# FINAL REPORT

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## ASSESSMENT OF TILE DRAINAGE SYSTEMS IN ADDISON COUNTY AND THE JEWETT BROOK WATERSHED


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# Executive Summary

In Vermont and across the Lake Champlain Basin, the extent of tile drainage systems and their potential impacts on water quality have not been adequately assessed. A previous study by Stone Environmental (Stone) for the Lake Champlain Basin Program in the Jewett Brook watershed in Franklin County (Braun et al. 2019) revealed that subsurface drainage systems in agricultural fields can discharge significant quantities of phosphorus (P). This project adds to the previous work by measuring nutrient and sediment concentrations and loads in tile drainage water in a second agricultural area, Addison County, and comparing these values with nutrient and sediment concentrations and loads measured in tile drains in the Jewett Brook watershed.

Ten agricultural tile drains were selected for monitoring, five in Addison County and five in the Jewett Brook watershed in Franklin County. Four out of five of the Addison County tile drains drain silage cornfields, and the fifth (ACT4) drains a hayfield. In the Jewett Brook watershed, monitoring begun in 2017 (described in Braun et al. 2019) was extended at five tile drains for an additional 16 months. Four of the Jewett Brook tile drains drain silage cornfields and one (JBT11) drains an alfalfa hayfield with low P inputs. All ten tile drainage systems are constructed of standard, perforated, corrugated drainpipe, installed 3-5 feet below the ground surface, arrayed in a pattern of parallel laterals. All were installed since 2006.

Flow-proportional composite samples were processed approximately weekly and analyzed for total phosphorus (TP), total dissolved phosphorus (TDP), total nitrogen (TN), and total suspended solids (TSS) concentrations. Across the 10 tile drains, median TP concentrations ranged from 20 – 570 µg/L (mean = 189 µg/L) and median TDP concentrations ranged from 9 – 208 µg/L (mean 81 µg/L). Concentrations in individual composite samples reveal even greater variability than do these site medians: across all sites, TP concentrations ranged from 11 – 3,193 µg/L (median = 120 µg/L) and TDP concentrations ranged from 6 – 1,735 µg/L (median 56 µg/L) in individual samples. These P concentrations are more comparable to ranges observed in Ontario (20 – 9,700 µg/L; Miller 1979), Ohio (110 – 300 µg/L; King 2014), and Wisconsin (80 – 1,780 µg/L; Madison et al. 2014) than to the few Lake Champlain Basin studies available (Benoit 1973, Young 2015, and Klaiber 2015).

The five Addison County tile drains selected for this monitoring study had significantly higher TP and TSS concentrations than the five Jewett Brook watershed tile drains, when grouped by county/watershed. Differences in TDP and TN concentrations were not significant. TP, TDP, TN, and TSS loads were all significantly higher in the Addison County tile drains than in the Jewett Brook watershed tile drains. The greater TP concentrations and TP and TDP loading from the Addison County tile drains could have resulted from a variety of factors (for example, differences in tile drain construction, agronomic history, and storm intensity and timing relative to nutrient application) that were not analyzed in detail in this study, given the relatively small number of tile drains representing each county/watershed. The overriding conclusion is that substantial P concentrations and loads in tile drainage water in the Lake Champlain Basin occur in Addison County and are not confined to tile drains in the Jewett Brook watershed.

An interesting exception to the pattern of nutrient and sediment concentrations and loading in the Addison County tile drains was the ACT1 tile drain, which drains a cornfield with loamy sand soils. The ACT1 tile drain delivered significantly lower concentrations and loads of TP, TDP, and TSS and higher concentrations of total nitrogen (TN) than the other Addison County tile drains, which have clay soils. We attribute these differences to differing soil texture.

P filters composed of reactive media have been shown to be effective in reducing total and dissolved P loading from agricultural tile drains prior to discharge to receiving waters (Braun 2017, McDowell et al. 2008, Penn et al. 2012, Bryant et al. 2012). Widespread adoption of tile drain P filters has the potential to reduce P loading to Lake Champlain and improve its water quality. For this project, Stone designed, constructed, and monitored two large, up-flow, gravity P filters in trenches excavated near the outlet of one of the monitored tile drains—JBT05—in St. Albans. The JBT05 P filters were constructed in October-November 2019, after the Addison County/Jewett Brook watershed tile drain monitoring program was completed. These P filters were able to treat substantial volumes of water, with flow rates up to approximately 250 L/min. Filter A contained only crushed Swanton black shale and reduced TP and TDP concentrations by about 40%, while Filter B contained crushed Swanton black shale, zero-valent iron shavings, and activated alumina beads and achieved ~60% reduction in TP and ~65% reduction in TDP concentrations and ~60% reductions in TP and TDP loads. The TP and TDP reduction efficiencies of both filters improved with increasing TP and TDP inflow concentrations.

Analysis of paired inflow/outflow data over 38 weeks of automated, flow-proportional, composite sample collection indicates a combined removal between the two filters of approximately 1.6 kg (3.5 lb.) of TP and 1.1 kg (2.4 lb.) of TDP. Since 2020 had an exceptionally dry summer and fall, with no tile drain flow for extended periods, greater P removal should be possible in most years. Furthermore, because the filters discharge to an agricultural ditch that was frequently backwatered, substantial bypass flow occurred. Similar filters constructed in less flood prone locations should treat a higher proportion of tile drain flow and remove more P.

We believe this project demonstrated that Stone's basic concept of developing large, in-ground, up-flow, gravity filters containing a coarse (~1/2-inch diameter) aggregate amended with one or more P sorbing materials to remove P from tile drainage water is sound. The analysis of P reduction efficiency indicated that reasonably consistent dissolved P removal occurred at inflow concentrations above 60 µg/L of TDP. This threshold may be a useful guide in selecting tile drains for implementation of P filters, until a more complete benefit-cost analysis is completed for the tile drain P filter evaluation Stone is now conducting in Lake Carmi watershed in Franklin, Vermont.

# Assessment of Tile Drainage Systems in Addison County and the Jewett Brook Watershed

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# 1. Introduction

### 1.1. Background

Lake Champlain (Vermont – New York – Quebec) continues to suffer from the effects of excessive phosphorus (P) loading from sources in the Lake Champlain Basin (LCB). One factor that may contribute to the slow pace of progress in attaining water quality goals is the loss of P via agricultural tile drainage systems. For many years, relatively scant attention was given to potential tile drainage contributions of P to local receiving waters due to the prevailing view that, because soils have an affinity for P, losses of P via subsurface drainage should be minimal. However, recent research has revealed that tile drainage systems in agricultural fields can discharge significant quantities of P under a wide range of soil characteristics and management practices. Vadas et al. (2007), Sims et al. (1998), Kleinman et al. (2003), Beauchemin et al. (2003), and King et al. (2014) all demonstrated that a considerable amount of P can be transported beneath the surface in tile drained fields.

Phosphorus concentrations in tile drainage water reported in the literature frequently exceed the U.S. EPA threshold of 100 µg/L for eutrophication in surface waters (U.S. EPA 1994). In the UK, total phosphorus (TP) concentrations exceeding 1000 µg/L have been observed in tile drainage water, with up to roughly 90% in dissolved form (Heckrath et al. 1995, Gardner et al. 2002). Algoazany et al. (2007) reported annual mean dissolved P concentrations of 86–194 µg/L in drainage water in Illinois. Kinley et al. (2007) reported mean concentrations of 230 µg/L TP and 60 µg/L dissolved P in drainage samples from cropland fields in Nova Scotia. Madison et al. (2014) measured average annual TP concentrations of 21–1300 µg/L in tile drainage from Wisconsin field sites.

Phosphorus exported from agricultural fields in tile drainage water can represent a significant component of overall nonpoint source P loads. In southern Quebec, Eastman (2008, 2010) reported TP loss in drainage water of 1.2 to 4.0 kg/ha, the same order of magnitude reported in surface runoff from agricultural fields. King et al. (2014) reported that tile drainage from an Ohio watershed contributed 0.48 kg/ha of TP, compared to an average annual watershed TP export of 0.98 kg/ha. Drainage water accounted for 47% of the dissolved P and 40% of the TP exported from the watershed. In Wisconsin, Madison et al. (2014) reported annual TP loads in tile drainage of 0.24–2.73 kg/ha, contributing 17 to 41% of all TP loss and up to 72% of dissolved P loss. Smith et al. (2015) documented that 49% of dissolved P and 48% of TP losses from Indiana research fields occurred via tile discharge.

Subsurface tile drainage is an essential agronomic practice on many agricultural fields, enabling timely equipment access, reduced soil compaction, and increased crop yields in fields otherwise too wet to efficiently farm. Tile drainage can provide significant environmental benefits, from reduced soil erosion to more efficient nutrient uptake by crops to enabling more timely application of conservation measures, because producers face fewer delays due to wet field conditions. By drawing down the water table and providing rapid conveyance of subsurface water to an outlet, tile drainage can significantly change the hydrologic behavior of a field, reducing surface runoff by enhancing infiltration and ground water transmission. We now know that, management remaining equal, the net result of reduced surface runoff P losses and increased subsurface P losses may be positive or negative, depending on the field and the year.

Although research is not yet conclusive on the factors driving P export via tile drains, characteristics that appear to enhance P loss include: the presence of macropores (e.g., soil cracks and worm holes), especially on clay soils (Beauchemin et al. 1998, Kleinman et al. 2003, Eastman 2010); high drainage flows associated with precipitation or snowmelt events (Gentry et al. 2007); excessive accumulations of P in soils (Beauchemin et al. 2003, Kinley et al. 2007, Toor and Sims 2015); and high nutrient inputs, especially manure applications to soils with high or excessive soil test P (Sims et al. 1998, Kinley et al. 2007).

In Vermont, as in much of the nation, the pace of tile drain installation has accelerated in recent years. As the area of systematically drained cropland rises, concern regarding nutrient losses and other water quality impacts related to tile drainage has increased. In the LCB, the extent of tile drainage systems and the potential impacts of tile drainage systems on water quality have not been adequately assessed. Recent research, including a previous study by Stone Environmental (Stone) for the Lake Champlain Basin Program (LCBP) in the Jewett Brook watershed in Franklin County (Braun et al. 2019), has revealed that subsurface drainage systems in agricultural fields can discharge significant quantities of P, and should thus be considered in management strategies seeking to minimize nonpoint source pollution of surface waters.

Beginning in the 1930’s, the USDA Soil Conservation Service, now the Natural Resources Conservation Service (NRCS), began developing conservation practices to reduce soil erosion and nutrient losses from cropland. Today we have a long list of conservation practice standards concerning everything from manure and silage leachate management in barnyards to erosion prevention and sediment and nutrient control on cropland. Practices targeting surface runoff, however, may not be sufficient to meet water quality targets if a substantial portion of the P loading from tile-drained agricultural land is delivered through subsurface drainage. Currently, there is no national NRCS practice standard addressing phosphorus losses via tile drainage, although Vermont NRCS has a relevant standard (Phosphorus Removal System, Code 782), adopted in 2013.

Phosphorus removal systems installed at the outlets of tile drains that direct flow through filtering media can significantly reduce P loads to drainage ditches and receiving waters (Braun 2017, McDowell et al. 2008, Penn et al. 2012, Bryant et al. 2012). Widespread adoption of tile drain treatment systems has the potential to reduce P loading to Lake Champlain and improve its water quality.

### 1.2. Current Project

This tile drainage project had two parts. The first part was a monitoring program to improve our understanding of tile drainage system nutrient losses in the Lake Champlain Basin. We monitored five representative tile drainage systems in the Jewett Brook watershed in Franklin County and five in Addison County to measure nutrient and sediment concentrations and estimate nutrient and sediment mass loads in tile drainage water. The five tile drains monitored in the Jewett Brook watershed were selected from among 12 tile drains monitored from April

2017–April 2018 by Braun and others (2019), extending the monitoring period at these tile drains through August 2019.

The second part of this project involved the design, construction, and monitoring of tile drainage water treatment systems (or “P filters”). Such P filters can reduce P loading from agricultural tile drains prior to discharge to receiving waters. Stone has been working to develop suitable P filters for the last seven years. In this project, two large P filters containing reactive media were constructed near the outlet of one of the monitored tile drains—JBT05—in St. Albans. The JBT05 P filters were constructed in October-November 2019, after the Addison County/Jewett Brook watershed tile drain monitoring program was finished, and monitored through December 2020.

### 1.3. Project Objectives

The objectives of this project were:

- To characterize field areas drained by tile drainage systems selected for monitoring in Addison County and in the Jewett Brook watershed in Franklin County.
- To measure total and dissolved P concentrations and flow and calculate P loads from representative tile drainage systems in Addison County and in the Jewett Brook watershed in Franklin County.
- To characterize the distributions of total nitrogen and total suspended solids concentrations in drain flow from representative tile drainage systems in Addison County and in the Jewett Brook watershed in Franklin County.
- To design and construct two P filters and evaluate their performance in reducing total and dissolved P loading from an agricultural tile drain.

# 2. Tasks Completed

The following tasks were accomplished to meet the study objectives.

**Project Review Committee:** A Project Review Committee (PRC) was assembled to advise Stone in execution of this project. The PRC included representatives from LCBP, the University of Vermont, the University of Vermont Extension Service, the Vermont Agency of Agriculture, Food & Markets, and the Vermont Agency of Natural Resources. At an April 24, 2019 PRC meeting, Stone presented the selection and characterization of the Addison County tile drain sites as well as draft engineering plans for the tile drain P filters to be installed at the JBT05 site in St. Albans. Constructive feedback was received from PRC members regarding the P filter designs.

**Prepare Quality Assurance Project Plan (QAPP):** A primary data QAPP addressing the monitoring phases of the project was approved on November 21, 2018. This QAPP was amended to incorporate the P filter experiment. The amended QAPP (Version 2.0, Amendment 1) was approved on March 26, 2019. This QAPP is included as Appendix A.

**Select and Characterize Tile Drainage Systems:** In the Jewett Brook Watershed, 5 of the 12 tile drainage systems monitored during the original tile drainage assessment (Braun et al. 2019) were selected for continued monitoring in this project.

In Addison County, Stone conducted a comprehensive outreach effort to farmers and agricultural agents to identify tile drainage systems suitable for monitoring. Considering location, access, drainage area, and crop type, five tile drained fields were selected for monitoring that best met the objectives of the study. Stone submitted a report describing the selection and characterization of the Addison County tile drains, portions of which are incorporated in this final report. The tile drainage systems selected for monitoring are described in Section 3.

**Collect Agronomic Data:** Stone interviewed the participating farmers and recorded direct observations regarding farming activities. These results are presented in Section 3.

**Install Monitoring Systems:** Stone completed installation of the tile drain monitoring stations at the five Addison County sites. The stations were operational as of November 21, 2018. In the months prior, Stone made any repairs needed at the five continuing Jewett Brook watershed stations. This task is discussed in more detail in Section 4.

**Perform Monitoring Activities**: Stone monitored the selected tile drainage systems according to the project workplan and the approved primary data QAPP. The methods and results of this task are presented in Section 4 and Section 7. We estimate that field technicians made about 800 visits to the tile drain monitoring stations over the course of this project. A great deal of effort was expended collecting and processing flow data. The resulting tile drain hydrographs are included in Appendix B.

**Sample Analysis:** The Vermont Agriculture and Environmental Laboratory (VAEL) completed analysis of all water samples submitted in this study. The Agricultural and Environmental Testing Lab (AETL) at the University of Vermont and the Maine Agricultural and Forestry Experiment Station (MAFES) Lab at the University of Maine, Orono, completed analysis of all submitted soil samples. Approved water quality data are presented in Appendix C. Results of sol sample analyses are presented in Section 3.

**Design and Construct P Filters:** Stone designed and oversaw construction of two P filters at the JBT05 site in St. Albans. This task is described in Section 5. The as-built filter drawings are presented in Appendix D.

**Maintain Facilities:** Stone maintained the tile drain monitoring stations throughout the monitoring period and decommissioned the stations when monitoring was complete.

**Prepare Reports:** Stone submitted quarterly progress reports throughout this project. Stone also submitted an interim report describing the selection and characterization of the Addison County tile drains, the design and construction of the P filters, and the installation of the monitoring systems.

This final report covers aspects of site characterization, monitoring station installation and maintenance, design and construction of the P filters, monitoring activities, tile drain monitoring data, and an evaluation of the P filters.

# 3. Tile Drain Characterization

## 3.1. Selection of Jewett Brook Watershed Tile Drains for Continued Monitoring

Among the 12 tile drainage systems monitored during the original Jewett Brook watershed tile drainage assessment project (Braun et al. 2019), 5 were selected for continued monitoring. The Jewett Brook tile drains ("JBT") where monitoring was extended were JBT05, JBT06, JBT07, JBT11, and JBT18. These tile drains and fields were described by Braun and others (2019) in LCBP Technical Report Number 92: https://lcbp-089519.s3.us-east-2.amazonaws.com/techreportPDF/92_20190830-Jewett-Brook-Tile-Drain-Assessment-Final-Report-Approved_web.pdf.

In most cases the decision to extend monitoring was based on the continued cooperation of the participating farmer. Three of the original study participants, accounting for six of the original JBT sites, declined to participate further. One monitoring station, JBT19, was eliminated from consideration due to heaving of soil into the monitoring manhole.

Although we had very little choice in which Jewett Brook watershed tile drains to select for continued monitoring, the selected set represent an interesting range of conditions. One permanent hay site (JBT11) was included and differences in the management of the four remaining crop fields provided representative agronomic variation.

## 3.2. Selection of Addison County Tile Drains and Study Fields

Stone conducted a comprehensive outreach effort to farmers and agricultural agents operating in Addison County to identify tile drainage systems suitable for monitoring. A meeting was organized in May 2018 with six Addison County farmers with tile drained cropland. During the meeting three farmers expressed a willingness to participate. These farmers were interviewed to identify specific tile drained fields under their management and site visits were then made to 11 fields. Considering location, access, drainage area, and crop type, five Addison County tile drainage systems, "ACT1" through "ACT5" (Figures 1 – 5), were selected for monitoring that best met the objectives of the study The ACT study fields included four cornfields and one hayfield. Stone secured access agreements with the three farmers managing the selected study fields.


*Figure 1. ACT1 outlet*


*Figure 2. ACT2 outlet*


*Figure 3. ACT3 outlet*


*Figure 4. ACT4 outlet*


*Figure 5. ACT5 outlet*

### 3.3. Characterization of Tile Drains and Study Fields

Data describing the tile drained fields selected for monitoring in Addison County and in the Jewett Brook watershed were obtained through field reconnaissance, interviews with participating farmers, review of nutrient management plans, and analysis of the USDA-NRCS SSURGO soils dataset. The extent of the drained area, the tile drain lateral spacing and depth, and the system construction and age were recorded from information provided by the participating farmer, as was information about the cropping system and inputs of manure and fertilizer. Soil type and slope class data were acquired from the SSURGO database. Soil test P data were assembled from nutrient management plans. Data describing the monitored tile drainage systems and study fields are presented in Table 1.

*Table 1. Tile drainage system construction*

| Site | Year installed | Area (A) | Outlet diam. (in.) | Outlet position | Tile drain depth (ft) | Tile drain spacing (ft) | Surface inlets | Soil survey data % of area, soil type, slope, hydrologic group | Soil test P (ppm) |
|---|---|---|---|---|---|---|---|---|---|
| JBT05 | 2011 | 94 | 8 | usually underwater | 3-4 | 35 | none known | 30%: Kingsbury clay, 0-3%, D<br>30%: Massena stony loam, 0-3%, C/D<br>29%: Covington clay, D<br>10%: Georgia stony loam, 3-8%, C | 2 |
| JBT06 | 2014 | 91 | 12 | surcharges | unknown | unknown | 3 standpipes plus diversion inlet from neighboring field | 51%: Covington clay, D<br>36%: Massena stony loam, 0-3%, C/D<br>7%: Kingsbury clay, 0-3%, D<br>6%: Georgia stony loam, 3-8%, C | n.d. |
| JBT07 | 2011 | 28 | 4 | surcharges | 3-4 | 40 | none known | 53%: Covington clay, D<br>37%: Kingsbury clay, 0-3%, D<br>10%: Massena stony loam, 0-3%, C/D | 12 |
| JBT11 | 2010 | 51 | 8 | surcharges | 3-4 | 40 | none known | 58%: Massena stony loam, 0-3%, C/D<br>16%: Georgia stony loam, 3-8%, C<br>15%: Georgia stony loam, 0-3%, C<br>11%: Covington clay, D | 4 |
| JBT18 | 2006 | 11 | 6 | surcharges | 3 | 80 | none known | 43%: Kingsbury clay, 0-3%, D<br>25%: Massena stony loam, 0-3%, C/D<br>17%: Georgia stony loam, 0-3%, C<br>15%: Covington clay, D | n.d. |
| ACT1 | ~2015 | ~40 | 6 | on slope | 3-5 | 25 | none known | 100%: Swanton FS loam, 0-3%, C/D | 7 |
| ACT2 | ~2013 | ~30 | 8 | in ditch, will surcharge | 3-5 | 25 | none known | 95%: Vergennes clay, 2-6%, D<br>5% Covington silty clay, 0-3%, D | 3 |
| ACT3 | 2017 | ~35 | 8 | ditch | 3-5 | 25 | none known | 90% Covington silty clay, 0-3%, D<br>10%: Vergennes clay, 2-6%, D | 3 |
| ACT4 | 2014 | ~25 | 6 | in ditch, will surcharge | 3-5 | 20 | none known | 90% Covington silty clay, 0-3%, D<br>10%: Vergennes clay, 2-6%, D | 8 |
| ACT5 | ~2014 | ~15 | 6 | on slope | 3-5 | 20 | none known | 80%: Vergennes clay, 2-6%, D<br>20% Vergennes clay, 12-25%, D | 2 |

n.d. = no data available

The following sections describe critical aspects of the construction of the tile drainage systems as well as agronomic factors in the study fields. These sections refer to data presented in Tables 1 and 2.

### 3.4. Tile Drainage System Construction

#### 3.4.1. Jewett Brook Watershed

The five JBT tile drains selected for continued monitoring are constructed of standard, perforated, corrugated drainpipe arrayed in a pattern of parallel laterals. They were installed since 2006 (Table 1). The outlets of these systems range in diameter from 4–12 inches.

The selected Jewett Brook watershed tile drains discharge to drainage ditches, close to the bottom of the ditch such that submergence of the outlet is common. The depths of the tile drains generally range from 3–4 feet below ground surface. The spacing of the laterals is in the typical range of 25–40 feet, except for JBT18, which has unusually wide, 80-foot spacing.

Surface water may enter subsurface drainage systems in a variety of ways, including standpipe inlets and rock inlets (French drains) constructed in field depressions, blind inlets, and diversions of concentrated flow from ditches, culverts, and roof drains into tile drain mains. Vermont's Required Agricultural Practices (VAAFM 2018) distinguish between surface inlets and diversion structures. There are no known surface inlets or diversions to tile drains JBT05, JBT07, JBT11, or JBT18. However, JBT06 has a cluster of three standpipes connected to the underlying drainage system in a wet area at the south end of the field. It was recently revealed that there is another inlet at the southern end of the JBT06 field, a diversion which conveys both surface runoff and tile drain flow from a large, adjacent field in corn production.

#### 3.4.2. Addison County

All five Addison County tile drainage systems selected for monitoring are constructed of standard, perforated, corrugated drainpipe arrayed in a pattern of parallel laterals. Tile drains were installed in all the study fields since 2013 (Table 1). The depths of the tile drains generally range from 3–5 feet below ground surface, with most in the 3–4-foot range. There do not appear to be any exceptionally shallow or deep tile drains. All five ACT tile drains have closely spaced laterals; the 20-foot lateral spacing in the ACT4 and ACT5 fields is unusually close in Vermont. The outlets of the ACT tile drains range in diameter from 6–8 inches; there are three 6-inch and two 8-inch diameter outlets. The ACT2 and ACT4 tile drains (Figures 2 and 4) discharge close to the bottom of drainage ditches, such that submergence is common. Submergence is not likely at the outlets of the remaining three tile drains.

There are no known surface inlets into any of the five tile drainage systems monitored in Addison County. In the ACT2 field there are several piped runoff diversions near the downslope end of the field; however, these discharge directly into the ditch, bypassing the tile drainage system.

### 3.5. Study Field Soil Types

#### 3.5.1. Jewett Brook Watershed

Two soil complexes comprise most of the area of the Jewett Brook watershed study fields. These complexes are the Kingsbury-Covington clays and the Massena-Lyons stony loams. Kingsbury-Covington clays are the principal soils in four of the five fields (Table 1). Massena and Georgia stony loams are the principal soils in the JBT11 field.

Clays in the Kingsbury-Covington complex are deep and somewhat poorly drained to poorly drained (Flynn and Joslin 1979). They formed in water laid deposits of clay on old lake plains. Kingsbury soils are at a higher position in the landscape than Covington soils. Both soils have a seasonal high water table. Without drainage, crop production on Kingsbury-Covington soils may be limited by wetness due to their slow permeability.

Massena-Lyons soils are deep, level to gently sloping, somewhat poorly drained and poorly drained, loamy soils in depressional areas (Flynn and Joslin 1979). These soils formed in glacial till. Massena-Lyons soils have a seasonal high water table. Without drainage, crop production on Massena-Lyons soils may be limited by wetness and a high water table.

Georgia stony loam comprises 31 percent of field JBT11, 17 percent of JBT18, and 10 percent of JBT05. Georgia stony loams are moderately well drained (Flynn and Joslin 1979), in contrast to the predominant soils among the study fields. They formed in glaciated uplands in western Franklin County and are deep and stony or extremely stony.

#### 3.5.2. Addison County

Three soil series comprise most of the area of the Addison County study fields. These soils are Vergennes clay, Covington silty clay, and Swanton fine sandy loam. Vergennes clay is the principal soil in two fields (ACT2 and ACT5), Covington silty clay in two fields (ACT3 and ACT4), and Swanton fine sandy loam in one field, ACT1 (Table 1). Vergennes and Covington clays in Addison County are deep and somewhat poorly drained to poorly drained (Griggs, 1971). As with the Kingsbury-Covington complex in Franklin County, Vergennes and Covington soils formed in water-laid deposits of clay on old lake plains. Covington soils are at a higher position in the landscape and are less sloped than Vergennes soils. Both soils have a seasonal high-water table. Without drainage, crop production on Vergennes and Covington soils may be limited by wetness due to their slow permeability.

ACT1 is the exception in this group of fields due to its sandy textured soils. Despite its sandy surface texture, the ACT1 field is considered somewhat poorly to poorly drained, because Swanton fine sandy loams form in depressional areas and are usually underlain by a layer of heavy clay. Tile drainage can increase crop production in these soils and prevent crop loss due to wetness.

### 3.6. Crop Production in Study Fields

Seven of the ten study fields (JBT05, JBT06, JBT07, ACT1, ACT2, ACT3, and ACT5) were in continuous silage corn production between 2017 and 2019 (Table 2). Two study fields, JBT11 and ACT4, were in continuous hay production: alfalfa/grass at JBT11 and grass at ACT4. The JBT18 field was seeded in 2016 for clover hay production, but was converted to organic corn production in 2018, then soybeans in 2019.

### 3.7. Soil Test Phosphorus Levels in Study Fields

The available soil test phosphorus concentration data presented in Table 1 were taken from nutrient management plans. The JBT07 field had a soil test P value of 12 ppm, in the high range but not considered excessive (University of Vermont Extension, 2020). The JBT05 and JBT11 fields had low to medium soil test P values.

The Addison County study field with the highest reported available phosphorus concentration was ACT4, the field in hay production. However, this concentration, 8 ppm, is not especially high, falling near the low end of the high soil test P range. Fields ACT2, ACT3, and ACT5 all had low to medium soil test P concentrations, and the P concentration at ACT1 is considered optimum from an agronomic standpoint.

### 3.8. Manure and Fertilizer Applications in Study Fields

Table 2 presents the available fertilizer and manure application data for the study fields for the period 2017-2019.

### 3.8.1. Jewett Brook Watershed

Liquid manure was usually injected in the JBT05 and JBT06 fields in the fall after the corn was chopped. However, manure was spread and incorporated in the spring of 2018 on both fields and again on JBT06 in 2019. At the JBT07 field, manure was apparently spread in the fall in 2016, not at all in 2017, both fall and spring in 2018, and only in spring in 2019.

Since the field was seeded in 2015 no manure was applied on the JBT11 hayfield until 2019.

### 3.8.2. Addison County

A small amount of starter fertilizer containing P was applied at planting on all the cornfields. The manure application methods of the three participating farmers on the study fields differed considerably. Manure application methods on the cornfields included fall surface application (ACT2 and ACT3) and fall injection (ACT5). To the best of our knowledge, these practices remained consistent between 2017 and 2019. At the ACT1 field, manure was spread in the spring of 2017, the fall of 2018, and the spring of 2019.

The one hayfield (ACT4) received three surface applications of manure in 2017; however, the participating farmer started injecting manure on this field in 2018.

*Table 2. Agronomic data for the study fields*

| Site | Year | Crop | Fertilizer application | Manure application | Cover crop |
|---|---|---|---|---|---|
| JBT05 | 2016 | silage corn | pop-up at plant | fall manure injection | winter rye |
| | 2017 | silage corn | pop-up at plant | fall manure spread ~10/10/17 and injected ~10/24/17 on portion | winter rye |
| | 2018 | silage corn | may have spread N ~6/20-29/18 | spring manure incorporated | unknown |
| | 2019 | silage corn | unknown | fall manure spread ~12/15/19 | NA |
| JBT06 | 2016 | silage corn | pop-up at plant | fall manure injection | winter rye |
| | 2017 | silage corn | pop-up at plant | fall manure injection | winter rye |
| | 2018 | silage corn | N spread 6/20/18 | spring manure ~4/24/18 - 5/1/18; fall manure on portion ~10/4-12/18 | unknown |
| | 2019 | silage corn | unknown | spring manure ~6/11/19 | NA |
| JBT07 | 2016 | silage corn | 5 gal/A pop-up at plant; 300 lb./A urea-ammonium sulfate-potash spread 7/4/16 | fall: 6,000 gal/A spread | none |
| | 2017 | silage corn | 10 gal/A starter + potash at plant; liquid N+P applied in summer | none | none |
| | 2018 | silage corn | 200 lb./A urea applied 6/20/18 | 6,000 gal/A spread 5/16/18; fall manure spread before 12/2/18 | none |
| | 2019 | silage corn | 200 lb./A urea applied 7/10/19 | 6,000 gal/A manure spread ~6/5//19 | none |
| JBT11 | 2016 | continuous alfalfa hay | 200 lb./A potash-ammonia sulfate-boron after 1st and 2nd cuts | none | NA |
| | 2017 | continuous alfalfa hay | 250 lb./A potash-ammonia sulfate-boron after 1st and 2nd cuts | none | NA |
| | 2018 | continuous alfalfa hay | 200 lb./A urea applied 7/6/18 | none | NA |
| | 2019 | continuous alfalfa hay | 200 lb./A urea applied 7/13/19 | 5,000 gal/A manure spread 7/15/18 & ~8/22/19 | NA |
| JBT18 | 2016 | hay (grass/clover) | no P | 12 ton/A liquid in mid-May | NA |
| | 2017 | hay (grass/clover) | no P | none | NA |

| Site | Year | Crop | Fertilizer application | Manure application | Cover crop |
|---|---|---|---|---|---|
| | 2018 | silage corn | 100 lb./A urea applied 7/13/18 | 0.5 -1.0 ton/A composted chicken manure spread 5/20/18 | none |
| | 2019 | soybeans | none | none | NA |
| ACT1 | 2017 | silage corn | starter at plant | spring manure | winter rye |
| | 2018 | silage corn | unknown | fall manure | grass |
| | 2019 | silage corn | unknown | spring manure before 4/10/19 | NA |
| ACT2 | 2017 | silage corn | starter at plant | fall spread, no-till | winter rye |
| | 2018 | silage corn | unknown | fall spread before 11/29/18 (multiple dates?) | grass |
| | 2019 | silage corn | unknown | fall spread before 10/16/19 (multiple dates?) | NA |
| ACT3 | 2017 | silage corn | starter at plant | fall spread, no-till | winter rye |
| | 2018 | silage corn | unknown | fall manure? | grass |
| | 2019 | silage corn | unknown | fall (~10/8/19) | NA |
| ACT4 | 2017 | hay (grass) | none | fall: 3 applications | NA |
| | 2018 | hay (grass) | urea in spring | injected | NA |
| | 2019 | hay (grass) | urea in spring | injected ~7/18/19 | NA |
| ACT5 | 2017 | silage corn | starter at plant | fall injection | triticale |
| | 2018 | silage corn | starter at plant | fall injection | winter wheat |
| | 2019 | silage corn | starter at plant | fall injection | NA |

### 3.9. JBT05 Field Soil Characterization

Further characterization of the JBT05 field in St. Albans was warranted because the JBT05 tile drainage system was chosen as the site of the tile drain P filters. At the JBT05 field, soil physical and chemical properties data were obtained through soil sample collection and analysis. Soil samples were collected on June 19, 2019. The study field was sectioned in two portions, a lower section comprised of clay soils (mapped as Covington and Kingsbury clays) and an upland section comprised of loam soils (mapped as Massena and Georgia stony loams). A representative composite sample was collected from each section.

