	3,801	59%	112.0	65.4	12.1	7.0	**42%**
11/16/15	1.79	16,812	6%	132.2	63.2	62.9	30.1	**52%**
2015 Arithmetic Average =	**1.07**	**6,659**				**29.8**	**10.6**	
2015 Flow-Weighted Average =				**158.2**	**56.1**			
2015 Totals =	**11.8**	**86,567**				**387.9**	**137.6**	
2015 Load Capture Efficiency ± 95% Confidence Interval								**64.5% ± 9.4%**

Table 4. Monitoring Results Summary for 2016. N/D = No Data; Percent Exceedance is by Filtered Volume IN.

				Phosphate					**Total Phosphorus**				
Rainfall Start	**Rainfall depth [in]**	**Flow Volume IN [ft^3]**	**Percent Exceedance**	**EMC IN [µg/L]**	**EMC OUT [µg/L]**	**Load IN [g]**	**Load OUT [g]**	**Load Capture [%]**	**EMC IN [µg/L]**	**EMC OUT [µg/L]**	**Load IN [g]**	**Load OUT [g]**	**Load Capture [%]**
5/23/16	1.93	13,611	9%	20.8	17.3	8.0	6.7	**17%**	168.7	62.7	65.0	24.2	**63%**
5/27/16	0.3	6,802	31%	18.3	16.6	3.5	3.2	**9%**	213.5	109.8	41.1	21.1	**49%**
6/3/16	0.36	2,200	84%	89.1	13.8	5.6	0.9	**85%**	752.4	60.0	46.9	3.7	**92%**
6/12/16	0.74	1,400	97%	95.3	17.0	3.8	0.7	**82%**	1,516.4	83.0	60.1	3.3	**95%**
6/17/16	0.16	2,400	78%	78.0	15.5	5.3	1.1	**80%**	186.9	63.4	12.7	4.3	**66%**
7/5/15	1.89	7,405	25%	N/D	N/D	N/D	N/D	N/D	241.3	73.8	50.6	15.5	**69%**
7/10/16	0.62	1,600	94%	80.4	16.1	3.6	0.7	**80%**	138.4	56.4	6.3	2.6	**59%**
8/10/16	2.88	7,209	28%	358.3	109.5	73.1	22.4	**69%**	488.0	184.8	99.6	37.7	**62%**
8/12/16	0.07	6,402	34%	291.8	100.0	52.9	18.1	**66%**	373.5	135.0	67.7	24.5	**64%**
8/19/2016a	1.03	3,004	72%	284.2	84.8	24.2	7.2	**70%**	575.7	148.2	49.0	12.6	**74%**
8/19/2016b	0.46	17,211	0%	322.2	126.6	157.0	61.7	**61%**	365.8	176.4	178.3	86.0	**52%**
8/23/16	0.05	2,200	81%	132.2	63.5	8.2	4.0	**52%**	324.1	117.6	20.2	7.3	**64%**
8/27/16	0.21	1,800	91%	96.0	12.0	4.9	0.6	**87%**	755.7	79.0	38.5	4.0	**90%**
8/29/16	1.87	10,615	19%	252.5	55.9	75.9	16.8	**78%**	421.2	97.9	126.6	29.4	**77%**
8/31/16	1.28	13,606	13%	180.2	84.0	69.4	32.4	**53%**	307.2	128.6	118.3	49.6	**58%**
9/6/16	0.03	6,203	38%	208.8	94.2	36.7	16.6	**55%**	376.3	142.0	66.1	24.9	**62%**
9/9/16	0.02	5,401	44%	151.5	39.0	23.2	6.0	**74%**	294.4	99.4	45.0	15.2	**66%**
9/15/16	0.33	4,401	53%	N/D	N/D	N/D	N/D	N/D	1,166.4	342.5	145.3	42.7	**71%**
10/16/16	0.34	3,401	69%	50.2	42.3	4.8	4.1	**16%**	183.3	106.2	17.6	10.2	**42%**
10/18/16	N/D	4,601	50%	62.0	35.0	8.1	4.6	**43%**	141.8	78.1	18.5	10.2	**45%**
2016 Arithmetic Average =	**0.77**	**6,074**				**31.6**	**11.5**				**63.7**	**21.5**	
2016 Flow-weighted Average =				**165.2**	**60.3**				**370.3**	**124.7**			
2016 Totals =	**14.6**	**121,474**				**568.2**	**207.5**				**1,273.6**	**429.0**	
2016 Load Capture Efficiency ± 95% Confidence Interval								**63.5% ± 12.2%**					**66.3% ± 6.7%**

Flow volume, phosphate EMC and load for each event in 2015 and 2016 are shown in Figures 18 and 19. The influent phosphate EMC for all events in 2015 was less than 250 µg/L, though most events were less than 150 µg/L (Figure 18). The effluent EMCs, however, were less than 100 µg/L and most were less than 70 µg/L. By contrast, the influent EMC for one event in 2016 exceeded 350 µg/L and several events had influent EMCs of 200 – 350 µg/L. Only two events in 2016 had effluent EMCs that exceeded 100 µg/L and more than half of the events (10 out of 18) had effluent EMCs less than 50 µg/L. This reveals that the influent phosphate EMCs increased from 2015 to 2016, but the effluent EMCs were nearly the same.

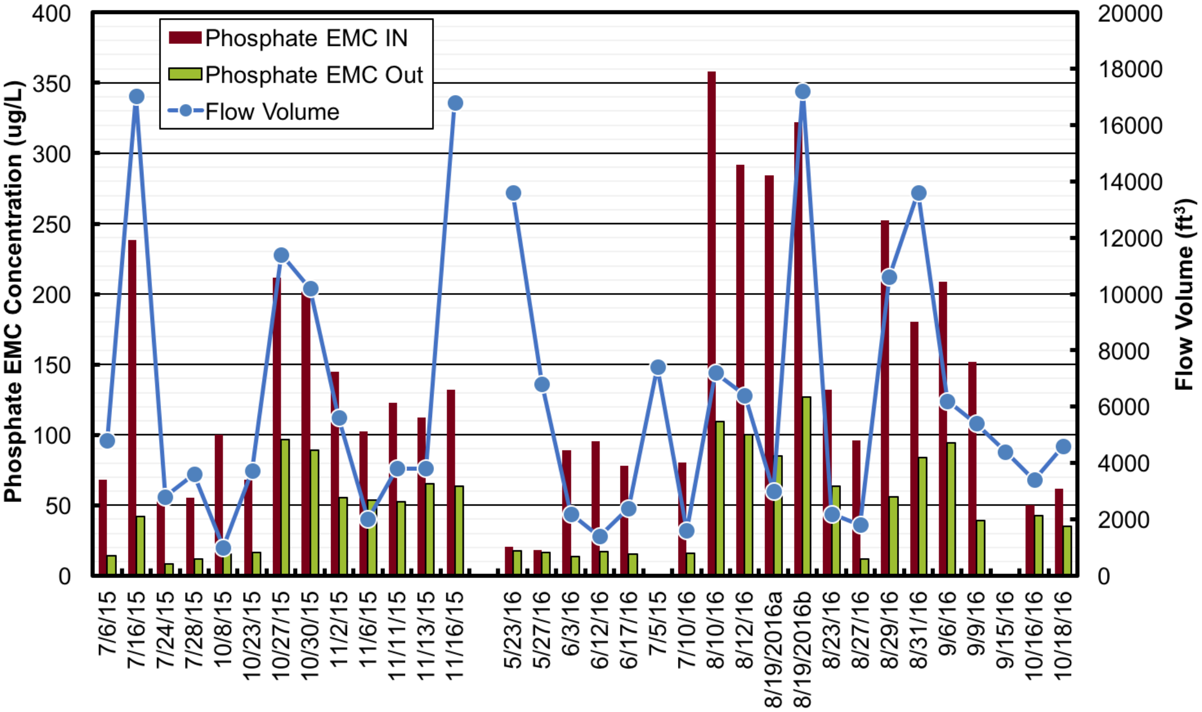

Figure 18. Flow volume, phosphate EMC influent and effluent for 2015 and 2016.

The phosphate load (load = EMC x flow volume) decreased for all events during the 2015 and 2016 monitoring seasons. The influent phosphate load varied from 2.8 to 157 grams per event with a flow-weighted average load of 42.3 grams per event and a total influent load of 956.1 grams. The effluent load varied from 0.4 to 61.7 grams per event with a flow-weighted average of 15.6 grams per event and a total effluent load of 345.1grams. The phosphate capture performance can be expressed as the percent reduction in phosphate load between the influent and effluent (Erickson et al. 2013). For this study, the load reduction for each event varied from 9% to 87% for 31 events with an overall phosphate load reduction of 63.9% and a 95% confidence interval of ± 7.7%. This suggests that there is 95% confidence that the phosphate load reduction is 63.9% ± 7.7%.

The influent phosphate load for all events in 2015 and 2016 was 956.1 grams (Table 1). A substantial portion of that load (271.9 grams, 28%) was contributed by two events: 8/19/16b in

2016 (157 grams) and 7/16/15 in 2015 (114.8 g), as shown in Figure 19. These two events only contributed approximately 16.5% of the flow volume (34,230 ft^3). Seven other events each contributed between 50 and 80 grams of phosphate load in 2015 and 2016, which accounts for approximately 461 grams (48%) of the overall influent phosphate load and 36.7% of the flow volume (76,257 ft^3). Thus, nine of the 31 events (29%) contributed approximately 76.7% of the influent phosphate load and 53.1% of the flow volume. This shows that a relatively small number of large events contributed most the phosphate load and flow volume.

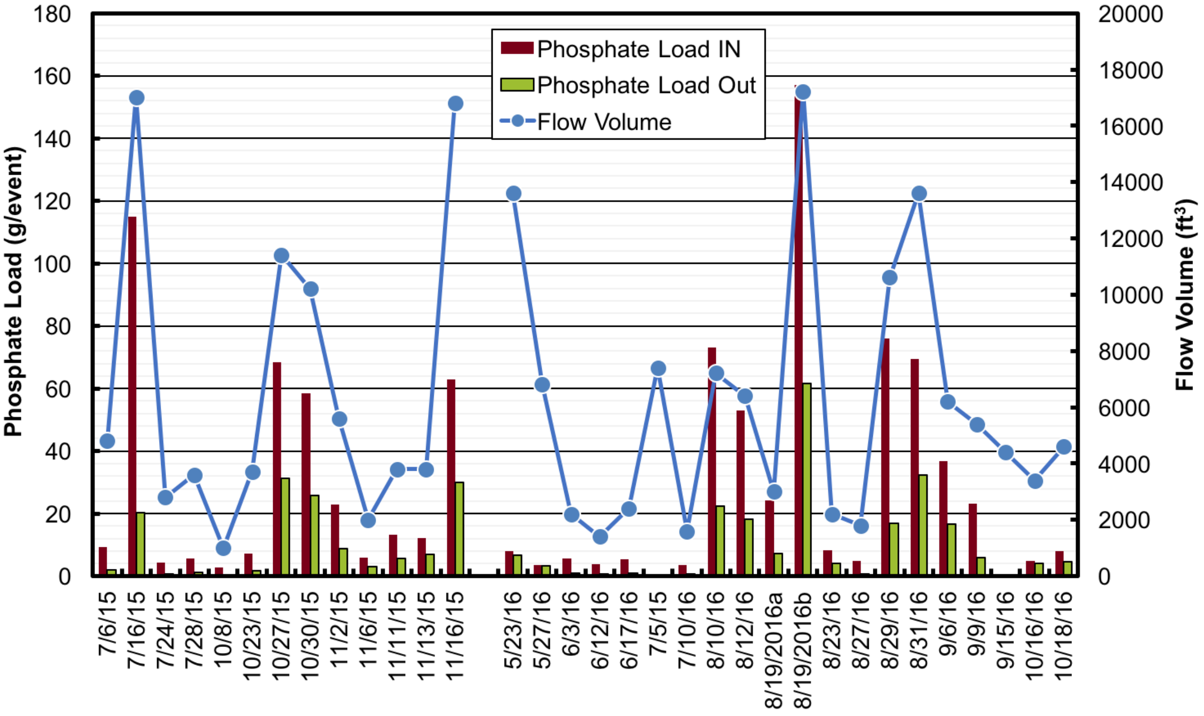

Figure 19. Flow volume, phosphate influent and effluent load for 2015 and 2016.

Flow volume, total phosphorus EMC and load for each event in 2015 and 2016 are shown in Figures 20 and 21. Total phosphorus EMC varied from 138.4 to 1,516 µg/L in the influent samples with a flow-weighted average of 370.3 µg/L for 20 events, all of which were in 2016. For comparison, the EMC in the effluent samples varied from 56.4 to 342.5 µg/L with a flow-weighted average of 124.7 µg/L. All events exhibited positive total phosphorus capture (i.e., effluent EMC < influent EMC). Similarly, the total phosphorus load also decreased for all events. The influent total phosphorus load varied from 6.3 to 178.3 grams per event with a flow-weighted average load of 74.3 grams per event and a total influent load of 1,273.6 grams. The effluent load varied from 2.6 to 86 grams per event with a flow-weighted average of 26.4 grams per event and a total effluent load of 429.0 grams. The total phosphorus load reduction for each event varied from 42% to 95% for 20 events with an overall total phosphorus load reduction of 66.3% and a 95% confidence interval of ± 6.7%. This suggests that there is 95% confidence that the total phosphorus load reduction is 66.3% ± 6.7%. A discussion of soluble, particulate, and total phosphorus capture is provided in the section Soluble Fraction below.

For total phosphorus (Figure 20), two events had influent EMCs greater than 1000 µg/L, but most events had influent EMCs between 200 and 800 µg/L. By contrast, only one event had an effluent EMC greater than 200 µg/L and approximately half of the events (9 out of 20) had effluent EMCs less than 100 µg/L for total phosphorus. This shows that the IESF exhibited positive performance for total phosphorus capture, likely due to chemical reactions with the soluble phosphorus fraction (phosphate) and particulate capture by the filter media.

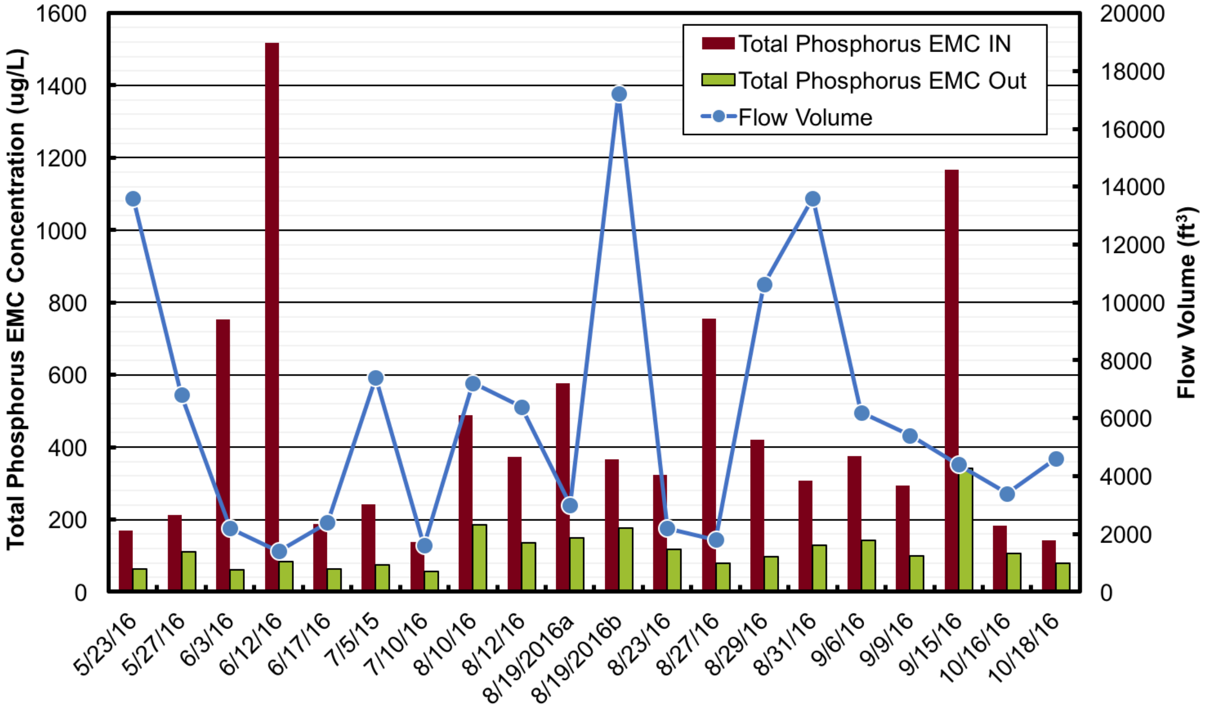

Figure 20. Flow volume, total phosphorus EMC influent and effluent for 2015 and 2016.

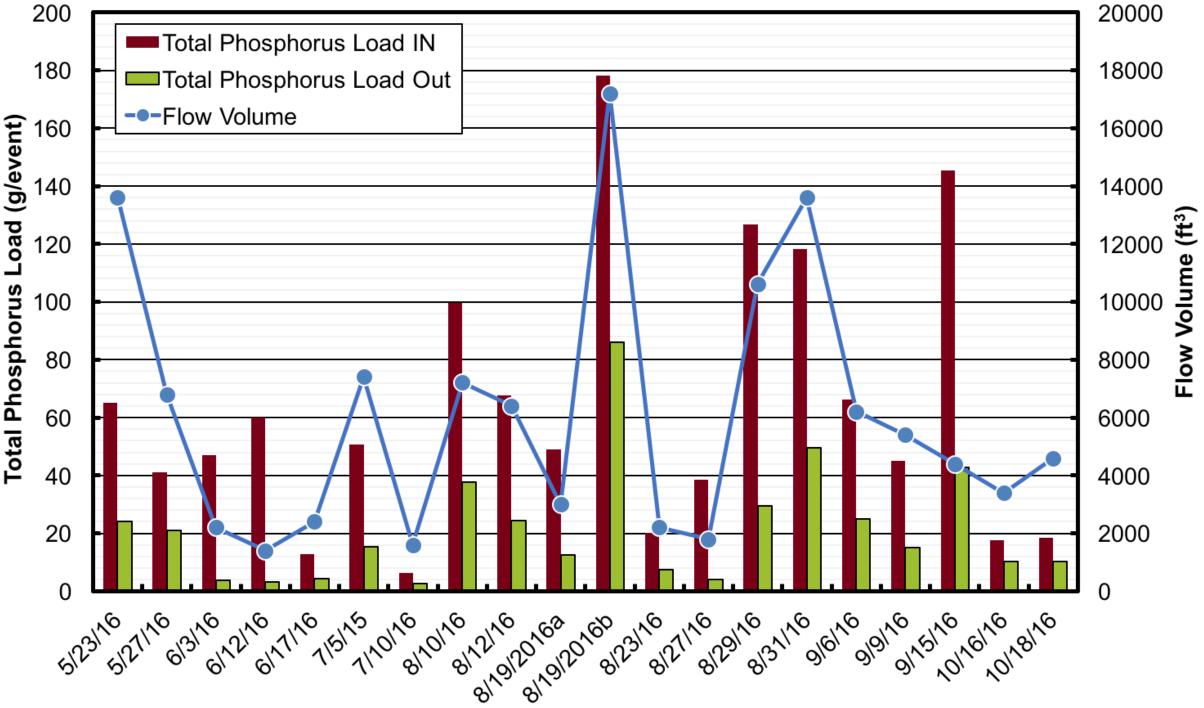

Figure 21. Flow volume, total phosphorus influent and effluent load for 2015 and 2016.

Total phosphorus was not measured in samples from 2015, but the total phosphorus influent load for all 2016 events was 1,273.6 grams (Table 1). If this load is attributed to the entire 18.4-acre contributing watershed, the total phosphorus load per land area is approximately 0.15 lbs/ac (2.8 lbs / 18.4 ac). This load only represents load from flows between June and November 2016, and excludes any load that may have been contributed by non-sampled events (see Figures 27 & 28) and events prior to June 2016 and after November 2016. Thus, the 2016 water year (October 2015 - September 2016) total phosphorus load for the IESF site is expected to be greater than 0.15 lbs/ac. By comparison, ten Discovery Farms Minnesota (DFM) sites reported total phosphorus loads for the entire 2016 water year ranging from 0.01 to 0.14 lbs/ac for tile drainage flow (DFM 2017). The IESF site appears to be contributing more total phosphorus load per acre in tile drain flow than the DFM sites.

A substantial portion of the influent total phosphorus load (323.6 grams, 25%) was contributed by two events: 8/19/16b (178.3 grams) and 9/15/16 (145.3 grams), as shown in Figure 21. These two events contributed approximately 17.8% of the flow in 2016. Three other events each contributed between 100 and 130 grams of total phosphorus load, which accounts for approximately 344.6 grams (27%) of the overall influent total phosphorus load and 26% of the flow volume (31,430 ft^3). Thus, five of the 20 events (25%) contributed approximately 52.5% of the influent total phosphorus load and 43.7% of the flow volume. This shows that a relatively small number of large events contributed most the total phosphorus load and flow volume.

