

# **Blackstone River Water Quality Monitoring Program 2017 Sampling Season Report**

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# **Blackstone River Water Quality Monitoring Program**

## **2017 Field Season**

### **1.0 Introduction**

In 2012, the Upper Blackstone Water Pollution Abatement District (Upper Blackstone) initiated a voluntary program to monitor river quality in response to treatment plant upgrades and subsequent treatment process refinements. This report presents water quality data collected on behalf of Upper Blackstone along the mainstem of the Blackstone River between April and November in 2017. It includes a brief overview of trends in total phosphorus, total nitrogen, chlorophyll-a, and periphyton data observed since the start of the sampling program in 2012. Hydrologic data for the period 2012-2017 are also presented. Additional details of periphyton and macroinvertebrate sampling are available under separate cover from Normandeau Associates<sup>1</sup>. More detailed technical information regarding the sampling program is available from the Field Sampling Plan and the Quality Assurance Project Plan (QAPP) for this project. Water quality reports and factsheets for each sampling season are available upon request. The Blackstone River water quality data collected as part of Upper Blackstone's monitoring program are publicly available by request (email: [tdrury@umass.edu](mailto:tdrury@umass.edu)) or via download through the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI, [www.cuahsi.org](http://www.cuahsi.org)) Hydrologic Information System (HIS) database and servers ([data.cuahsi.org](http://data.cuahsi.org)), which are sponsored by the National Science Foundation.

### **2.0 Background**

The Blackstone River watershed encompasses an area of approximately 480 mi<sup>2</sup> in central Massachusetts and northern Rhode Island. The watershed lies within EPA's Nutrient Ecoregion XIV, subregion 59, the Eastern Coastal Plain. The River flows from its headwaters in the hills above Worcester, MA, through Woonsocket, RI, and finally joins the Seekonk River in Pawtucket, RI, just below the Slater Mill Dam. The Seekonk River discharges into the Providence River, which flows into Narragansett Bay. Six major tributaries, including the Quinsigamond, Mumford, West, Mill, Peters, and Branch rivers, as well as many smaller tributaries, join the mainstem of the Blackstone River. The watershed includes over 1,300 acres of lakes and ponds. Reservoirs in the northwest portion of the basin are used for the City of Worcester water supply. Several U.S. Geological Survey (USGS) streamflow gaging sites are located in the watershed, and hourly precipitation data are available for several locations in and near the watershed from the National Weather Service (NWS) National Centers for Environmental Information (NCEI). The Blackstone River is one of the largest contributors of freshwater to Narragansett Bay, providing on average almost one quarter of the

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<sup>1</sup> Blackstone River 2017 Periphyton and Benthic Macroinvertebrate Study Final Report (Normandeau Associates, Inc., 2017)

freshwater flow to the Bay (Ries, 1990; Ely, 2002; Save the Bay, 2006), and plays an important role in the health of the Bay.

The Blackstone River Valley is acknowledged as the “Birthplace of the American Industrial Revolution.” Over its 48-mile run towards Narragansett Bay, the Blackstone drops approximately 440 feet (Shanahan, 1994; BRNHC, 2006), a steeper gradient than the Colorado River (Arizona Humanities Council, 2006). The Blackstone River and its watershed were transformed from a farming area in colonial days into one of the 19th century’s great industrial areas due to this hydraulic potential, starting with the first milldam built by Samuel Slater at the outlet of the river in 1793. Water powered textile mills proliferated up and down the river, and at one point, the river had almost one dam for every mile along it run. The historical significance of the river has been recognized at both local and federal levels. In 1986, an Act of Congress established the John H. Chafee Blackstone River Valley National Heritage Corridor. In 1998, the Blackstone was designated as an American Heritage River. In 2002, it was one of eight rivers included in an urban river restoration pilot study lead by the U.S. Environmental Protection Agency (EPA) and the U.S. Army Corps of Engineers (ACOE). In 2014, the Blackstone River Valley National Historical Park was established as the 402<sup>nd</sup> park in the national park system.

There are nine wastewater treatment facilities (WWTFs) that discharge into the Blackstone River and its tributaries, Table 1. The largest, in terms of volume, is the Upper Blackstone. There are twenty named dams remaining along the mainstem of the Blackstone River. The locations of the WWTFs and remaining dams along the mainstem of the Blackstone River are shown in Table 2 based on river mile. The outlet of the Blackstone River in Pawtucket, RI, is denoted as river mile zero, with river mile increasing in the upstream direction. The locations of federally regulated and controlled (licensed by the Federal Energy Regulatory Commission [FERC]) and minor dams along the river elevation profile are depicted in Figure 1. The industrial past of the Blackstone, urbanization, and a high population density have resulted in a legacy of complex water quality issues.

In 2003, Upper Blackstone requested the Massachusetts Water Resources Research Center (MaWRRC) at UMass Amherst and Camp Dresser & McKee (CDM, now CDM Smith) to initiate a watershed assessment study to improve understanding of these complex dynamics. The study included river monitoring in 2005 and 2006, historical data analysis, and modeling to evaluate trends in river quality as well as management opportunities for improving water quality and aquatic habitat throughout the basin. Upper Blackstone has supported additional water quality data collection in 2010 and 2011, and since 2012 has supported consistent year to year water quality monitoring at several sampling locations along the mainstem Blackstone River to support the assessment of the river’s response to reduced nutrient concentrations in the wastewater treatment plant effluent. While Upper Blackstone’s monitoring program has always followed strict sample collection and analysis procedures, sampling was conducted under a Quality Assurance Project Plan (QAPP) approved by the Massachusetts Department of Environmental Protection (MassDEP) from 2014 - 2016. A newly approved QAPP covers sampling in 2017 – 2019. Having the approved QAPP in place allows MassDEP to use the data in the agency’s future watershed assessments.

Upper Blackstone's routine river monitoring program provides a multi-year data record over the period 2012 – 2017. The routine river monitoring program data indicate that total nitrogen, total phosphorus, and algal growth in the river as measured by chlorophyll-a are decreasing.

Figure 1: River elevation profile

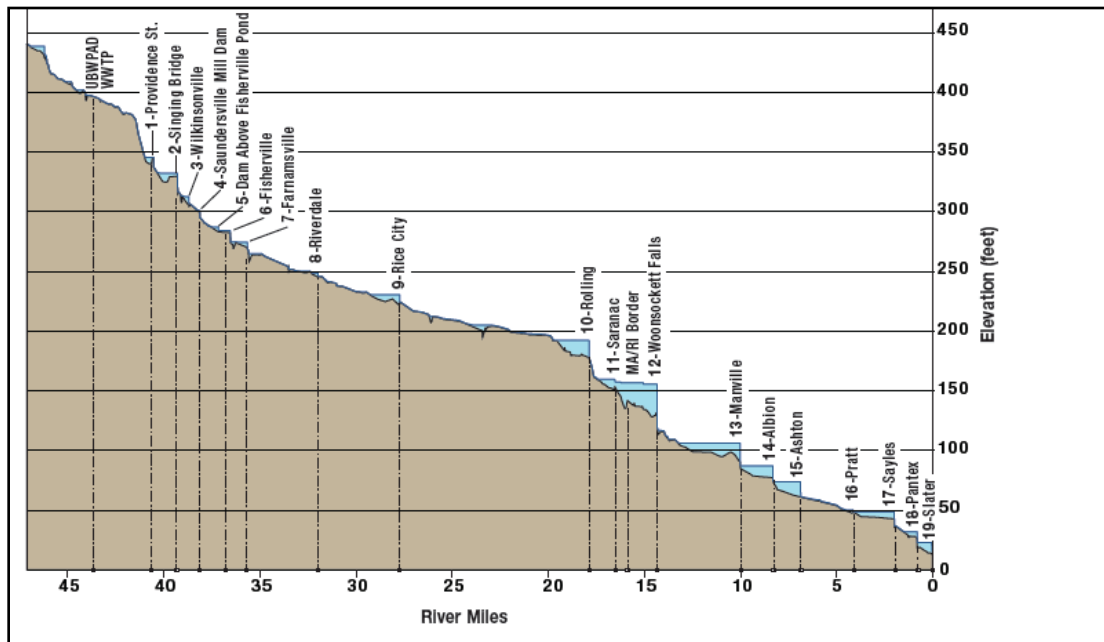


Table 1: 2017 data for WWTFs in the Blackstone River watershed <sup>a</sup>

WWTP	Receiving Waters	Average <sup>b</sup>		
		Flow (MGD)	Total Phosphorous Load (kg/d)	Total Nitrogen Load (kg/d)
Upper Blackstone	Blackstone River	30.0	26.3	943
Woonsocket	Blackstone River	6.03	8.40	100
Grafton	Blackstone River	1.72	5.70	97.4
Northbridge	Blackstone River	0.865	1.15	16.1
Burrillville	Branch River	0.975	1.16	41.3
Uxbridge	Blackstone River	0.886	1.66	33.2
Hopedale	Mill River	0.426	0.190	24.7
Douglas	Mumford River	0.161	0.167	3.85
Upton	West River	0.195	0.095	4.69

Notes: <sup>a</sup> Obtained from the EPA ECHO Enforcement and Compliance History Online database, except for Upper Blackstone data, which were obtained from CDM Smith.

<sup>b</sup> Average of reported non-zero monthly values

Table 2: List of dams, impoundments, hydroelectric plants and WWTFs on the Blackstone River mainstem (adapted from Wright et al., 2001)

Mile	Description	Mile	Description
46.6	Mill Brook/Middle River Confl.	22.0	Uxbridge WWTF
46.4	Worcester CSO	17.8	Tupperware Dam
44.4	Upper Blackstone WWTF	16.5	Blackstone Dam
43.9	McCracken Rd Dam	15.5	Thundermist Hydro Dam
41.0	Millbury Electric Dam	12.8	Hamlet Ave. Dam
39.8	Singing Dam	12.4	Woonsocket WWTF
39.2	Wilkinsonville Dam	9.9	Manville Dam
38.7	Saundersville Dam	8.2	Albion Dam
36.5	Fisherville Dam	6.8	Ashton Dam
35.6	Farnumsville Hydro Dam	4.1	Lonsdale Dam
35.4	Grafton WWTF	2.0	Central Falls Dam
31.9	Riverdale Hydro Dam	0.8	Pawtucket Hydro Dam
29.2	Northbridge WWTF	0.0	Slater Mill Dam
27.8	Rice City Pond Dam		

### 3.0 Blackstone Water Quality Sampling Program

In 2017, the river monitoring program included monthly water quality sampling for nutrients and chlorophyll-a. Three Rhode Island sites were co-sampled with the Narragansett Bay Commission (NBC). Monthly sampling was conducted from April through November. Three synoptic periphyton sampling surveys were conducted in coordination with Normandeau Associates to capture a more in-depth “snapshot” of river biological response to water quality during low flow river conditions. Periphyton sampling was performed at four sampling locations over a short period (1 - 2 days) of relatively steady hydrologic conditions. In addition, continuous dissolved oxygen and temperature monitoring was conducted at the four periphyton sampling locations in partnership with MassDEP and Normandeau.

Sampling locations for routine and periphyton monitoring were selected based on several criteria, in order to:

- Provide reference data for the river above and below the confluence with Upper Blackstone’s effluent channel;
- Correspond with locations monitored by MassDEP in 2008;
- Correspond with long-term monitoring locations maintained by NBC;
- Build upon Upper Blackstone sampling efforts that were first initiated in 2004;
- Provide information on both run-of-river and impoundment sites along the river;
- Provide information on both the nutrient and biological status of the river; and
- Build a database to facilitate identification of temporal trends in water quality within the river.

Although this is Upper Blackstone’s monitoring program, the data collected as part of this water quality-monitoring program are generally denoted “UMass 2017 data” in graphs and tables to avoid potential confusion with 1) the location where Upper Blackstone effluent enters the Blackstone River and 2) the river monitoring location immediately downstream of this confluence. A brief overview of Upper Blackstone’s monitoring programs is presented in the sections below. Detailed descriptions of sampling methods, quality control measures, and additional technical details are available in yearly field sampling plans and the project QAPP (approved by MassDEP in 2017), available upon request. A brief summary of sample collection and processing is provided in Appendix A. Laboratory methods and detection limits are provided in Appendix B.

#### 3.1 Overview

Monitoring locations and data collection type are summarized in Table 3 and on Figure 2. Monthly water quality sampling for nutrients and chlorophyll-a are conducted from April through November every four weeks at nine sites along the mainstem of the Blackstone River, including three Rhode Island sites that are co-sampled with NBC. Periphyton sampling is performed three times a year, in July, August, and September, at three of the nutrient sampling sites plus one additional site sampled by MassDEP in 2008. In 2017, continuous dissolved oxygen and temperature data were also collected at the periphyton sampling locations from June – September.



Table 3: Blackstone River 2017 sampling sites

Site ID#	Site Name	Lat	Lon	River Mile <sup>2</sup>	HSPF Reach <sup>2</sup>	Sampling Details <sup>3</sup>
<sup>1</sup> RSMD	Slater Mill Dam, Pawtucket, RI	41.877	-71.382	0.0	200	N
<sup>1</sup> R116	Rte 116 Bikepath Bridge, Pawtucket, RI	41.938	-71.434	6.3	228	N
<sup>1</sup> RMSL	State Line, RI	42.010	-71.529	15.5	268	N
W1779	Below Rice City Pond Sluice Gates, Hartford St., Uxbridge, MA	42.097	-71.622	27.8	326	N
W0767	USGS gauge near Sutton St. Bridge, Northbridge, MA	42.154	-71.653	33.4	348	N
W1242	Route 122A, Grafton, MA	42.177	-71.688	36.3	360	N
Depot	Depot St., Sutton, MA	42.177	-71.720	38.0	--	P
W1258	Central Cemetery, Millbury, MA	42.194	-71.766	42.7	392	NP
UBWPAD2	New Confluence site, shifted downstream	42.206	-71.781	44.6	402	NP
W0680 <sup>4</sup>	New Millbury St bridge, Worcester, MA	42.228	-71.787	45.2	414	NP

<sup>1</sup> Locations of co-sampling with NBC

<sup>2</sup> Corresponding river mile and model reach in Blackstone River HSPF model: *Blackstone River HSPF Water Quality Model Calibration Report* (CDM Smith and UMass, August 2008) and the *Blackstone River HSPF Water Quality Model Calibration Report Addendum* (CDM Smith and UMass, October 2011).

<sup>3</sup> Sampling Types: N = 9 sites, nutrients & chlorophyll-a 1 event/4-weeks; P = 4 sites, Periphyton event/month July - Sept.

<sup>4</sup> W0680 is located between the Worcester CSO discharge and UBWPAD2.

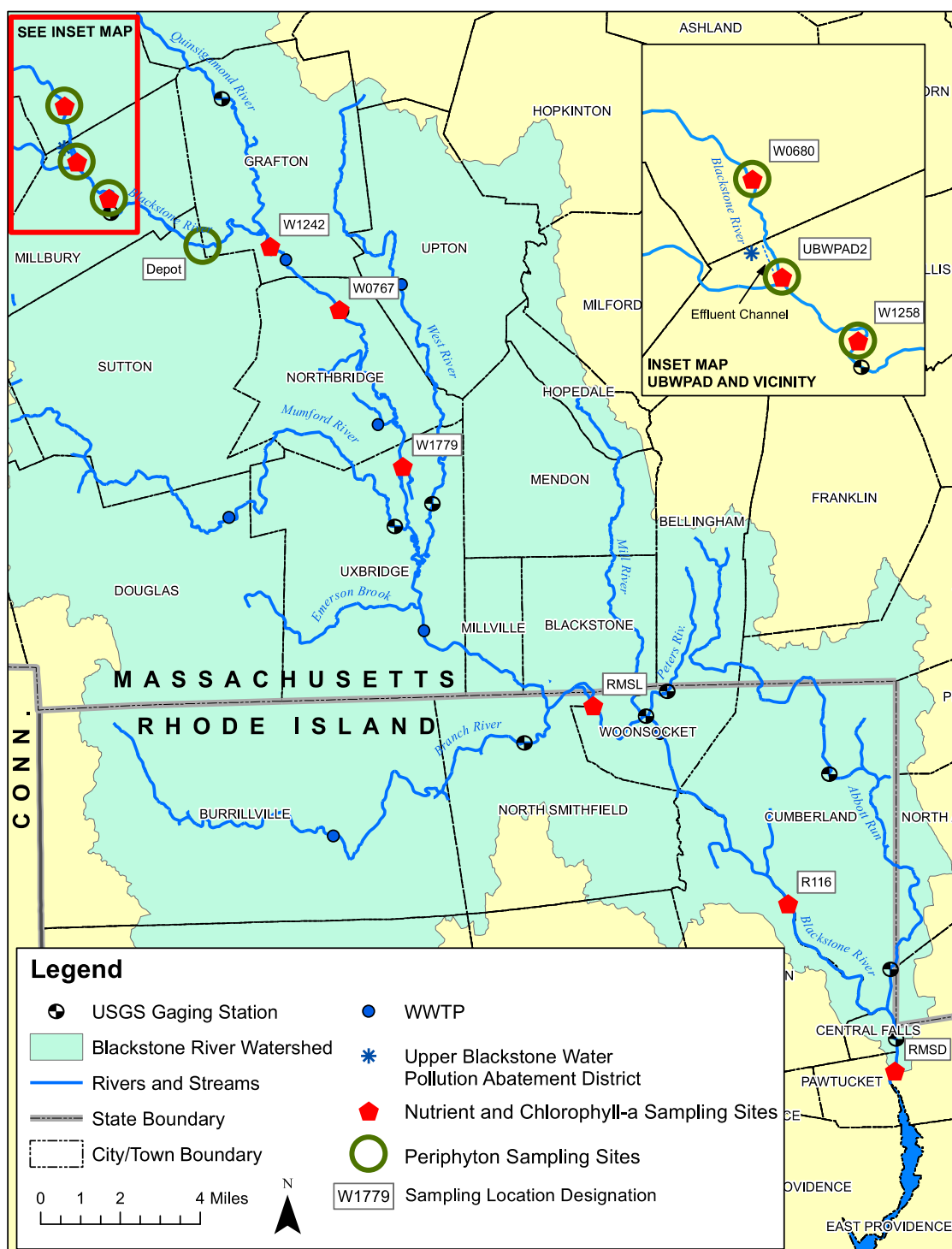


Figure 2: Blackstone River 2017 Nutrient, Chlorophyll-a, and periphyton sampling sites. Continuous DO and temperature data were also collected at the periphyton sites.

### 3.2 Sampling Dates and Data Collected

Sampling dates for the nutrient, chlorophyll-a, and periphyton monitoring program are summarized in Table 4 for 2017.

Table 4: 2017 river nutrient and periphyton sampling dates

SITE	12-April, 2017 <sup>a</sup>	10-May, 2017 <sup>a</sup>	7-June, 2017 <sup>a</sup>	6-July, 2017 <sup>a</sup>	26-27 July, 2017 <sup>b</sup>	2-August, 2017 <sup>a</sup>	21-22 August, 2017 <sup>b</sup>	30-August, 2017 <sup>a</sup>	14-15 September, 2017 <sup>b</sup>	27-September, 2017 <sup>a</sup>	25-October, 2017 <sup>a</sup>	29-November, 2017 <sup>a</sup>
RSMD	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>
R116	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>
RMSL	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>
W1779	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>
W0767	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>
W1242	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>		X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>
DEPOT <sup>e</sup>					X <sup>d</sup>		X <sup>d</sup>		X <sup>d</sup>			
W1258 <sup>e</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>d</sup>	X <sup>c</sup>	X <sup>d</sup>	X <sup>c</sup>	X <sup>d</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>
UBWPAD2 <sup>e</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>d</sup>	X <sup>c</sup>	X <sup>d</sup>	X <sup>c</sup>	X <sup>d</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>
W0680 <sup>e</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>d</sup>	X <sup>c</sup>	X <sup>d</sup>	X <sup>c</sup>	X <sup>d</sup>	X <sup>c</sup>	X <sup>c</sup>	X <sup>c</sup>

Notes: <sup>a</sup> Nutrient + chlorophyll-a monthly sampling dates

<sup>b</sup> Periphyton sampling dates

<sup>c</sup> Full set of nutrients and chlorophyll-a data collected at this site/date

<sup>d</sup> Periphyton and limited nutrient data collected at this site/date

<sup>e</sup> Continuous dissolved oxygen and temperature monitoring, June - September

X - Data collection completed

Samples collected for nutrient analysis are analyzed for total ammonia nitrogen (TAM), total nitrite-nitrate nitrogen (NO<sub>23</sub>), either total Kjeldahl nitrogen (TKN) or total nitrogen (TN) depending on the analysis laboratory, total orthophosphate (TOP), total phosphorus (TP), total suspended solids (TSS), and chlorophyll-a (chl-a), Table 5. Additional water samples are collected for analysis of chlorophyll-a and TP during the week of periphyton sampling. Samples collected at the three sites co-sampled with NBC are also analyzed for dissolved nutrients. Samples are analyzed at Upper Blackstone's laboratory, NBC's laboratory, the UMass Environmental Analysis Laboratory (EAL), and/or the UMass Dartmouth (UMD) laboratory depending on the parameter as noted in the table.

Table 5: 2017 river sampling program analytes and laboratories

Parameter	Upper Blackstone Lab	NBC Lab	UMass EAL	UMD Lab
Dissolved Ammonia (dTAM)	--	Apr – Nov 3 RI Sites	--	Apr – Nov All sites
Dissolved Nitrite/Nitrate (dNO <sub>23</sub> )	--	Apr – Nov 3 RI Sites	--	Apr – Nov All sites
Total Dissolved Nitrogen (TDN)	--	Apr – Nov 3 RI Sites	--	Apr – Nov All sites
Total Nitrogen (TN)	--	--	--	Calculated
Particulate Organic Nitrogen (PON)	--	--	--	Apr – Nov All sites
Dissolved Orthophosphate (DOP) – 3 RI Sites	Apr – Nov 3 RI Sites	Apr – Nov 3 RI Sites	--	--
Total Orthophosphate (TOP)	Apr – Nov All sites	--	--	--
Total Dissolved Phosphorus (DP) – 3 RI Sites	--	--	Apr – Nov 3 RI Sites	--
Total Phosphorus (TP)	--	--	Apr – Nov All sites	--
Total Suspended Solids (TSS)	Apr – Nov All sites	Apr – Nov 3 RI Sites	--	--
Chlorophyll-a (chl-a)	--	--	Apr – Nov All sites	--

## 4.0 Sampling Season Environmental Conditions

Precipitation, temperature, and flow influence how the river and bay systems respond to inputs of nutrients. In wet years, the WWTF effluent comprises a smaller fraction of the river volume, and nutrients from WWTF effluent and other sources tend to be flushed from the river system more quickly, reducing the opportunity for algal growth in impoundments. For example, when flows are  $\sim 4,000$  cfs<sup>2</sup> at Woonsocket, RI, it takes a “parcel” of water approximately two days to travel from the Blackstone headwaters at river mile 46.6 to the outlet. Large storm events can scour the streambed, washing periphyton and macrophytes downstream. Conversely, in dry years, in-stream nutrient concentrations tend to be higher. Lower stream water depths enhance the penetration of light to the stream bottom, and lower flows reduce scour, providing conditions amenable for periphyton growth. The time it takes for water to move from the headwaters to the outlet of the river greatly increases, to approximately 30 days, when river flows are near  $\sim 85$  cfs<sup>3</sup> at Woonsocket, RI, providing conditions that promote the growth of algae in impoundments. A cold spring tends to maintain the snowpack and keep river and impoundment temperatures below conditions amenable for algal and periphyton growth. Warmer air temperatures result in higher water temperatures, which in turn promote algal and periphyton growth.

Data describing the 2017 environmental conditions are presented in this section. Precipitation and air temperature data are presented in Section 4.1, followed by a summary of the river flow conditions in Section 4.2. Section 4.3 provides a brief summary of the potential relative impacts of these conditions on river quality compared to previous sampling years.

### 4.1 Precipitation and Air Temperature

Snowfall records are available from the National Weather Service (NWS) since 1892 for Worcester. This 124-year record is summarized in Figure 3 based on published monthly data. Snowfall accumulations from the winters of 2011 – 2012 through 2016 - 2017 are highlighted due to their potential influence on the subsequent sampling season results. The six sampling seasons span the range of typical snow accumulation, ranging from a total of 30.1 inches (winter of 2011-2012) to 119.7 inches (winter of 2014 – 2015). The historical ranking of each sampling year in terms of snow accumulation is summarized in Table 6. The 2017 sampling season was preceded by the twenty-sixth snowiest winter on record, with 78.3 inches of snowfall.

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<sup>2</sup> A flow of 4,000 cfs is exceeded  $\sim 1\%$  of the time at the Woonsocket stream gaging station

<sup>3</sup> 85 cfs is the lowest average discharge over a period of seven days that occurs on average once every 10 years (7Q10) at the Woonsocket stream gaging station

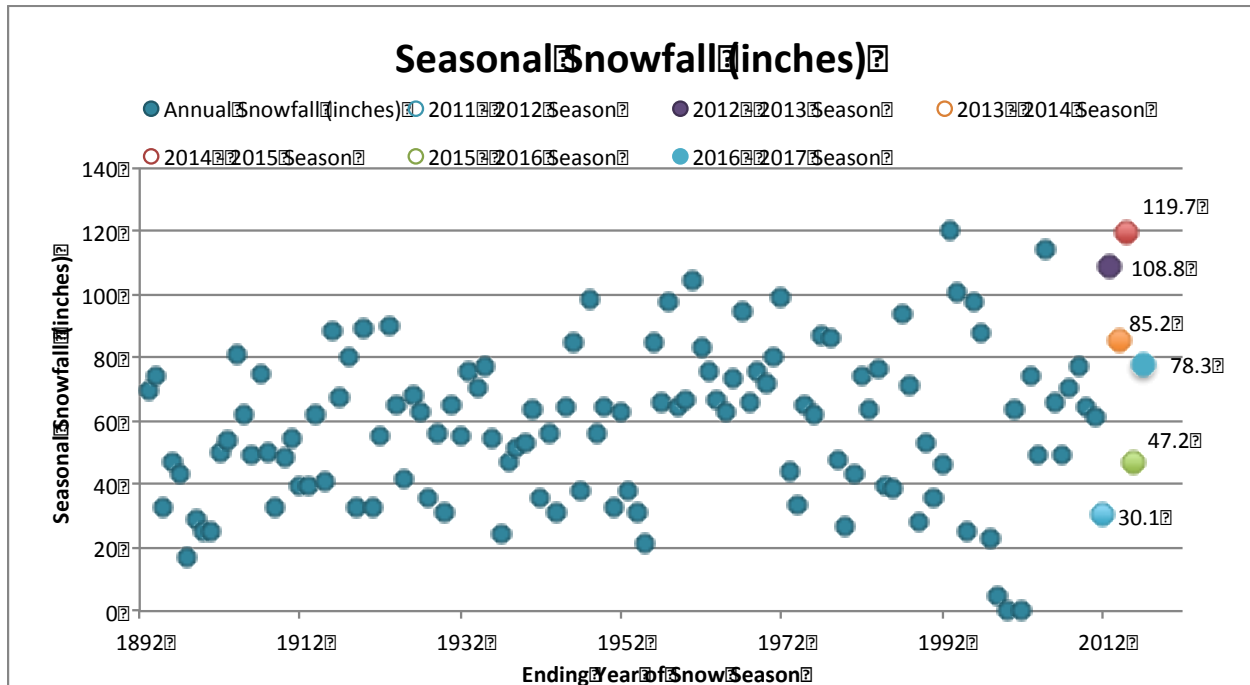


Figure 3: Seasonal snowfall (inches) in Worcester from 1893 through 2017, inclusive  
(Note: year plotted is end of snow season)

Table 6: Snowfall totals winters 2011-2012 to 2016-2017

	Snow (in)	Rank in 124 years of record (1 = snowiest)
Winter 2011 - 12	30.1	112 <sup>th</sup>
Winter 2012 – 13	108.8	4 <sup>th</sup>
Winter 2013 – 14	85.2	19 <sup>th</sup>
Winter 2014 – 15	119.7	2 <sup>nd</sup>
Winter 2015 – 16	47.2	85 <sup>th</sup>
Winter 2016 - 17	78.3	26 <sup>th</sup>

Air temperature data for Worcester are available from the NWS starting in 1948. Monthly average temperature data since 1948 are summarized on Figure 4 as a boxplot, with the data for 2017 highlighted in blue. The box plots provide a summary of the distribution of the data, with the box showing the first quartile, median, and third quartile, and the whiskers showing 1.5 times the interquartile range above the upper quartile and below the lower quartile of the data. The small black circles above and below the whiskers represent observed data that are statistically considered “outliers.” The winter (e.g., December – February) of 2016 - 2017 was warmer than normal, followed by a variable spring in terms of temperature. While temperatures in March and May were below normal, the month of April was quite warm compared to historical data. Temperatures in June were at the upper quartile of observed data, followed by cooler than average July and August temperatures. Temperatures in September and October were again higher than normal, then fell below normal for the remainder of the year.

Figure 4 presents three statistics to summarize monthly temperature conditions since sampling began in 2012. The average mean temperature (black solid line) is determined based on the average daily temperature for each day in the given month. The average low temperature (solid blue line) is determined based on the average of the low temperatures observed on each day in the given month while the average high temperature (solid red line) is determined based on the average of the high temperatures observed on each day. These data are plotted against the published normal monthly data for each statistic, based on the 30-year period from 1981 to 2010, shown as a dashed line of the same color. Instances where the solid line falls above the dashed line indicate warmer than typical conditions, whereas instances where the solid line falls below indicate cooler than normal conditions. The 2017 sampling season was preceded by one of the warmer winters compared to previous sampling years; however, the summer was on the cooler side of recent sampling years.

Annual precipitation totals for Worcester from the NWS since 1949 are shown on Figure 6, with the years since routine sampling began in 2012 noted with their associated accumulation. The annual precipitation in 2017, 45.6 inches, was close to the average of the observed values since 1949 (47.6 inches). Figure 7 summarizes monthly precipitation conditions since sampling began in 2012, shown as a solid green line, compared to published normals from the NWS based on the 30-year period 1981 – 2010, shown as a dashed green line. There is significant variability in monthly precipitation year-to-year and month-to-month.

Figure 4: Worcester monthly air temperatures 1948 - 2017

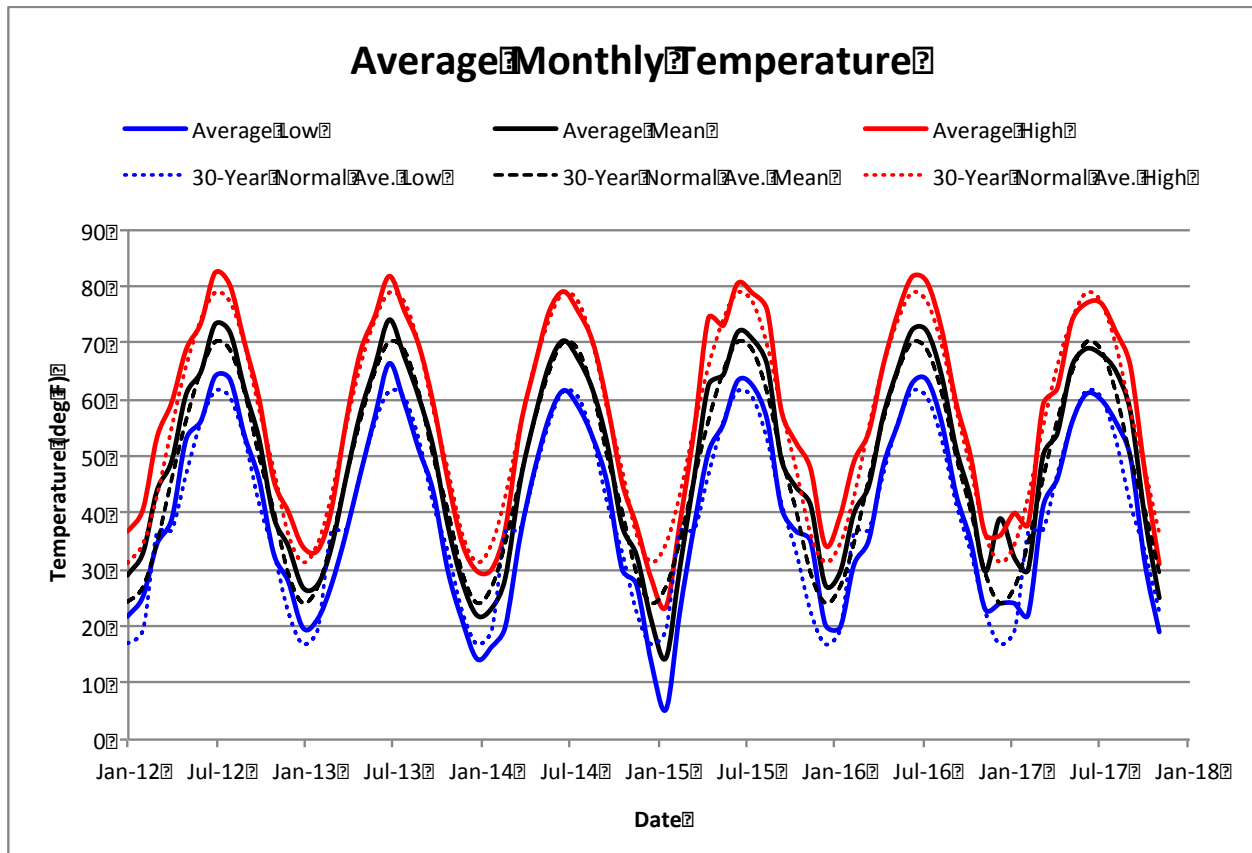
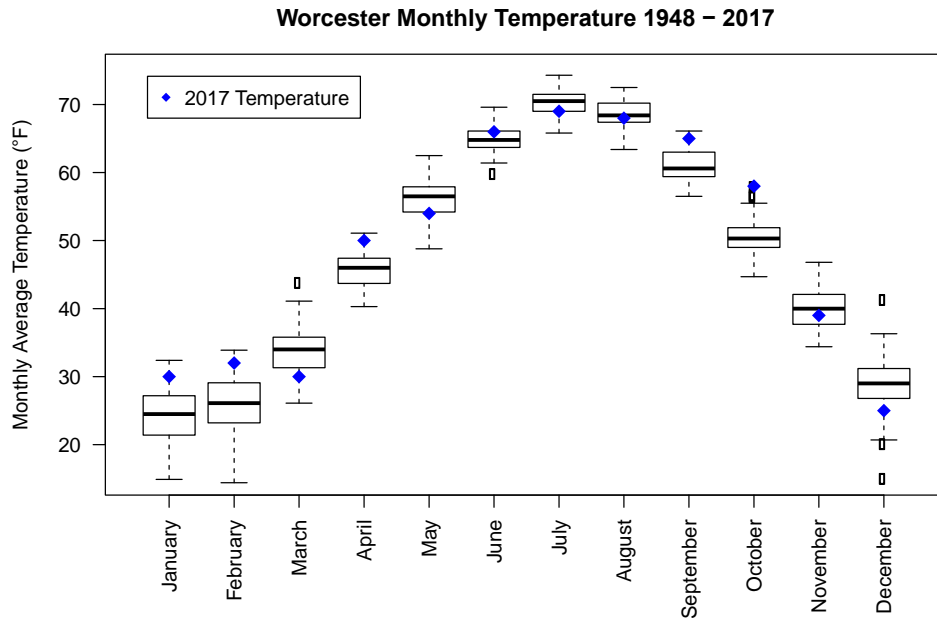




Figure 5: Average monthly low, mean, and high air temperature values observed since 2012  
Notes: Observed values for each month (solid lines) are compared to the normal for the month (dashed lines) based on NWS monthly data for Worcester from 1981 – 2010, available online: [www.ncdc.noaa.gov/cdo-web/datasets#GHCND](http://www.ncdc.noaa.gov/cdo-web/datasets#GHCND)

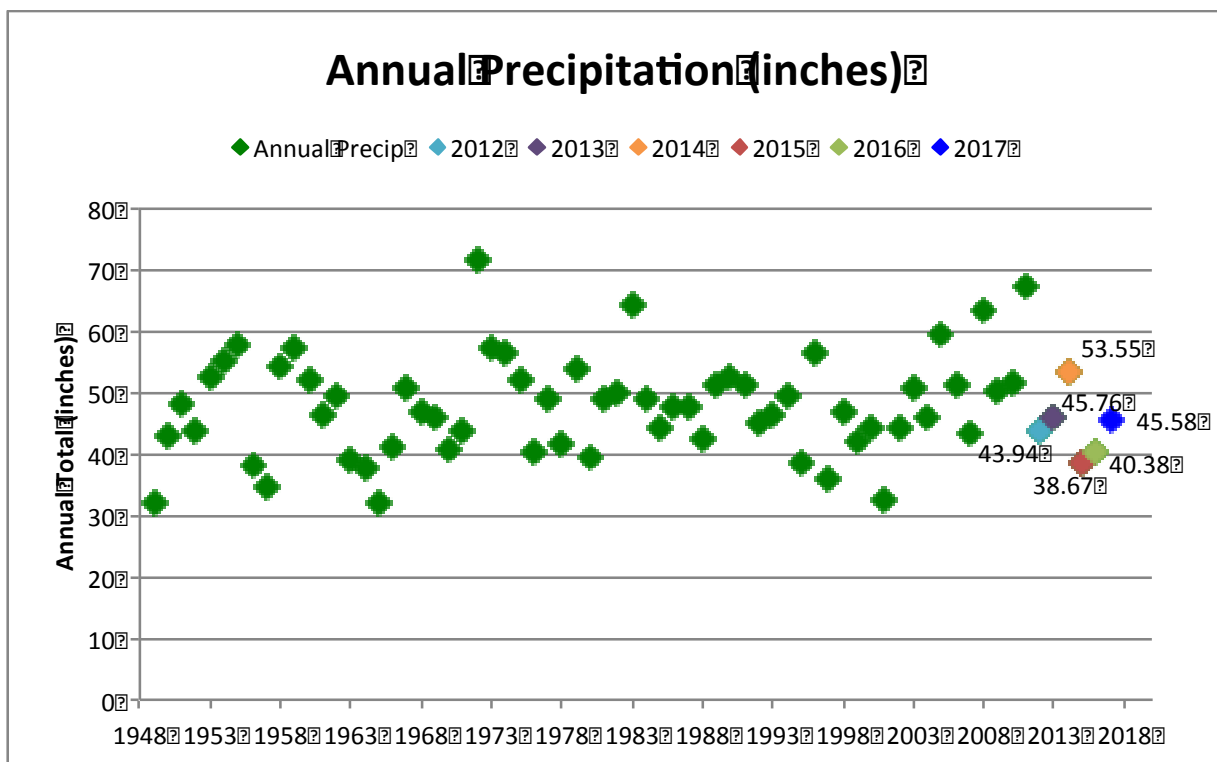


Figure 6: Annual precipitation (inches) in Worcester since 1949

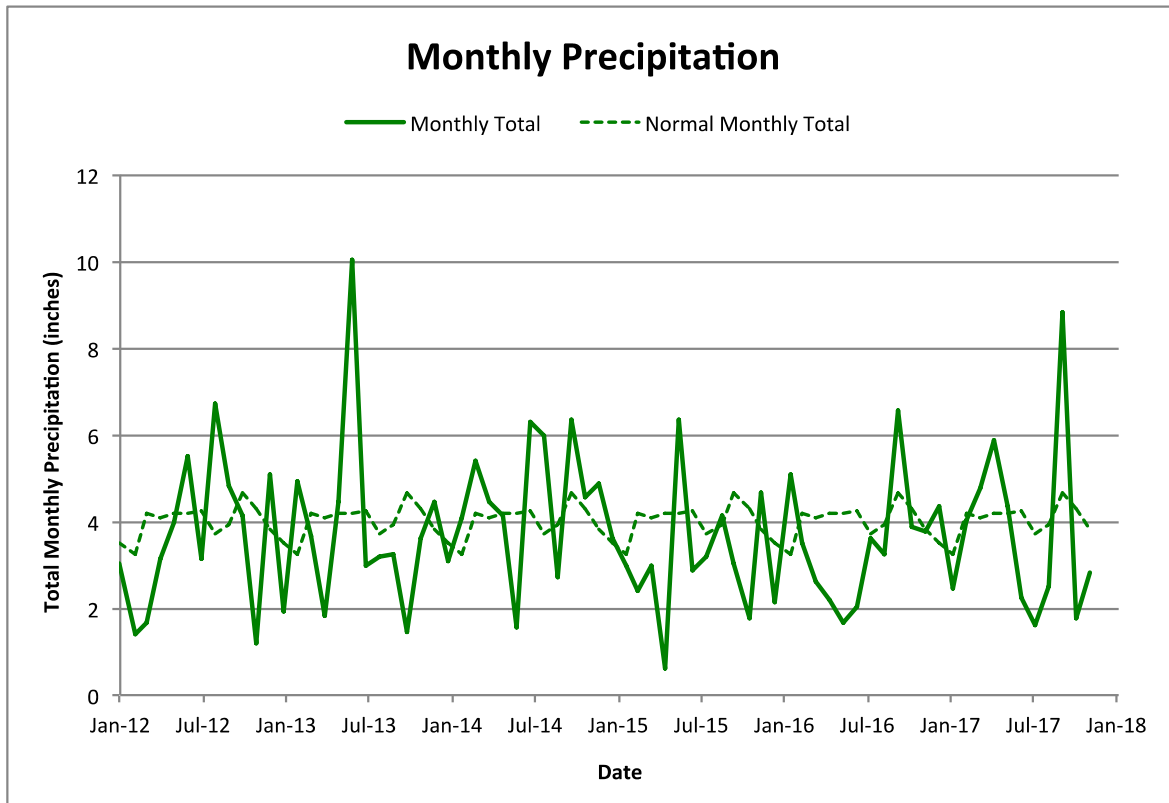


Figure 7: Monthly precipitation totals 2012-2017 compared to normal monthly totals  
Notes: Observed totals for each month (solid line) are compared to the normal for the month (dashed lines) based on NWS monthly data for Worcester from 1981 – 2010

Monthly precipitation totals since 1949 for Worcester are summarized using boxplots on Figure 8. Data for 2017 are highlighted in blue. Rainfall totals from January through June fell mainly within the interquartile range of historical values except for May, which in 2017 was slightly higher than the historical interquartile range of observed data. In comparison, the latter half of the year was relatively dry. Rainfall totals from July through December, except for October, were either at or below the lower quartile of observed values. Additional monthly precipitation condition data for the 2017 sampling years compared to the NWS 30-year normal are provided in Appendix C.

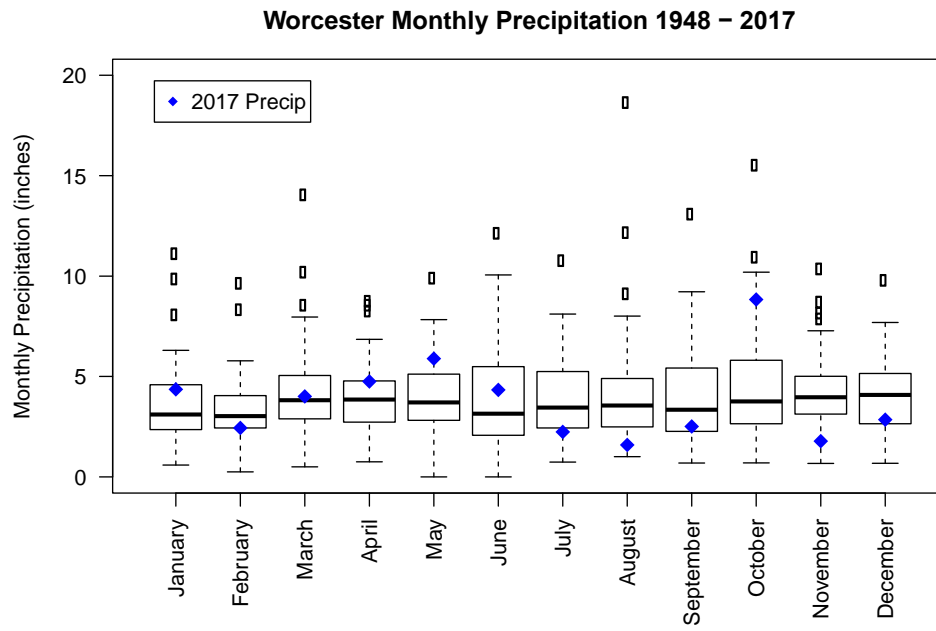


Figure 8: Worcester monthly precipitation 1948 - 2017

Daily precipitation data as measured at the Worcester Airport are plotted on Figure 9 for 2017. The precipitation on sampling dates is highlighted. Cumulative precipitation for the year is also plotted and compared against the historical data, calculated as the cumulative sum of 50<sup>th</sup> percentile daily normal for Worcester from 1981 - 2010. Total precipitation was 45.6-inches in 2017. Cumulative rainfall in 2017 was close to the historical cumulative until early July, after which precipitation was lower than normal as discussed earlier.

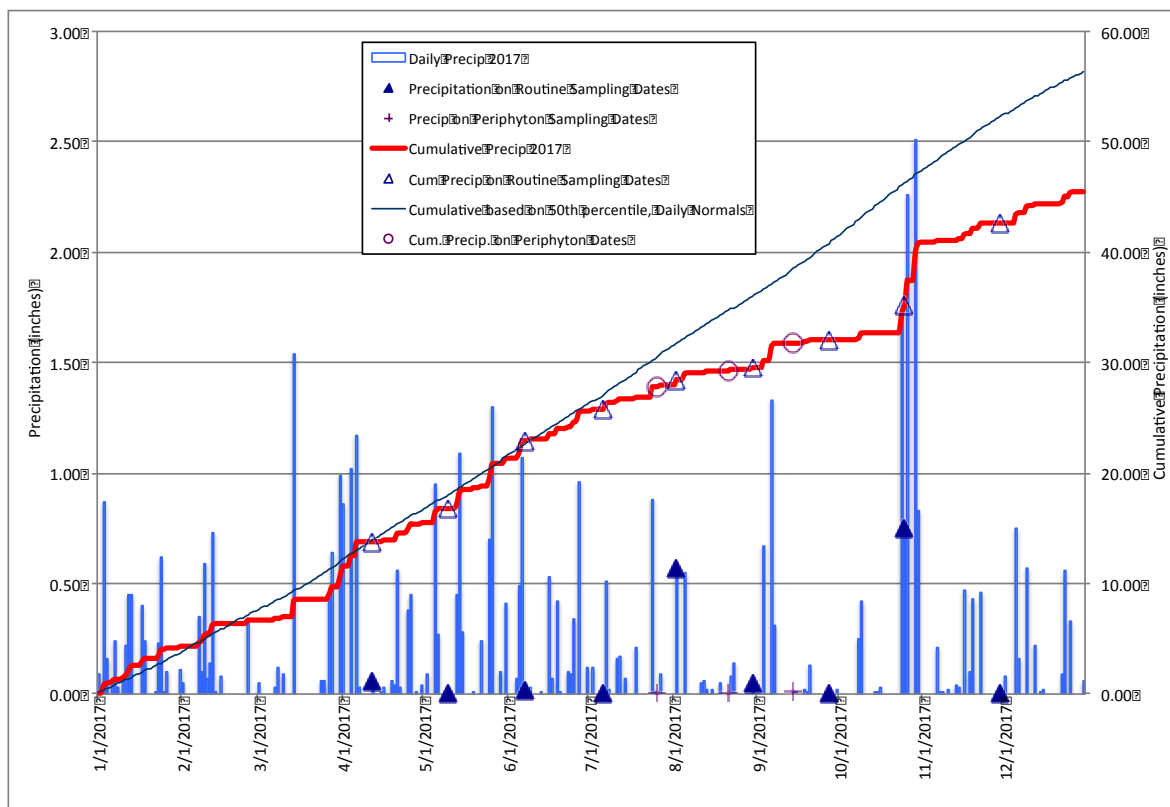


Figure 9: 2017 sampling season daily precipitation at Worcester Airport (KORH) compared against 50<sup>th</sup> percentile daily normal precipitation

The occurrence of precipitation relative to the occurrence of routine sampling can have an impact on the measured levels of in-stream constituents such as nutrients, chlorophyll-a, and periphyton. Sampling day and antecedent precipitation conditions are summarized in Table 9 for all routine sampling dates in 2017. Most routine sampling in 2017 occurred on days with little to no precipitation, except for on October 25<sup>th</sup>. Sampling on August 2<sup>nd</sup> was concluded prior to the start of precipitation. Significant rainfall (>0.5 inches) occurred during the week prior to sampling in April, May, June, and October 2017, and the day prior to both the June and October sampling dates. While it is not possible to fully account for the impacts of rainfall on results, stream sampling results can be summarized and reviewed based on the prevailing streamflow conditions on the sampling days. This issue is addressed further in the next sections.