Soil samples from the 0–15 cm depth were collected at nodes in a sampling grid (Figure 6) using a stainless-steel soil probe. Individual soil samples were blended in a bucket using a garden trowel. The trowel was used to transfer approximately two cups (0.5 L) of the composited sample into a labelled polyethylene bag. Soil samples were held under ambient conditions and transported to the Agricultural and Environmental Testing Laboratory at UVM in Burlington, VT. Samples were analyzed for pH and cation exchange capacity. Available macronutrients and micronutrients were analyzed following extraction in modified Morgan solution. Organic matter was quantified by the loss on ignition method and reported in Walkley-Black method equivalents. Soil particle size was analyzed by wet sieving and the hydrometer method.

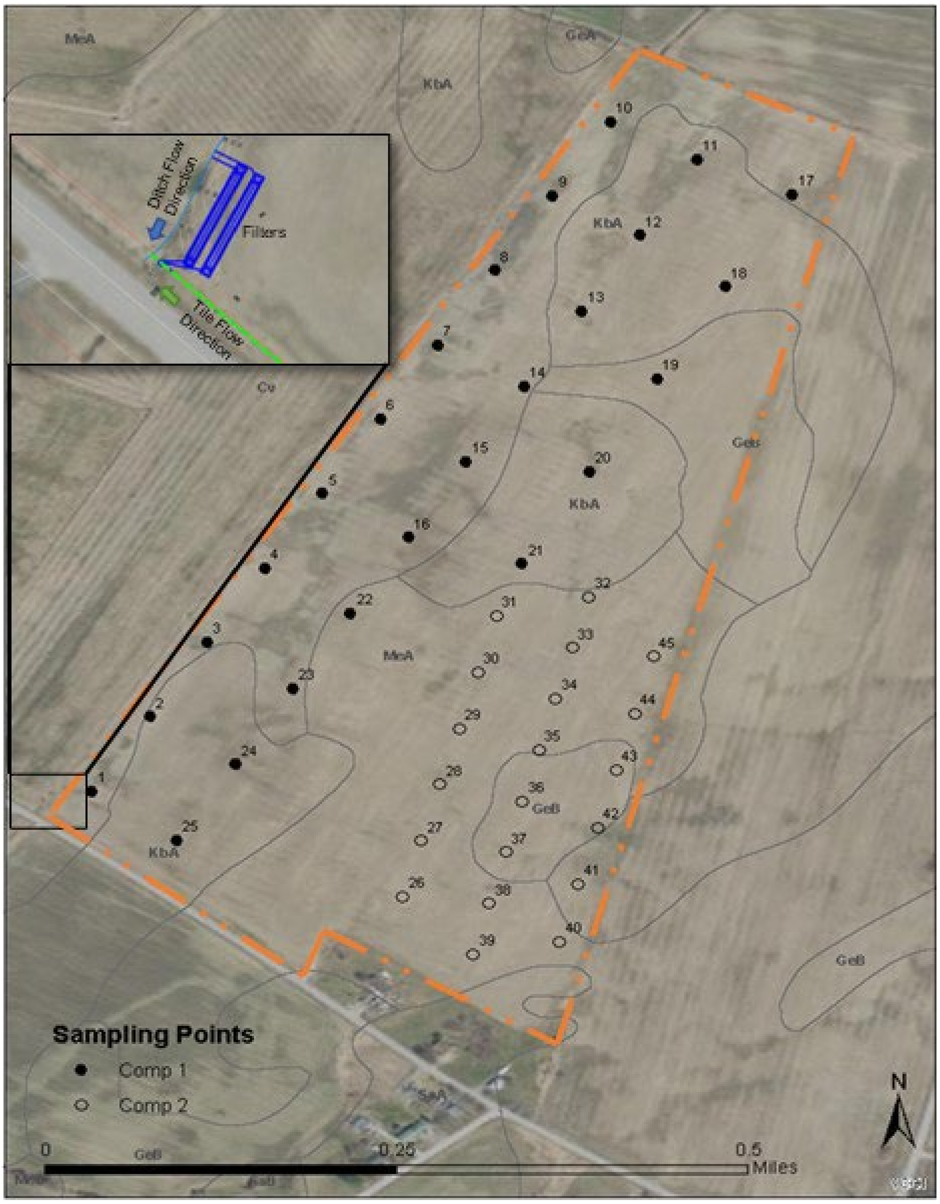



*Figure 6. Soil sampling locations in the JBT05 study field*

Soils data for the JBT05 study field are presented in Table 3.

*Table 3. Soil characterization of the JBT05 study field*

| | Optimum range or Average value[1] | Composite 2 sample | Composite 1 sample | Composite 1 (dupe) | Composite 1 (mean) |
|---|---|---|---|---|---|
| **Texture class** | NA | Loam | Clay loam | Clay loam | Clay loam |
| **Particle size analysis** | | | | | |
| Sand % | NA | 36.1 | 25.0 | 25.2 | 25.1 |
| Silt % | NA | 38.7 | 37.5 | 37.7 | 37.6 |
| Clay % | NA | 25.2 | 37.5 | 37.1 | 37.3 |
| **Soil pH (2:1, water)** | | 6.4 | 6.9 | 6.9 | 6.9 |
| **Macronutrients** | | | | | |
| Phosphorus (ppm) | 4 - 7 | 16.6 | 19.4 | 15.6 | 17.5 |
| Potassium (ppm) | 100-130 | 408 | 277 | 288 | 283 |
| Calcium (ppm) | ** | 2029 | 2988 | 2923 | 2956 |
| Magnesium (ppm) | 50-100 | 330 | 520 | 522 | 521 |
| Sulfur (ppm) | 11* | 15 | 16 | 19 | 18 |
| **Micronutrients** | | | | | |
| Iron (ppm) | 7.0* | 2.8 | 4.3 | 5.1 | 4.7 |
| Manganese (ppm) | 8.0* | 6.6 | 6.1 | 6.6 | 6.4 |
| Boron (ppm) | 0.3* | 0.5 | 0.5 | 0.5 | 0.5 |
| Copper (ppm) | 0.3* | 1.7 | 1.5 | 1.7 | 1.6 |
| Zinc (ppm) | 2.0* | 1.5 | 1.8 | 1.6 | 1.7 |
| **Sodium (ppm)** | 20* | 45.0 | 45.0 | 46.0 | 45.5 |
| **Aluminum (ppm)** | 35* | 11 | 12 | 13 | 12.5 |
| **Soil Organic Matter (%)** | ** | 4.5 | 4.8 | 5.1 | 5.0 |
| **Effective CEC (meq/100g)** | ** | 13.9 | 20.0 | 19.7 | 19.9 |
| **Base Saturation** | | | | | |
| Calcium Saturation (%) | 40-80 | 68.8 | 74.8 | 74.2 | 74.5 |
| Potassium Saturation (%) | 2.0-7.0 | 7.1 | 3.6 | 3.7 | 3.7 |
| Magnesium Saturation (%) | 10-30 | 18.7 | 21.7 | 22.1 | 21.9 |

1. From *Nutrient Recommendations for Field Crops in Vermont* (University of Vermont Extension, 2020)

* Micronutrient and sulfur deficiencies are rare in Vermont and optimum ranges are not defined; thus, average values in Vermont soils are shown instead.

** Ranges shown are for Field Crops; Vegetable ranges are higher. Ranges for calcium, organic matter, and effective CEC vary with soil type and crop.

# 4. Tile Drain Monitoring Methods

### 4.1. Installation of Monitoring Systems

The Jewett Brook watershed and Addison County tile drain monitoring stations were nearly identical. The only important exceptions were the flow monitoring systems at JBT06 and ACT3. Aside from these exceptions, which are described in Sections 4.1.1 and 4.1.2, the following general description applies to all the JBT and ACT stations.

Monitoring manholes, instrument shelters, and solar panels were installed at each site. Manholes were constructed by excavating to a depth ~2 feet below the tile drain line, cutting out a section of the existing pipe, attaching a rigid pipe trap on the incoming tile line, and installing a 36-inch diameter, double walled culvert vertically over the pipe trap. The vertical culvert was notched to fit over the incoming and outgoing pipes. The outgoing pipe is the existing tile line, which remains at its pre-construction elevation. The pipe trap ensures that water flows into the manhole under full-pipe conditions. Drainage stone and soil were backfilled around the manhole up to grade. A plywood cover was placed over the manhole for safety purposes.

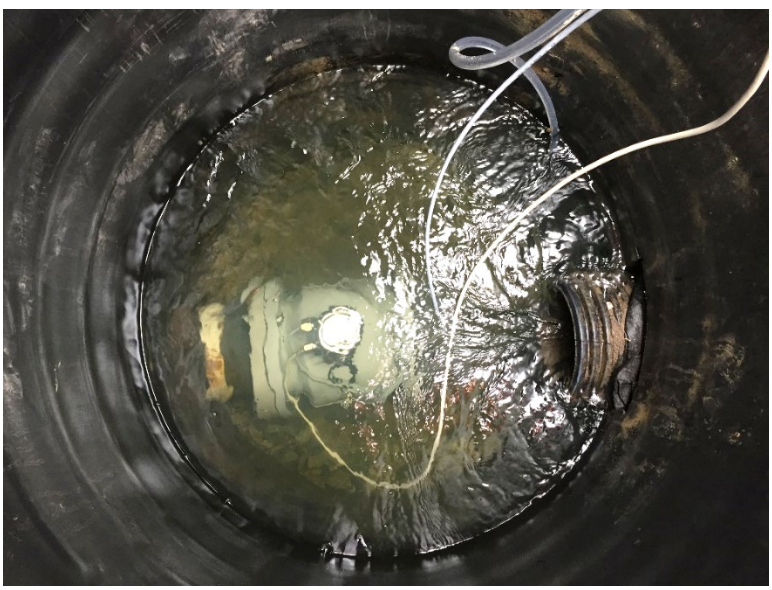


*Figure 7. 8-inch Waterflux 3000 flowmeter in JBT11 manhole*

All stations except JBT06 and ACT3 were equipped with Waterflux 3000 electromagnetic flowmeters (Figure 7). Each Waterflux 3000 flowmeter was cabled to a Krohne IFC-100W signal converter, which processes electrical signals into meaningful flow data. The signal converter was connected to an ISCO 2105ci datalogger/modem for continuous storage and transmission of flow data and to an ISCO 6712 autosampler for collection of flow-paced composite water samples. The wiring and programming of these instruments were highly customized for this monitoring application.

In each monitoring shelter (Figure 8), an ISCO 6712 autosampler was mounted on a custom manifold consisting of funnels and hoses to dispense water to a carousel of four 10-L carboys. Sample lines were run into the monitoring manhole. The flowmeters were programmed to transmit an electrical pulse to the autosampler for every 100 liters that passed through the tile line. The autosamplers were programmed to dispense 95-mL aliquots of sample to the carboys upon receiving a specific number of electrical pulses. The sampling interval was set with the goal of collecting between 2 L and 20 L of sample at each station during a week-long sampling period.

Figure 8. JBT11 monitoring station

ISCO 2105ci modems were programmed to transit flow and sampling data to a computer server at Stone's office in Montpelier. Each modem has a static IP address, allowing two-way communication and remote control of the autosampler. These data were checked periodically to assess whether the monitoring systems were working as intended.

The ACT stations were installed and operational as of November 21, 2018. Any repairs and maintenance needed at the five continuing JBT stations were performed in the months prior.

#### 4.1.1. JBT06 flow monitoring

Due to the large (12-inch) diameter of the JBT06 tile drain main, it was not feasible to install a pipe trap for an electromagnetic flowmeter or a manhole over the pipeline. Therefore, a different type of access structure was designed, a large plywood box (8 ft. long x 4 ft. x 4 ft.) containing a 90-degree V weir. The long dimension of the box was installed in-line with the tile drain. A 6-ft. long section of the tile drain was cut out and the box was constructed to span the gap. The end walls of the box were notched to accommodate the ends of the pipe. A plywood, 90-degree V weir plate was installed in the box and sheet metal strips were affixed to it to form a sharp crested, 90-degree V weir. The notch in the weir was approximately 3 inches (8 cm) higher than the invert of the outgoing pipe. A hatch was constructed on the top of the weir box for access and installation of monitoring instruments.

An ISCO 2110 ultrasonic flowmeter was installed for continuous measurement of water level. The stated accuracy of this instrument is the greater of ±0.00396 m or 0.00256 m per foot (0.305 m) from the calibration point. The sensor for this flowmeter was installed on a bracket on the upstream side of the weir, over the water surface. The flowmeter computes discharge from measured water level using a rating equation developed for this structure. Based on 32 paired, manual measurements of stage and flow rate made between 2017-2019, a rating equation was developed to compute flow rate from continuously recorded stage data. This rating provides a slightly improved estimate of flow rate as compared with the standard equation for a 90°V weir. The rating equation was programmed in the 2110 flowmeter to enable accurate computation of flow. The standard 90°V weir equation (from Teledyne ISCO, 2013) and our empirically derived rating equation are:

90°V weir equation: Flow rate (L/s) = $(\text{stage in cm}/5.5469)^{2.5}$
Rating equation: Flow rate (L/s) = $(\text{stage in cm}/5.072)^{2.7367}$

The ISCO 2110 flowmeter was connected to an ISCO 2105ci datalogger/modem for continuous recording and transmission of flow data. The 2105ci modem/logger was also wired to an ISCO 6712 autosampler enabling collection of flow-paced composite samples.

#### 4.1.2. ACT3 flow monitoring

ACT3 was monitored differently because the outlet does not become submerged. At ACT3, flow was measured using a 15-inch Thelmar weir and an ISCO 2110 ultrasonic level sensor mounted within the monitoring manhole. The sensor was installed on a bracket on the upstream side of the weir, over the water surface. The ISCO 2110 flowmeter computes discharge from measured water level using a weir equation, while an ISCO 2105ci datalogger/modem transmits flow data to Stone and enables a connected ISCO 6712 autosampler to collect flow-paced composite samples.

### 4.2. Monitoring Activities

Monitoring activities were performed in accordance with the project Quality Assurance Project Plan, Version 2.0, Amendment 1 (Appendix A). At the Jewett Brook watershed sites, monitoring continued from May 2018 through August 2019 (16 months). Monitoring of the Addison County tile drain sites was initiated in November 2018 and continued through November 2019.

Flow-proportional sampling is challenging because flow rates are highly variable and difficult to predict. If sample aliquot collection is too infrequent (e.g., in small flow events), insufficient sample volume may be collected to perform the intended analyses. If sample aliquots are collected too frequently (e.g., in an unexpectedly large flow event), the bulk sample container may not have the capacity to contain samples over the entire event, resulting in a non-representative sample. To minimize the occurrence of under-sampling and overfilling, a two-part program was used whereby the autosampler pumps sample aliquots to two sets of containers at different intervals of accumulated flow. Each bottle set consisted of two 10-L polyethylene carboys. The first bottle set (Set A) was intended to capture a representative sample at low flow rates and the second bottle set (Set B) was intended to capture a representative sample at high flow rates. Set B was filled at approximately one tenth the frequency of Set A. The second bottle in each set was filled only after the first became full, at the same frequency as the first.

Sampling personnel selected either Set A or Set B for analysis, but not both sets. Any sample in the bottle set not chosen was discarded. If the combined volume of Set A was less than ~14 L, Set A was processed, and Set B was discarded. If the combined volume of Set A was greater than 14 L, Set B was processed, and Set A was discarded.

In most events, only the first bottle in the selected bottle set contained sample. However, if both bottles #1 and #2 in the selected set contained sample, the sample volumes were combined in the large capacity (14-L) churn splitter used to obtain sample splits (Figure 9), unless doing so would exceed the capacity of the churn splitter. If greater than 14 L was collected in total in the selected bottle set, then bottles #1 and #2 were processed independently. Split samples from both bottles were submitted for analysis to allow calculation of total P flux.

Adjustments to the autosampler programs to increase or decrease the sampling frequency were made either directly or via remote access. Failure of the system to collect at least three sample aliquots in bottle Set A during a weekly period or exceeding the capacity of all sample bottles in Set B typically resulted in rejection of the sample as non-representative.

At each of the monitored tile drains, flow was recorded continuously, and flow-proportional composite water samples were collected approximately weekly to provide TP, TDP, TN, and TSS concentration data representing the preceding period.

Over the winter months, grab samples were collected approximately weekly from December 2018 until early April 2019, at which time flow-paced composite sampling was resumed.

Collected water samples were transported on ice to VAEL within the stated holding times for each analyte. Samples were tracked using a Chain of Custody form that was completed by the sampler and accompanied all water samples delivered to VAEL. Once the water samples were accepted by VAEL, they were subject to the lab's internal tracking system.


*Figure 9. Processing a composite water sample*

#### 4.2.1. Challenges Encountered

Short days, cold temperatures, and snow accumulation on the solar panels caused periodic low voltage problems and power outages at ACT2 from November 21–29, 2018 and at JBT11 from December 1–7, 2018. A second battery and extra solar panel were installed at JBT11 and the solar panel at ACT2 was relocated. No power outages occurred after these adjustments. After heavy snowfall, additional site visits were required to clear the solar panels.

The flowmeter at the JBT05 site began malfunctioning on February 2, 2019. The cause of the periodic, erratic readings was not readily apparent. Ultimately, we needed to wait until water levels in the monitoring manhole dropped enough to allow removal of the submerged flow tube. The flow tube was removed on March 21, 2019 and found to be irrevocably damaged. Delivery of a replacement flow tube from the Netherlands was slow. In the interim, an ISCO 2150 Area-Velocity flowmeter was installed in the manhole outlet pipe to record flow velocity. In evaluating the resulting JBT05 flow dataset, we determined that enough of the data were either missing or potentially erroneous that the JBT05 flow data should be excluded from the analyses.

The ground surrounding the JBT18 monitoring manhole eroded badly in the winter of 2018-2019. Despite our repeated visits to shore up the manhole by hand, the farmer ultimately removed the manhole and the instrument shelter and regraded the edge of the field, prematurely ending monitoring of this site.

### 4.3. Water Sample Analysis

Water samples were analyzed according to VAEL's standard methods. These methods and relevant data quality objectives, assessment procedures, and reporting limits are described in VAEL's Quality Systems Manual, Revision 23, dated December 18, 2015. The methods of analysis are summarized in Table 4.

*Table 4. Water analysis methods*

| Analyte | Lab | Method |
|---|---|---|
| TP | VAEL | 4500-P H |
| TDP | VAEL | 4500-P H |
| TN | VAEL | 4500-N C-modified |
| TSS | VAEL | 2540-D |

References: Standard Methods for the Examination of Water and Wastewater; 21st Ed. 2005.

Approved analytical data for the ACT and JBT tile drain monitoring stations are included in Appendix C.

### 4.4. Monitoring Station Maintenance

Regular maintenance of the monitoring stations and instruments minimized the incidence of instrument malfunctions and other problems. Certain basic maintenance activities were conducted after each sampling event, to clean bulk sample containers, churn splitters, and sampler lines and to reset the autosampler. Routine maintenance included checking/replacing instrument desiccant and clearing vegetation from around the stations.

Monitoring station readiness was assessed through routine (minimum of twice weekly) review of flowmeter, autosampler, and battery voltage data transmitted in near real-time to Stone's computer server. Several important and not uncommon problems may be detected remotely and quickly using these data, for example, sampler error messages, erroneous autosampling attempts, and low battery voltage. Early detection of these problem conditions enabled timely response by sampling technicians to visit the monitoring station in question and correct the problem. Non-routine maintenance included clearing snow from solar panels, swapping in charged batteries when necessary, resetting autosampler programs, and troubleshooting cellular modems.

# 5. P Filter Design, Construction, and Monitoring

The proposed design for the P filters to be constructed at the JBT05 site were distributed to the PRC in April 2019. These designs were informed by literature review, discussions with other scientists and engineers, and benchtop experiments conducted by Stone, which are described below. Several design changes were made in response to feedback from the PRC. The P filters were installed in October-November 2019. As-built design drawings for the P filters are included as Appendix D.

## 5.1. Summary of Benchtop Experiments

### 5.1.1. Model P Filter Testing

A benchtop experiment was conducted using heavy duty gear sleds filled with porous media to model P filter trenches. Three benchtop filters were assembled. Short sections of 4-inch diameter perforated drainpipe were placed at either end of the sleds to distribute water and collect it at the opposite end after passage through the media. These pipes spanned the "length" of the filter, 73 cm. The sections of 4-inch diameter pipe in each sled were parallel and at the same elevation, allowing water to flow laterally through the media to the collection pipe. The filter "width" between the distribution and collection pipes (center to center) was 81 cm. A collection barrel was placed at the outlet of each filter and a pump was used to recirculate water from the collection barrel up to the distribution pipe. Figure 10 shows the constructed filters.

200 L of Montpelier tapwater was added to each collection barrel and circulated through the filter. The P concentration of the added water was negligible (<10 µg/L), and its pH was approximately neutral. A float switch in each collection barrel turned on the pump when the water level rose above a preset level. The pumps have a flow rate of 18.5 L per minute. A gate valve on the outlet pipe was partially closed during normal operation to restrict the flow rate of each filter to approximately 3 L per minute. With the pump shut off and the outlet valve open, each filter retained approximately 40 L of water below the level of the outlet pipe, leaving 160 L in the barrel. The filters were covered with plastic sheeting to reduce evaporation; however small water volumes were occasionally added to maintain the volume in each filter system (filter plus barrel) at approximately 200 L.

The volume of saturated media between the distribution and collection pipes (the effective media volume) was approximately 3.9 cubic feet (0.11 $m^3$). The media used in each filter was as follows:

1. PEA filter: washed ½-inch diameter pea gravel (the control)
2. AA filter: washed ½-inch diameter pea gravel with ~5% (by volume) activated alumina beads

3. SGB filter: crushed Swanton black shale screened to ¾ inch minus and rescreened by hand using ¼-inch hardware cloth to remove fines

The porosity (0.34) and hydraulic conductivity of the pea gravel were tested to aid in design of the full-scale filters. The hydraulic conductivity was high, 3.9 cm/s (0.15 ft/s), which indicated that ½-inch diameter stone should be suitable for use in subsurface P filters.

*Figure 10. Three filter sleds recirculating P solution*

#### *5.1.1.1. P removal*

On April 28, 2019, the filter sled experiment was begun by adding P to the collection barrel for each filter. Between April 28 and May 26, a target P concentration of 350 µg/L was maintained through regular additions of P. The 350 µg/L influent P concentration was intended to simulate a slightly elevated, but not unreasonably high, tile drainage water P concentration. For comparison, the annual flow-weighted average TP concentration of tile drainage water from the JBT05 tile drain was 197 µg/L during the 2017-2018 monitoring period.

Daily or twice daily P additions were made to bring the concentration of the recirculating water back to approximately 350 µg/L. The P concentration in the collection barrel was measured using a HACH DR 900 Multiparameter Colorimeter and PhosVER3 reagent. Note that the P fraction measured according to this method is total (unfiltered) reactive P. The mass of P required to return the P concentration to 350 µg/L was calculated based on the instantaneous P concentration in the collection barrel (assuming a system water volume of 200 L), and the appropriate amount of 316.0 mg/L, or later 2,686 mg/L, P solution was weighed and added to the collection barrel. Note that on May 7, 2019, a more concentrated stock solution was mistakenly added; the P additions on this date were approximately eight times the intended additions.

Beginning on May 26, 2019, a target P concentration of 3,000 µg/L was used. This higher concentration was used to gain a better understanding of the sorption capacities of the media within a reasonable period of time. Figure 11 shows the cumulative addition of P to each filter.

Our findings from this experiment were:

1. The PEA control filter removed essentially all the first addition of P (68 mg P) within the first 16 hours of operation, as did the AA and SGB filters. However, although the PEA filter continued to remove some P even six weeks into the experiment, its performance was poor. After the second day of the experiment, the concentration of the PEA filter outflow never fell below 230 µg/L. The total P mass removed over the experiment was less than 2 g.
2. The AA and SGB filters continued to sorb P for the duration of the experiment. P removal by the AA and SGB filters was similar though the first month of the experiment; however, the removal rates diverged in the second half of the experiment, with the AA filter removing more P mass than the SGB filter. The total amount of P sorbed by the AA filter (7.0 g) exceeded the amount sorbed by the SGB filter (5.2 g).
3. While the P sorption capacities of the SGB and AA media were not exhausted, the P removal efficiencies of both media declined over the course of the experiment. Following P additions on May 26, it took less than 24 hours for P concentrations to decline from 3,000 µg/L to 500–600 µg/L. Whereas, following P additions on June 17, it took 18 days of continuous recirculation for P concentrations to decline from 3,000 µg/L to 300–400 µg/L.

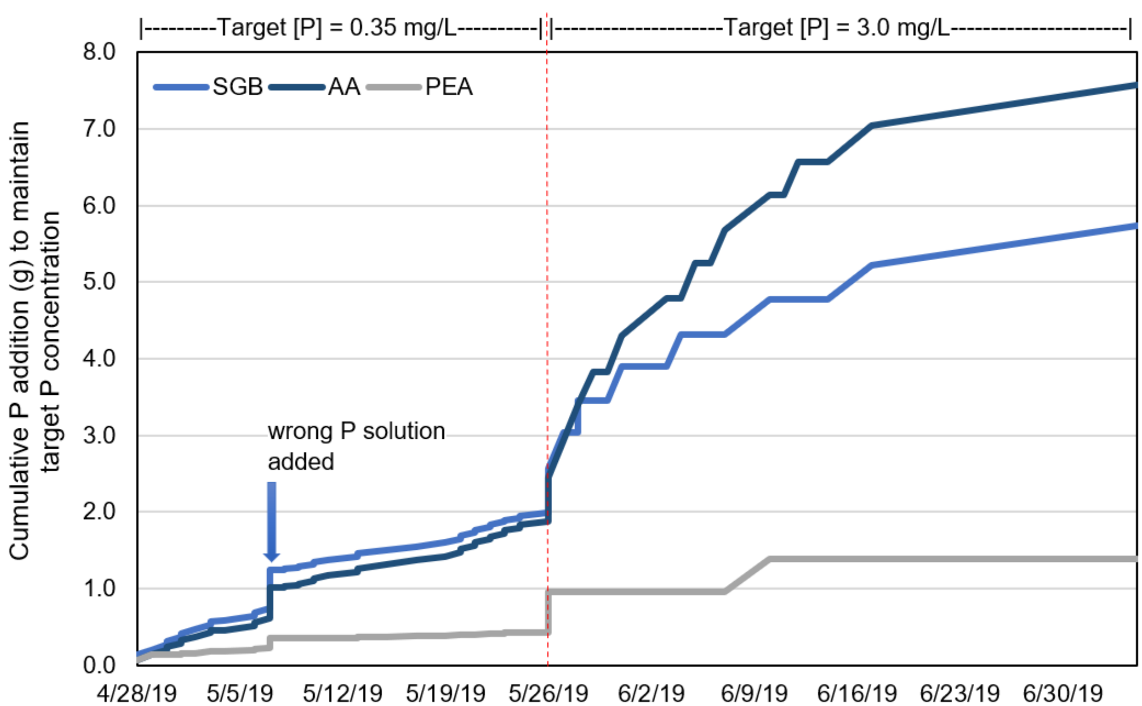



*Figure 11. Cumulative P additions to benchtop media filters*

#### *5.1.1.2. pH and Conductivity*

The pH of the recirculating P solution was tested periodically to identify any substantial effects of the media. The pH of the SGB water was slightly lower (range 7.1–8.1) than the pH of the AA water (7.9–8.4) and the PEA water (8.1–8.4). None of these readings suggested a concern for receiving water quality. Specific conductance was measured on one date, June 19, 2019, after water had cycled through the filters continuously for 52 days. The specific conductance of the

PEA water (366 µS/cm) and the AA water (301 µS/cm) were low; however, water in the SGB filter had substantially elevated specific conductance, 2,430 µS/cm. The Swanton black shale appears to confer greater electrical conductivity on water passing through it.

#### 5.1.2. Jar Testing of Drinking Water Treatment Residuals

Drinking water treatment residuals (DWTR) produced by the Champlain Water District have been shown to have impressive P sorption potential (ex., Braun 2017). From our experience, the difficulty with this material is that its fine particle size precludes its use in filters with high flow rates, such as the tile drain filters designed in this study. Therefore, we have begun to examine ways to combine this material with more conductive aggregates. Jar testing was conducted to provide relative information on the amount of P retained by different combinations of aggregate type, binding agent, and amount of DWTR. We found that 1) DWTR alone, 2) Portland cement coated on pea gravel aggregate, and 3) Portland cement and DWTR coated on pea gravel aggregate all appeared to provide rapid removal of dissolved P. An adhesive product we tested to bind DWTR to stone reduced the effectiveness of the DWTR and was difficult to use. Even applied sparingly, the adhesive drained to the bottom of the jar and set in a hard mass.

In this study we were not able to solve the problem of how to produce a suitable media incorporating DWTR in quantities sufficient for use in full-scale filters. However, Stone recently constructed a P filter to treat stormwater pond outflow that consists of 8% DWTR (by volume) mixed in well-graded ½-inch Swanton black shale. The DWTR adhered adequately to the wet stone during mixing and installation. Data describing performance of this stormwater pond outflow P filter are in development.