Influent and effluent EMCs are not enough to describe the performance of a treatment practice because it does not account for the flow volume. For example, rainfall events on 8/10/16, 8/12/16, 8/19/16a, and 8/19/2016b had approximately similar EMCs as shown in Figure 18 (275 – 375 µg/L). These events, however, had very different phosphate loads as shown in Figure 19 (25 - 160 g/event) because the flow volume for these events varied by over a factor of 5. The event on 8/19/16b had more than twice the phosphate load compared to the other three events. For total phosphorus (Figures 20 and 21), the influent EMC for the event on 6/12/16 was four times greater than the EMC for the event on 8/19/16b, but the influent load was three times greater on 8/19/16b compared to 6/12/16. This illustrates the importance of using multiple metrics when determining performance.

The concentrations in the automatically-collected samples are consistent with the grab samples for both phosphate (Figures 11 and 18) and total phosphorus (Figure 12 and 20). Phosphorus capture performance cannot be calculated from the grab samples without accurate flow measurement, but the grab sample concentrations can be used to provide some knowledge of the concentrations before, during, and after monitoring equipment was installed. For example, monitoring equipment was not installed until June 2015, but grab samples were collected in March and April of 2015. Thus, grab samples provide additional supporting information about the influent and effluent concentration characteristics. For verification, the concentrations of the grab samples in July 2015 (~50 – 250 µg/L) are consistent with flow-weighted composite samples collected by the automatic samplers in July 2015.

Cumulative rainfall and 5-min average flow rate data for the rainfall event on 7/16/2015 are shown in Figure 22. This data are similar in shape to many events measured during this study in that approximately 30 minutes after rainfall began, the flow rate increased quickly in response. Once the flow rate peaked, most events exhibited a sharp initial decrease in flow rate followed by a more gradual decrease in flow rate until baseflow was reached or another rainfall event occurred. Most events were one to three days in length, as described in Tables 1, 3, and 4. Some events occurred sequentially (i.e., back to back) in response to a single large rainfall or multiple rainfalls that occurred before baseflow was reached. Figures similar to Figure 22 are provided in Appendix A for all events in Tables 3 and 4.

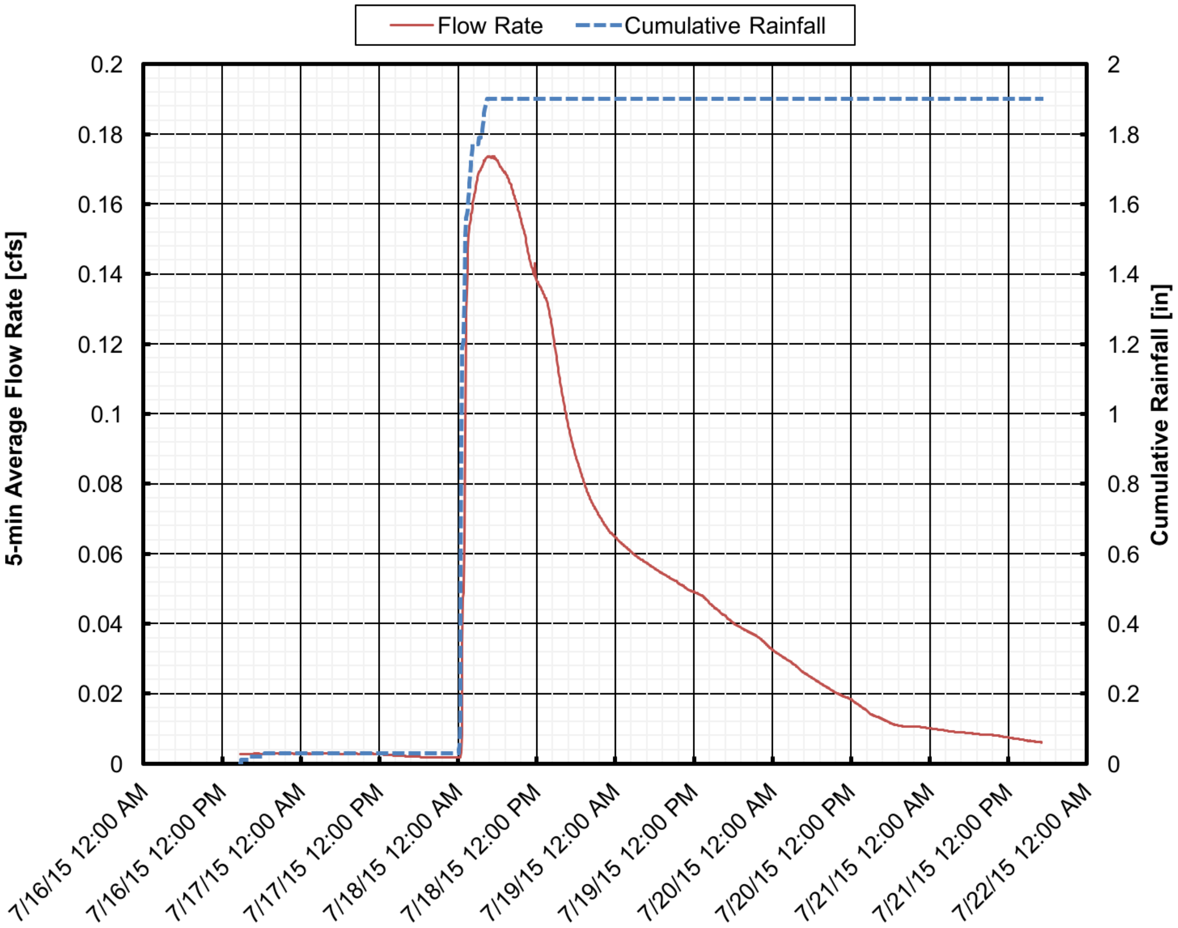

Figure 22. Flow rate and cumulative rainfall during rainfall event on 7/18/15.

Performance by Event Size

Some performance metrics organize events by size (large vs. small) to illustrate performance trends (e.g., percent exceedance; Erickson et al. 2013). Events measured in this study were sorted from largest to smallest flow volume and performance is plotted as a function of event size in Figures 23 – 25. The rainfall and flow volume are shown in Figure 23, ranked from largest to smallest by flow volume. Events with low ranks are large events (e.g., #1 largest, #2 largest, etc.) and events with high ranks are small events (e.g., #30 largest, etc.).

As shown in Figure 23, flow volume decreases consistently from large events to small events, but rainfall depth varies. For example, some events will have small values of rainfall depth but moderate values of flow volume (e.g., events 12, 13, and 15) which is in part because some events are continuations of previous rainfall events.

Phosphate influent and effluent loads and load reduction (as percent) are shown plotted against event rank in Figure 24 and it appears there is a correlation between influent load and event size. It is important to note, however, that Event Size (horizontal axis) and Event Load (vertical axis) are both directly related to the flow volume, which means the axes are cross-correlated and expected to show a relationship. Total phosphorus loads and load reduction are shown in Figure 25, though no apparent correlation exists between these and event size.

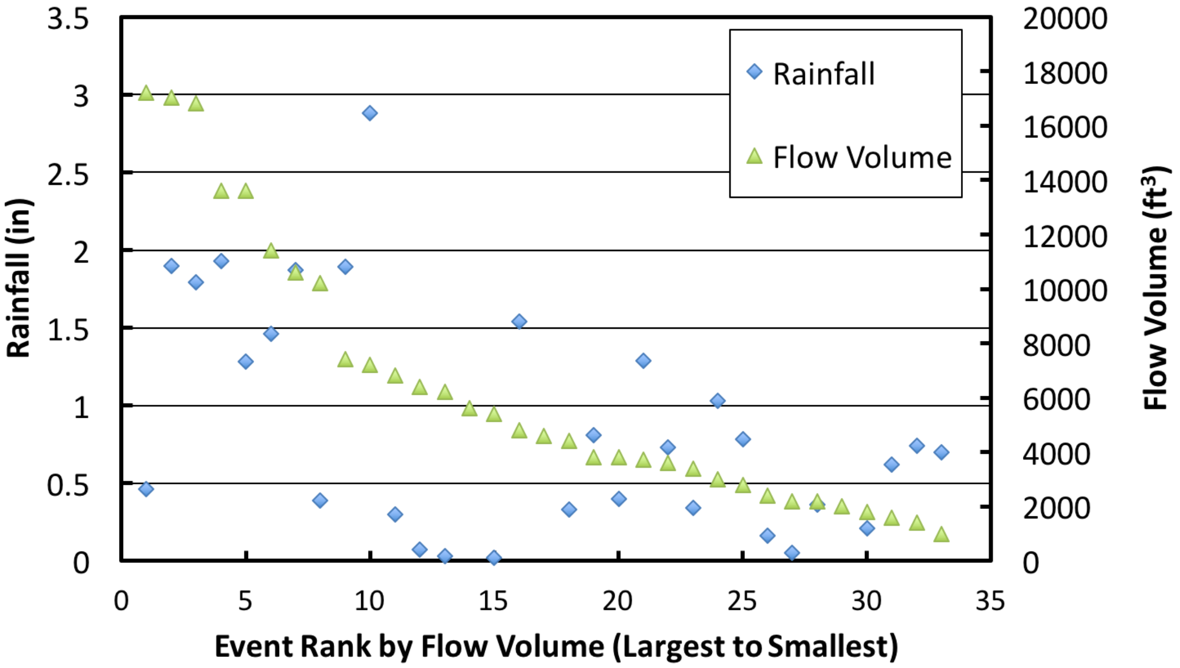

Figure 23. Rainfall depth and Flow Volume by Event Size

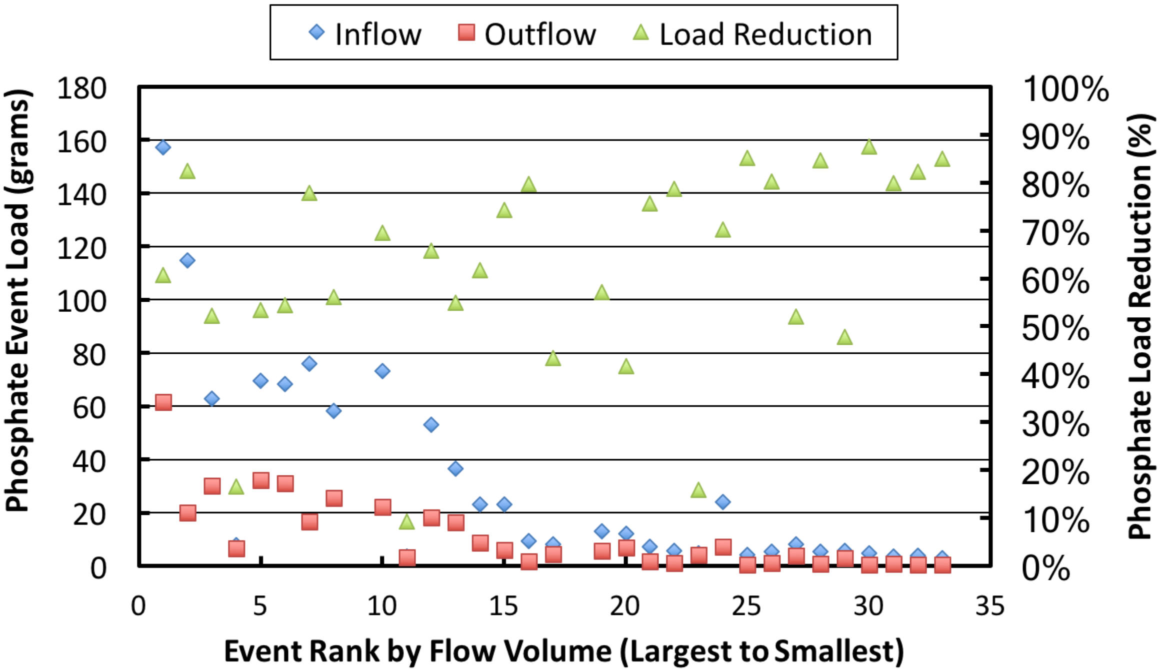

Figure 24. Phosphate load and load reduction by Event Size

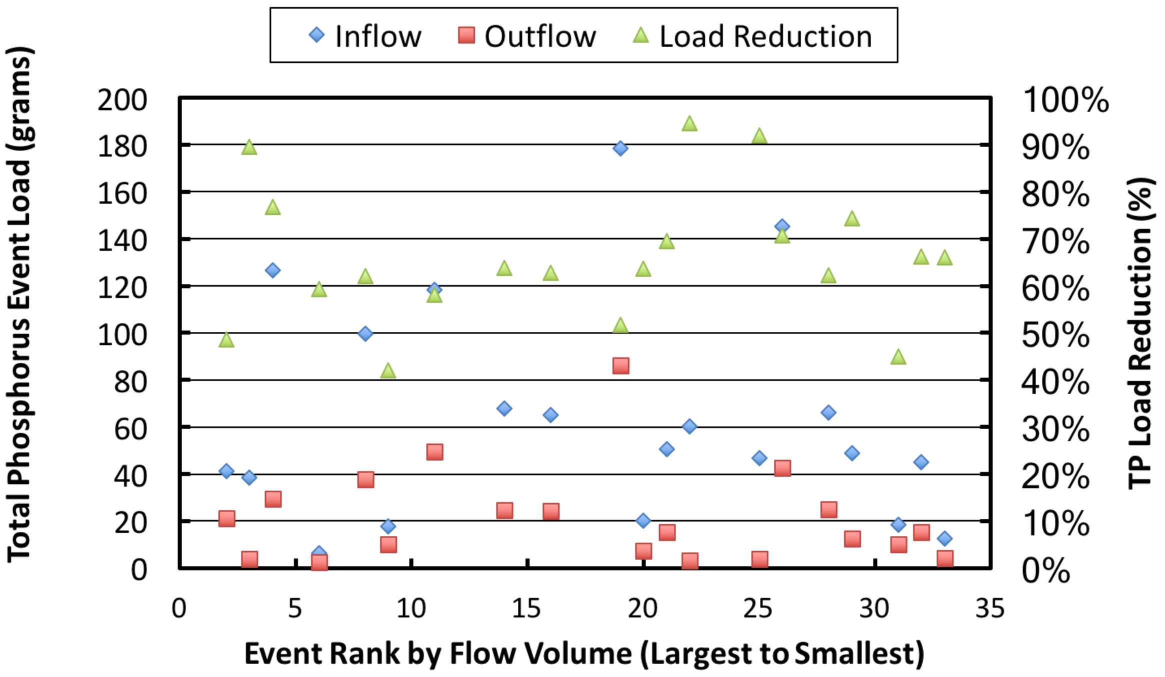

Figure 25. Total Phosphorus load and load reduction by Event Size

Soluble Fraction

A pollutant can either exist in soluble phase (e.g., molecule) or in particulate phase (e.g., sand grain). Thus, the total concentration is the sum of the soluble concentration and particulate concentration. The soluble phase of a pollutant is operationally defined as smaller than 0.45 µm in size (APHA 1998). The difference between the soluble concentration and the total concentration (total concentration - soluble concentration) is the particulate concentration, which are particles larger than 0.45 µm in size. The soluble fraction is calculated by dividing the soluble concentration by the total concentration. When evaluating performance of a stormwater control measure such as the IESF studied in this project, calculating the soluble fraction can provide insight into the relative performance of the different treatment mechanisms. For IESFs, particulates are captured by physical sieving on the surface and within the media of the filter. A portion of the soluble phase of phosphorus (soluble reactive phosphorus, or phosphate) will react with the iron within an IESF and become captured within the filter.

Figure 26 shows summary statistics of the soluble fraction in percent for both the rainfall event samples and grab samples collected throughout this project. For the rainfall event samples, the influent soluble fraction varied from approximately 5% to 90%, with an average of 43%, which is similar to values measured in urban stormwater (Erickson et al. 2007, 2012). The effluent varied from approximately 15% to 75% with an average of 44%. For comparison, nine Discovery Farms Minnesota (DFM) sites reported an average of 60% soluble fraction for tile drainage flow samples collected between 2011 and 2016.

Performance data previously discussed in the Rainfall Event Performance section of this report show that phosphate and total phosphorus were captured by the IESF. It is likely that both particulate and soluble phosphorus (phosphate) were captured by the IESF and it is also likely that this occurred at approximately the same rate because 1) the IESF showed positive capture of soluble and total phosphorus, 2) the average soluble fraction of influent and effluent were similar (i.e., 43 and 44%, respectively), and 3) the variability in soluble fraction decreased from the influent to the effluent.

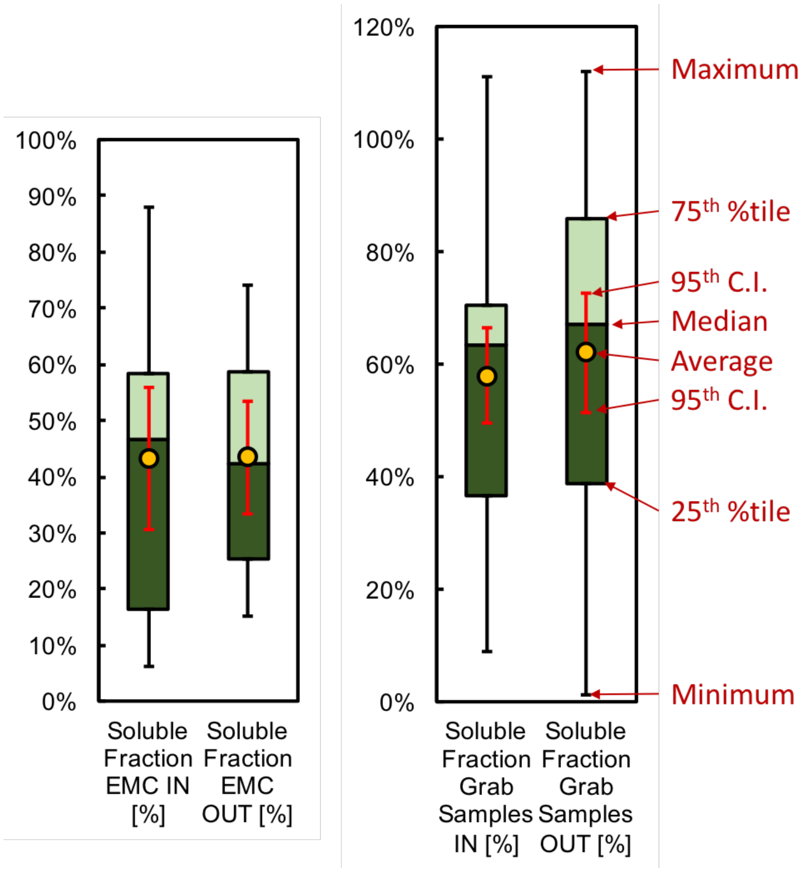

Figure 26. Rainfall event sample (left) and grab sample (right) data for the soluble fraction of phosphorus. Note: %tile = Percentile and C.I. = Confidence Interval

When considering the grab sample data (Figure 26, right), the soluble fraction varied from approximately 10% to 110% in the influent with an average of 58%. The effluent grab sample soluble fraction varied from approximately 1% to 110% with an average of 62%. The reason the soluble fraction in some grab samples was greater than 100% was because the measured soluble (phosphate) concentration was greater than the measured total concentration. There is no physical explanation for this condition, and it is attributed to measurement error as reported from the laboratory. One possible explanation is changes in the laboratory operating procedure or equipment used for analysis of the grab samples, though this is unconfirmed.

Baseflow Performance

Urban watersheds typically produce runoff in response to rainfall events within a few minutes to a few hours, and runoff typically persists for a few hours to a few days. By contrast, agricultural watersheds can produce drain tile flow whenever there is excess soil moisture. As a result, this project measured drain tile flow near-continuously when monitoring equipment was operational at the site. It is unclear whether this is typical, or if rainfall and runoff characteristics for 2015 and 2016 were unusual. It is also unclear if or to what extent the upstream wetland affected the flow conditions during the monitoring study. Flow data were separated into rainfall event flow and baseflow, as described in the Flow Rate Measurement section above. Figures 27 and 28 show all flow data that were collected as well as rainfall event data (for sampled and non-sampled events) and baseflow data.