Table 7: Day-of and antecedent precipitation on routine sampling dates in 2017

Sampling Date	Precipitation in Worcester, MA (NWS Station KORH) - inches			
	Day Of	1-day Prior	Total over 3-days Prior	Total over 7-days Prior
12 April <sup>a</sup>	0.06	0.0	0.0	1.20
10 May <sup>a</sup>	0.0	0.0	0.0	1.22
7 June <sup>a</sup>	0.02	1.07	1.63	2.04
6 July <sup>a</sup>	0.0	0.0	0.0	0.24
2 August <sup>a</sup>	0.57 <sup>b</sup>	0.0	0.0	0.09
30 August <sup>a</sup>	0.05	0.0	0.0	0.14
27 September <sup>a</sup>	0.0	0.00	0.0	0.13
25 October <sup>a</sup>	0.75	1.76	1.76	1.76
29 November <sup>a</sup>	0.0	0.0	0.0	0.46

Notes: <sup>a</sup> Nutrient + chlorophyll-a monthly sampling dates

<sup>b</sup> Rain started after sampling concluded

## 4.2 Flow Conditions

Flow conditions during the 2017 sampling season are described in this section. It should be noted that some of the USGS flow data were still considered provisional at the time they were accessed for compilation of this report. Data are considered provisional until they undergo a formal review by USGS staff. During the formal review, small adjustments to the data may be made based on the most up-to-date field quality control data, particularly for very high or low flows. As a result, the data presented here might vary slightly from the final approved data.

Monthly average flow data collected by the USGS at Millbury, MA, since July 2002 are summarized on Figure 10 as a boxplot, with the data for 2017 highlighted in blue. Data for the USGS gauge at Woonsocket, RI, collected since March 1929, are similarly presented on Figure 11. Monthly flows for each month of the routine sampling season are compared against the median, average and minimum monthly data for both Millbury and Woonsocket in Table 8. Flows were close to the upper quartile of observed values in April, May, June, and October at both Millbury and Woonsocket. Flows fell from July through September, falling below the interquartile range at both sites by September. While high rainfall in October increased flows at both Millbury and Woonsocket to the upper quartile of historical values, the flow again fell to below normal by the end of the year.

Table 8: Mean monthly flows in 2017 compared to median, mean, and minimum

<b>Millbury (cfs)</b>	<b>Apr</b>	<b>May</b>	<b>Jun</b>	<b>Jul</b>	<b>Aug</b>	<b>Sep</b>	<b>Oct</b>	<b>Nov</b>
<i>2017 Monthly Qave</i>	<i>332</i>	<i>223</i>	<i>177</i>	<i>89</i>	<i>59</i>	<i>58</i>	<i>154</i>	<i>149</i>
Median 2003 - 2016	275	156	136	96	81	79	136	146
Average 2003 - 2016	273	169	172	115	101	109	165	163
Minimum 2003 - 2017	95	112	67	49	53	47	75	75
<b>Woonsocket (cfs)</b>	<b>Apr</b>	<b>May</b>	<b>Jun</b>	<b>Jul</b>	<b>Aug</b>	<b>Sep</b>	<b>Oct</b>	<b>Nov</b>
<i>2017 Monthly Qave</i>	<i>1744</i>	<i>1232</i>	<i>792</i>	<i>441</i>	<i>268</i>	<i>157</i>	<i>572</i>	<i>852</i>
Median 1930 - 2016	1321	841	462	246	235	233	313	524
Average 1930 - 2016	1431	875	652	341	308	324	464	670
Minimum 1930 – 2017	461	303	137	120	72	95	123	127

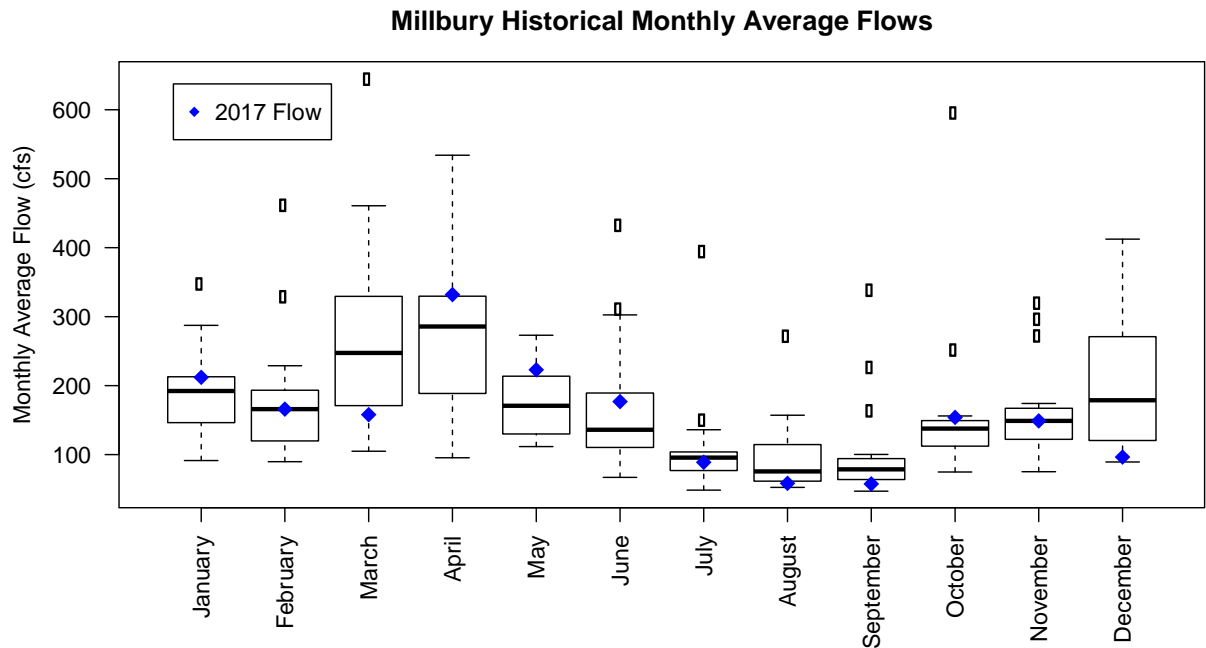


Figure 10: Millbury, MA, USGS gauging station historical monthly average flows

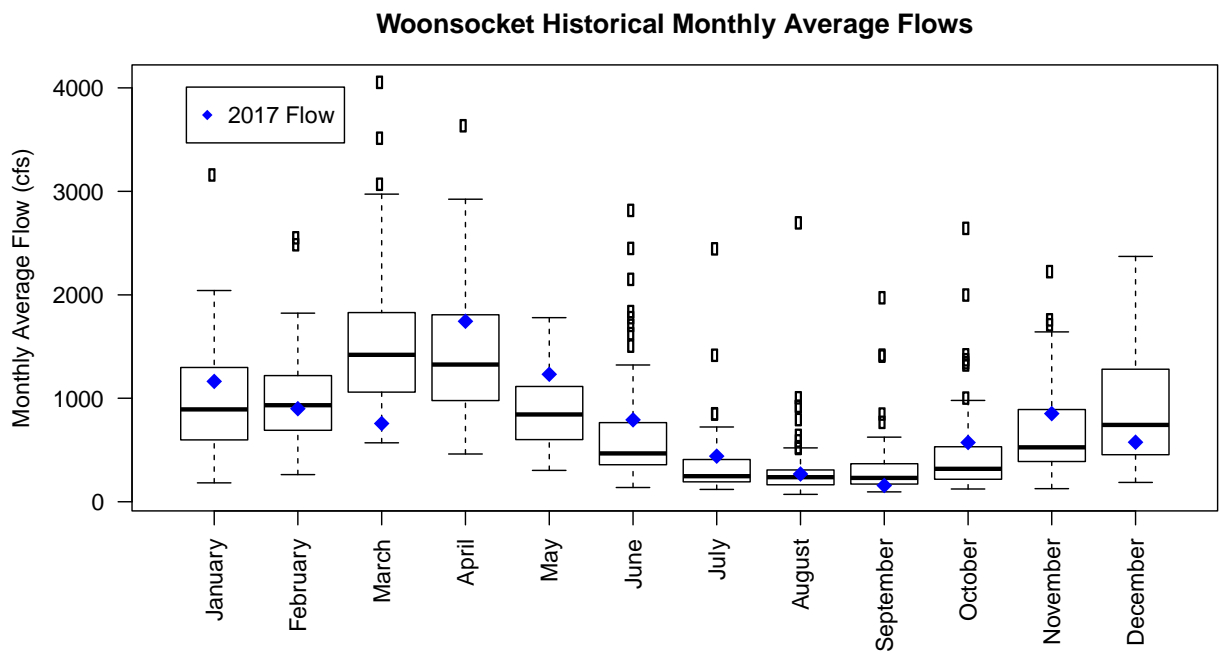


Figure 11: Woonsocket, RI, USGS gauging station historical monthly average flows

The lowest average discharge over a period of seven days that occurs on average once every 10 years (7Q10) is around 85 cfs at Woonsocket. This is a flow condition that is often utilized in regulations. Because of its still relatively short period of record (2002 – 2017), 7Q10 flow has not been officially computed for the Millbury gauge by the USGS, but the data may be utilized to generate an estimate. Millbury 7Q10 conditions are estimated to be around 38 cfs. Average 7-day flows (7Q) did not fall below 7Q10 conditions at either Millbury or Woonsocket in 2017. For reference, average daily flows at Woonsocket and Millbury for each day two weeks prior to periphyton sampling are provided in the appendix, along with the 7-day average flows for the week prior, for comparison against the 7Q10 conditions noted. Table 9 summarizes the minimum 7Q flows observed at Millbury since routine sampling began.

Table 9: Minimum 7-day average flows by year since routine sampling began

<b>Year</b>	<b>Minimum 7Q (cfs)</b>	
	<b>Millbury</b>	<b>Woonsocket</b>
2012	49	152
2013	51	127
2014	47	74
2015	42	58
2016	37	64
2017	40	107
7Q10 Estimate	38	85

Mean daily streamflows measured at Millbury and Woonsocket are compared to historic mean daily flows on Figures 12 and 13 for the 2017 sampling season. The solid blue line represents the observed daily mean flow for the given year, while the orange solid line represents the historic mean daily flow. The dates of routine sampling are indicated by green triangles, while periphyton sampling dates are noted with purple crosses. It has already been noted that monthly flows were low throughout the last half of the 2017 sampling season. Daily flows were also below average historic conditions on most sampling dates except in June and October. While flow on the April sampling data were close to the historic mean daily flow, April sampling occurred at the end of a high flow period when flows were dropping sharply. Sampling in May occurred during a brief low flow period between events, while sampling in June occurred during the peak flow for an event. Table 10 provides routine sampling day flow data from the figures in tabular format, compared to the mean daily discharge for that day based on the historical record. Note that the historic mean daily discharge is for a specific *day* of the month, rather than the month as a whole, thus the numbers in Table 10 are unique and, in some instances, very different for a given month.



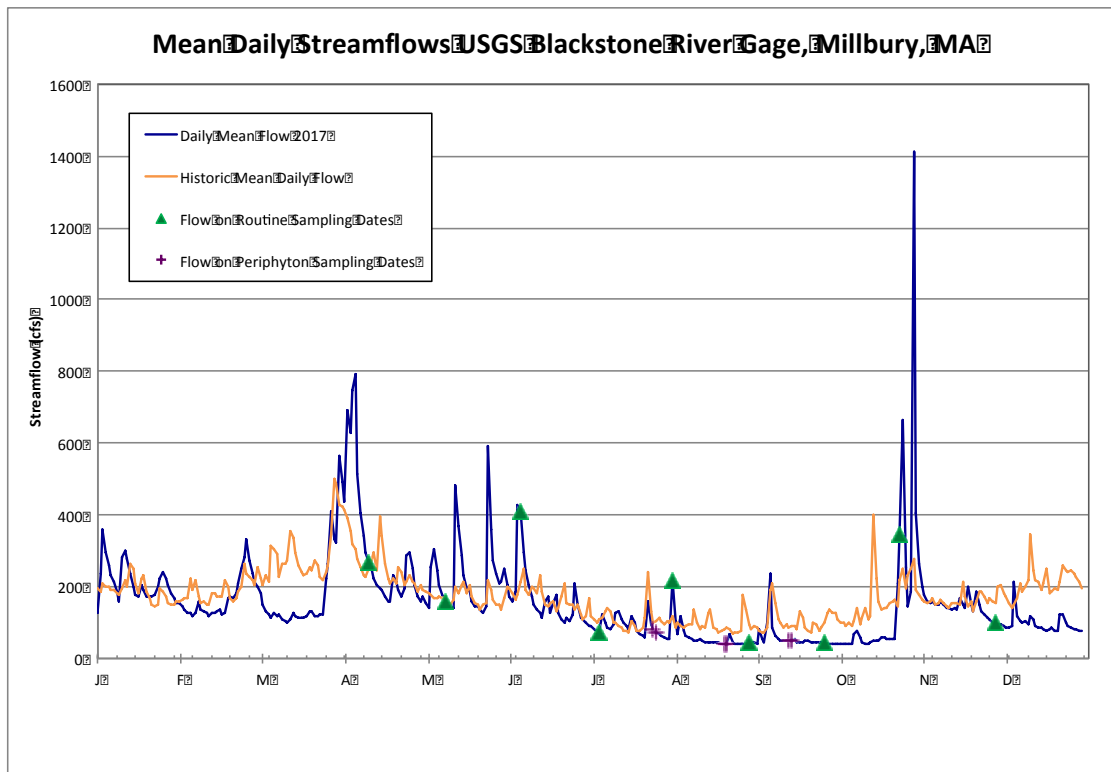


Figure 12: 2017 mean daily streamflows at USGS Millbury, MA gauge  
(Notes: Historical Mean Daily Flow data through 2017)

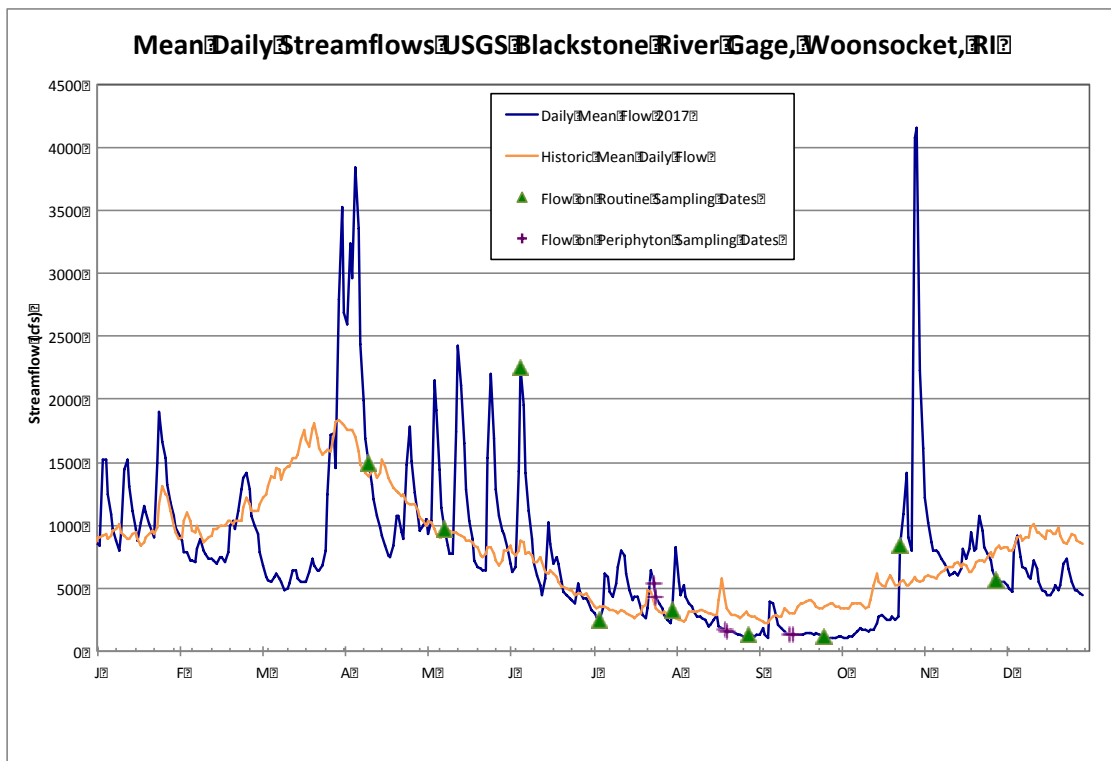


Figure 13: 2017 mean daily streamflows at USGS Woonsocket, RI gauge  
(Notes: Historical Mean Daily Flow data through 2017)

Table 10: Routine sampling day-of flow conditions 2017

Sampling Date	Woonsocket, RI – USGS Station 01112500			Millbury, MA – USGS Station 01109730		
	2017 Mean Daily Q (cfs)	<sup>b</sup> Historic Mean Daily Q (cfs)	% of normal	2017 Mean Daily Q (cfs)	<sup>b</sup> Historic Mean Daily Q (cfs)	% of normal
12 April <sup>a</sup>	1490	1390	107%	267	252	106%
10 May <sup>a</sup>	973	925	105%	159	173	92%
7 June <sup>a</sup>	2250	879	256%	409	215	190%
6 July <sup>a</sup>	244	356	69%	71	109	65%
2 August <sup>a</sup>	330 <sup>c</sup>	275	120%	217 <sup>c</sup>	116	187%
30 August <sup>a</sup>	128	293	44%	44	97	45%
27 September <sup>a</sup>	120	353	34%	43	99	44%
25 October <sup>a</sup>	845	550	154%	345	220	157%
29 November <sup>a</sup>	561	814	69%	100	155	64%

Notes: <sup>a</sup> Nutrient + chlorophyll-a monthly sampling dates  
<sup>b</sup> Historic Mean Daily Q (cfs) based on data through 2017  
<sup>c</sup> Rainfall and rise of flow started after sampling complete

### 4.3 Environmental Condition Summary

A mix of environmental conditions in relation to sampling dates characterized the 2017 sampling season. Routine sampling dates in July through September and November were characterized by low antecedent precipitation and below normal flows. Temperatures in May, July, August, and November were at to below normal. April, June, and October were characterized by higher precipitation, flow, and temperatures compared to historical data. The impact of these mixed conditions on stream water quality is discussed in the next section.

## 5.0 Upper Blackstone Effluent

Upper Blackstone facility seasonal permit limits for total phosphorus (TP) and total nitrogen (TN) are listed in Table 11<sup>4</sup>. Upper Blackstone has been taking steps to comply with the 2008 permit limits. These steps include:

- Implementation of interim measures to further improve plant operation and control, and performance to result in more stable operation and improved effluent quality;
- Facilities Planning to evaluate necessary nutrient removal facility improvements to achieve 2008 permit limits, including development of future flows and loads and an Alternatives Analysis Screening and Evaluation, as well as an analysis of ancillary facilities;
- WWTF upgrade construction to implement successfully tested interim measures and to modernize facility SCADA and data collection systems (in progress);
- Design of phosphorus removal system to meet 2008 permit limits (in progress); and
- Integrated Wet Weather Management planning with the City of Worcester.

The facility is operated to remove nitrogen and phosphorus year-round, even though it only has a May – October seasonal nitrogen permit limit, and much less stringent wintertime limits for total phosphorus. Figure 14 shows the actual effluent TN and TP average annual concentrations since 2006, while Table 12 summarizes TP and TN effluent concentrations by season<sup>5</sup>, corresponding to the permit limits, since 2012. Figure 15 shows the nutrient loading from Upper Blackstone to the Blackstone River over time on an annual basis since 2006. Nutrient loading based on the winter and summer seasonal permit is also shown from 2009 - 2017. The nutrient loads to the river have decreased significantly since 2009. The loads have been even lower since 2013 when Upper Blackstone began implementing interim measures, which focused on optimizing the plant's Biological Nutrient Removal (BNR) process. The percent reduction in average daily TN and TP effluent loads compared to performance prior to 2009 (2006-2008) is summarized in Table 13. Table 14 summarizes changes in annual load. On average, the total annual load of nitrogen from Upper Blackstone's facility has been reduced by 44 - 62% depending on the year, including to about 588,000 pounds in 2017 from over 1.0 million pounds per year on average in 2006-8, a 44% reduction. The annual reduction in phosphorus load to the river is even more dramatic, ranging from 78 – 90% depending on the year, including to just under 21,000 pounds in 2017 from more than 152,000 pounds per year on average in 2006 – 2008.

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<sup>4</sup> TP 'summer' limits are for April through October; TP 'winter' limits are for November through March. TN 'summer' limits are for May through October; TN 'winter' limits are for November through April.

<sup>5</sup> TP 'summer' performance is based on the average of available data for a given year between April 1<sup>st</sup> and October 31<sup>st</sup>; TP 'winter' performance is based on the average of available data between November 1<sup>st</sup> of the prior year and March 31<sup>st</sup> of the year. TN 'summer' performance is based on the average of available data for a given year between May 1<sup>st</sup> and October 31<sup>st</sup>; TN 'winter' performance is based on the average of available data between November 1<sup>st</sup> of the prior year and April 30<sup>th</sup> of the given year.

Table 11: Upper Blackstone 2008 permit limits

<b>Total Phosphorus (mg/L)<sup>1</sup></b>	
Apr – Oct (summer)	0.1 <sup>2</sup>
Nov – Mar (winter)	1.0
<b>Total Nitrogen (mg/L)</b>	
May – Oct (summer)	5.0
Nov – Apr (winter)	Report

Notes: <sup>1</sup> Upper Blackstone effluent limits are typically listed in mg/L. The conversion is 1 mg/L = 1000 ppb.

<sup>2</sup> The 0.1 mg/L total phosphorus limit is a 60-day rolling average limit.

Table 12: Upper Blackstone average permit season TP and TN effluent concentrations

	<b>2012</b>	<b>2013</b>	<b>2014</b>	<b>2015</b>	<b>2016</b>	<b>2017</b>
<b>Total Phosphorus (mg/L)</b>						
Apr – Oct (summer)	0.48	0.17	0.35	0.18	0.20	0.17
Nov – Mar (winter)	0.34	0.18	0.19	0.18	0.55	0.34
<b>Total Nitrogen (mg/L)</b>						
May – Oct (summer)	5.04	4.3	4.7	4.6	3.9	4.5
Nov – Apr (winter)	5.34	5.5	4.6	5.2	5.9	8.7

Table 13: Percent reduction in average daily TN and TP effluent loads compared to plant performance 2006-2008

<b>Year</b>	<b>TN</b>	<b>TP</b>
2012	56%	75%
2013	57%	88%
2014	59%	83%
2015	52%	87%
2016	54%	78%
2017	34%	85%

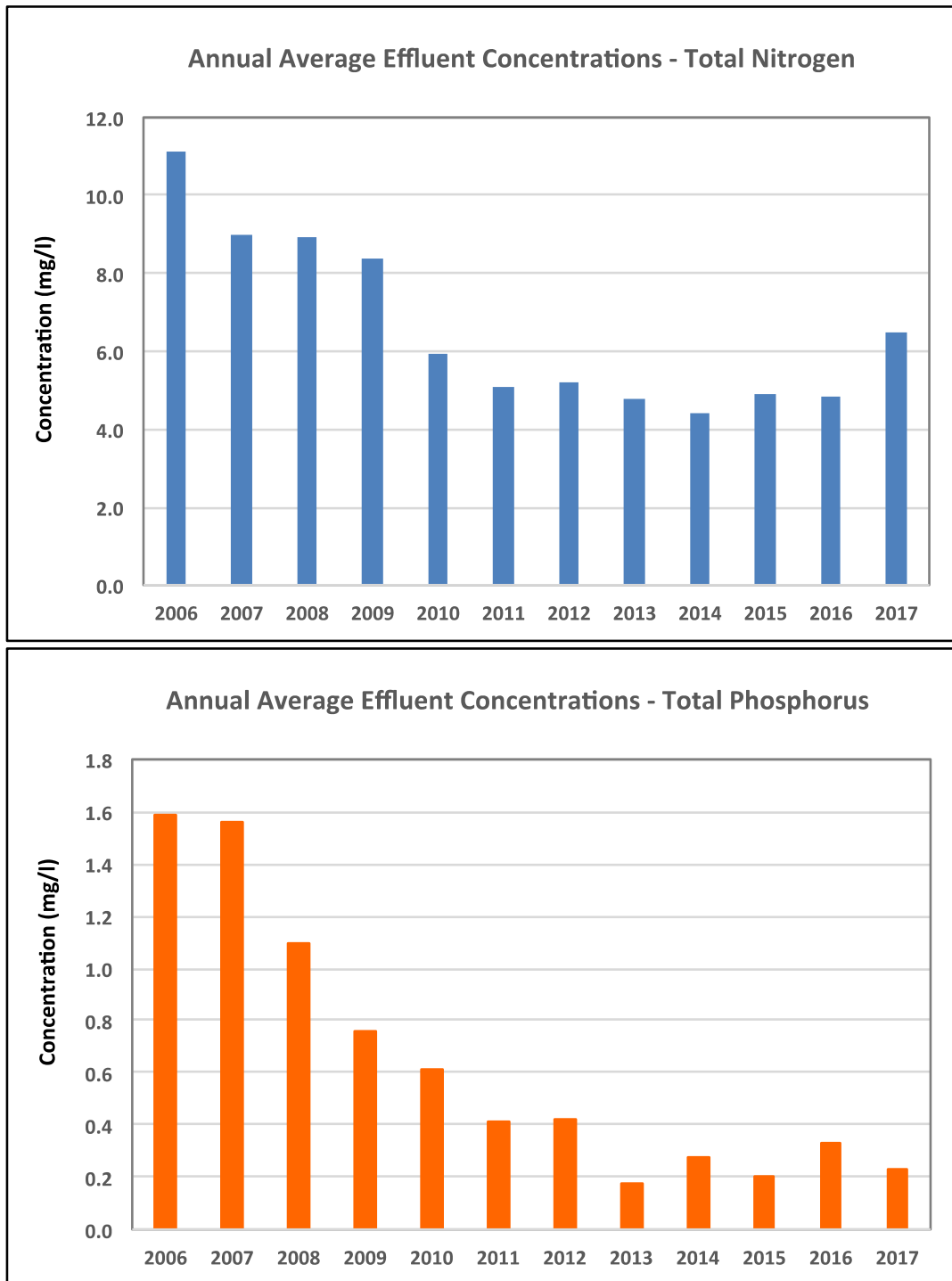


Figure 14: Annual average effluent total nitrogen and total phosphorus concentrations 2006 - 2017  
(Stream data are reported as ppb in this report. To compare effluent and stream data, note that  
1 mg/L = 1000 ppb.)

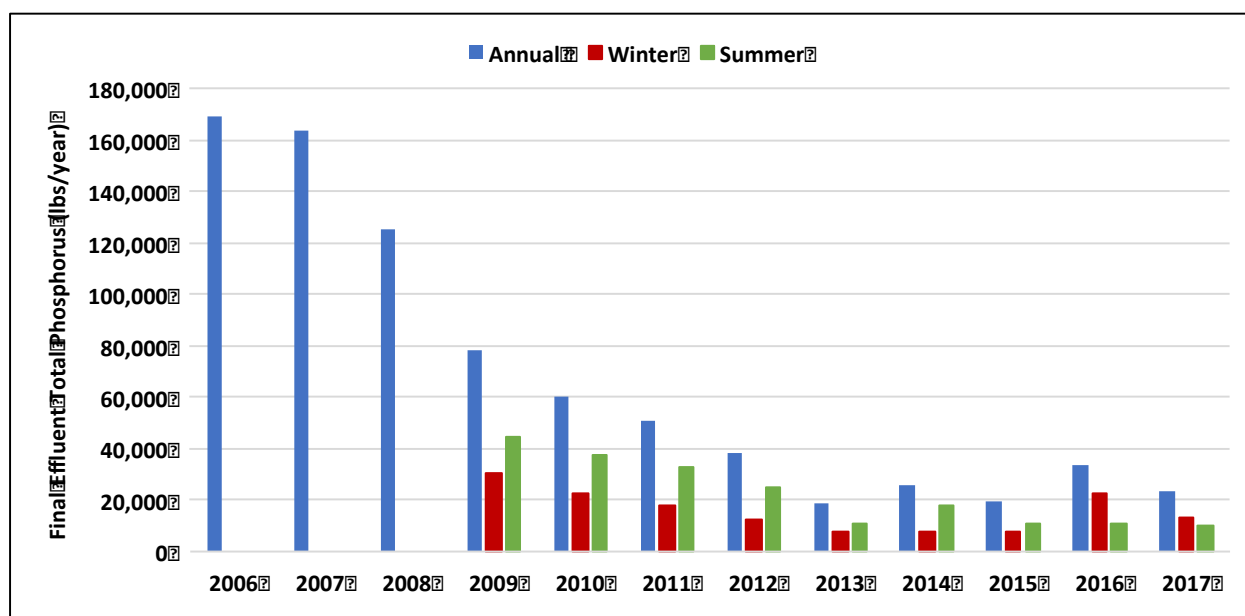
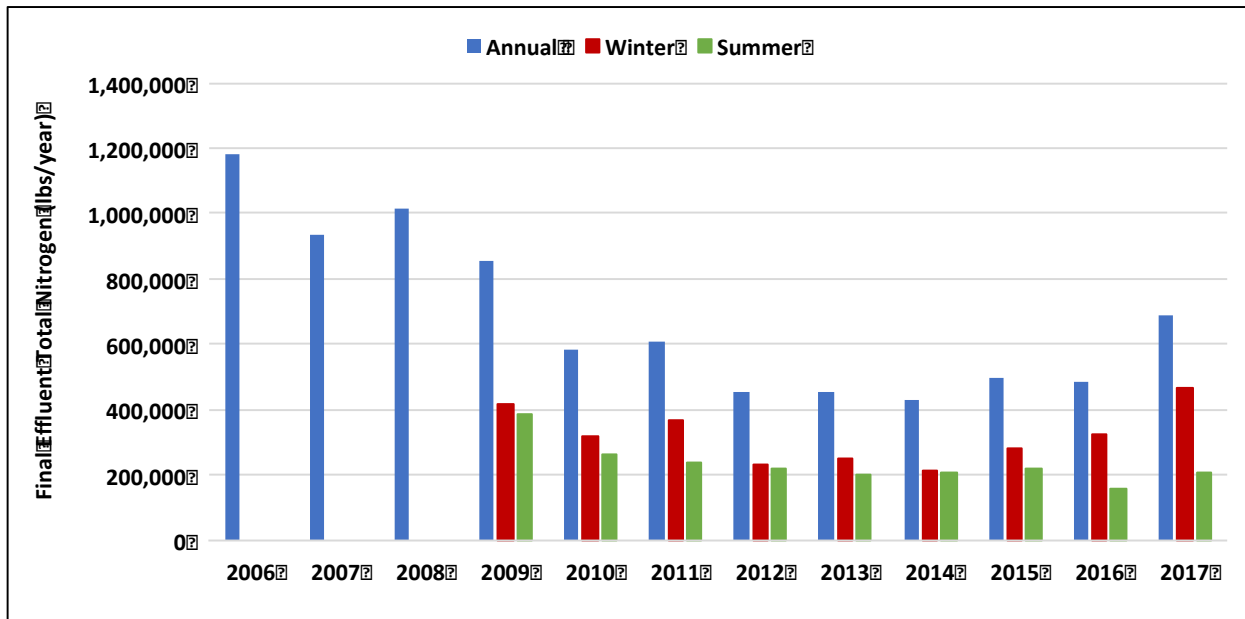


Figure 15: Total annual, winter permit, and summer permit total nitrogen and total phosphorus loads to the Blackstone River 2006 – 2017

Table 14: Percent reduction in yearly TN and TP effluent load compared to plant performance  
2006-2008

Year	TN (lb/yr)	TN % Reduction	TP (lb/yr)	TP % Reduction
2006 – 2008	1,045 x 10 <sup>3</sup>	--	152 x 10 <sup>3</sup>	--
2012	457 x 10 <sup>3</sup>	56%	38.2 x 10 <sup>3</sup>	75%
2013	452 x 10 <sup>3</sup>	57%	18.9 x 10 <sup>3</sup>	88%
2014	428 x 10 <sup>3</sup>	59%	25.6 x 10 <sup>3</sup>	83%
2015	499x 10 <sup>3</sup>	52%	19.6 x 10 <sup>3</sup>	87%
2016	484 x 10 <sup>3</sup>	54%	33.8 x 10 <sup>3</sup>	78%
2017	690 x 10 <sup>3</sup>	34%	23.3 x 10 <sup>3</sup>	85%

The highest biological activity in the river typically occurs during the warmest months of the year, from June through September. It is thus also useful to identify year-to-year differences in effluent nutrient characteristics for this summer growing period, which may provide insight into river conditions captured by the monitoring program. Available effluent nutrient and flow data during each year from 2006 - 2017 were utilized to calculate the daily average concentration and load from June through September, Table 15. A boxplot of the daily data from June through September each year is shown on Figure 16 for concentrations and Figure 17 for loads from 2012 – 2017. The boxplots provide an indication of the day-to-day variability during the June – September growing period each year of the monitoring program. The interquartile range of daily TN effluent loads from June – September has been relatively constant since 2012 with the notable exception of 2016, when the summer interquartile of daily TN loads leaving the plant fell below that of previous years. Daily growing season TN loads in 2017 were more on par with data from 2012 – 2015, although the interquartile range was narrower, and the median daily load was the lowest of the years since 2012 other than 2016. TP effluent loads during the summer growing season showed very little day-to-day variability, as indicated by a small interquartile range, in 2013, 2015, 2016, and 2017 but larger variability in 2012 and 2014. Time series plots of effluent TP and TN characteristics, as well as flow, are included in Appendix D.

Table 15: Average of the daily effluent nutrient characteristics during the June – September growing season in 2006 to 2017

<b>Year</b>	<b>Effluent TP</b>		<b>Effluent TN</b>	
	<b>June – September Ave. Daily Conc. (mg/L)</b>	<b>June – September Ave. Daily Load (lb/d)</b>	<b>June – September Ave. Daily Conc. (mg/L)</b>	<b>June – September Ave. Daily Load (lb/d)</b>
2006	1.7	403	NA	NA
2007	2.1	424	8.3	1,687
2008	1.5	421	8.0	2,178
2009	0.9	238	7.8	2,090
2010	1.0	209	6.1	1,180
2011	0.4	139	4.2	1,300
2012	0.4	86	4.6	948
2013	0.1	42	3.8	963
2014	0.5	102	4.8	989
2015	0.2	40	4.5	1,050
2016	0.2	38	3.8	680
2017	0.2	33	4.4	914



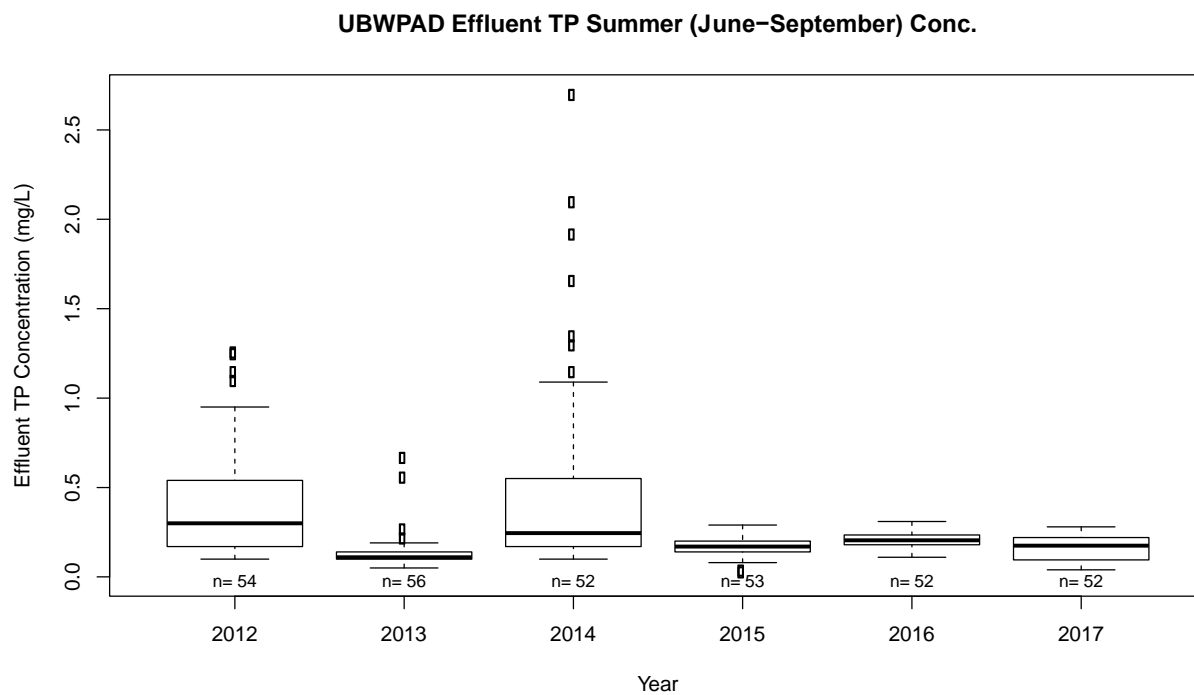
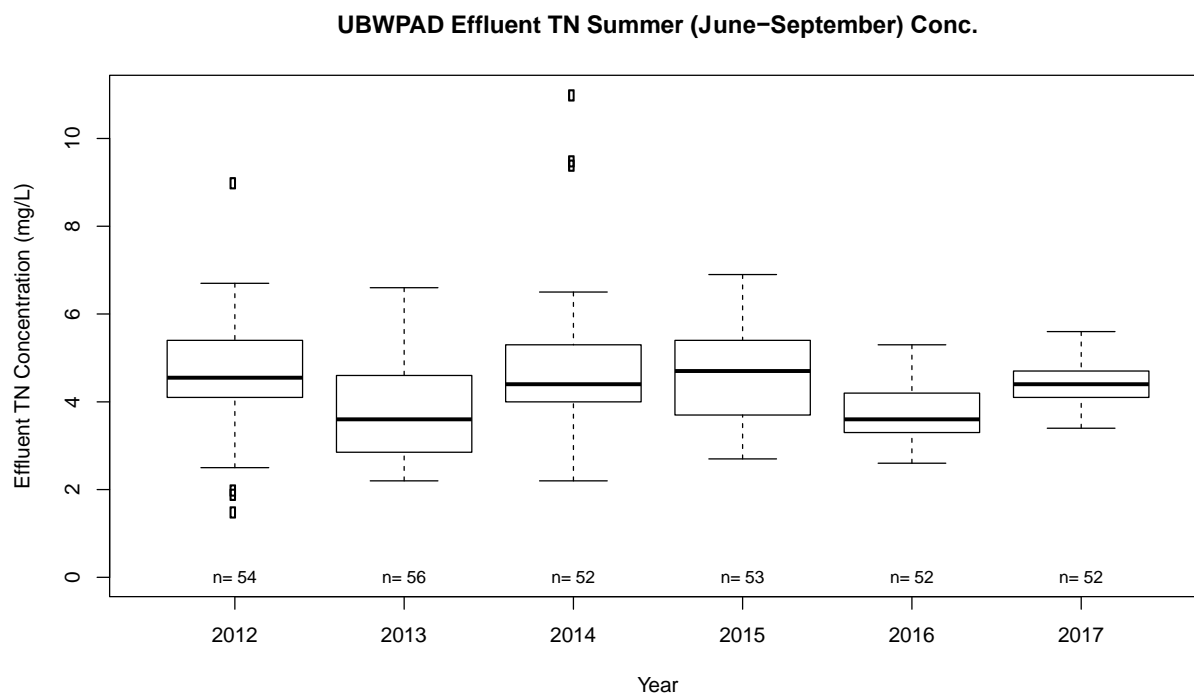


Figure 16: Upper Blackstone daily effluent TN and TP concentrations by year from June - September

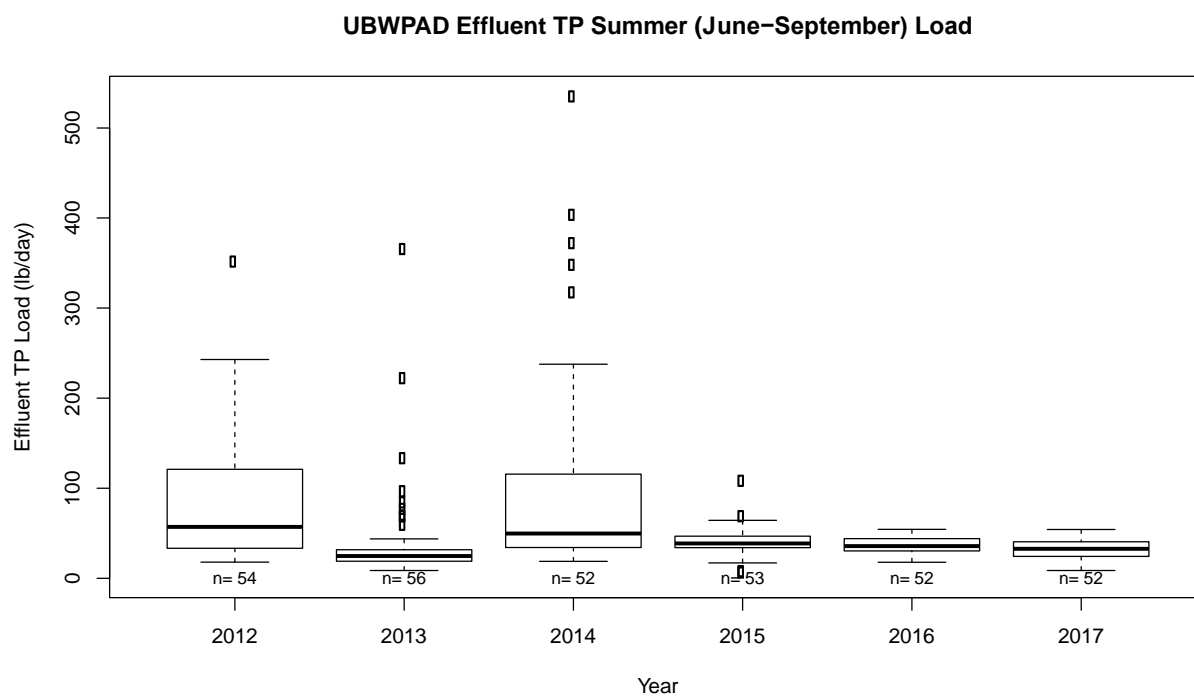
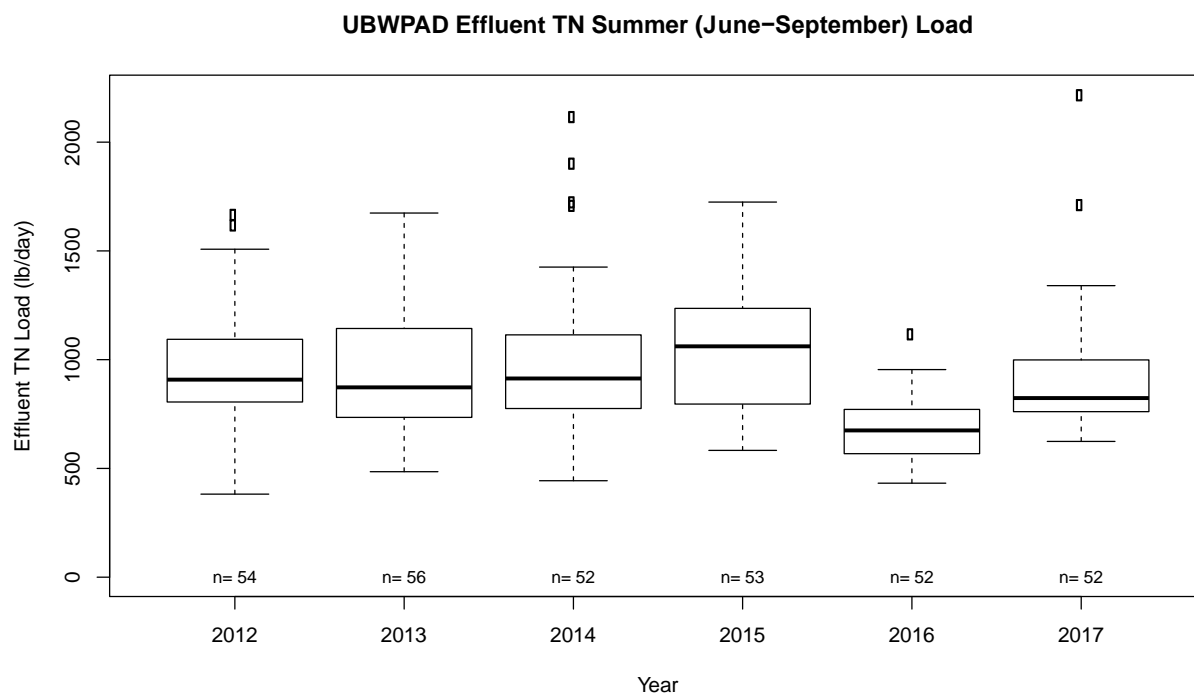


Figure 17: Upper Blackstone daily effluent TN and TP loads to the river by year from June - September

Upper Blackstone's effluent discharge can account for a large percentage of the flow that exits the headwaters of the watershed, providing, according to the literature, up to 75% of the flow in this portion of the Blackstone River during the summer months (Chaudhury et al., 1998 and Ji et al., 2002). The average effluent contributions to summer flows at Millbury on a daily basis since 2003 are summarized in Table 16 for two summer periods of interest in terms of in-stream algae growth, June-August and June-September. While productivity typically starts to decrease in September, annual low flows in the Blackstone River typically occur then, followed fairly quickly by increases in baseflow associated with fall precipitation. In 2017, Upper Blackstone effluent contributed between 16% (minimum) and 41% (maximum) of the daily flow at Millbury (data not shown). Averaging the daily values over the two periods of interest, the average daily effluent contribution was 46% from June to August, and 50% from June to September.

Table 16: Historical variations in the % of flow at Millbury<sup>1</sup> comprised of plant effluent on a daily basis

<b>Year</b>	<b>June – August</b>	<b>June - September</b>
2003	47%	50%
2004	58%	56%
2005	62%	64%
2006	43%	45%
2007	52%	57%
2008	42%	40%
2009	34%	39%
2010	53%	59%
2011	35%	33%
2012	49%	49%
2013	40%	42%
2014	57%	59%
2015	53%	59%
2016	63%	65%
2017	46%	50%

Note: <sup>1</sup> Calculated as the reported daily effluent flow divided by the measured daily streamflow at Millbury, converted to a percentage. The average is based on the daily plant effluent percent contribution values, averaged over the indicated time period

Effluent contributions during the growing season may also be summarized on a lumped volume basis, smoothing the data to account for the travel time between the confluence and the Millbury stream gauge. Table 17 summarizes the total volume of water passing the Millbury stream gauge from June to August each year since 2003. These data may be compared to the effluent volume entering the river from Upper Blackstone during the same time periods. This difference represents the “natural flow” in the river at the Millbury gauge. On a volume basis (e.g., based on data in Table 17), the effluent comprised 37% of the flow in the river at Millbury over the period June – August in 2017.