### 5.2. P Filter Design and Construction

Stone designed two large, in-ground filters to remove P from tile drainage water at the JBT05 site, one filter (“Filter A”) containing Swanton black shale and a second, nearly identical filter (“Filter B”) containing Swanton black shale amended with activated alumina beads and elemental (zero-valent) iron shavings (Appendix D). Tile drain flow was split between the two filters. This side-by-side comparison provided information about the performance of Swanton black shale by itself and whether the addition of P sorbing amendments to Swanton black shale can be a cost-effective strategy for removing P from drainage waters.

Anticipated flow rates, media hydraulic conductivity, water residence time, and practical filter size were fundamental considerations in the filter design process. The filters needed to be large because the JBT05 system drains a very large field, approximately 94 acres. Flow rates at the JBT05 tile drain outlet ranged from zero to 1,800 L/min over the year-long monitoring period (April 2017-April 2018) in the original Jewett Brook watershed tile drain study (Braun et al. 2019). The filter dimensions we ultimately specified were the practical upper size limit we could construct in this study. We assumed a design flow rate of 250 L/min per filter, or 500 L/min total, beyond which water would begin to bypass the filters. Approximately 67% of the cumulative flow volume during the April 2017–April 2018 monitoring period occurred at flow rates of 500 L/min or less. At the 250 L/min per filter design flow rate, the estimated contact time of water in the filter media was 20 minutes.

Each filter was constructed in a 5-ft. wide trench excavated ~3.0 ft. below the elevation of the tile drain invert (Figure 12). The filter trenches were excavated perpendicular to the tile drain main line and parallel with a drainage ditch and with each other. The trenches were lined with

10-mil plastic. A 6-inch diameter, perforated pipe running along the bottom of the trench was installed as a sediment collector, to enable cleanout of sediments using a pump or sewer jet.

Drainage water was diverted from the JBT05 tile drain at the existing monitoring manhole, located immediately upstream of the existing tile drain outlet. In this manhole, tile drain flow was split between Filter A, Filter B, and a normally dry bypass pipe. The bypass pipe was the existing 8-inch diameter tile drain outlet to the receiving ditch. A 45-degree fitting, oriented upwards, was attached to the outflow pipe, which raised the elevation of the overflow about eight inches.

Parallel, 6-inch diameter perforated pipes installed near the bottom of each filter close to either trench wall distribute the drainage water. These distribution pipes were set ~2.3 ft. below the elevation of the tile drain invert. The distribution pipes were covered with 2.1 ft. of media. Two parallel, 6-inch diameter perforated collection pipes were installed over the media bed, and more media was added to cover the collection pipes. The filter was covered in 10-mil plastic and the trenches were backfilled with native soil, mounding excess soil to avoid surface runoff and ponding over the filters.

Drainage water flows out the perforations in the distribution pipes, up through the media bed, and into the collection pipes, which discharge to a monitoring manhole at the end of the filter (Figure 14). Treated water then flows from the monitoring manhole through a pipe to the receiving ditch. Both filter outlets and the bypass pipe from the JBT05 manhole are typically submerged in the receiving ditch.

*Figure 12. Excavating trench for Filter B*

*Figure 13. Spreading and raking in activated alumina and iron*

*Figure 14. View down filter outlet manhole*

The rate of flow through the filter can be controlled by opening and closing valves installed at the outlets of the collection pipes.

### 5.2.1. Filter Media

We used crushed Swanton black shale in both JBT05 filters because it is a locally available, inexpensive stone with acceptable hydraulic properties and the capacity to remove some P. This material was generously donated from the Swanton Limestone quarry by Rock Dust Local, a private company based in Bridport, Vermont. While our benchtop testing suggested that the P sorption capacity of a filter composed only of Swanton black would be inadequate to achieve substantial P reductions over the long term, we concluded that good P removal might be achieved at reasonable cost by amending Swanton black shale with complementary materials with higher P sorption rates.

The Swanton black shale used in both filters was graded to ~1/2-inch by screening the crushed stone between 9/16-inch and 7/16-inch screens, removing most fines. Filter A contains 100% Swanton black shale. In Filter B, the Swanton black shale was mixed with 3/16-inch activated alumina beads and ground, zero-valent (elemental) iron shavings. The P sorption achieved by the activated alumina in our benchtop testing was impressive considering the relatively small quantity used (5% by volume). Zero-valent iron has been shown to be a strong P sorbent in stormwater bioretention area media, although two designers cautioned me to use it sparingly to avoid hardening of the media mixture. In Filter B, the activated alumina and iron were added to the stone in successive lifts and raked in (Figure 13). Table 5 summarizes the composition of the filters by volume.

Table 5. Filter media

| | Filter A | Filter B |
|---|---|---|
| Media | 100% Swanton black shale (60 tons) | 90% Swanton black shale (55 tons)<br>8% activated alumina (2,700 lb.)<br>2% elemental iron (2,000 lb.) |

### 5.2.2. Filter Construction Cost

The total cost of construction, excluding engineering, was $5,000 for Filter A and $11,000 for Filter B (Table 6). The $6,000 cost difference between the filters was the cost of the iron and activated alumina.

*Table 6. P filter construction cost*

| Component | Filter A | | Filter B | |
|---|---|---|---|---|
| Filter media | Swanton black shale | $0 | Swanton black shale | $0 |
| | | | Activated alumina | $4,270 |
| | | | Zero valent iron | $1,740 |
| Pipe and fittings | | $1,810 | | $1,810 |
| Excavation/construction | | $3,210 | | $3,210 |
| **Total** | | **$5,020** | | **$11,030** |

### 5.3. Monitoring the P Filters

Upon completion of the JBT05 P filters in November 2019, monitoring of the JBT05 tile drain resumed and monitoring of the P filter outlets began and continued through December 2020. Monitoring activities were consistent with the tile drain monitoring methods described in Section 4, except for modifications we made to extend the period of flow-proportional composite sampling into the winter months. These included installing custom racks to suspend the autosamplers inside the monitoring manholes to take advantage of ground heat (Figure 15). The autosampler racks fit two carboys. Thus, while two-part sampling programs were still used, there was only one 10-L carboy per set rather than two.


*Figure 15. Custom autosampler rack in monitoring manhole*

Continuous autosampling was attempted at the JBT05 site and both filter outlets through the winter of 2019-2020. Despite insulating the monitoring manholes and deploying low power heaters inside them, multiple weeks in January and February were not consistently sampled due to ice in the manholes and in the autosampler lines. However, these efforts certainly did extend the automated sampling window much longer than would otherwise have been possible.

There was a period in March–April 2020 during the COVID-19 state of emergency during which we held samples for later analysis because the VAEL laboratory was effectively closed.

The P filter monitoring results are presented in Section 8 and Appendix C.

# 6. Quality Assurance Tasks Completed

The project data-quality objective was to collect, provide, maintain, analyze, display, and document valid water quantity and quality data. Field quality assurance measures included adherence to the QAPP, Version 2.0, Amendment 1, approved March 2019 (Appendix A).

The analytical laboratory for the water samples was VAEL. VAEL is accredited by New Hampshire under the National Environmental Laboratory Accreditation Program (NELAP) for the specified water quality parameters. Sample analyses by VAEL were conducted according to the laboratory's established procedures, which are described in VAEL's Quality Systems Manual, Revision 23, dated December 18, 2015. This manual identifies the analytical methods and relevant data quality objectives, assessment procedures, and reporting limits applied.

For the QC samples, field duplicates were collected of TP, TDP, TN, and TSS samples. Duplicates were collected on a rotating basis among stations. Grab samples collected during the winter months were collected in duplicate according to the same scheme used for the composite sample splits. Field quality control sampling consisted of the following:

- Approximately 10% of composite water sample splits were duplicated in the field by collecting a second aliquot from the churn splitter for delivery to the lab.
- One of two composite soil sample splits was duplicated in the field by collecting a second aliquot from the sample bucket for delivery to the lab.

Data from field duplicates were accepted if the RPD was less than or equal to 20%; in such cases, the mean of the field duplicates was used to represent data from the sample involved.

Sampling QC excursions were evaluated by the Project Manager. Field duplicate sample results were used to assess the entire sampling process, including environmental variability; therefore, the arbitrary rejection of results based on predetermined limits was not practical. The professional judgment of the Project Manager was relied upon in evaluating results.

The primary reason for rejecting certain sample results was determination that samples were not representative due to a malfunction with the flowmeter or autosampler, an extreme environmental condition affecting sample quality (such as flooding), or an error on the part of the technician. Data and observations describing such malfunctions, extreme conditions, and errors were recorded in the field and are distilled in notes included in Appendix C in the following fields: "Sample Quality Notes", "Processing Comments", and "Additional Comments from Field".

# 7. Tile Drain Monitoring Results

Constituent concentrations in flow-proportional composite samples represent mean concentrations over the approximately weeklong sampling periods. The flow volumes and constituent concentrations for individual flow-proportional composite sampling periods are presented in Appendix C. Appendix C also includes concentration data for grab samples collected during winter periods; however, these data are for reference only. Only data from flow-proportional composite samples are analyzed in this report. Appendix C also includes data for the JBT01 tile drain, but these data are not analyzed because the record is insufficient since sampling was discontinued when the farmer ceased participation.

Constituent loads are calculated as the product of constituent concentration and the tile drainage flow volume over the corresponding sampling period. These loads were then divided by the duration of the sampling period (in days) and by the area drained by the tile drainage system (in hectares) to express loading as mass per day per hectare. These loading data are tabulated in Appendix C.

Tables 7 through 16 present descriptive statistics for flow volumes and constituent concentrations and loads in tile drainage water sampled at individual Jewett Brook watershed and Addison County tile drains. No descriptive statistics for flow volumes and constituent loads are presented for the JBT05 site (Table 7) due to missing flow data, as discussed in Section 4.2.1.

*Table 7. Descriptive statistics for concentrations at JBT05 (pre-filter period)*

| | **Concentration** | | | |
|---|---|---|---|---|
| | **TP (µg/L)** | **TDP (µg/L)** | **TN (mg/L)** | **TSS (mg/L)** |
| Count | 50 | 50 | 30 | 23 |
| Min | 31 | 18 | 2.2 | 2 |
| Max | 443 | 385 | 42.0 | 28 |
| Mean | 108 | 79 | 24.1 | 13 |
| Median | 82 | 58 | 24.1 | 14 |
| St. Dev. | 90 | 72 | 9.9 | 8 |

*Table 8. Descriptive statistics for flow volumes, concentrations, and loads at JBT06*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| Count | 32 | 31 | 31 | 20 | 17 | 31 | 31 | 20 | 17 |
| Min | 23.2 | 36 | 17 | 0.1 | 2 | 0.0084 | 0.0040 | 0.00055 | 0.0049 |
| Max | 17700 | 1100 | 348 | 63.6 | 125 | 28 | 22 | 4.8 | 0.96 |
| Mean | 4360 | 206 | 117 | 33.6 | 22 | 4.0 | 2.8 | 0.66 | 0.16 |
| Median | 1390 | 145 | 108 | 34.2 | 14 | 1.1 | 0.68 | 0.12 | 0.069 |
| St. Dev. | 5320 | 208 | 78 | 15.1 | 30 | 6.4 | 4.6 | 1.1 | 0.24 |

*Table 9. Descriptive statistics for flow volumes, concentrations, and loads at JBT07*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| Count | 30 | 30 | 30 | 15 | 17 | 30 | 30 | 15 | 17 |
| Min | 0.3 | 20 | 13 | 0.6 | 3 | 0.000077 | 0.000064 | 0.0000079 | 0.00060 |
| Max | 1760 | 3190 | 1740 | 22.5 | 200 | 47 | 25 | 0.33 | 2.9 |
| Mean | 388 | 353 | 217 | 10.7 | 41 | 3.2 | 2.0 | 0.073 | 0.38 |
| Median | 131 | 241 | 98 | 10.0 | 28 | 0.27 | 0.12 | 0.024 | 0.058 |
| St. Dev. | 509 | 570 | 332 | 6.4 | 49 | 8.7 | 4.9 | 0.11 | 0.83 |

*Table 10. Descriptive statistics for flow volumes, concentrations, and loads at JBT11*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| Count | 32 | 32 | 32 | 18 | 20 | 32 | 32 | 18 | 20 |
| Min | 0.0 | 11 | 6 | 0.2 | 2 | 0 | 0 | 0 | 0 |
| Max | 5440 | 159 | 68 | 13.2 | 67 | 2.7 | 1.5 | 0.53 | 1.4 |
| Mean | 1145 | 43 | 21 | 2.3 | 17 | 0.35 | 0.19 | 0.043 | 0.091 |
| Median | 153 | 31 | 16 | 1.4 | 12 | 0.014 | 0.0087 | 0.00092 | 0.010 |
| St. Dev. | 1650 | 35 | 15 | 3.0 | 17 | 0.59 | 0.33 | 0.12 | 0.32 |

*Table 11. Descriptive statistics for flow volumes, concentrations, and loads at JBT18*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| Count | 32 | 28 | 28 | 16 | 17 | 28 | 28 | 16 | 17 |
| Min | 0.3 | 39 | 16 | 0.9 | 15 | 0.0013 | 0.0012 | 0.000047 | 0.0032 |
| Max | 1300 | 580 | 370 | 66 | 314 | 9.7 | 2.4 | 0.41 | 3.8 |
| Mean | 233 | 190 | 61 | 10.2 | 66 | 1.7 | 0.39 | 0.063 | 0.67 |
| Median | 61 | 154 | 50 | 3.9 | 43 | 0.35 | 0.093 | 0.011 | 0.29 |
| St. Dev. | 325 | 128 | 68 | 16.1 | 87 | 2.5 | 0.59 | 0.11 | 1.0 |

*Table 12. Descriptive statistics for flow volumes, concentrations, and loads at ACT1*

| | | Concentration | | | | Loading | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| Count | 26 | 26 | 26 | 12 | 24 | 26 | 26 | 12 | 24 |
| Min | 1.5 | 13 | 6 | 12.8 | 2 | 0.0007 | 0.0002 | 0.0009 | 0.0001 |
| Max | 2530 | 52 | 31 | 70.8 | 18 | 0.81 | 0.40 | 1.8 | 0.13 |
| Mean | 655 | 21 | 11 | 42.0 | 3 | 0.13 | 0.072 | 0.34 | 0.022 |
| Median | 599 | 20 | 9 | 38.9 | 2 | 0.12 | 0.063 | 0.20 | 0.015 |
| St. Dev. | 581 | 8 | 5 | 18.6 | 3 | 0.16 | 0.083 | 0.49 | 0.027 |

*Table 13. Descriptive statistics for flow volumes, concentrations, and loads at ACT2*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| Count | 34 | 34 | 34 | 18 | 33 | 34 | 34 | 18 | 33 |
| Min | 2.1 | 46 | 15 | 0.4 | 4 | 0.0075 | 0.0019 | 0.0000 | 0.0011 |
| Max | 4540 | 1490 | 760 | 37.6 | 494 | 170 | 85 | 2.0 | 55 |
| Mean | 1690 | 304 | 139 | 15.4 | 115 | 13 | 6.8 | 0.58 | 4.3 |
| Median | 913 | 164 | 81 | 17.2 | 71 | 2.2 | 1.1 | 0.36 | 0.28 |
| St. Dev. | 1680 | 321 | 169 | 12.3 | 116 | 30 | 16 | 0.70 | 10 |

*Table 14. Descriptive statistics for flow volumes, concentrations, and loads at ACT3*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| Count | 24 | 24 | 23 | 14 | 24 | 24 | 23 | 14 | 24 |
| Min | 3.6 | 54 | 19 | 2.9 | 36 | 0.012 | 0.0029 | 0.0015 | 0.0046 |
| Max | 1850 | 1600 | 838 | 35.4 | 1730 | 36 | 16 | 1.2 | 45 |
| Mean | 707 | 629 | 218 | 24.3 | 376 | 7.0 | 2.4 | 0.28 | 4.3 |
| Median | 568 | 570 | 171 | 22.5 | 242 | 3.6 | 1.4 | 0.17 | 1.1 |
| St. Dev. | 580 | 339 | 164 | 8.3 | 358 | 9.8 | 3.5 | 0.34 | 9.7 |

*Table 15. Descriptive statistics for flow volumes, concentrations, and loads at ACT4*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| Count | 33 | 33 | 33 | 15 | 32 | 33 | 33 | 15 | 32 |
| Min | 3.0 | 199 | 89 | 1.4 | 18 | 0.024 | 0.011 | 0.00020 | 0.0021 |
| Max | 843 | 1020 | 673 | 4.0 | 278 | 7.0 | 5.1 | 0.040 | 0.61 |
| Mean | 174 | 405 | 232 | 2.5 | 45 | 1.3 | 0.80 | 0.012 | 0.11 |
| Median | 55 | 388 | 206 | 2.5 | 35 | 0.46 | 0.34 | 0.0062 | 0.040 |
| St. Dev. | 211 | 153 | 112 | 0.8 | 45 | 1.8 | 1.2 | 0.015 | 0.15 |

*Table 16. Descriptive statistics for flow volumes, concentrations, and loads at ACT5*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| Count | 28 | 28 | 28 | 14 | 28 | 28 | 28 | 14 | 28 |
| Min | 3.2 | 21 | 9 | 6.4 | 9 | 0.0021 | 0.0009 | 0.0008 | 0.010 |
| Max | 1320 | 600 | 56 | 36.2 | 1090 | 22 | 2.1 | 0.96 | 40 |
| Mean | 384 | 125 | 21 | 17 | 125 | 2.0 | 0.31 | 0.24 | 2.3 |
| Median | 359 | 99 | 18 | 14.4 | 84 | 0.86 | 0.15 | 0.15 | 0.41 |
| St. Dev. | 388 | 113 | 11 | 8.2 | 198 | 4.4 | 0.49 | 0.32 | 7.6 |

Median values from Tables 7-16 are tabulated in Table 17 for ease of reference. Minimums, maximums, and means of the median values are also included. Among the 10 Addison County and Jewett Brook watershed tile drains sampled, median TP concentrations ranged from a low of 20 µg/L at ACT1 to 570 µg/L at ACT3, and averaged 189 µg/L. Median TDP concentrations ranged from a low of 9 µg/L at ACT1 to 206 µg/L at ACT4, and averaged 81 µg/L.

*Table 17. Median flow volumes, concentrations, and loads by site*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow (m$^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| JBT05 (pre-filter) | | 82 | 58 | 24.1 | 14 | | | | |
| JBT06 | 1390 | 145 | 108 | 34.2 | 14 | 1.1 | 0.68 | 0.12 | 0.069 |
| JBT07 | 131 | 241 | 98 | 10.0 | 28 | 0.27 | 0.12 | 0.024 | 0.058 |
| JBT11 | 153 | 31 | 16 | 1.4 | 12 | 0.014 | 0.0087 | 0.00092 | 0.010 |
| JBT18 | 61.2 | 154 | 49 | 3.9 | 43 | 0.35 | 0.093 | 0.011 | 0.29 |
| ACT1 | 599 | 20 | 9 | 38.9 | 2 | 0.12 | 0.063 | 0.20 | 0.015 |
| ACT2 | 913 | 164 | 81 | 17.2 | 71 | 2.2 | 1.1 | 0.36 | 0.28 |
| ACT3 | 568 | 570 | 171 | 22.5 | 242 | 3.6 | 1.4 | 0.17 | 1.1 |
| ACT4 | 55.0 | 388 | 206 | 2.5 | 35 | 0.46 | 0.34 | 0.0062 | 0.040 |
| ACT5 | 359 | 99 | 18 | 14.4 | 84 | 0.86 | 0.15 | 0.15 | 0.41 |
| Minimum | 55.0 | 20 | 9 | 1.4 | 2 | 0.014 | 0.0087 | 0.00092 | 0.010 |
| Maximum | 1390 | 570 | 206 | 38.9 | 242 | 3.6 | 1.4 | 0.36 | 1.1 |
| Mean | 470 | 189 | 81 | 16.9 | 55 | 1.0 | 0.44 | 0.12 | 0.25 |

Figures 16 through 23 present box plots of TP, TDP, TN, and TSS concentration and loading data from flow-proportional composite samples collected from the Jewett Brook watershed and Addison County tile drains. All data are presented on log scale. The top and bottom of the vertical box indicate the 75th and 25th percentiles, respectively, of the data distribution for the category, defining the interquartile range. The horizontal line across each box indicates the median (50th percentile) of the data distribution. The top and bottom vertical lines (“whiskers”) for each box define the [3rd quartile + 1.5 x interquartile range] and the [1st quartile – 1.5 x interquartile range], respectively. Points beyond each whisker represent outliers.