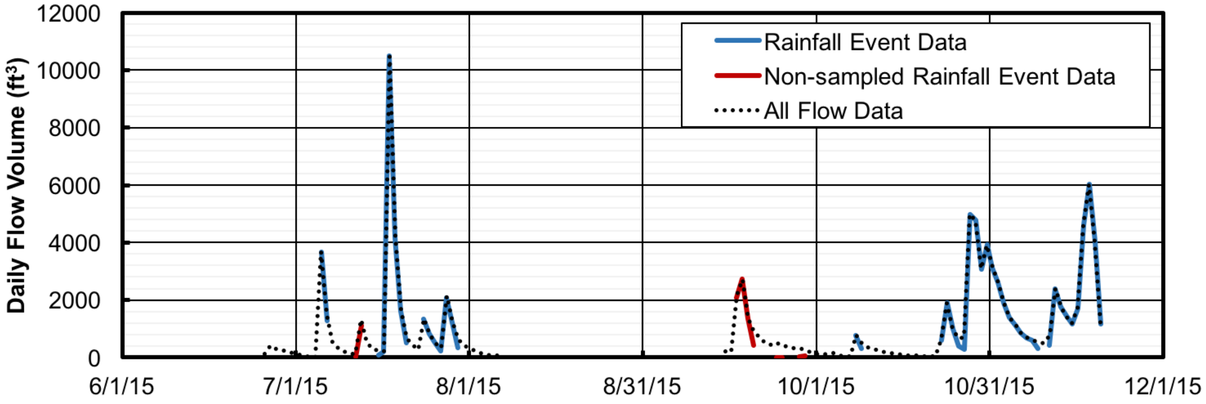

Figure 27. All flow data (daily flow volume) including rainfall event flow (blue) and non-sampled rainfall event flow (red) data for 2015 rainy season. Flow not identified as rainfall event flow is baseflow.

In 2015, several rainfall events were not captured by the monitoring equipment (e.g., 9/18/15) due to equipment failure, excessive downstream flooding, interference from frogs and/or other animals, among others. In addition, some events are listed in Table 3 as discrete events but are sequential as shown in Figure 27 (e.g., 11/11/15, 11/13/15, and 11/16/15). In 2015, approximately 111,839 ft^3 (3167 m^3) of flow was measured through the iron enhanced sand filter (IESF) from June 26th to November 20th. Of this flow, approximately 87,911 ft^3 (2489 m^3) was rainfall event flow in which samples were collected (Table 3), approximately 7,806 ft^3 (221 m^3) was non-sampled rainfall event flow, and approximately 16,122 ft^3 (457 m^3) was baseflow. This corresponds to approximately 86% rainfall event flow (7% non-sampled) and 14% baseflow.

Several rainfall events were also not captured by the monitoring equipment in 2016, as shown in Figure 28 (e.g., 6/15/15, 8/4/15). Equipment failure, flow exceeding the calibration range, and a vehicular collision with the Agri Drain unit contributed to loss of data. Similar to 2015, some events are listed in Table 4 as discrete events but are sequential as shown in Figure 28 (e.g., 8/10/16 and 8/12/16). In 2016, approximately 225,606 ft^3 (6388 m^3) of flow was measured through the iron enhanced sand filter (IESF) from May 14th to November 7th. Of this flow, approximately 129,006 ft^3 (3653 m^3) was sampled rainfall event flow, 80,579 ft^3 (2282 m^3) was non-sampled rainfall event flow, and approximately 16,022 ft^3 (454 m^3) was baseflow. This corresponds to approximately 93% rainfall event flow (36% non-sampled) and 7% baseflow.

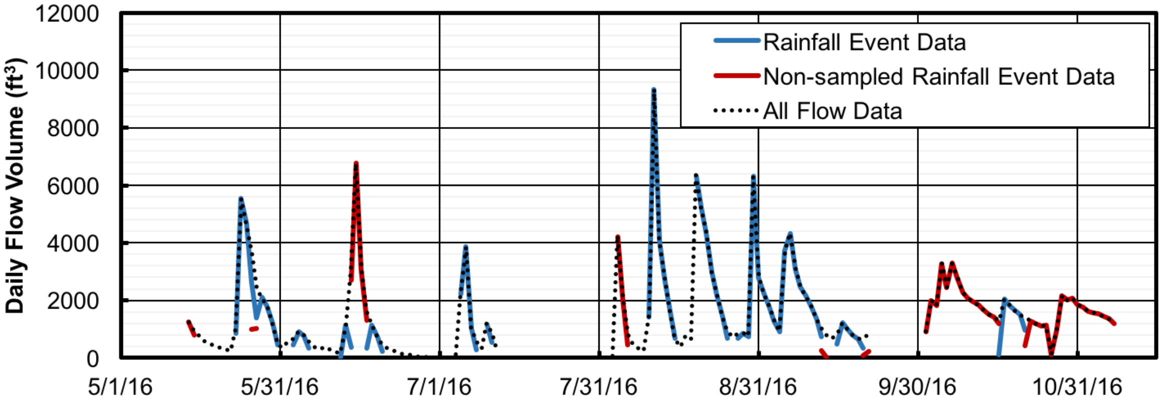

Figure 28. All flow data (daily flow volume) including rainfall event flow (blue) and non-sampled rainfall event flow (red) data for 2016 rainy season. Flow not identified as rainfall event flow is baseflow.

Approximately twice as much flow was measured in 2016 compared to 2015 and the percent of baseflow decreased (14% to 7%). The decrease in baseflow is expected because the increase in total flow is in response to more rainfall event flow, while the baseflow remained nearly identical (16,122 ft^3 in 2015 vs. 16,022 ft^3 in 2016). Overall, approximately 337,445 ft^3 (9555 m^3) of flow was measured through the IESF in 2015 and 2016. Of this, approximately 216,917 ft^3 (6142 m^3) was sampled rainfall event flow, 88,385 ft^3 (2503 m^3), and approximately 32,143 ft^3 (910 m^3) was baseflow, which corresponds to 90% rainfall event flow and 10% baseflow.

Hydraulic and Phosphate Loading Rate

A common metric for understanding the longevity of IESFs is the depth of water treated (Erickson et al. 2007, 2012). This depth represents the amount of water that has passed through the IESF since its construction, and indirectly represents the amount of phosphate that has been captured by the IESF. To calculate the treated depth, the total volume of water treated by the IESF is divided by the surface area of the IESF from the time it was constructed. The total volume of water treated can be estimated from the hydraulic loading rate, historical rainfall and flow data, and computer modeling of hydrologic processes.

The IESF in this study was constructed around October 30, 2012. Rainfall and flow data were not collected at the IESF until June 2015 and is thus unknown. Rainfall is measured, however, at a municipal airport (Buffalo, MN; KCFE) approximately 5.4 miles (8.7 km) northwest of the IESF. The rainfall data measured at KCFE is correlated to the rainfall data measured at the IESF during this project, as shown in Figure 29, and the correlation coefficient is acceptable (R^2 = 0.869).

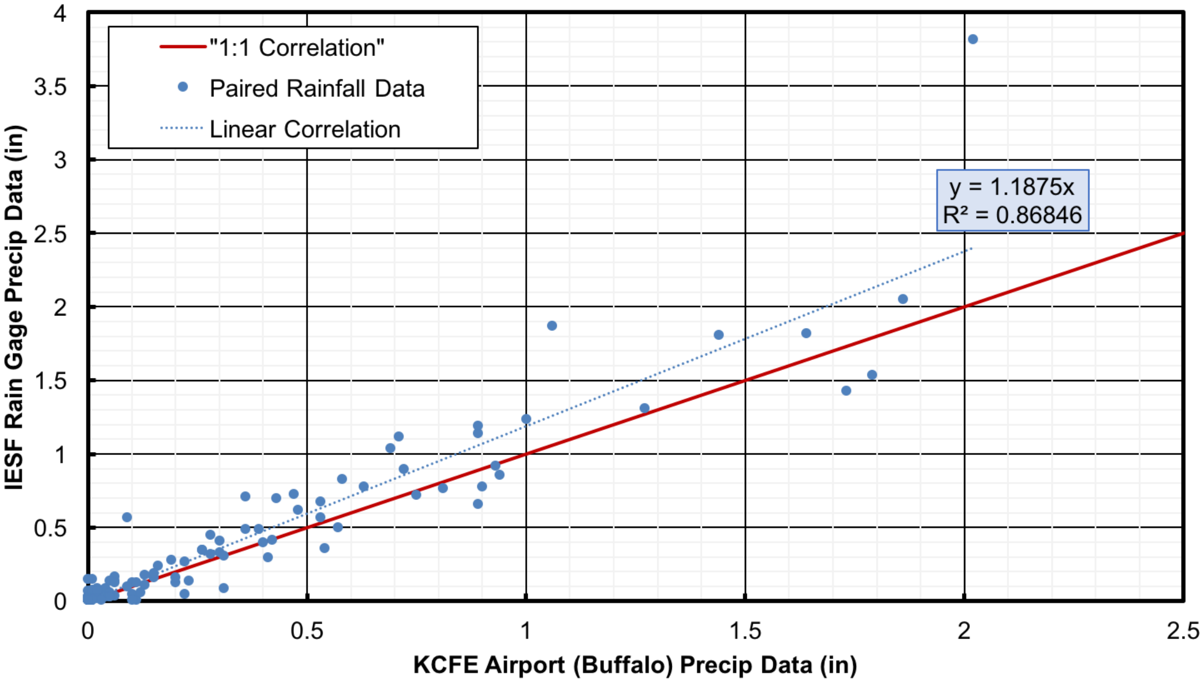

Figure 29. Relationship between rainfall data measured at IESF and rainfall data measured at Buffalo, MN Municipal airport (KCFE) for events between 6/26/15 and 10/29/16.

Using the correlation in Figure 29 as given in Equation (3), the rainfall at the IESF can be predicted from historical rainfall data at KCFE. Approximately 99.85 inches (253.6 cm) of precipitation fell at KCFE between October 30, 2012 and October 18, 2016, which can be extrapolated to precipitation depth of approximately 118.6 in (301.2 cm) at the IESF.

$$Rainfall_{IESF}=1.1875\left[Rainfall_{Buffalo\ Airport}\right] \tag{3}$$

The watershed contributing to the IESF studied in this project is approximately 18.4 acres. Multiplying this area by the rainfall depth (118.6 in) yields a predicted rainfall volume of approximately 7,900,000 ft^3 (224,000 m^3). As previously discussed in Rainfall Event Performance, an estimated drain tile flow "runoff coefficient" for this watershed is approximately 0.12. Applying this to the predicted rainfall volume yields an estimated drain tile flow volume of approximately 950,000 ft^3 (27,000 m^3), which corresponds to the total volume of water treated by the IESF since it was constructed.

The total volume of water treated by the IESF can be converted to a depth treated, which adjusts the volume for the size of the IESF and accounts for over- or under-sizing. Dividing the volume treated (950,000 ft^3) by the surface area of the IESF (1,000 ft^2; 92.9 m^2) yields a depth treated of approximately 950 ft (290 m). This exceeds previously tested limits of IESF performance (656 ft, 200 m; Erickson et al. 2007, 2012), and thus, could be in a range where reduced performance may exist.

Maintenance

Regular, routine maintenance began within one or two years of construction and consisted of Wright SWCD staff visiting the site once or twice per month to 1) remove vegetation, iron ochre, and algae from the IESF, and 2) scrape and level the surface as needed. These activities occurred during the months of May through September of each year and required one or two individuals less than approximately one hour each to complete per site visit. In addition, non-routine maintenance was needed in May 2016 to remove a substantial accumulation of vegetation, iron ochre, and algae from the surface and required two individuals for approximately 2 hours each.

Figure 30 is a picture of the IESF when it was ready for routine maintenance. Vegetation is growing in a few locations across the surface of the filter (to be removed). Iron ochre is a waste product from bacteria that oxidize dissolved minerals such as iron. Iron ochre is visible on the IESF as a rust colored sludge when wet (top left in the pooled water) and as a rust colored thin crust/cake when dry (bottom left). It is likely that the dissolved iron in the water from the tile drainage (Figure 9) was enough to support bacteria that produce iron ochre. It is possible that the dissolved iron in the tile drainage water is from a local a perched water table associated with side hill seeps or springs and/or the shallow wetland upstream of the IESF.

The accumulation of iron ochre and subsequent biofouling reduced the hydraulic capacity of the IESF in locations near the inlet, resulting in small pools of water between rainfall events. Algae (top left in the pooled water) sometimes grew within standing water on the IESF surface, and was also removed during routine maintenance. The combination of iron ochre, algae, and biofouling caused “creeping failure” on the surface of the IESF, moving slowly from the inlet towards the outlet. If vegetation, iron ochre, and algae were not removed during routine maintenance, accumulation would begin to clog the entire IESF surface and prevent treatment of influent water.

Figure 30. Iron Enhanced Sand Filter when maintenance is needed. (Note: the black perforated tile line on the surface of the IESF was used to distribute flow evenly across the surface, though it was unsuccessful because it became clogged with iron ochre. It was subsequently removed shortly after this picture was taken).

Application to Other Locations

The intention of this project was to measure the performance of an IESF with regards to the capture of total phosphorus and phosphate from episodic rainfall-induced agricultural tile drainage. The performance of this IESF is specific to this design, this location, and the period of time over which it was monitored. It is feasible, however, that IESF could be installed in other locations to capture total phosphorus and phosphate. To do so, there are several important design considerations which are listed below. A design example follows the list of considerations.

IESF Design Considerations:

- The IESF must be allowed to drain, and therefore the outlet of the underdrain system below the IESF must be placed above the high-water elevation of the downstream conveyance system and/or waterbody. This will prevent inundation of the filter.
- Intermittent flow onto the IESF is recommended. As the current study has shown, however, near-continuous flow may be allowable if the IESF continues to perform adequately.

- The IESF should be designed with 8% or less of iron by weight. Iron content greater than 8% may become clogged and not allow flow through the system (Erickson et al. 2010, 2012). Many IESF systems, including the one studied in this project, have used 5% iron by weight. In addition, it is recommended that the iron be mixed thoroughly with clean washed sand such as ASTM C33.
- The iron used in the IESF should be high purity (90%+ elemental iron) with little or no toxic impurities (e.g., copper, cadmium, lead, etc.). In addition, the iron should be reactive with phosphate. Iron and impurity content should be verified independently of the supplier to ensure purity and prevent the leaching of contaminants into the filtered runoff.
- For maintenance considerations, a filtration rate of 4 inches per hour vertically down and through the filter media can be used to estimate the IESF surface area needed to treat a known or estimated (peak) flow rate. The smaller the IESF surface area, the greater the frequency of required maintenance.
- For lifetime capacity considerations, a sorption capacity of 5 mg P per gram Fe (Erickson et al. 2012) can be used to estimate the amount of iron needed to treat a known or estimated phosphate load.

<u>Example Design Calculation:</u> An agricultural watershed may produce approximately 10 – 15% tile drainage flow. Assuming an annual precipitation of 30 inches and 15% tile drainage runoff, a 20-acre agricultural watershed may produce approximately 7.5 ac-ft of tile drainage per year.

$$20\ ac \times \frac{30\ inches\ per\ year}{12\ inches\ per\ ft} \times 15\% = 7.5\ ac - ft\ per\ year$$

Assuming an influent phosphate concentration of 100 μg/L (0.1 mg/L) and knowing that 1 mg P/L = 2.72 lb P/ac-ft, then approximately 2.04 lbs of phosphate would be contributed from the watershed per year.

$$\frac{7.5\ acre - ft}{year} \times 0.1\ mg/L \times \frac{2.72\ lb\ P/(acre - ft)}{1\ mg/L} = 2.04\ lbs\ P\ per\ year$$

Assuming a sorption capacity of 5 mg P per gram of Fe (5 lbs P per 1000 lbs Fe), then a 20-year lifetime would require approximately 8,160 lbs of Fe

$$2.04\ lbs\ P\ per\ year\ \times\ 20\ years = 40.8\ lbs\ P$$

$$\frac{40.8\ lbs\ P}{5\ lbs\ P\ per\ 1000\ lbs\ Fe} = 8{,}160\ lbs\ Fe$$

Assuming 5% iron by weight, then the total filter weight would be 163,200 lbs (155,040 lbs Sand + 8,160 lbs Fe). Assuming a bulk density of iron-sand media of approximately 110 lb/ft^3, the total filter media volume is approximately 1,484 ft^3 = 55 yd^3 (163,200 lbs / 110 lbs/ft^3). The peak flow rate could be measured for a specific site, or estimated using a Rationale method or other peak flow estimation technique. Assuming a peak flow rate of 0.2 cfs (8,640 in-ft^2/hour), the surface area of the IESF would be approximately 2,160 ft^2.

$$\frac{8{,}640\ in - ft^2\ per\ hour}{4\ inches\ per\ hour} = 2{,}160\ ft^2$$

With a total filter media volume of 1,484 ft^3 and a surface area of 2,160 ft^2, the media depth is approximately 0.687 ft (1,484 ft^3 / 2,160 ft^2 = 0.687 ft = 8.25 inches). It is often best to include extra filtration media to allow for years with higher phosphate concentrations, which will deplete the iron capacity more quickly. For this example, the media depth (8.25 inches) could be increased by 20% to 10 inches or by 45% to 12 inches. The amount of iron and sand would also be increased accordingly.

Conclusions

An iron enhanced sand filter (IESF) was installed in Wright County, MN upstream of Martha Lake in order to treat agricultural tile drainage to reduce soluble (phosphate) and total phosphorus loads received by the lake. For this study, grab samples were collected from 2012 through 2017, and monitoring equipment was installed to monitor IESF performance with regards to phosphorus capture during natural rainfall events and subsequent flow during the rainy seasons of 2015 and 2016. During the study period, 33 rainfall events were monitored and IESF capture performance was determined for phosphate and total phosphorus.

The rainfall depth of events measured from approximately June through November in 2015 and again in 2016 varied from 0.02 to 2.88 inches and totaled 26.4 inches. For these events, phosphate load reduction varied from 9% to 87% with a flow-weighted mean reduction of 63.9% ± 7.7% ($\alpha = 0.05$) for 31 events (2015 and 2016). For total phosphorus, load reduction varied from 42% to 95% with a flow-weighted mean reduction of 66.3% ± 6.7% ($\alpha = 0.05$) for 20 events (all in 2016). In addition, the influent soluble fraction for monitored rainfall events varied from approximately 5% to 90%, with an average of 43%. Influent and effluent grab sample concentrations were similar to influent and effluent concentrations of monitored natural rainfall events, indicating that phosphorus capture performance when grab samples were taken was likely similar to the performance observed during monitoring. This performance is specific to this IESF and this contributing area, which may not be applicable to other sites and designs.

Flow rate was measured and grab samples were collected between rainfall events to estimate baseflow contributions of phosphate and total phosphorus. For the study period, approximately 90% of the total flow volume corresponded to rainfall event flows and approximately 10% corresponded to baseflows. Samples were not collected from several events throughout the two-year period due to equipment errors, resulting in several non-sampled rainfall events (corresponding to approximately 26% of total flow).

Overall, the performance of the IESF in this study (63.9% ± 7.7% phosphate load reduction, 66.3% ± 6.7% total phosphorus load reduction) is comparable to other studies of IESFs. Laboratory experiments of IESFs in previous studies found an average of 88% phosphate capture with a total treated depth of 656 ft (200m) (Erickson et al. 2012). Field applications of an IESF trench after one year of operation exhibited an average of 60% phosphate load reduction for 7.2% iron by weight, and 78.8% phosphate load reduction for 10.7% iron by weight (Erickson et al. 2010). The amount of water treated by the IESF in this study from the time it was constructed until the end of the study (October 2012 - October 2016) was approximately 950 ft (290 m) of treated depth, which exceeds previously investigated treated depths (656 ft, 200 m; Erickson et al. 2007, 2012). It was observed that the effluent concentration of phosphate increased over the course of the study period, which may be an indication that the IESF capacity for phosphate capture has decreased over time. It is also important to note that this design may not perform similarly in other watersheds or locations.

Maintenance of the IESF consisted of 1) removal of vegetation, iron ochre, and algae and 2) leveling and scraping of the IESF surface. This occurred approximately once or twice per month during the growing season (May - September) of each year and each occurrence required typically less than one hour per person for one or two people. This level of maintenance was satisfactory to ensure proper flow and contact between the water and the IESF media and is expected to continue throughout the life of the IESF.

Products

This report represents the primary product and final deliverable under this contract and includes a description of the work completed and data collected. As requested, an electronic summary of all data for the EQuIS database has also been provided. In addition, at least two refereed journal publications will be published using data from this project:

1. Erickson, A.J., Gulliver, J.S., and Weiss, P.T. (2017, in preparation). "Phosphate Removal from Agricultural Drain Tile Flow with Iron Enhanced Sand." Journal of Water Special Issue: Additives in Stormwater Filters for Enhanced Pollutant Removal.
2. Erickson, A.J., Weiss, P.T., and Gulliver, J.S. (2017, accepted). "Monitoring and Maintenance of Phosphate Adsorbing Filters." Journal of Environmental Engineering Special Issue: Environment and Sustainable Systems: A Global Overview.

Preliminary results were disseminated in an October 2016 edition of UPDATES email newsletter (http://stormwater.safl.umn.edu/updates) distributed to more than 2400 subscribers. Another UPDATES article will be prepared and distributed with final results and recommendations from this project. In addition, a description of the project was published in the Board of Soil and Water Resources (BWSR) online newsletter, Snapshots, in January 2015.

Photos

Several photos are provided in this section to show the IESF studied as part of this project. Some photos have been submitted as separate files with this Final Report.

Figure 31. Construction: Excavation complete.

Figure 32. Construction: Impermeable liner.