Table 17: Relative contributions by volume (million gallons) June – August

<b>Year</b>	<b>Millbury</b>	<b>Effluent</b>	<b>Difference</b>	<b>Effluent Contribution</b>
2003	10,289	3,649	6,640	35%
2004	5,285	2,634	2,651	50%
2005	6,061	2,950	3,111	49%
2006	9,637	2,989	6,648	31%
2007	5,237	2,266	2,971	43%
2008	8,111	2,877	5,235	35%
2009	13,911	3,557	10,354	26%
2010	4,757	2,156	2,601	45%
2011	11,239	2,867	8,372	26%
2012	6,088	2,398	3,690	39%
2013	12,238	3,115	9,123	25%
2014	4,447	2,278	2,169	51%
2015	6,306	2,575	3,730	41%
2016	3,463	2,003	1,460	58%
2017	6,385	2,376	4,009	37%

## 6.0 Sampling Season Data for 2017

Routine monitoring was conducted monthly from April to October for nutrients and chlorophyll-a at nine in-stream locations. Nutrient sampling was conducted monthly, regardless of flow conditions. Thus, looking at the data as a whole can mask improvements in the river due to point load reductions, which have a greater impact during low flow conditions. In order to provide a more focused look at the impact of plant facility improvements on river water quality, the data are presented in terms of both concentration and load. Flow data for each sampling date were available from two USGS gauging sites, located at Millbury, MA and Woonsocket, RI. Observed sampling day flows at these locations were utilized to provide flow estimates for load calculations at each sampling location based on the simulation results from the HSPF model developed for the Blackstone River (UMass and CDM Smith, 2008). Further analyses were conducted by looking at flow-adjusted concentrations.

Periphyton sampling was conducted three times during summer low flow conditions. The four sampling locations were all located in Massachusetts, including one upstream of the confluence with Upper Blackstone's effluent channel, and three downstream locations. Periphyton scrapings were analyzed for chlorophyll-a content as well as periphyton species and area coverage. While periphyton chlorophyll-a data are presented in this report, a complete report on periphyton data is available under separate cover from Normandeau Associates.

Continuous DO and temperature monitoring data were collected from June to November at the four periphyton survey locations. MassDEP deployed the data loggers, and UMass/Normandeau supported the collection of control data. CDM Smith performed data correction of the continuous data following guidance in the 2014 – 2016 QAPP. In addition, the procedures described in the USGS guidance document *Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting* (USGS Techniques and Methods 1-D3) were used to assess the continuous temperature and dissolved oxygen data.

In this section, flow conditions on routine sampling days are first described. River water quality conditions are then summarized by presenting the TP, TN, chlorophyll-a, periphyton, and continuous DO and temperature monitoring results. In-stream data are reported as ppb in this report. To compare with effluent data from the previous sections, note that 1 mg/L = 1000 ppb.

### 6.1 Flow Conditions on Routine Sampling Days

Section 4.2 presented a discussion of monthly and day of sampling conditions in a general historical context with regards to streamflow. It is also of interest to directly compare flow conditions on sampling days. Data were subdivided into samples collected during low flow, average, and high flow conditions. Low flow conditions were defined as less than half of the average flow in a reach, high flow conditions were defined as greater than 1.5 times the average flow in a reach, and all other flows were categorized as average. Because distinct flow condition categories exist for each reach, it is possible for sampling sites along the river to have different flow categories for a given sampling date as effects of precipitation-runoff processes move through the basin. In such instances,

sites close to the threshold were re-categorized to reflect the dominant flow condition category for the sampling date. Table 18 summarizes how the sampling events since 2012 were categorized by flow condition. Sampling date “low” flow conditions are summarized for the 2012 through 2017 sampling seasons, as well as for historical data that were similarly categorized by flow conditions, on Figure 18. The data for 2017 are shown as a black line with square symbols. Only dates characterized as “low flow” days are included in the average of sampling day flow conditions shown on the figure. The historical data are drawn from data collected by MassDEP, USGS, RIDEM, URI/NBC, and UMass from 1998 – 2008. In general, the lowest low-flow conditions on sampling days since routine monitoring began in 2012 occurred during the 2017 sampling season. In the subsequent discussion, TP and TN concentration data are similarly summarized based on flow condition for comparison against data from other time periods.

Table 18: Summary of flow conditions during routine monitoring  
(D = low, A = average, W = high)

Year	April	May	June	July	August	September	October	November
2012	D	A	A	D	D	D	A/D <sup>1</sup>	A
2013	A	D/A <sup>1</sup>	W	D	D	D	D	D
2014	A	A	D	D	D	D	D	D
2015	A	D	A	D	D	D	D	D
2016	A	D	D	D	D	D	D	D
2017	W/A <sup>1</sup>	A	W	D	D <sup>2</sup>	D	A/W/A <sup>1</sup>	A

Notes: <sup>1</sup> Flow conditions on sampling dates during these months were too disparate to be classified as the same condition; variable conditions listed from downstream (left) to upstream (right)

<sup>2</sup> In 2017, the river was sampled on 8/2/17 and 8/30/17. Conditions were dry both dates.

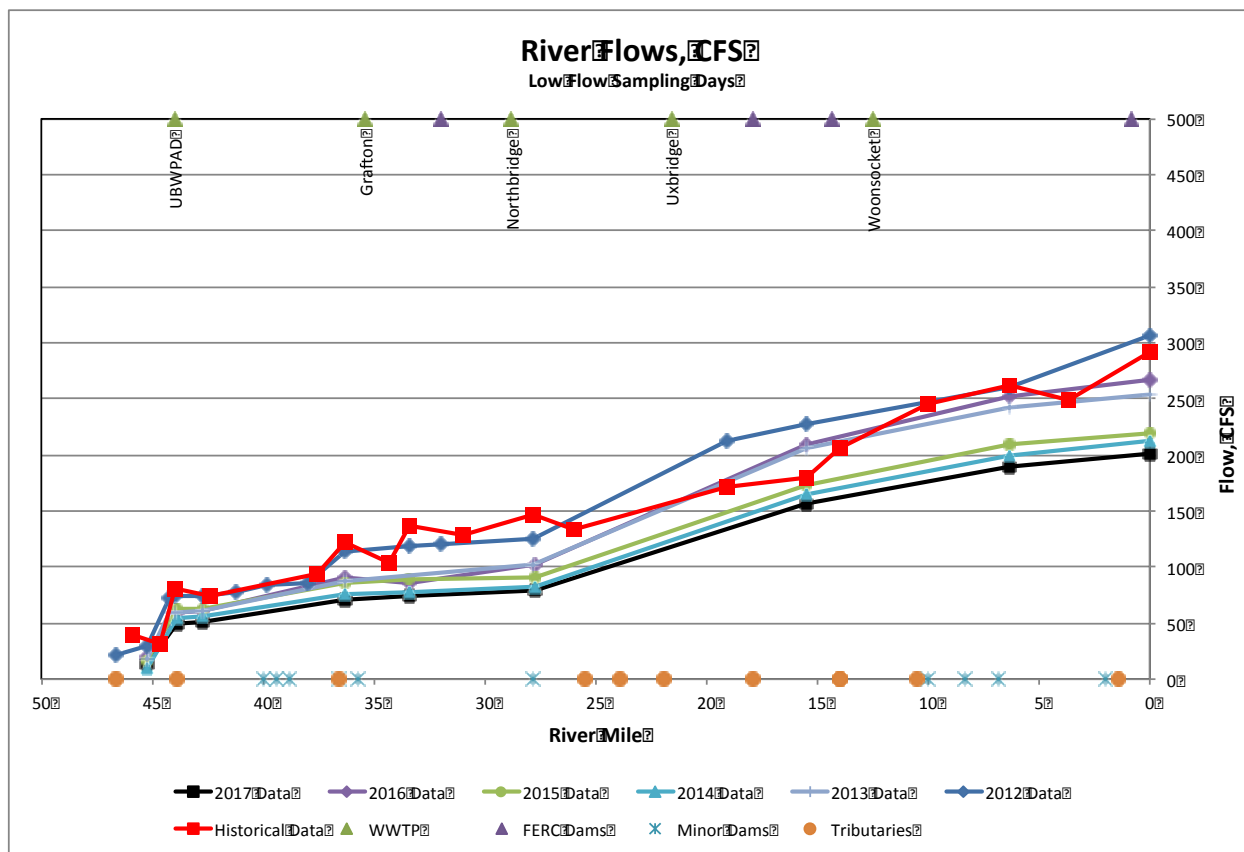


Figure 18: Comparison of average flow conditions on sampling date by year, sorted for sampling dates categorized as “low flow”

## 6.2 Routine Monitoring Data

Sampling data results for TP, TN, and chlorophyll-a are summarized in sections 6.1.1, 6.1.2, and 6.1.3, respectively, using a uniform series of plots and analyses. Sufficient data are now available to conduct a more robust trend analysis based on flow-weighted concentration data. Flow-weighted concentration trend analyses are presented for TP, TN, and chlorophyll-a in Section 6.1.4. Additional information on nitrogen and phosphorus subspecies, as well as laboratory QAQC data, is available upon request.

### 6.2.1 Total Phosphorus

Available TP concentration data for the Blackstone River since 1996 are summarized in Figure 19 using boxplots. Data for all sampling locations are grouped by year. As explained previously, the median of the data for each year is shown by the dark bar in each box, the lower and upper quartile of the observed data are shown by the body of the box, the whiskers identify 1.5 times the interquartile range above the upper quartile and below the lower quartile of the data, and the small black circles above and below the whiskers represent observed data that are statistically considered “outliers.” TP concentrations since Upper Blackstone upgrades came online in 2009 are less variable and are lower than historical concentrations. Upgrades to the plant have translated to improved river conditions. The TP concentrations observed during routine sampling in 2017 were characterized by a relatively small interquartile range and median value compared to earlier sampling years, however there were a number of higher concentrations identified as outliers. The TP concentration data points identified as outliers in 2017 on Figure 19 are mainly (5 of the 6 outliers) associated with the October 25, 2017 sampling date. This routine sampling occurred on a day when 0.75 inches of rain fell, following 1.76 inches of rain on the day prior (Table 7). The other identified outlier was for the UBWPAD2 sampling site and occurred during the September 27, 2017 routine sampling during a period of falling flows. The flow on this day at Millbury was only 44 cfs.

The mean summer (June – September) TP concentration at each sampling location in the Blackstone River is shown on Figure 20 for sampling data collected since 2012. Data are clustered by sampling site, plotted from the headwaters (left) to the outlet (right). Each year is shown as a different color, with 2017 in green. At most sampling locations, average TP concentrations in 2017 were about average compared to other sampling years, higher than those observed in 2013 and 2015, but lower than values observed in 2012, 2014, and 2016. In 2014, identified with grey bars, Upper Blackstone conducted several pilot studies as part of interim measures to optimize nutrient removal. During pilot testing, two upsets were observed in the plant’s biological nutrient removal (BNR) process impacting treatment plant performance. Upper Blackstone made immediate operational adjustments to stabilize the treatment process; however, the plant upsets resulted in higher than typical phosphorus loading to the river during portions of the 2014 summer growing season.



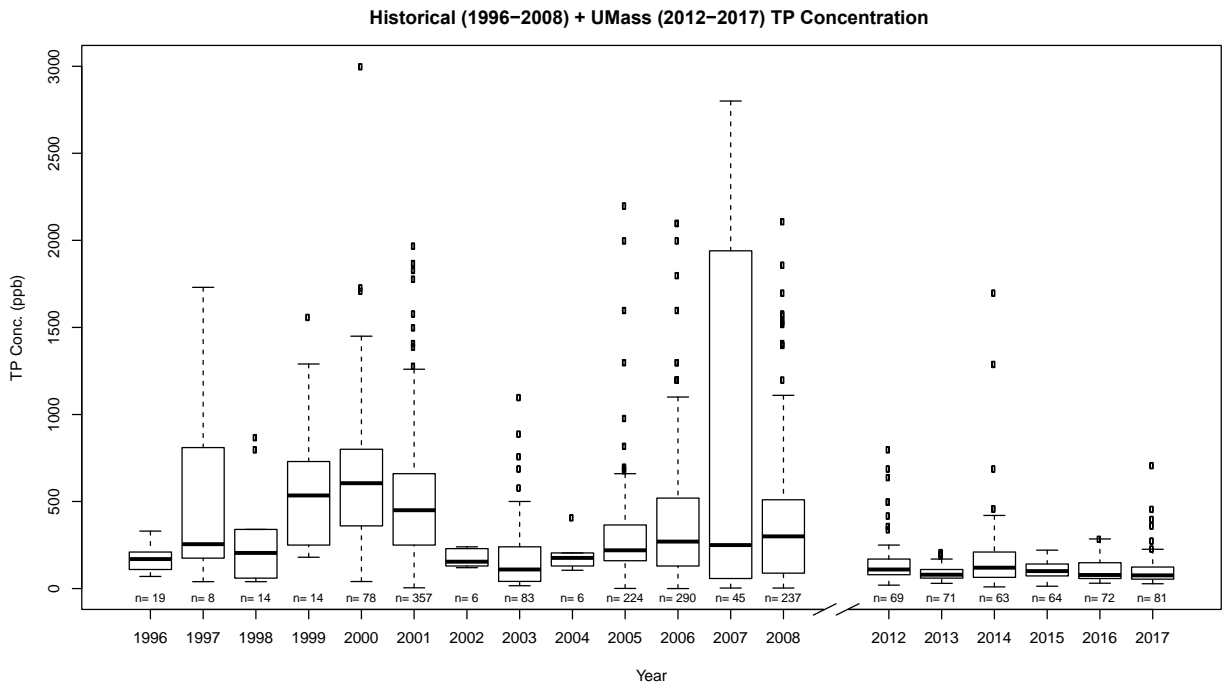


Figure 19: TP concentrations observed in the river 1996 – 2008 and 2012 – 2017

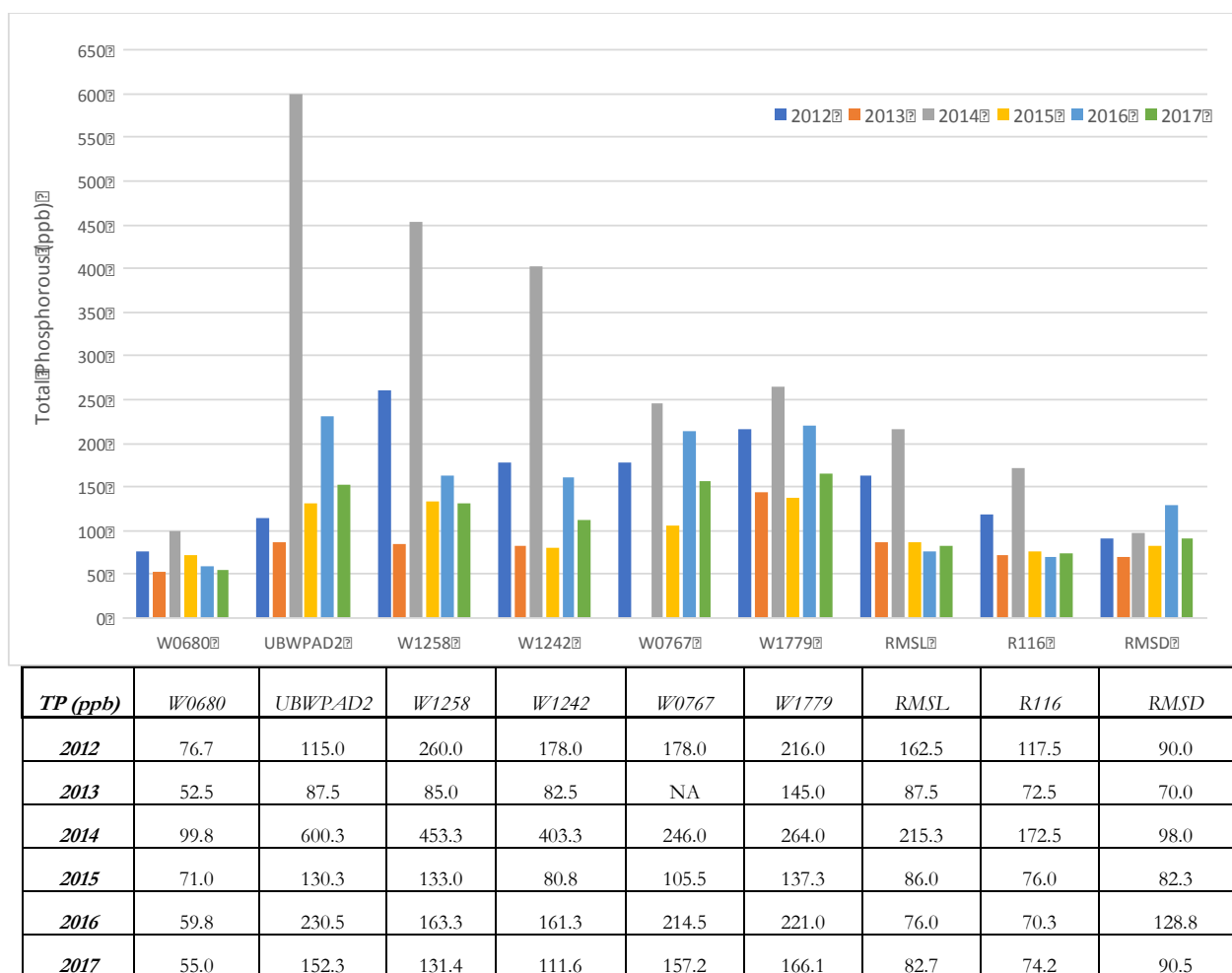


Figure 20: Mean summer (June – September) TP concentrations observed by site since 2012

The full range of TP concentrations observed at each site since 2012 is summarized in Figure 21, with sites plotted from the headwaters (left) to outlet (right) as above. TP concentrations identified as outliers at each sampling location occur over a range of dates, Table 19. Potential factors contributing to the high concentrations on these dates are suggested where possible. Average concentrations in 2017 are highlighted for both “low” flow (grey diamonds) and all data (blue diamonds), regardless of flow conditions. Average concentrations during “low” and all flow conditions are very similar. It should be noted that data collection at the UBWPAD site occurred from 2012 – 2013, when the site was moved to a better-mixed location downstream, UBWPAD2, where data collection started in 2013 and continues. Average TP concentrations in 2017 fell within the interquartile range of values observed since 2012 at all sampling sites but were at the upper quartile limit for sampling location W0767.

Table 19: TP concentration outliers identified by sampling site for routine sampling dates

<b>Routine Sampling Date</b>	<b>Sampling Locations with Outliers</b>	<b>Potential Factors</b>
May 9, 2012	W1258, W1242, W1779	Unknown, but sampling on rising limb of an event. No effluent data available for 5/9 but “high” effluent TP observed on 5/8/12 (1.25 mg/L).
July 3, 2012	W1779, RMSL	Unknown. Falling limb of event with peak Q on 6/25/12.
September 26, 2012	W1258, W1242	Unknown, but period of higher effluent loads.
June 25, 2014	UBWPAD2, W1258, W1242	Plant upset.
August 20, 2014	W0680, W1242, W0767, W1779, RMSL, R116	Plant upset.
September 17, 2014	W1258, W1242, RMSD	Plant upset.
June 24, 2015	W0680	Falling limb hydrograph with peak on 6/21/15. Effluent TP elevated 6/24/15 (0.2 mg/L compared to 0.14 mg/L day before and 0.04 mg/L two days later).
October 15, 2015	R116	Large event peak 9/30/15 dropping back to low flows. Effluent 84% of flow at Millbury this day.
June 22, 2016	RMSD	Unknown.
July 20, 2016	RMSD	Unknown.
June 7, 2017	RMSD	High flow event with peak on 6/6/17.
September 27, 2017	UBWPAD2	Unknown, but TP effluent elevated (0.22 mg/L on 9/26/18 and 0.28 mg/L on 9/28/17) and flow low, with effluent 71% of flow at Millbury on this day.
October 25, 2017	W1242, W0767, W1779	High rainfall on sampling day and day prior

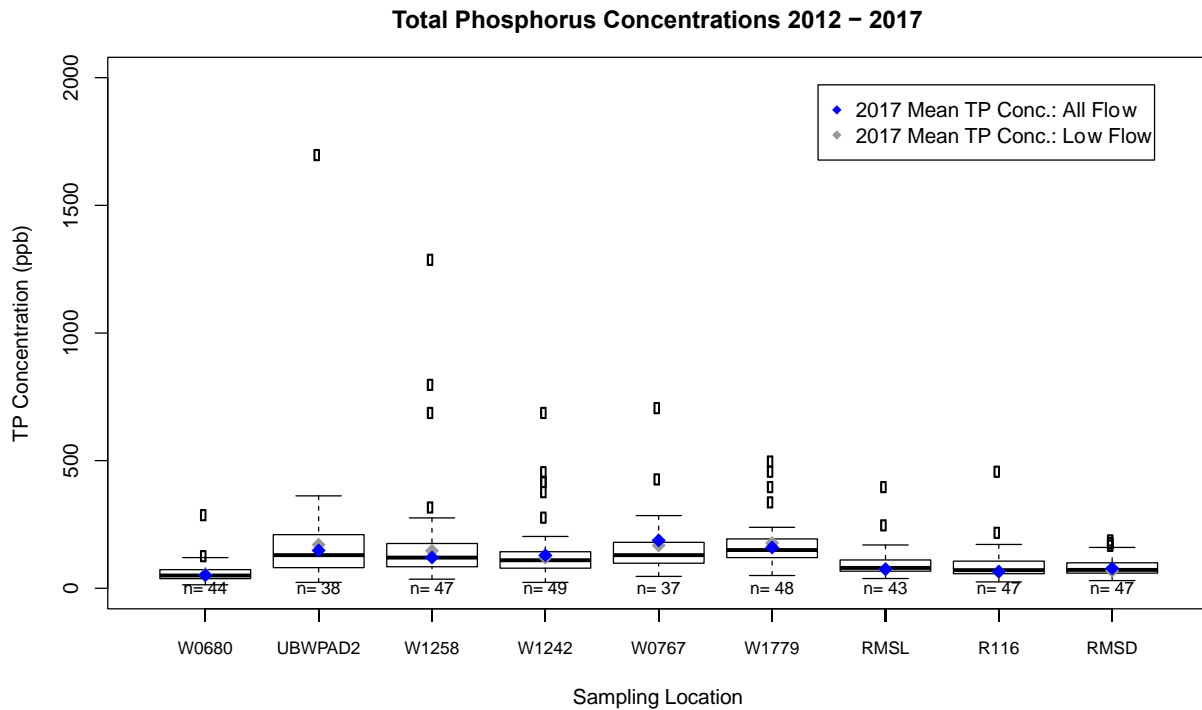


Figure 21: TP concentrations by site from 2012 - 2017

Average TP concentrations during low flow conditions in 2012 – 2017 are compared to historical concentrations during similar conditions in Figure 22, plotted against river mile with headwater locations on the left (river mile 50) and the outlet on the right (river mile 0), analogous to the earlier plots where site name is indicated instead of river mile. Data from June 2014, which were affected by plant operations and pilot testing, are removed from the 2014 calculation. The average low flow TP concentrations at the three RI sites in 2017 were the lowest since routine sampling began in 2012 and were in the middle of observed data across the MA sampling locations. Upper Blackstone's efforts to reduce effluent TP translate into reductions in stream TP levels even during the driest conditions.

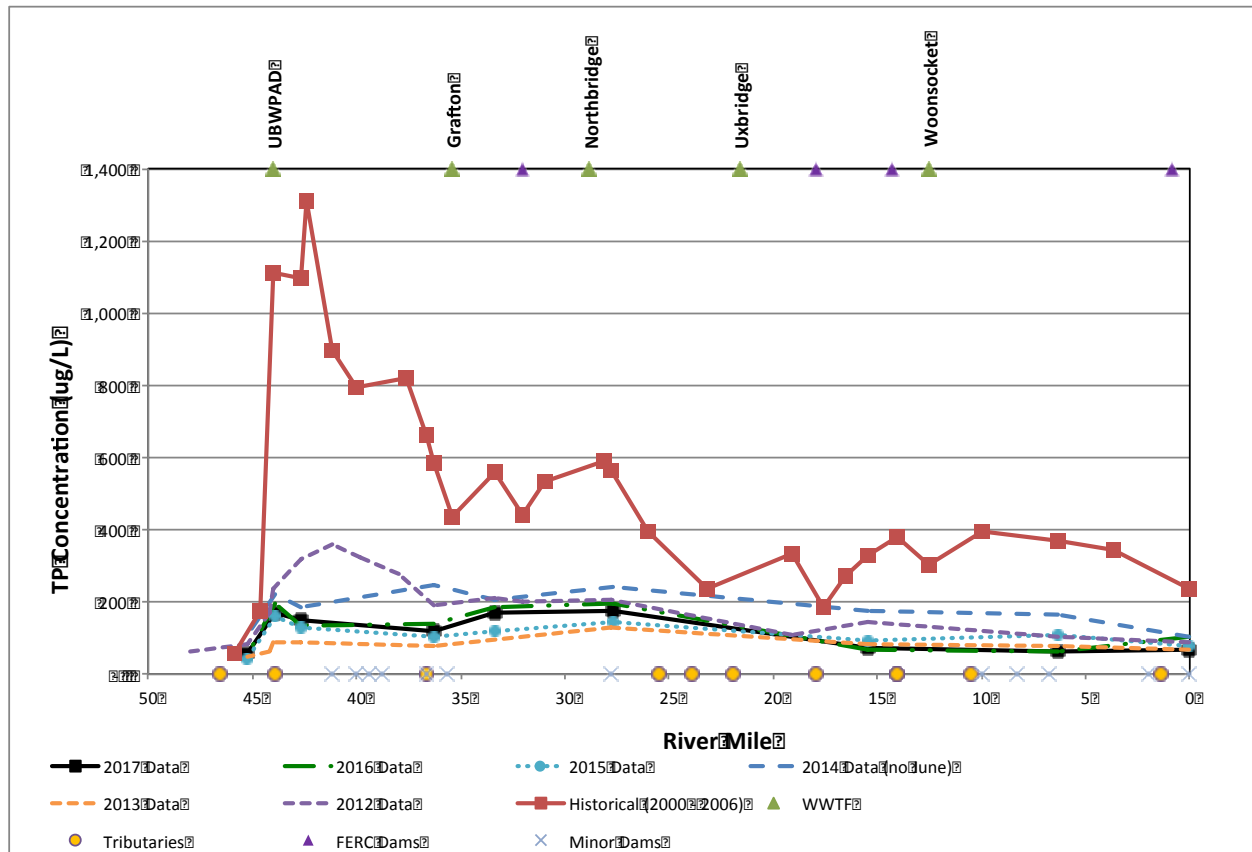


Figure 22: Along stream TP concentrations on low flow days

Estimates of mass flux (or load) based on the observed concentrations and discharge estimates provide more relevant information on the benefits of the plant upgrades for receiving waters, such as Narragansett Bay. Estimates of TP loads since 1996 in the Blackstone River are summarized in Figure 23. Data for all sampling locations along the river are grouped by year. There is an even larger reduction in TP load (versus concentration) in the river since Upper Blackstone upgrades came online in 2009. Average riverine loads since routine sampling started in 2012 are less variable and overall lower. The full range of TP loads observed at each site since 2012 is summarized in Figure 24, with data for 2017 highlighted as before. Loads associated with “low” flow sampling events in 2017 were below the median of observed values at all sites. High loads on “average” and “wet” days resulted in the 2017 “all flows” average TP load (blue diamonds) falling above the interquartile range at all sampling locations. Along stream average TP loads during low flow conditions summarized by year and site, Figure 25, further illustrate the impact of flow condition on load estimates. The TP load transported by the river during low flow conditions was near the lowest on record for all sampling sites in 2017.

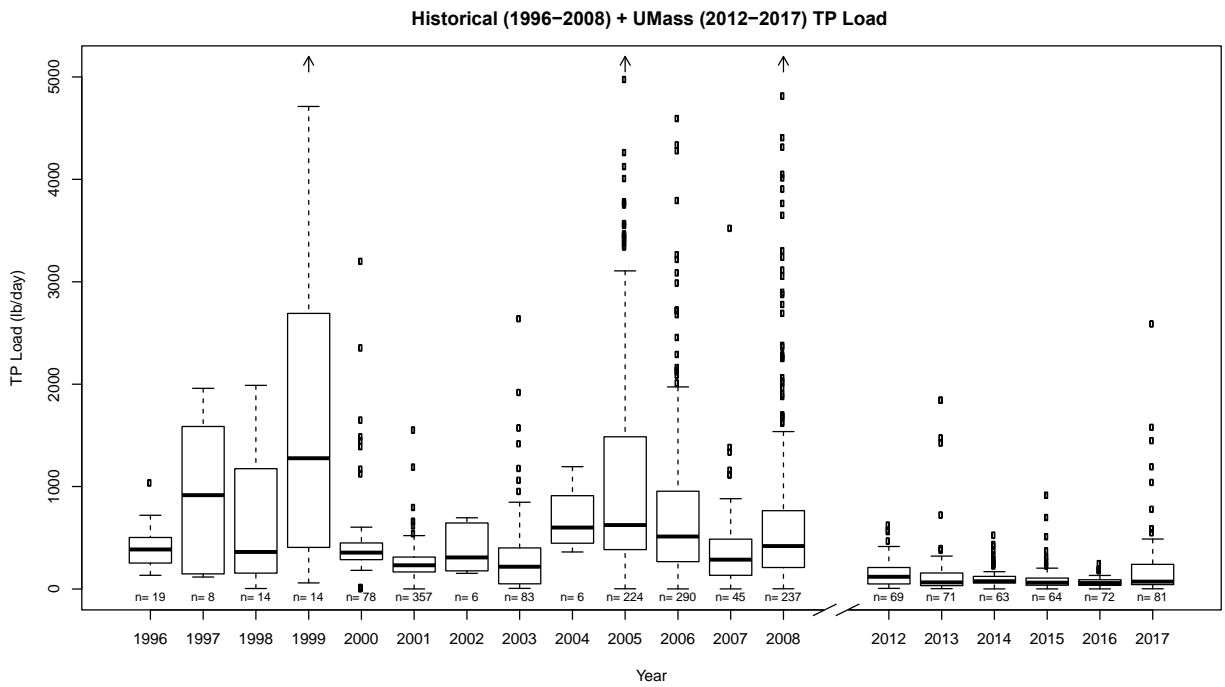
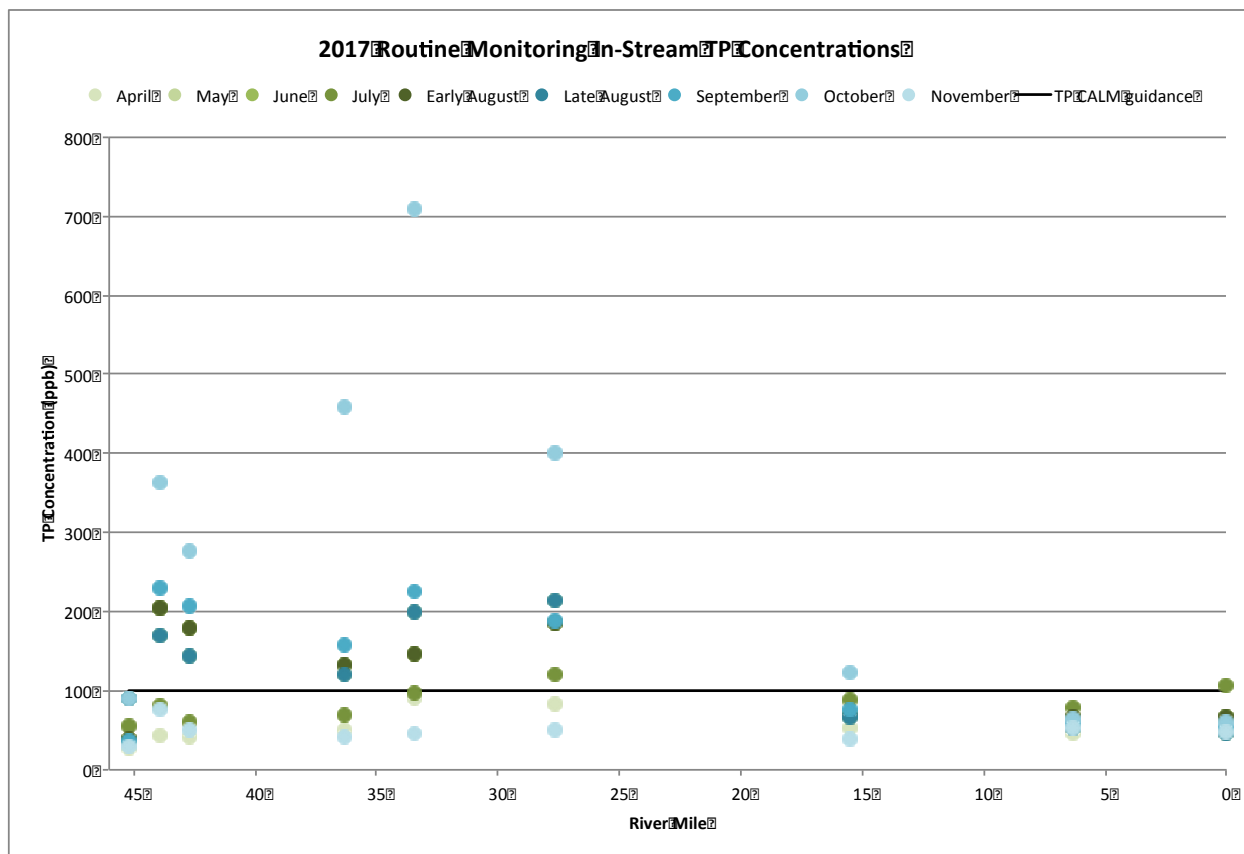


Figure 23: Summary of TP loads observed in the river 1996 – 2008 and 2012 – 2017 (note, additional outliers not shown, as indicated by arrows)



In 2017, total phosphorus concentrations in the Blackstone River were below the MassDEP 2016 CALM screening threshold of 100 ppb 65% of the time, Figure 26. The most excursions occurred at W1779, the sampling site below RCP at river mile 27.8, where only 3 of 9 samples (33%) were below the threshold. Compliance was 56% at the three sampling locations immediately downstream from the confluence, and 44% at the Sutton Street Bridge, the next sampling location (W0767) at river mile 33.4.

Figure 26: Compliance with MA CALM guidance for TP in 2017





### 6.2.2. Total Nitrogen

Available TN concentration data for the Blackstone River since 1996 are summarized in Figure 27. The 2008 permit limits reduced TN effluent concentrations by 40% during summer months. The impact of the new limits and associated plant upgrades which came online in 2009 are evident. In recent years, fewer extreme TN concentrations have been observed, and the overall variability of in-stream concentrations has been reduced even though the median TN concentration has not changed drastically from pre- to post-upgrade. The TN concentration data points identified as outliers in 2017 on Figure 27 are associated either with the falling limb of an event (4/12/17) or low river flows with effluent contributing >70% of the flow paired with effluent concentrations >4.0 mg/L (8/30/17 and 9/27/17).

Since 2014, there has been a steady reduction in both the span and magnitude of the interquartile range of TN concentrations observed in the river. The upper quartile of observed TN concentrations in 2017 is approximately equivalent to the 2016 median, while the 2017 median is approximately equivalent to the lower quartile of the 2016 TN data. Trends in TN are discussed further below.

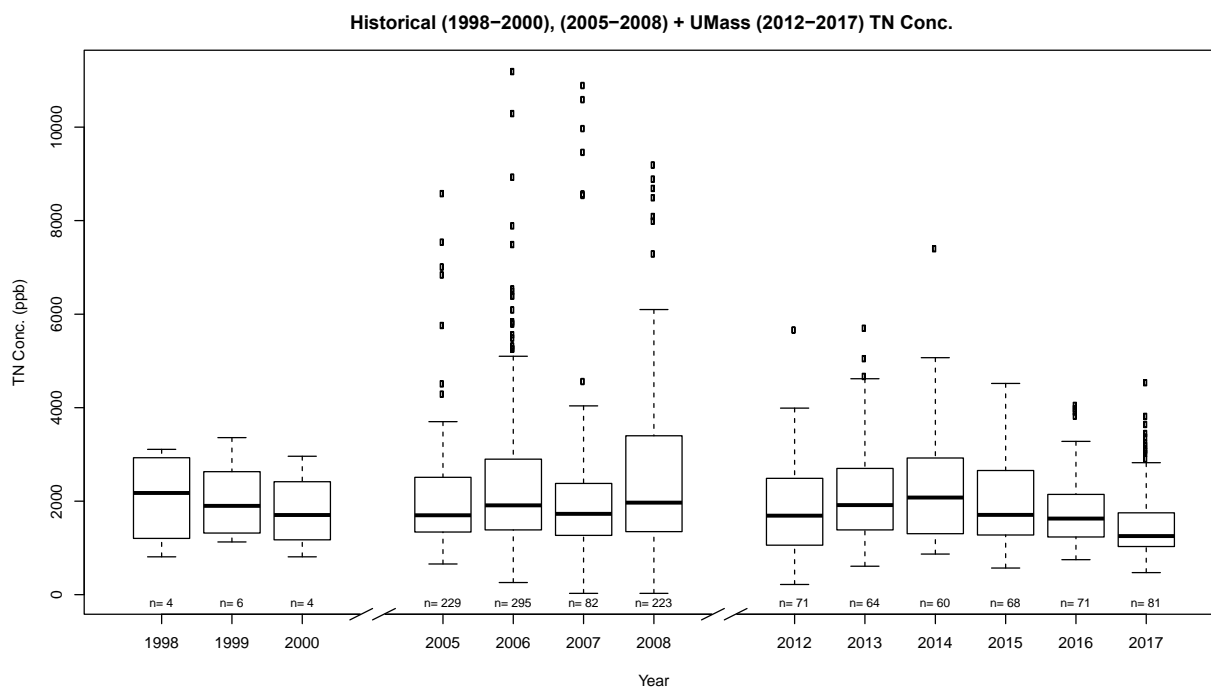


Figure 27: Summary of TN concentrations observed in the river, 1996 – 2008 and 2012 - 2017

The mean summer (June – September) TN concentration at each sampling location in the Blackstone River is shown on Figure 28 for sampling data collected since 2012. Data are clustered by sampling site, plotted from the headwaters (left) to the outlet (right). Each year is shown as a different color, with 2017 in green. As noted above, in 2014 (grey bar) Upper Blackstone conducted several pilot studies as part of interim measures to optimize nutrient removal. During pilot testing, two upsets were observed in the plant’s biological nutrient removal (BNR) process impacting treatment plant performance. Upper Blackstone made immediate operational adjustments to stabilize the treatment process, however the plant upsets resulted in slightly higher than typical nitrogen loading to the river during portions of the 2014 summer growing season, particularly in June and September. The upset impacted effluent and in-stream TN concentrations less than it did TP. It should be noted that the apparent increase in mean summer TN concentrations at sampling site UBWPAD2, downstream of the confluence with Upper Blackstone’s effluent channel, from 2012 to 2013 is an artifact of relocation of the site further downstream to a more well-mixed location in 2013. The original site, included here for the year 2012, had lower values because it was not appropriately capturing the impacts of the effluent. In addition, site W0767 was not sampled in 2013. Mean summer TN concentrations observed in 2017 were lower or approximately equivalent to previous years at all sites except for UBWPAD2 and W1242.

The full range of TN concentrations observed at each site since 2012 is summarized in Figure 29, with sites plotted from the headwaters (left) to outlet (right) as above. TN concentrations identified as outliers at each sampling location occur over a range of dates, Table 20. Potential factors contributing to the high concentrations on these dates are suggested where possible. The only sampling date overlapping with dates when TP outliers were also observed is August 20, 2014. Average concentrations for 2017 are highlighted for both “low” flow (grey diamonds) and all data (blue diamonds), regardless of flow conditions. Data for both the original UBWPAD site (2012 – 2013) and new site, UBWPAD2 (where data collection started in 2013 and continues) are included. Average TN “low flow” and “all flow” concentrations in 2017 fell within the interquartile range of values observed since 2012 at all sampling sites, and in fact the “all flow” average TN concentration at each location was less in 2017 than the median of the data collected since 2012. Average TN concentrations during low flow conditions in 2012 – 2016 are compared to historical concentrations during similar conditions in Figure 30, plotted against river mile with headwater locations on the left (river mile 50) and the outlet on the right (river mile 0). Data from June 2014, which were affected by plant operations and pilot testing, are removed from the 2014 calculation. A solid black line with square symbol indicates data for 2017. The along stream low flow concentration data for 2017 define the lower envelope of data for half of the sampling locations and are at the low end of the range for the remaining locations. TN levels in the river have steadily decreased since 2012.



Figure 28: Mean summer (June – September) TN concentrations observed by site since 2012

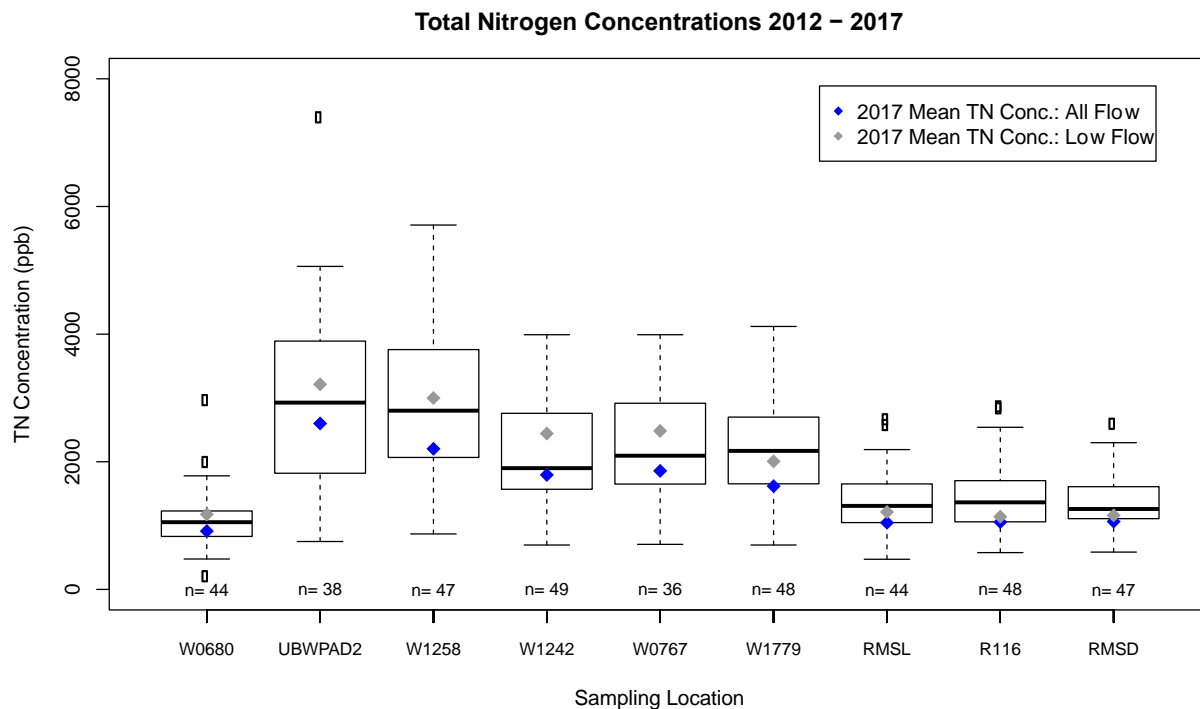
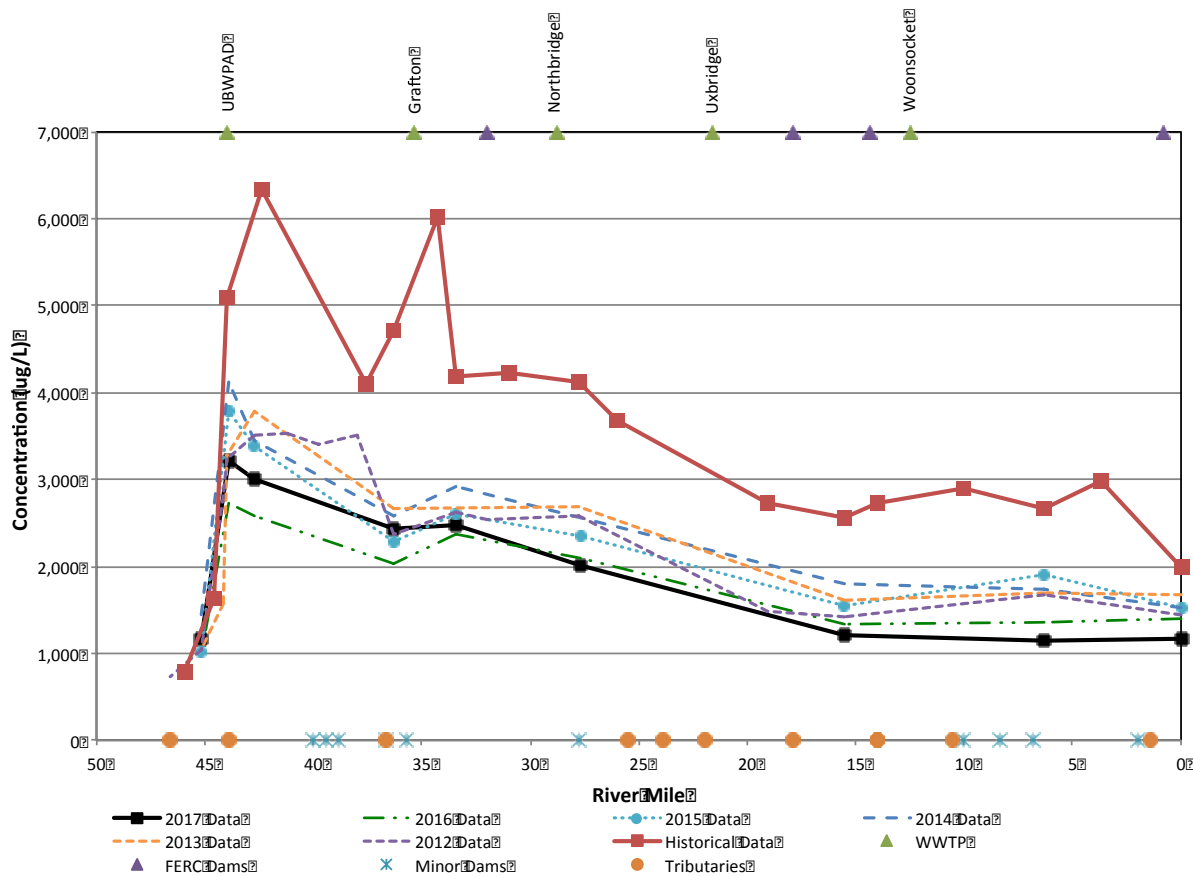


Figure 29: TN concentrations by sampling location from 2012 - 2017

Table 20: TN concentration outliers identified by sampling site for routine sampling dates

<b>Routine Sampling Date</b>	<b>Sampling Locations with Outliers</b>	<b>Potential Factors</b>
June 6, 2012	W0680	Unknown.
September 18, 2013	RMSD	Unknown, but period of relatively low flows following an event with peak on 9/13/13.
August 20, 2014	W0680, RMSL, R116	Plant upset.
October 15, 2014	UBWPAD2, RMSL	Unclear. Relatively high effluent TN concentrations (6.4 mg/L) paired with low flow where 79% of streamflow is comprised of effluent.
September 16, 2015	R116	Unclear. Relatively high effluent TN concentrations (4.6 mg/L) paired with low flow where 68% of streamflow is comprised of effluent.
April 27, 2016	W0680	Unknown.

Figure 30: Along stream TN concentrations on low flow days



Estimates of TN loads since 1996 in the Blackstone River are summarized in Figure 31. Data for all sampling locations along the river are grouped by year. The TN load data (versus concentration), suggest a decrease in TN loads transported by the river since Upper Blackstone's upgrades were online in 2009. The interquartile range of observed TN loads from 2012 through 2017 are smaller than from 1999 through 2008. In addition, the interquartile ranges for years 2012 - 2017 fall below the median of historical data collected in years 1999 - 2008. The full range of TN loads observed at each site since 2012 is summarized in Figure 32, with data for 2017 highlighted as before. Loads associated with "low" flow sampling events in 2017 fell at or below the interquartile range of observed values, while average TN loads across all flow conditions were elevated, falling at or above the upper quartile of observed values at all sites. While the interquartile range (body of box) of TN concentrations tended to decrease downstream (Figure 29), the interquartile range of TN loads (Figure 32) increased in the downstream direction, reflecting the impact of flow volume on the load estimate. This increase is more pronounced for TN than observed for TP. As the flow estimates utilized in the load calculation are the same for TN as for TP, the underlying cause is likely due to

differences in the variability of TN and TP concentration in the downstream direction. In 2017, variability in TN concentrations was lower than in previous years.