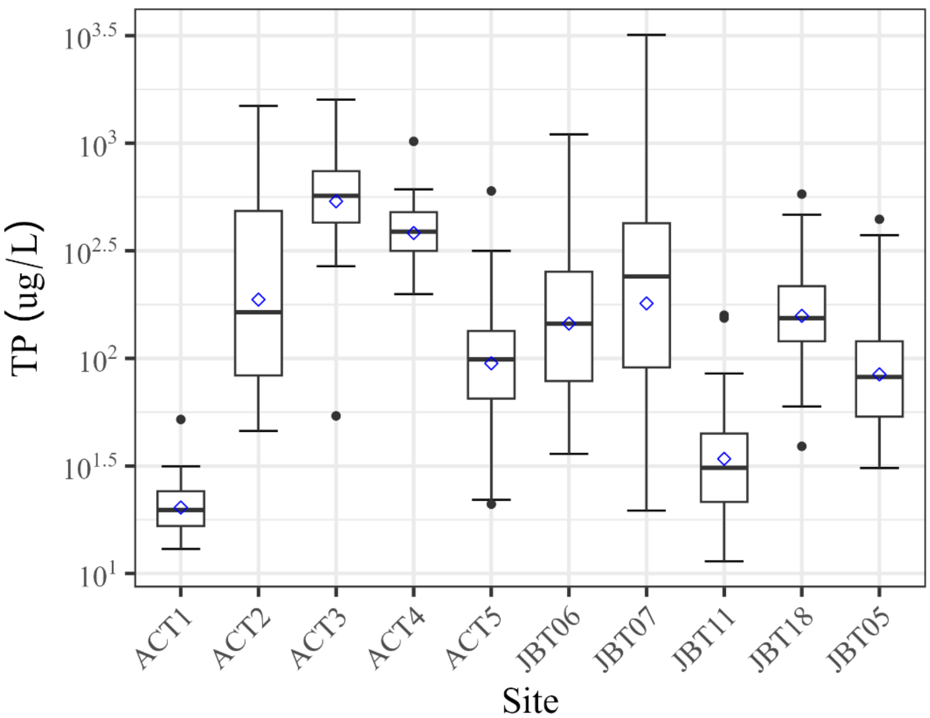



*Figure 16. TP concentration distributions by site*

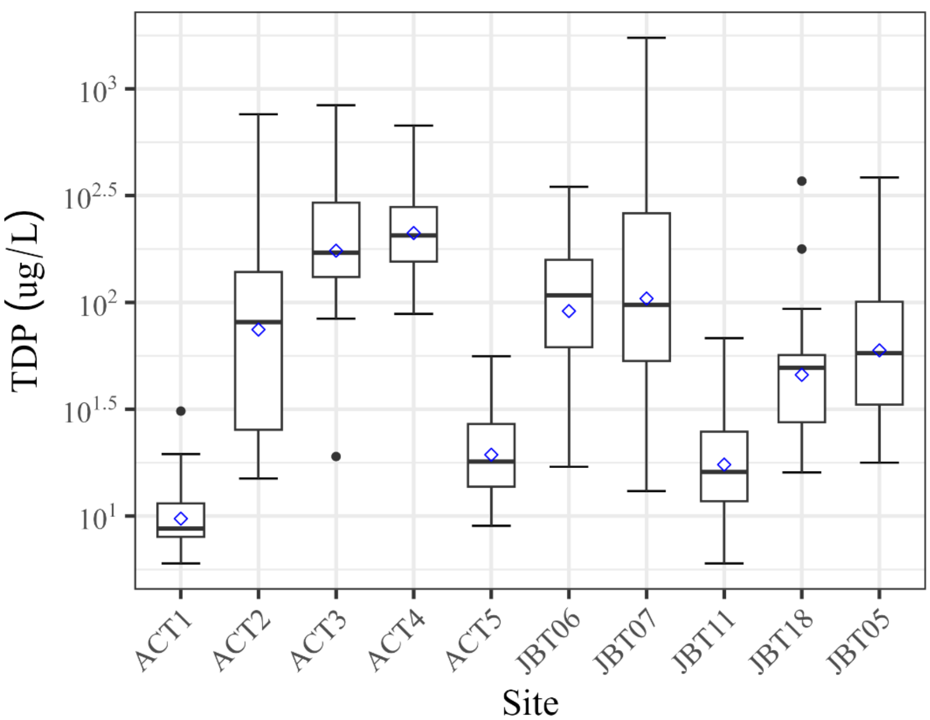



*Figure 17. TDP concentration distributions by site*

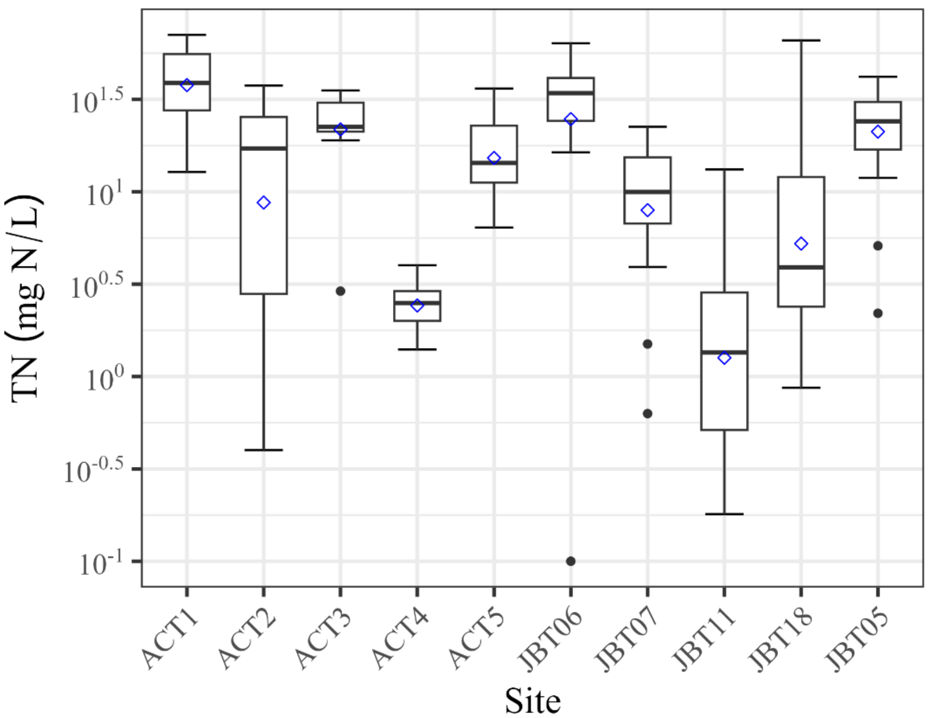



*Figure 18. TN concentration distributions by site*

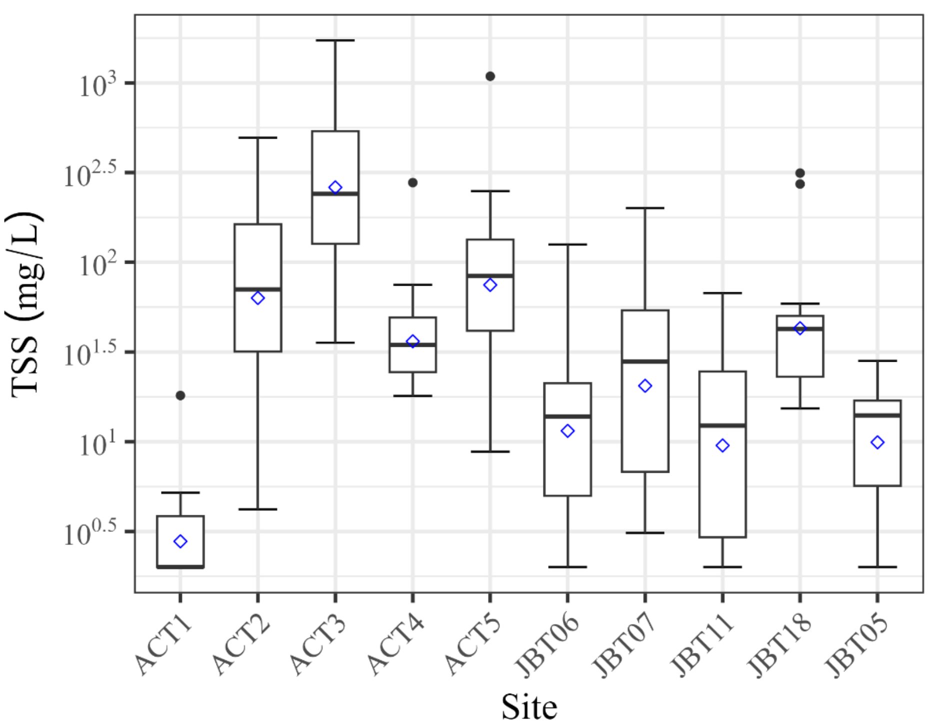



*Figure 19. TSS concentration distributions by site*

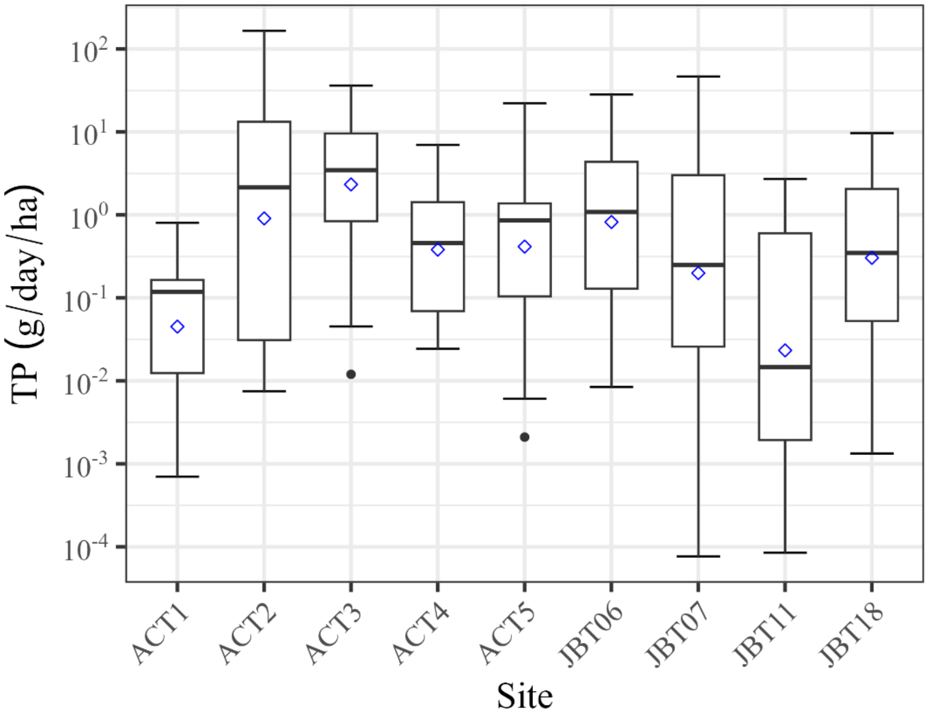



*Figure 20. TP load distributions by site*

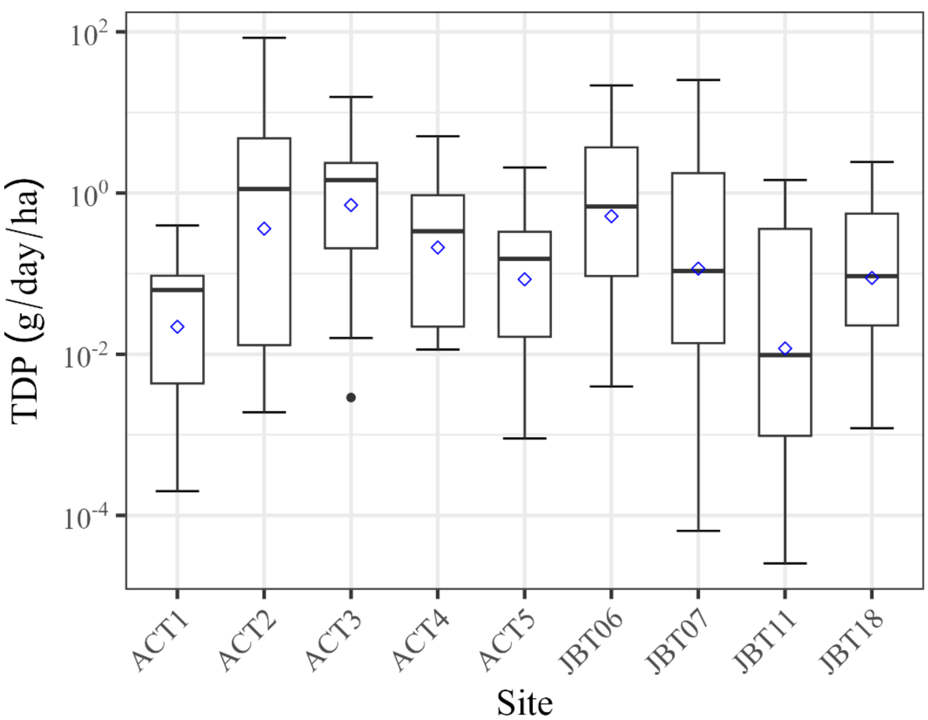



*Figure 21. TDP load distributions by site*

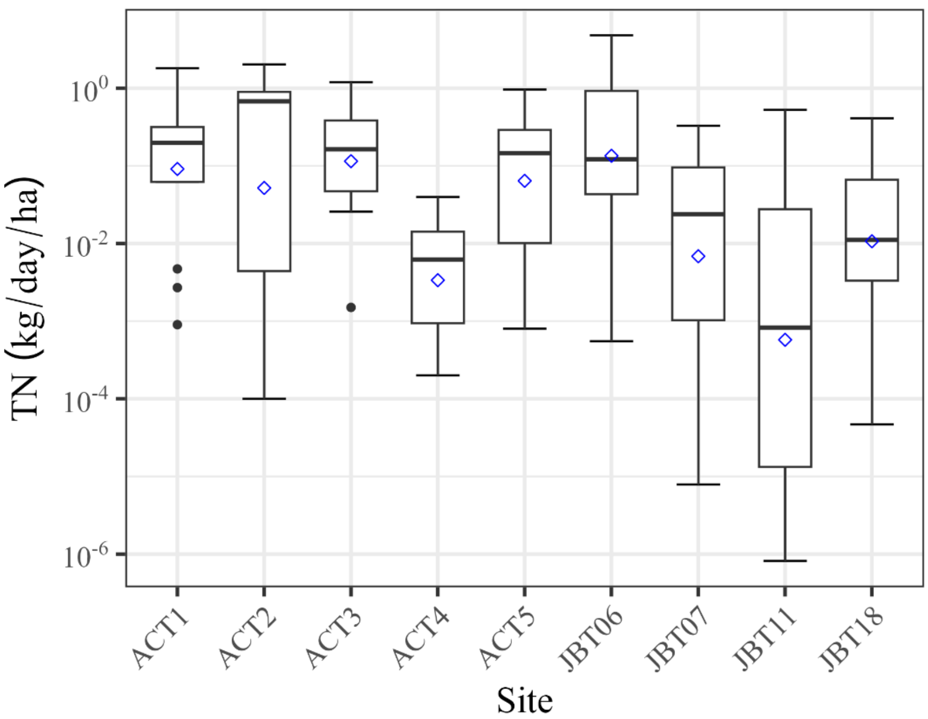



*Figure 22. TN load distributions by site*

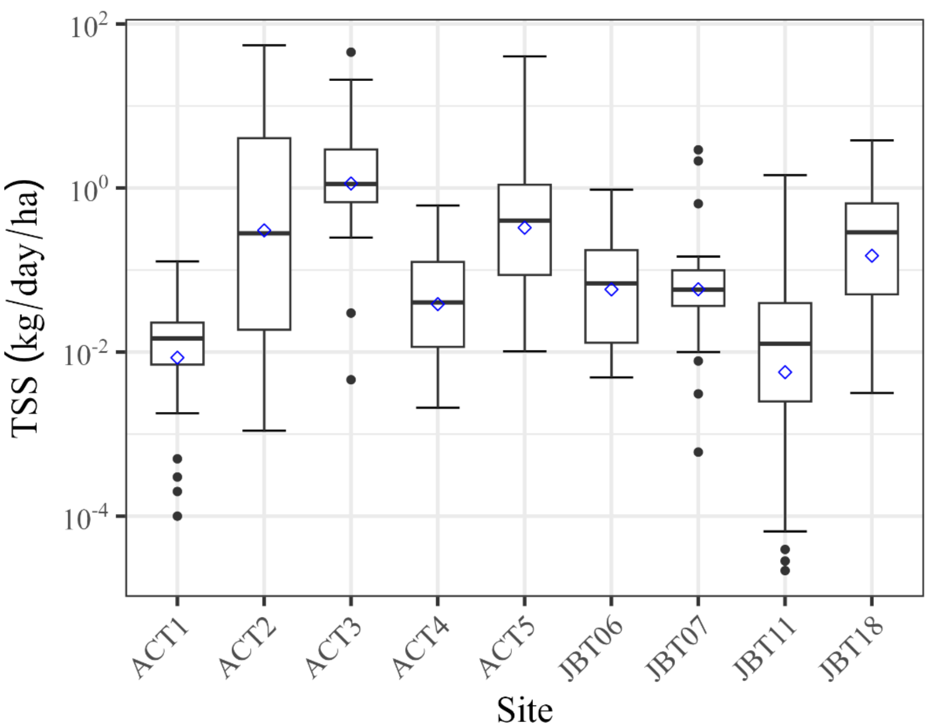



*Figure 23. TSS load distributions by site*

Tile effluent phosphorus concentrations in Addison County and Jewett Brook watershed tile drainage were higher than those previously reported from similar land uses in the LCB region (Stone 2016). Benoit (1973) reported all tile drainage samples from corn silage and hay plots in Franklin, VT contained less than 20 µg/L TP, the detection limit. More recently, Young (2015) reported TP concentrations of 23 – 175 µg/L (mean 98 µg/L) and dissolved reactive P concentrations of 9 – 41 µg/L (mean 11 µg/L) in tile drainage water on five farms in Clinton and St. Lawrence Counties, NY. In the same region, Klaiber (2015) reported a mean TP concentration of 29 µg/L and a mean dissolved reactive P concentration of 12 µg/L in tile drainage from seven events over a year. Note that all these data were reported from seasonal or multi-event data, not from samples collected throughout the year.

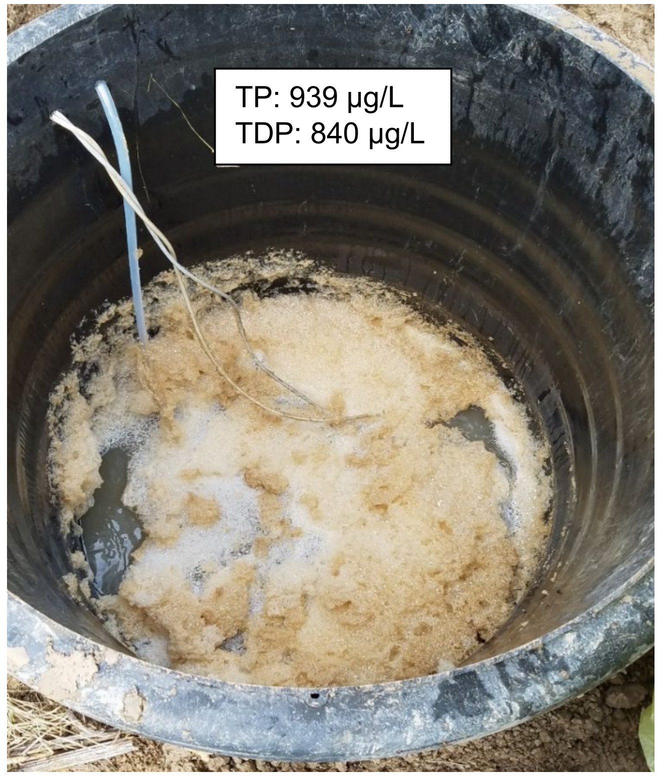



*Figure 24. Foam in ACT4 manhole, Dec. 3, 2018*

P concentrations observed in ACT and JBT tile drainage were more comparable to the range observed in Ontario (20 – 9,700 µg/L; Miller 1979), Ohio (110 – 300 µg/L; King 2014), and in Wisconsin (80 – 1,780 µg/L; Madison et al. 2014) than to the few LCB studies available (Benoit 1973, Young 2015, and Klaiber 2015).

Occasional high TP and TDP concentrations were measured in the ACT and JBT tile drain flow following manure application. On several events, we observed foam (Figure 24) or discolored water indicating manure had leached into the tile drain.

### 7.1. Comparing Jewett Brook Watershed and Addison County Tile Drains

Figures 25 through 29 illustrate the TP, TDP, TN, and TSS concentration distributions grouped by county/watershed.

The Addison County tile drains had higher 25$^{th}$ percentile, median, and 75$^{th}$ percentile TP concentrations than the Jewett Brook watershed sites (Figure 25). Median and 75$^{th}$ percentile TDP concentrations (Figure 26) were higher across the Addison County sites than at the Jewett Brook watershed sites, but the 25$^{th}$ percentile TDP concentration was lower, reflecting a larger TDP concentration interquartile range at the ACT sites.

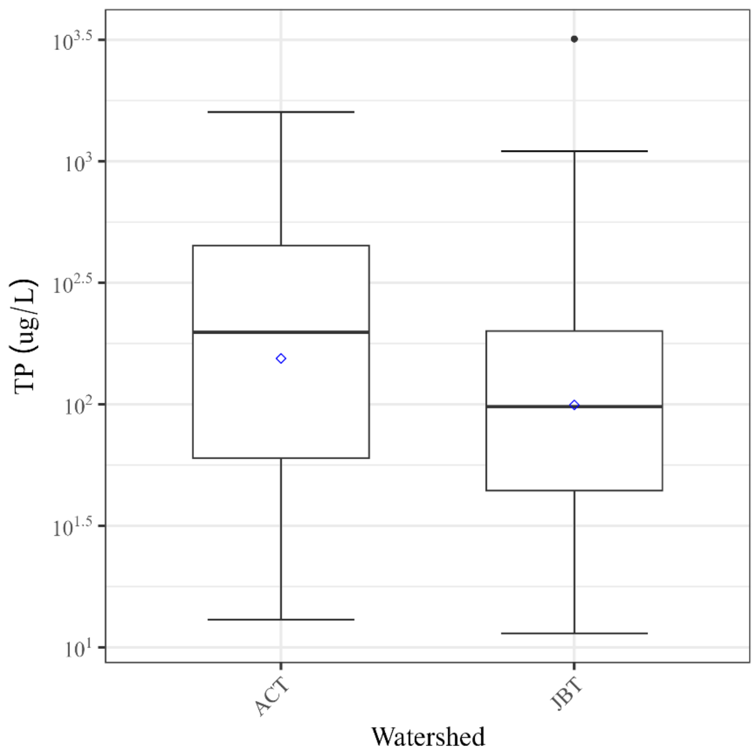



*Figure 25. Comparing TP concentration distributions at ACT and JBT sites*

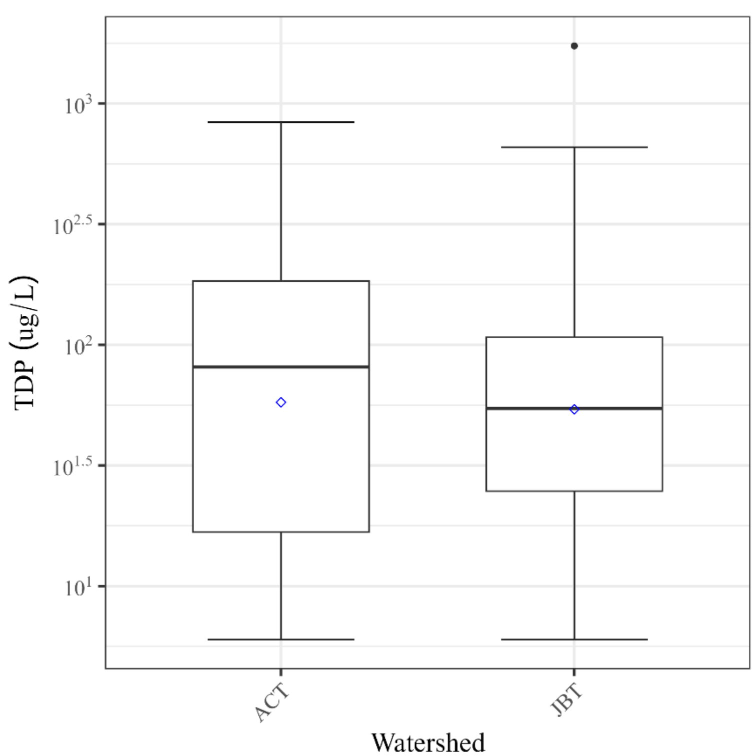
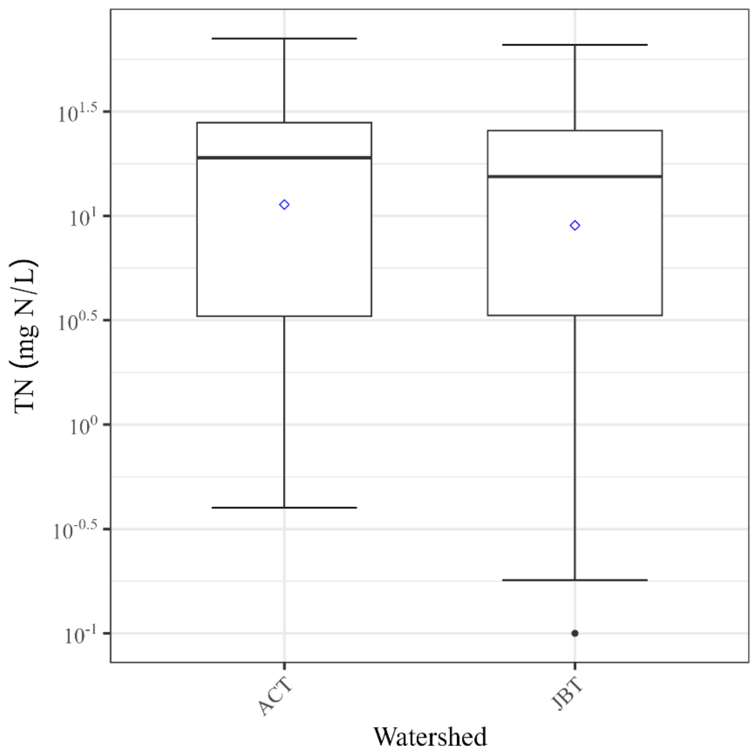
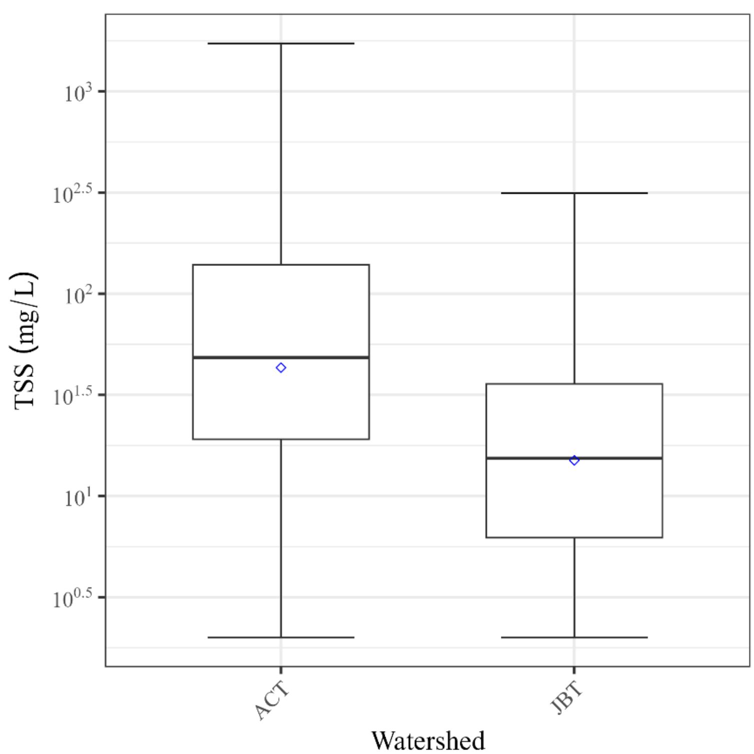



*Figure 26. Comparing TDP concentration distributions at ACT and JBT sites*




The TN concentration distributions were similar at the ACT and JBT sites (Figure 27).

*Figure 27. Comparing TN concentration distributions at ACT and JBT sites*




As with the TP concentration comparison, grouped ACT sites had substantially higher 25th percentile, median, and 75th percentile TSS concentrations than the JBT sites (Figure 28).

*Figure 28. Comparing TSS concentration distributions at ACT and JBT sites*

Table 18 compares minimum, maximum, and median concentrations and loads grouped by county/watershed. For each constituent, the Addison County sites had higher median concentrations and loads. Median TP concentrations were approximately twice as high at the Addison County sites and TSS concentrations were a factor of three greater. Median TP, TDP, TN, and TSS loads were between 4X (TN load) and 20X (TP load) higher at the Addison County sites than the Jewett Brook watershed sites. The primary reason for the dramatic differences in loading was likely differences in rainfall. Between March and August 2019, most of Addison County had surplus rainfall, 125-150% of normal, while most of Franklin County had a rainfall deficit, 75-100% of normal (Northeast Climate Data Center 2023).

*Table 18. Concentrations and loads grouped by county/watershed*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sites | Statistic | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| ALL | min | 11 | 6 | 0.1 | 2 | 0 | 0 | 0 | 0 |
| | max | 3193 | 1735 | 70.8 | 1726 | 166 | 85 | 4.8 | 55 |
| | median | 120 | 56 | 16.4 | 31 | 0.16 | 0.073 | 0.027 | 0.050 |
| ACT | min | 13 | 6 | 0.4 | 2 | 0.00070 | 0.00020 | 0 | 0.00010 |
| | max | 1595 | 838 | 70.8 | 1726 | 166 | 85 | 2.0 | 55 |
| | median | 198 | 81 | 19.0 | 48 | 0.62 | 0.15 | 0.053 | 0.12 |
| JBT | min | 11 | 6 | 0.1 | 2 | 0 | 0 | 0 | 0 |
| | max | 3193 | 1735 | 66.0 | 314 | 47 | 25 | 4.8 | 3.8 |
| | median | 98 | 55 | 15.4 | 15 | 0.030 | 0.017 | 0.014 | 0.015 |

Two-sided Wilcoxon rank sum tests were performed to evaluate the significance of differences between constituent concentrations at the Addison County tile drains and Jewett Brook watershed tile drains. The results in Table 19 demonstrate that the tile drains monitored in Addison County had significantly higher TP and TSS concentrations than the Jewett Brook watershed sites. There were no significant differences in TDP or TN concentrations between the Addison County and Jewett Brook watershed sites.

TP, TDP, TN, and TSS loads were statistically greater at Addison County sites than at Jewett Brook watershed sites, after normalizing by tile drainage area (Table 19). Particularly with respect to TDP and TN loads, these results suggest that higher flow volumes contributed to significantly greater loading across ACT sites than at JBT sites.

*Table 19. Results of Wilcoxon rank sum tests between ACT and JBT concentrations and loading[1]*

| | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|
| | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| p-value | **<0.01** | 0.60 | 0.50 | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |

1. Statistically significant differences in bold

### 7.2. Comparing Addison County Tile Drains by Soil Type

Since the outset of monitoring, P concentrations measured at the ACT1 tile drain (Figure 29) in Addison County were surprisingly low. The most obvious difference between ACT1 and the other ACT study fields is in soil type. The ACT2, ACT3, ACT4, and ACT5 fields have predominantly clay or silty clay soil. The ACT1 field is unique in this study in having light textured, fine loamy sand soil. Therefore, the ACT sites were grouped and analyzed according to soil type. Distributions of TP, TDP, TSS, and TN concentration data by soil type are presented in Figures 30 through 33.

The TP concentrations (Figure 30) and TDP concentrations (Figure 31) at ACT1 were consistently very low relative to the other ACT sites.

*Figure 29. ACT1 tile drain outlet*

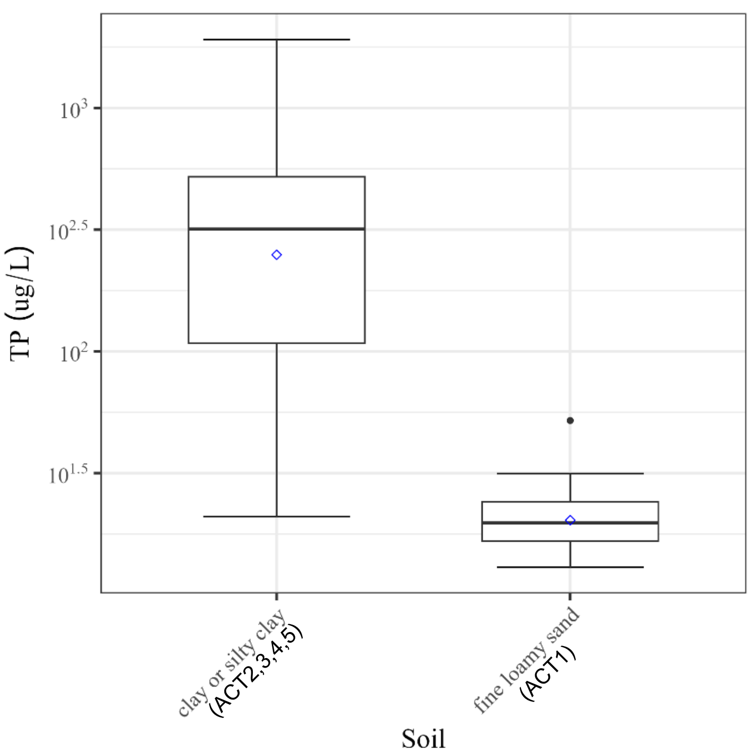



*Figure 30. TP concentration distributions at ACT sites by soil texture*

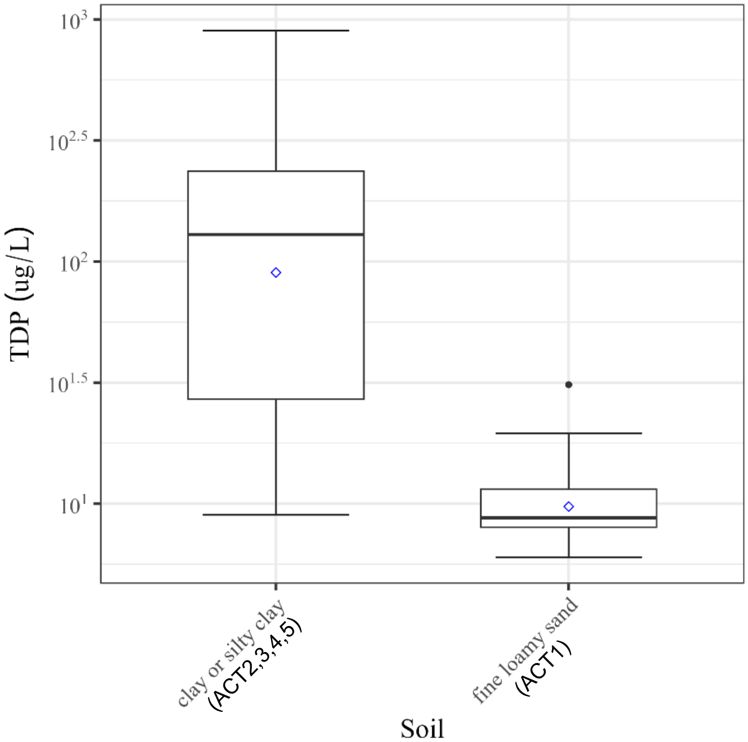
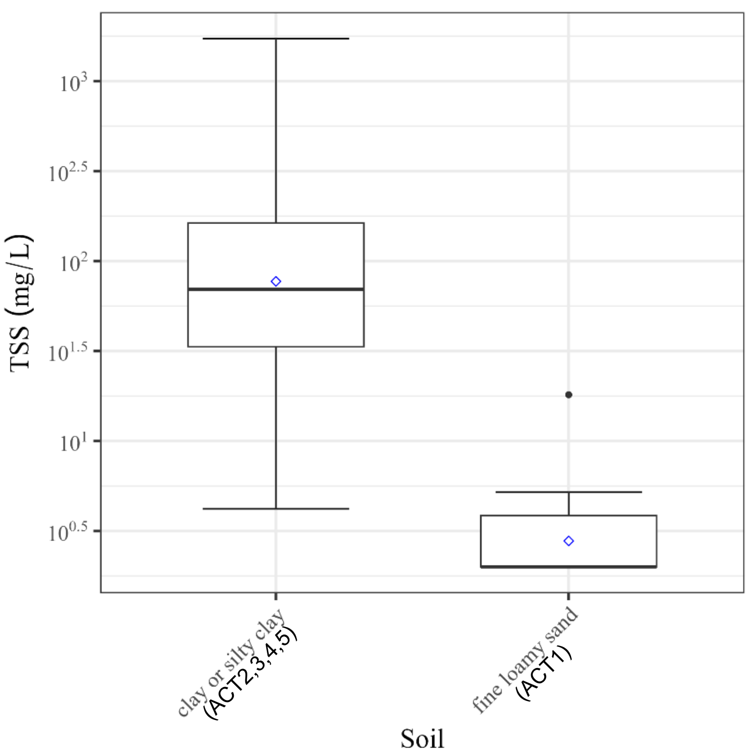



*Figure 31. TDP concentration distributions at ACT sites by soil texture*




As with the TP and TDP concentrations, TSS concentrations (Figure 32) were similarly dramatically lower at ACT1 than at the other ACT sites.

*Figure 32. TSS concentration distributions at ACT sites by soil texture*

Conversely, TN concentrations were higher at ACT1 than at the other ACT tile drains (Figure 33).

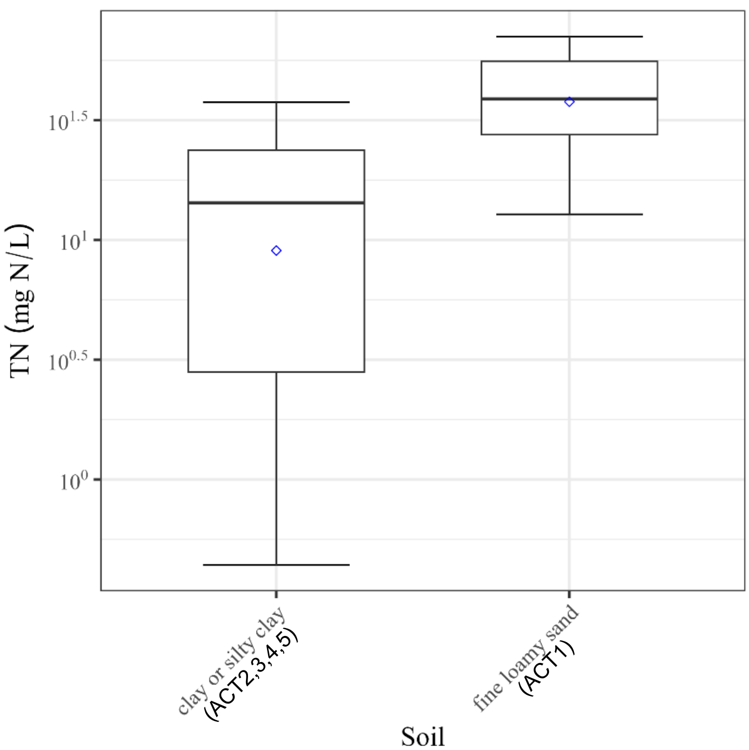



*Figure 33. TN concentration distributions at ACT sites by soil texture*

The statistical significance of the apparent differences between the ACT sites with clay/silty clay soils and ACT1 with loamy fine sand was assessed using two-sided Wilcoxon rank sum tests (Table 20). TP, TDP, and TSS concentrations were significantly lower, and TN concentrations were significantly higher, at the ACT1 site than at the ACT sites with clay soils. A similar pattern is apparent in the loading data, with significantly lower TP, TDP, and TSS loads at ACT1 than at the other ACT sites, except that the difference in TN loading was non-significant.

While we recognize evaluating a category (sandy soil) represented by only one site (ACT1) necessitates cautious interpretation of these results, the fact that the water quality at this tile drainage system is markedly different from the other ACT sites, and indeed the Jewett Brook watershed sites as well, deserves special mention. Given that the ACT1 field is in continuous corn under conventional management, we attribute ACT1's lower TP, TDP, and TSS concentrations and loading and higher TN concentrations to its sandy soil.

*Table 20. Results of Wilcoxon rank sum tests between ACT sites with clay soils and ACT1*[1]

| | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|
| | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d/ha) | TDP (g/d/ha) | TN (kg/d/ha) | TSS (kg/d/ha) |
| p-value | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.30 | **<0.01** |

1. Statistically significant differences in bold

# 8. Tile Drain Phosphorus Filter Results

The JBT05 tile drain (the “inflow” station) and the Filter A and Filter B outflows were monitored between December 2019 and December 2020. Flow-proportional composite samples were collected and processed approximately weekly for as much of the period as was possible. Installing autosamplers within monitoring manholes with insulated covers did extend the time window for automated sampling considerably; however, despite considerable efforts, including an attempt to heat the manholes with low-power electric heaters, consistent operation through January and February was not possible. During the coldest weeks, grab samples were collected (Appendix C).

## 8.1. Water Quality at the JBT05 Tile Drain and Filter Outflows

Tables 21 through 23 present flow volume, concentration, and loading data for samples collected at the filter inflow (JBT05) and outflow stations. Note that the JBT05 data presented in Table 21 do not include data collected in the previous monitoring period, which are summarized in Section 7. Tile drainage water inflows to the filters had TP concentrations ranging from 36 to 1380 µg/L—a large range— and a median concentration of 93 µg/L. TDP concentrations were in a similar range, 21–1410 µg/L, although the median TDP concentration was lower, 55 µg/L. Inflow concentrations of TN were relatively high (range = 2.2–43.5 mg/L; median = 20.4 mg/L). TP, TDP, and TN loads at JBT05 ranged from 0.88–590 g TP per day, 0.41–570 g TDP per day, and 0.087–18 kg TN per day. When the receiving ditch was flooded and during the highest flow events, a portion of the tile drain flow bypassed the P filters, and they received a fraction of these calculated JBT05 loads.