Figure 33. Construction: iron aggregate spread across sand layer

Figure 34. Construction: iron aggregate being mixed with sand by rototiller. Note: Sheet plywood along perimeter to protect impermeable liner from rototiller blades.

Figure 35. Monitoring: Protective (green) cabinets holding monitoring equipment (ISCO 6712 automatic water sampler visible).

Figure 36. Monitoring: ISCO 6712 automatic water sampler (left), Campbell Scientific CR1000 datalogger (top right inside white box), and Raven XT cellular data modem (bottom left inside white box).

Figure 37. Monitoring: Texas Instruments rain gauge (white cylinder with gold lid) and cellular antenna (white cylinder).

Figure 38. Monitoring: Agri Drain Inline Water Level Control Structure^{TM} (black lid).

Figure 39. IESF after rainfall with standing water, vegetation, iron ochre, and algae. Black perforated distribution pipe shown on surface.

Long-term Results

Long-term Outcomes

This project addresses a widespread and substantial problem for Minnesota: removing excess phosphate and total phosphorus from drain tile flow delivered to surface water resources. Iron enhanced sand filtration (IESF) is one tool that can be used to capture phosphate and total phosphorus from urban runoff (Erickson et al. 2007, 2012) and from agricultural drain tile flow, as shown in this project. This project has the potential for substantial long-term outcomes if IESF can be adapted into more agricultural watersheds to reduce the amount of phosphate and total phosphorus entering surface water resources.

Partnerships and Alliances

This project would not have been possible without the partnership between the Minnesota Pollution Control Agency, Wright SWCD, and the University of Minnesota St. Anthony Falls Laboratory (SAFL). Wright SWCD and SAFL have already begun expanding their partnership by applying for more research and monitoring funding to continue to collect data at the IESF studied during this project. This will allow for continued learning of IESF for agricultural watersheds. In addition, Wright SWCD and SAFL have discussed other potential projects for this (IESF) and other water quality improvement technologies. It is anticipated that the conclusion of this project and dissemination of its results will lead to other partnerships with similar organizations tasked with treating discharge from agricultural watersheds.

Sharing of Results

In addition to the reports, journal publications, and email newsletter articles described above, the project or results have been, or will be, disseminated at the presentations listed below. It is estimated that these efforts have reached over 1000 participants, including watershed planners, municipal engineers, and consulting environmental or stormwater engineers.

1. Gulliver, J.S. “Gismos for Stormwater Treatment,” John S. Gulliver, Presentation to the Villanova Center for the Advancement of Sustainability in Engineering, Villanova University, Villanova, PA, July 14, 2014.
2. Gulliver, J.S. “Current and Unfolding LID and Stormwater BMP Research at the University of Minnesota,” Minnesota Water Resources Conference, St. Paul, MN, October 14-15, 2014.
3. Gulliver, J.S. “Stormwater Assessment and Maintenance: Resources and Tools,” A.J. Erickson and J.S. Gulliver (Presentation by A. Erickson), 2015 Minnesota Water Resources Conference, St. Paul, MN, October 13-14, 2015.
4. Erickson, A.J. October 28, 2015. "Using Innovative Technologies to Mitigate Phosphorus Impacts from Urban and Ag Runoff." Oral Presentation. Board of Soil and Water Resources Academy. Breezy Point, MN.

5. Erickson, A.J. September 15, 2016. Invited to present "Advanced Stormwater Treatment for Capturing Phosphate." Oral Presentation. Stormwater Management: Navigating the Currents. Hosted by the City of Boise. Boise, ID.
6. Erickson, A.J. June 30, 2016. Invited to present "Capturing Phosphates with Iron Enhanced Sand Filtration." Webinar. Forester U.
7. Gulliver, J.S. "Stormwater Systems and Other Innovative Stuff," B. Loida, B. Neuendorf, and J.S. Gulliver, 2016 Public Works Stormwater Summit, American Public Works Association PWX Conference, Minneapolis, MN, August 29, 2016.
8. Gulliver, J.S. "LID Research in the USA," Technology Advancement and Case Studies in Low Impact Development, University of Pusan, Busan, Korea, February 8 – 9, 2017.
9. Erickson, A.J. March 10, 2017. "Recent, Current, and Developing Stormwater Research at the University of Minnesota." Oral Presentation. 2017 CCWMO Stormwater Workshop. Chaska, MN.
10. Gulliver, J.S. "Gismos for Stormwater Runoff," Presentation for the H. G. Stefan Fellowship Award, St. Anthony Falls Laboratory, University of Minnesota, Minneapolis, MN April 28, 2017.
11. Erickson, A.J. May 25, 2017. "Phosphate Capture from Urban and Agricultural Runoff." ASCE-EWRI Congress 2017.
12. Weiss, P.T., J.S. Gulliver, and A.J. Erickson, "Iron enhanced sand filtration for dissolved phosphorus removal," Indiana Association for Floodplain and Stormwater Management Annual Conference, September 6-8, 2017, South Bend, IN.

Results were, and will continue to be incorporated into Stormwater 'U' and Stormwater Management and Erosion Control Certification courses and workshops. Results have already been included in senior and/or graduate urban hydrology classes at the University of Minnesota and Valparaiso University, Valparaiso, IN.

Final Expenditures

The project was completed on time and within budget. The Final Expenditures can be found in a separate spreadsheet document listing individual Objectives, Tasks, and line items categories.

References

Aldridge, K.T. and G.G. Ganf, 2003. Modification of sediment redox potential by three contrasting macrophytes: implications for phosphorus adsorption/desorption. *Marine & Freshwater Research*, 54(1): 87-94.

American Public Health Association (APHA), 1998. 4500-P Phosphorus, *Standard Methods for the Examination of Water and Wastewater*, Washington D.C.

ASTM. (2002). “Standard specification for concrete aggregates.” *Annual Book of American Society for Testing and Materials (ASTM) Standards. C33-02a*, Philadelphia.

Discovery Farms Minnesota (DFM). (2017). “2016 Year in Review.” *Discovery Farms Minnesota.* April 2017. http://www.discoveryfarmsmn.org/

Erickson, A.J. and J.S. Gulliver, 2010. "Performance Assessment of an Iron-Enhanced Sand Filtration Trench for Capturing Dissolved Phosphorus." *St. Anthony Falls Laboratory Project Report #549.* Prepared for the City of Prior Lake. University of Minnesota, Minneapolis, MN. http://purl.umn.edu/115602

Erickson, A.J., Gulliver, J.S., and P.T. Weiss, 2007. Enhanced sand filtration for storm water phosphorus removal. *Journal of Environmental Engineering*, 133(5): 485-497.

Erickson, A.J., Gulliver, J.S., and P.T. Weiss, 2012. Capturing Phosphates with Iron Enhanced Sand Filtration. *Water Research*, 46(9), 3032–3042, 2012.

Erickson, A.J., Weiss, P.T., and J.S. Gulliver, 2013. Optimizing Stormwater Treatment Practices: A Handbook of Assessment and Maintenance. Springer Publishing, New York, NY, USA, 2013.

Franzini JB, Finnemore EJ, 1997. Fluid mechanics with engineering applications. 9th edn. McGraw Hill, New York, NY

Pitt, R. et al., 2005. Evaluation of NPDES Phase 1 Municipal Stormwater Monitoring Data. *University of Alabama and the Center for Watershed Protection.*

Schindler, D.W., 1977. Evolution of phosphorus limitation in lakes: Natural mechanisms compensate for deficiencies of nitrogen and carbon in eutrophied lakes. *Science*, 195(4275): 260-262.

Sharpley, A.N., Smith, S.J., Jones, O.R., Berg, W.A., Coleman, G.A., 1992. The Transport of Bioavailable Phosphorus in Agricultural Runoff. *Journal of Environmental Quality*, 21(1): 30-35.

Stumm, W., Morgan, J.J., 1981. Aquatic chemistry: an introduction emphasizing chemical equilibria in natural waters. Wiley, New York, xiv, 780 p. pp.

U.S. EPA., 1999. Preliminary data summary of urban storm water best management practices. *EPA-821-R-99-012, U.S. Environmental Protection Agency,* Washington, D.C.

Villemonte, J. (1947). Submerged Weir Discharge Studies. *Engineering News Record*, December 25th, 1947.

Weiss, P.T., Gulliver, J.S., and Erickson, A.J. (2007). Cost and Pollutant Removal of Stormwater Treatment Practices. *Journal of Water Resources Planning and Management*, 133(3), pp. 218-229. http://dx.doi.org/10.1061/(ASCE)0733-9496(2007)133:3(218)

Wright SWCD. 2015. Local Water Management Plan. *Wright Soil and Water Conservation District.* Downloaded April 4, 2017 from http://www.wrightswcd.org/docs/WaterPlan.pdf

Wright SWCD. 2011. Amendment to the Local Water Management Plan. *Wright Soil and Water Conservation District.* Downloaded April 4, 2017 from http://www.wrightswcd.org/docs/Wright2011Amendment.pdf

Appendix A - Event Data

This appendix contains a combination of three plots for each event listed in Tables 3 and 4. For the event in which rainfall began on 7/6/15, for example, Figure A1 shows the flow rate and cumulative rainfall on the left side; the phosphate EMC IN and EMC OUT on the top right side; and the phosphate Load IN and Load OUT on the bottom right side. For events in 2016, the total phosphorus EMC and Load were also measured, and thus beginning with Figure A14 the layout will be as follows: Flow rate and cumulative rainfall on the left side; phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT on the top right side; and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT on the bottom right side.