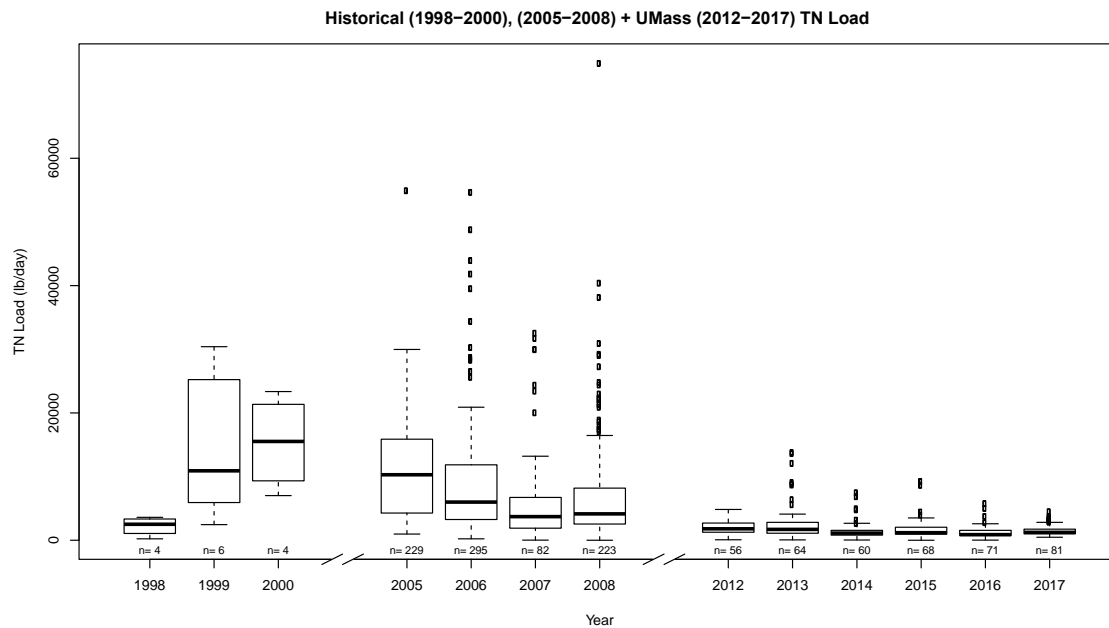


Figure 31: TN loads observed in the river 1996 – 2008 and 2012 – 2017

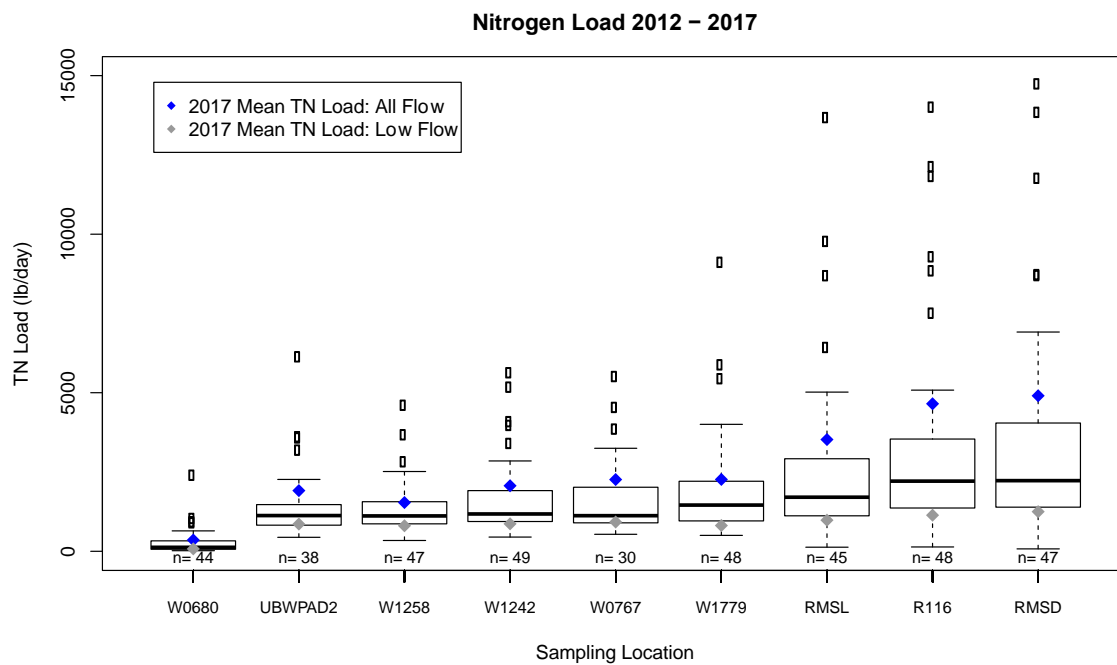


Figure 32: TN load data by sampling location 2012 - 2017

Along stream average TN loads during low flow conditions, as summarized by year and site, Figure 33, further indicate on-going improvements in the river and for receiving waters. The average TN load on low flow days in 2017 defined the lower envelope of data observed from 2012 through 2017, as well as compared to historic data, at almost all sampling locations.

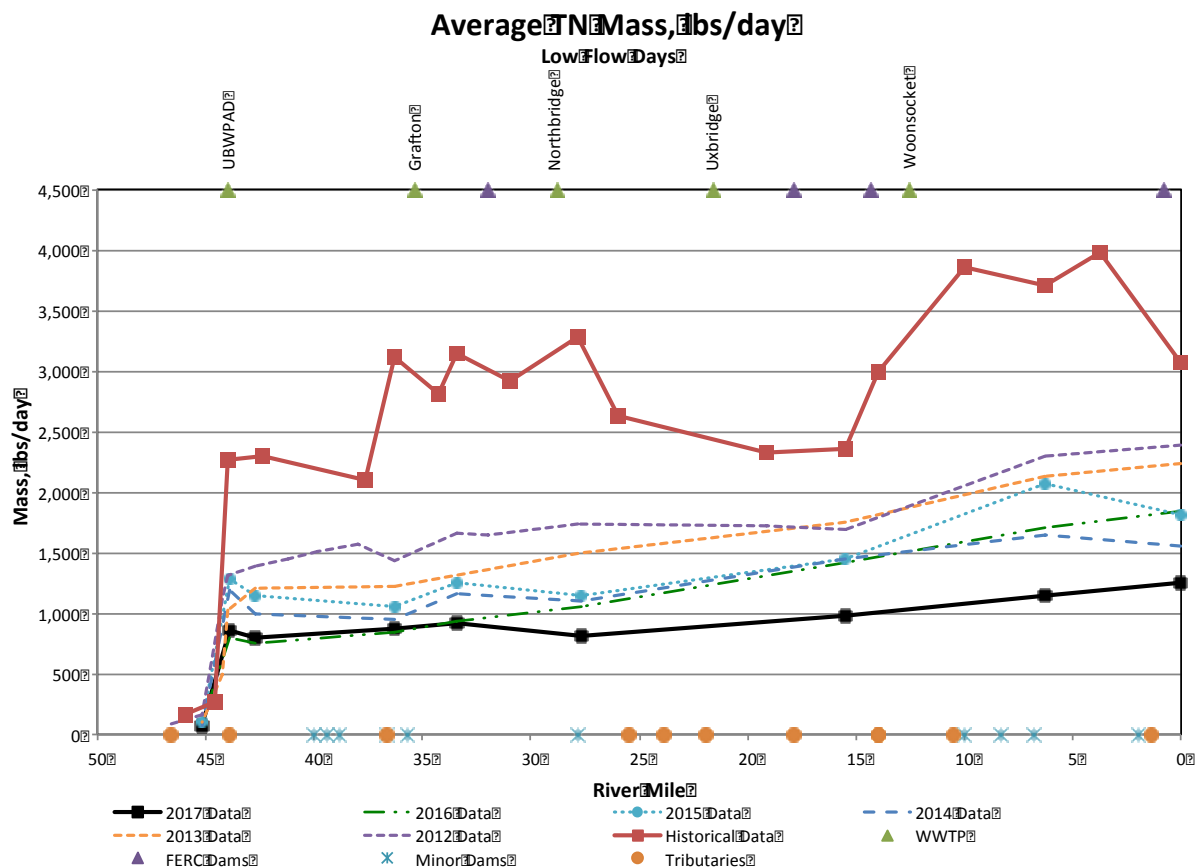


Figure 33: Along stream TN loads on low flow days

### 6.2.3. *Chlorophyll-a*

Chlorophyll-a concentrations observed during the summer months (June – September) since 2012 are summarized by year in Figure 34. Overall, summertime chlorophyll-a levels in 2017 exhibited an interquartile range comparable to those observed in 2013 and 2015, with a smaller spread and lower values than the other years. The same data are summarized by site in Figure 35 for just the months of June – September, plotted from the headwaters (left) to the outlet (right). At individual sampling locations, mean summer concentrations in 2017 when all data (blue diamonds) versus low flow data (grey diamonds) are compared are generally similar. At three locations, low flow chlorophyll-a average summertime concentrations are visibly higher (W0767, W1779, and RMSL).

The mean summer (June – September) chlorophyll-a concentration for each year and sampling location on the Blackstone River are also summarized on Figure 36. Data are clustered by sampling site, again plotted from the headwaters (left) to the outlet (right). As already noted, chlorophyll-a concentrations tend to generally increase in the downstream direction, with average summertime concentration levels highest some years in RI and other years at the most downstream site in MA (W1779). In 2017, summertime chlorophyll-a levels were low compared to historical data near the outlet in RI (sampling sites R116 and RMSD) but relatively higher in the lower MA portion of the river (sampling sites W1242, W0767, W1779 and RMSL).

Average and maximum chlorophyll-a concentrations during low flows in 2012 – 2017 are compared to historical data during similar conditions in Figures 37 and 38, respectively. The data are again plotted from the headwaters (left) to the outlet (right). WWTF effluent discharge points along the river are indicated by the green triangles along the top of the graph, while the locations of FERC dams are indicated by the purple triangles. Along the bottom axis of the graph, purple X's denote the location of minor dams along the river. A solid black line with square symbols indicates the data for 2017. The highest average and maximum chlorophyll-a concentrations observed since 2012 at most sampling locations occurred in 2014.

The average chlorophyll-a concentration data for 2017, Figure 37, fall along the upper envelope of data on low flow days for the upper portion of the river, but define the lowest range of data for the two most downstream sampling locations, R116 and RMSD. While not as drastic, the maximum chlorophyll-a concentrations observed at each sampling location follow a similar trend in 2017 compared to historical data, Figure 38. Similar “opposite” differences for the MA and RI portions of the river were also observed in 2016 (green dash, double dot line) compared to 2012 – 2015 and historical data. In particular, the post-upgrade chlorophyll-a concentrations appear higher downstream of Rice City Pond than occurred prior to the upgrade. This also occurs, to a lesser extent, at other sites between mile 35 and 15 (+/-). Complex transport dynamics influenced by the federally licensed and minor dams along the lower portion, drier conditions associated with sampling dates in 2016 and 2017, and decreasing nutrient concentrations in WWTF effluent are all likely factors contributing to the observed decline in chlorophyll-a concentrations in recent years from the



MA to RI sampling sites. A detailed sampling study will be conducted in 2018 to try and understand the dynamics around Rice City Pond that may be contributing to these shifting conditions.

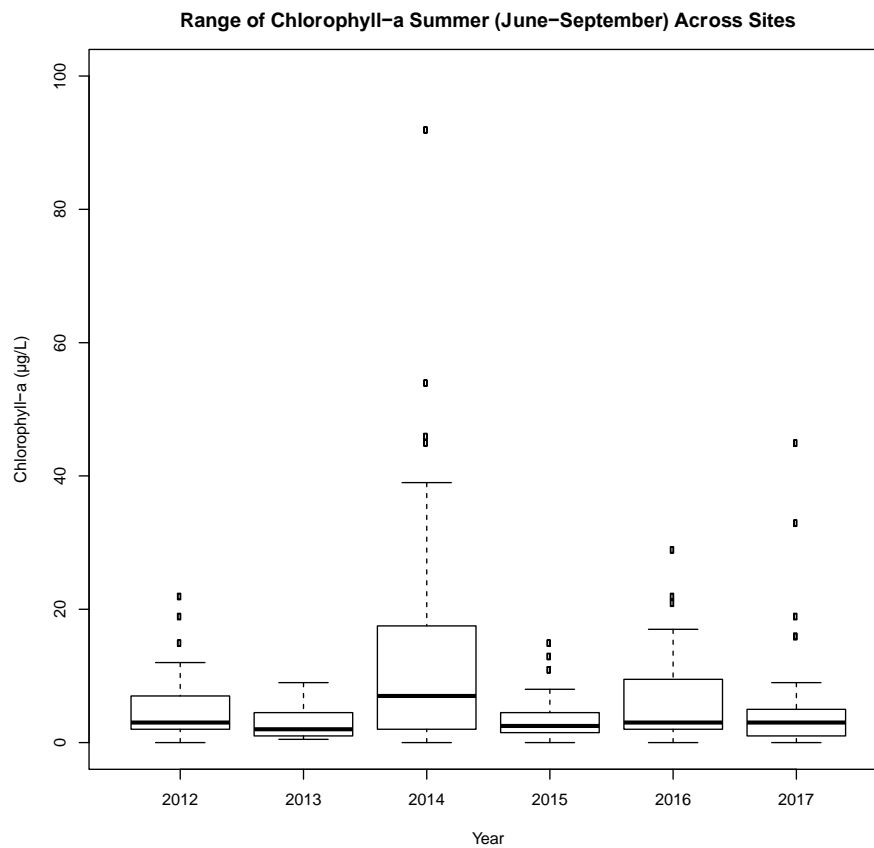


Figure 34: Chlorophyll-a concentrations observed during June, July, August, and September since 2012, summarized by year

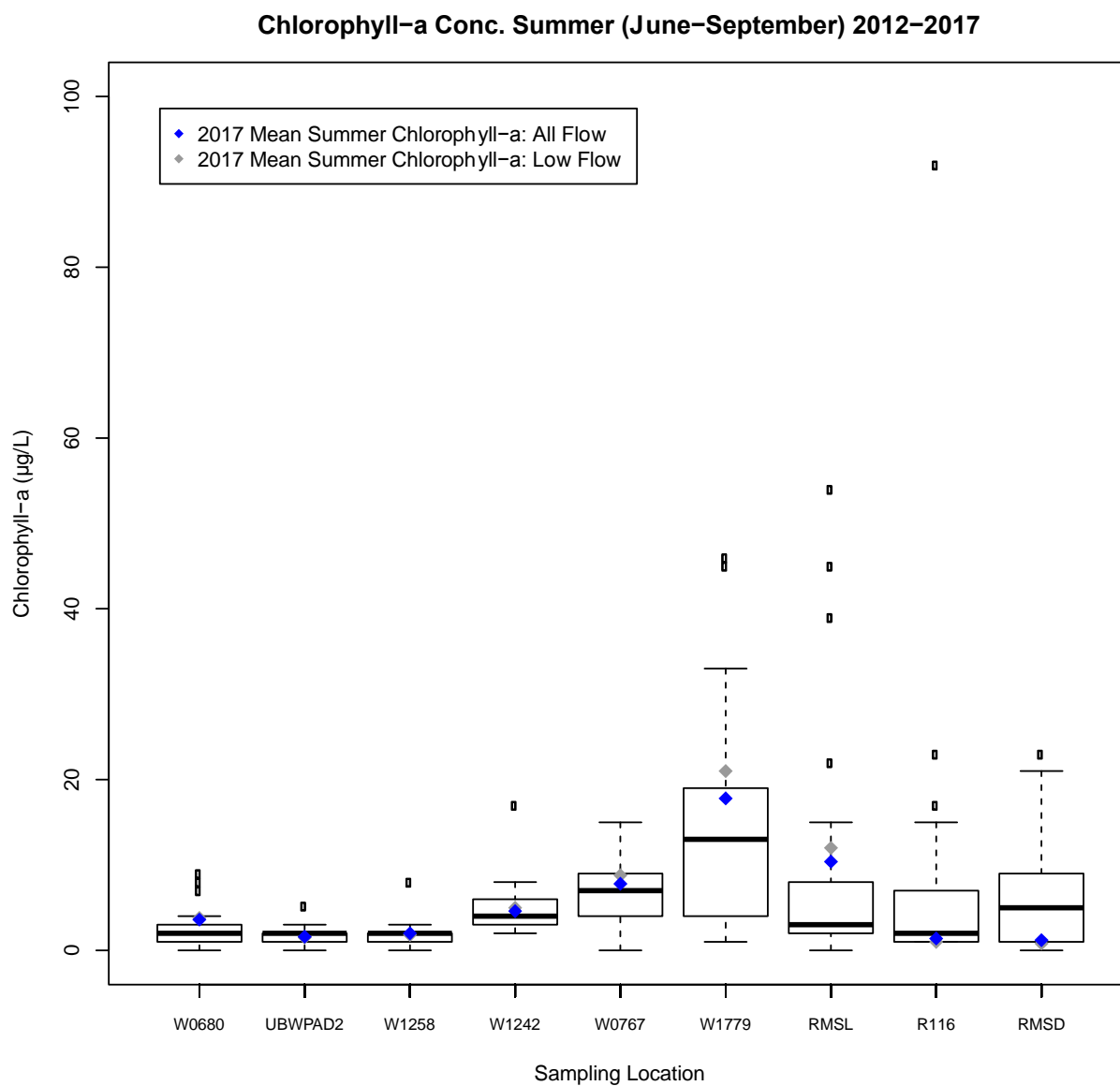


Figure 35: Chlorophyll-a concentrations observed during June, July, August, and September since 2012, summarized by sampling location

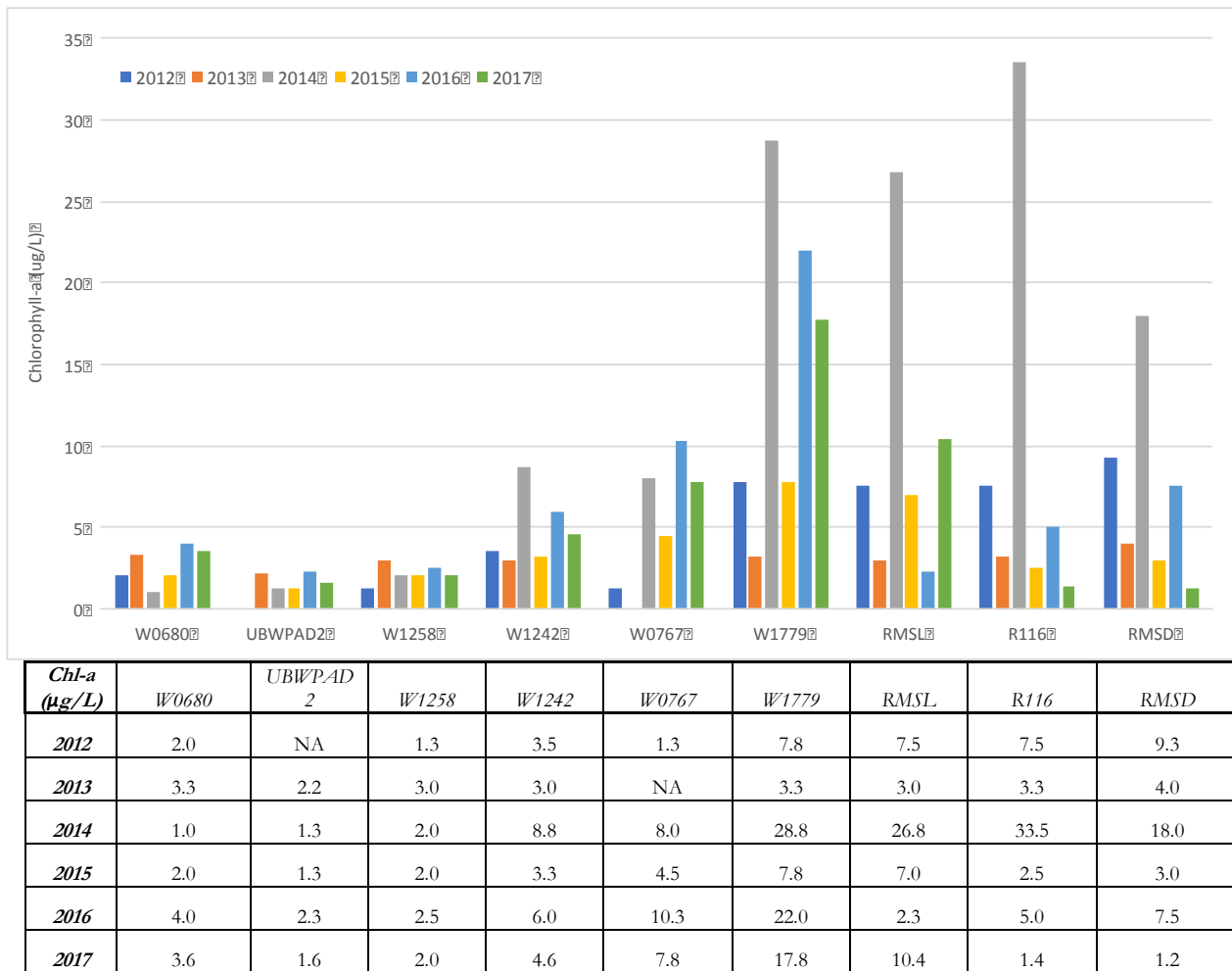


Figure 36: Mean summer (June – September) chlorophyll-a concentrations by site since 2012

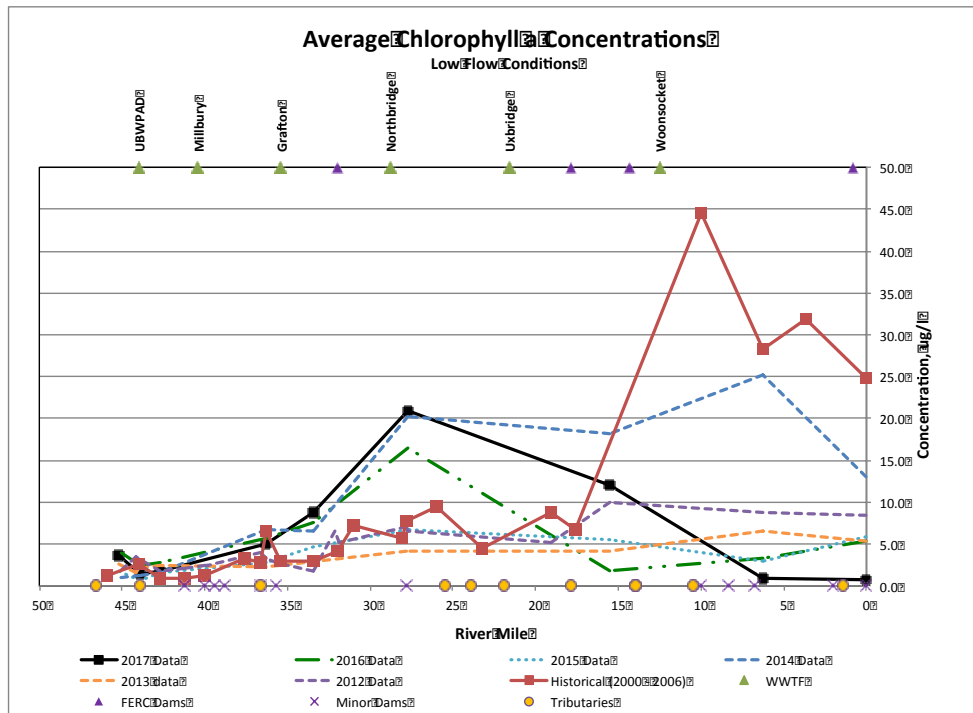


Figure 37: Along stream average chlorophyll-a levels on low flow days

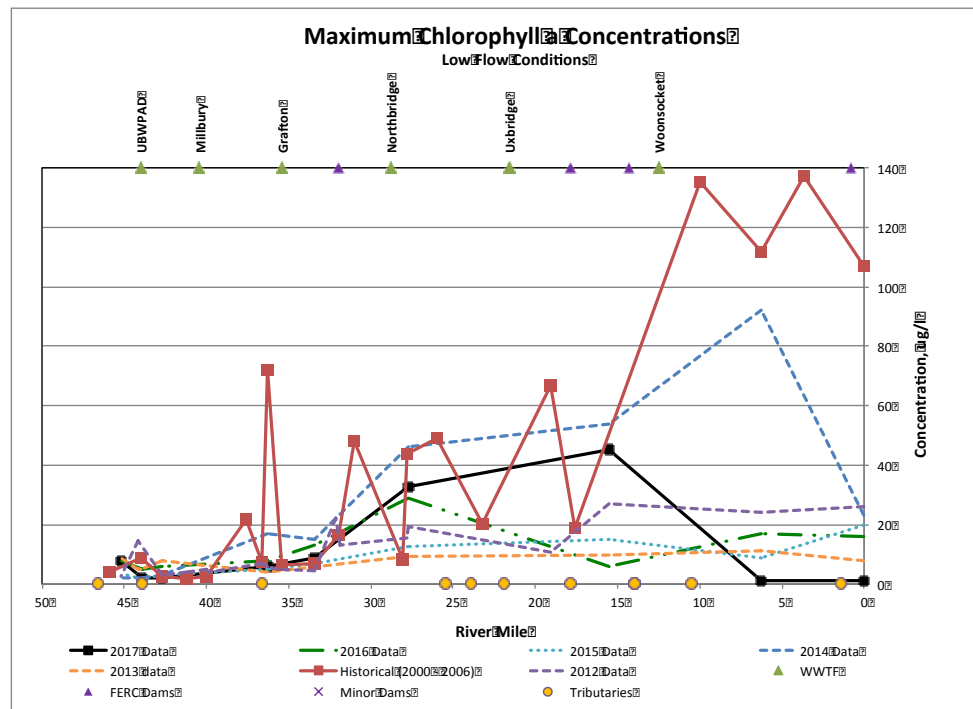


Figure 38: Along stream maximum chlorophyll-a levels on low flow days

In 2017, chlorophyll-a concentrations in the Blackstone River were below the MassDEP 2016 CALM screening threshold of 16 µg/L 96% of the time, Figure 39. The most excursions occurred at W1779, the sampling site below RCP at river mile 27.8, where only 3 of 9 samples (33%) were below the threshold. Compliance was 56% at the three sampling locations immediately downstream from the confluence, and 44% at the Sutton Street Bridge, the next sampling location (W0767) at river mile 33.4 (not presented in figure).

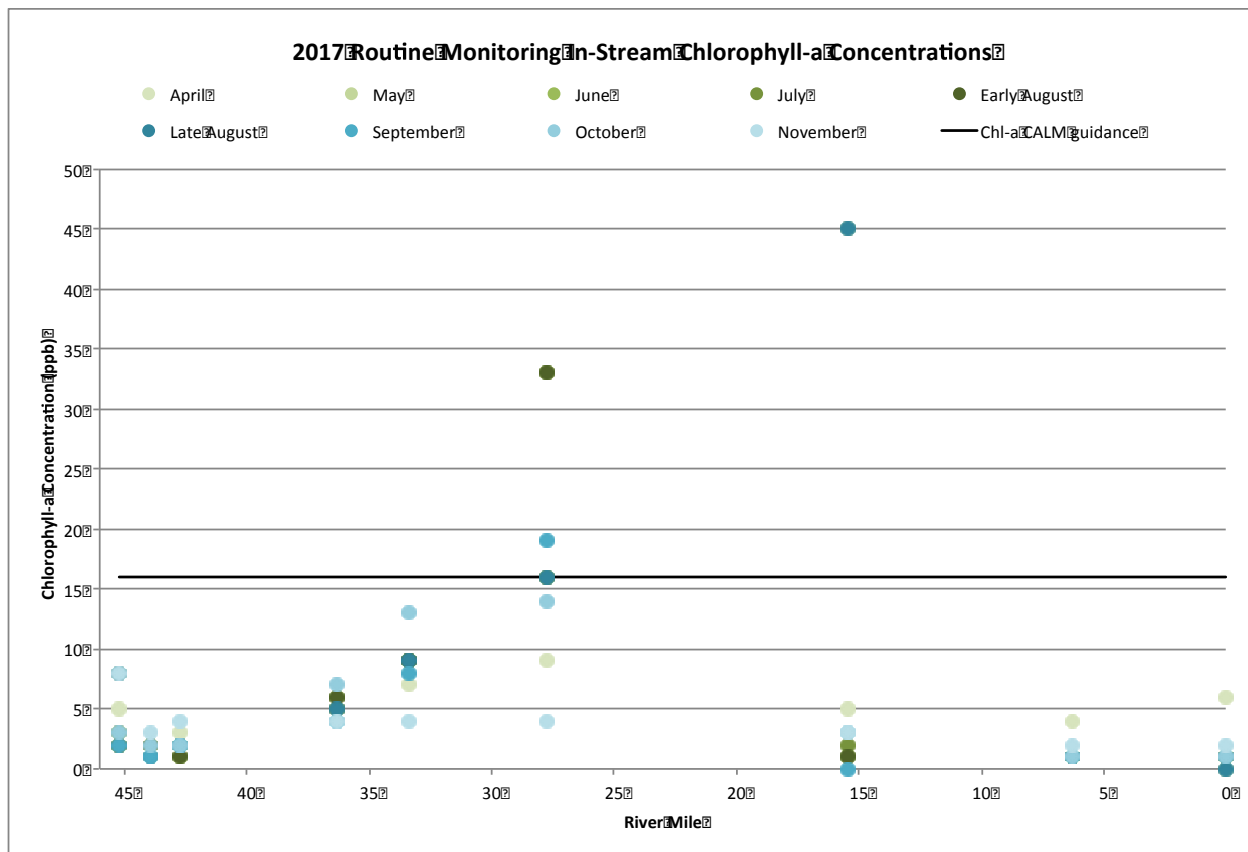


Figure 39: Along stream maximum chlorophyll-a levels on low flow days

#### 6.2.4. Flow-weighted concentration trend analysis

Correlations between flow and concentration make it difficult to identify trends in water quality without a more robust statistical analysis. However, flow-weighted concentrations, which account for differences in flow conditions, can be used to evaluate trends and to additionally account for the influence of location, season, or month on water quality. Flow-weighted concentration was calculated based on a locally weighted scatterplot smooth (LOWESS) between concentration and streamflow. Flow-weighted concentrations are the residuals (e.g., the absolute value of the difference between the observed concentration and the LOWESS smooth). Trends in water quality were then

evaluated using a seasonal Mann-Kendall test (Helsel, 2006) computed on the flow-weighted concentration data collected since 2012. The trend analysis was conducted for each site individually by season. While the data set is limited due to the length of record, sufficient data were available to complete the analysis at all sampling locations, Tables 21 - 23. The Mann-Kendall analysis becomes more robust as more data become available. The analysis found:

- When all sites are considered together, there is a statistically significant decreasing trend at the 99% significance level in both TP and TN flow-weighted concentrations when the data are analyzed accounting for either season or month.
- A subset of individual sites also exhibit statistically significant decreasing trends in flow-weighted TP concentration. Decreasing trends in TP are noted at the state line (RMSL) and Slater Mill Dam (RMSD) sampling sites when the data are blocked monthly (90% significance level) or seasonally (95% significance level). There is also a decreasing trend at the 90% significance level at Route 122, Grafton (W1242) when sampling month is accounted for in the analysis.
- Decreasing trends in TN flow-weighted concentration are observed at either the 95% or 99% significance level at all sites except for the Sutton Street Bridge in Northbridge (W0767) and the most upstream site, W0680, when the data are blocked monthly. When the data are blocked seasonally, no trend is observed below the Upper Blackstone effluent confluence with the river, site UBWPAD2, in addition to W0767 and W0680, and the significance level at several sites decreases.
- Increasing trends in seasonal flow-weighted chlorophyll-a concentration data are observed when the data are blocked by month and all sites are lumped together (99% significance level). Increasing trends when the individual site data are blocked either monthly or seasonally are also observed at site W1258, Central Cemetery in Millbury, MA (95% and 90% significance level based on monthly or seasonal blocking, respectively) and the most upstream site, W0680, at the New Millbury Street Bridge in Worcester, MA (99% and 95% significance level based on monthly or seasonal blocking, respectively).
- A decreasing trend in seasonal flow-weighted chlorophyll-a concentration data at the 95% significance level is observed at the most downstream site, Slater Mill Dam in Pawtucket, RI (RMSD) when the data are blocked seasonally.

Table 21: Flow-weighted seasonal trend analysis results for TP

Site	Type	Block	Trend	Significance
All	Flow-weighted TP	Site + Month	Negative	99%
RMSD	Flow-weighted TP	Month	Negative	90%
R116	Flow-weighted TP	Month	--	--
RMSL	Flow-weighted TP	Month	Negative	90%
W1779	Flow-weighted TP	Month	--	--
W0767	Flow-weighted TP	Month	--	--
W1242	Flow-weighted TP	Month	Negative	90%
W1258	Flow-weighted TP	Month	--	--
UBWPAD2	Flow-weighted TP	Month	--	--
W0680	Flow-weighted TP	Month	--	--
All	Flow-weighted TP	Site + Season	Negative	99%
RMSD	Flow-weighted TP	Season	Negative	95%
R116	Flow-weighted TP	Season	--	--
RMSL	Flow-weighted TP	Season	Negative	95%
W1779	Flow-weighted TP	Season	--	--
W0767	Flow-weighted TP	Season	--	--
W1242	Flow-weighted TP	Season	--	--
W1258	Flow-weighted TP	Season	--	--
UBWPAD2	Flow-weighted TP	Season	--	--
W0680	Flow-weighted TP	Season	--	--

Table 22: Flow-weighted seasonal trend analysis results for TN

Site	Type	Block	Trend	Significance
All	Flow-weighted TN	Site + Month	Negative	99%
RMSD	Flow-weighted TN	Month	Negative	95%
R116	Flow-weighted TN	Month	Negative	99%
RMSL	Flow-weighted TN	Month	Negative	95%
W1779	Flow-weighted TN	Month	Negative	99%
W0767	Flow-weighted TN	Month	--	--
W1242	Flow-weighted TN	Month	Negative	99%
W1258	Flow-weighted TN	Month	Negative	99%
UBWPAD2	Flow-weighted TN	Month	Negative	95%
W0680	Flow-weighted TN	Month	--	--
All	Flow-weighted TN	Site + Season	Negative	99%
RMSD	Flow-weighted TN	Season	Negative	95%
R116	Flow-weighted TN	Season	Negative	95%
RMSL	Flow-weighted TN	Season	Negative	90%
W1779	Flow-weighted TN	Season	Negative	95%
W0767	Flow-weighted TN	Season	--	--
W1242	Flow-weighted TN	Season	Negative	95%
W1258	Flow-weighted TN	Season	Negative	95%
UBWPAD2	Flow-weighted TN	Season	--	--
W0680	Flow-weighted TN	Season	--	--



Table 23: Flow-weighted seasonal trend analysis results for chlorophyll-a

Site	Type	Block	Trend	Significance
All	Flow-weighted chl-a	Site + Month	Positive	99%
RMSD	Flow-weighted chl-a	Month	--	--
R116	Flow-weighted chl-a	Month	--	--
RMSL	Flow-weighted chl-a	Month	--	--
W1779	Flow-weighted chl-a	Month	--	--
W0767	Flow-weighted chl-a	Month	--	--
W1242	Flow-weighted chl-a	Month	--	--
W1258	Flow-weighted chl-a	Month	Positive	95%
UBWPAD2	Flow-weighted chl-a	Month	--	--
W0680	Flow-weighted chl-a	Month	Positive	99%
All	Flow-weighted chl-a	Site + Season	--	--
RMSD	Flow-weighted chl-a	Season	Negative	95%
R116	Flow-weighted chl-a	Season	--	--
RMSL	Flow-weighted chl-a	Season	--	--
W1779	Flow-weighted chl-a	Season	--	--
W0767	Flow-weighted chl-a	Season	--	--
W1242	Flow-weighted chl-a	Season	--	--
W1258	Flow-weighted chl-a	Season	Positive	90%
UBWPAD2	Flow-weighted chl-a	Season	--	--
W0680	Flow-weighted chl-a	Season	Positive	95%

## 6.3 Periphyton Sampling

### 6.3.1. Sampling procedures and criteria

Normandeau Associates conducted periphyton sampling at four sites in July, August, and September of 2017. Three sampling sites (UBPWAD<sup>6</sup>, W1258, and Depot) are located in areas where the MassDEP conducted its periphyton sampling in 2008 (MassDEP and Beskeniss, 2009). Three of the sampling sites (W0680, UBWPAD, and W1258) correspond with routine monthly sampling locations. Periphyton sampling occurs along the reach upstream and downstream of the location where the routine monthly surface water sample is collected. Normandeau has conducted periphyton sampling at all four sites since 2012.

Sampling was conducted based on the MassDEP Standard Operating procedures (SOPs) for Percent Cover and Periphyton Collection Determinations. Sampling reaches were approximately 100 to 300 m long and were characterized by at least partially open canopy, riffle/runs, and a cobble bottom. At each location, samples from four parallel transects in riffle/run areas were collected.

<sup>6</sup> Periphyton sampling occurs along a stretch of the river that is representative of both routine sampling locations termed UBWPAD and UBWPAD2 and consistent with the MassDEP sampling location referred to as UBWPAD. Thus, the periphyton sampling location is simply termed UBWPAD, denoting this stretch.

Transects were spaced at least 5 meters apart and were selected to maintain habitat uniformity. Three sub-samples were collected from three cobbles, located on the left, middle, and right of each transect. A 1-inch diameter circle was scraped, scrubbed, and rinsed from each cobble utilizing a modified MassDEP sampling strip and SOP. The subsamples from transects 1 and 2 were combined into one composite sample, while subsamples from transects 3 and 4 were combined into a second composite sample, and each composite bottle was filled to 500 mL with bottled water. The collected scrapings were analyzed for chlorophyll-a content and reported as chlorophyll-a in mg/m<sup>2</sup>. The value reported for each composite is the average of three separate filter determinations (e.g., ~50 mL aliquots filtered, then the filters processed for analysis, and the results of the three aliquots averaged). The final number presented is the average of all six aliquots, or the average of the two composite samples.

High flow conditions prior to periphyton sampling dates can impact results due to scour. MassDEP guidance requires a no-sampling period of two to three weeks following high flow events with a potential to cause scouring to ensure adequate time for the algal community to re-establish so that representative densities are present during sampling. MassDEP guidance utilizes three times (3x) the median average monthly flow as the criteria for potential scour. Table 24 summarizes the 3x median average monthly flow values for the USGS Millbury gauge for the 2017 sampling season. The 3x median criteria utilized in 2017 were based on data from 2002 through 2016, as data for 2017 were not available.

The sampling team draws upon additional guidance from the literature as well as best professional judgment when making sampling decisions. Specifically, additional consideration is given to:

- Three times the annual or period of record, rather than three times the monthly median flow, as the metric for scour potential (see Biggs, 2000 and Clausen and Biggs, 1997)<sup>7</sup>. In 2017, this equated to a mean daily flow of 381 cfs at Millbury.
- Short periods of flow, rather than daylong or greater excursion, may also cause scour and impact periphyton densities. Data in the literature on the effects of flow velocity on biomass, however, are limited. One study in southeastern Australia suggests that flow velocities greater than 1.8 ft/s significantly impact filamentous chlorophytes (Ryder et al., 2006).
- In lieu of real-time velocity data, rough estimates of velocity calculated based on the observed discharge and stage at Millbury, paired with sampling reach width data collected by Normandeau, suggest that periphyton communities in the Blackstone River are acclimated to velocities associated with instantaneous flows up to ~400 cfs. Periphyton sampling preferentially does not take place for at least two weeks after an instantaneous flow value >400 cfs is recorded at Millbury.

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<sup>7</sup> The Millbury period of record mean daily value (updated through 2016) is 127 cfs, resulting in a 3x median value equal to 381 cfs for this guidance in 2017. These values shift slightly each year, as new data are added and the values updated.

- To provide extra protection, if at all feasible, the sampling team tries to allow for at least a two-week period between when instantaneous flows rise above ~250 cfs, roughly the average of the mean daily 3x median monthly values for July, August, and September.

Table 24: Monthly mean daily summer discharge (cfs) for the USGS Millbury gauge  
(Period of Record mean daily value = 127 cfs; 3x = 381 cfs)

Year	June	July	August	September
2002 <sup>a</sup>	NA	54.2	55.6	72.2
2003	303	96.2	125	100
2004	80.1	98.2	88.1	165
2005	107	136	63.1	78.7
2006	312	103	75.7	73.9
2007	136	77.3	52.5	54.3
2008	114	151	143	228
2009	146	396	157	79.4
2010	114	60.9	65.9	47.1
2011	202	92.9	273	340
2012	136	67.8	105	88.0
2013	434	105	85.2	81.8
2014	80.2	76.7	67.7	70.3
2015	164	95.7	59.9	71.7
2016	67.1	48.6	59.4	47.8
2017	177	89.0	58.5	57.5
<b>Average<sup>b</sup></b>	172	115	101	109
<b>Median<sup>b</sup></b>	136	96.0	80.5	79.1
<b>3xMedian<sup>b</sup></b>	408	288	241	237
<b>Minimum<sup>b</sup></b>	67.1	48.6	52.5	47.1

Note: <sup>a</sup> Data for 2002 were included as this is the earliest year included in the MassDEP evaluation of their 2008 data (Beskenis, 2009), however the June average is based only on 10 years of data as the June 2002 monthly average was not reported by USGS

<sup>b</sup> Summary calculations based on data through 2016

The flow criteria data for periphyton sampling described above are summarized graphically for the 2017 sampling season compared to observed flows and sampling dates on Figure 40. The mean daily data as observed at the USGS Millbury gauge are shown as orange dots, while the 15-minute flow data are shown by the solid blue line. A line representing the MassDEP sampling guidance criteria of 3x the median daily flow for the month is included on the figure (July - green, August - purple, and September - turquoise) for a two-week period prior to the periphyton sampling which occurred in that month, indicated by the purple crosses. The light blue, dotted horizontal line shown for the entire time period indicates 3x the median average daily flow for the period of record, while the red dashed line indicates the target instantaneous flow value of 250 cfs, both of which are more restrictive than conditions suggested by the MassDEP guidance. In addition, the number of days in each month when mean daily flow exceeded three times the period of record median mean daily value for the USGS Millbury gauge is summarized in Table 25. To further explore potential impacts of flow conditions on observed periphyton levels, antecedent rain, mean daily discharge, and daily instantaneous peak flow data are tabulated for 7 days prior to periphyton sampling in Table 26 for 2017. Key observations include:

- July 2017 sampling occurred 2 days after 0.88 inches of rainfall, causing mean daily flows to rise to 157 cfs (below the 3x median monthly flow criterion of 288 cfs for July) and instantaneous values to 403 cfs (above the instantaneous flow target of 250 cfs).
- August 2017 sampling met all antecedent flow criteria.
- September 2017 sampling began one week after mean daily flows rose to 236 cfs (below the 3x median monthly flow criteria of 237 cfs for September) and instantaneous values reached 565 cfs (above the instantaneous flow target of 250 cfs).

In summary, in 2017 flows for two weeks prior to all three periphyton sampling events fell below the 3x median daily monthly flow criterion set by MassDEP. However, instantaneous flows rose above the 250 cfs target level set by the sampling team a few days prior to the July sampling event, and one week prior to the September sampling event. While these excursions may have resulted in some scour, overall periphyton sampling during 2017 are reflective of the best sampling opportunities available based on precipitation and flow conditions.<sup>8</sup>

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<sup>8</sup> For comparison purposes, figures and tables for flow conditions in 2012, 2013, 2014, 2015, and 2015 are provided in Appendix C and D.

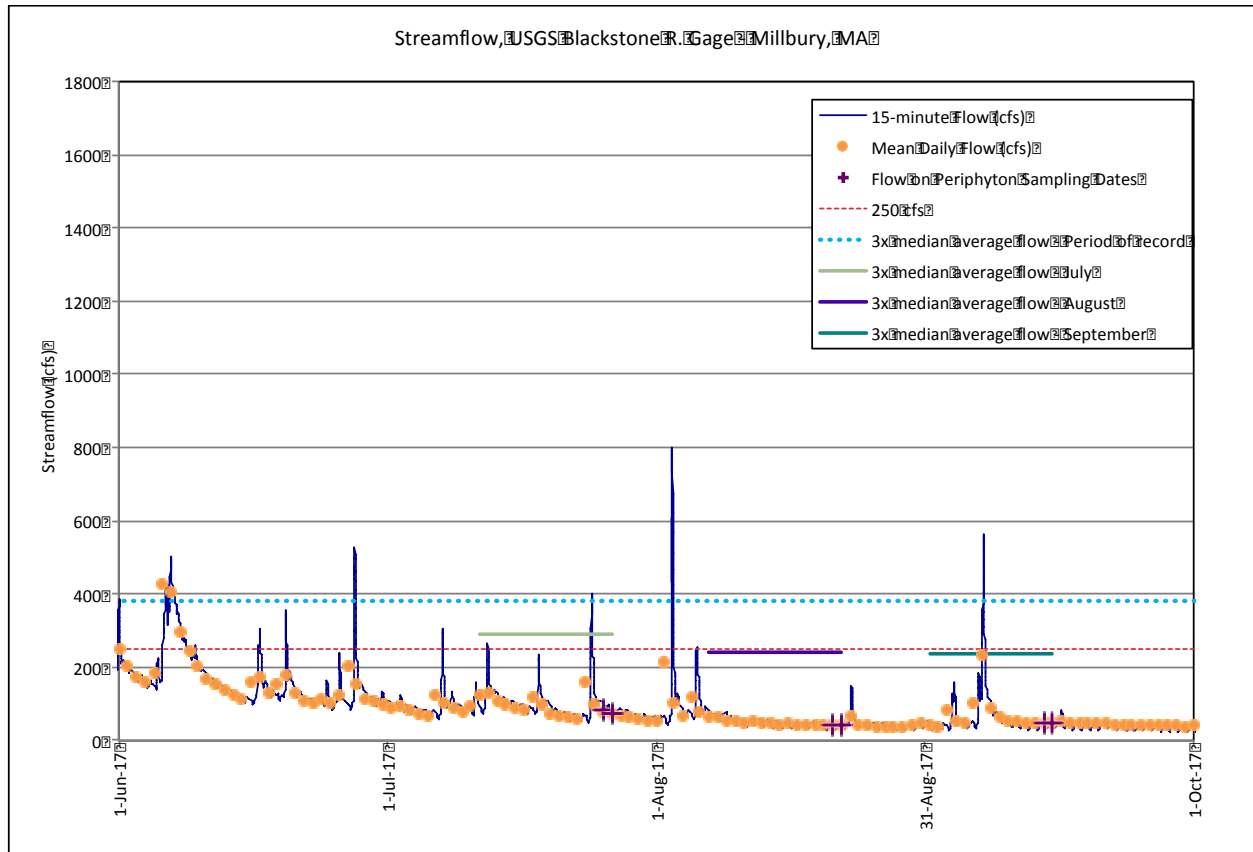


Figure 40: Summary of 2017 flows relative to periphyton sampling

Table 25: Number of days mean daily flow at Millbury exceeded 3x the period of record median

Year	June	July	August	September
2002	NA	0	0	0
2003	3	0	1	1
2004	0	1	0	4
2005	0	2	0	0
2006	8	0	0	0
2007	0	0	0	0
2008	1	1	0	2
2009	1	10	1	0
2010	0	0	0	0
2011	2	0	6	6
2012	0	0	1	0
2013	12	0	0	0
2014	0	0	0	0
2015	2	1	0	1
2016	0	0	0	0
2017	2	0	0	0

Table 26: 2017 periphyton sampling antecedent rain and discharge conditions

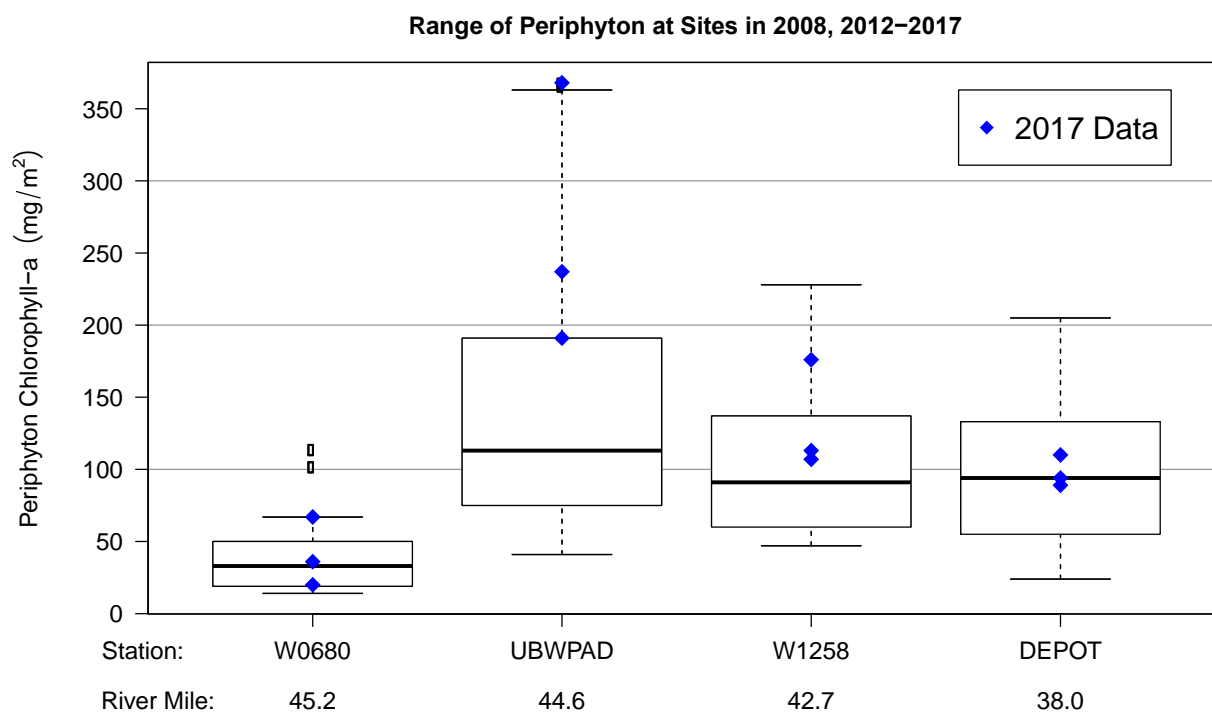
2017 Date	Daily Precipitation, Worcester, MA (inches)	Mean Daily Discharge (cfs) – Millbury, MA	Peak Daily Discharge (cfs) – Millbury, MA
July 19	0.00	99.3	129
July 20	0.00	75.2	96.0
July 21	0.00	66.5	80.8
July 22	T	61.6	75.3
July 23	0.00	57.4	71.3
July 24	0.88	157	403
July 25	0.01	97.0	140
July 26	0.00	80.5	101
July 27	0.09	72.8	89.7
August 14	0.00	47.0	54.6
August 15	0.02	44.9	52.4
August 16	0.00	45.8	52.4
August 17	0.00	43.4	51.4
August 18	0.00	43.5	51.4
August 19	0.05	43.9	51.4
August 20	0.00	41.1	51.4
August 21	0.00	41.7	49.4
August 22	0.08	42.0	52.4
September 7	0.31	236	565
September 8	0.00	86	104
September 9	0.00	62.8	67.4
September 10	0.00	54.2	56.8
September 11	0.00	51.6	53.5
September 12	0.00	48.9	50.4
September 13	0.00	47.9	48.4
September 14	0.01	48.0	49.4
September 15	0.01	49.5	71.3

Note: <sup>a</sup> Periphyton sampling dates are shaded

### 6.3.2. *Periphyton survey results*

Periphyton survey results from 2012 - 2017<sup>9</sup> are presented in Figure 41 as a simple boxplot, including the 2008 MassDEP data, and tabulated in Table 27. Periphyton levels in 2017 spanned a wide range of the historical data at the most upstream site, W0680, were on the higher end of observed data at the UBWPAD and W1258 transects, and were about average compared to historical data at Depot Street.