*Table 21. Descriptive statistics for flow volumes, concentrations, and loads at JBT05 (filter period)*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3$) | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d) | TDP (g/d) | TN (kg/d) | TSS (kg/d) |
| Count | 48 | 45 | 44 | 45 | 42 | 45 | 44 | 45 | 42 |
| Min | 61.1 | 36 | 21 | 2.2 | 3 | 0.88 | 0.41 | 0.087 | 0.072 |
| Max | 6230 | 1380 | 1410 | 43.5 | 140 | 590 | 570 | 18 | 45 |
| Mean | 1120 | 183 | 138 | 20.0 | 27 | 48 | 40 | 3.1 | 4.2 |
| Median | 429 | 93 | 55 | 20.4 | 12 | 5.2 | 3.7 | 1.3 | 0.92 |
| St. Dev. | 1430 | 244 | 240 | 8.2 | 33 | 110 | 100 | 4.0 | 8.5 |

*Table 22. Descriptive statistics for flow volumes, concentrations, and loads in Filter A outflow*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Flow ($m^3$)** | **TP (µg/L)** | **TDP (µg/L)** | **TN (mg/L)** | **TSS (mg/L)** | **TP (g/d)** | **TDP (g/d)** | **TN (kg/d)** | **TSS (kg/d)** |
| Count | 40 | 38 | 38 | 38 | 34 | 38 | 38 | 38 | 34 |
| Min | 6.0 | 23 | 11 | 2.0 | 3 | 0.022 | 0.011 | 0.000 | 0.028 |
| Max | 1180 | 685 | 690 | 36.9 | 88 | 41 | 41 | 5.3 | 3.4 |
| Mean | 201 | 110 | 84 | 19.4 | 16 | 4.0 | 3.2 | 0.69 | 0.41 |
| Median | 135 | 57 | 38 | 19.5 | 6 | 1.3 | 0.80 | 0.28 | 0.11 |
| St. Dev. | 249 | 137 | 137 | 8.5 | 20 | 7.7 | 7.2 | 1.0 | 0.75 |

*Table 23. Descriptive statistics for flow volumes, concentrations, and loads in Filter B outflow*

| | | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Flow ($m^3$)** | **TP (µg/L)** | **TDP (µg/L)** | **TN (mg/L)** | **TSS (mg/L)** | **TP (g/d)** | **TDP (g/d)** | **TN (kg/d)** | **TSS (kg/d)** |
| Count | 42 | 40 | 40 | 40 | 37 | 40 | 40 | 40 | 37 |
| Min | 5.6 | 14 | 8 | 1.2 | 2 | 0.029 | 0.029 | 0.000 | 0.071 |
| Max | 1070 | 328 | 265 | 39.3 | 78 | 13 | 7.6 | 6.2 | 8.6 |
| Mean | 274 | 72 | 49 | 17.8 | 15 | 2.6 | 1.9 | 0.91 | 0.62 |
| Median | 214 | 44 | 33 | 18.2 | 8 | 1.6 | 1.1 | 0.58 | 0.22 |
| St. Dev. | 220 | 71 | 52 | 8.1 | 19 | 2.7 | 1.9 | 1.1 | 1.4 |

Only paired inflow/outflow concentration data are plotted in the boxplots presented in Figures 34 through 37. These figures illustrate lower TP (Figure 34) and TDP (Figure 35) concentrations in outflow from both filters than in inflow. TSS concentrations also appear lower in outflow from both filters than in inflow (Figure 37), although the differences are less dramatic. There is little change in TN concentrations (Figure 36) between the inflows and filter outflows.

Further, the outflow concentrations of TP and TDP from Filter B appear lower than from Filter A (Figures 34 and 35). The median TP (44 µg/L) and TDP (33 µg/L) concentrations in Filter B outflow are lower than in Filter A outflow (57 µg/L TP and 38 µg/L TDP), as are the maximums. Only marginal decreases are seen in TN concentrations, with median concentrations of 20.4 mg/L in the inflow, 19.5 mg/L in Filter A outflow, and 18.2 mg/L in Filter B outflow.

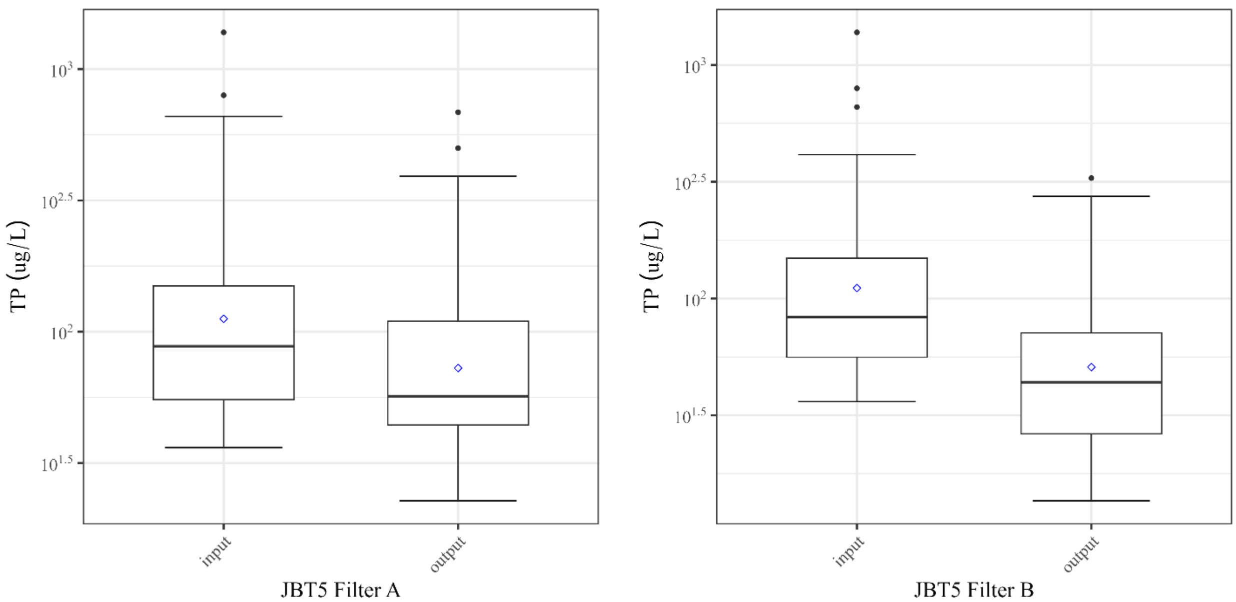



*Figure 34. TP concentration distributions in Filter A (left) and Filter B (right) inflows and outflows*

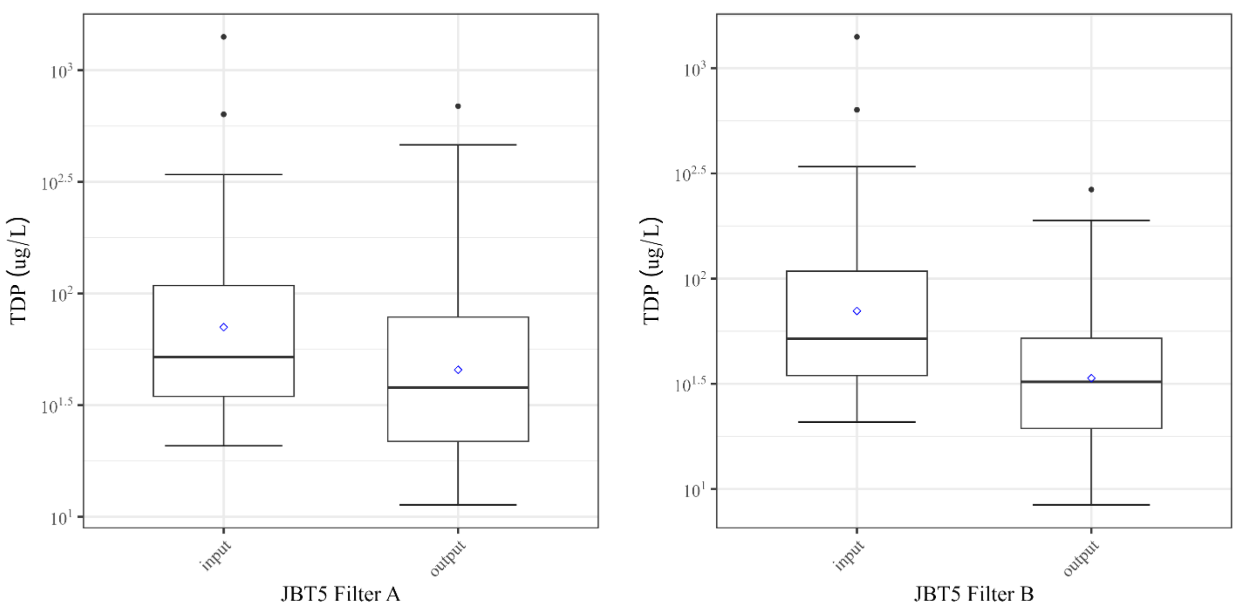



*Figure 35. TDP concentration distributions in Filter A (left) and Filter B (right) inflows and outflows*

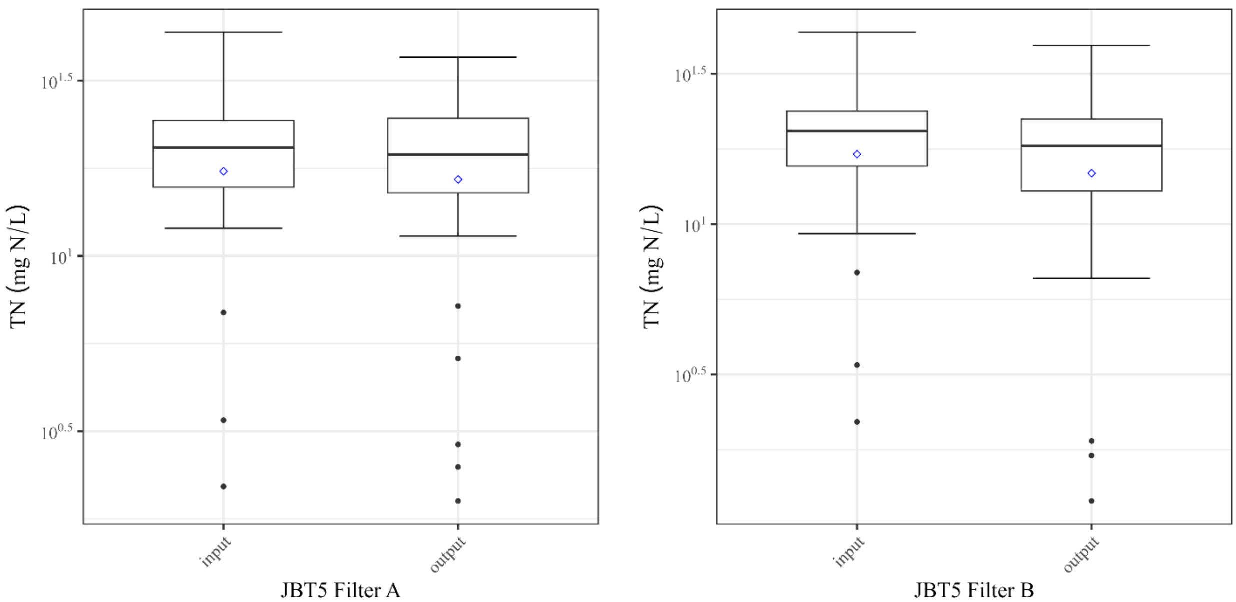



*Figure 36. TN concentration distributions in Filter A (left) and Filter B (right) inflows and outflows*

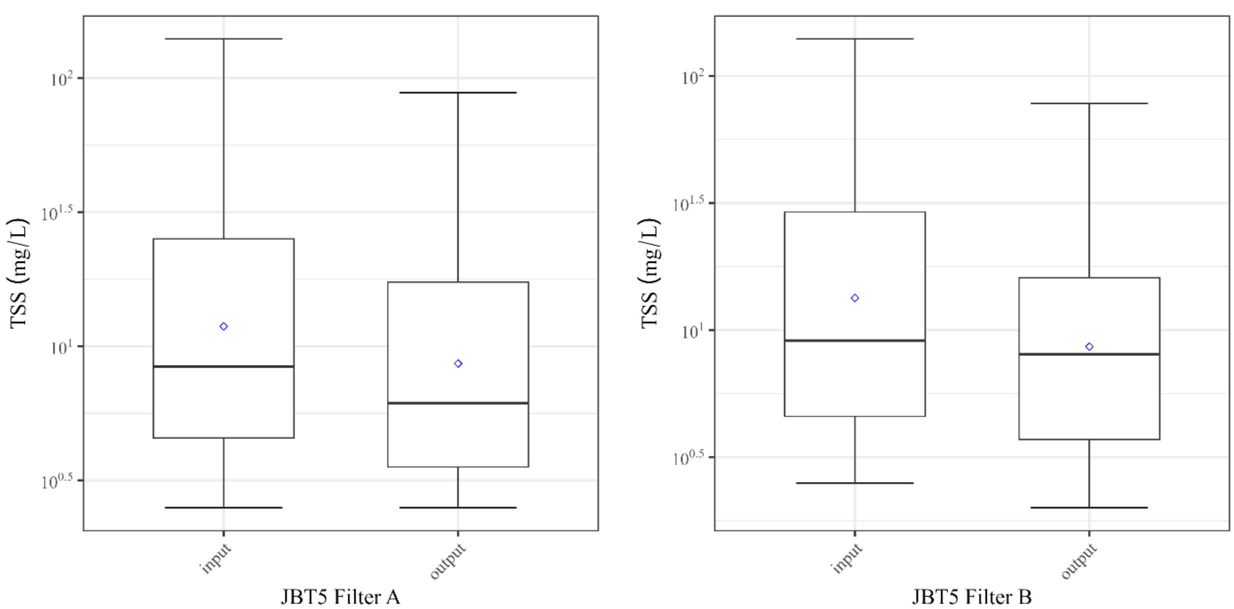



*Figure 37. TSS concentration distributions in Filter A (left) and Filter B (right) inflows and outflows*

Figures 38 through 41 present distributions of loads in filter inflows and outflows. Only paired inflow/outflow loading data are plotted in these boxplots. Since inflow rates to the filters were not independently measured, we assumed that filter inflow volumes were equivalent to the monitored outflow volumes in this boxplot series and in all subsequent loading comparisons. The filters were constructed in clay soil and are lined in durable plastic; therefore, minimal groundwater exchange should occur. Furthermore, the approximately weeklong duration between sample collection events should ameliorate short-term lag effects through the filters. Filter inflow loads were calculated as the inflow concentration multiplied by the outflow volume. Because tile drain flow is split between the two filters and also bypasses the filters at high flow rates and when the receiving ditch is backwatered, the effective inflow volumes and loads to each filter do not match the JBT05 values in Table 21.

At both Filter A and Filter B, TP loads (Figure 38) and TDP loads (Figure 39) appear lower in the outflow than in the inflow. TSS loads (Figure 41) also appear lower in outflow from both filters than in the inflow, though the differences are less dramatic. There is little change in TN loads (Figure 40) between the inflows and outflows.

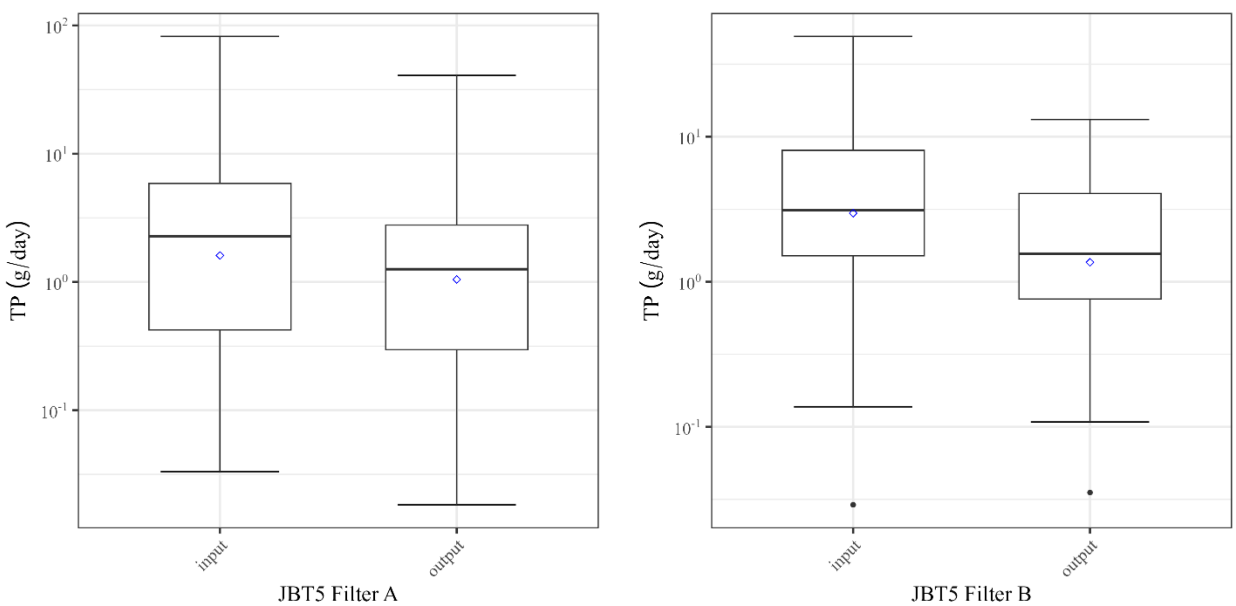



*Figure 38. TP load distributions in Filter A (left) and Filter B (right) inflows and outflows*

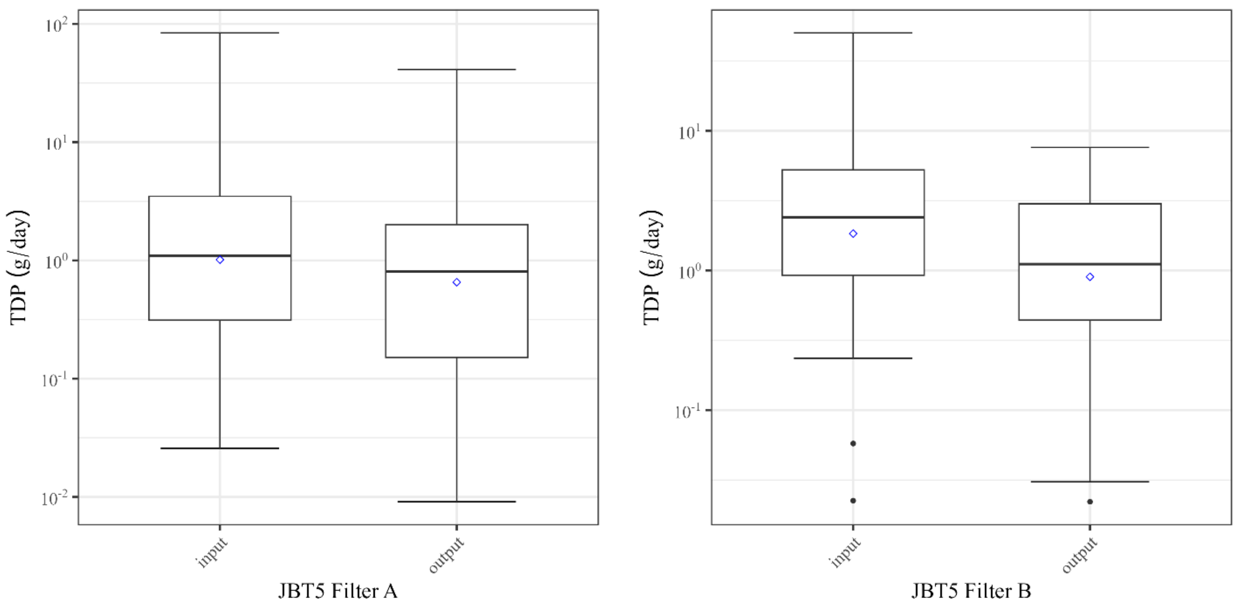



*Figure 39. TDP load distributions in Filter A (left) and Filter B (right) inflows and outflows*

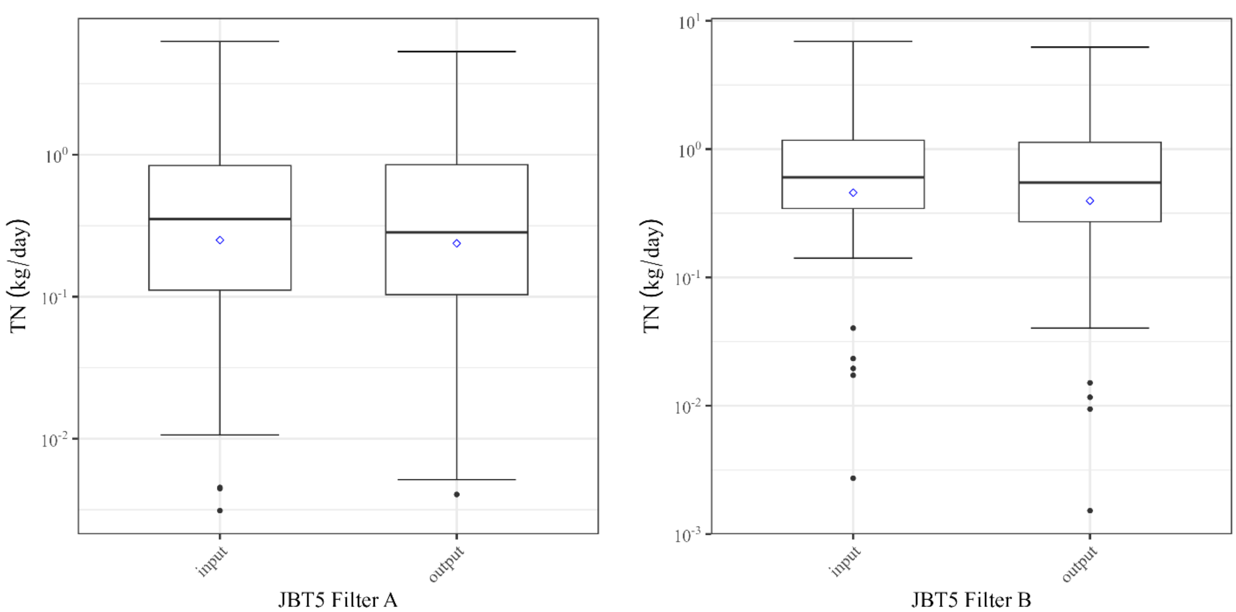



*Figure 40. TN load distributions in Filter A (left) and Filter B (right) inflows and outflows*

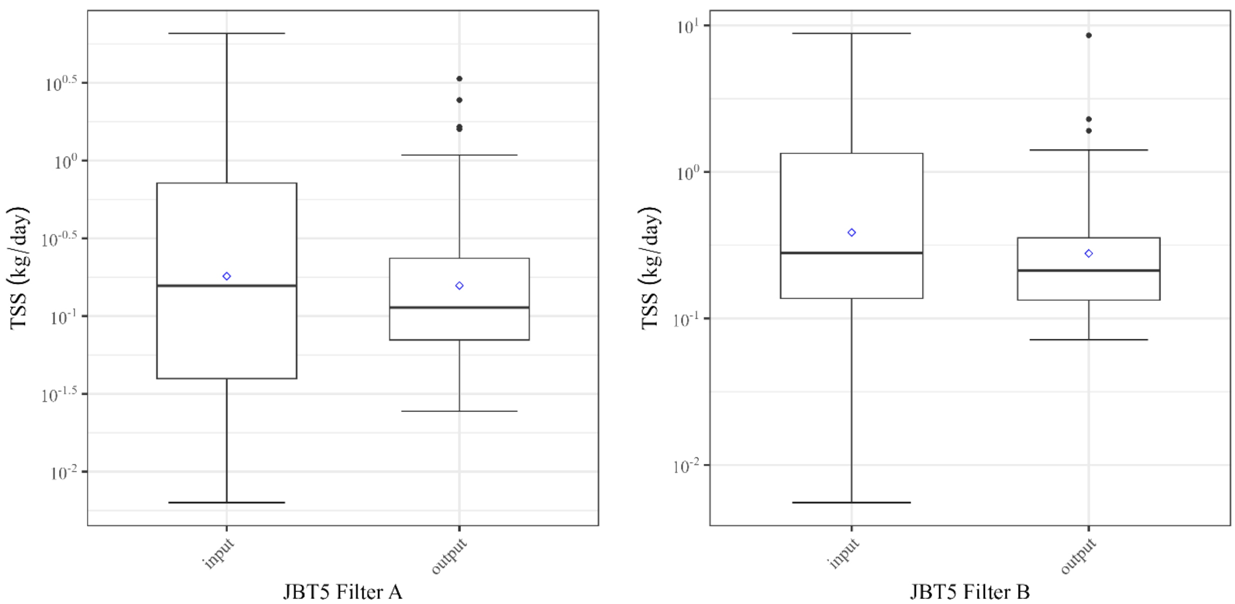



*Figure 41. TSS load distributions in Filter A (left) and Filter B (right) inflows and outflows*

### 8.2. Filter Hydraulics

Since the proportion of flow bypassing the filters is a function of both the tile drain flow rate and the water elevation in the receiving ditch, the threshold flow at which bypass occurs is not a constant. During many late winter/early spring events substantial tile drain flow bypassed the filters because the water elevation in the receiving ditch approached the water elevation in the JBT05 manhole. While water continues to flow out the tile drain bypass, there was little flow through the filters under these conditions, because there was negligible hydraulic head difference between the JBT05 manhole and the filter outlets. An extreme example of this is shown in Figure 42, when flood waters inundated the site.

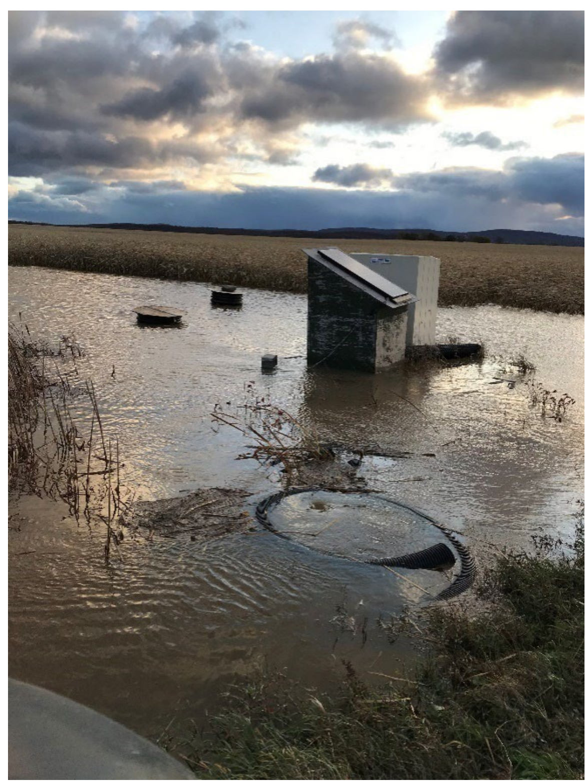


*Figure 42. Flooding of the P filters, Nov. 1, 2019*

Flow rates from Filter A and Filter B during summer events when the water level in the receiving ditch did not rise substantially provide a reasonable indication of the hydraulic capacity of the filters. For example, on June 3, 2022 in-situ hydraulic conductivity measurements were made between the inflow and outflow manholes of Filters A and B. Flow measurements were 134

L/min (0.079 $ft^3$/s) for Filter A and 177 L/min (0.104 $ft^3$/s) for Filter B. Both filter outlets were submerged and there was no bypass flow on this date. The hydraulic head differences between the inflow and outflow manholes were 0.13 ft. for Filter A and 0.10 ft. for Filter B. These differences in head and the minimum distance through the media between the top of the distribution pipes and the inverts of the collection pipes (1.5 ft) were used to calculate the hydraulic gradient. Using the flow rates, hydraulic gradients, and filter dimensions, the hydraulic conductivities of the filters were: k= 0.0036 ft/s for Filter A and k= 0.0063 ft/s for Filter B. A possible explanation for the greater hydraulic conductivity of Filter B is that we did a better job of excluding soil from the Filter B trench during construction. These full-scale, empirically derived hydraulic conductivity values will be useful in designing future P filters.

### 8.3. P Filter Performance

Statistical analysis of the filter inflow and outflow data was conducted according to EPA guidance for monitoring and evaluating nonpoint source management practices (Dressing et al. 2016) using an "input/output" experimental design. The reduction efficiencies of the tile drain P filters were calculated using the percent reduction in concentrations and loads as well as regression of outflow vs. inflow concentrations and loads, after Dressing et al. (2016).

As described in Section 8.1, the inflow volume to each filter was assumed to equal the monitored outflow volume. Given this assumption, the fraction of a given constituent removed during an individual sampling period should be equivalent whether comparing concentrations or loads. Therefore, in this filter performance comparison, we have emphasized concentration reductions.

Concentration datasets were tested for normality using the Shapiro-Wilks method in R. Apart from TN concentrations in Filter A outflow (p = 0.057) and Filter B outflow (p = 0.13), the data do not follow normal distributions. Therefore, non-parametric Wilcoxon rank sum tests were used to assess significant differences between inflows and outflows. Filter performance was quantified using trimmed datasets with non-paired data removed. There were 38 paired events at both Filter A and Filter B. Eight events with valid inflow concentration data and no or invalid Filter A outflow data were excluded, as were six events with no or invalid Filter B outflow data.

The results of two-sided Wilcoxon rank sum tests are provided in Tables 24 and 25. Using this test, significant differences at p <0.1 were found in TP and TDP concentrations for Filter A (Table 24). For Filter B, significant differences were found in both TP and TDP concentrations and loads (Table 25). No significant differences were found in TN or TSS concentrations or loads.

*Table 24. Results of Wilcoxon rank sum tests between Filter A inflows and outflows[1]*

| | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|
| | **TP (µg/L)** | **TDP (µg/L)** | **TN (mg/L)** | **TSS (mg/L)** | **TP (g/d)** | **TDP (g/d)** | **TN (kg/d)** | **TSS (kg/d)** |
| p-value | **0.03** | **0.03** | 0.73 | 0.25 | 0.28 | 0.33 | 0.87 | 0.81 |

1. Statistically significant reductions in bold face

*Table 25. Results of Wilcoxon rank sum tests between Filter B inflows and outflows[1]*

| | Concentration | | | | Load | | | |
|---|---|---|---|---|---|---|---|---|
| | TP (µg/L) | TDP (µg/L) | TN (mg/L) | TSS (mg/L) | TP (g/d) | TDP (g/d) | TN (kg/d) | TSS (kg/d) |
| p-value | **<0.01** | **<0.01** | 0.22 | 0.13 | **<0.01** | **0.04** | 0.69 | 0.39 |

1. Statistically significant reductions in bold face

Table 26 presents long-term efficiency and load reduction estimates for Filters A and B. Long-term efficiency is determined by calculating the average concentrations for inflows and outflows and using these values to calculate the percent reduction in concentration. Because average concentrations are compared, this estimate does not consider paired data. Similarly, the load reductions in Table 26 compare the sums of all monitored (and paired) inflow and outflow loads.