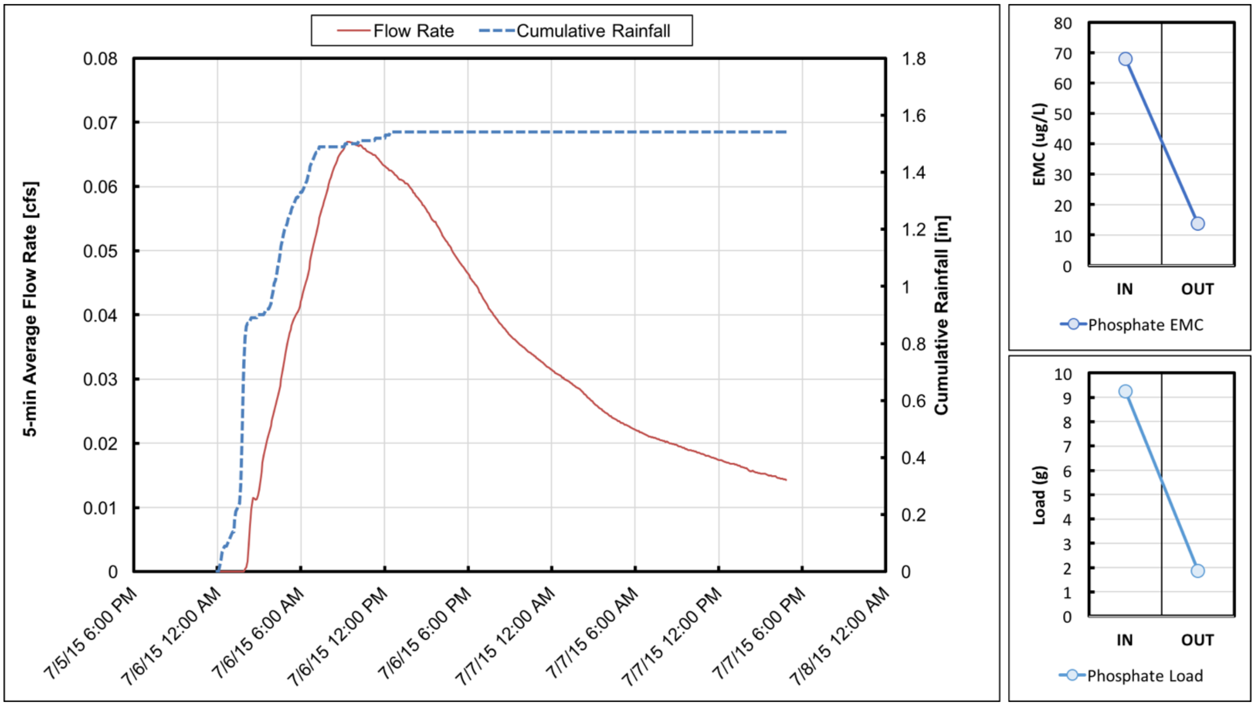

Figure A1. Event 7/6/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

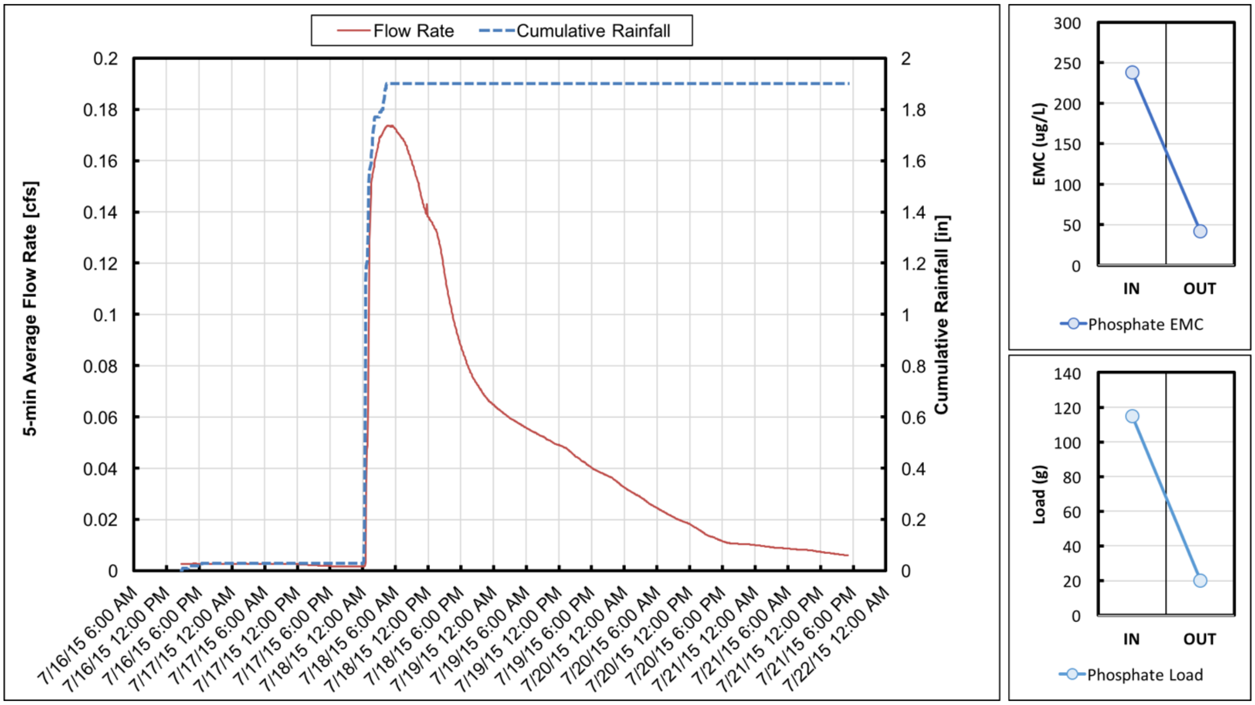

Figure A2. Event 7/16/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

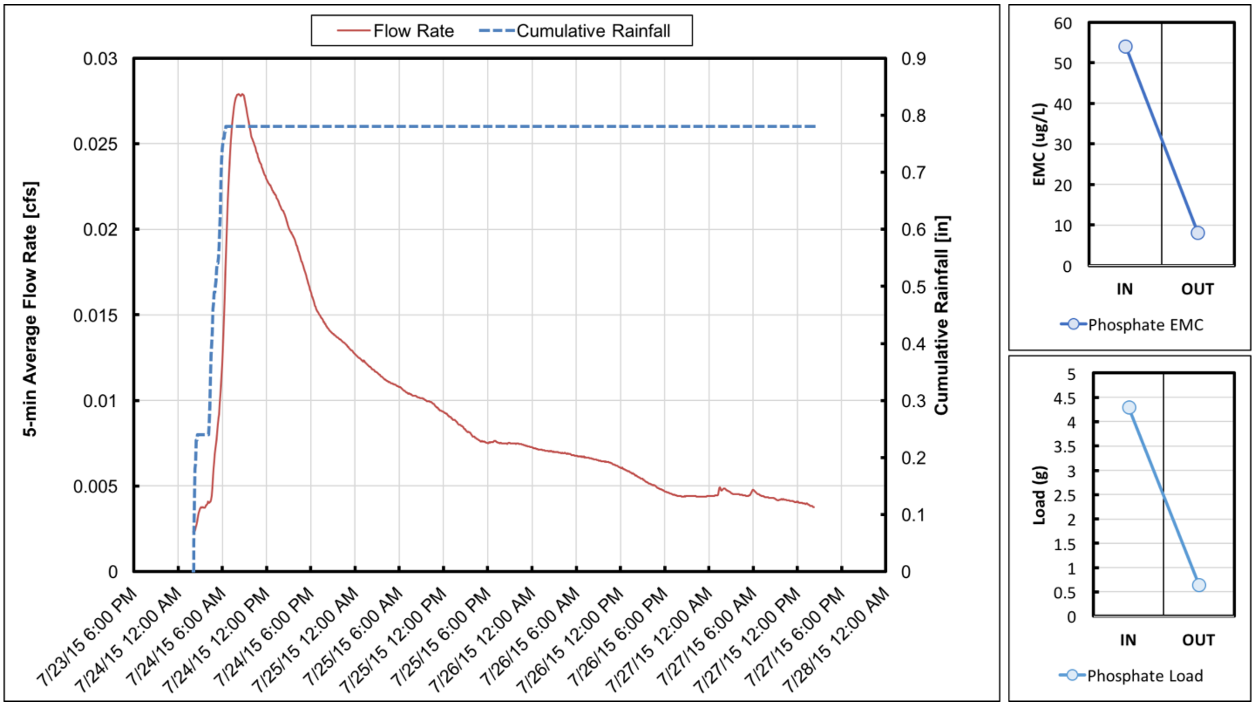

Figure A3. Event 7/24/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

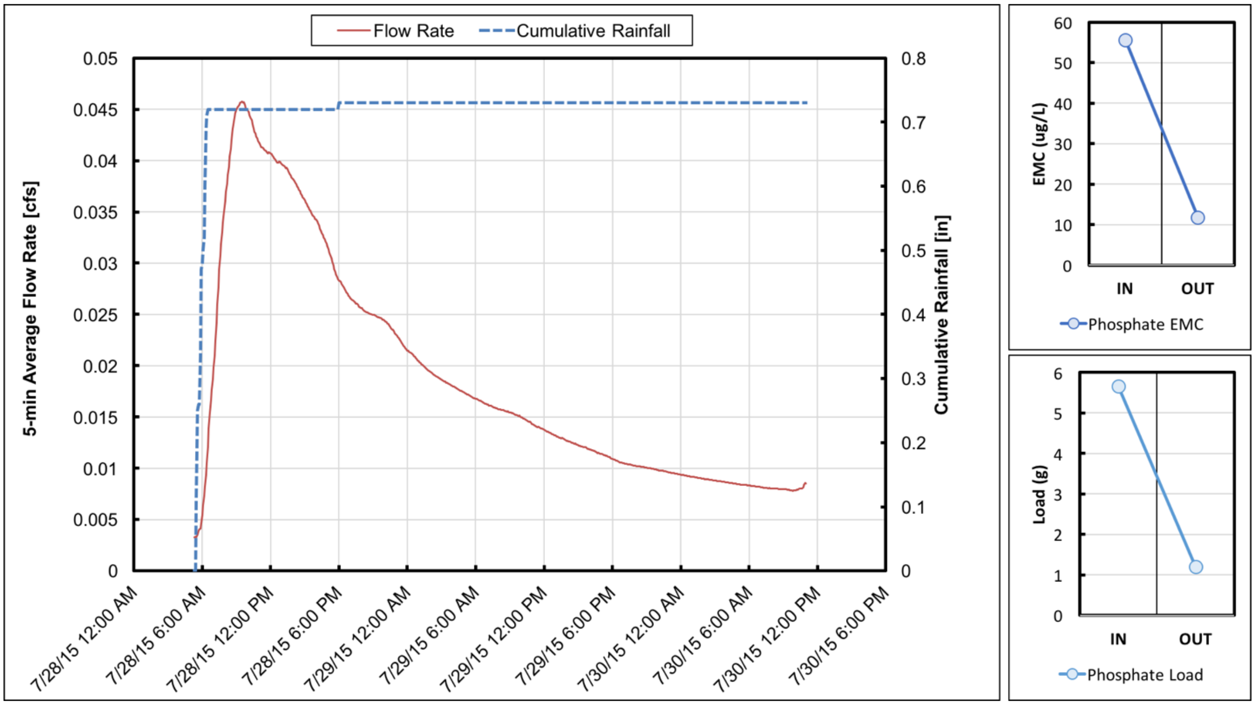

Figure A4. Event 7/28/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

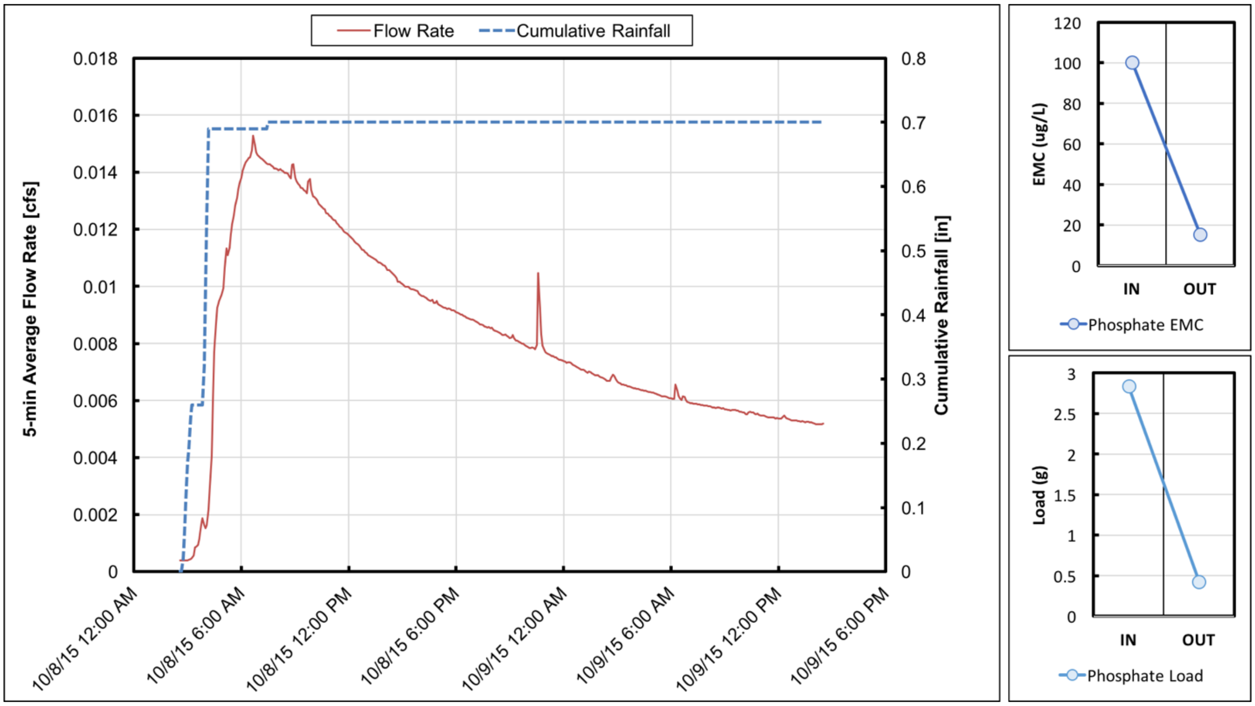

Figure A5. Event 10/8/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

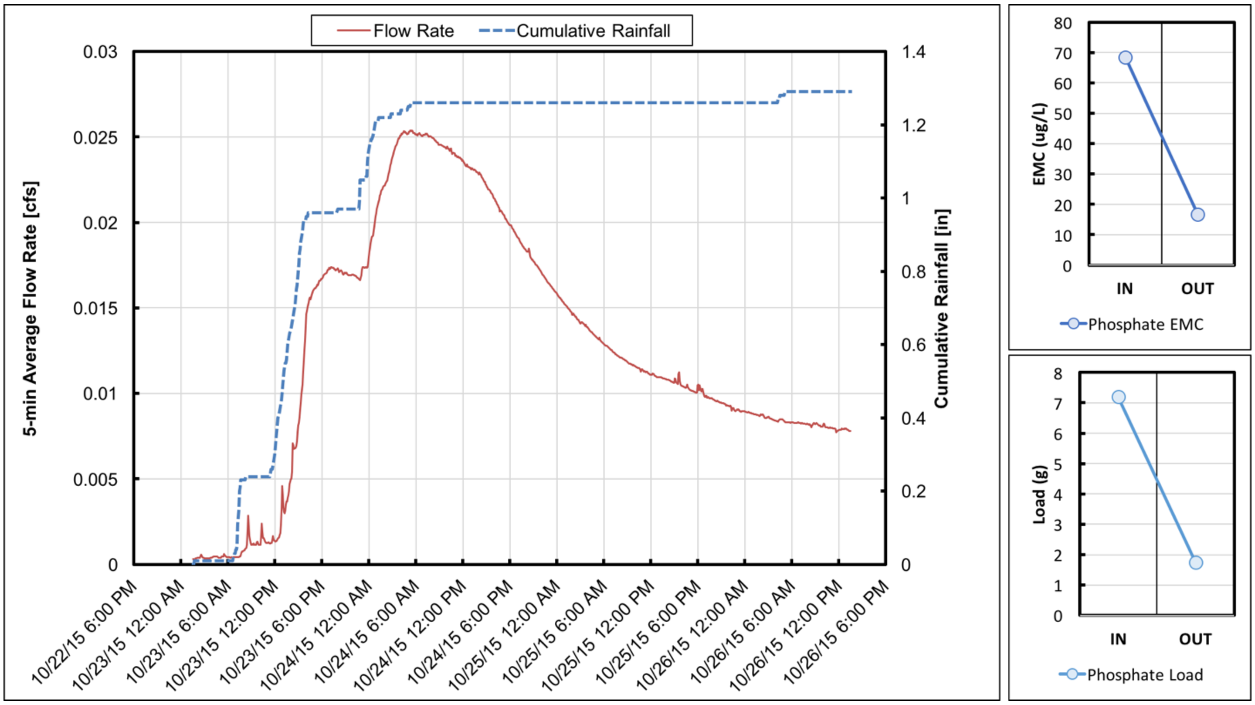

Figure A6. Event 10/23/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

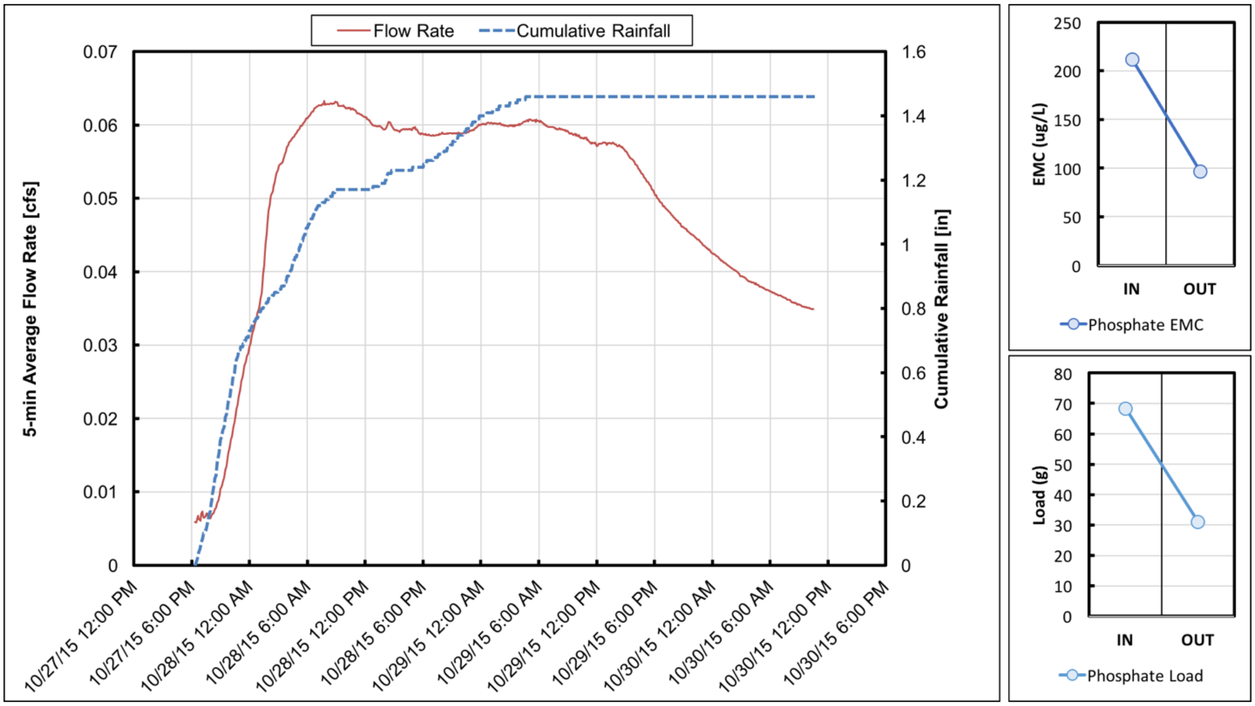