Figure 41: Range of periphyton chlorophyll-a at sampling sites in 2008, 2012 - 2017



<sup>9</sup> In 2014, periphyton sampling was also conducted in June.

Table 27: Available periphyton chlorophyll-a data for the Blackstone River

Month	Site	Periphyton (Chlorophyll-a mg/m <sup>2</sup> )						
		2008 <sup>a</sup>	2012	2013 <sup>b</sup>	2014	2015	2016	2017
June	W0680	--	--	--	24	--	--	--
	UBWPAD	--	--	--	75	--	--	--
	W1258	--	--	--	110	--	--	--
	Depot	--	--	--	24	--	--	--
July	W0680	--	--	33 and 18	133	30	102	20
	UBWPAD	65	--	84 and 58	119	83	363	191
	W1258	51	--	59 and 78	62	59	137	107
	Depot	26	--	--	133	77	205	94
August	W0680	--	15	14	107	23	60	36
	UBWPAD	--	41	42	189	113	366	237
	W1258	--	82	47	141	76	169	113
	Depot	--	37	--	107	55	178	89
September	W0680	--	15	14	149	39	114	67
	UBWPAD	138	90	71	190	89	313	368
	W1258	105	59	60	168	91	228	176
	Depot	110	34	--	149	79	139	110

Notes: <sup>a</sup> Data collected by MassDEP (MassDEP and Beskenis, 2009)

<sup>b</sup> In 2013, periphyton was sampled twice in July, once in early July and once in late July

Boxplots of the periphyton chlorophyll-a data separated by site and year are presented in Figure 42. Periphyton chlorophyll-a levels dropped in 2017 compared to 2016, which was generally characterized by the highest observed levels since sampling began. The most elevated levels in 2017 occurred downstream from the confluence, at the UBWPAD site. MassDEP utilizes 200 mg/m<sup>2</sup> as the target maximum periphyton chlorophyll-a level in rivers. All data collected in 2012 through 2015 fall below this target level, but values above the target level were observed in 2016 and 2017. In 2017, excursions above the 200 mg/m<sup>2</sup> target were limited to the August and September data at the UBWPAD sampling transects.

Boxplots of the periphyton chlorophyll-a data separated by site and month are shown in Figure 43, with the 2017 sampling results noted with blue diamonds. Timing of maximum levels during the summer season varies from year-to-year and site-to-site, Table 27 and Figure 43, but occurs in either August or September. The September 2017 periphyton chlorophyll-a level measured at the UBWPAD site was the highest observed since the start of sampling.



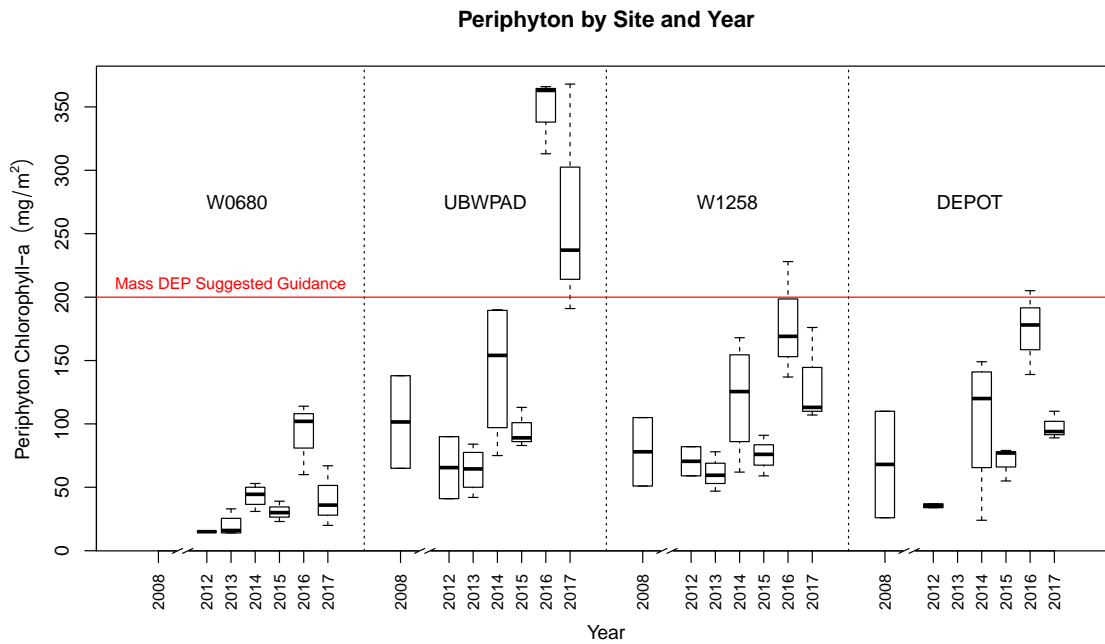
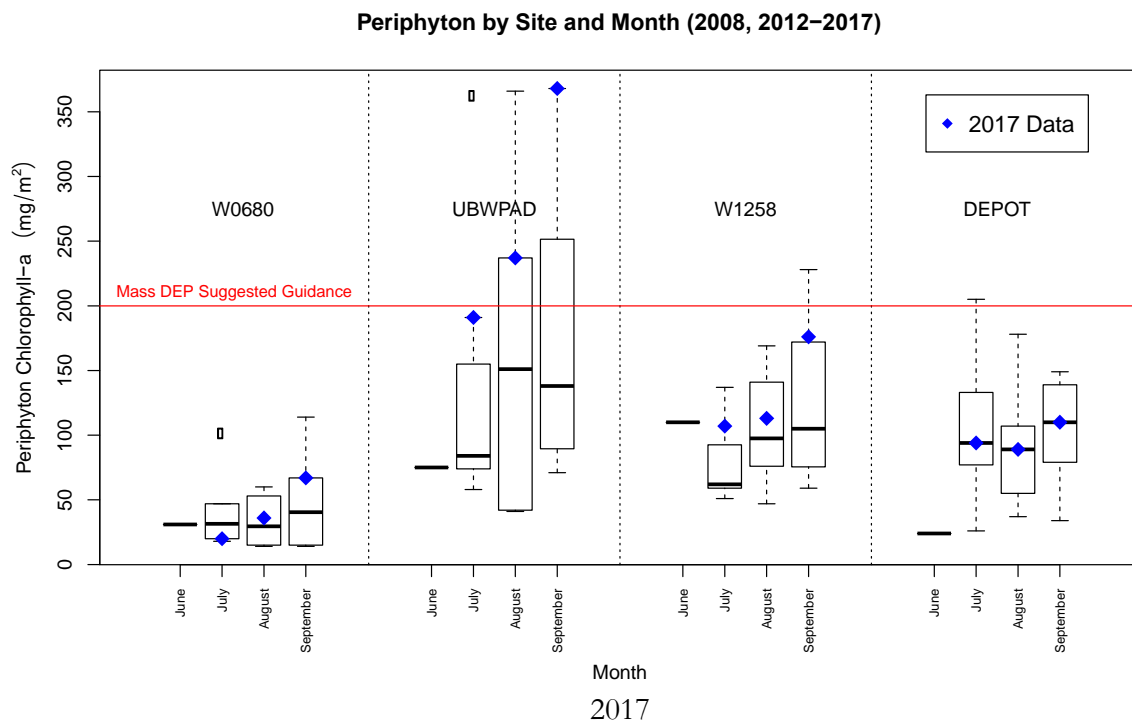


Figure 42: Summary of available periphyton chlorophyll-a data by sampling site and year

Figure 43: Periphyton chlorophyll-a concentrations by sampling site and month 2008 and 2012 -



Starting in 2014, water column samples were collected at the time of periphyton sampling and analyzed for TP and chlorophyll-a, Table 28. Nutrient levels in the stream may influence periphyton growth, however similar in-stream TP concentrations can have very different corresponding periphyton chlorophyll-a concentrations, Figure 44, suggesting that other factors also influence algal growth. In this figure, data points representing the observed periphyton levels at the UBWPAD periphyton sampling location are highlighted. Points falling along the same horizontal line are characterized by the same periphyton chlorophyll-a levels, but are characterized by different water column TP concentrations. For example, periphyton chlorophyll-a levels greater than 350 mg/m<sup>2</sup> have been observed three times, twice in 2016 and once in 2017. However, the corresponding water column TP concentrations varied from 171 to 341 ppb. Mean summertime (June – September) TN and TP concentrations (earlier Figures 20 and 27) provide information on the longer-term availability of nutrients during the periphyton growing season. Data are available for three of the periphyton monitoring sites, W0680, UBWPAD, and W1258. The highest average June - September TN and TP concentrations observed occurred in 2014, however the highest observed periphyton chlorophyll-a concentrations were observed in 2016 and 2017. Nutrient availability is only one of several environmental conditions that may impact periphyton growth.

Table 28: Available water column Chlorophyll-a and TP data collected during the week of periphyton sampling

Month	Site	Water Column Chlorophyll-a (ppb)				Water Column TP (ppb)			
		2014	2015	2016	2017	2014	2015	2016	2017
June	W0680	3	--	--	--	47	--	--	--
	UBWPAD	1	--	--	--	171	--	--	--
	W1258	3	--	--	--	109	--	--	--
	Depot	1	--	--	--	107	--	--	--
July	W0680	2	1	4	4	39	51	75	60
	UBWPAD	1	1	4	1	121	167	341	212
	W1258	2	2	3	1	103	89	213	126
	Depot	3	1	4	2	85	240	165	89
August	W0680	2	4	3	3	--	48	50	36
	UBWPAD	2	2	2	2	--	147	202	134
	W1258	2	2	3	6	--	134	171	143
	Depot	3	3	6	3	--	102	147	129
September	W0680	1	2	2	1	20	16	44	28
	UBWPAD	2	1	1	1	280	164	171	183
	W1258	1	1	1	1	320	117	155	137
	Depot	3	5	3	2	320	71	137	118

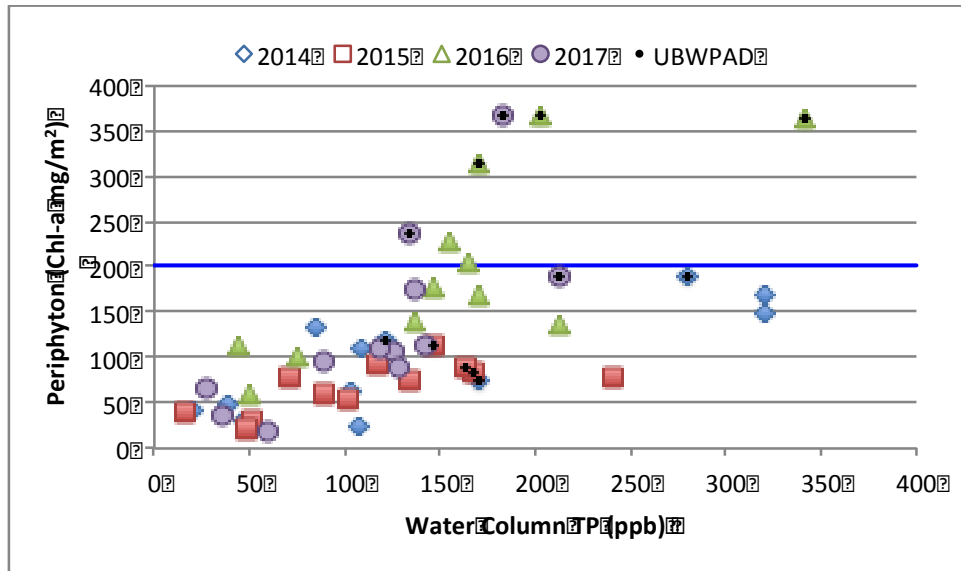


Figure 44: Measured periphyton chlorophyll-a concentrations in 2014 - 2017 plotted against water column TP concentration. Data for the UBWPAD periphyton monitoring location are noted.

#### 6.4 In-Situ Temperature and Dissolved Oxygen Monitoring

In 2017, MassDEP offered to install continuous temperature (T) and dissolved oxygen (DO) probes in the Blackstone River to augment existing data collection efforts by Upper Blackstone. Continuous meters were deployed at the four periphyton sampling locations: one upstream (W0680) and three downstream of the Upper Blackstone effluent discharge location (UBWPAD, W12580, and DEPOT). The four meters were calibrated and deployed by MassDEP. Calibration measurements were collected approximately monthly using a calibrated hand-held T/DO probe by UMass and Normandeau staff throughout the deployment period, while the last in-situ calibration measurement was taken by MassDEP the day before the meters were removed. The continuous meters were not cleaned or recalibrated during the five-month monitoring period. All four meters were deployed on June 2, 2017 and removed on November 2, 2017.

As continuous monitoring was not originally planned for the 2017 period, it is not covered in the current QAPP, valid for the 2017 – 2019 monitoring program. However, continuous monitoring was included in the 2014 – 2016 QAPP (UMass and CDM Smith, 2015). Therefore, the continuous metering results were assessed using the guidance of the 2014-2016 QAPP, which specifies:

Data will be corrected for drift as per USGS guidelines by collecting a paired reading from an identical, freshly calibrated hand-held unit [...] The resulting offset will be used to apply a linearly increasing correction factor to the data as necessary.

CDM Smith conducted the data correction procedures and an assessment of the data. This report is available under separate cover and is also included as Appendix E in this document.

A summary of the continuous DO data compared to MA water quality standards and guidance is provided in Table 29. The data were recorded at 30-minute intervals and the percent of time or number of days the data did not meet the water quality criteria is indicated. The percentages are calculated as the actual number of 30-minute data intervals either below 5 mg/L or above 125% saturation compared against the total number of valid 30-minute data intervals. The days where the diel change in dissolved oxygen exceeds 3 mg/L was calculated as a count of the number of days where the difference between the minimum and maximum measurement on that day exceeded 3 mg/L. Observed DO data was in compliance with the MA DO standard of 5 mg/l nearly all of the time, with occasional non-compliance at the UBWPAD2 station. The data were in compliance with DO percent saturation guideline of < 125% saturation at all sites and all days of valid data. There were a handful of days at three of the four meters (W0680, UBWPAD2, and W1258) where diel (diurnal) variation in DO exceeded guidelines.

Table 29: Compliance of observed continuous DO data with MA DO standards

Metric	W0680	UBWPAD2	W1258	MID2 (Depot)
Days of valid data	139	62	38	139
% of the time DO < 5.0 mg/L [MA Class B Standard]	0.3%	4.8%	0.6%	0%
% of the time DO > 125% saturation [2016 CALM guidance]	0%	0%	0%	0%
Days where diel $\Delta$ DO > 3.0 mg/L [2016 CALM guidance]	4	6	14	4

## 7.0 Discussion

A combination of factors, including temperature, exposure to sunlight, flow, nutrient availability on the days preceding routine sampling, and along-stream transport dynamics likely contribute to the observed year-to-year differences in water column chlorophyll-a and periphyton levels.

While TP summer concentrations were about average at most sampling sites, 2017 summertime TN concentrations were on the low end of observed data and may have been a factor limiting growth along the lower stretches of the river. As an initial evaluation of possible impacts of shifting N:P ratios on productivity, trends in the ratio of TN to TP on routine sampling dates from 2012 to 2017 were examined. Figure 45 summarizes these data by sampling site and year. Two horizontal lines are included on the figure, one at an N:P ratio of 16, reflecting the Redfield<sup>10</sup> ratio, and one at 29, representing an N:P level noted in the literature as a level where algal biomass shifts may occur. Based on this initial analysis, no clear linkages can be drawn between observed water column chlorophyll-a levels and trends in N:P ratio by site or year. For example, the highest observed chlorophyll-a levels in the river occurred in 2014 at all sites, however the N:P ratio compared to other years is not consistently higher or lower in 2014. As another example, in 2017 the highest chlorophyll-a levels occurred at W1779, but the N:P ratios at W1779 were the lowest observed across the sites. More in-depth exploration of the data is necessary to elucidate any potential impacts of shifting N:P ratios on productivity.

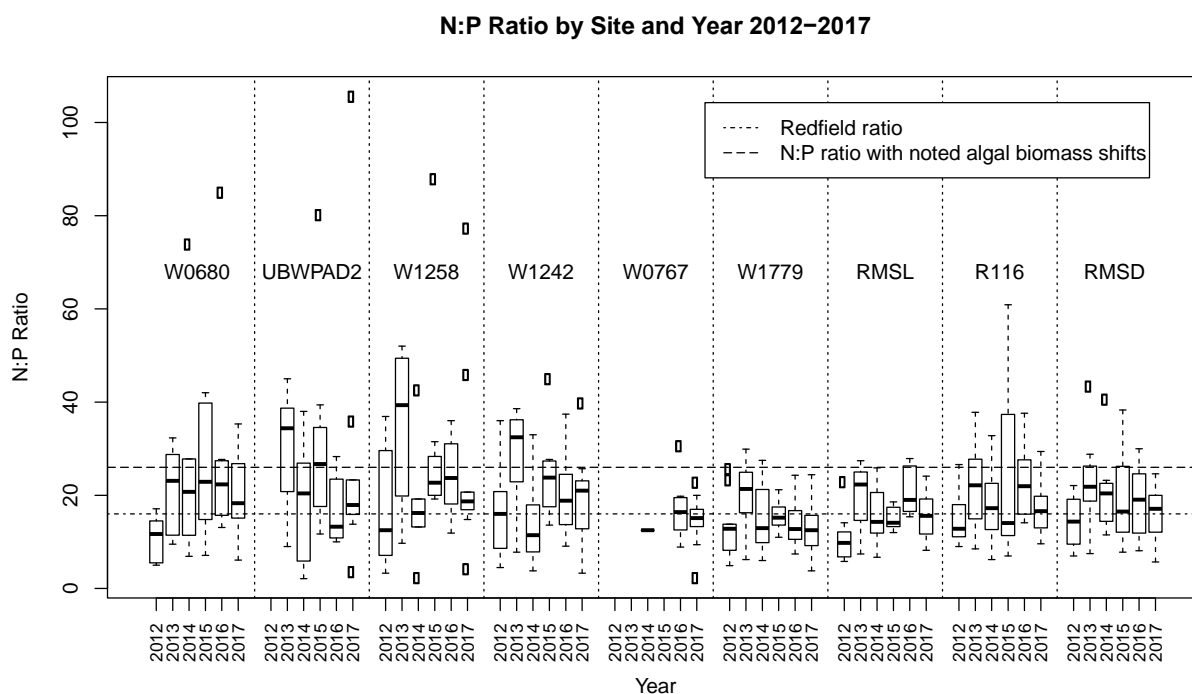


Figure 45: Shifts in N:P Ratios by site and year, 2012 - 2017

<sup>10</sup> The plotted data are for TN: TP while the Redfield ratio is actually for total nitrogen to phosphate.

River flows on low flow sampling days in 2017 were the lowest observed since routine sampling began in 2012. The relative impact of low flows versus TP levels on periphyton growth was explored with a series of three-way, or 3D, plots. Figure 46 shows the relationship between observed periphyton chlorophyll-a levels, mean flow over the 7 days prior to sampling, and mean effluent TP load over the 7 days prior to sampling. Figure 47 shows the relationship between observed periphyton chlorophyll-a levels, mean flow over the 7 days prior to sampling, and mean water column TP concentration over the 7-days prior to sampling. Based on these figures there appears to be a strong correlation between periphyton chlorophyll-a levels in exceedance of 200 mg/m<sup>2</sup>, mean 7-day prior flows less than 60 cfs, and water column TP concentrations greater than 130 ppb. All periphyton samples collected at the UBWPAD station (circles) associated with 7-day mean flows less than 60 cfs and TP concentrations greater than 130 ppb exceeded the suggested MassDEP guidance for periphyton. The only exceedances noted for sampling sites located farther downstream at W1258 and Depot occurred when 7-day mean flows were even lower, below ~50 cfs.

Complex river hydrodynamics make it impossible to fully understand the impacts of rainfall, other wastewater facilities, and nonpoint source wet weather contributions of nutrients to the river based on data from the current sampling scheme alone. A more comprehensive sampling scheme would need to be devised in order to better understand such influences, including temporal sampling during wet weather events, and targeted spatial sampling to identify contributions from additional sources. In order to better understand when discharge from the Upper Blackstone becomes comparatively less important to overall water quality, ideally a sampling metric that provides a “signature” of the treatment plant should be identified. In addition, hydraulic modeling is necessary to understand the complexities of along stream transport dynamics, including influence of the dams on downstream delivery of nutrients. An extension of the current HSPF model, facilitating its use through the most recent sampling season, would provide such insight.

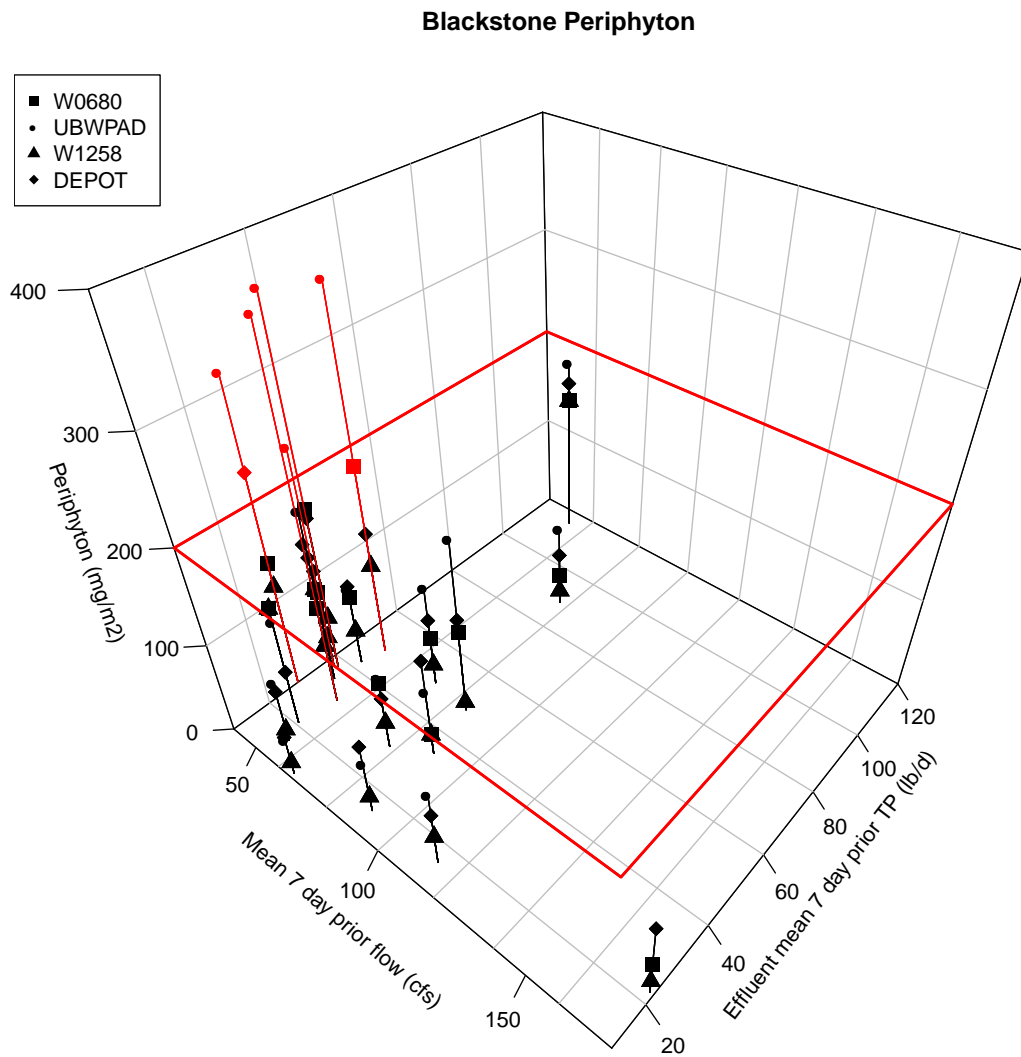


Figure 46: Relationship between periphyton chlorophyll-a levels, 7-day mean flow prior to sampling, and 7-day mean effluent load prior to sampling

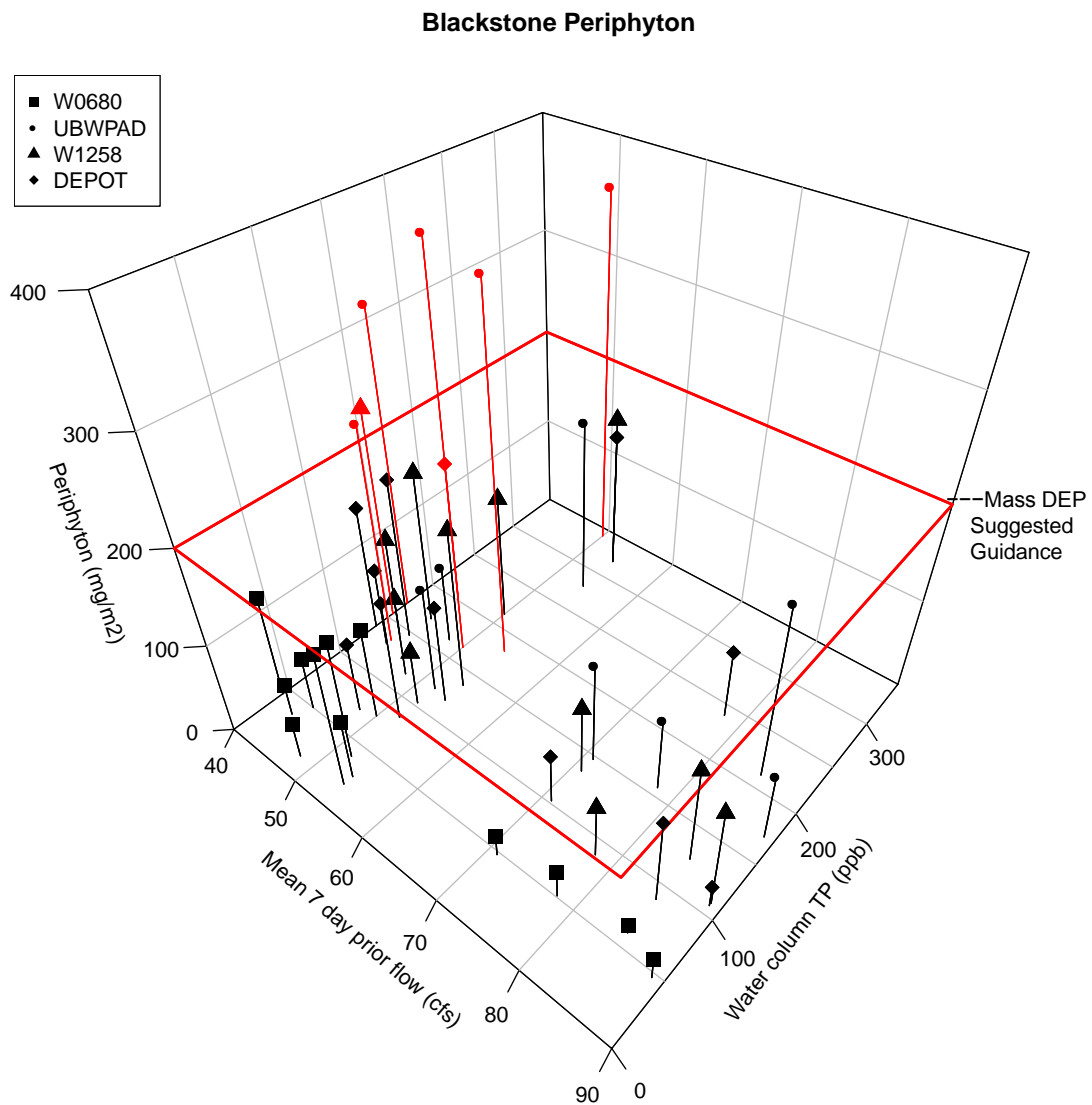


Figure 47: Relationship between periphyton chlorophyll-a level, 7-day mean flow prior to sampling, and water column TP concentration on the day of sampling



## 8.0 Summary

Upper Blackstone has conducted water quality monitoring and periphyton sampling since 2012. This report presents the 2017 field data. In addition, trends in water quality and the potential impacts of flow and effluent concentrations on in-stream river water quality are examined. Review of the sampling results indicates:

- Upper Blackstone continues to refine its treatment process to minimize nutrient loads and daily variability, particularly in the summer months. The facility performed well against its seasonal nutrient limits in 2017. TN concentrations and loads from the plant were higher than average from November to April, when there are no numeric TN limits, which contributed to the highest annual TN effluent load observed during the period 2012 – 2017.
  - The percent reduction in yearly TN and TP effluent load in 2017 compared to plant performance 2006 – 2008 was 34% and 85%, respectively.
  - Effluent average summertime (June - September) TP daily loads in 2017 were the lowest observed since plant upgrades went online in 2010, and TN daily loads were the second lowest.
  - Overall, summertime daily average TN effluent concentrations were slightly elevated in 2017 compared to 2016, but lower than earlier years, while summertime daily average TP effluent concentrations were the lowest observed since the plant upgrade in 2009.
    - Upper Blackstone facility average April – October permit season TP effluent concentration was similar in 2017, 2016, 2015 and 2013. The average winter (November – March) permit season TP effluent concentration in 2017 was double that of 2013 – 2015 but lower than in 2016.
    - Upper Blackstone facility average April – October permit season TN effluent concentration was also similar to prior years, but higher than in 2016. However, the average winter permit season TN effluent concentration was the highest observed since 2012.
    - The interquartile range of summertime effluent concentrations remained tight for both TN and TP, indicating strong control of the treatment process.
- Air temperatures in 2016 – 2017 were quite variable in comparison to historic data, following no systematic trend. The impact of temperature on in-stream productivity is not clear; water temperature data are likely more important but inconsistent availability of data since 2012 makes this difficult to assess.
  - Spring air temperatures were variable, with periods both below and above normal monthly temperatures.
  - Air temperatures in June were at the upper quartile of observed data.
  - Air temperatures in July and August were cooler than average

- Warmer than normal air temperatures were observed in September and October.
- Periphyton levels in exceedance of the 200 mg/m<sup>2</sup> CALM guidance were associated with stream water temperatures above 23° C.
- High rainfall in April – June in 2017 may have helped moderate productivity in the river during the month of July; however, 7-day and 30-day average Q values were notably lower throughout much of August and September compared to 2012 - 2015, likely contributing to elevated periphyton levels during these months in 2017.
  - The winter of 2016 - 2017 was about average in terms of snowfall.
  - In terms of precipitation, the total accumulation of 45.6 inches in 2017 at Worcester was just slightly below the long-term average from 1949 to 2017 of 47.6 inches; however, monthly accumulations were quite variable. Rainfall in April through June was above normal, followed by low monthly totals in July – September. October was comparatively wet.
  - Calculations based on the average of daily contributions suggest that in 2017, effluent comprised approximately 50% of the river flow at Millbury from June through September 2017. Effluent contributions to summertime (June – September) flows have varied from 33% to 65% since 2003.
  - In 2017, only July, August, and September were characterized as low flow sampling days.
  - Low mid-to-late summer precipitation was reflected in lower than average flows in July – September at Millbury and in August – September at Woonsocket.
    - While flows were not as low as during the 2016 sampling season, which was the driest summer season sampled to date by Upper Blackstone’s routine monitoring program (2012 – 2016), the minimum 7-day average flow at Millbury in 2017 was 40 cfs, the second lowest since 2012 (lowest 7-day average was 37 cfs in 2016), and occurred in early October.
    - In terms of biological activity, low flows provide conditions amenable for plant growth with high penetration of light through the water column and reduced dilution of the available nutrients.
- In-stream TP and TN levels in the river in 2017 show continued improvement. In-stream TP concentrations were below the Massachusetts CALM guidance of 100 ppb 65% of the time.
  - Average water column TP and TN concentrations in 2017 fell within the interquartile range of values observed since 2012 at all sampling sites. For TN, the values fell below 2012 – 2017 median levels at all sites.
  - TP and TN loads observed in the river that were associated with “low” flow sampling events were amongst the lowest observed at all sites since sampling began in 2012.

- Trends in water quality were evaluated using a seasonal Mann-Kendall test computed on flow-weighted TP and TN data collected since 2012.
  - Decreasing TP trends were noted when accounting for either season or month at 2 sites (RMSL and RMSD) and when accounting for sampling month (but not season) at W1242.
  - Decreasing TN trends were noted at all sites *except for* W0767 and W0680 when accounting for month and at all sites *except for* W0767, UBWPAD2, and W0680 when accounting for season.
- Chlorophyll-a concentrations were below the CALM guidance of 16 µg/L 96% of the time in 2017. However, trend analysis of the data collected since 2012 suggests that overall chlorophyll-a levels are increasing slightly. This trend is not consistent across sites. Chlorophyll-a levels in 2017 at the two most downstream sites were the lowest observed since routine sampling began in 2012, and a statistically significant decreasing trend is evident at the most downstream site when data are blocked by season.
  - In general, summertime chlorophyll-a levels in 2017 exhibited an interquartile range comparable to those observed in 2013 and 2015 and were characterized by a smaller spread and lower values than in 2012, 2014, and 2016.
  - Average summer chlorophyll-a levels were elevated compared to other years at W0767, just below Rice City Pond (W1779) and the state line (RMSL). Maximum sampling season chlorophyll-a concentrations in 2017 at W1779 and RMSL were only lower than previously observed during the 2014 sampling season.
  - Average and maximum summer chlorophyll-a levels were the lowest observed since 2012 at the two sampling sites in RI (R116 and RSMD).
  - Trends in water quality were evaluated using a seasonal Mann-Kendall test computed on flow-weighted chlorophyll-a concentration data collected since 2012.
    - An increasing trend at the 99% significance level was observed when the data are blocked by month and all sites are lumped together.
    - Decreasing trends in chlorophyll-a were noted when accounting for season at the most downstream site, Slater Mill Dam (RMSD).
    - Increasing trends in chlorophyll-a were observed at W1258 and W0680 when accounting for season.
- Periphyton chlorophyll-a levels were below the CALM guidance of 200 mg/m<sup>2</sup> 83% of the time in 2017.
  - MassDEP utilizes 200 mg/m<sup>2</sup> as guidance for “nuisance levels” of periphyton chlorophyll-a based on the literature (MassDEP, 2009; NEIWPCC, 2001). Data collected in 2012 through 2015 fall below this target level, but the August and September 2017 samples collected at the

site downstream from the confluence exceeded this target level. Concentrations above 200 mg/m<sup>2</sup> were also observed in 2016.

- Water column TP concentrations when periphyton chlorophyll-a levels greater than 200 mg/m<sup>2</sup> have been observed have typically been above 130 ppb; however, environmental conditions such as river flow conditions, air and water temperatures, and light penetration also influence growth.
- The years 2014, 2015, 2016, and 2017 were all fairly dry years: however, only sampling dates when the mean 7-day prior flow fell below ~55 cfs and water column TP concentrations were above 130 ppb resulted in periphyton exceedances at the UBWPAD sampling site UBWPAD, which is the confluence of the Blackstone River and the effluent channel. At W1258 and Depot Street, exceedances only occurred when the mean 7-day prior flow fell below 50 cfs.
- Data from continuous DO meters installed in the river in 2017 show compliance with the Massachusetts standards nearly all, if not all, of the time.
  - In 2017, MassDEP installed continuous T/DO probes at the four periphyton sampling locations in the Blackstone River from June 2 to November 2. The continuous meters were not cleaned or recalibrated during the five-month monitoring period. Calibration measurements were collected approximately monthly using a calibrated hand-held T/DO probe.
  - Observed DO data was in compliance with the MA DO standard of 5 mg/L (MA Class B Standard) nearly all of the time, with occasional non-compliance at UBWPAD2.
  - The data was in compliance with DO percent saturation guideline of < 125% saturation (CALM) at all sites and all days of valid data.
  - There were a handful of days at three of the four meters (W0680, UBWPAD2, and W1258) where the maximum diel (diurnal) variation in DO was greater than 3 mg/L (CALM).

## 9.0 Future Work

Upper Blackstone plans to continue water quality monitoring in the Blackstone River in 2018 to track the impacts of reduced nutrient concentrations in Upper Blackstone plant effluent. Blackstone River data collected in 2017 will be added to the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) database, which is sponsored by the National Science Foundation ([www.cuahsi.org](http://www.cuahsi.org)). The 2017 data, in addition to the data from 2012 – 2016, will be publicly available for download through the CUAHSI Hydrologic Information System (HIS) databases and servers ([data.cuahsi.org](http://data.cuahsi.org)). In addition, the 2017 data will be submitted to MassDEP to supplement the data already submitted.

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## **Appendix A: Sample Collection and Processing**



The field program was conducted based on the Standard Operating Procedures (SOPs) on file as part of the QAP for the project. The QAP was designed to serve as an umbrella document for any field sampling conducted as part of the project. A Field Sampling Plan (FSP) developed each year provides details of the sampling program and is available upon request for both 2015 and 2016. The discussion below provides a brief overview.

Bottles were cleaned with non-phosphate containing detergent between each sampling event and tested for conductivity prior to approval for use, as per the project FSP and QAP. At least two spare bottles of each type were available per sampling trip in case of mishap. Labels for the bulk sample bottles were printed prior to the event with space available for noting the collection time.

Surface water samples were collected from locations believed to be generally representative of net water quality within the river. Prior to collecting samples, the sampling location was visually inspected and general information on weather condition, river flow and appearance, observable sources of potential contamination, and presence of wildlife was recorded. At each sampling location, the collection date, time, and additional collection details were recorded on data sheets prepared for the sampling event. Any sampling issues were noted on project forms as detailed in the QAP. At the end of the day, all sampling data sheets were transferred to UMass and retained as part of the monitoring record.

Collection bottles and caps were rinsed three times with river water before collection of the stream sample. Samples were always collected upstream from the sampler, and rinse water was emptied away from the sampling location. Bulk water samples for nutrient analysis were collected from either a bridge, utilizing a Nalgene 2-L wide-mouth HDPE bottle attached to a rope and reel, from the stream bank using a Nalgene 1-L wide mouth HDPE bottle attached to a sampling pole, or by wading into the stream with a Nalgene 4-L wide mouth HDPE bottle. Samples were collected at the three co-sampled RI sites by filling a 40-L Nalgene carboy bottle utilizing NBC's peristaltic pump. The large volume was necessary to provide splits for both NBC and UMass from the same bulk sample. Cross-contamination between the three sites due to pumping was minimized by rinsing the tubing thoroughly with river water prior to collecting the sample. Samples for chlorophyll-a analysis were collected in amber containers, protected from sunlight, and filtered as soon as possible as detailed in the SOP and summarized below. Samples were placed in a cooler with packed ice until they could be transferred to a refrigerator or freezer for longer storage as detailed in the respective lab SOPs.

Aliquots for dissolved nutrients were filtered in the field, while aliquots for the remaining parameters were prepared after transfer to the lab for splitting. Labels for the aliquots were printed prior to the event and filled in at the time of filling with the sampling date and time. Aliquot bottles were rinsed three times with sample prior to filling. QAQC samples, including field duplicates, field splits, and blanks, were processed utilizing the same procedures as the bulk sample for a given site and analyte. Chain of custody forms were completed for all aliquots, checked and signed by UMass staff, then transferred to the appropriate analysis lab for lab staff signature. Copies of the chain of custody forms are retained as part of the project documentation and are available upon request.

No generally accepted cutoff exists for the separation of particulate and dissolved fractions (Moorleghem et al., 2011). Samples at the three RI sites were field filtered immediately utilizing a Jensen 0.45  $\mu$ m disposable groundwater filter cartridge (FGI0600-4518V) and field pump to duplicate procedures utilized by NBC. A new filter and clean suction lines/tubing were utilized at each site. The tubing was rinsed three times and the filter primed with sample water prior to filtering the aliquots. Samples at all sites were also field filtered with Millipore (SLGP033RS) 0.22-micron filter units attached to a Millex-GP syringe for analysis of the nitrogen series at UMD as well as DP at EAL. A new syringe and filter unit were utilized at each site. Samples for chlorophyll-a analysis were filtered as soon as possible through a 47 mm diameter Whatman GF/F 0.7  $\mu$ m pore size glass microfiber filter in the lab. Filtering for chlorophyll-a was conducted at Upper Blackstone's lab rather than in the field in order to more carefully control environmental conditions, such as exposure to sunlight, during filtering than could be in the field.

The remainder of the bulk sample for each site was transported back to the Upper Blackstone lab, where it was split into smaller volume bottles for preservation and subsequent analysis for the rest of the analytes.

## **Appendix B: Analysis Methods & Detection Limits**

Samples were analyzed by the Upper Blackstone, NBC, UMD or EAL lab depending on site and analyte. To enable inter-comparison of data between labs, data for additional parameters were calculated based on the laboratory analysis results. The parameters calculated varied between the labs, based on the analytes and methods available for each. A summary of the data calculated by each lab, laboratory analysis methods, detection limits, and calculations are summarized in Tables 30 and 31.

Table 30: Parameters calculated based on lab results

Lab	Parameter	Calculation <sup>1</sup>
Upper Blackstone	Total Organic Nitrogen	$tON = TKN - TAM$
	Dissolved Organic Nitrogen	$dON = dTKN - dTAM$
	Total Inorganic Nitrogen	$TIN = NO_{23} + TAM$
	Dissolved Inorganic Nitrogen	$DIN = dNO_{23} + dTAM$
	Total Dissolved Nitrogen	$TDN = TAM + NO_{23}$
	Total Nitrogen	$TN = TKN + NO_{23}$
NBC	Dissolved Inorganic Nitrogen	$DIN = dNO_{23} + dTAM$
	Dissolved Organic Nitrogen	$dON = TDN - DIN$
	Dissolved Kjeldahl Nitrogen	$dTKN = TDN - dNO_{23}$
UMD	Total Nitrogen	$TN = TDN + PON$

Note: <sup>1</sup> Half the detection limit was utilized in the calculation for parameters and sampling dates below the detection limit.

Table 31: Nutrient analyses, laboratories, methods, and limits

Narragansett Bay Commission		
Parameter	Method	Detection Limit
dTAM	EPA 349	7 ppb
dNO23	EPA 353.4	6 ppb
DOP	EPA 365.5	5 ppb
dNO2	EPA 353.2	5 ppb
TDN	Lachat QuikChem Method 31-107-04-3-A	100 ppb
TN	Lachat QuikChem Method 31-107-04-3-B	200 ppb
TSS	Standard Method 2540D	2 ppm
Chl-a	Chlorophyll extraction and analysis with a Turner Fluorometer (URI/GSO's method)	1 ppm
Upper Blackstone Water Pollution Abatement District		
Parameter	Method	Detection Limit
dTAM, TAM	EPA 350.1	70 ppb / 40 ppb
dNO23, NO23	Easy Nitrate Method (1-Reagent)	36.2 ppb / 16.8 ppb
dNO2, NO2	STD Method 18 <sup>th</sup> ed, 4500NO3-F	50 ppb
dTKN, TKN	EPA 351.2	240 ppb / 103 ppb
DP, TP	EPA 365.4-01	20 ppb / 6 ppb
DOP, TOP	Hach 8048 / EPA 365.1-02	17 ppb / 15 ppb
TSS	USGS I-3765-85 and EPA 160.2	2 ppm
UMass EAL		
Parameter	Method	Detection Limit
TP	STD Method 20 <sup>th</sup> ed., 4500P	8 ppb
TDP	STD Method 20 <sup>th</sup> ed., 4500P	8 ppb
Chl-a	STD Method 20 <sup>th</sup> ed., 10200 H	1 ppb
UMass Dartmouth		
Parameter	Method	Detection Limit
dTAM	STD Method 20 <sup>th</sup> ed, 4500-NH3-F	1.8 ppb
dNO23	STD Method 18 <sup>th</sup> ed, 4500-NO3-F	7 ppb
TDN	STD Method 218 <sup>h</sup> ed, 4500-Norg	10.8 ppb
POCN	Need to add	

## Appendix C: Additional Tables

Table 32: Summary of 2017 precipitation in relation to NWS 30-year normal monthly data

	Monthly Precipitation (inches)					
	Worcester, MA (NWS station KORH)			Taunton, MA (NWS station KTAN)		
	2017	Normal Month Total <sup>a</sup>	% of normal	2017	Normal Month Total <sup>a</sup>	% of normal
Jan	4.36	3.49	125%	3.48	3.98	87%
Feb	2.44	3.23	76%	1.26	3.56	35%
Mar	4.01	4.21	95%	3.87	5.11	76%
Apr	4.75	4.11	116%	7.21	4.61	156%
May	5.89	4.19	141%	3.97	3.59	111%
Jun	4.33	4.19	103%	1.95	3.63	54%
Jul	2.24	4.23	53%	3.34	3.75	89%
Aug	1.59	3.71	43%	1.16	4.08	28%
Sep	2.51	3.93	64%	4.70	4.32	109%
Oct	8.83	4.68	189%	5.41	4.29	126%
Nov	1.78	4.28	42%	3.05	4.50	68%
Dec	2.85	3.82	75%	2.45	4.32	57%

Notes: <sup>a</sup> Based on data from 1981 – 2010, NWS Normal Monthly Data, available online:  
[www.ncdc.noaa.gov/cdo-web/datasets#GHCND](http://www.ncdc.noaa.gov/cdo-web/datasets#GHCND)

Table 33: Summary of 2017 monthly flow conditions

	Monthly Mean Discharge (cfs)					
	Woonsocket, RI – USGS Station 01112500			Millbury, MA – USGS Station 01109730		
	2017	Ave 1930 – 2016	% normal	2017	Ave 2003 – 2016 <sup>a</sup>	% normal
Jan	1163	964	121%	212	188	113%
Feb	900	1,007	89%	166	187	89%
Mar	756	1,508	50%	158	284	56%
Apr	1,744	1,431	122%	332	273	122%
May	1,232	875	141%	223	169	132%
Jun	792	652	121%	177	171	103%
Jul	441	341	129%	89	111	77%
Aug	268	308	87%	59	98	58%
Sep	157	324	48%	58	107	53%
Oct	572	464	123%	154	161	93%
Nov	852	670	127%	149	163	91%
Dec	576	902	64%	97	210	46%

Note: <sup>a</sup> Long-term average in July – December based on data from 2002 – 2016.