*Table 26. Percent reductions[1] in concentrations and loads between filter inflows and outflows*

| | Concentration Reduction (%) | | Load Reduction (%) | | Load Reduction (kg) | |
|---|---|---|---|---|---|---|
| **Parameter** | **Filter A** | **Filter B** | **Filter A** | **Filter B** | **Filter A** | **Filter B** |
| TP | **41.3** | **60.8** | 36.2 | **59.5** | 0.57 | **1.0** |
| TDP | **39.6** | **65.1** | 32.2 | **58.7** | 0.38 | **0.70** |
| TN | 3.9 | 10.3 | 7.0 | 5.1 | 15 | 13 |
| TSS | 36.1 | 46.6 | 46.9 | 50.4 | 77 | 160 |

1. Statistically significant reductions in bold face

While the load reduction totals presented in Table 26 provide a reasonable basis for comparing the filters, these values are clearly underestimates for the monitoring year, since paired, flow-proportional composite samples were not obtained during some winter events and several large events in April-May 2020, mainly due to equipment malfunctions complicated by the Covid-19 state of emergency. Also, the summer and early fall of 2020 were exceptionally dry, with little tile drain flow from mid-June through mid-October. In most years, the filters would likely receive greater P loads.

Figures 43 through 46 present simple linear regressions of filter outflow concentrations versus inflow concentrations. The trendlines are forced through the origin. The slopes of the TP, TDP, and TSS concentration regression lines are substantially less than one for both Filter A and Filter B, suggesting reduction of these concentrations through the filters. Conversely, the slopes of the TN concentration regression lines (Figure 45) approach one for both Filter A and Filter B, suggesting little TN removal.

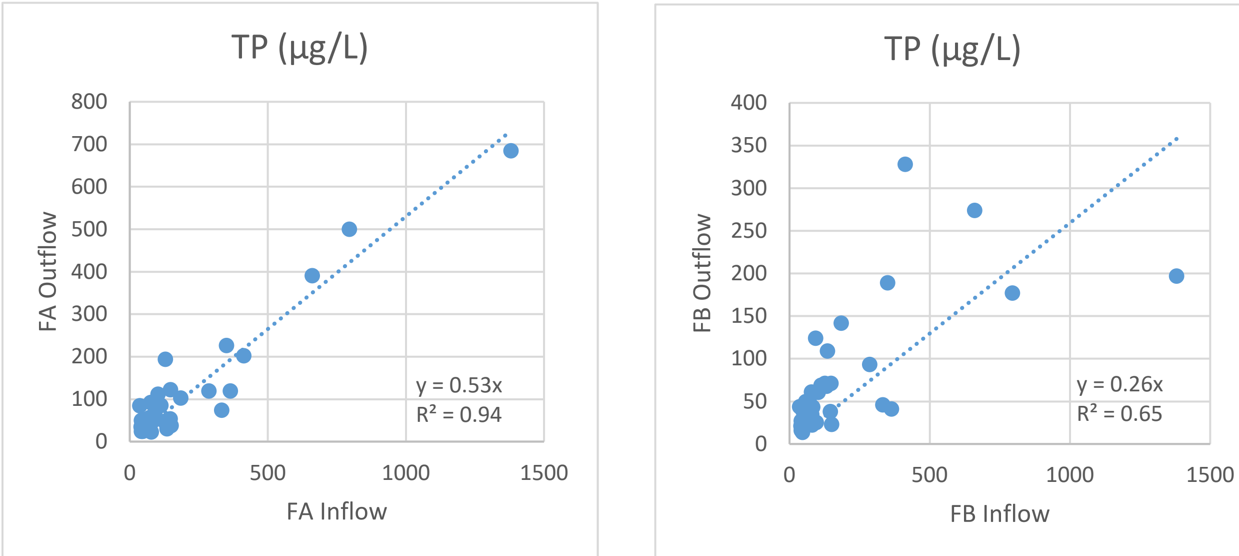



*Figure 43. Filter A (left) and Filter B (right) inflow/outflow TP concentration regressions*

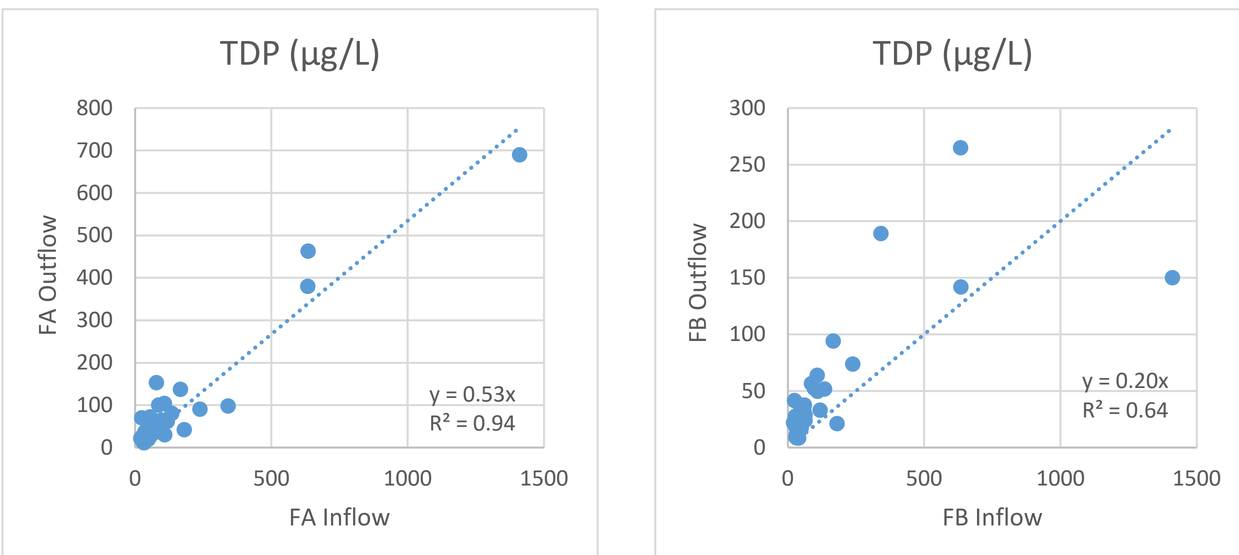



*Figure 44. Filter A (left) and Filter B (right) inflow/outflow TDP concentration regressions*

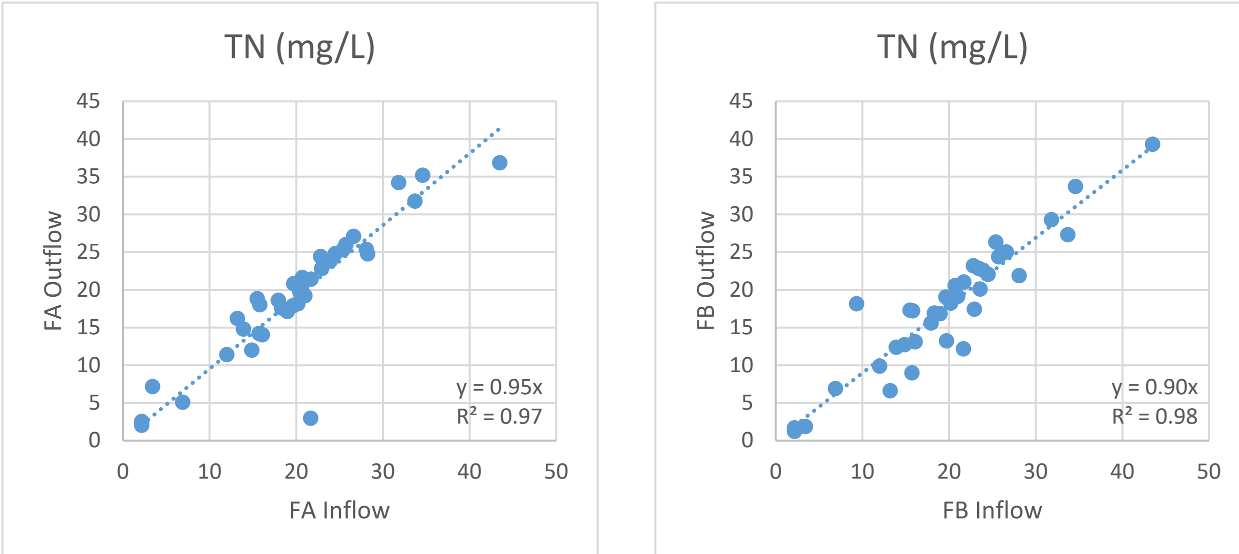



*Figure 45. Filter A (left) and Filter B (right) inflow/outflow TN concentration regressions*

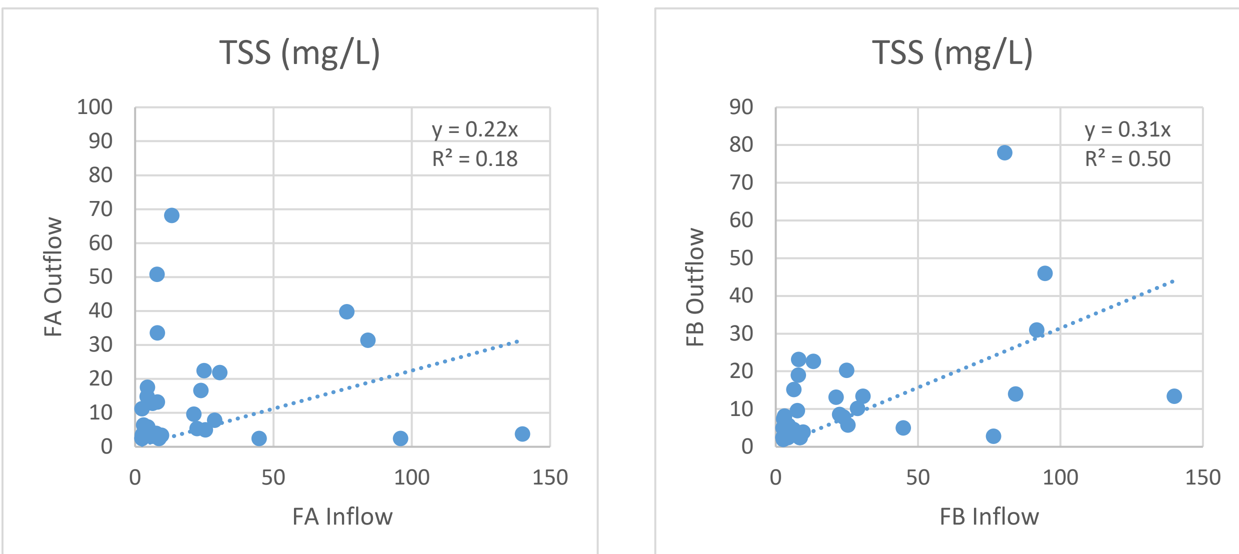
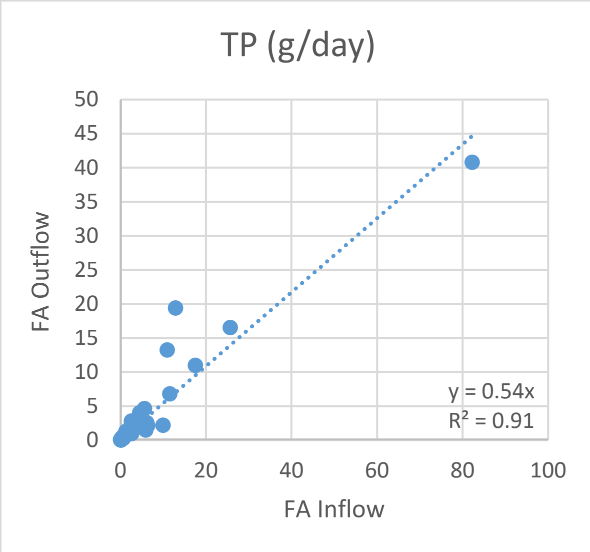



*Figure 46. Filter A (left) and Filter B (right) inflow/outflow TSS concentration regressions*

Similar patterns are apparent in simple linear regressions of filter outflow loads versus inflow loads (Figures 47-50). Again, the trendlines are forced through the origin. The slopes of the TP, TDP, and TSS load regression lines are substantially less than one for both Filter A and Filter B, suggesting removal through the filters, whereas the TN load regression lines (Figure 49) suggest little TN removal.



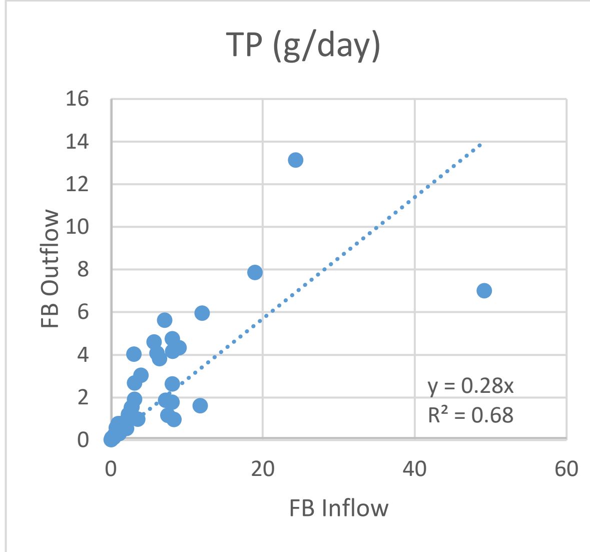
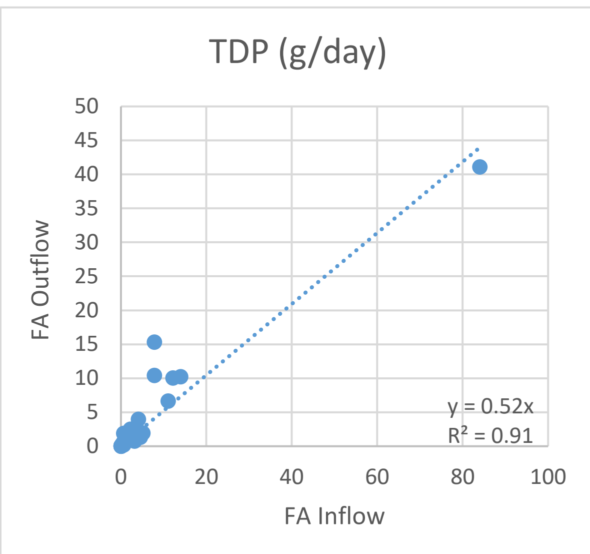




*Figure 47. Filter A (left) and Filter B (right) inflow/outflow TP loading regressions*



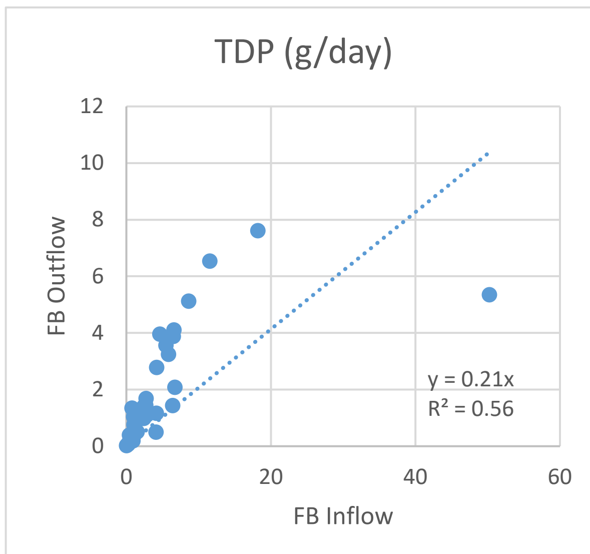




*Figure 48. Filter A (left) and Filter B (right) inflow/outflow TDP loading regressions*

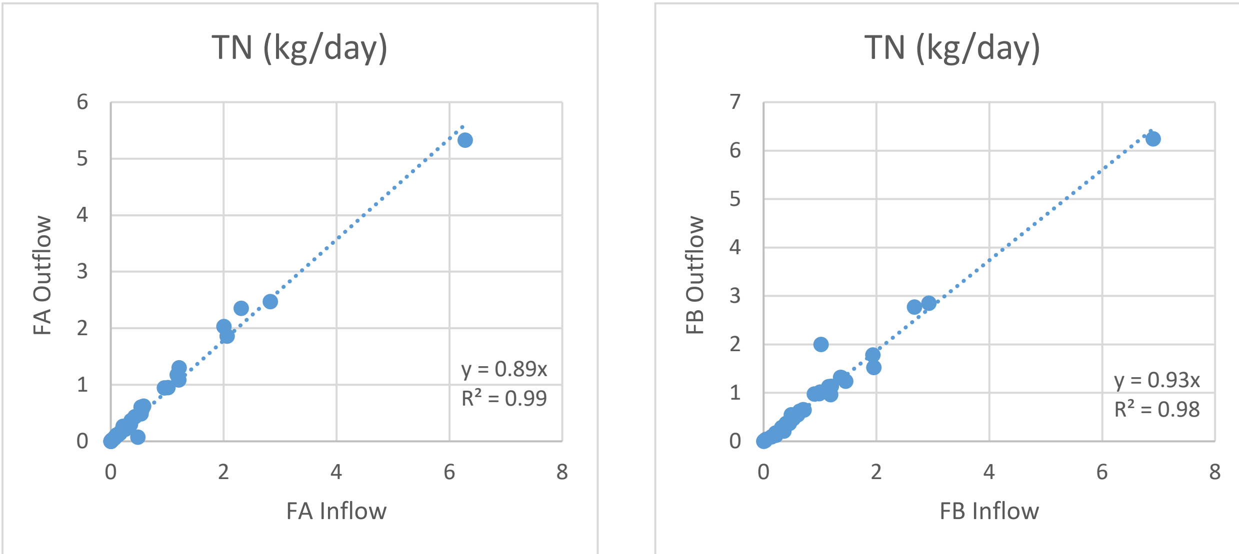



*Figure 49. Filter A (left) and Filter B (right) inflow/outflow TN loading regressions*

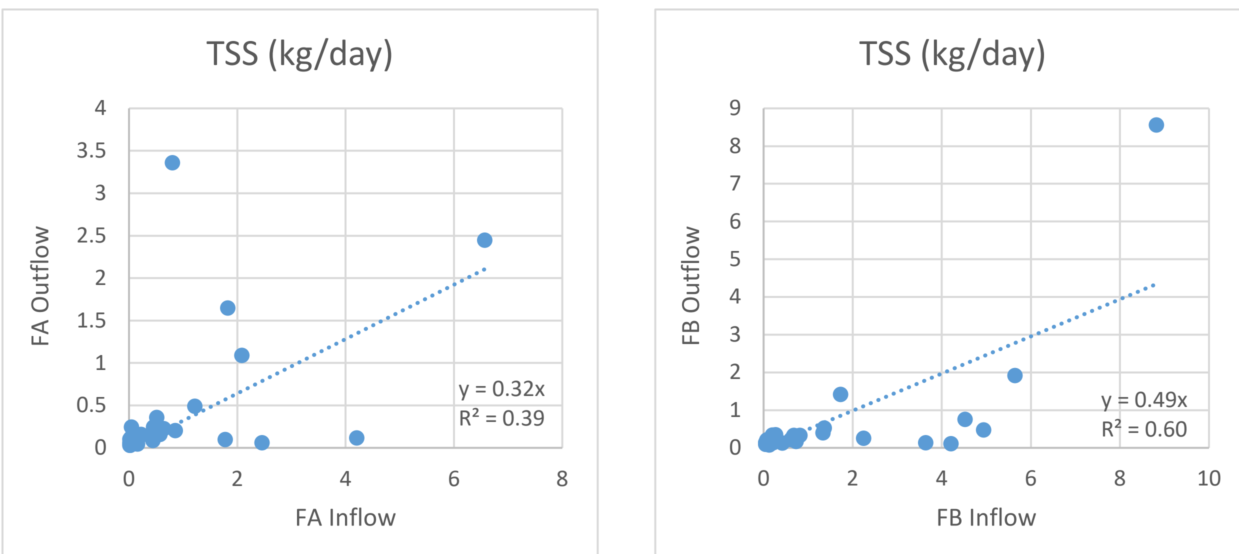



*Figure 50. Filter A (left) and Filter B (right) inflow/outflow TSS loading regressions*

The slopes of regression equations between inflow and outflow concentrations and loads provide alternate estimates of filter performance (Table 27). These estimates are all higher than the corresponding reduction estimates calculated from the unsorted, concentration and loading data (Table 26). The significance of the differences between inflow and outflow concentrations and loads was previously assessed using Wilcoxon rank sum tests (Tables 24 and 25).

*Table 27. Concentration and load reduction estimates[1] derived from linear regression equations*

| Parameter | Concentration Reduction Estimates from Regression Line Slopes (%) | | Load Reduction Estimates from Regression Line Slopes (%) | |
|---|---|---|---|---|
| | Filter A | Filter B | Filter A | Filter B |
| TP | **47** | **74** | 46 | **72** |
| TDP | **47** | **80** | 48 | **79** |
| TN | 5 | 10 | 11 | 7 |
| TSS | 78 | 69 | 68 | 51 |

1. Statistically significant reductions in bold face

Among the statistically significant results, Filter A reduced both TP and TDP concentrations by 47%. Filter B was substantially more effective, reducing TP and TDP concentrations by 74% and 80%, with similar reductions in loads. Any effect on TN was marginal and non-significant. Considerable reductions in TSS concentrations in both filters were suggested by the regression equations; however, these were non-significant using the Wilcoxon rank sum tests.

The final type of inflow/outflow analysis we performed was to regress the filter efficiency (percent reduction among paired inflow/outflow concentrations) against inflow concentration. This type of analysis is meaningful because the efficiency with which a filter may remove a given constituent often varies as a function of the constituent's inflow concentration. Establishing the concentration range over which a filter is effective is critical in selecting appropriate locations to install P filters.

As is often the case, there is a great deal of scatter in the removal efficiency data at low influent concentrations. This was true for TP, TDP, TN, and TSS (Figures 51-54).

At the low end of the influent TP concentration range (~40 µg/L), Filter B appears roughly 30-50% efficient, while Filter A performs poorly, with ~0-20% TP reduction (Figure 51). At an inflow TP concentration of 300 µg/L, Filter B appears 50-60% efficient, while Filter A removes ~30-40%. The TP reduction efficiency of both filters improves with increasing inflow TP concentration, with Filter B continuing to outperform Filter A.

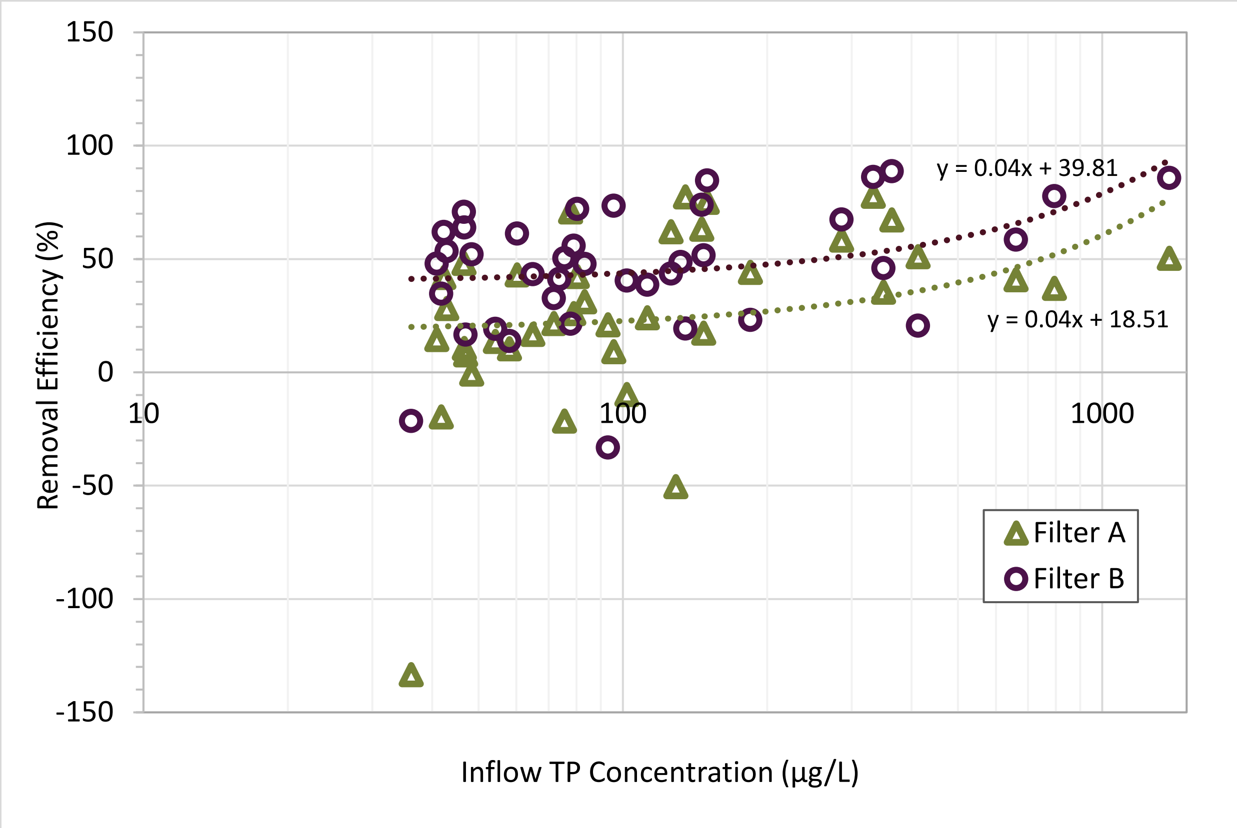



*Figure 51. TP removal efficiency versus inflow TP concentration*

The relationships between removal efficiency and inflow concentration follow a similar pattern for TDP (Figure 52). Filter B consistently outperforms Filter A over the entire range of inflow TDP concentrations, appears modestly effective at reducing TDP concentrations even at inflow concentrations in the 25-50 µg/L range, and is >50% efficient at inflow TDP concentrations above 300 µg/L.

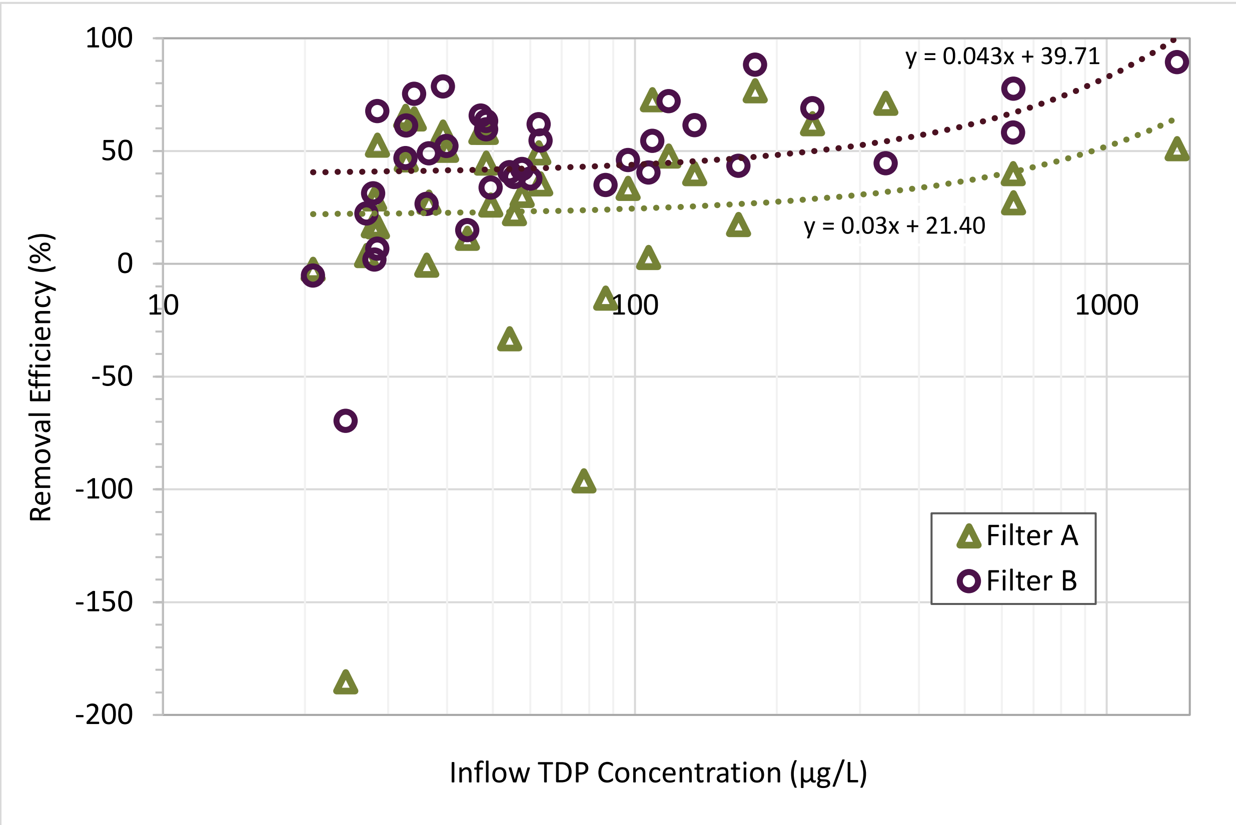



*Figure 52. TDP removal efficiency versus inflow TDP concentration*

Figure 53 illustrates a lack of TN reduction through the P filters regardless of inflow concentration.

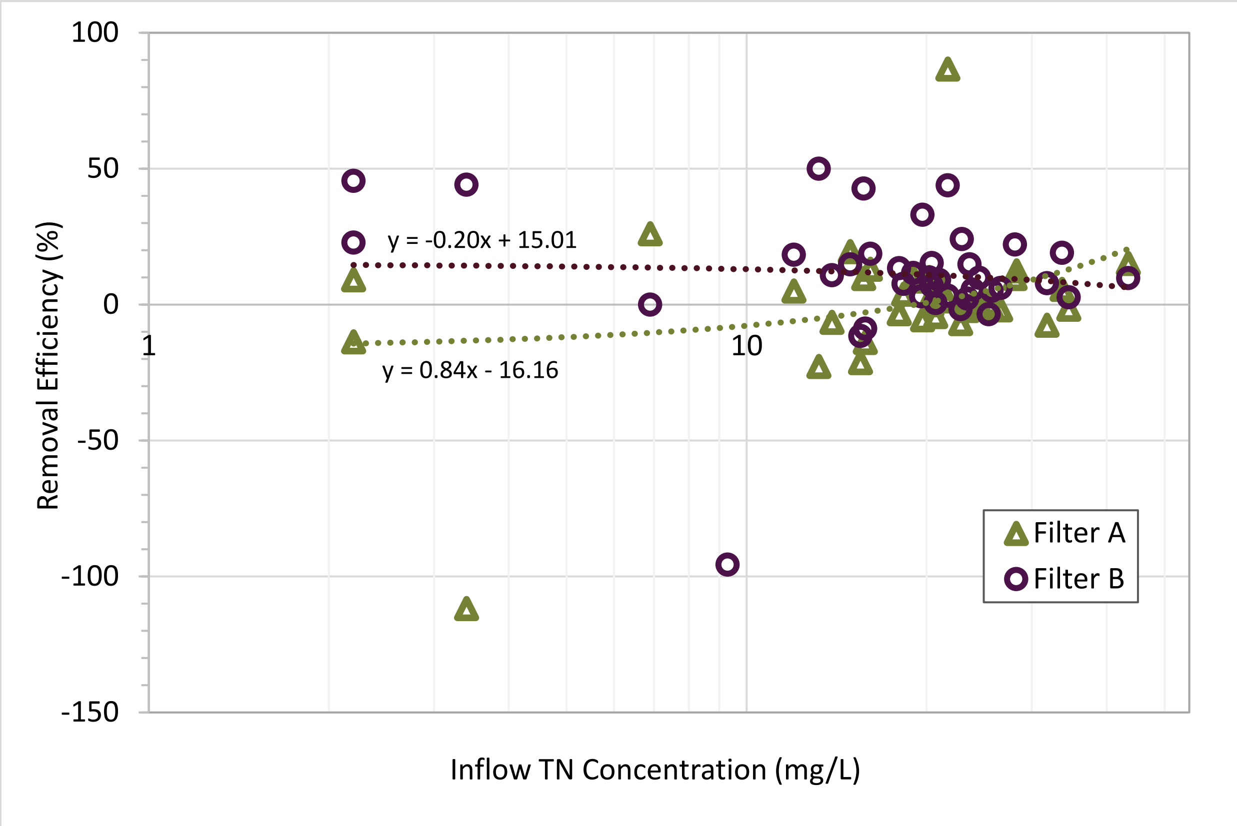



*Figure 53. TN removal efficiency versus inflow TN concentration*

There is a great deal of scatter in the TSS removal efficiency values at inflow TSS concentrations below about 15 mg/L (Figure 54). The limit of quantitation of TSS is 2 mg/L. At TSS concentrations approaching this limit, minor errors made during sample processing and analysis will become proportionally larger. Above ~15 mg/L of TSS in the inflow, the consistent TSS reduction we would expect to see is apparent.