Figure A7. Event 10/27/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

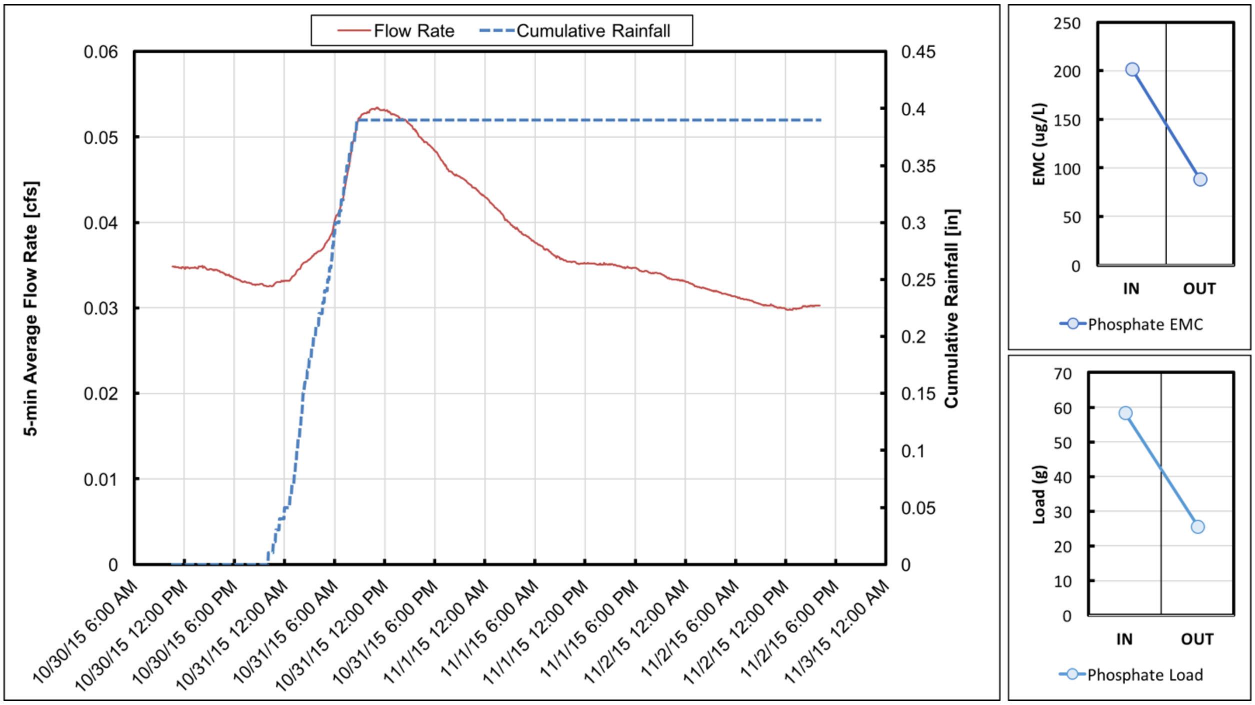

Figure A8. Event 10/30/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

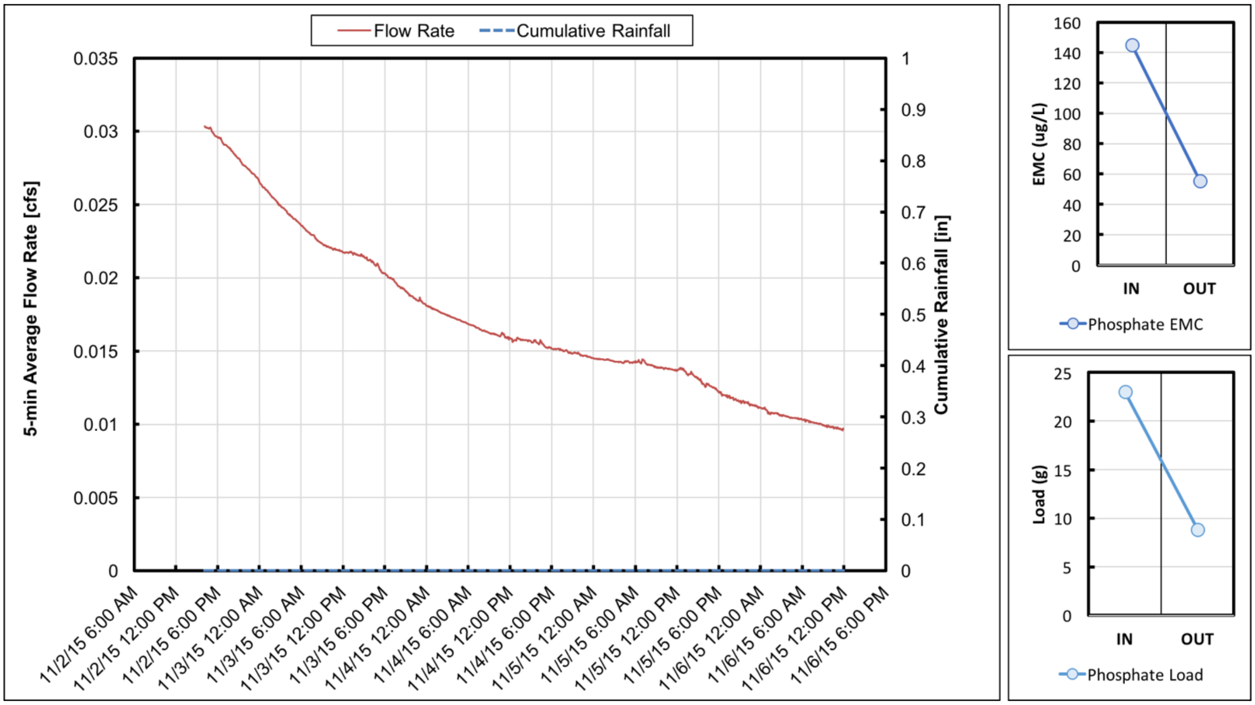

Figure A9. Event 11/2/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

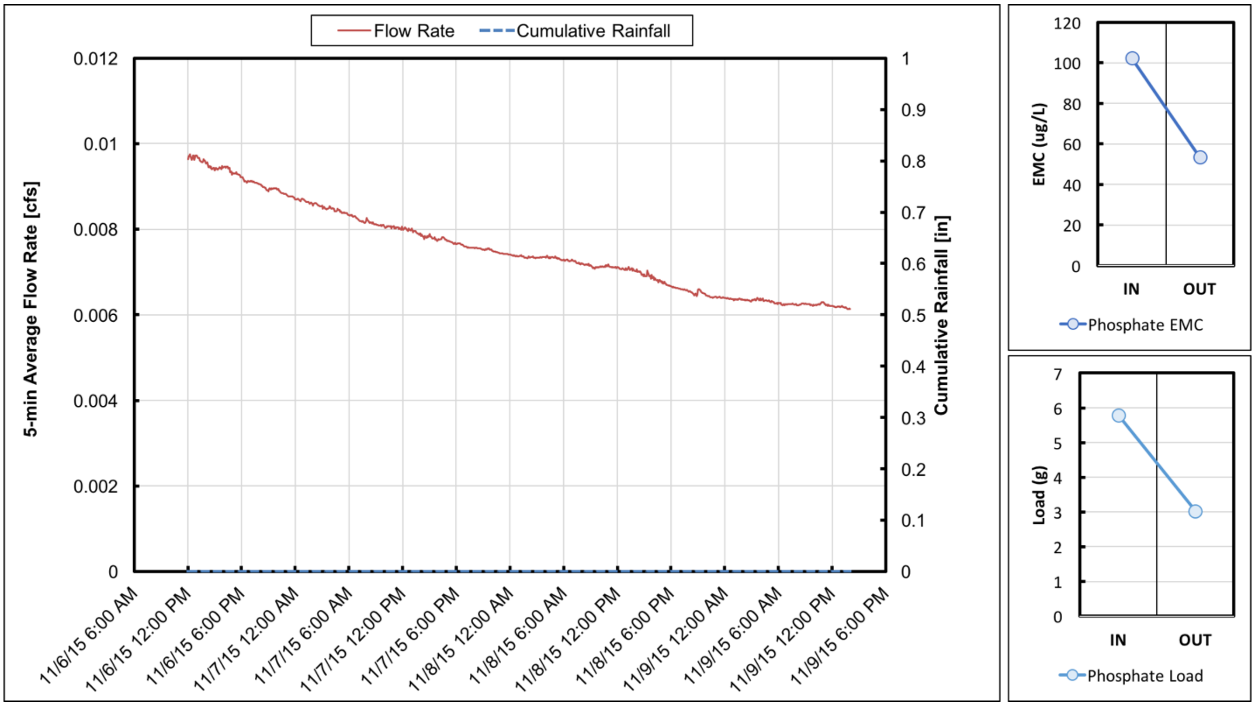

Figure A10. Event 11/6/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

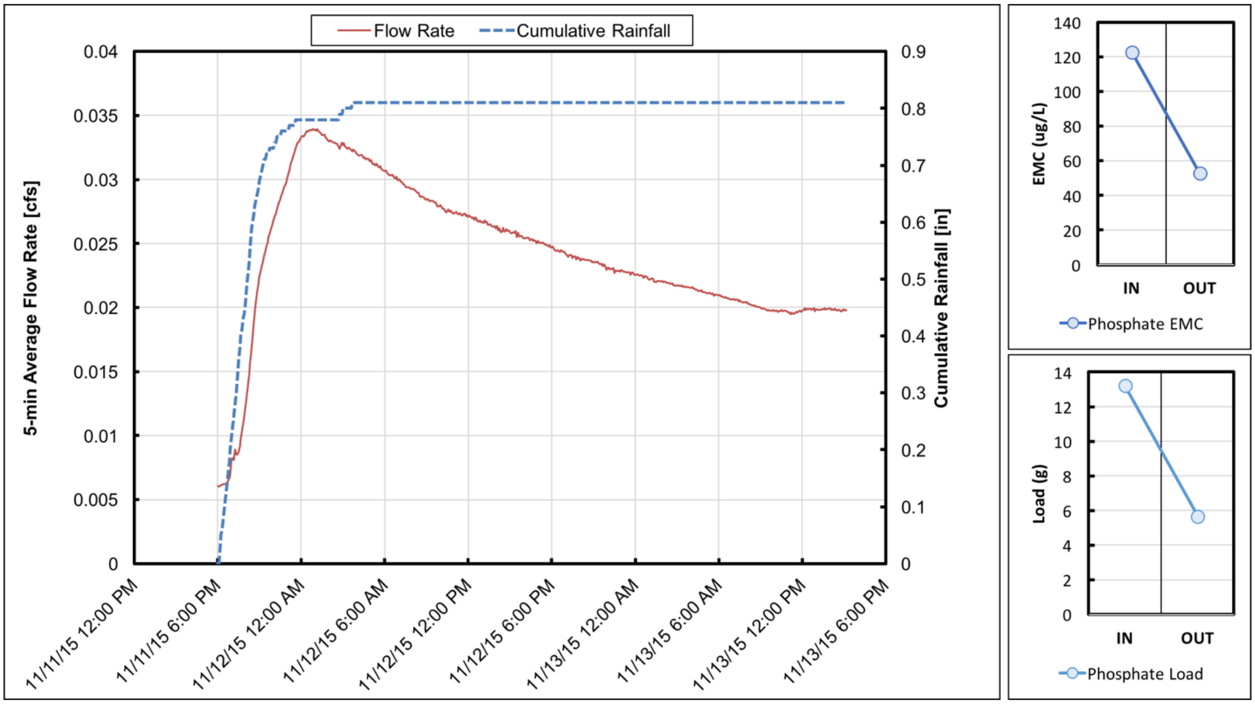

Figure A11. Event 11/11/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

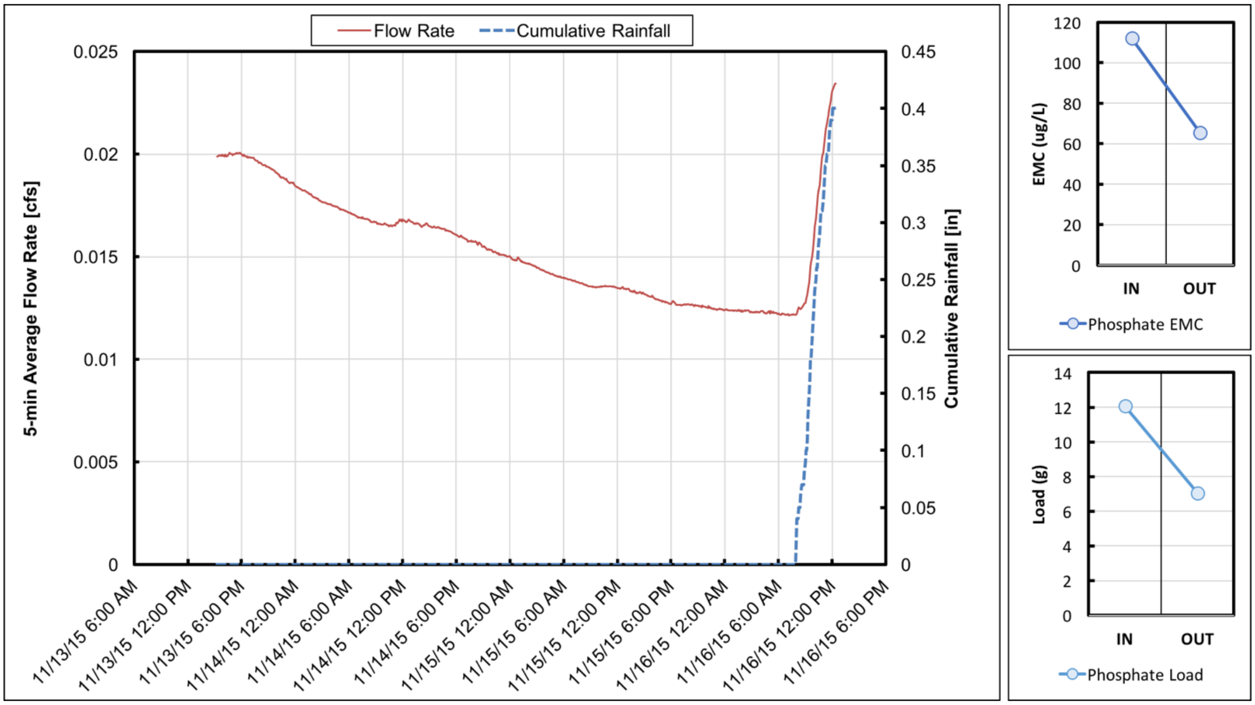

Figure A12. Event 11/13/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

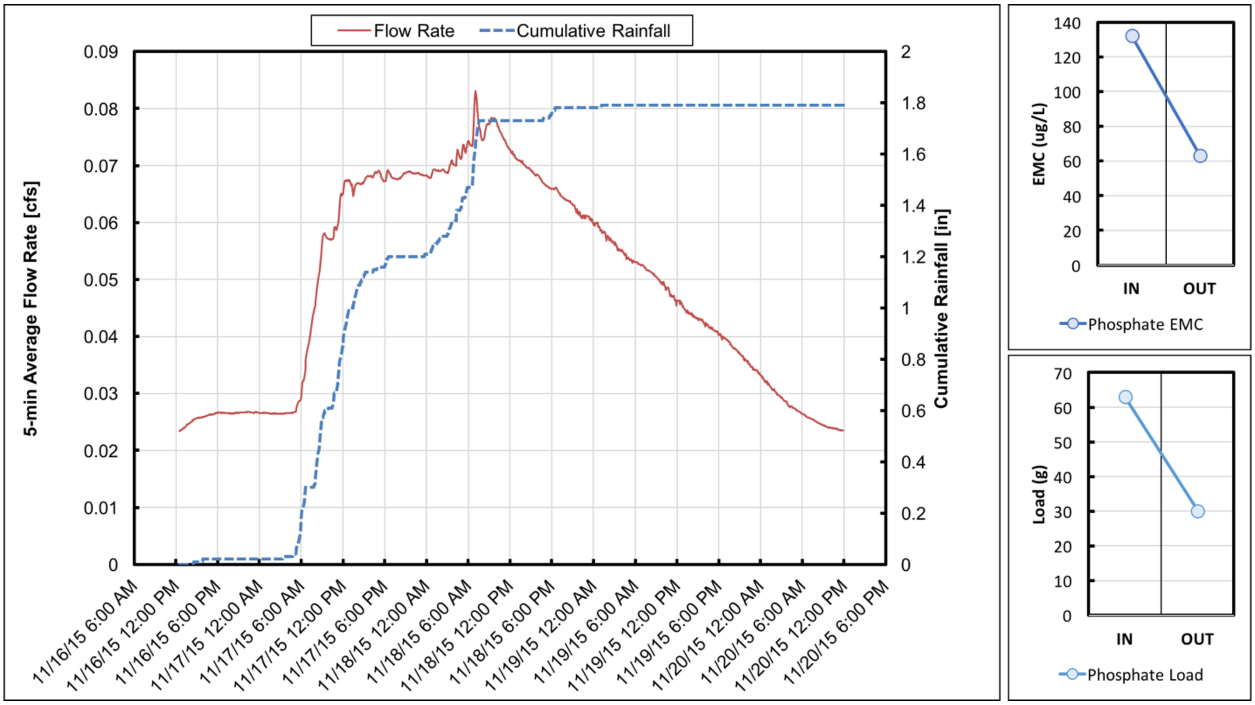

Figure A13. Event 11/16/15 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT (bottom right)