Table 34: Summer monthly mean streamflows (cfs) and water temperatures (deg F)

	<b>Monthly Mean Streamflow (cfs) at Millbury, MA – USGS Station 01109730</b>							
	<b>2008</b>	<b>2011</b>	<b>2012</b>	<b>2013</b>	<b>2014</b>	<b>2015</b>	<b>2016</b>	<b>2017</b>
June	114	202	136	434	80	164	67	177
July	151	93	68	105	77	96	49	89
August	143	273	105	86	68	60	59	59
September	228	340	88	82	70	72	48	58
	<b>Monthly Mean water temperature (°F) at Millville, MA - USGS Station 01111230</b>							
	<b>2008</b>	<b>2011</b>	<b>2012</b>	<b>2013</b>	<b>2014</b>	<b>2015</b>	<b>2016</b>	<b>2017</b>
June	NA	NA	NA	69.1	69.7	NA	NA	NA
July	NA	NA	NA	76.9	75.2	NA	NA	NA
August	NA	NA	NA	71.7	71.5	NA	NA	NA
September	NA	NA	NA	NA	68.0	NA	NA	NA

Table 35: Summary of flows and sampling dates occurring during 7Q10 conditions  
(only flows contributing to 7Q periods less than 7Q10 for the gauging site are listed)

Millbury, No 7-day flows < 38 cfs 2017  
Woonsocket, no 7-day flows < 85 cfs in 2017

## Appendix D: Additional Figures

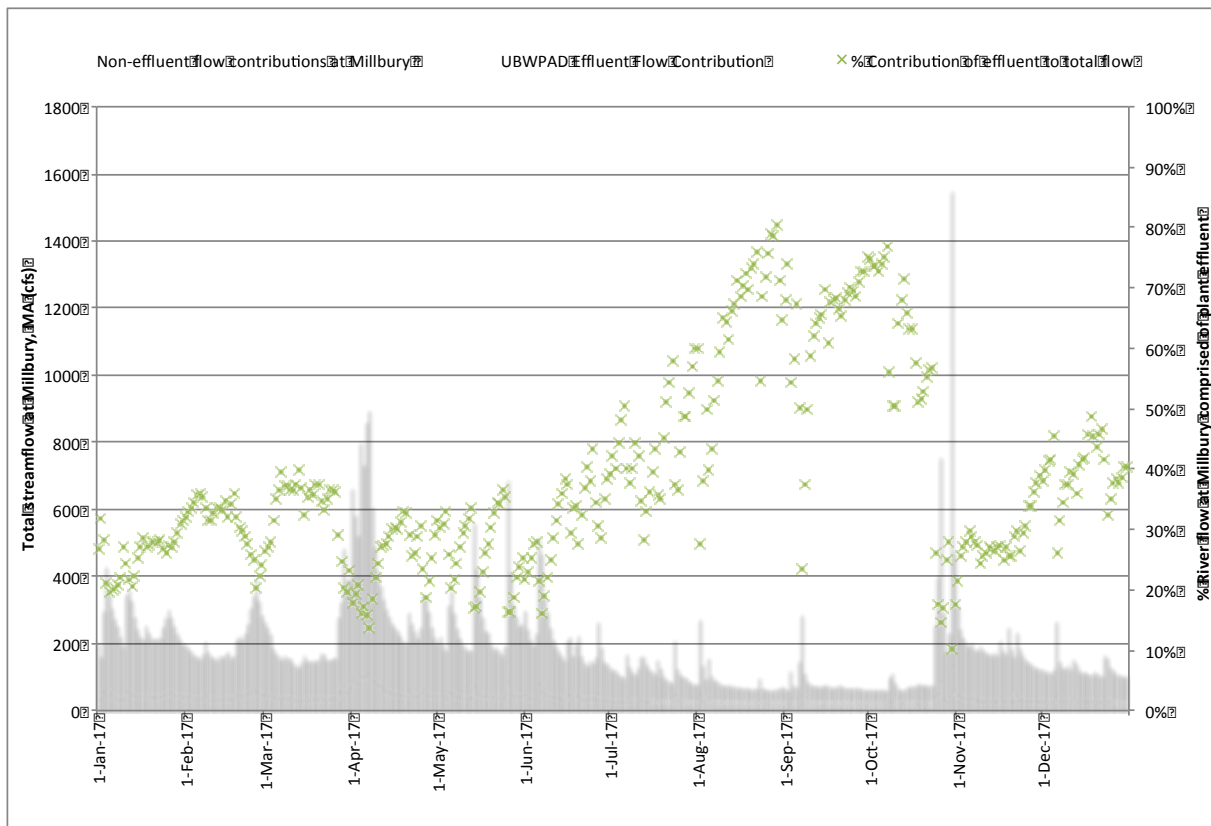


Figure 48: Effluent flow contributions at Millbury, 2017

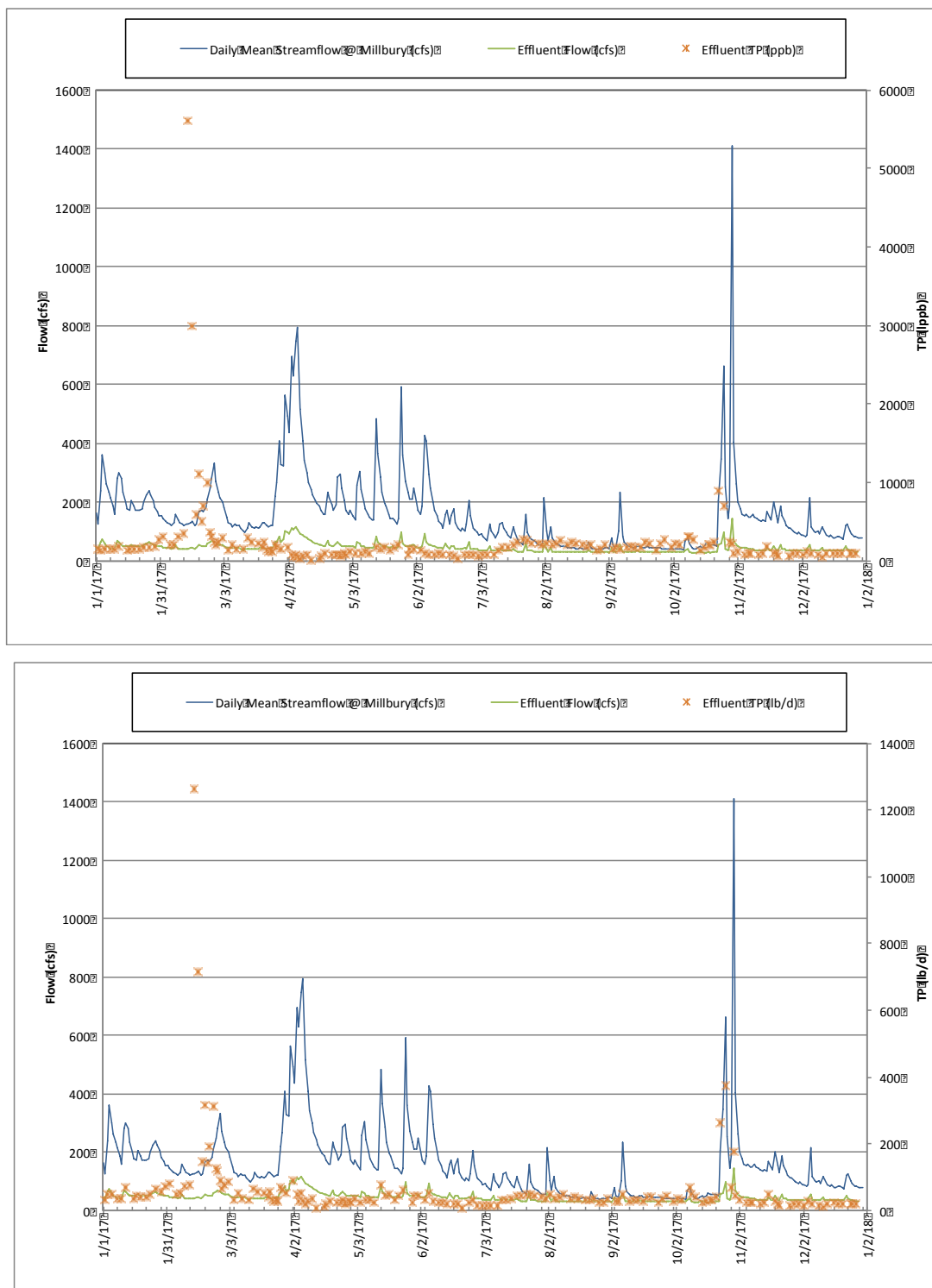


Figure 49: Effluent TP characteristics, 2017

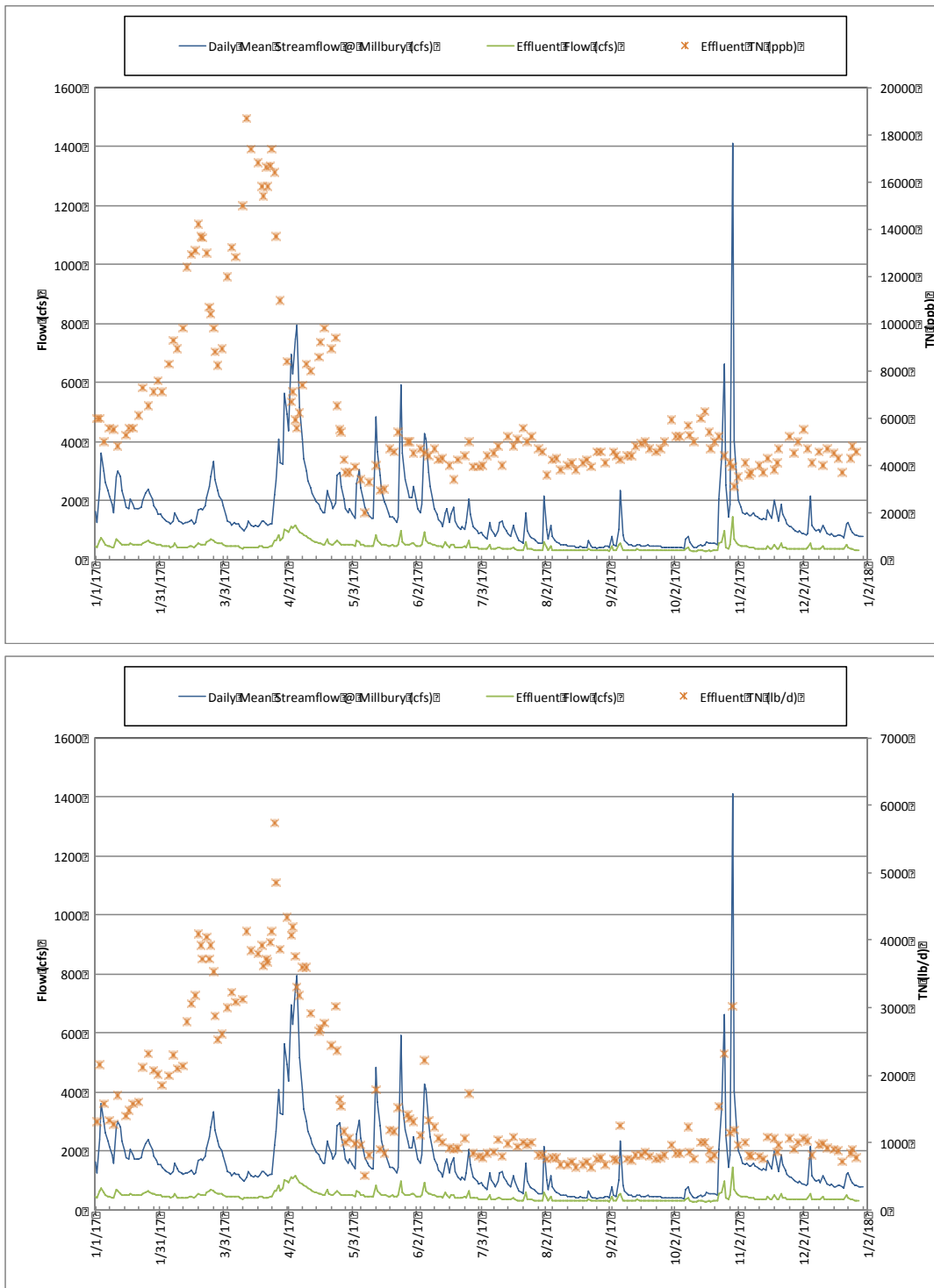


Figure 50: TN effluent characteristics, 2017

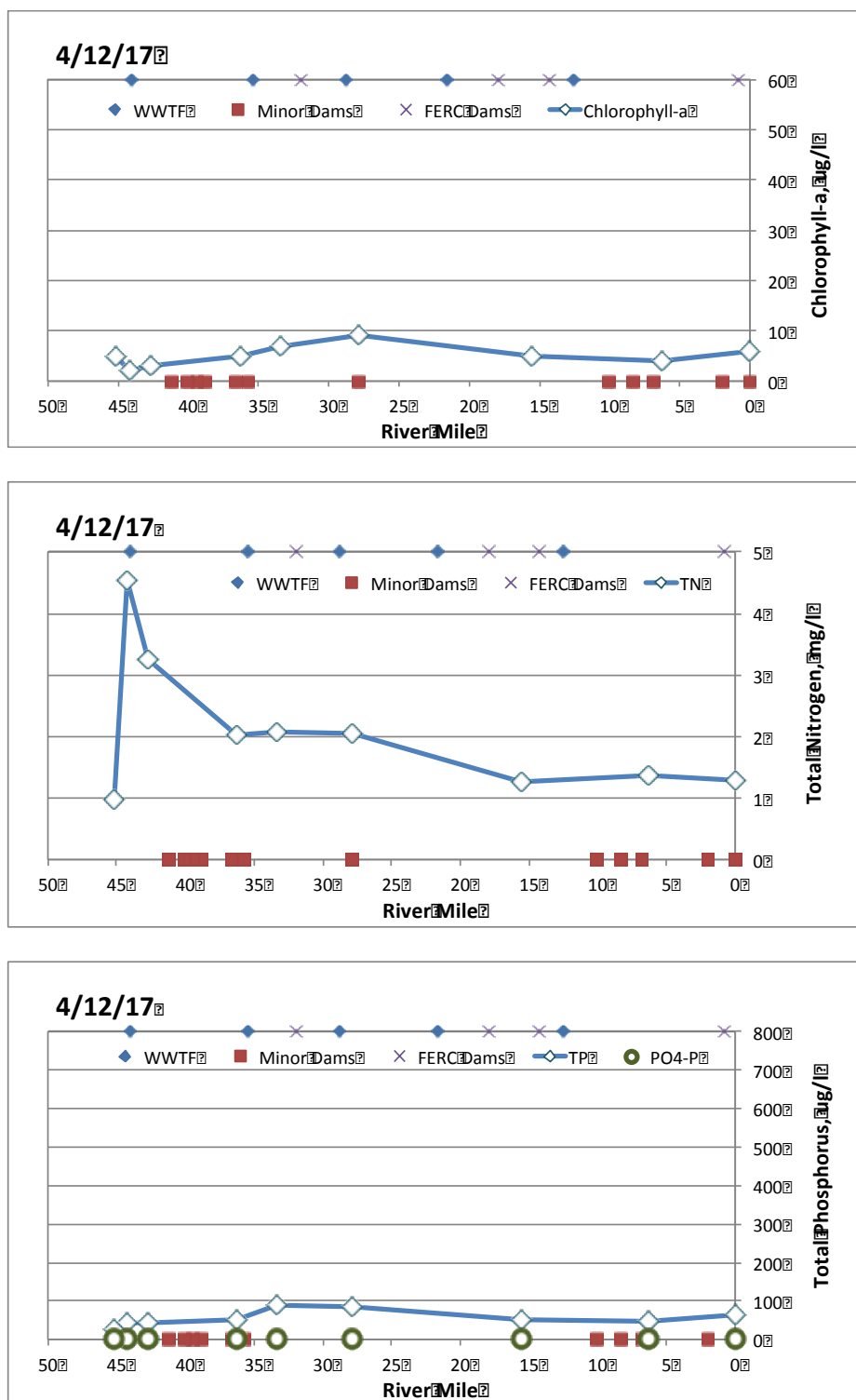


Figure 51: 12 April 2017 along stream concentration plots (Chl-a, TN, TP)

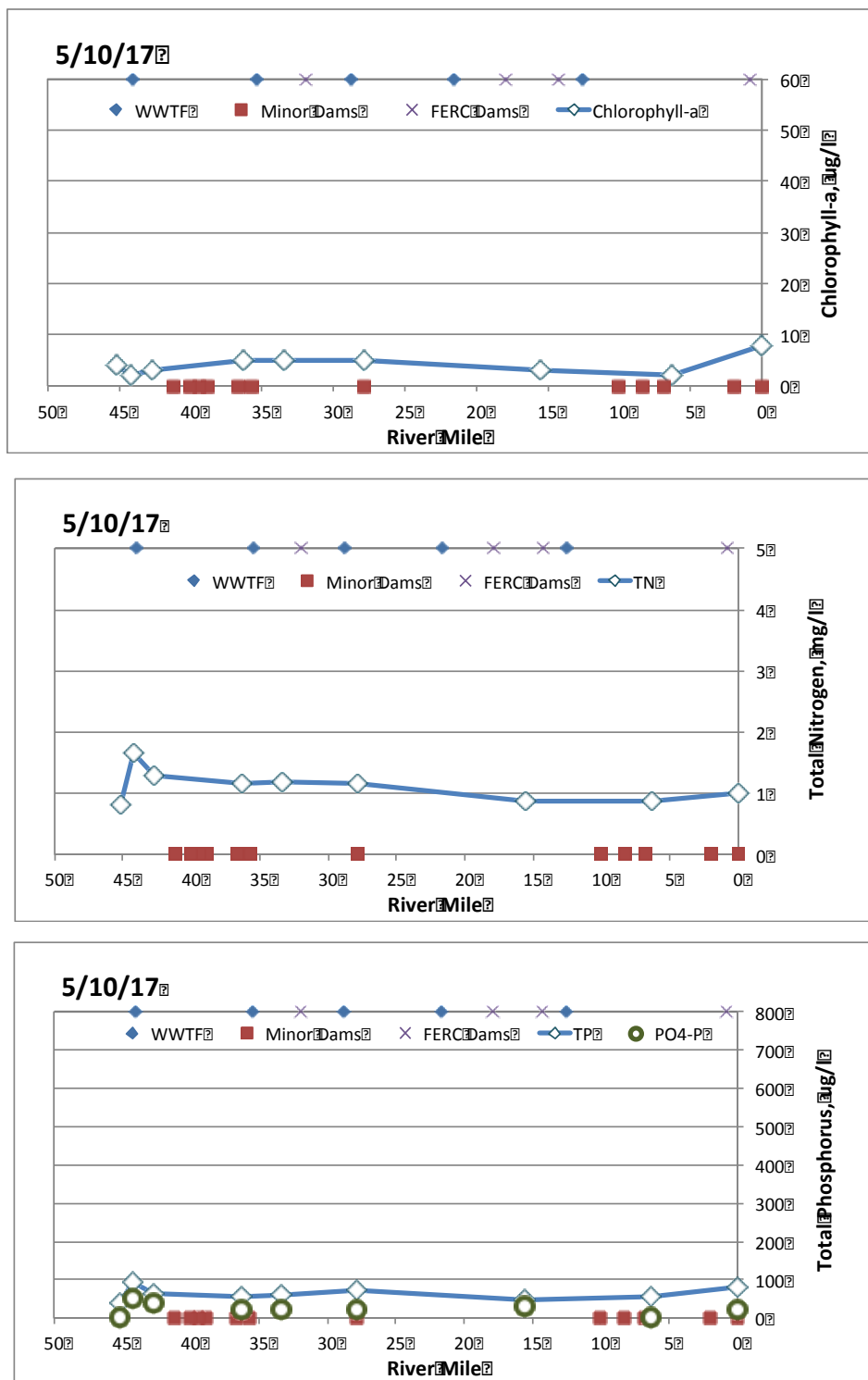


Figure 52: 10 May 2017 along stream concentration plots (Chl-a, TN, TP)

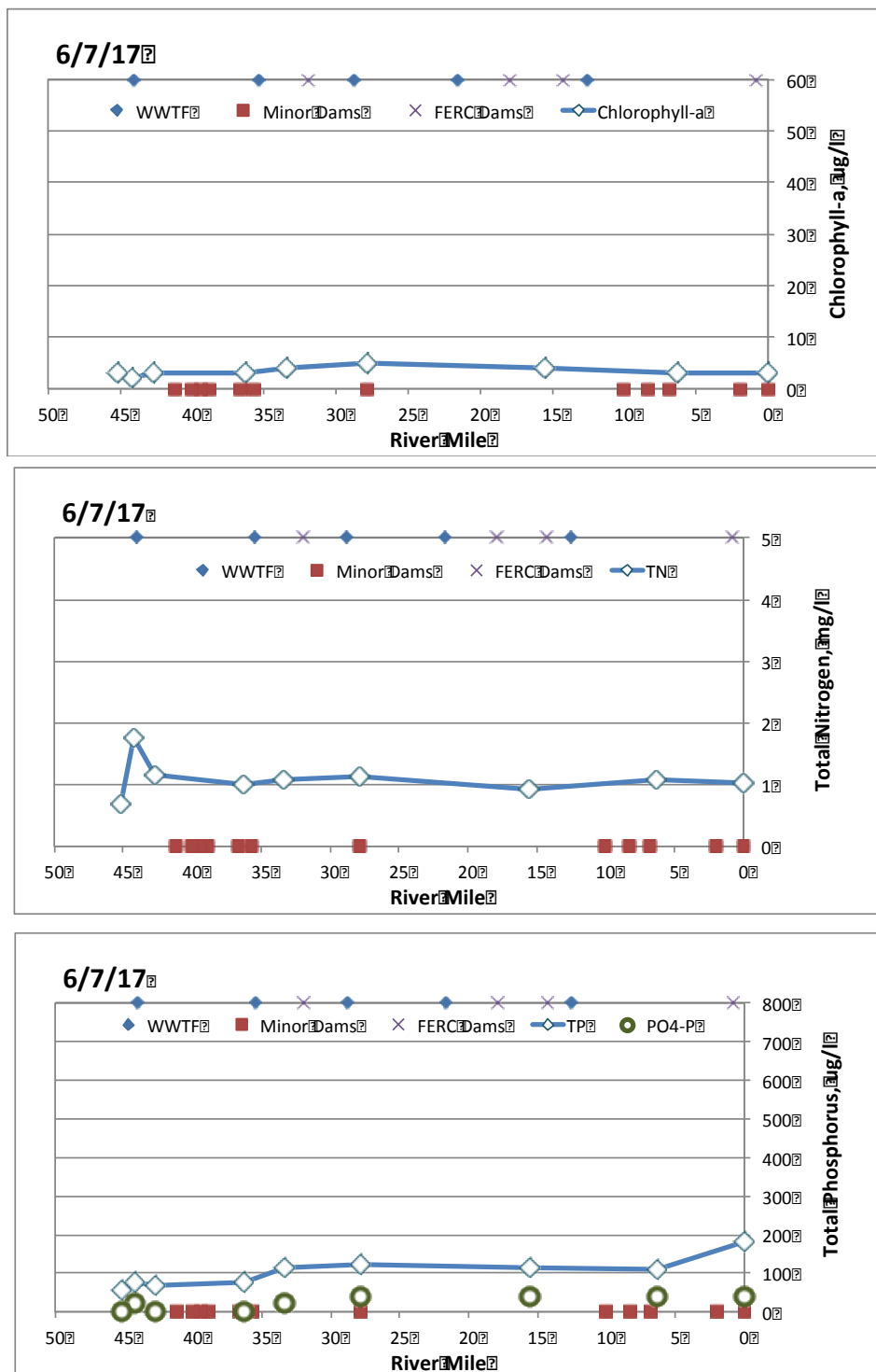


Figure 53: 7 June 2017 along stream concentration plots (Chl-a, TN, TP)



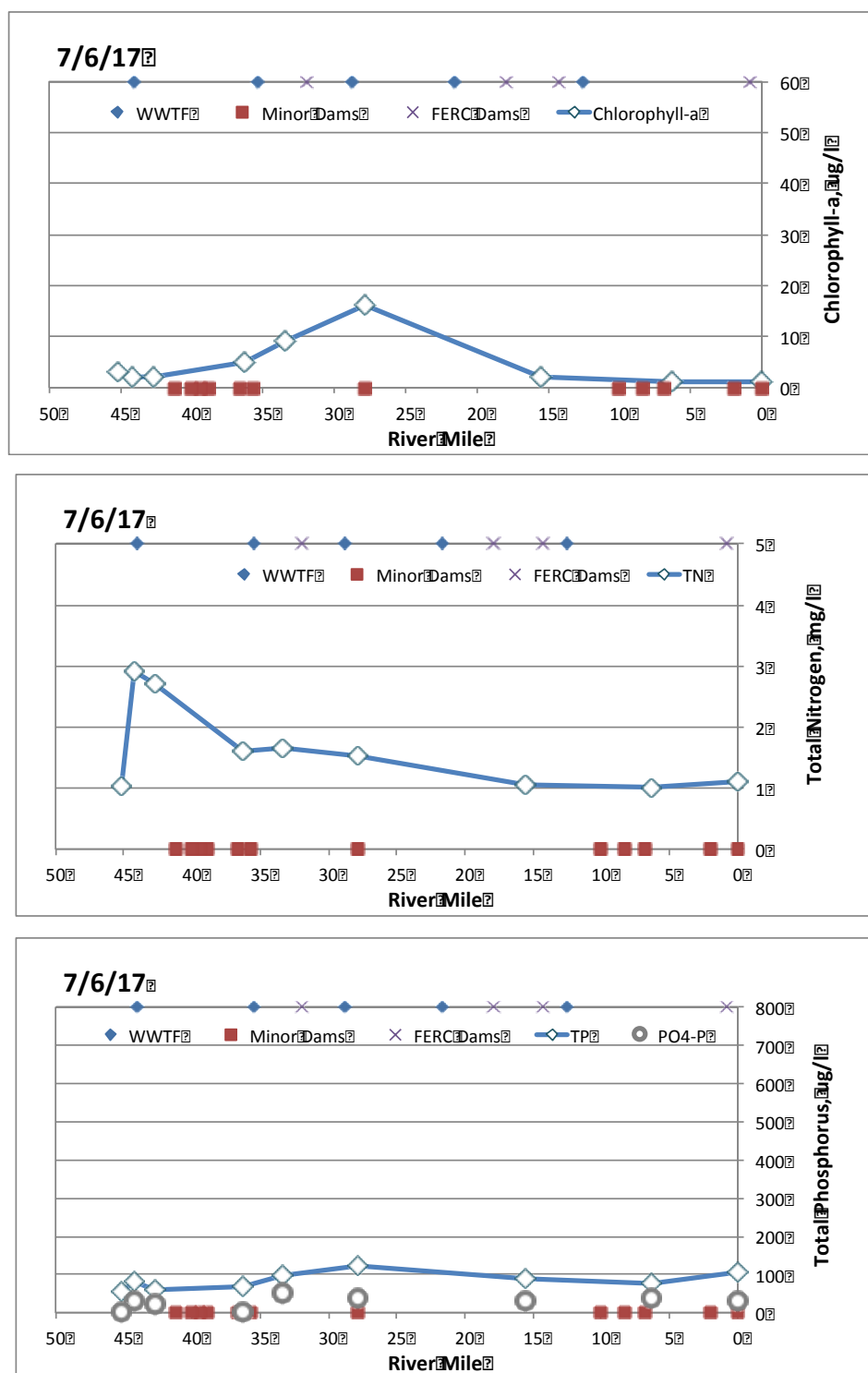


Figure 54: 6 July 2017 along stream concentration plots (Chl-a, TN, TP)

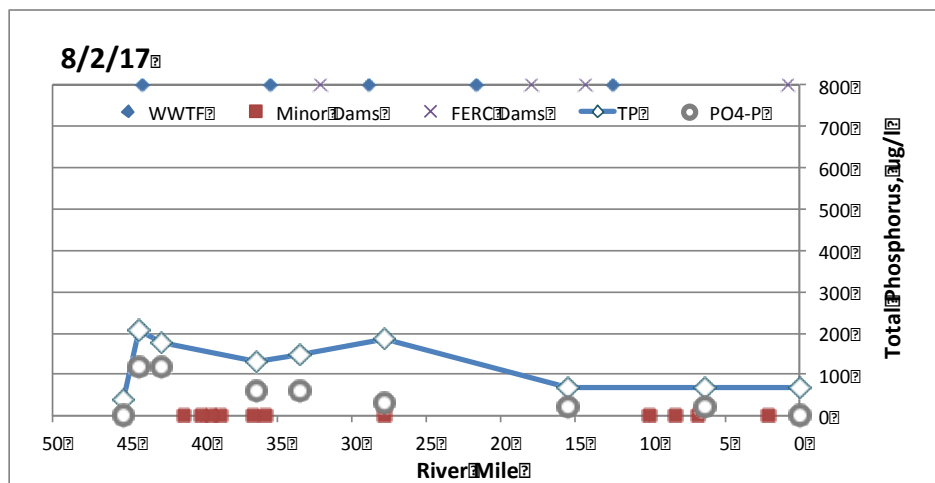
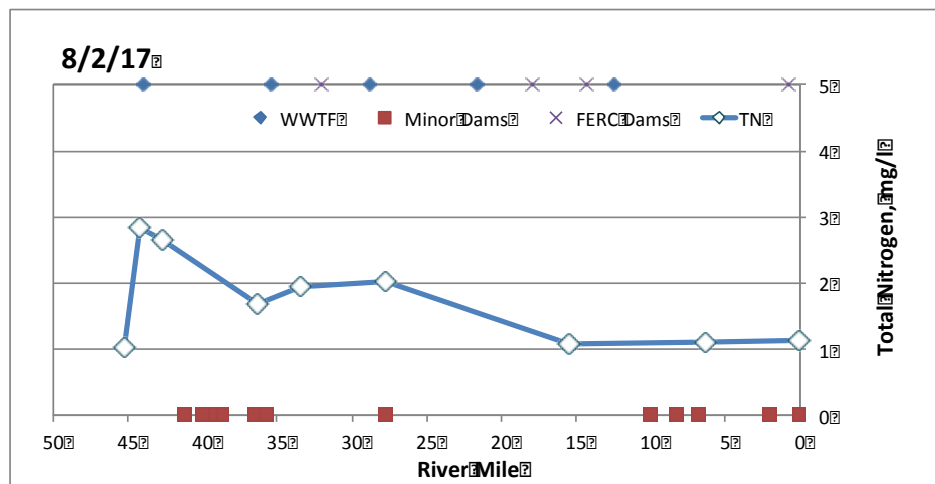
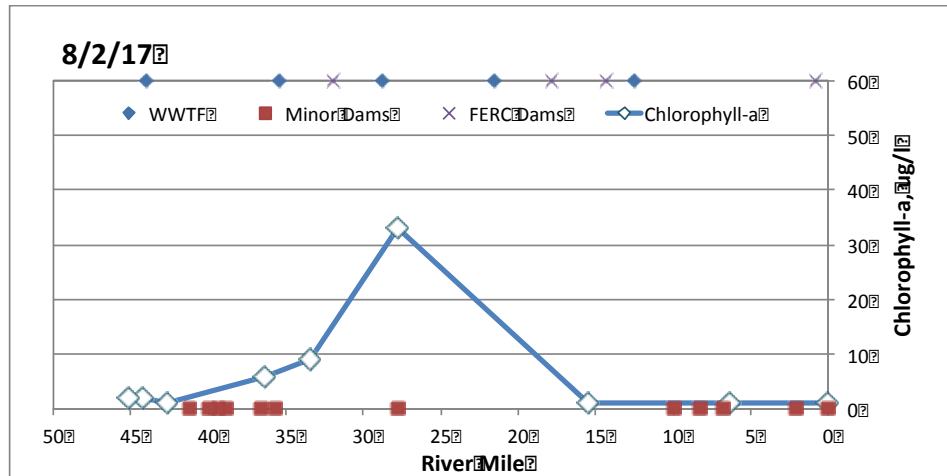


Figure 55: 2 August 2017 along stream concentration plots (Chl-a, TP, TN)

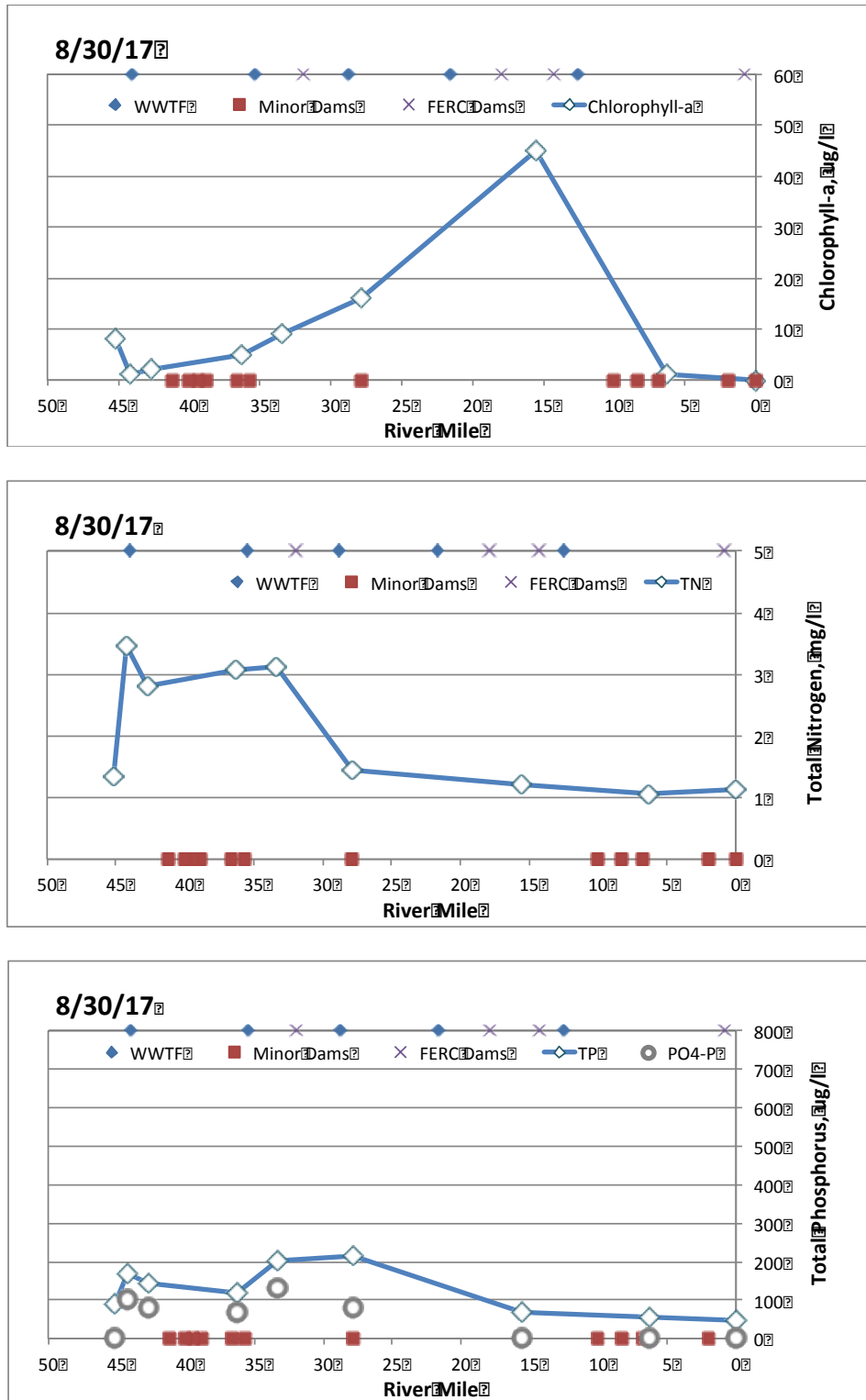


Figure 56: 30 August 2017 along stream concentration plots (Chl-a, TP, TN)

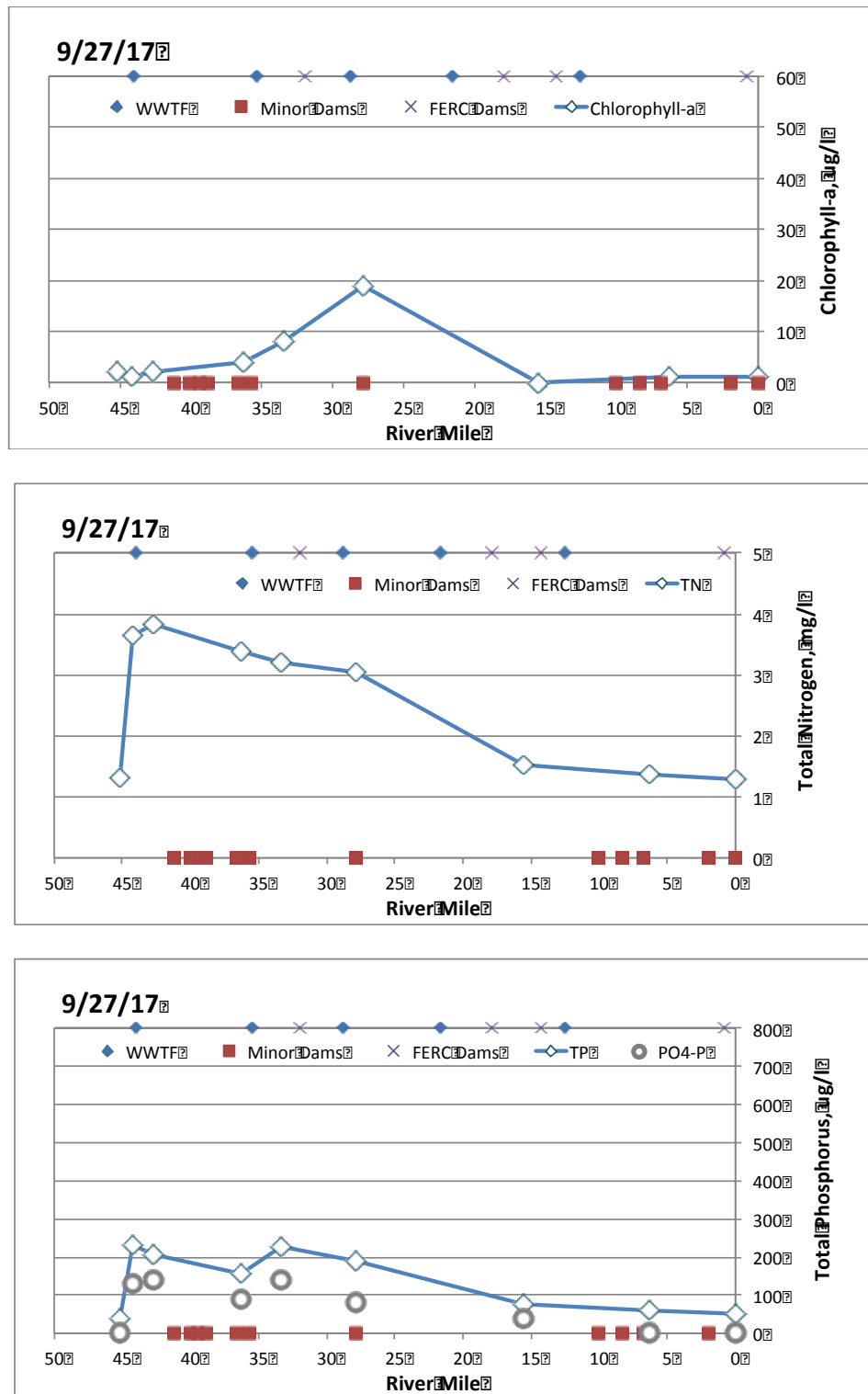


Figure 57: 27 September 2017 along stream concentration plots (Chl-a, TP, TN)

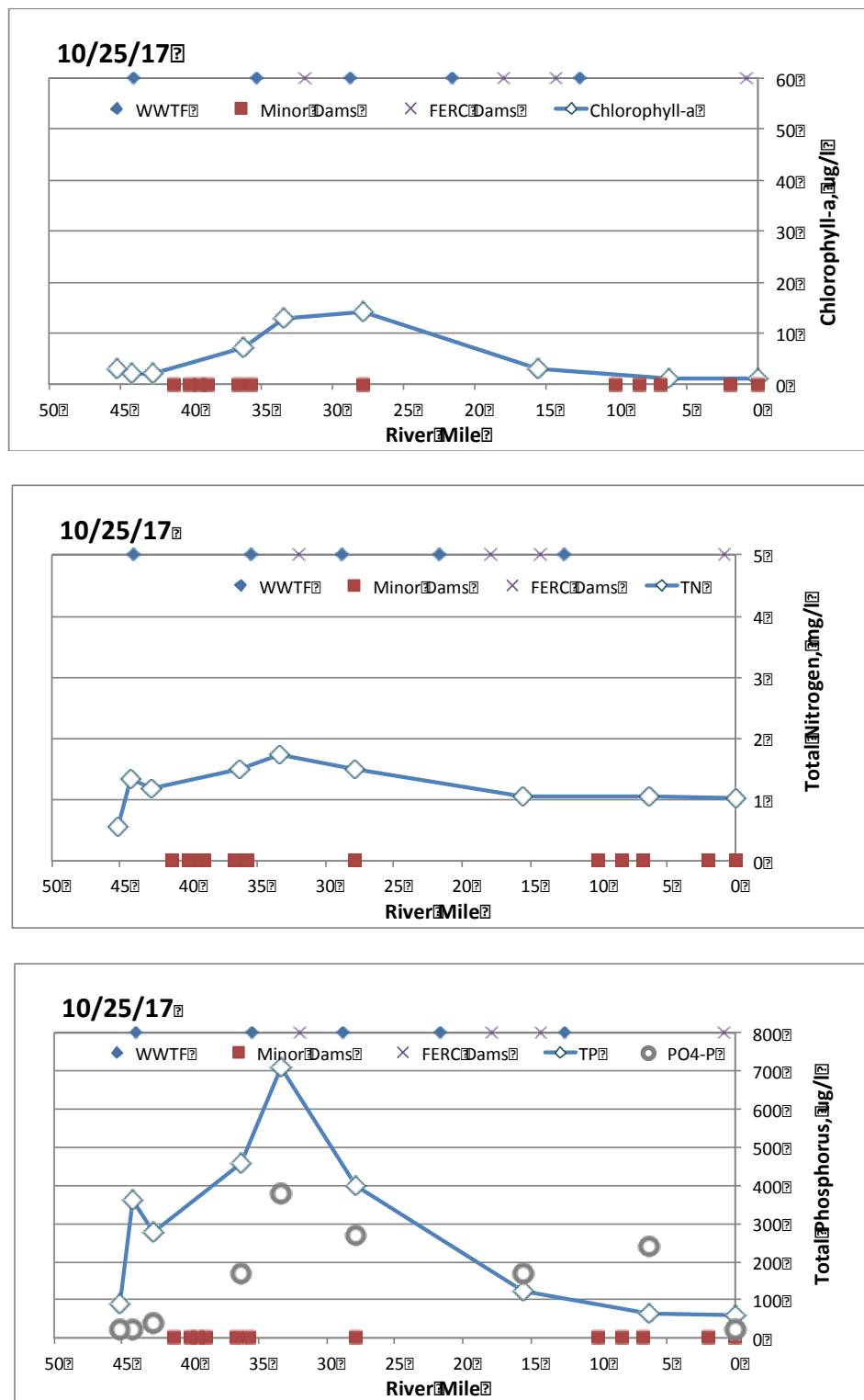


Figure 58: 25 October 2017 along stream concentration plots (Chl-a, TP, TN)

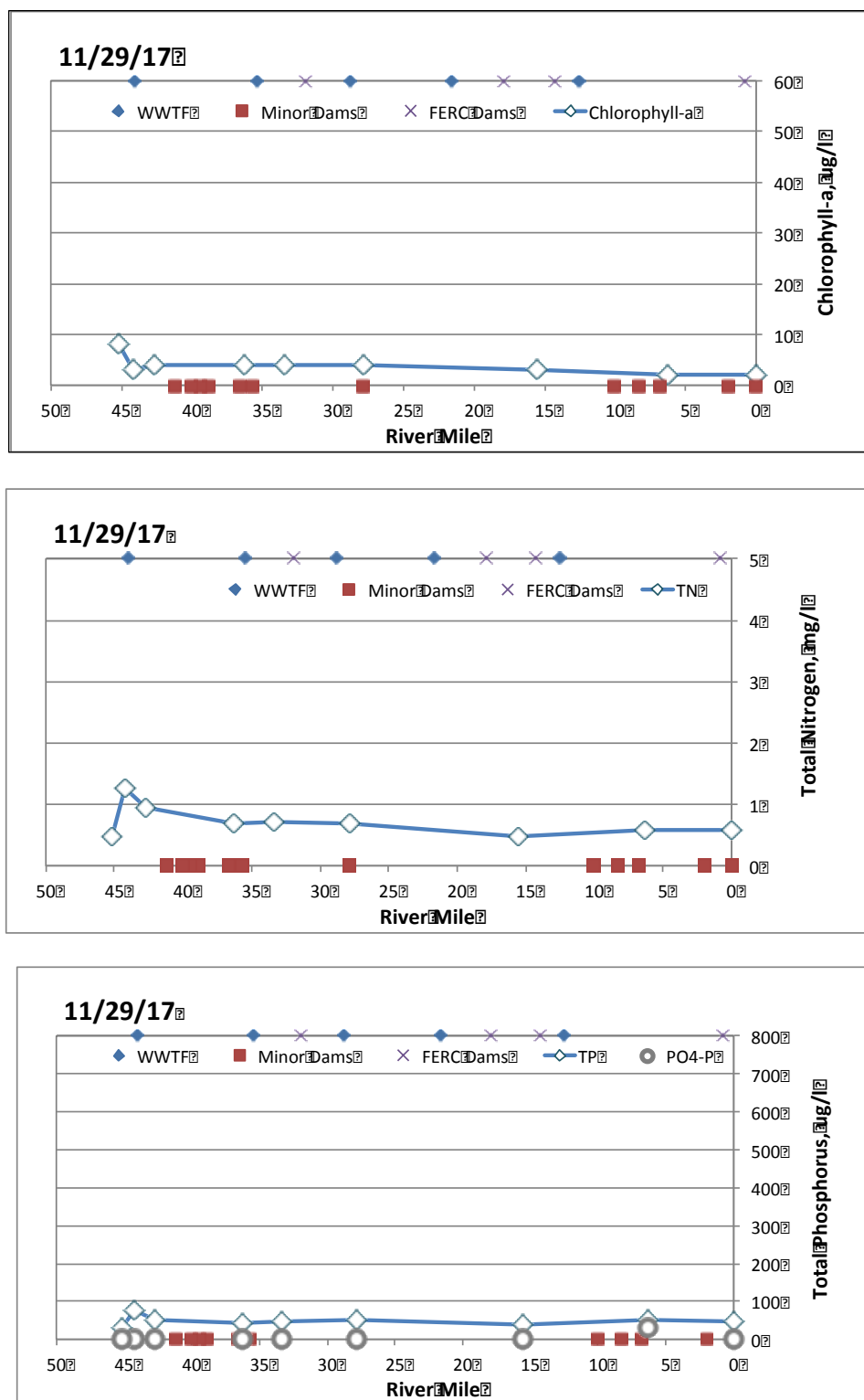


Figure 59: 29 November 2017 along stream concentration plots (Chl-a, TP, TN)