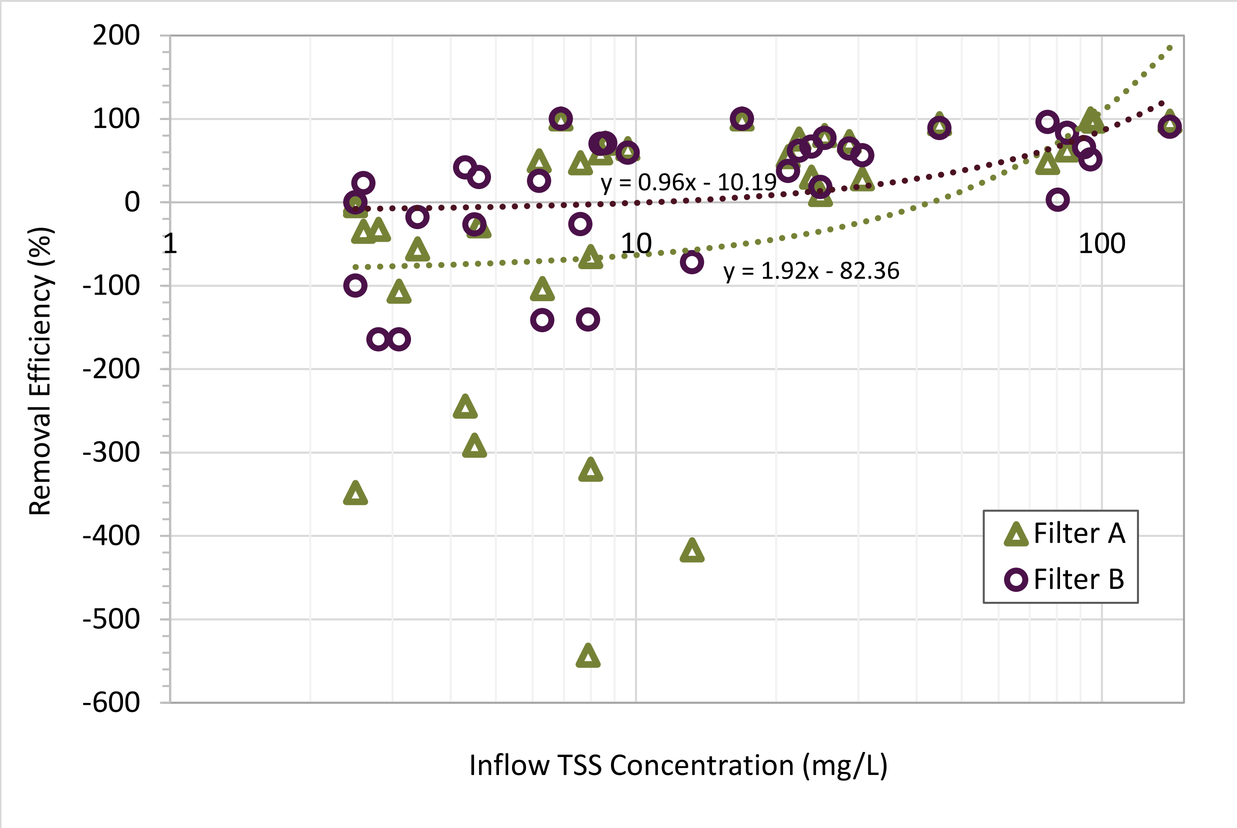



*Figure 54. TSS removal efficiency versus inflow TSS concentration*

Filter B removed a higher percentage of TP and TDP concentrations and loads than Filter A (Tables 26 and 27). Taken together, the two filters removed about 1.6 kg (3.5 lb.) of TP and 1.1 kg (2.4 lb.) of TDP over approximately 38 weeks between December 9, 2019 and January 5, 2021. The summer of 2020 was exceptionally dry; Jewett Brook stopped flowing and there was no tile drain flow for extended periods. Therefore, greater P removal should be possible in most years.

Substantial bypass flow occurred, which was not unexpected given the very large—94 acre—contributing field area. However, we had not fully appreciated the substantial impact high water levels in the receiving ditch could have on increasing bypass flow in this location. Similar filters constructed in less flood prone locations would treat a higher proportion of tile drain flow and remove more P. Despite this factor and the dry monitoring year, the P removal efficiency and flow rates through the filters were high enough that reasonably good P load reductions were obtained.

We believe this project demonstrated that our basic concept of building large, in-ground, up-flow, gravity filters containing a coarse (~1/2-inch diameter) aggregate amended with one or more P sorbing materials is sound. Filter A with Swanton black shale media significantly reduced TP and TDP concentrations, by about 40% using the more conservative estimates (Table 26). Amending the crushed shale with iron shavings and activated alumina (Filter B) substantially improved P removal relative to Filter A, achieving ~60% reduction in TP and ~65% reduction in TDP concentrations and ~60% reductions in TP and TDP loads, again using the more conservative estimates.

Given the short timeframe of the monitoring program, we were not able to adequately assess the life expectancy of the P filters. It is worth noting, however, that the highest flow rates recorded from Filter B (253 L/min) occurred on December 1, 2020 (Appendix B–Figure 4), more than a year after construction, and that on the final sampling date, January 5, 2021, the TP concentration was 72% lower in the Filter B outflow than in the inflow. The Filter A peak outflow rate on December 1, 2020 was nearly as high, 240 L/min (Appendix B–Figure 3), and the TP concentration reduction on the January 5, 2021 sampling date was reasonably good, 42%. These data suggest that neither the hydraulic function nor the P removal capacity of the filters were diminished one year from construction.

Considering P reduction efficiency as a function of inflow P concentration provides some insight into the relative benefit of constructing P filters at a given tile drain site. At low inflow P concentrations, both the P load available for treatment and the P reduction efficiency are lower. In this context, evaluating TDP removal efficiencies may be more meaningful than TP removal efficiencies because 1) the filters are intended as chemical treatment systems, not simply particle filters, and 2) dissolved phosphorus has greater impact in downstream waterbodies than the particulate fraction of TP, much of which is not biologically available. Figure 52 illustrates that relatively consistent TDP removal occurred in Filter B at inflow concentrations above about 60 µg/L. From this study, we suggest selecting tile drains having median inflow TDP concentrations above ~60 µg/L for construction of P filters. Total loading is a second criteria: if the cumulative P loading is too low, costs may outweigh the benefit of treatment. This is likely the case for tile drainage systems in fields of less than ~5 acres. A more complete benefit-cost analysis will be developed in Stone's upcoming tile drain P filter evaluation in the Lake Carmi watershed.

### 8.4. P Filter Design and Construction Improvements

Based on the results of this study, there are some refinements we recommend when siting, designing, and constructing P filters:

1. P filters constructed in an agricultural setting are an agricultural conservation practice. Vermont's Required Agricultural Practices (VAAFM, 2018) should be the prevailing regulations. P filters are installed on cropland, typically at the very edge of the field where the tile drain main passes from the cultivated portion of the field into a perennial buffer zone along a ditch or stream. The completed filter becomes a narrow "bump-out" along the edge of the cultivated field. In most tile drained fields, there is little flexibility regarding where a P filter can be sited given the layout of tile drain laterals. Recognizing these constraints, P filters should be set back from streams and ditches as far as possible without compromising their function.
2. While it is possible to design filters with submerged outlets, it is preferable to avoid this where possible. When the water level in the ditch approached the water surface elevation in the JBT05 manhole, the flow rate through the filters decreased and then occasionally stopped entirely (because the hydraulic head in the manhole and the ditch became equal), resulting in excessive bypass flow.

3. Use perforated, rigid pipe for distribution and collection pipes. The flexible tile drainpipe we used, while inexpensive, tends to float up and move as stone is added to the trench.
4. Prepare the filter media by blending materials on level ground before constructing the filters. Filling the filter trenches in lifts while raking in amendments was time consuming and difficult.
5. Simplify the piping to one distribution pipe and one collection pipe. The parallel pipes were likely unnecessary.
6. Replace the heavy plastic liner with geotextile.
7. Replace the distribution manhole with an Agri-drain water level control structure and buried pipes.
8. At some sites, it may be preferable to loop the treated water back to the existing tile drain main, downstream of the water level control structure, rather than creating a separate outlet for the filter. This design could add flexibility in filter siting and avoid some disturbance.

# 9. Conclusions

The Addison County tile drains selected for this study had significantly higher TP, TDP, and TSS concentrations than the Jewett Brook watershed tile drains. This finding is counter to the frequently expressed opinion that tile drains in the Jewett Brook watershed are likely to contribute more P than elsewhere in the Lake Champlain Basin (such as Addison County)—that, in this respect, the Jewett Brook watershed is essentially a non-representative outlier. We find that substantial P losses through tile drains are not confined to the Jewett Brook watershed but occur in Addison County also.

Our finding that P and TSS concentrations and loads in tile drainage water from the one field with sandy soils, ACT1, were dramatically lower than from the other Addison County fields, despite similar agronomic practices, is informative. While studies in other regions include similar findings (Beauchemin et al., 1998; Kleinman et al., 2003; Eastman, 2010), we are not aware of studies in the Lake Champlain Basin that have demonstrated effects of soil texture on P concentrations in tile drain flow. The earlier Jewett Brook tile drainage study by Braun et al. (2019) did not find significant differences in P concentrations or loads based on soil texture, possibly because differences in soil texture among the study fields were relatively minor.

The P filters Stone designed and constructed were able to treat substantial volumes of water, with flow rates up to approximately 250 L/min (except when the receiving ditch was full). The P filters significantly reduced TP and TDP concentrations in tile drainage water. Filter A containing only Swanton black shale reduced P concentrations by about 40%, while Filter B containing zero-valent iron and activated alumina reduced TP concentrations by approximately 60%, TDP concentrations by 65%, and TP and TDP loads by about 60%. Filter B also appeared to be more effective at removing P at low inflow concentrations than Filter A; under these conditions, the TP concentration in Filter A outflow was typically in the 30-50 µg/L range (minimum 23 µg/L), while the TP concentration in Filter B outflow was lower, in the 15-40 µg/L range (minimum 14 µg/L).

Considering only the 38 events with paired inflow and outflow data, Filter A removed approximately 0.6 kg of TP and 0.4 kg of TDP over the monitoring period, though these loading reductions were not statistically significant using Wilcoxon ranked sum tests. Filter B removed approximately 1 kg of TP and 0.7 kg of TDP, both significant reductions. Substantially higher P reductions would surely have been achieved if most of the tile drain flow did not bypass the filters during large events when the receiving ditch was full.

The analysis of P reduction efficiency indicated that reasonably consistent dissolved P removal occurred at inflow concentrations above 60 µg/L of TDP. This threshold may be a useful guide in selecting tile drains for implementation of P filters, until a more complete benefit-cost analysis is completed for the tile drain P filter evaluation Stone is now conducting in Lake Carmi watershed.

# 10. Deliverables Completed

Stone prepared quarterly progress reports within 10 days following the end of each calendar quarter. These quarterly reports provided updates on the progress of each task and described any problems encountered.

Stone prepared an interim report following completion of Task 6 of the workplan. This interim report described work performed through site characterization, monitoring station installation, and filter design and construction. The substance of this interim report has been incorporated in this final report.

This final report includes methods and results of both the extended tile drain monitoring and the tile drain P filter evaluation components of this project.

Stone presented its findings to the LCBP technical advisory committee on February 1, 2023, shortly following submission of the draft final report.

This study has been presented at the following events:

- Meeting of the Vermont Agency of Agriculture, Food, and Markets' Tile Drain Advisory Group, December 17, 2019.
- Finger Lakes Institute, Water Pollution Prevention in the Seneca-Keuka Watershed (webinar series), May 28, 2020.
- Meeting of the Vermont Agricultural Water Quality Partnership, Scientific Advisory Committee, May 2, 2022.

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# Appendix A: Quality Assurance Project Plan