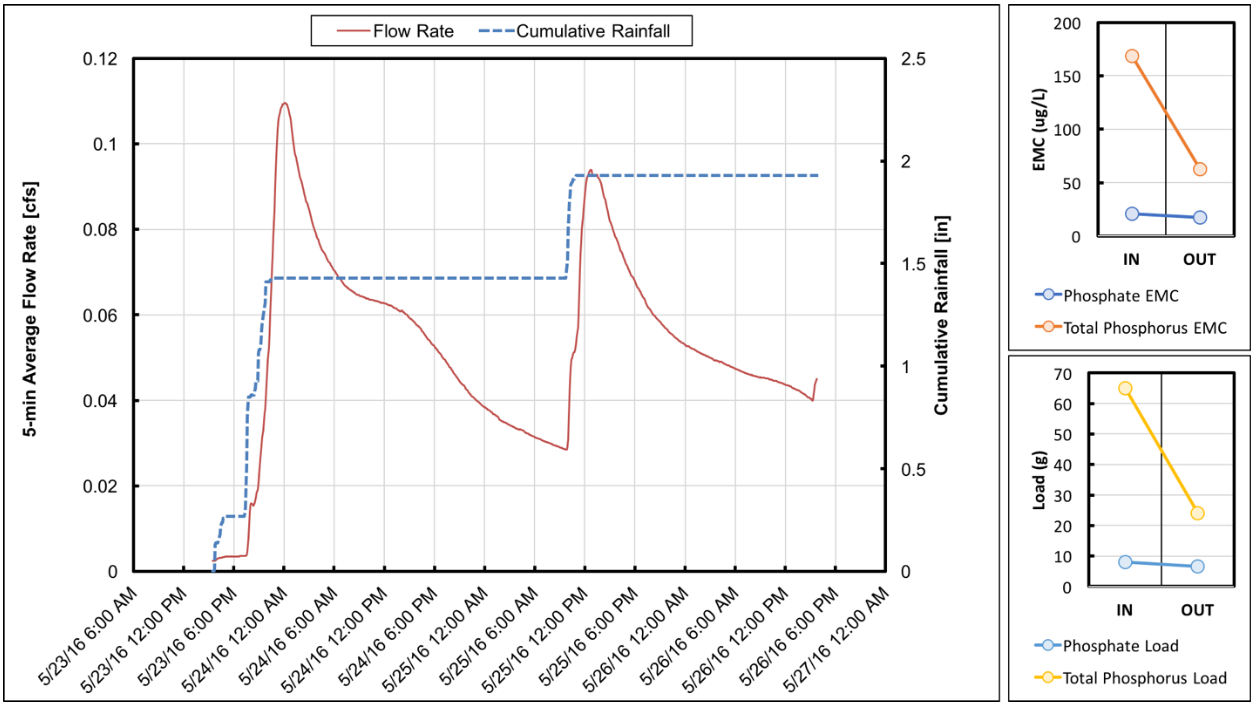

Figure A14. Event 5/23/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

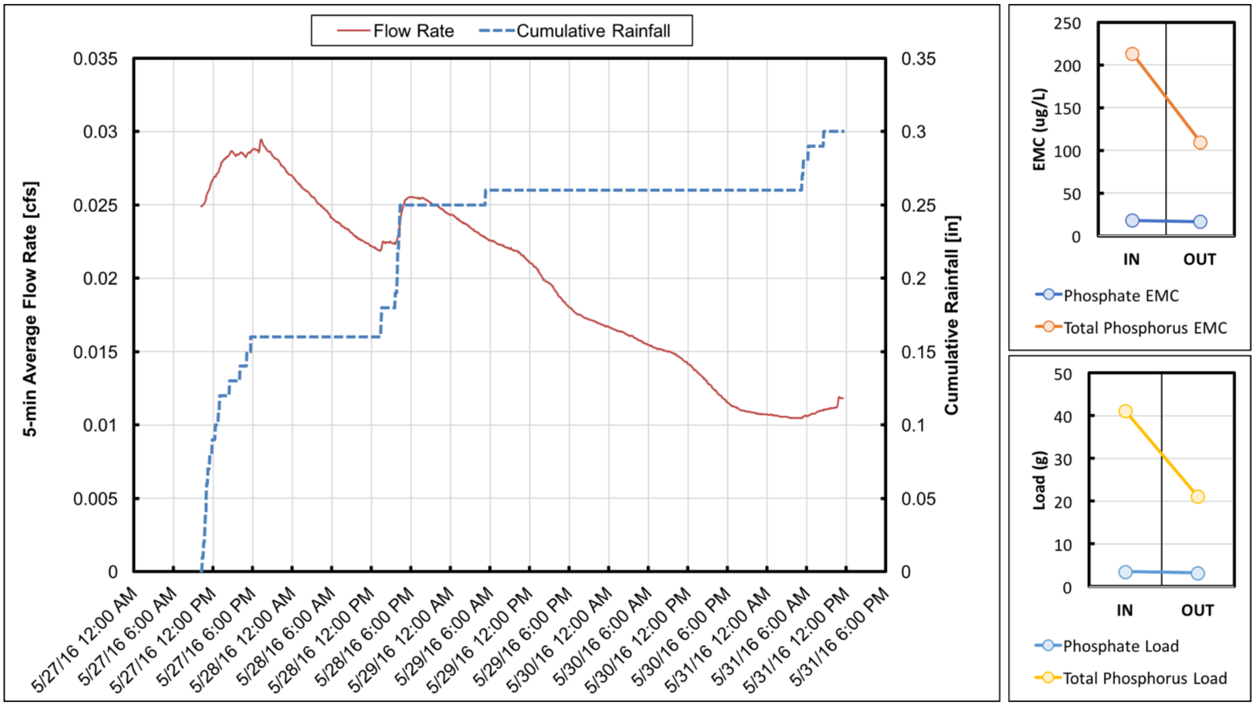

Figure A15. Event 5/27/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

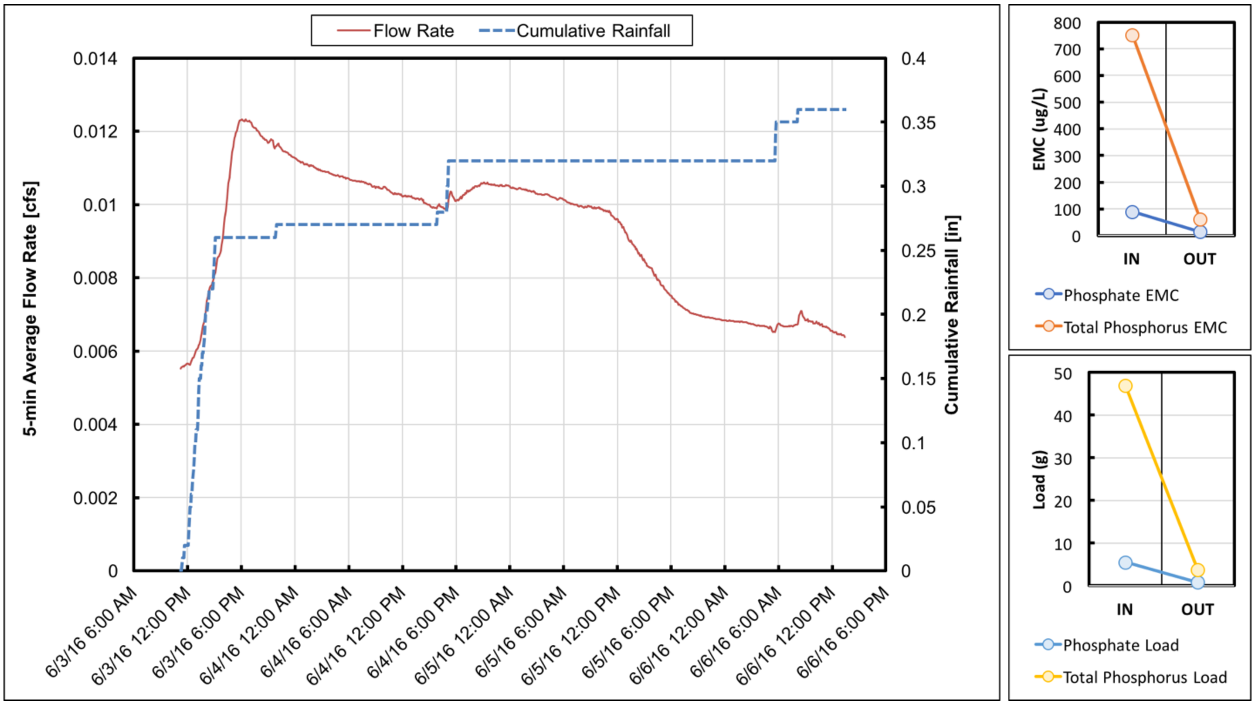

Figure A16. Event 6/3/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

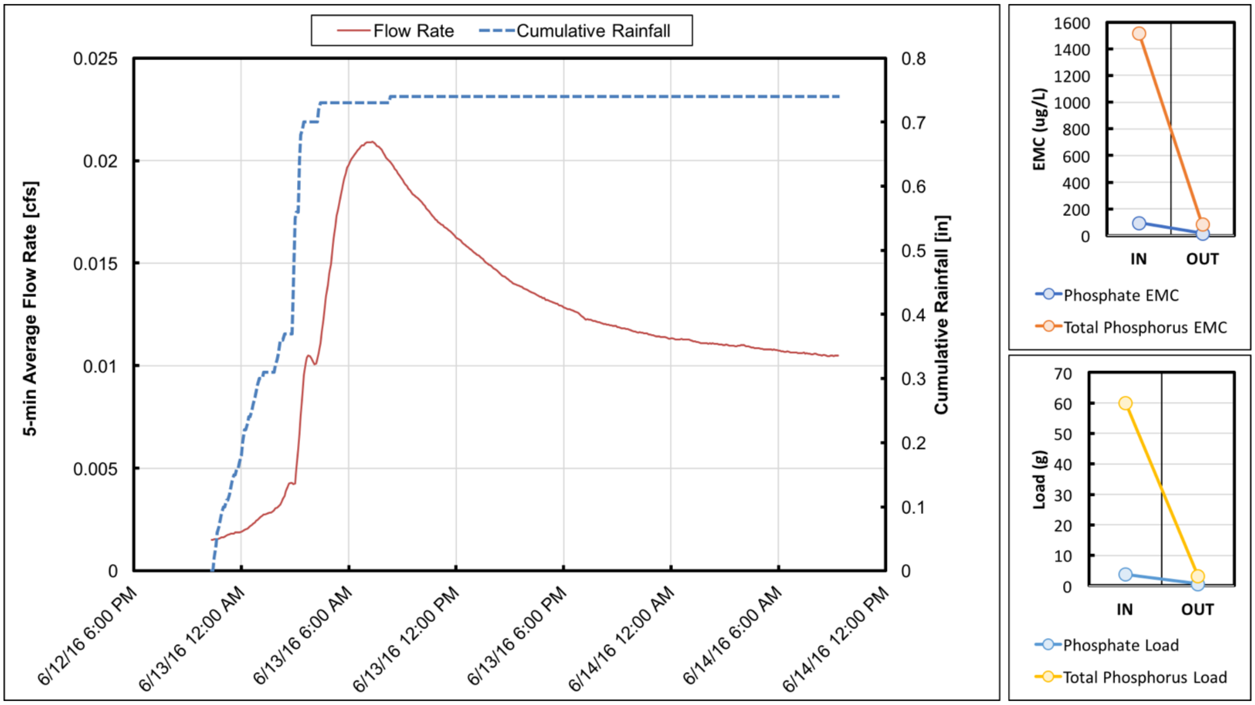

Figure A17. Event 6/12/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

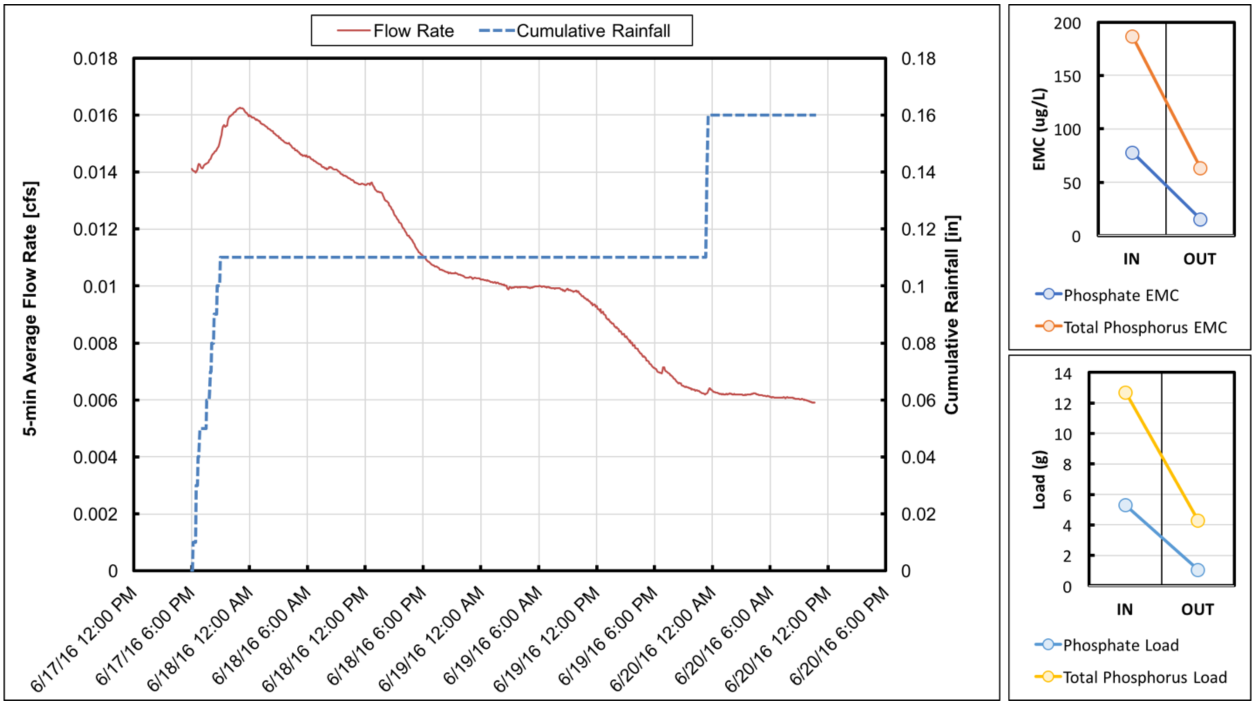

Figure A18. Event 6/17/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

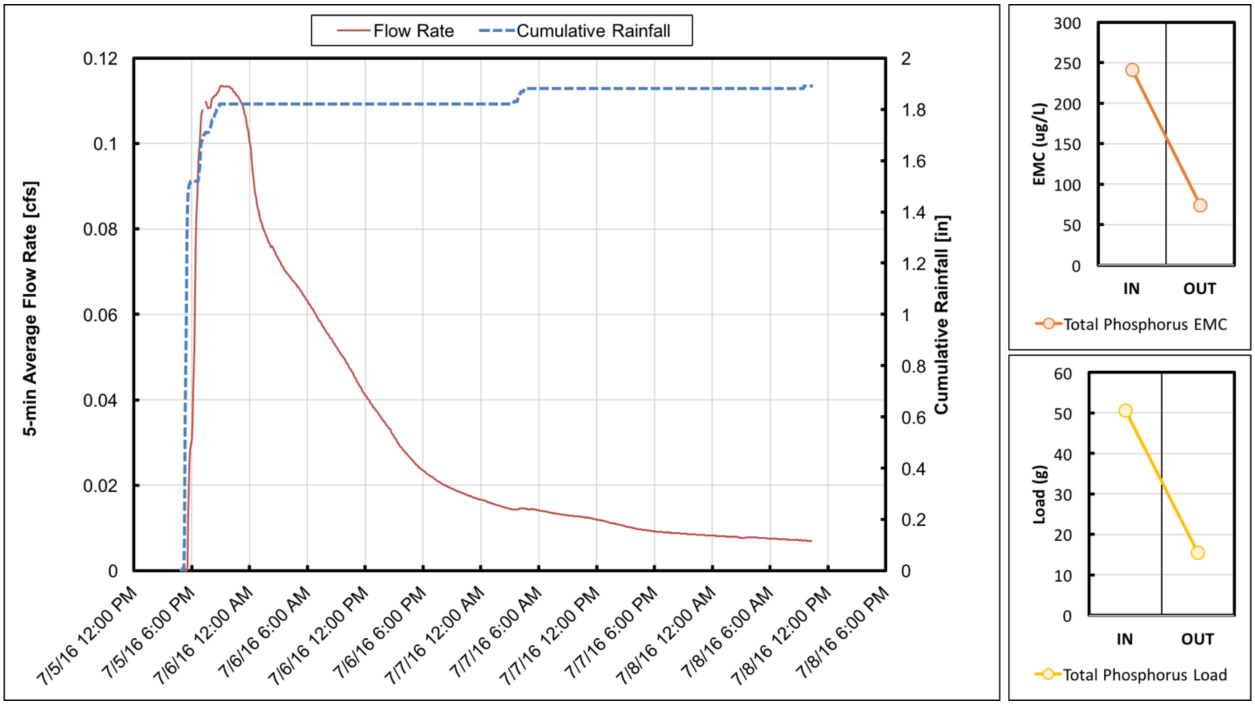

Figure A19. Event 7/5/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

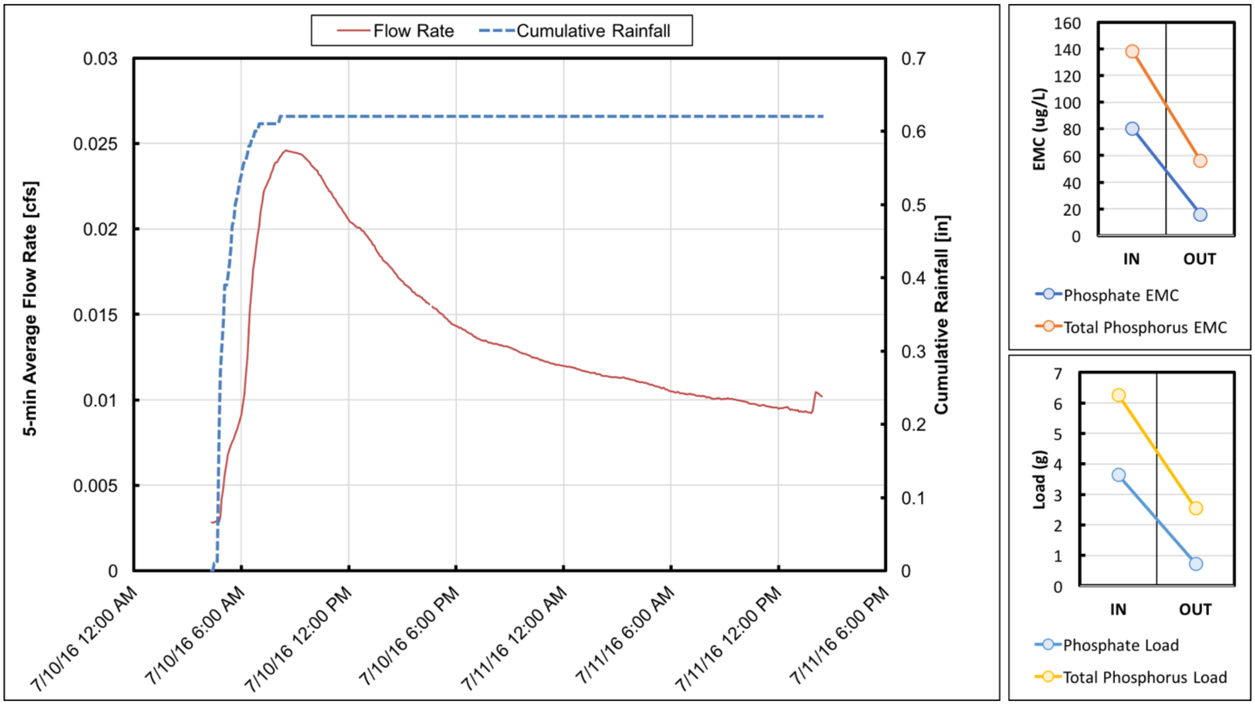

Figure A20. Event 7/10/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

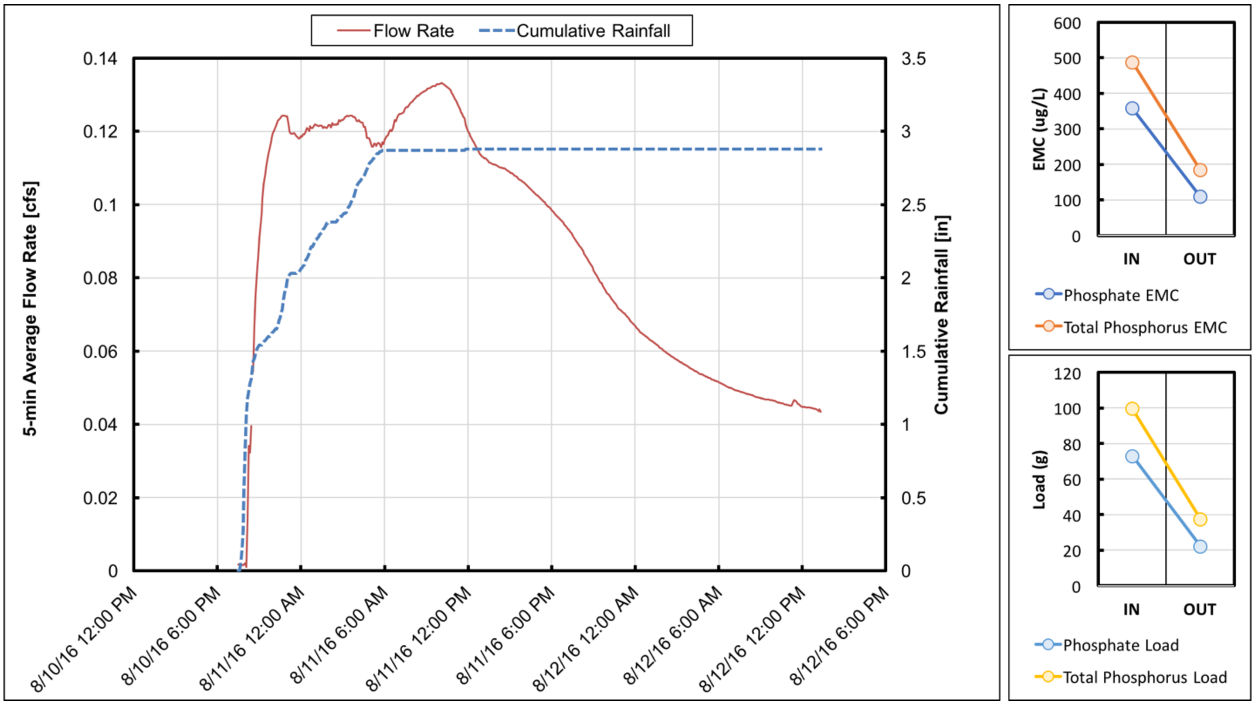

Figure A21. Event 8/10/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

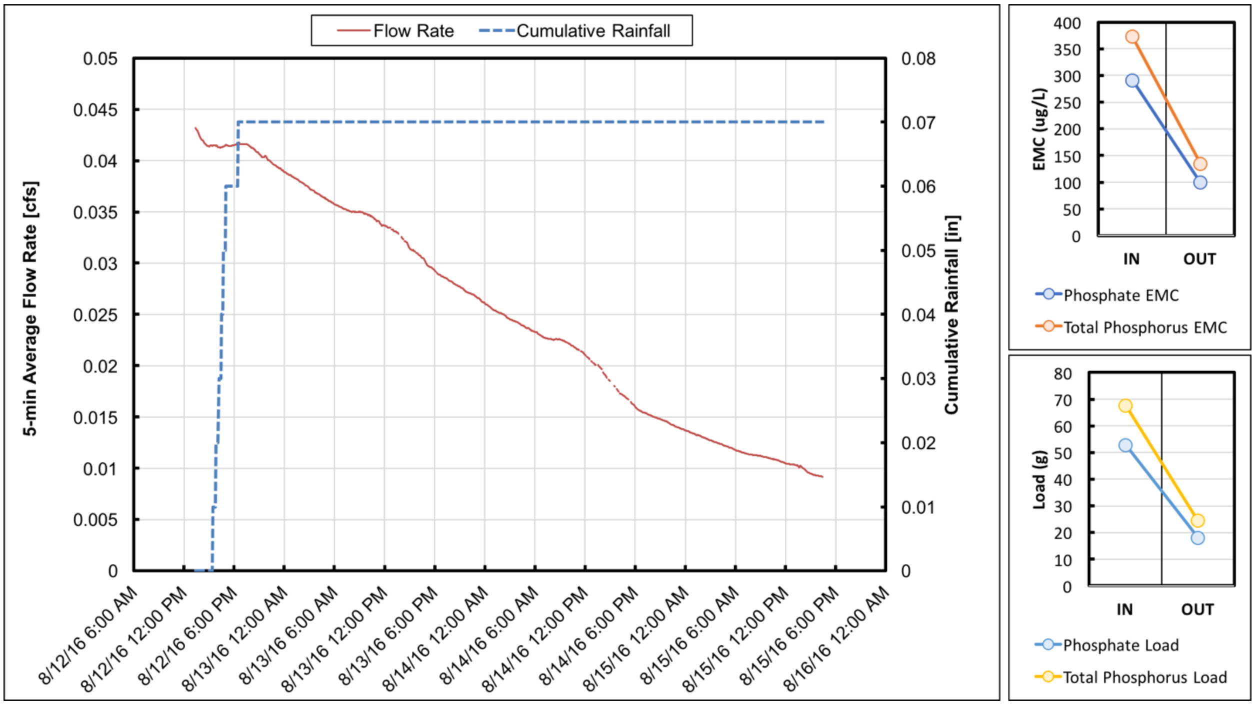

Figure A22. Event 8/12/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

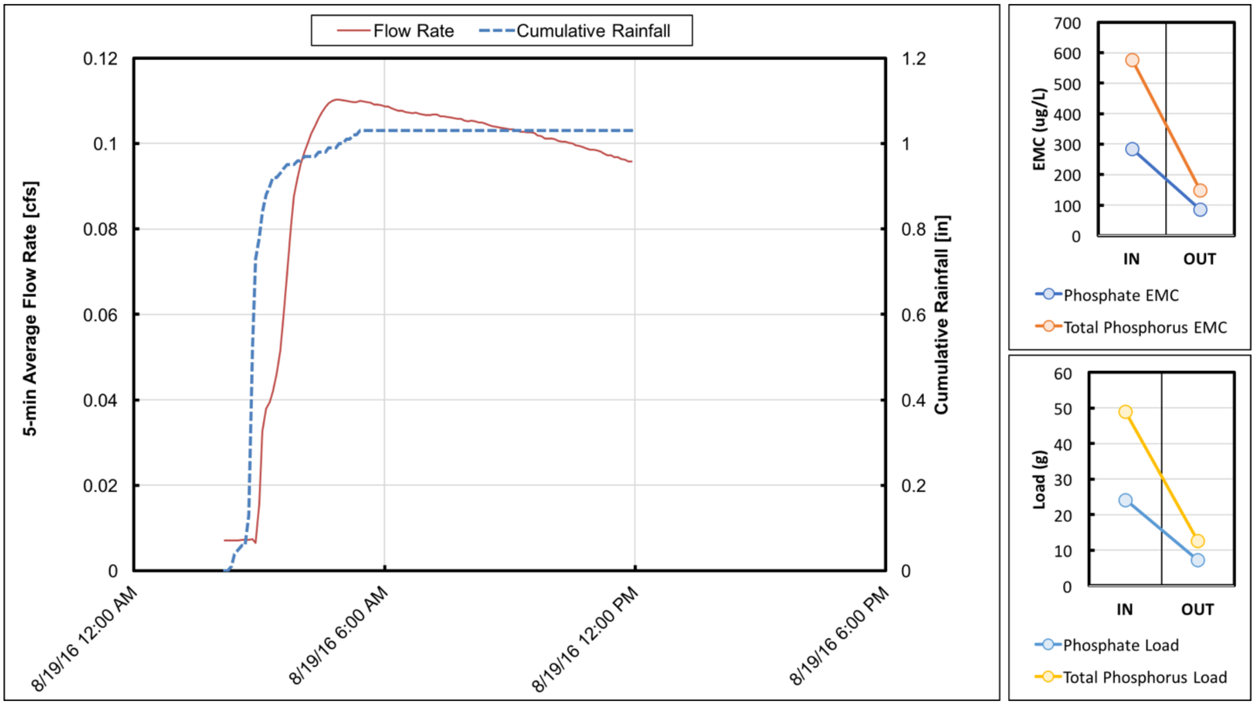

Figure A23. Event 8/19/2016a Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

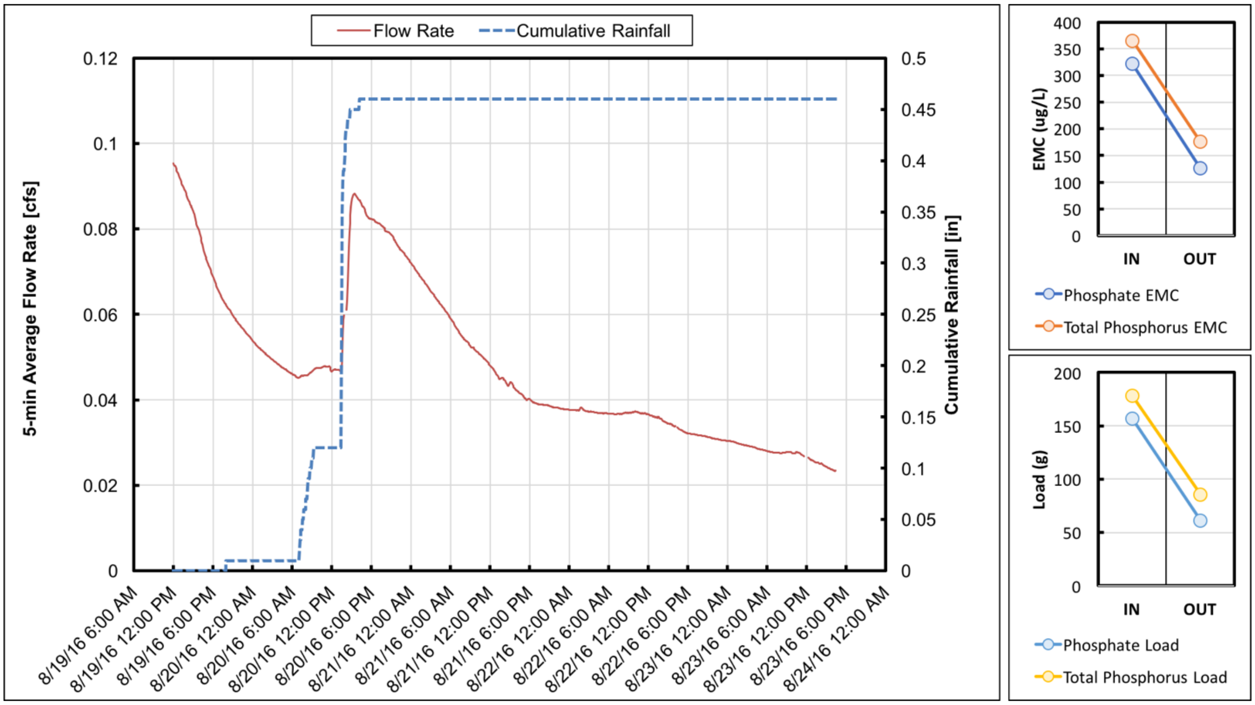

Figure A24. Event 8/19/2016b Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