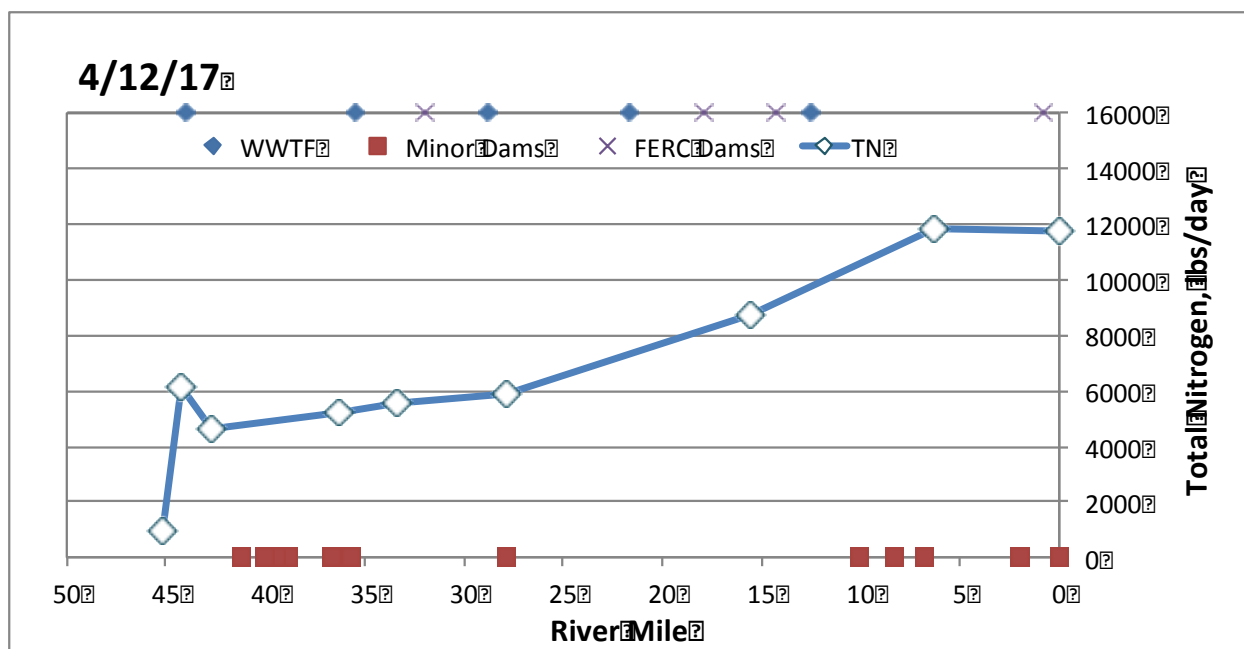
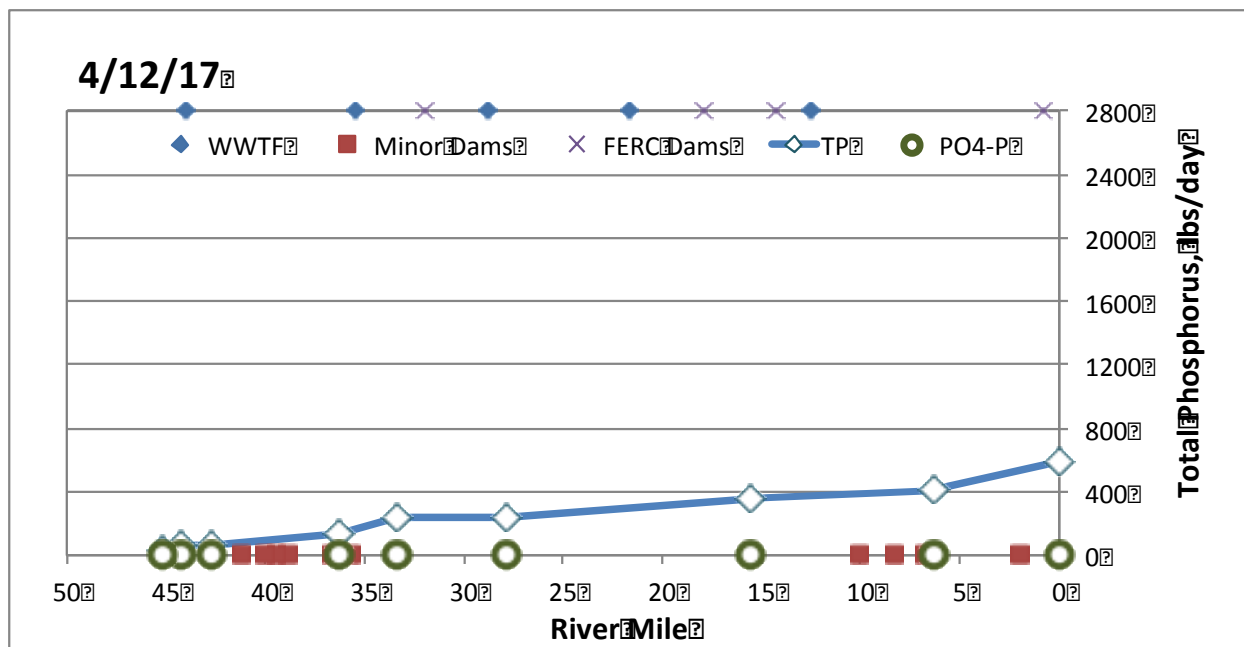


Figure 60: 12 April 2017 along stream load plots (TP, TN)

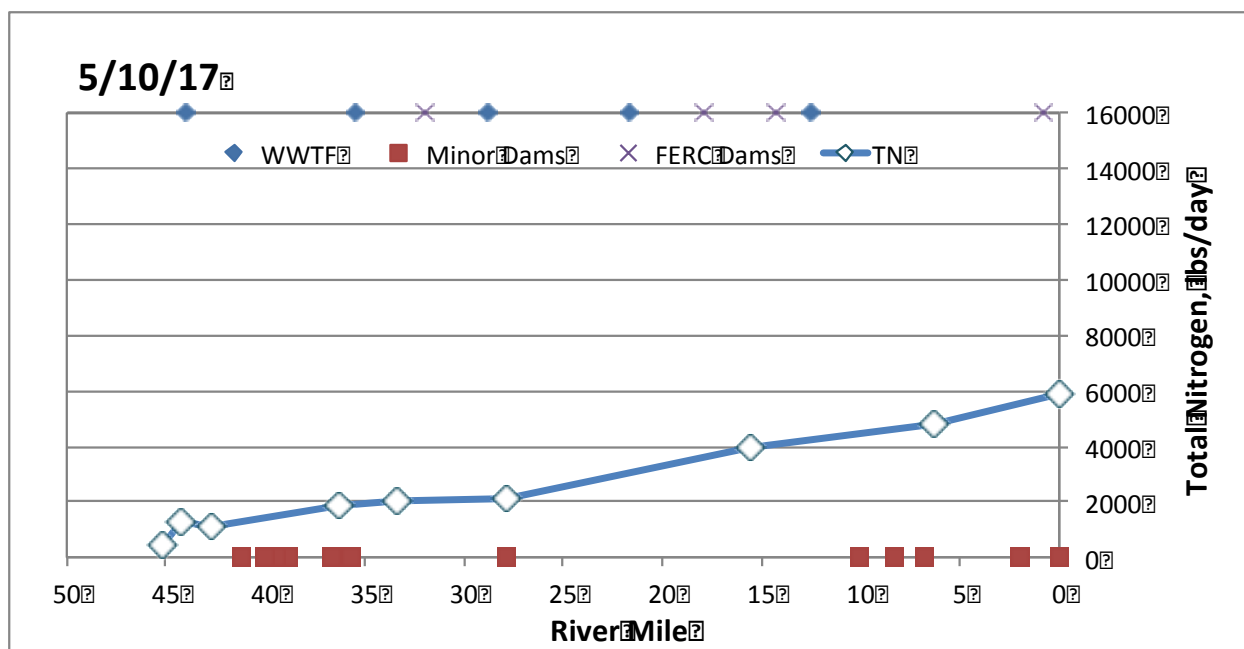
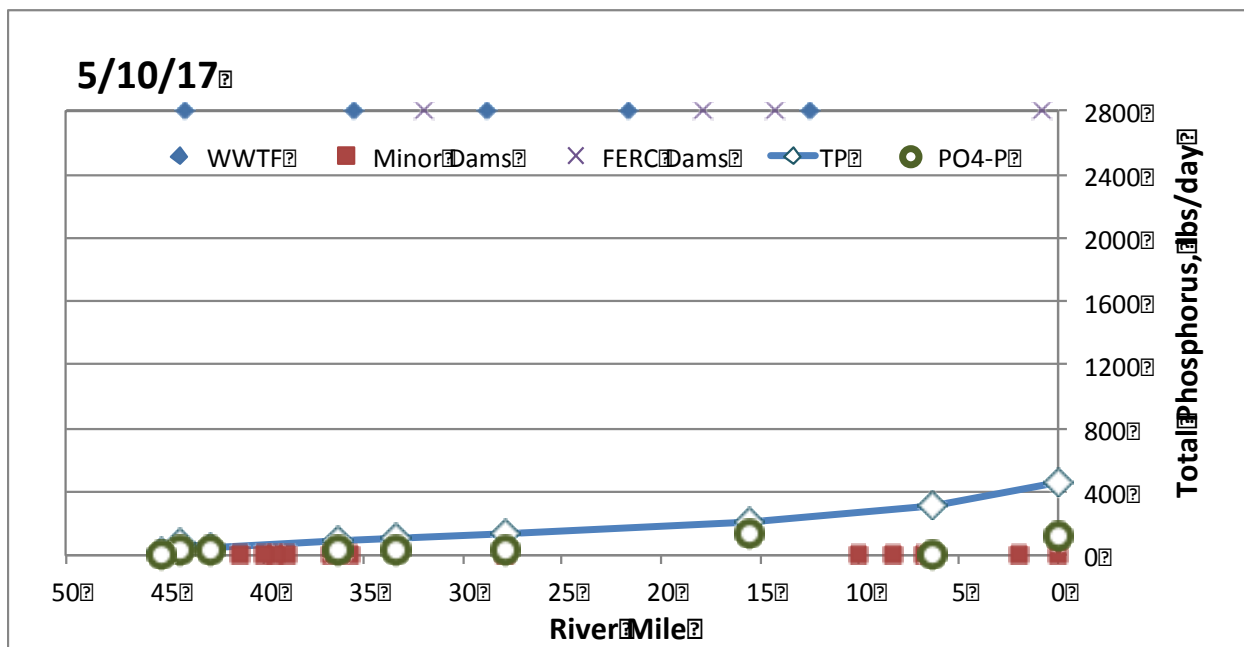


Figure 61: 10 May 2017 along stream load plots (TP, TN)



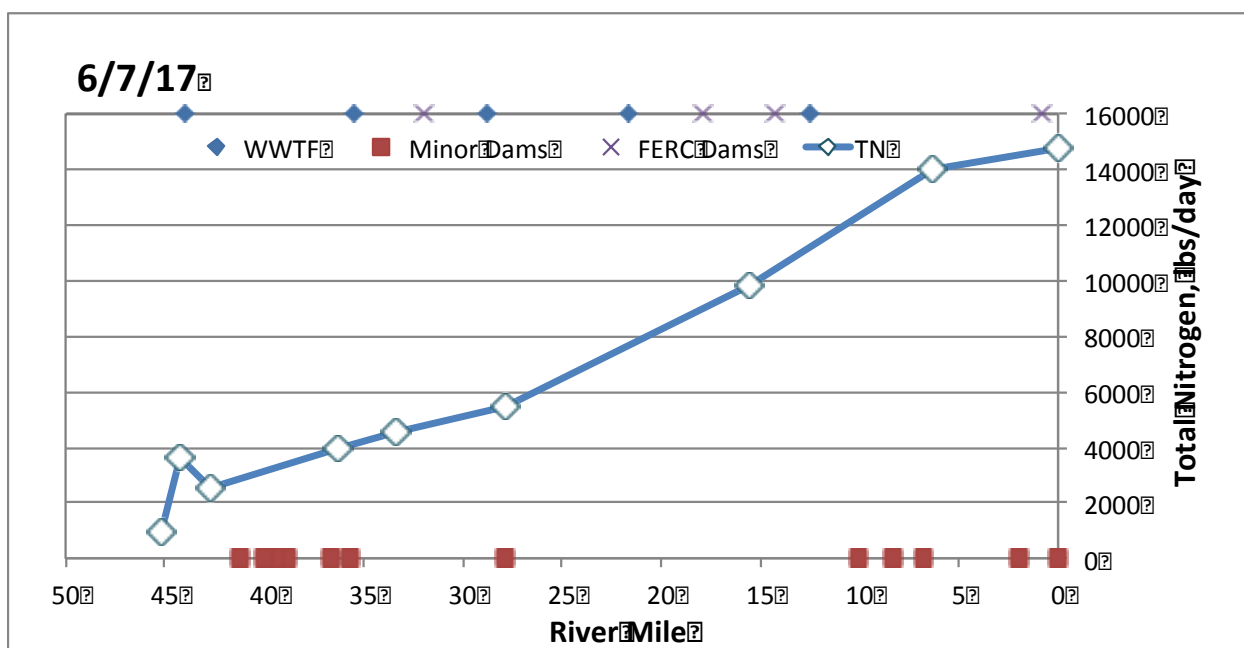
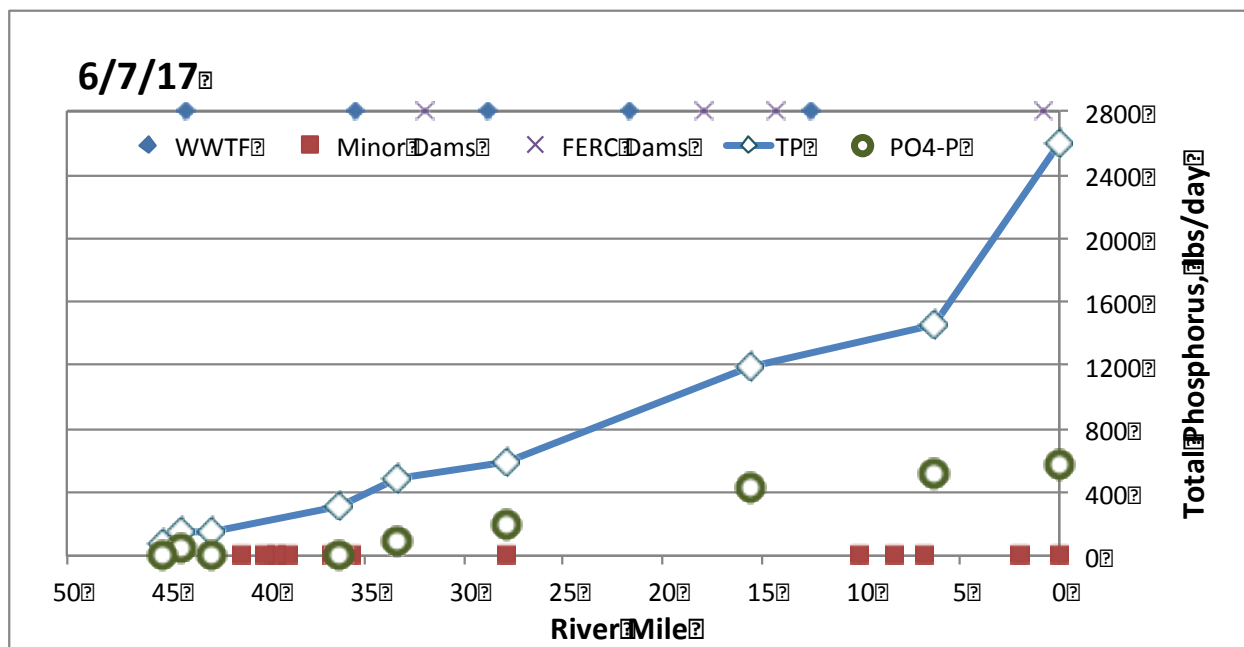


Figure 62: 7 June 2017 along stream load plots (TP, TN)

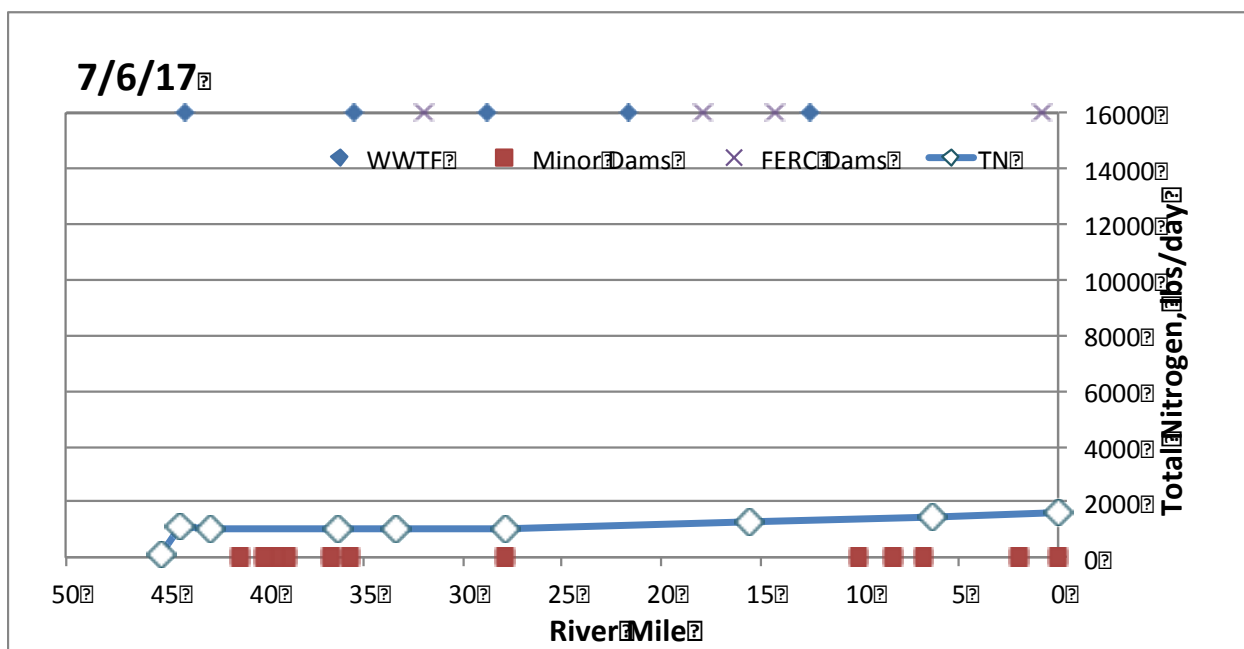
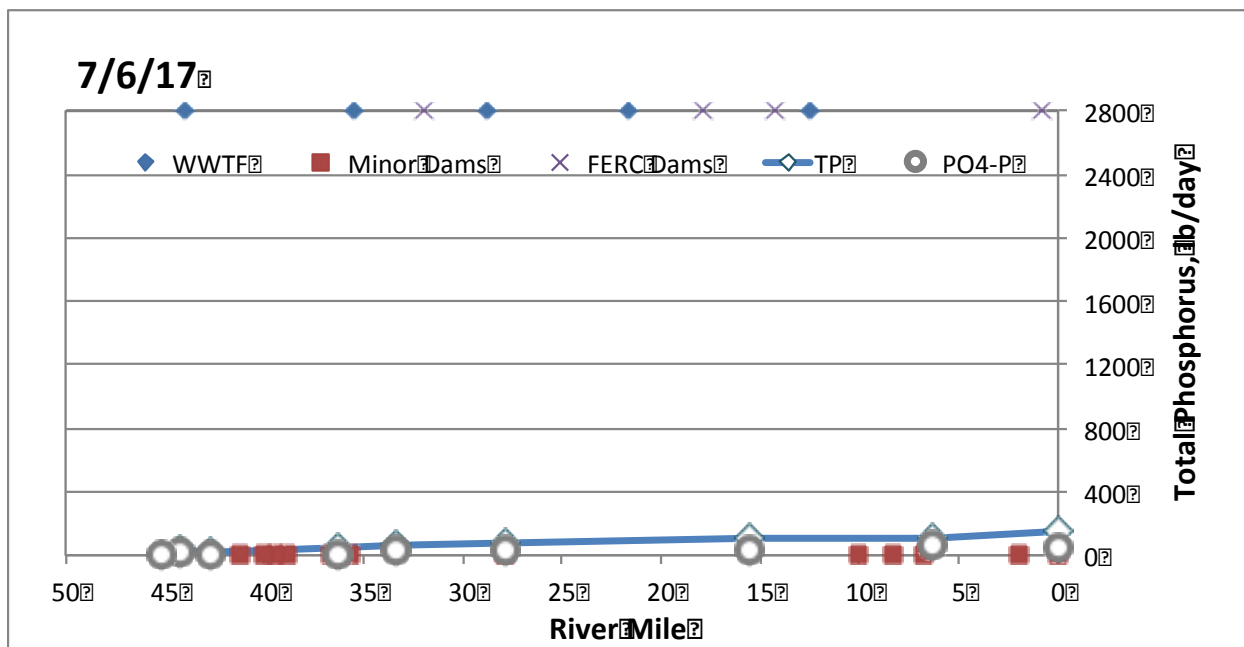


Figure 63: 6 July 2017 along stream load plots (TP, TN)

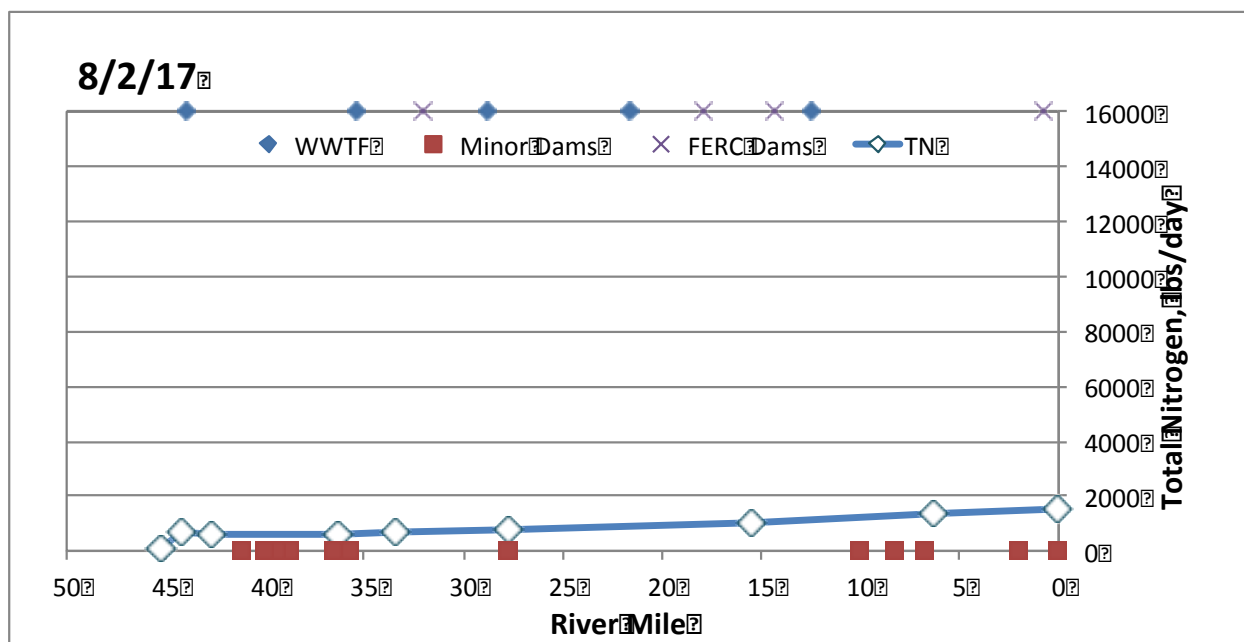
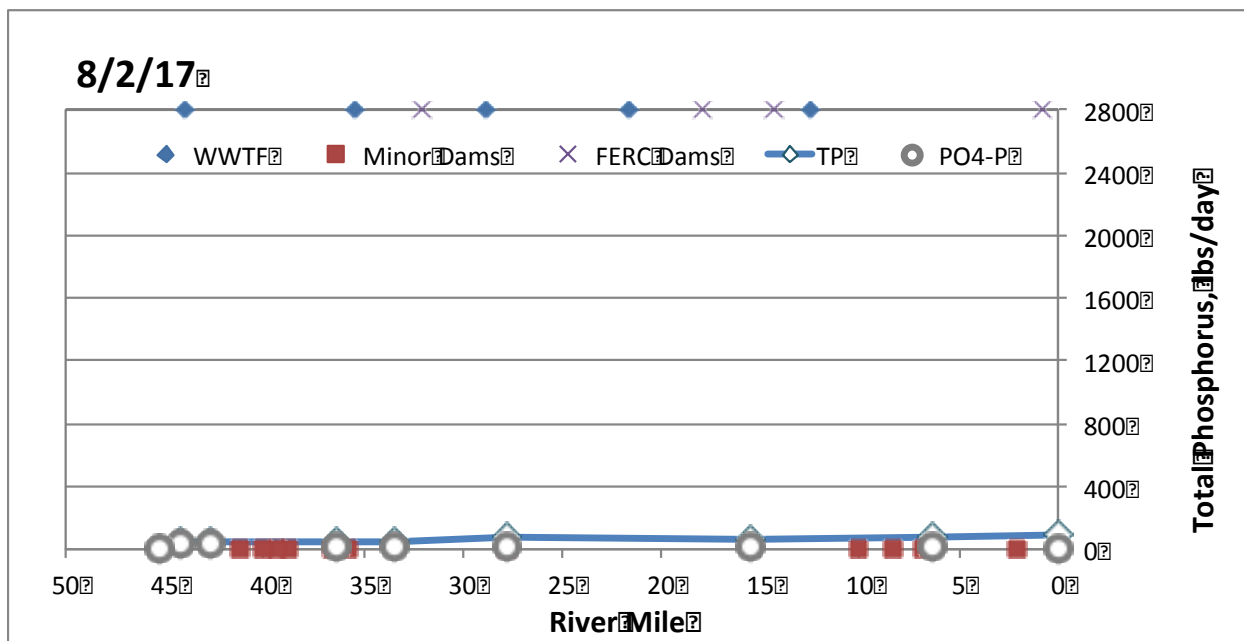


Figure 64: 2 August 2017 along stream load plots (TP, TN)

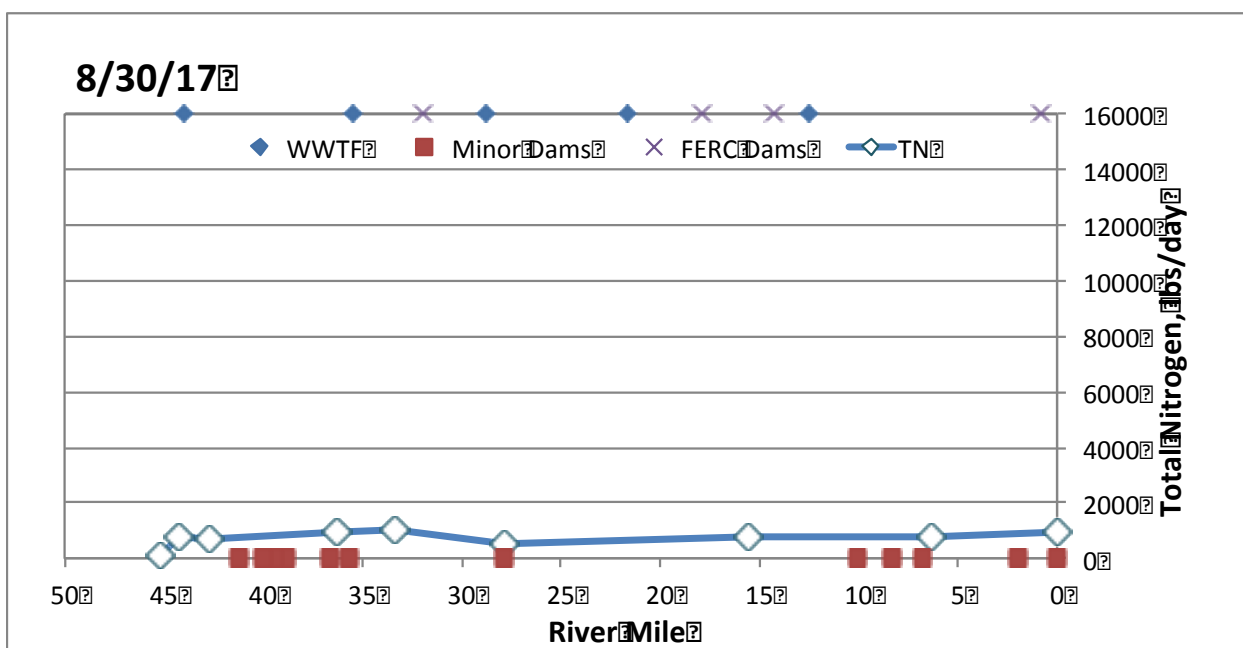
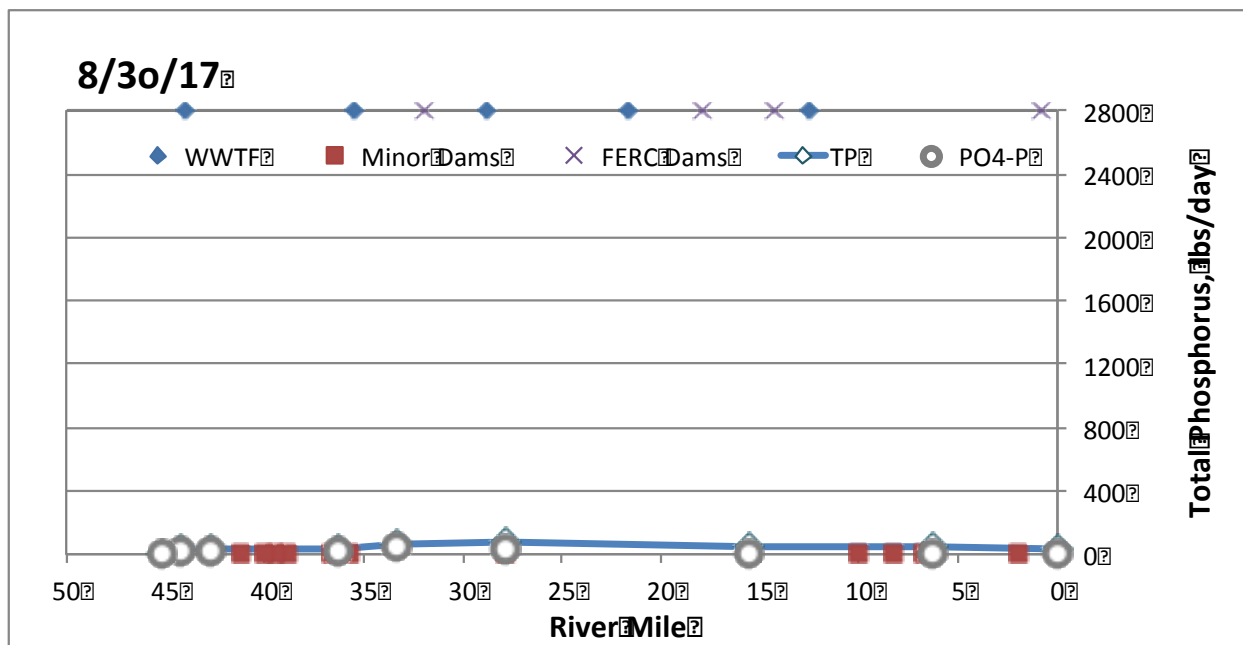


Figure 65: 30 August 2017 along stream load plots (TP, TN)

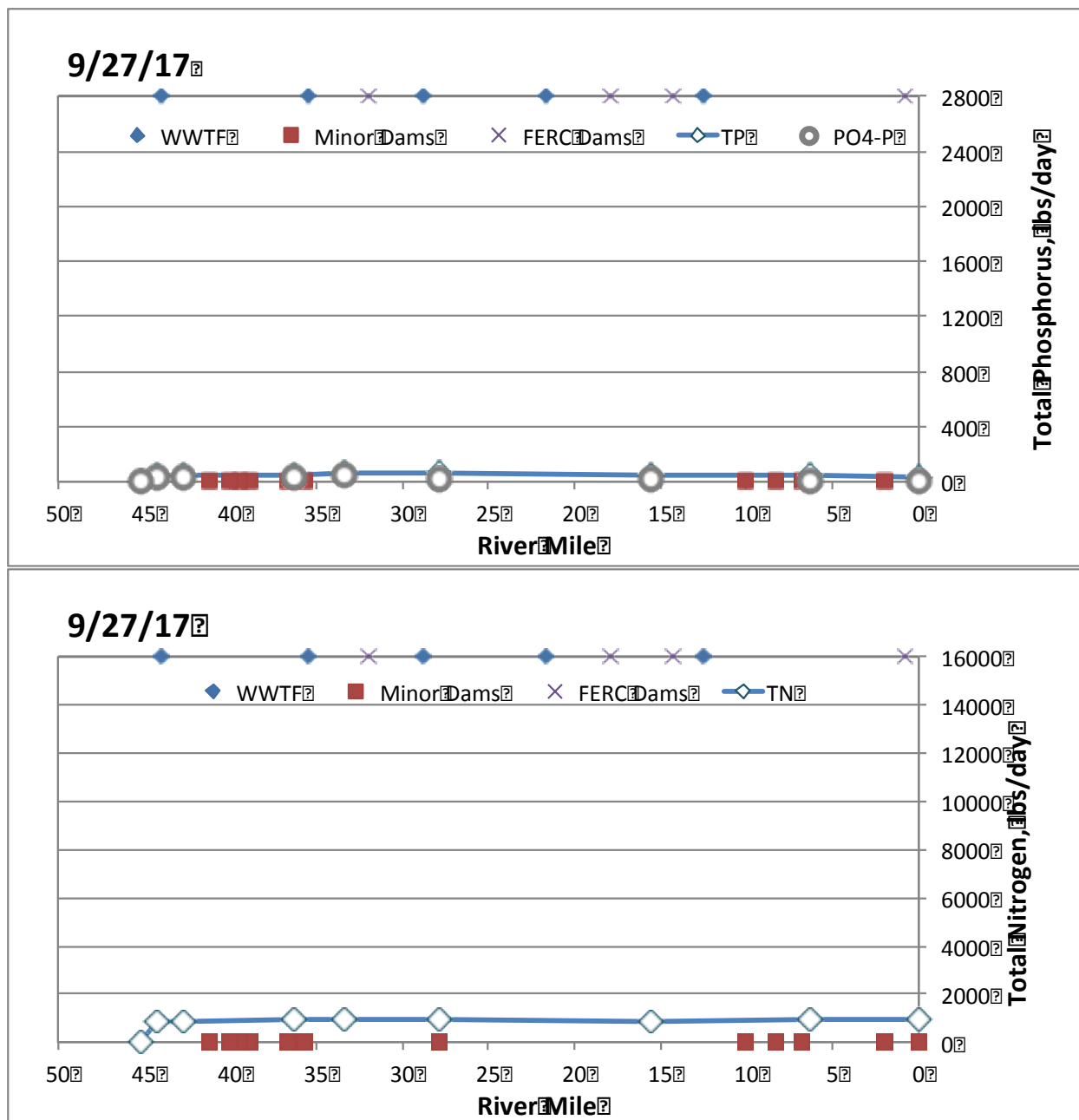


Figure 66: 27 September 2017 along stream load plots (TP, TN)

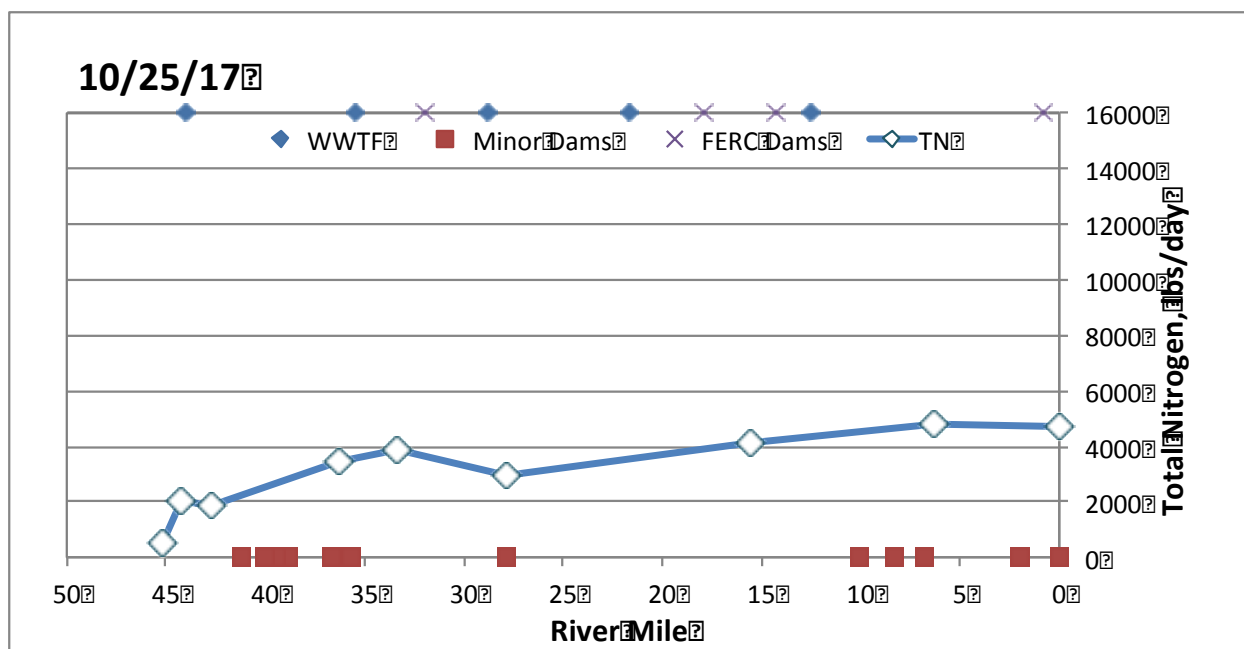
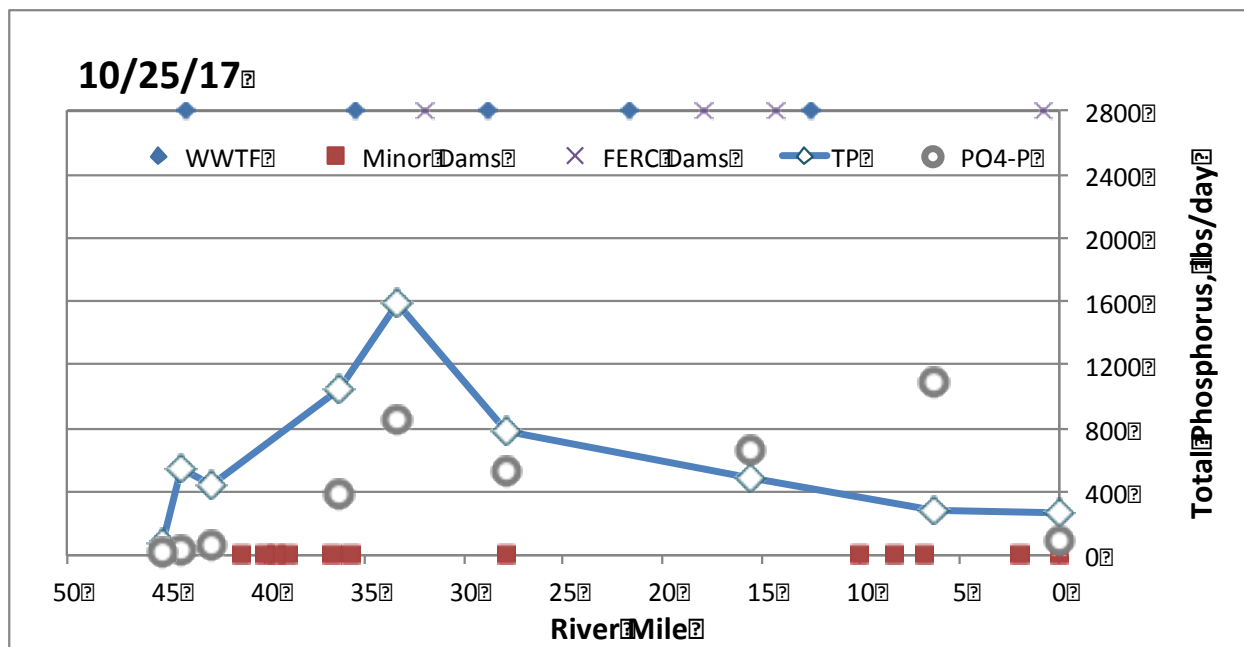


Figure 67: 25 October 2017 along stream load plots (TP, TN)

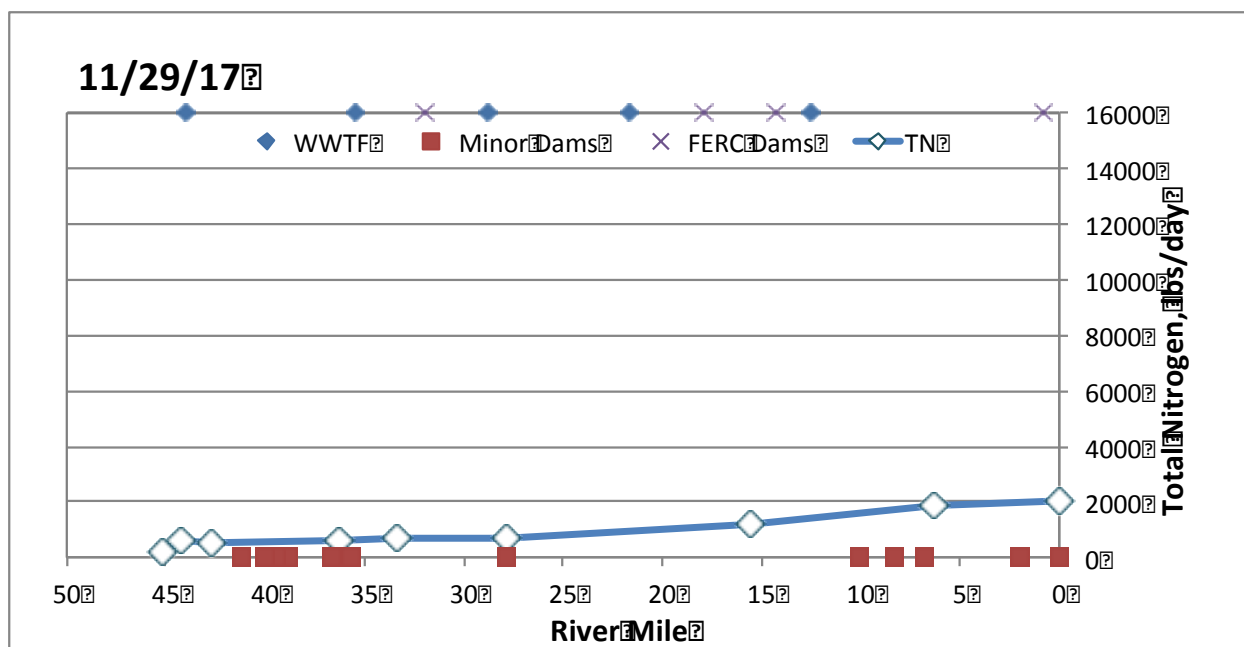
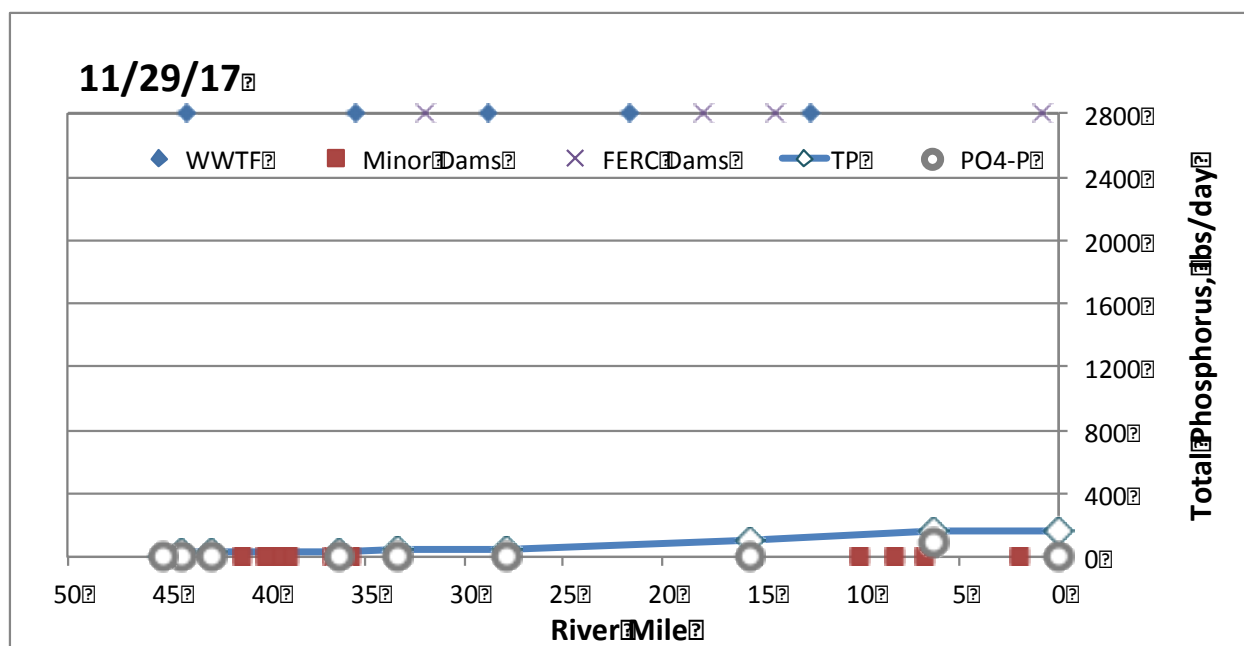


Figure 68: 29 November 2017 along stream load plots (TP, TN)