# Appendix B: Tile Drain Hydrographs

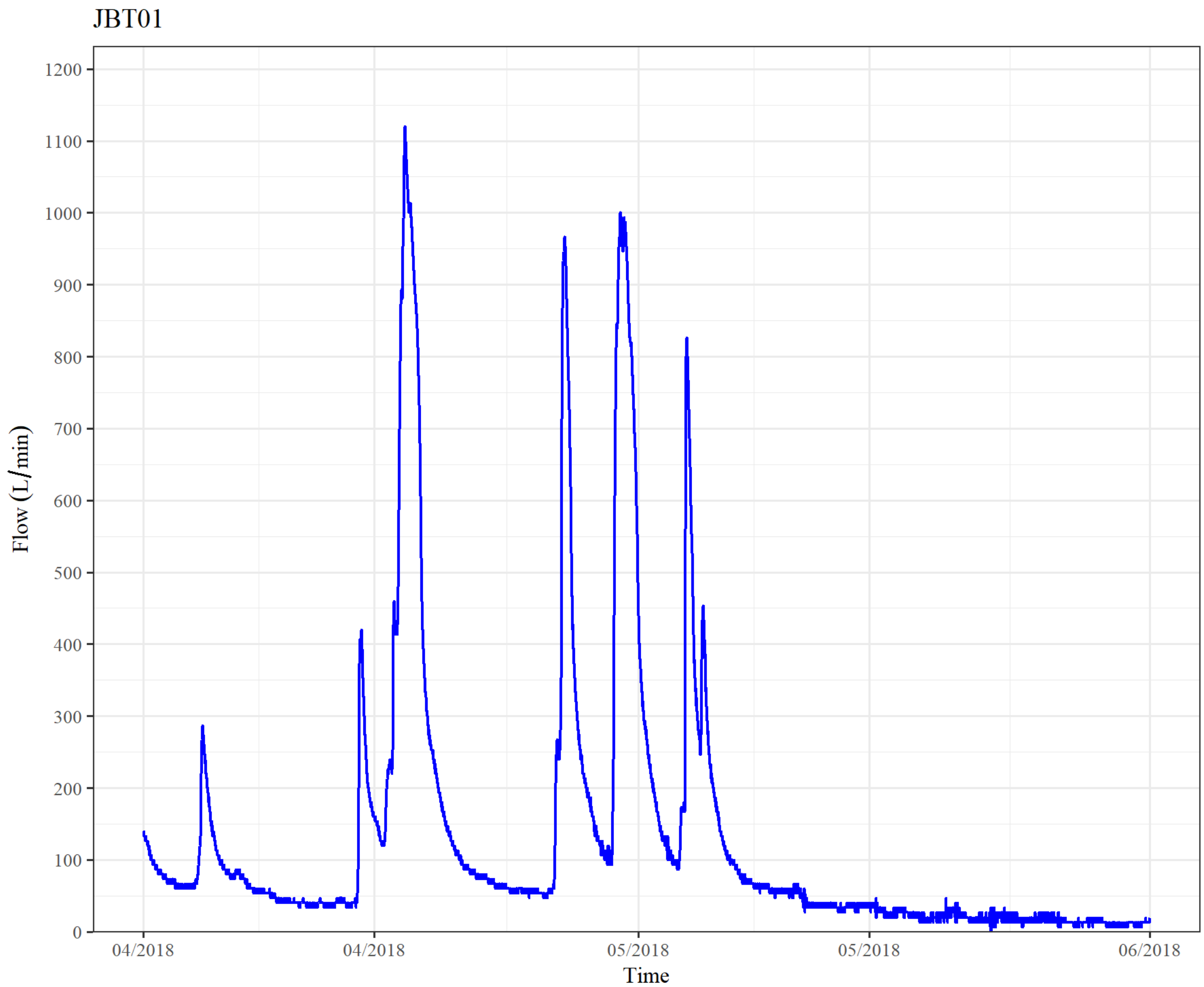


*Figure 1. Flow rate at the JBT01 tile drain monitoring station*

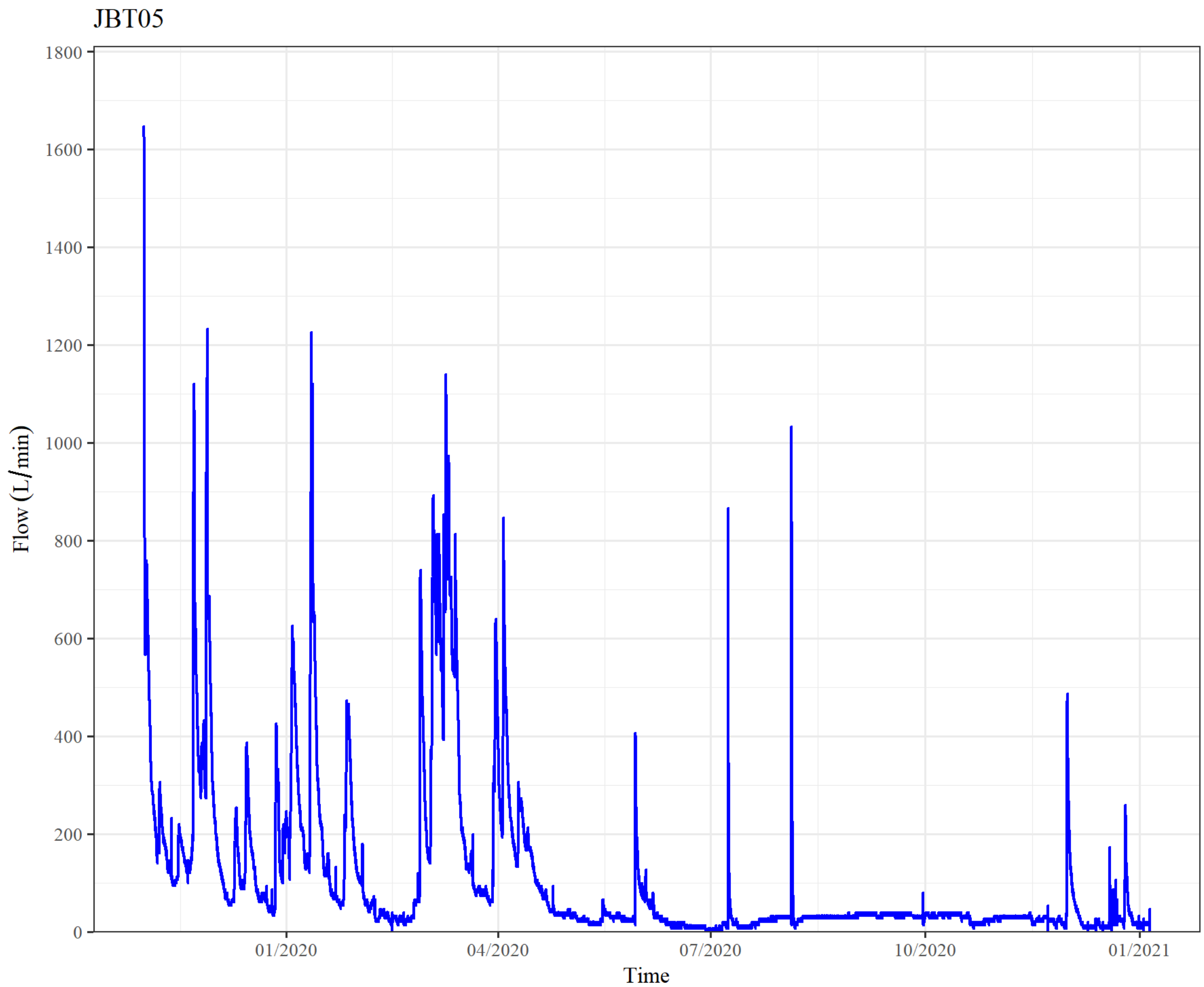


*Figure 2. Flow rate at the JBT05 tile drain monitoring station*

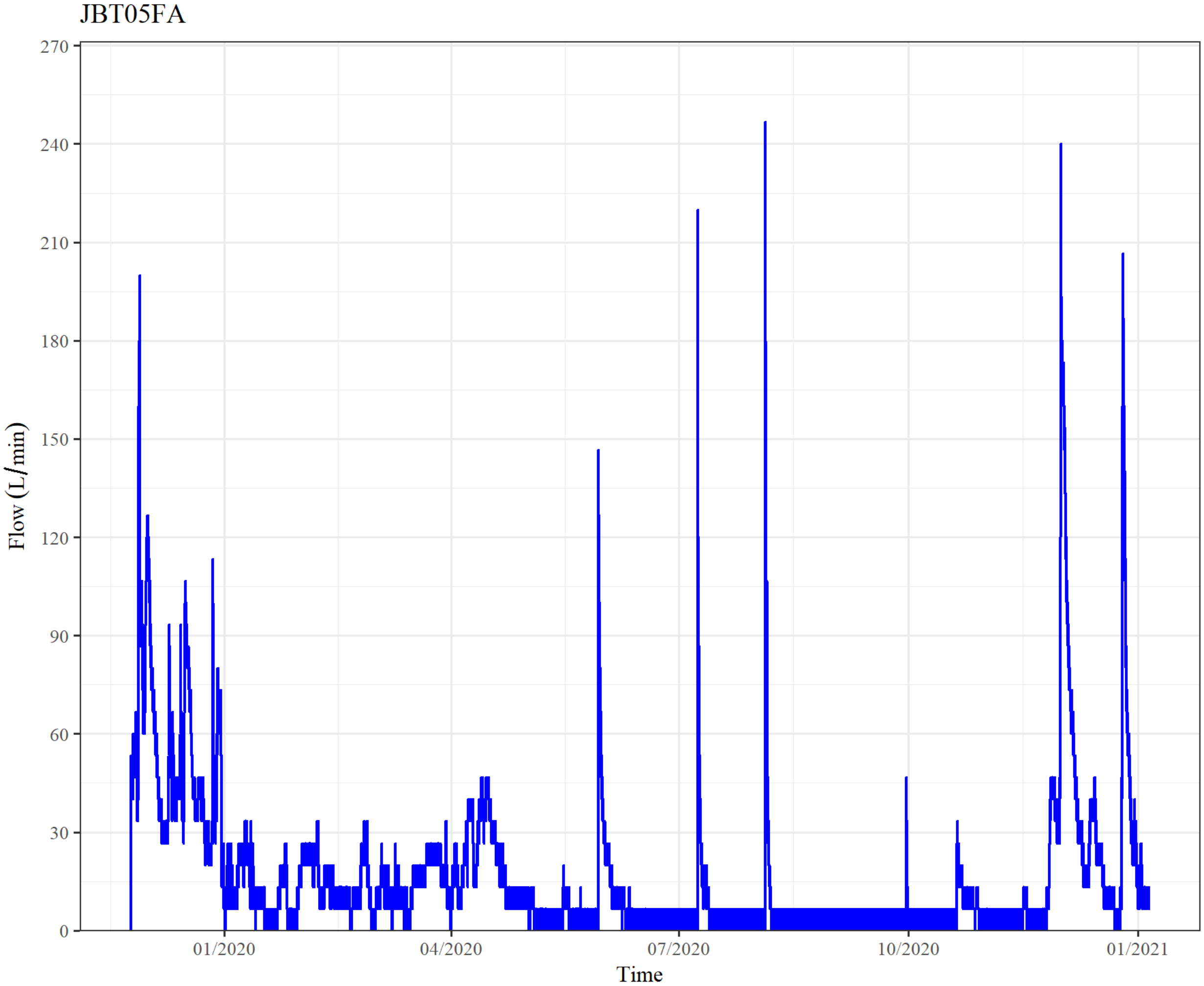


*Figure 3. Flow rate at the JBT05 Filter A tile drain monitoring station*

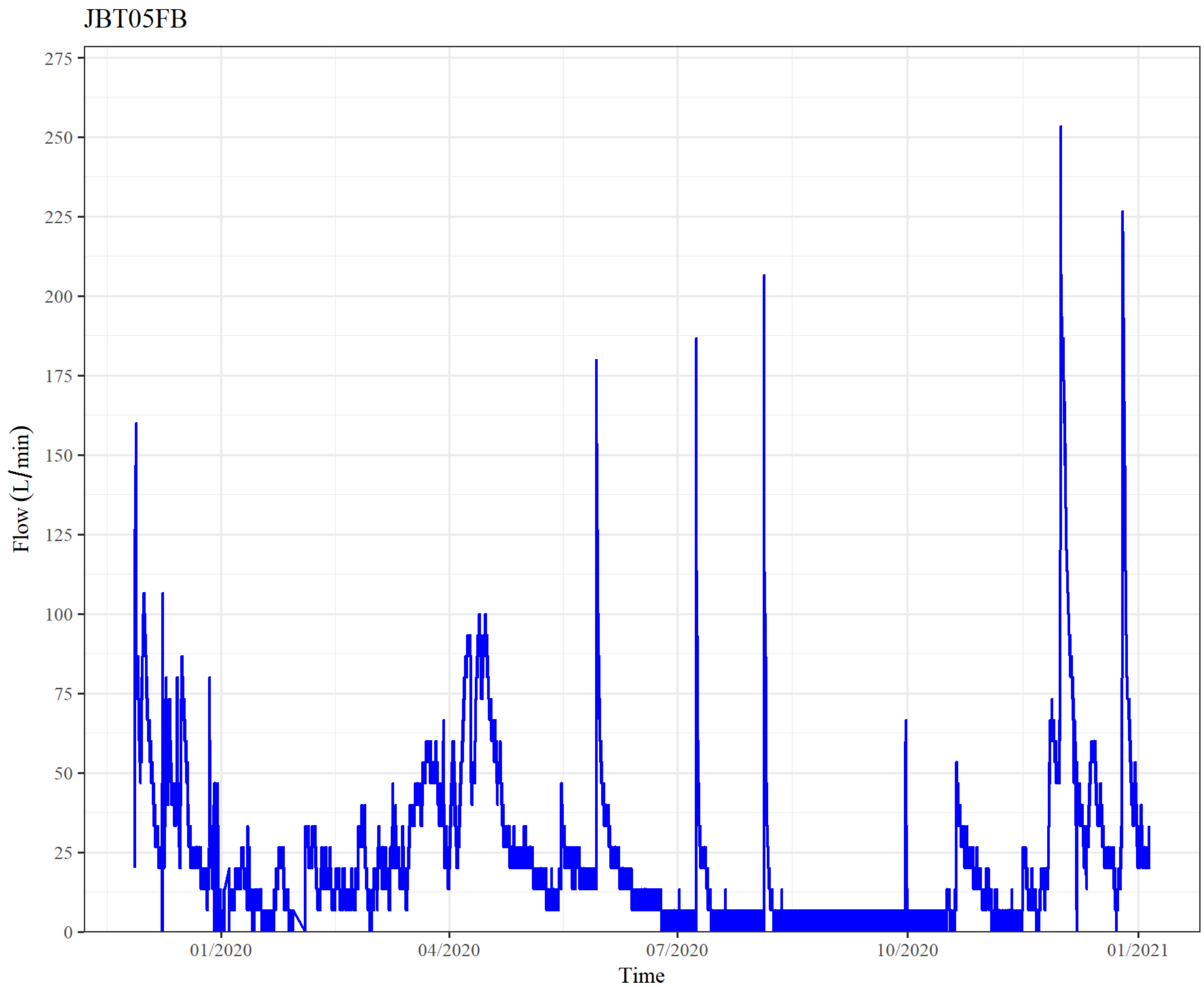


*Figure 4. Flow rate at the JBT05 Filter B tile drain monitoring station*

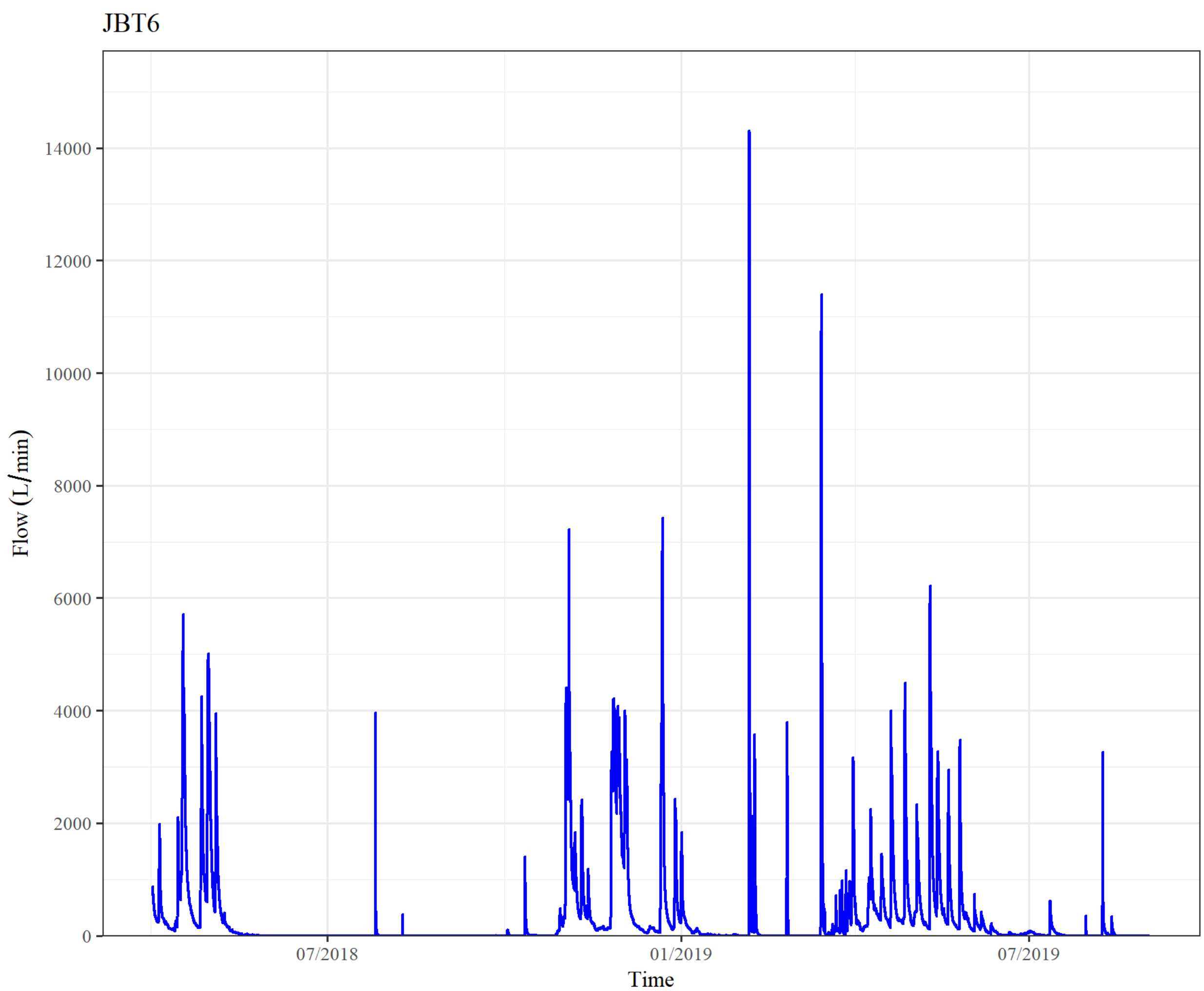


*Figure 5. Flow rate at the JBT06 tile drain monitoring station*

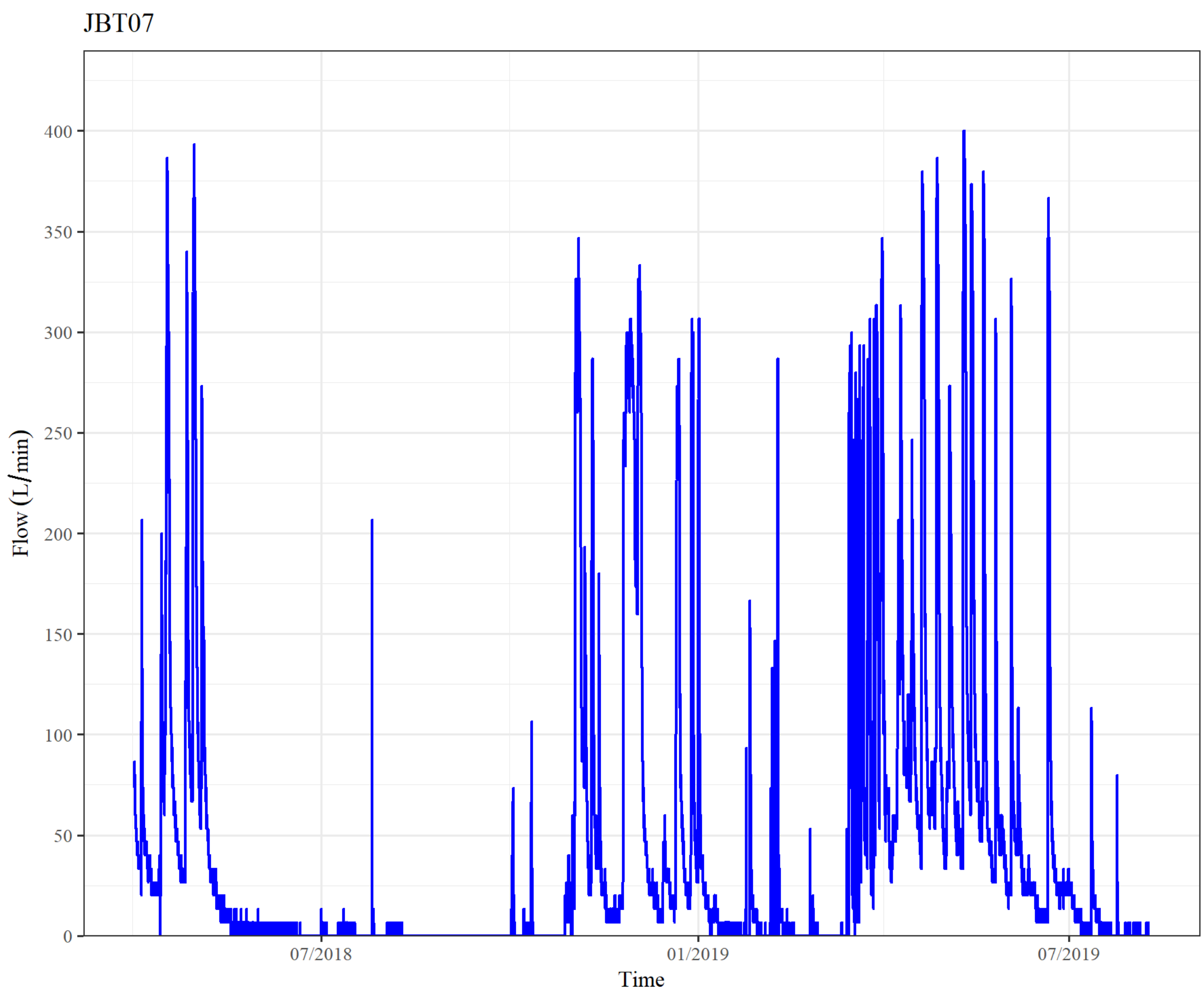


*Figure 6. Flow rate at the JBT07 tile drain monitoring station*

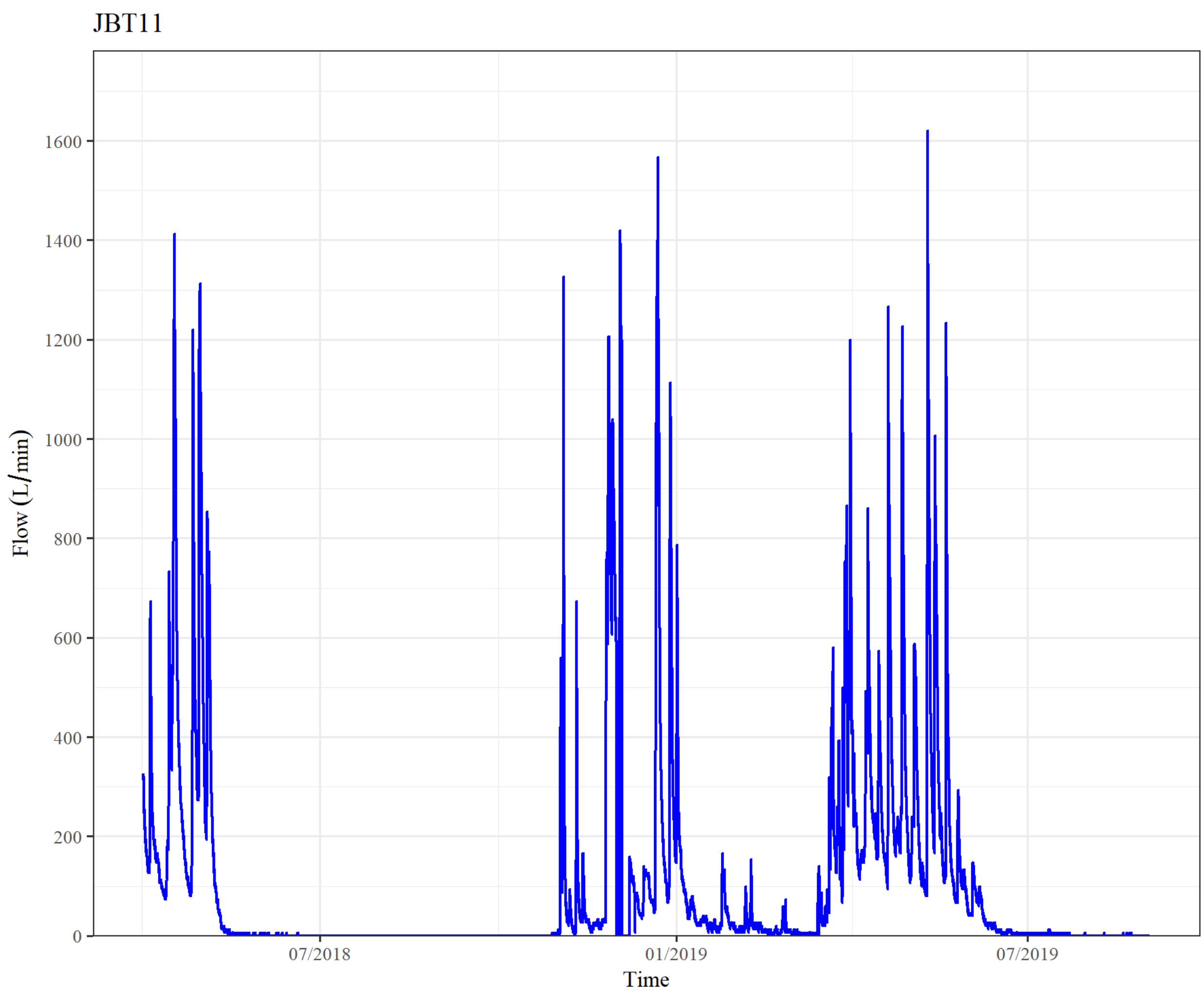


*Figure 7. Flow rate at the JBT11 tile drain monitoring station*

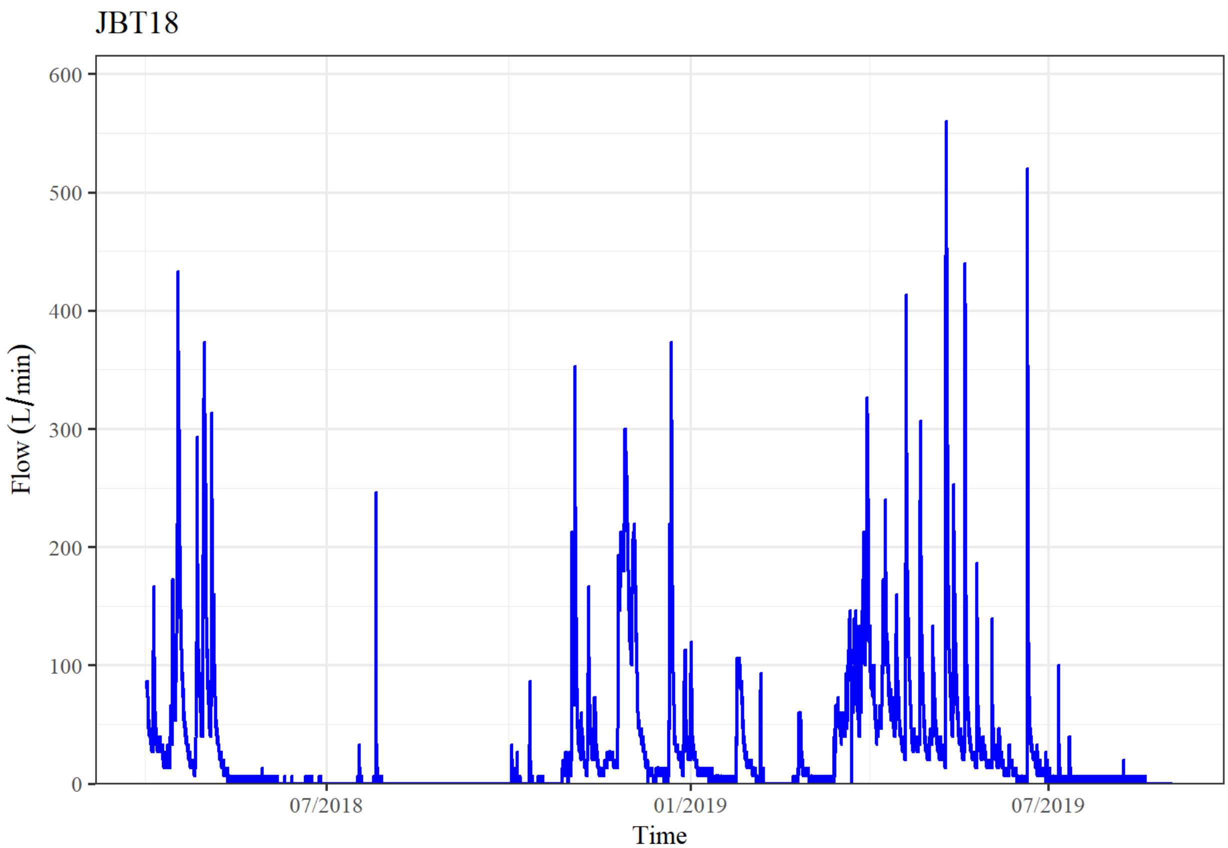


*Figure 8. Flow rate at the JBT18 tile drain monitoring station*

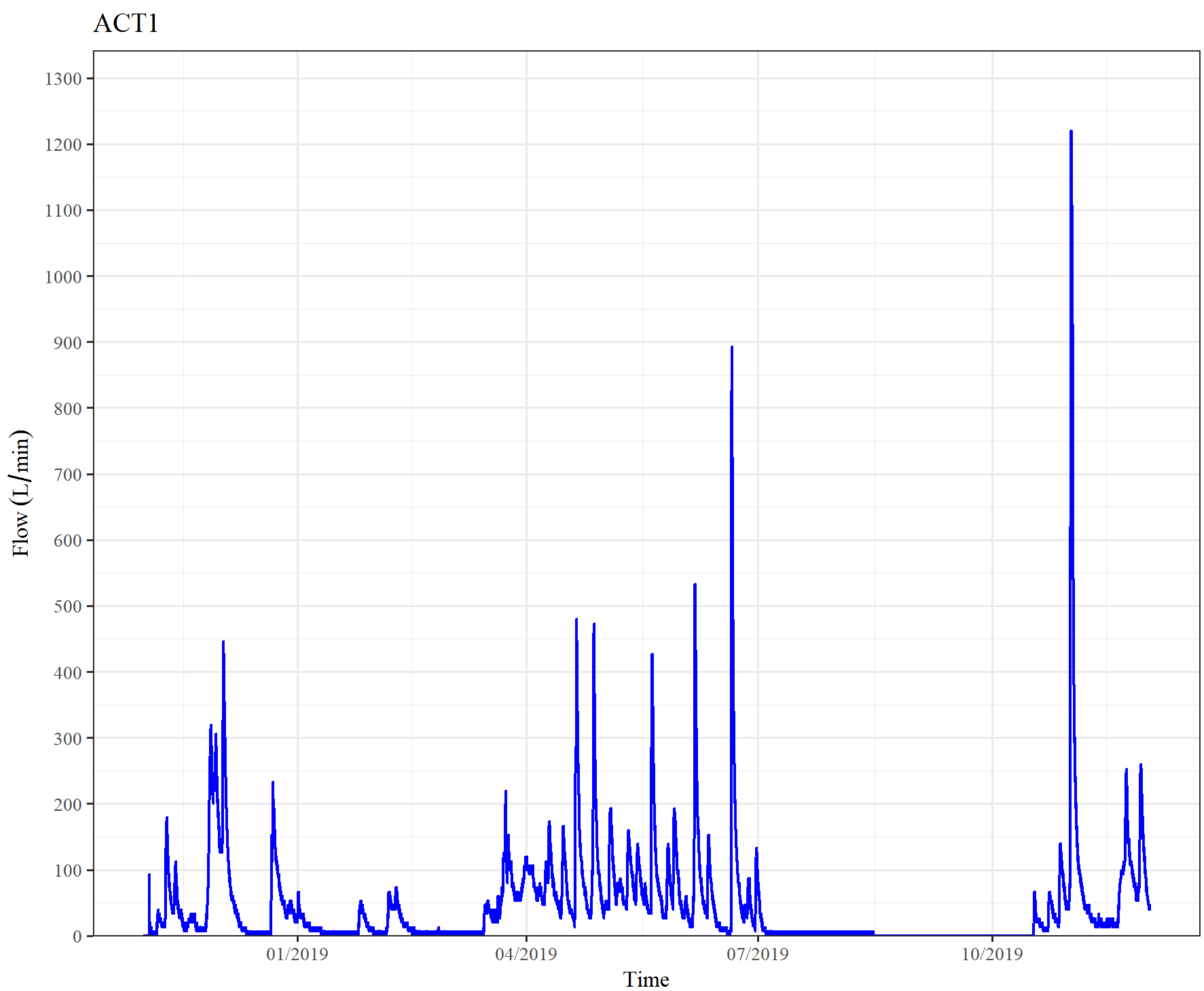


*Figure 9. Flow rate at the ACT1 tile drain monitoring station*

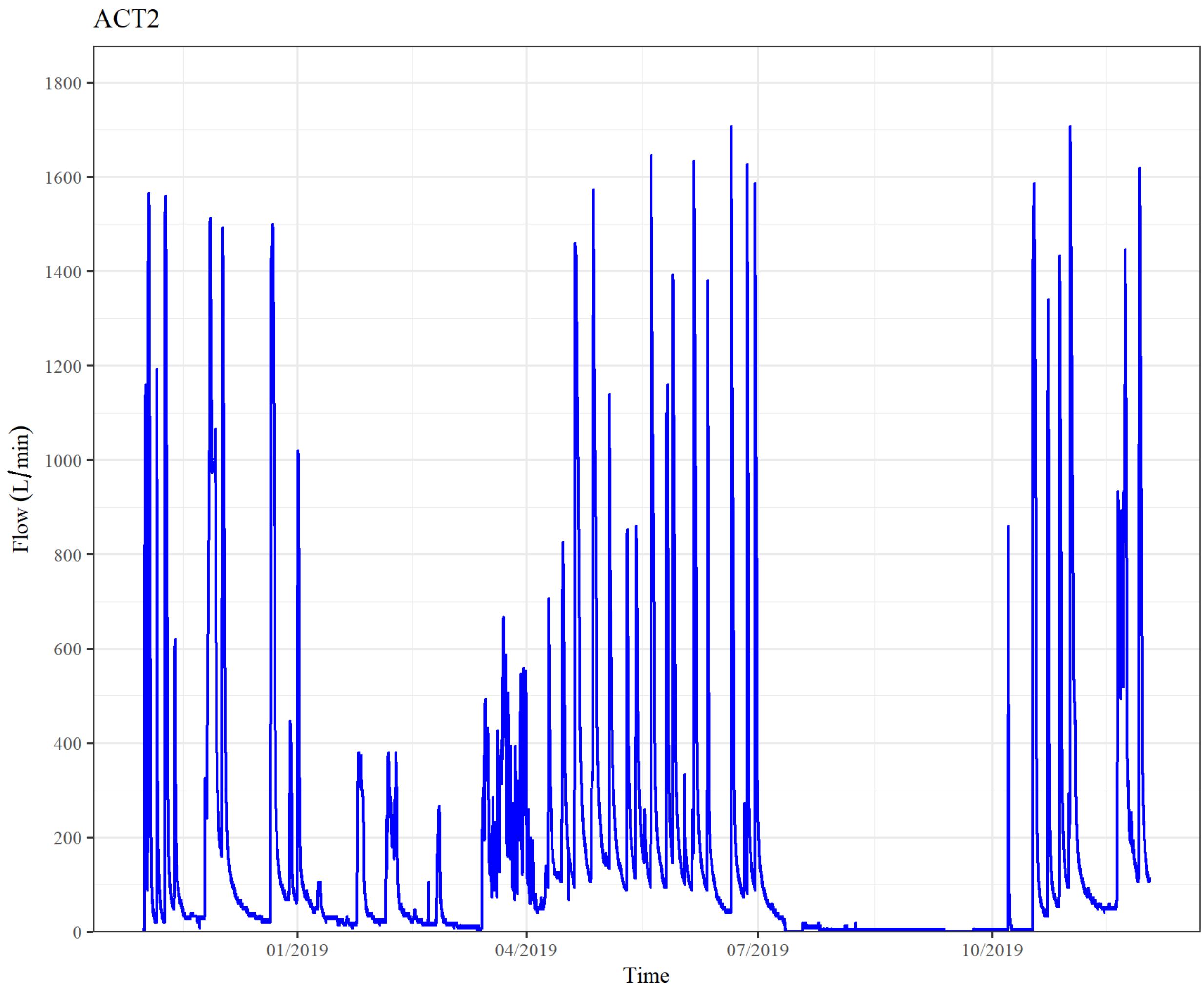


*Figure 10. Flow rate at the ACT2 tile drain monitoring station*

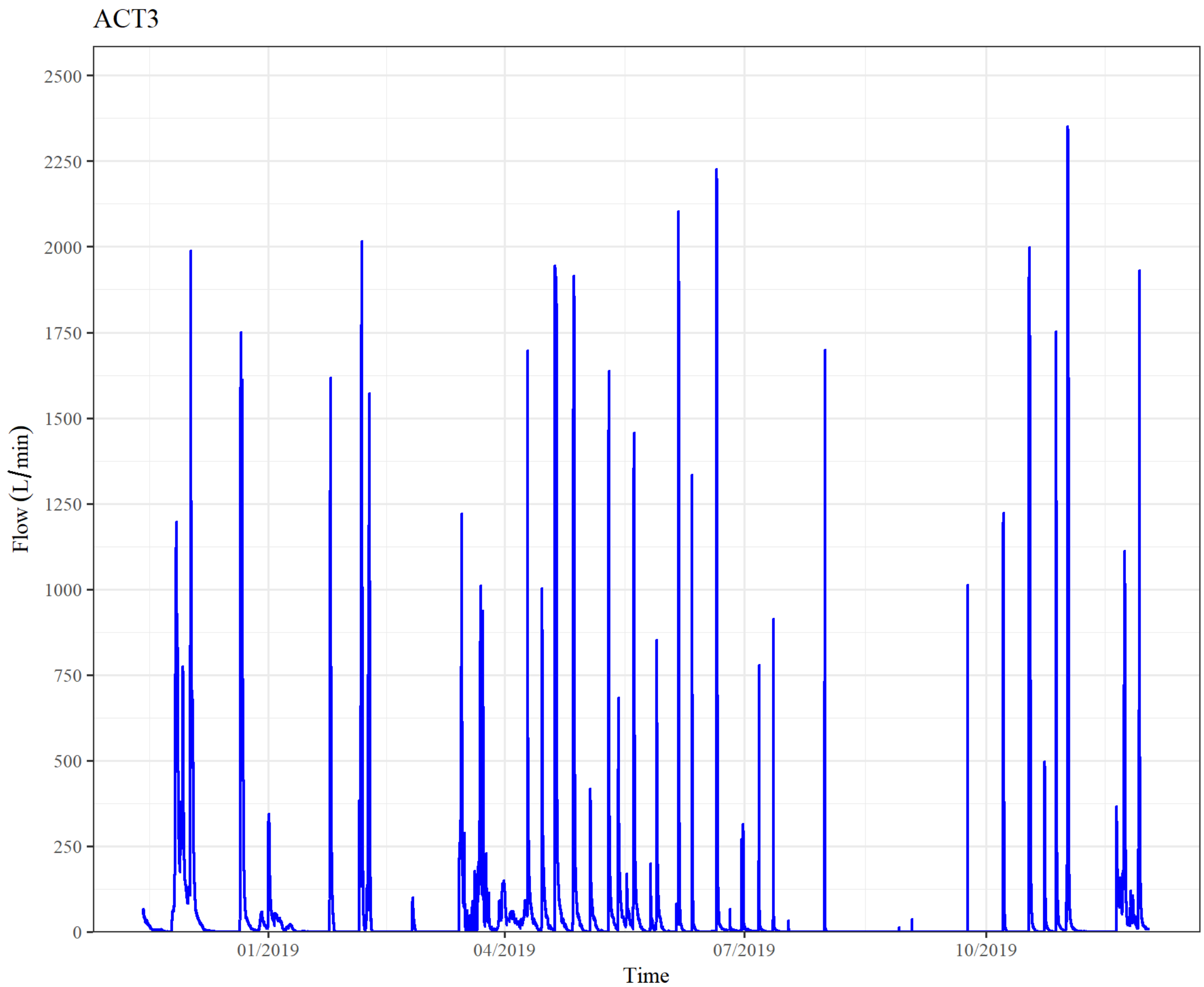


*Figure 11. Flow rate at the ACT3 tile drain monitoring station*

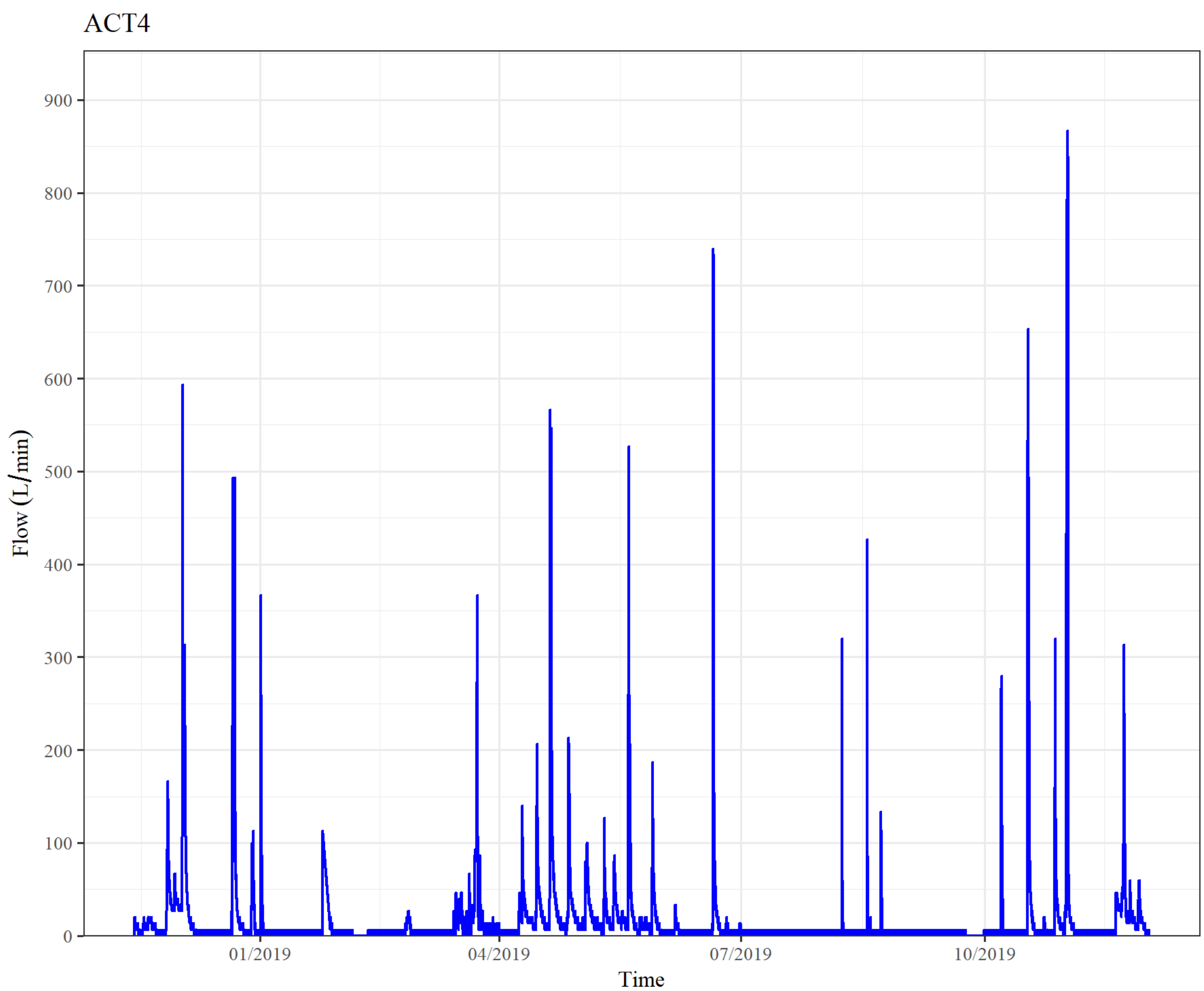


*Figure 12. Flow rate at the ACT4 tile drain monitoring station*

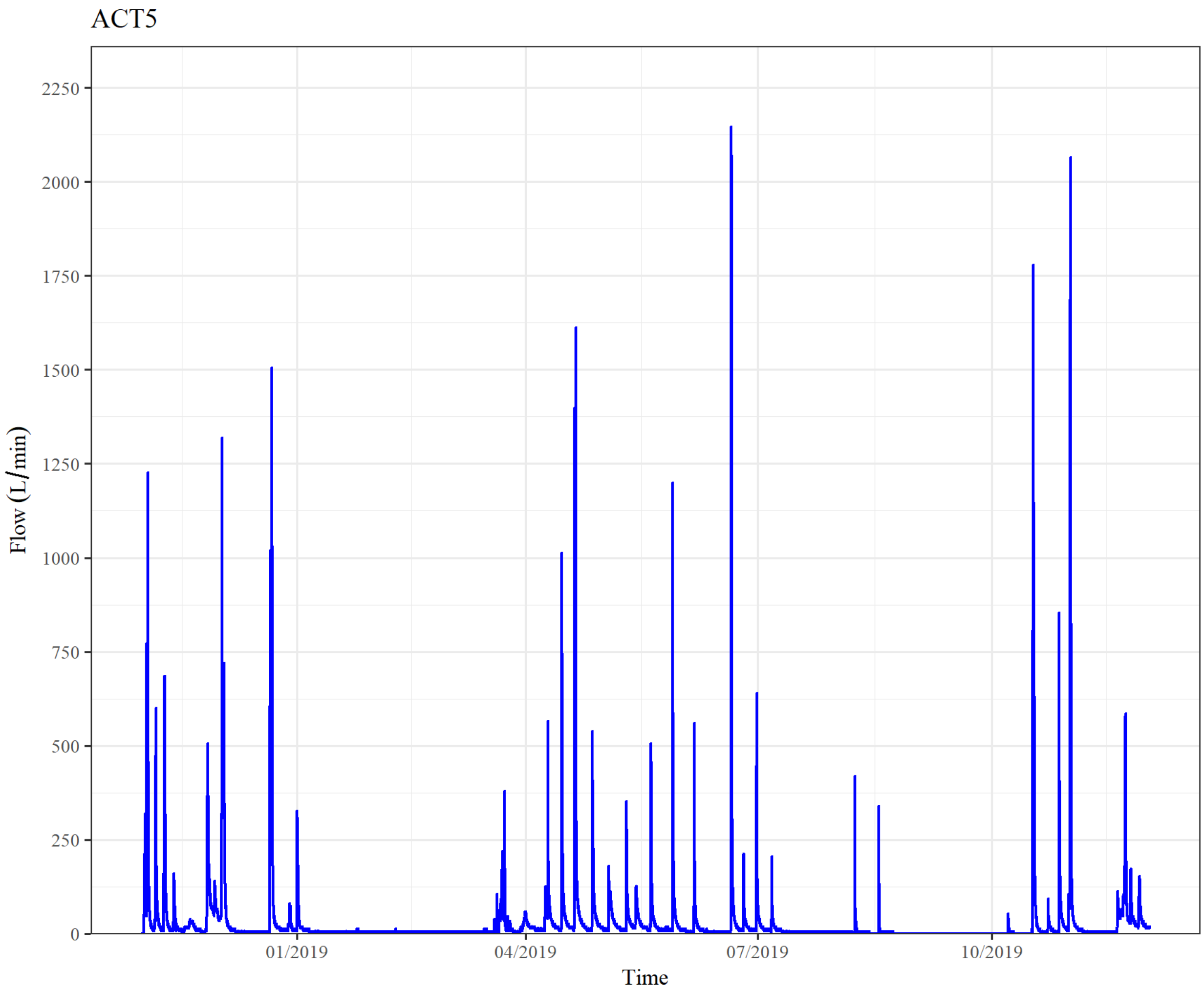


*Figure 13. Flow rate at the ACT5 tile drain monitoring station*

# Appendix C: Flow and Water Quality Monitoring Data

# Appendix D: As-built P Filter Drawings