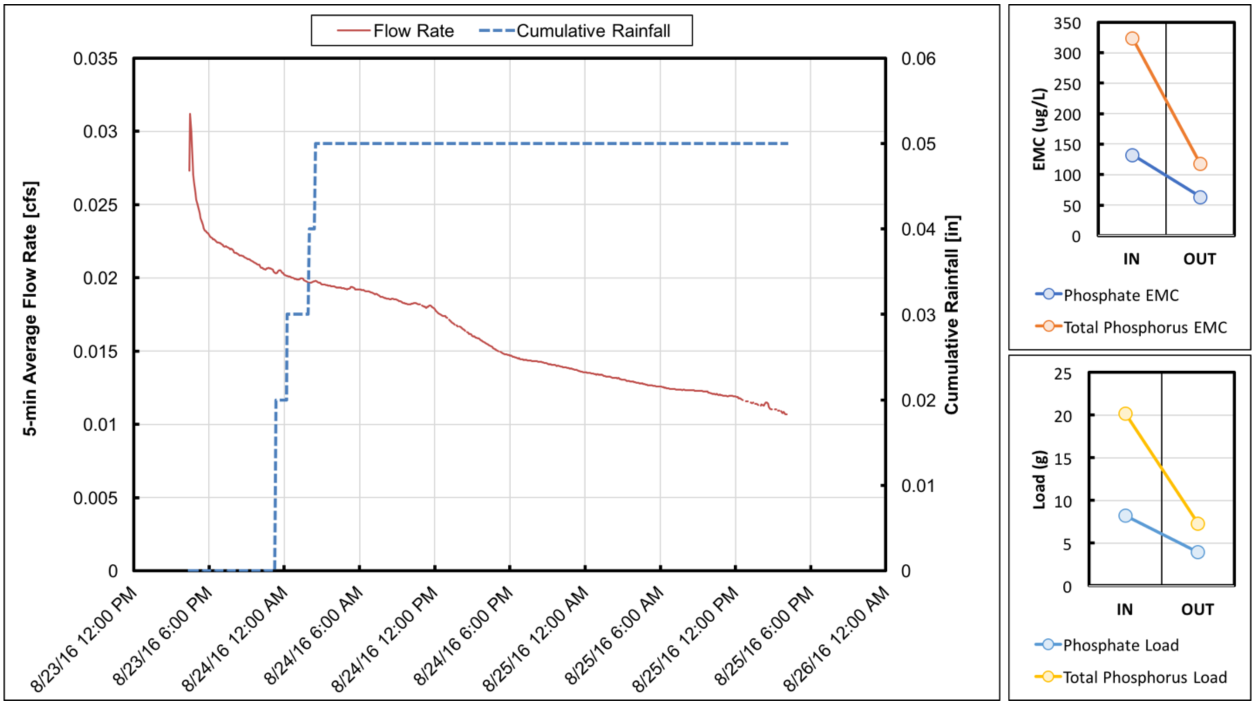

Figure A25. Event 8/23/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

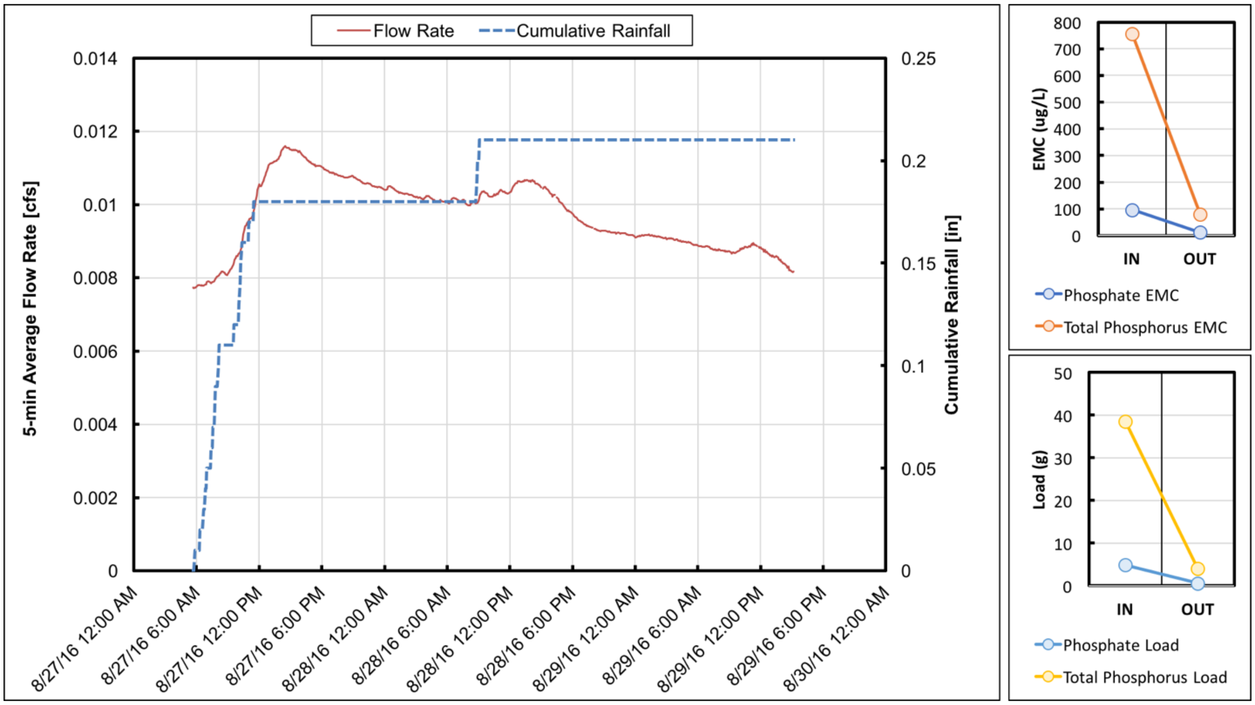

Figure A26. Event 8/27/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

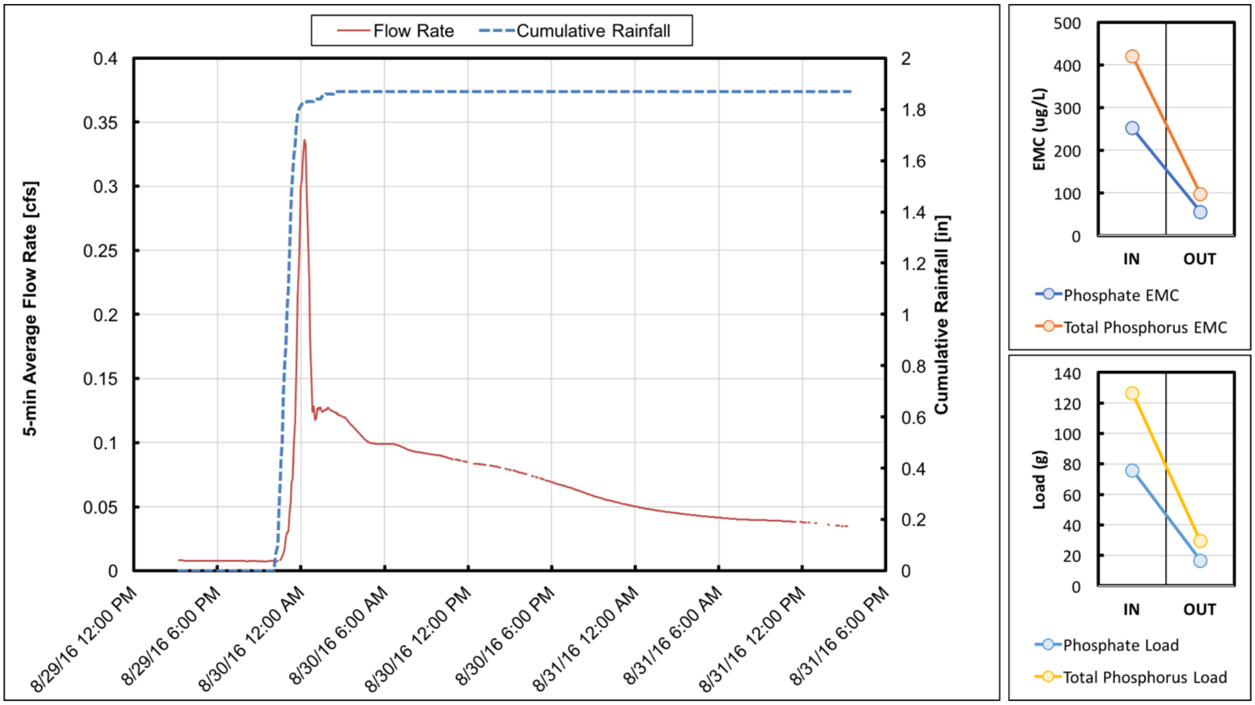

Figure A27. Event 8/29/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

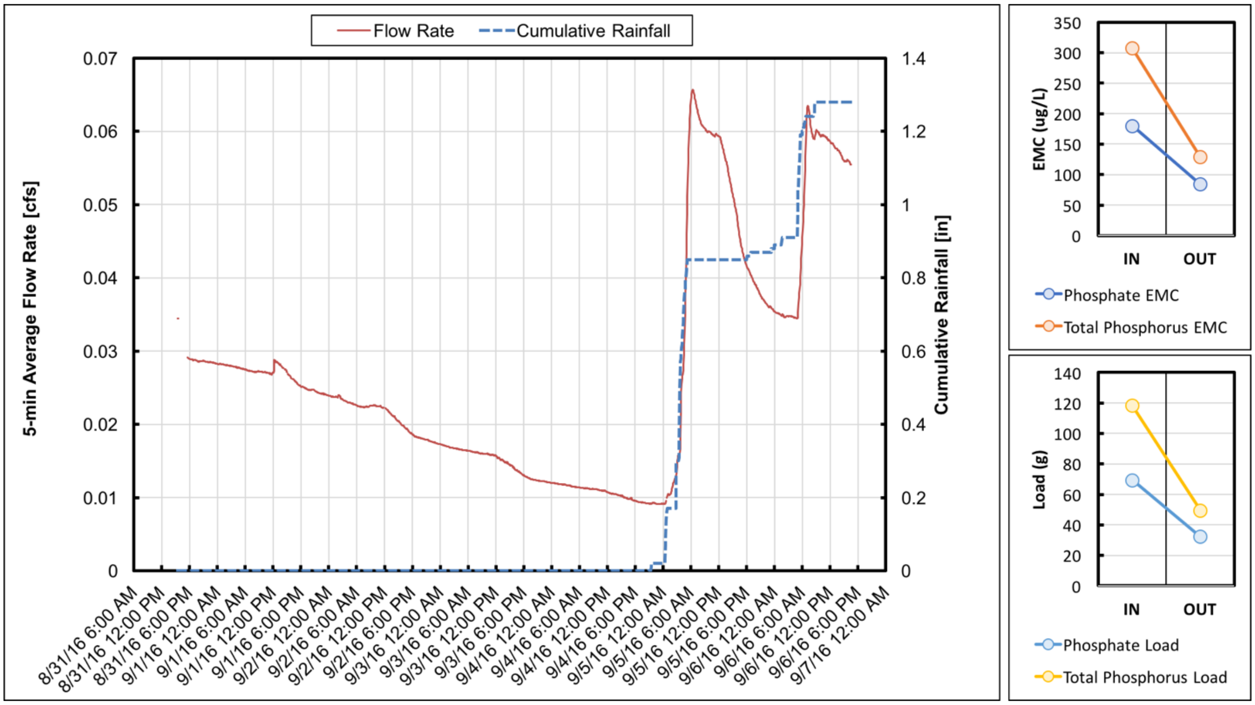

Figure A28. Event 8/31/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

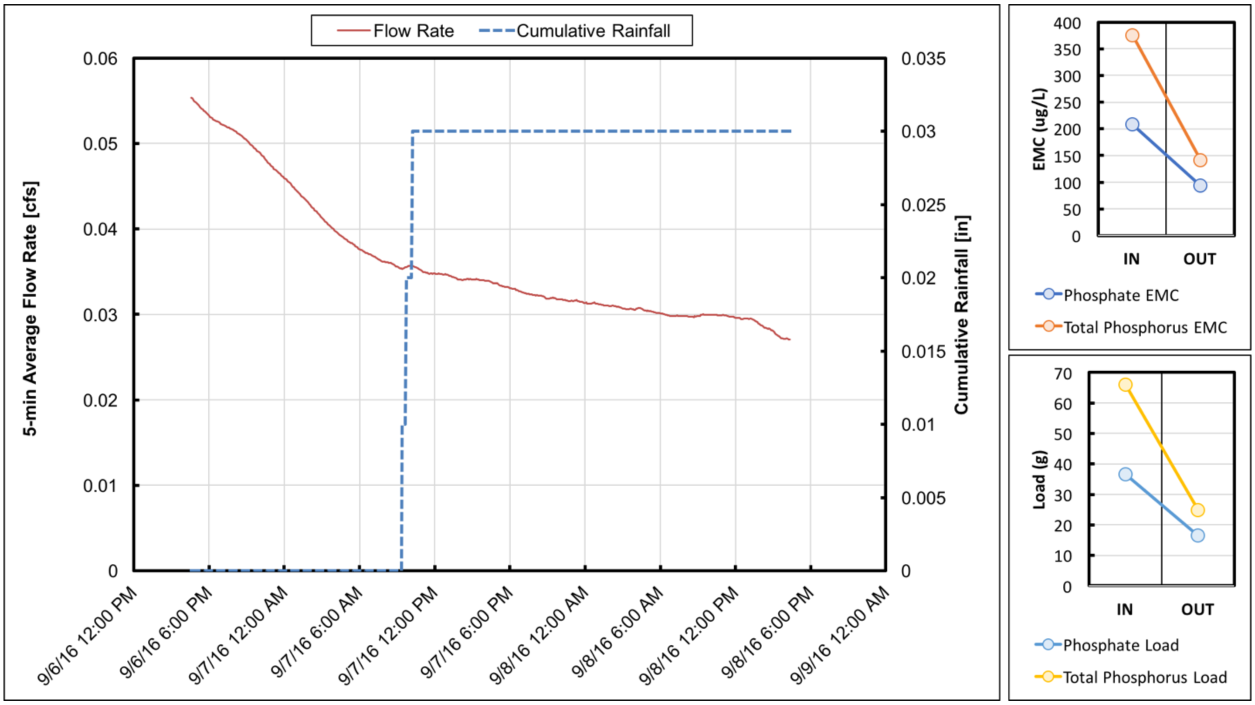

Figure A29. Event 9/6/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

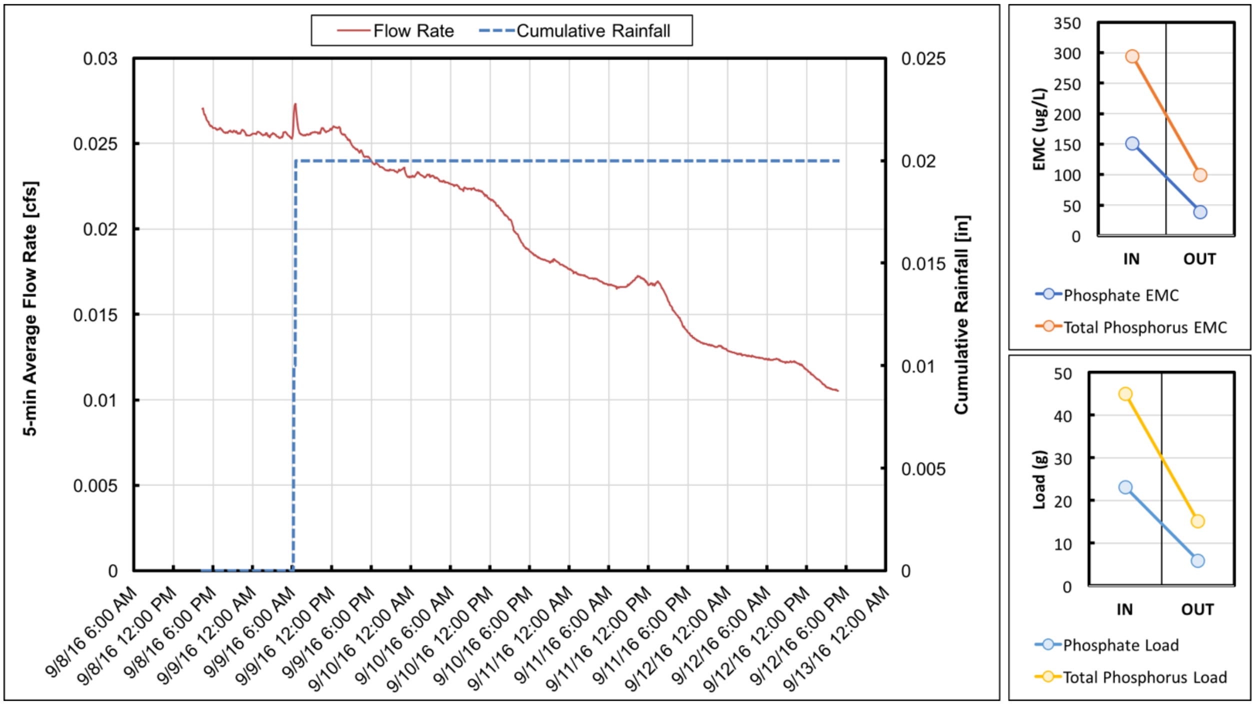

Figure A30. Event 9/9/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

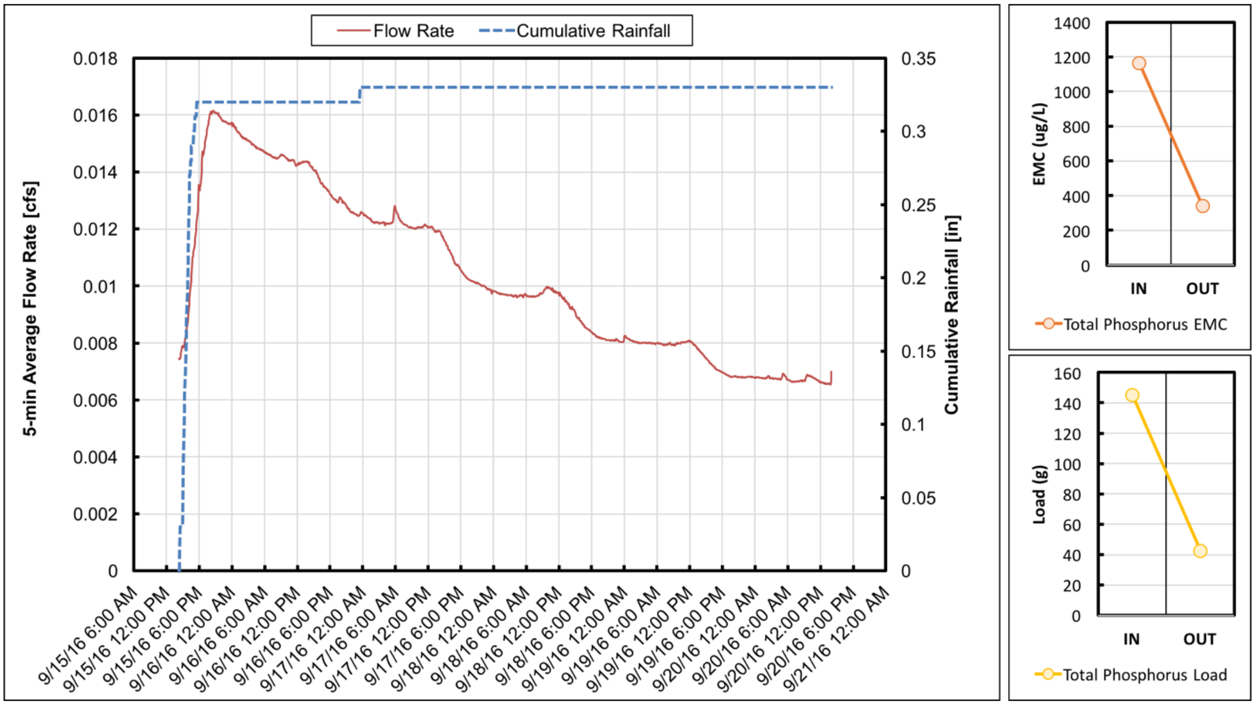

Figure A31. Event 9/15/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

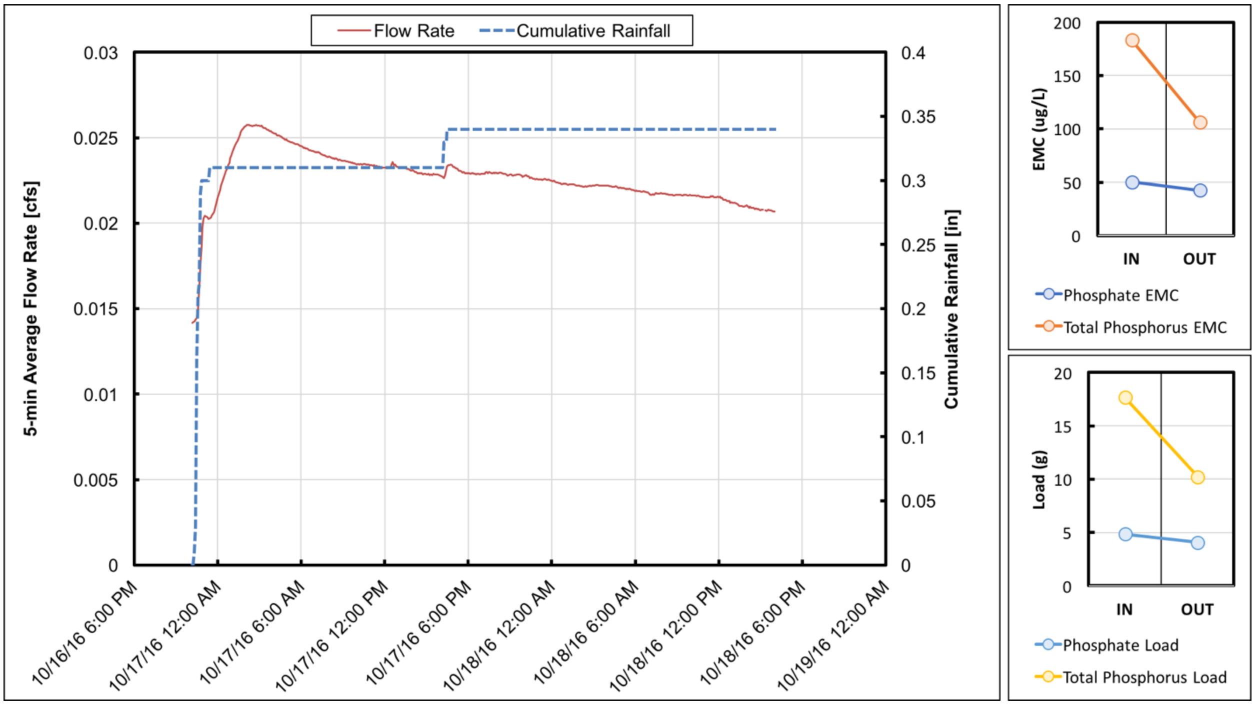

Figure A32. Event 10/16/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)

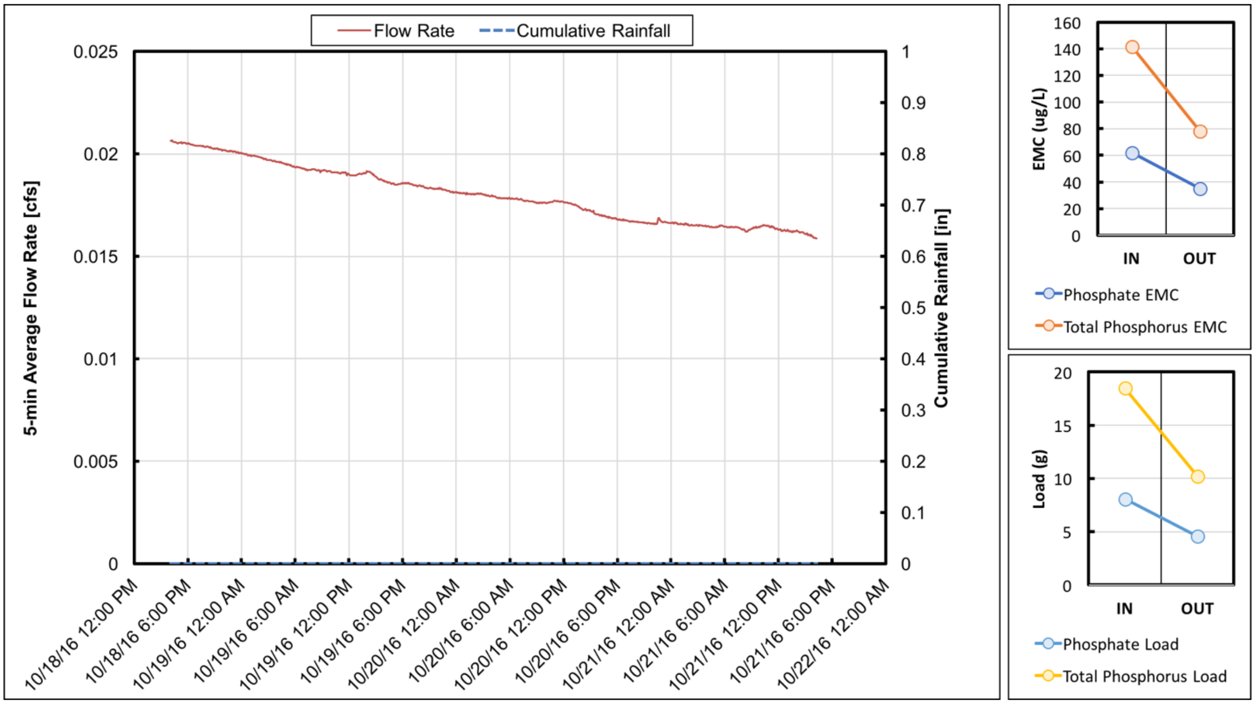

Figure A33. Event 10/18/2016 Flow rate and cumulative rainfall (left); phosphate EMC IN, EMC OUT and total phosphorus EMC IN, EMC OUT (top right); and phosphate Load IN, Load OUT and total phosphorus Load IN, Load OUT (bottom right)