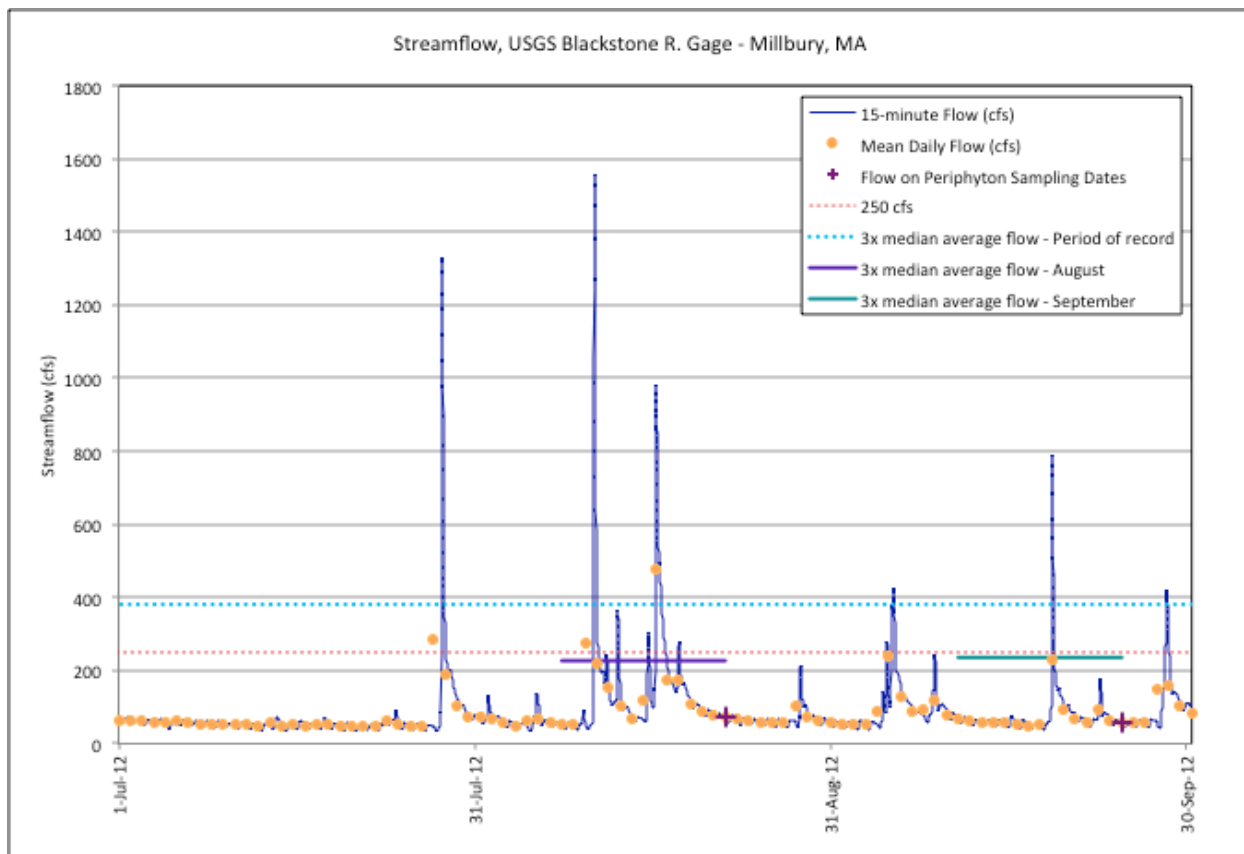


Figure 69: Summary of 2012 flows relative to periphyton sampling  
(3x median values based on daily data from 2002 – 2016 for consistency)



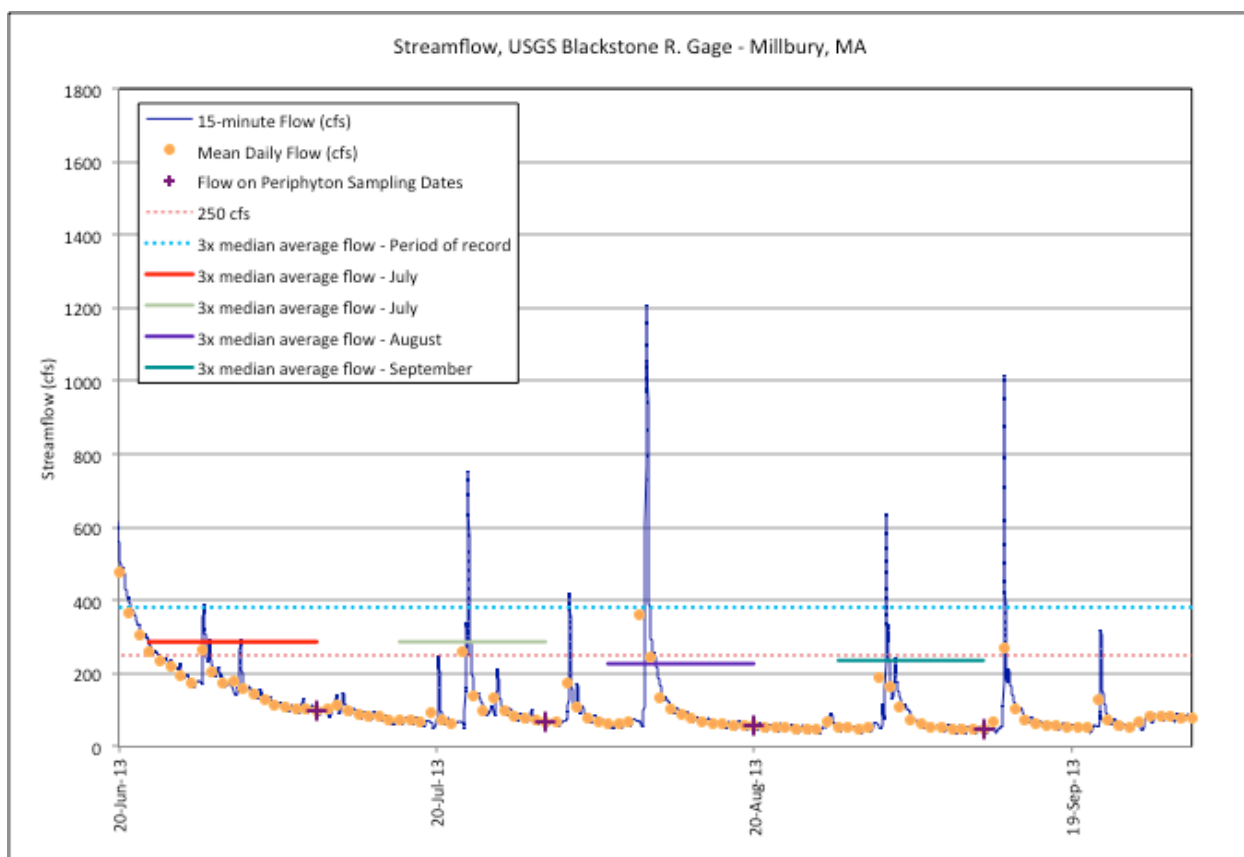


Figure 70: Summary of 2013 flows relative to periphyton sampling (3x median values based on daily data from 2002 – 2016 for consistency)

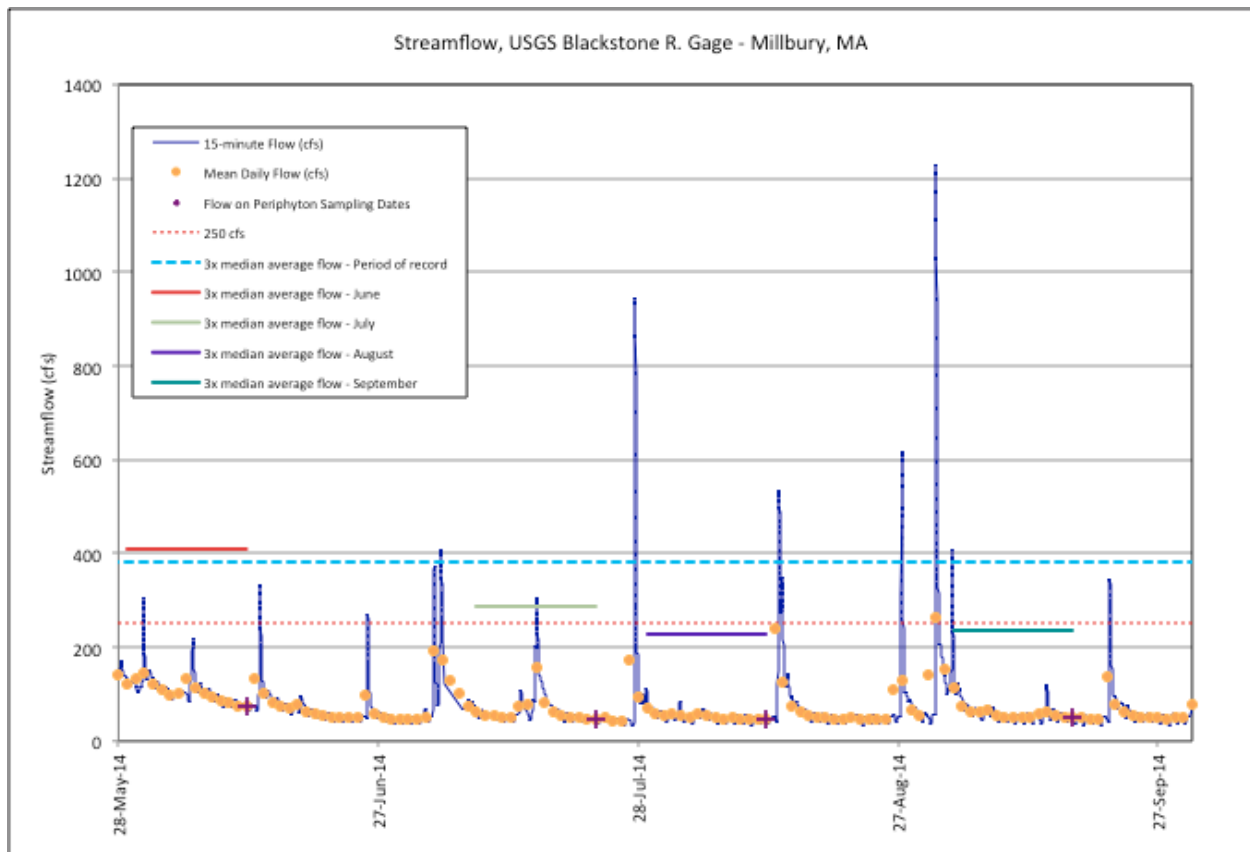


Figure 71: Summary of 2014 flows relative to periphyton sampling (3x median values based on daily data from 2002 – 2016 for consistency)

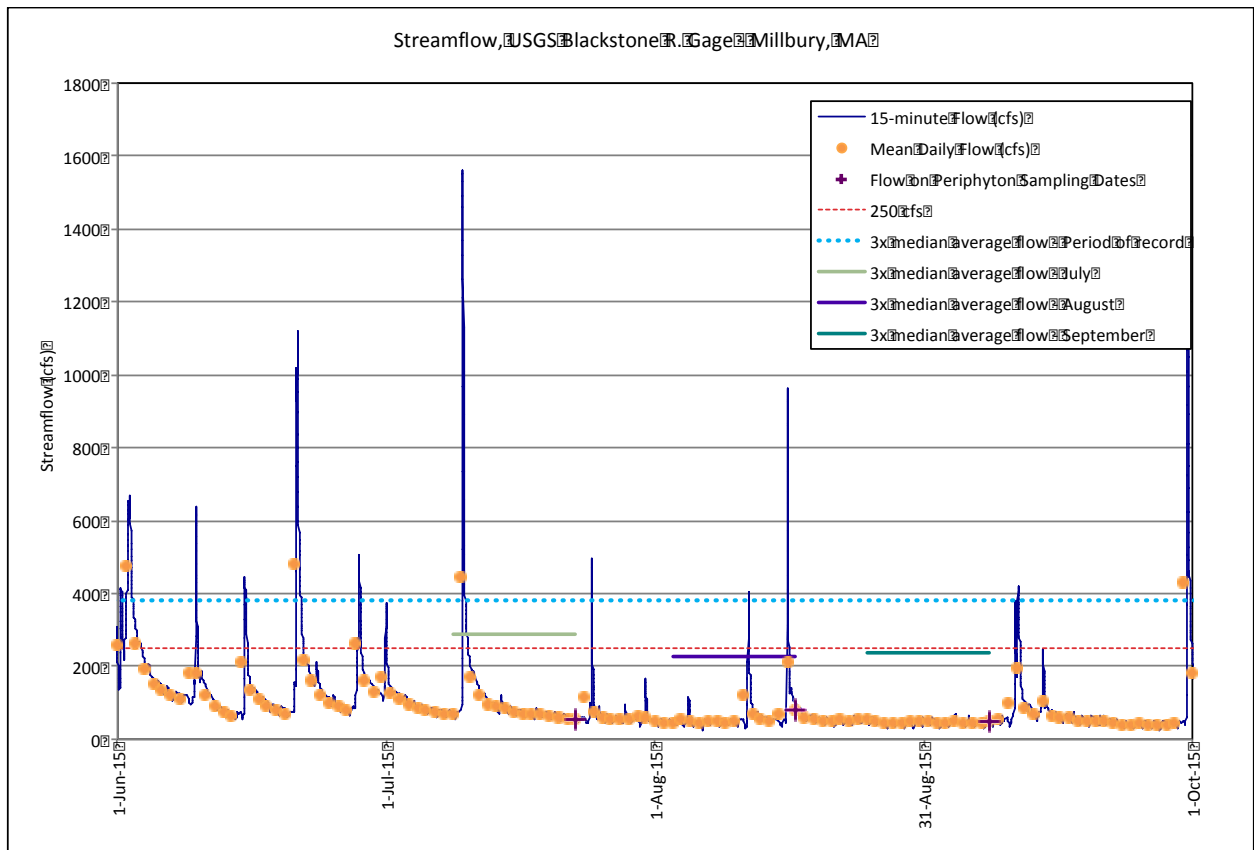


Figure 72: Summary of 2015 flows relative to periphyton sampling (3x median values based on daily data from 2002 – 2016 for consistency)

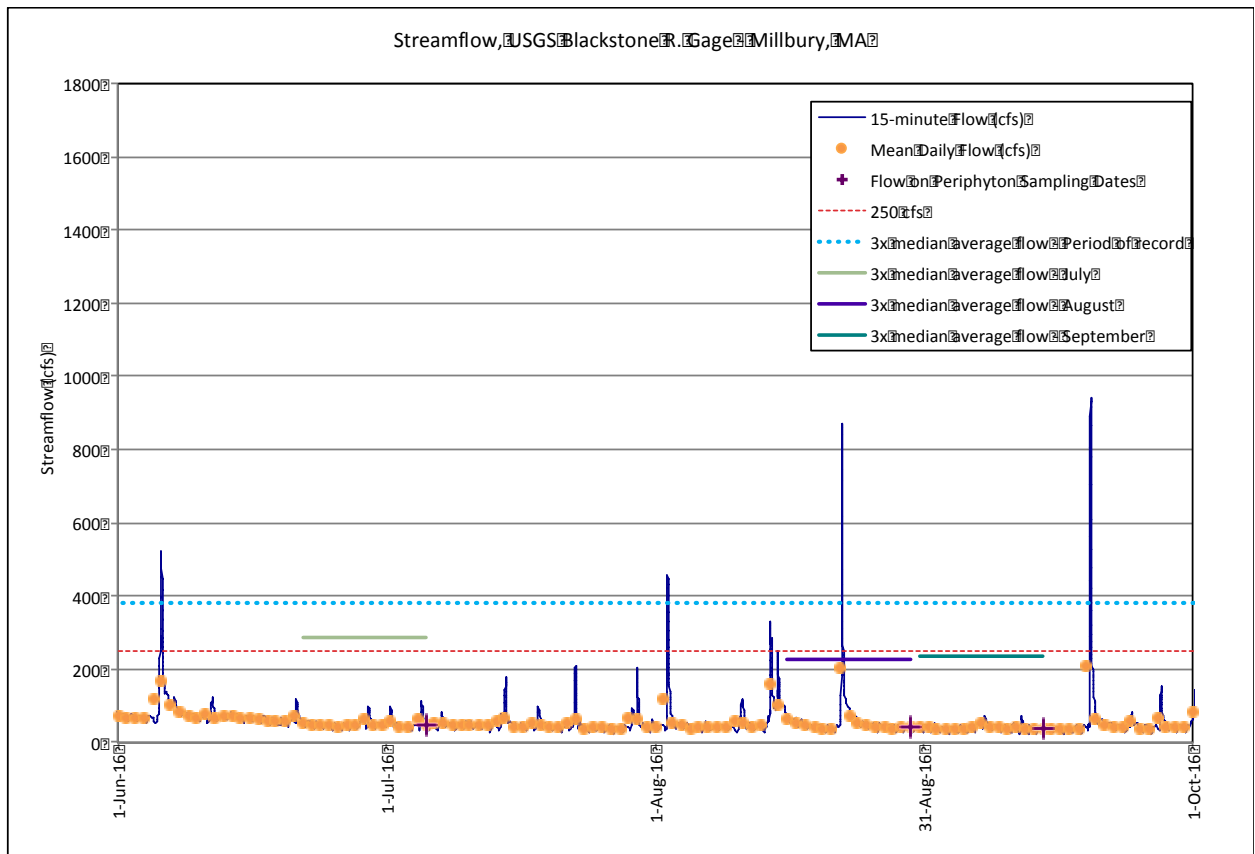


Figure 73: Summary of 2016 flows relative to periphyton sampling (3x median values based on daily data from 2002 – 2016 for consistency)

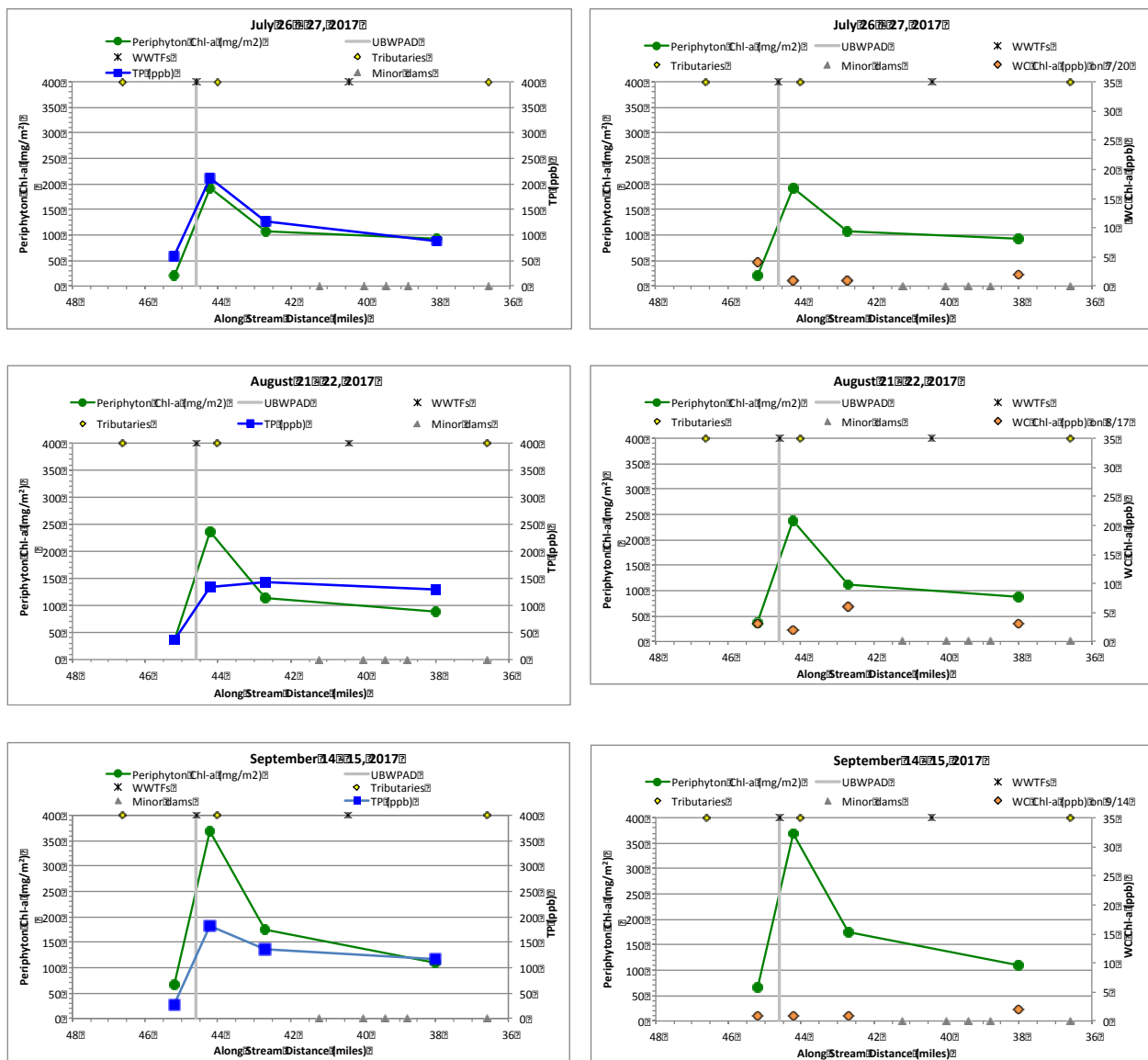


Figure 74: Periphyton along stream plots for individual sampling events, 2017

(Plots on the left show the periphyton and water column TP levels as measured on the three periphyton sampling dates. Plots on the right show the periphyton water column Chl-a data as measured on the three periphyton sampling dates.)

## **Appendix E: CDM Smith In-Situ Temperature and Dissolved Oxygen Monitoring Report**

# REPORT

## **In-Situ Temperature and Dissolved Oxygen Monitoring**

Blackstone River  
Jun – Nov 2017

Upper Blackstone Water  
Pollution Abatement  
District (UBWPAD)

April 5, 2018



# In-Situ Temperature and Dissolved Oxygen

## Monitoring: Blackstone River, Jun – Nov 2017

### Overview

Upper Blackstone Water Pollution Abatement District (Upper Blackstone), the Massachusetts Department of Environmental Protection (MassDEP), and the Water Resources Research Center at the University of Massachusetts (UMass) collaborated to deploy and manage four continuous temperature (T) and dissolved oxygen (DO) probes on the Blackstone River between June and November 2017. The meters recorded readings every 30 minutes. CDM Smith reviewed the data from the continuous metering program and corrected the DO data based on the monthly calibration points. This technical memorandum documents the continuous metering program and data review and correction procedures followed, presents the corrected data and assesses the corrected data relative to Massachusetts surface water quality standards and guidance for dissolved oxygen.

Upper Blackstone has been monitoring water quality in the Blackstone River since 2005. Since 2014, the sampling has been conducted in accordance with a sequence of approved Quality Assurance Project Plans (QAPP). In 2017, MassDEP offered to install the continuous T/DO meters to augment the existing data collection efforts. As continuous monitoring was not originally planned for the 2017 period, it is not covered in the current QAPP, valid for the 2017-2019 monitoring program. However, continuous monitoring was included in the 2014-2016 QAPP (UMass and CDM Smith, 2015). Therefore, the continuous metering results were assessed using the guidance in the 2014-2016 QAPP, which specifies:

Data will be corrected for drift as per USGS guidelines by collecting a paired reading from an identical, freshly calibrated hand-held unit prior to removal of the instrument for calibration and again following re-installation. The resulting offset will be used to apply a linearly increasing correction factor to the data as necessary.

### Meter Locations and Sampling Data

Continuous meters were deployed at four locations: one upstream and three downstream of the Upper Blackstone effluent discharge location, which is at river mile 44.4. Meter locations are described in Table 1 and shown in Figure 1. All four meters were deployed on June 2 and removed on November 2.



**Table 1: Blackstone River Continuous Meter Locations in 2017**

Meter	Location	River Mile	Sensor Depth (m)	Total Depth (m)	Notes
W0680	New Millbury St. Bridge, Worcester, MA; Upstream of UBWPAD effluent channel	45.2	0.4	0.5	
UBWPAD2	Downstream of UBWPAD effluent channel; Millbury, MA	44.6	0.4	n/a <sup>1</sup>	Meter failed on 9/7 and also found on the shore on 11/2; <i>in situ</i> measurements through 10/30
W1258	Central Cemetery, Millbury, MA	42.7	0.6	0.7	Meter failure 8/2
MID2(Depot)	Depot Street, Sutton, MA	38.0	0.8	1 <sup>2</sup>	

Notes: 1. Total depth not recorded by MassDEP field crew. 2. Field notes indicate that the total depth measurement is approximate at this site.

The four meters were calibrated and deployed by MassDEP. Calibration measurements were collected approximately monthly using a calibrated hand-held T/DO probe by UMass and Normandeau staff throughout the deployment period, while the last *in situ* calibration measurement was taken by MassDEP the day before the meters were removed. The DO measurements were collected next to and at the same depth as the *in situ* probe at each site. The continuous meters were not cleaned or recalibrated during the five-month monitoring period. The raw DO and temperature data are presented in Figure 2 and Figure 4, respectively.

**CDM  
Smith**

## Field Notes from Meter Deployment and Data Observations

The MassDEP staff collected detailed notes on site and meter conditions when the meters were deployed in June and when the meters were removed in November.

### *W0680 (Sonde ID 10476029)*

This meter was placed at a depth of 0.4 meters in 0.5 meters of water. The stream conditions were described as flowing through a fast riffle, slightly turbid, with a sewage/septic odor. When the meter was removed from the water in November the field crew noted that the meter had moved but remained in the water:

Cable was discovered running along bank but logger was still submerged; logger was in shallow water adjacent to instream structure associated with storm drain. Bank vegetation matted down in direction of flow.

It is not clear whether a high river flow event, which occurred on October 30, caused the meter displacement or whether meter displacement occurred earlier in the metering period.

### *UBWPAD 2 (Sonde ID 10476030)*

This meter was placed at a depth of 0.4 meters (the total water depth was not recorded). Field notes from the deployment date state that the water was flowing at around 3 – 5 ft/s, was brownish, with a musty odor.

The meter data indicate that the meter failed on September 7. The reason for meter failure is not known, but the meter was in the river when Normandeau collected the September 15 calibration point. However, based on MassDEP's notes, the meter did leave the water at some point during the metering program:

Out of water high on bank entangled with large dead branch. Swept down vegetation shows evidence [of] recent high water.

The T/DO record (see grey line in Figure 2) shows a significant temperature drop and a corresponding increase in measured DO (and DO saturation) during the late October high flow event. This suggests that the meter was removed from the water at the very end of the metering program.

### *W1258 (Sonde ID 10513780)*

This meter was placed at a depth of 0.6 meters in 0.7 meters of water. There was no reported odor, turbidity, or water color on the day of deployment. The meter was functional throughout the entire metering program, and the field crews did not note any evidence of sonde movement during the metering program.

### *MID2(Depot) (Sonde ID 10513781)*

This meter was placed at a depth of 0.8 meters in approximately 1 meter of water. The water was flowing with no odor, slightly turbid, an “unobservable” water color. The meter was functional throughout the entire metering program, and the field crew did not note any evidence of sonde movement during the metering program.

## Data Correction Procedures

Following the guidance in the 2014-2016 QAPP, the procedures described in the USGS guidance document *Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting* (USGS Techniques and Methods 1-D3)<sup>1</sup> were used to assess continuous temperature and dissolved oxygen data. In addition, the USGS procedures were used to correct the dissolved oxygen data for total drift, which combines fouling and meter drift.

The procedure used to correct the DO data collected in this study is described below.

1. Data were corrected for meter drift when the deviation between the continuous monitoring data and the calibration points differed by +/- 0.3 mg/l or 5% (whichever was greater). Correction was done using a two-point linear algorithm, assuming that the rate of drift is constant between calibration sample points. The percentage error at each calibration point was calculated as:

$$\%C_d = 100 \left( \frac{V_s - V_c}{V_c} \right)$$

where  $V_s$  is the value of the DO calibration measurement using the hand-held probe and  $V_c$  is the continuous meter reading at the same time. The percentage error was linearly interpolated between the two sampling points, and the continuous data were adjusted by the linearly interpolated percentage error. The final result is an adjusted dataset that matches the calibration points.

Two exceptions to this procedure occurred.

- As described in Table 1, two meters (UBWPAD2 and W1258) began reporting erroneous results midway through the monitoring period. These results were discounted.
- The dates when UBWPAD2 and W1258 failed did not coincide with calibration points. The UBWPAD2 data were truncated at the last valid calibration point (8/22). The data at W1258 did not meet the USGS quality guidance (discussed below) midway between the two calibration points bracketing the failure. Therefore, the W1258 data were truncated on 7/24, after which the data were deemed not valid.

Meter data accuracy was assessed using the classifications listed in Table 2. For dissolved oxygen, a classification is assigned based on the larger of the concentration or

<sup>1</sup> Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A. (2006). *Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting*. USGS Techniques and Methods 1-D3. <http://pubs.water.usgs.gov/tm1d3>.

percentage differences (on an absolute value basis) comparing the raw and corrected meter data.

**Table 2: Continuous Meter Accuracy Classifications for DO and Temperature<sup>1</sup>**

Data Type	Measurement Type	Excellent	Good	Fair	Poor	Not Valid
DO	Conc. or % Diff.	$\leq \pm 0.3$ mg/l or $\leq \pm 5\%$	$\pm 0.3$ - $0.5$ mg/l or $\pm 5$ - $10\%$	$\pm 0.5$ - $0.8$ mg/l or $\pm 10$ - $15\%$	$\pm 0.8$ - $2$ mg/l or $\pm 15$ - $20\%$	$> 2$ mg/l or $> 20\%$
Temperature		$\leq \pm 0.2^{\circ}\text{C}$	$\pm 0.2 - 0.5^{\circ}\text{C}$	$\pm 0.5 - 0.8^{\circ}\text{C}$	$\pm 0.8 - 2.0^{\circ}\text{C}$	$> 2.0^{\circ}\text{C}$

1. Modified from Table 18 in USGS (2006)

For this assessment, meter drift was assumed to occur linearly between calibration points, which means that the accuracy assessment could be independently evaluated for each 30-minute meter reading throughout the period of record.

## Post Deployment Calibration and Fouling Assessment

MassDEP calibrated each of the four meters prior to deployment, and assessed calibration drift and fouling in the laboratory post-deployment. The post-deployment assessment consisted of (1) allowing the meter to equilibrate in a 100% saturation environment and reading the reported value and (2) cleaning the sensor and then repeating the analysis in (1). Two post deployment determinations are made:

- Drift - If the meter calibration was stable (i.e., did not drift) then the meter would read 100% saturation in the first measurement.
- Fouling - If significant fouling occurred then the meter reading would be substantially different in the second measurement.

Table 3 presents the post-deployment meter tests and an assessment of the meter drift.

**Table 3: Post Deployment Meter Calibration and Fouling Assessment**

Meter	Pre-Cleaning					
	Temperature (°C)	Measured DO Concentration (mg/l) <sup>1</sup>	DO Saturation at Lab Temperature (mg/l) <sup>2</sup>	Measured DO Saturation (%) <sup>3</sup>	ΔDO (mg/l)	ΔDO (%)
W0680	20.66	8.91	8.80	101.3	0.11	1
UBWPAD2	20.54	8.99	8.84	101.7	0.15	2
W1258	20.52	9.44	8.84	106.8	0.6	6
MID2(Depot)	20.50	3.67	8.84	41.5	-5.17	-141
Meter	Post-Cleaning					
	Temperature (°C)	Measured DO Concentration (mg/l) <sup>1</sup>	DO Saturation at Lab Temperature (mg/l) <sup>2</sup>	Measured DO Saturation (%) <sup>3</sup>	ΔDO (mg/l)	ΔDO (%)
W0680	20.96	8.91	8.73	102.1	0.18	2
UBWPAD2	20.72	8.96	8.79	101.9	0.17	2
W1258	20.68	9.93	8.79	106.1	1.14	11
MID2(Depot)	20.50	8.94	8.82	101.4	0.12	1

- Notes:
1. Measured DO in the lab, 100% saturated conditions.
  2. DO saturation concentration at lab temperature. This is the concentration expected for the Measured DO Concentration if the meter was perfectly calibrated.
  3. DO saturation concentration computed from measured DO.

Fouling is assessed by comparing the saturation percentage between the pre-cleaning and the post-cleaning measurements. If the measurements are significantly different then fouling is interfering with meter performance. The data in Table 3 indicated that meter fouling likely compromised meter readings at MID2(Depot).

Post deployment meter drift is assessed by comparing the difference between the measured DO concentration and the calculated saturation DO concentration in laboratory conditions. If the difference exceeds 0.3 mg/l or 5% then sensor drift has occurred (based on USGS guidelines). The data in Table 3 indicate that sensor drift occurred at W1258. The final calibration point at this meter (7/28) had an absolute difference of 1.42 mg/l or 24%, which exceeds the “not valid” criterion in Table 3. Since significant fouling did not occur, it is likely that significant meter drift had already occurred before the meter failed a few days later.

## Final Corrected Data

Figure 2 shows the raw DO concentration values (blue), the corrected DO concentration values (yellow), calculated dissolved oxygen saturation concentration using the temperature recorded on the meter (green), and calibration sample points (red x) for each of the four sampling locations. For each continuous meter, Table 4 lists a comparison of the synchronous continuous meter DO and hand-held calibration meter values, and provides the corresponding USGS accuracy classification. Data is not shown for UBWPAD2 on 11/2/17 because the continuous meter was not in the water. The corrected DO data are also shown in Figure 3 without the raw data and calibration sample points,



**Table 4: Comparison of DO Calibration Data with Continuous Meter Data**

Site	Calibration Reading Date	Calibration DO Reading (mg/l)	Continuous DO Reading (mg/l)	Difference in DO Readings (mg/l)	Percent Difference in DO Readings (%)	Accuracy Rating
W0680	6/21/2017	7.86	7.93	-0.07	1%	Excellent
	7/6/2017	8.11	8.18	-0.07	1%	Excellent
	7/28/2017	8.15	8.37	-0.22	3%	Excellent
	8/21/2017	9.33	7.81	1.52	-19%	Poor
	9/15/2017	8.59	7.29	1.3	-18%	Poor
	11/2/2017	10.48	10.39	0.09	-1%	Excellent
UBWPAD2	6/21/2017	8	7.99	0.01	0%	Excellent
	7/6/2017	8.27	7.9	0.37	-5%	Good
	7/28/2017	7.82	7.05	0.77	-11%	Fair
	8/22/2017	8.17	7.47	0.7	-9%	Fair
	9/15/2017	8.11	4.16	3.95	-95%	Not Valid <sup>1</sup>
	11/2/2017	10.22	n/a <sup>2</sup>	n/a <sup>2</sup>	n/a <sup>2</sup>	n/a <sup>2</sup>
W1258	6/21/2017	8.47	8.58	-0.11	1%	Excellent
	7/6/2017	9.89	9.88	0.01	0%	Excellent
	7/28/2017	7.45	6.03	1.42	-24%	Not Valid <sup>1</sup>
	8/22/2017	7.38	-0.02	7.4	37000%	Not Valid <sup>1</sup>
	9/14/2017	8.58	-0.02	8.6	43000%	Not Valid <sup>1</sup>
	11/2/2017	9.31	9.89	-0.58	6%	Not Valid <sup>1</sup>
MID2(Depot)	6/21/2017	8.38	8.47	-0.09	1%	Excellent
	7/6/2017	9.11	9.16	-0.05	1%	Excellent
	7/28/2017	8.4	8.59	-0.19	2%	Excellent
	8/21/2017	9.91	9.34	0.57	-6%	Fair
	9/14/2017	9.8	8.53	1.27	-15%	Poor
	11/2/2017	10.48	10.3	0.18	-2%	Excellent

Note: 1. Meter failure occurred during deployment. 2. Meter not in water on 11/2 sampling date

Interpolated meter accuracy classifications are superimposed on Figure 2 describing the relative quality of data at each period within the monitoring period. The accuracy of the meter operation varied by meter and period. In general, accuracy declined through the summer months.

For the meters with a complete record (W0680 and MID2(Depot)), the entire timeseries was adjusted using the calibration points and assessed relative to the USGS accuracy classification described in Table 2. The two meters that failed in the middle of the monitoring period were corrected using concurrent calibration points.

- The meter at the UBWPAD2 location failed on September 7. Since the last calibration point before meter failure was collected on August 22, the period of valid data extends through the August 22 calibration point.

- Data from the meter at W1258 spans the shortest period (June 2 to July 24), only 38 valid days. This period of invalid data began on July 25<sup>th</sup> following the USGS data accuracy rating protocol, where the magnitude of the correction required to match the calibration point that exceeded 2 mg/l. However, on July 24<sup>th</sup> the meter recorded a 5.5 mg/l drop in dissolved oxygen from 6.7 mg/l to 1.2 mg/l over 2 hours; oxygen levels then remained around 1 mg/l for about 2 days, after which levels slowly recovered back to about 7.5 mg/l over 2 days, prior to meter failure. Lacking a rationale for such a drop, and given that this drop occurs during a period of “poor” data quality and is immediately followed by invalid data based on the USGS protocol, the July 24 data after the 5.5 mg/l drop are also considered not valid for this assessment based on engineering judgement.

The four continuous meters also recorded water temperature at 30-minute intervals. Figure 4 shows the temperature timeseries at each meter compared against the calibration points collected by UMass and Normandeau. A comparison between the continuous probe temperature and the independent grab temperature is presented in Table 5 for all four meters.

**Table 5: Comparison of Temperature Calibration Data with Continuous Meter Data, UBWPAD 2017 Continuous Meter Deployment**

Site	Date	Calibration T (°C)	Continuous T (°C)	T Error (°C)	T Error (%) <sup>1</sup>	Accuracy Rating
W0680	6/21/2017	24	24	0	0.0%	Excellent
	7/6/2017	23.8	23.72	0.08	-0.3%	Excellent
	7/28/2017	19.65	19.82	-0.17	0.9%	Excellent
	8/21/2017	20.85	21.06	-0.21	1.0%	Good
	9/15/2017	20.31	20.34	-0.03	0.1%	Excellent
	11/2/2017	11.75	11.78	-0.03	0.3%	Excellent
UBWPAD2	6/21/2017	22.27	22.24	0.03	-0.1%	Excellent
	7/6/2017	22.9	22.76	0.14	-0.6%	Excellent
	7/28/2017	22.12	22.38	-0.26	1.2%	Good
	8/22/2017	24.07	24.16	-0.09	0.4%	Excellent
	9/15/2017	23.58	23.64	-0.06	0.3%	Excellent
	11/2/2017	12.02	n/a <sup>2</sup>	n/a <sup>2</sup>	n/a <sup>2</sup>	n/a <sup>2</sup>
W1258	6/21/2017	22.56	22.54	0.02	-0.1%	Excellent
	7/6/2017	24	23.74	0.26	-1.1%	Good
	7/28/2017	21.32	21.52	-0.2	0.9%	Excellent
	8/22/2017	22.72	22.8	-0.08	0.4%	Excellent
	9/14/2017	22.64	22.7	-0.06	0.3%	Excellent
	11/2/2017	14.25	14.04	0.21	-1.5%	Good
MID2(Depot)	6/21/2017	23.63	23.58	0.05	-0.2%	Excellent
	7/6/2017	23.8	23.64	0.16	-0.7%	Excellent
	7/28/2017	20.21	20.22	-0.01	0.0%	Excellent
	8/21/2017	23	22.98	0.02	-0.1%	Excellent
	9/14/2017	22.51	22.6	-0.09	0.4%	Excellent
	11/2/2017	13.36	13.14	0.22	-1.7%	Good



Note: 1. While the percent error is presented for reference, the USGS protocol only considers the absolute temperature difference in the accuracy assessment for temperature data. 2. Meter not in water on 11/2 sampling date

The continuous temperature data accuracy was generally always equal to or better than the 0.2°C threshold used by USGS to differentiate between the “Excellent” and “Good” categories and to prompt meter recalibration. The temperature data were not corrected in this analysis.

## Discussion

The corrected dissolved oxygen and 100% saturation concentration data are presented in Figure 4. The corrected dissolved oxygen saturation percentage is presented in Figure 5, where the saturation concentration was calculated from the sonde temperature record at each meter. These data were compared to the Massachusetts water quality standards for Class B freshwater as well as the guidance described in the 2016 CALM, as follows:

- Minimum DO concentration greater than 5 mg/l (MA Class B Standard)
- DO saturation below 125% (CALM)
- Maximum diel DO change less than 3 mg/l (CALM)

The data were recorded at 30-minute intervals and the percent of time or number of days that the data did not meet the water quality criteria is provided in Table 6. The percentages are calculated as the actual number of 30-minute data intervals either below 5 mg/l or above 125% saturation compared against the total number of valid 30-minute data intervals. The days where the diel change in dissolved oxygen exceeds 3 mg/l was calculated as a count of the number of days where the difference between the minimum and maximum measurement on that day exceeded 3 mg/l.

**Table 6: Summary of Continuous DO Data Against MA Water Quality Standards and Guidance**

Metric	W0680	UBWPAD2	W1258	MID2(Depot)
Days of valid data	139	62	38	139
% of the time DO < 5.0 mg/l	0.3%	4.8%	0.6%	0%
% of the time DO >125% Saturation	0%	0%	0%	0%
Days where Diel $\Delta$ DO > 3.0 mg/l	4	6	14	4

Data from each of the meters show compliance with the Massachusetts minimum dissolved oxygen standard of 5 mg/l nearly all, if not all, of the time. Upstream of the MID2(Depot) meter there are limited instances when dissolved oxygen was <5 mg/l: in mid-July at UBWPAD2 and W1258, and in early October at W0680. The dip in DO in late October was also seen at the MID2(Depot) location but the minimum DO remained above 5 mg/l. The comparison to the CALM guidance indicates that at no time did the dissolved oxygen levels exceed 125% saturation, while there were a handful of days at each meter (except W1258 when there were additional days) when the daily diel variation in dissolved oxygen exceeded 3.0 mg/l.



Figure 2: Raw and Corrected Dissolved Oxygen Data

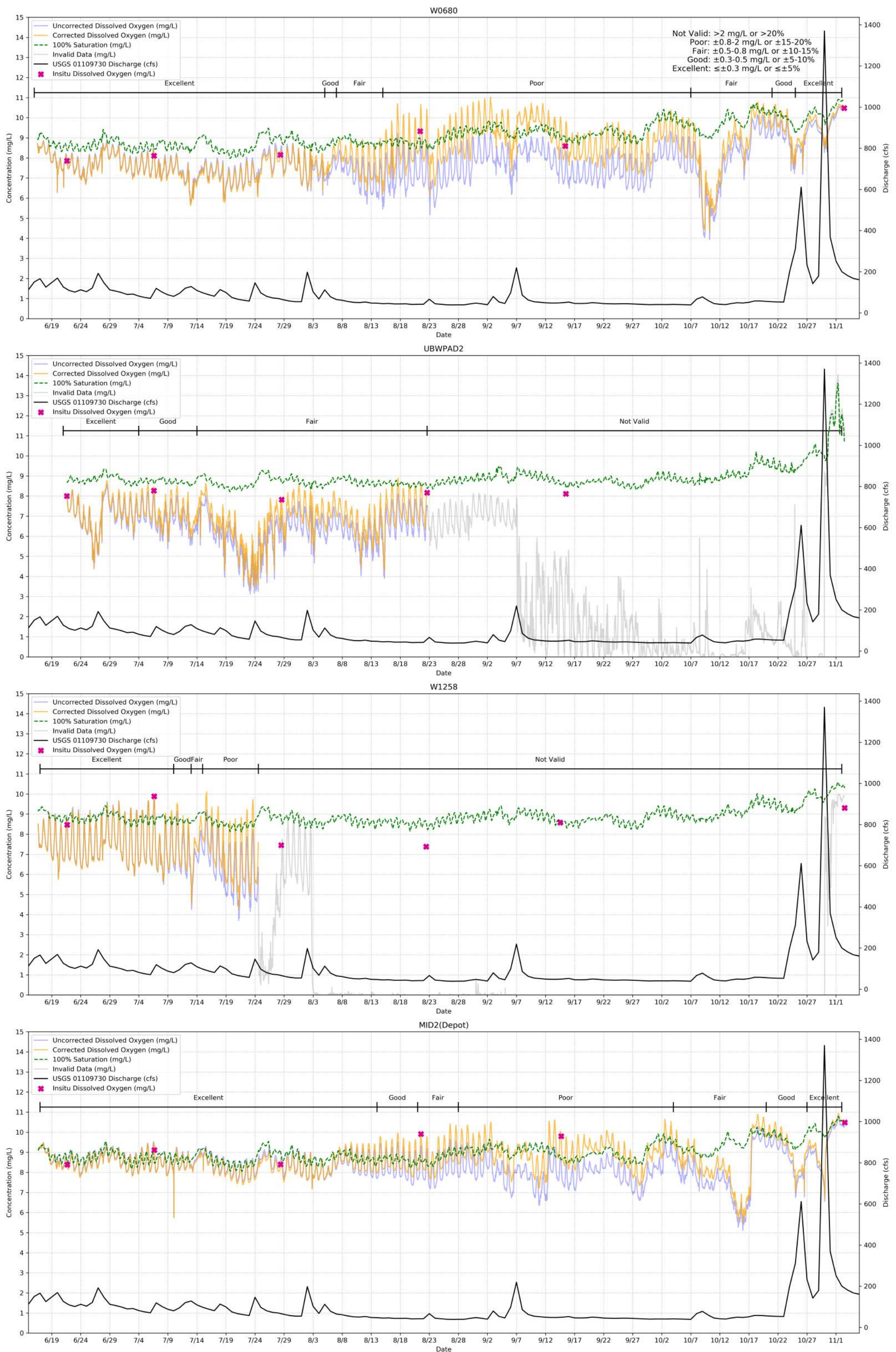




Figure 3: Corrected Dissolved Oxygen Data

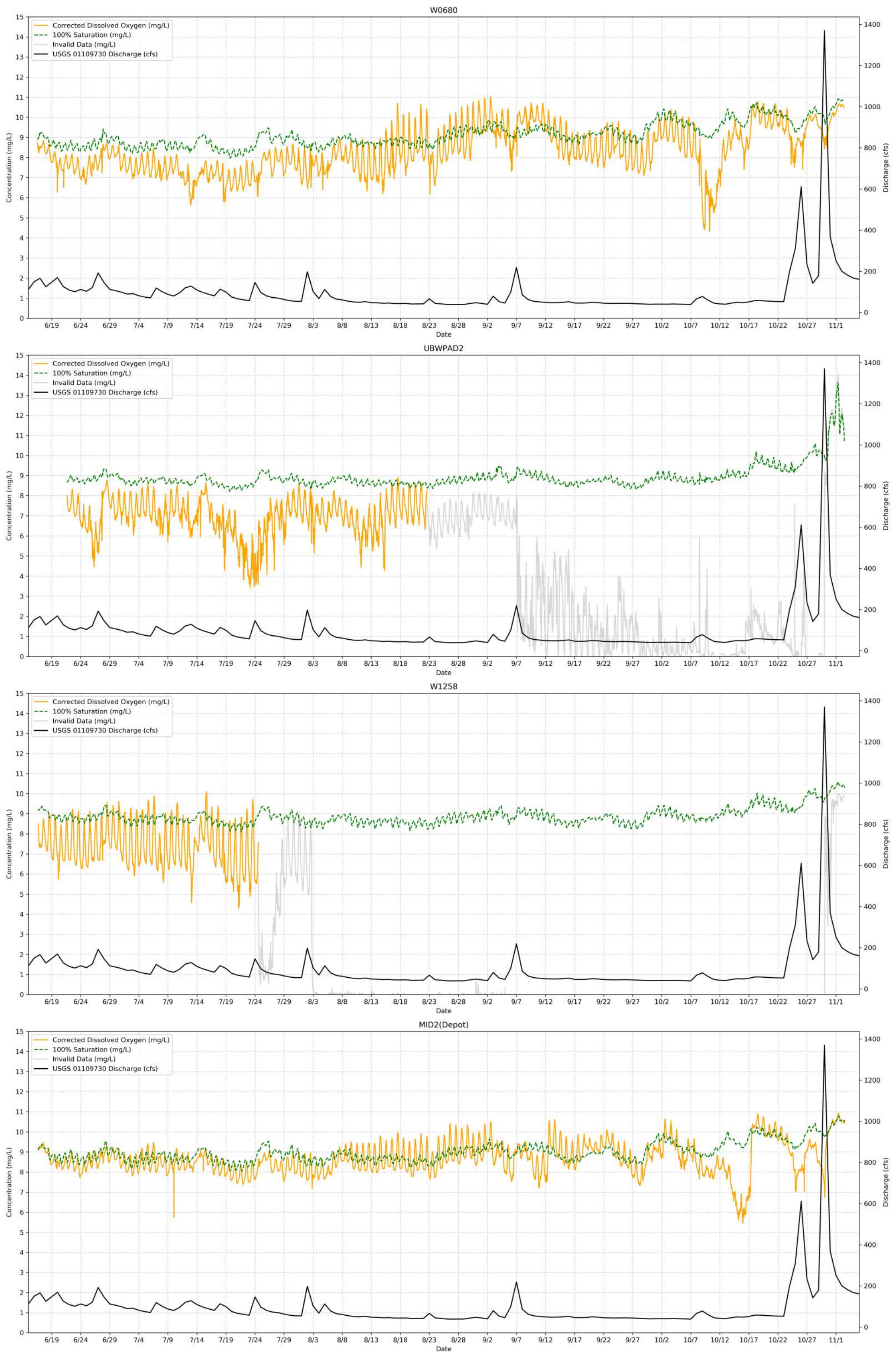




Figure 4: Raw Temperature Data

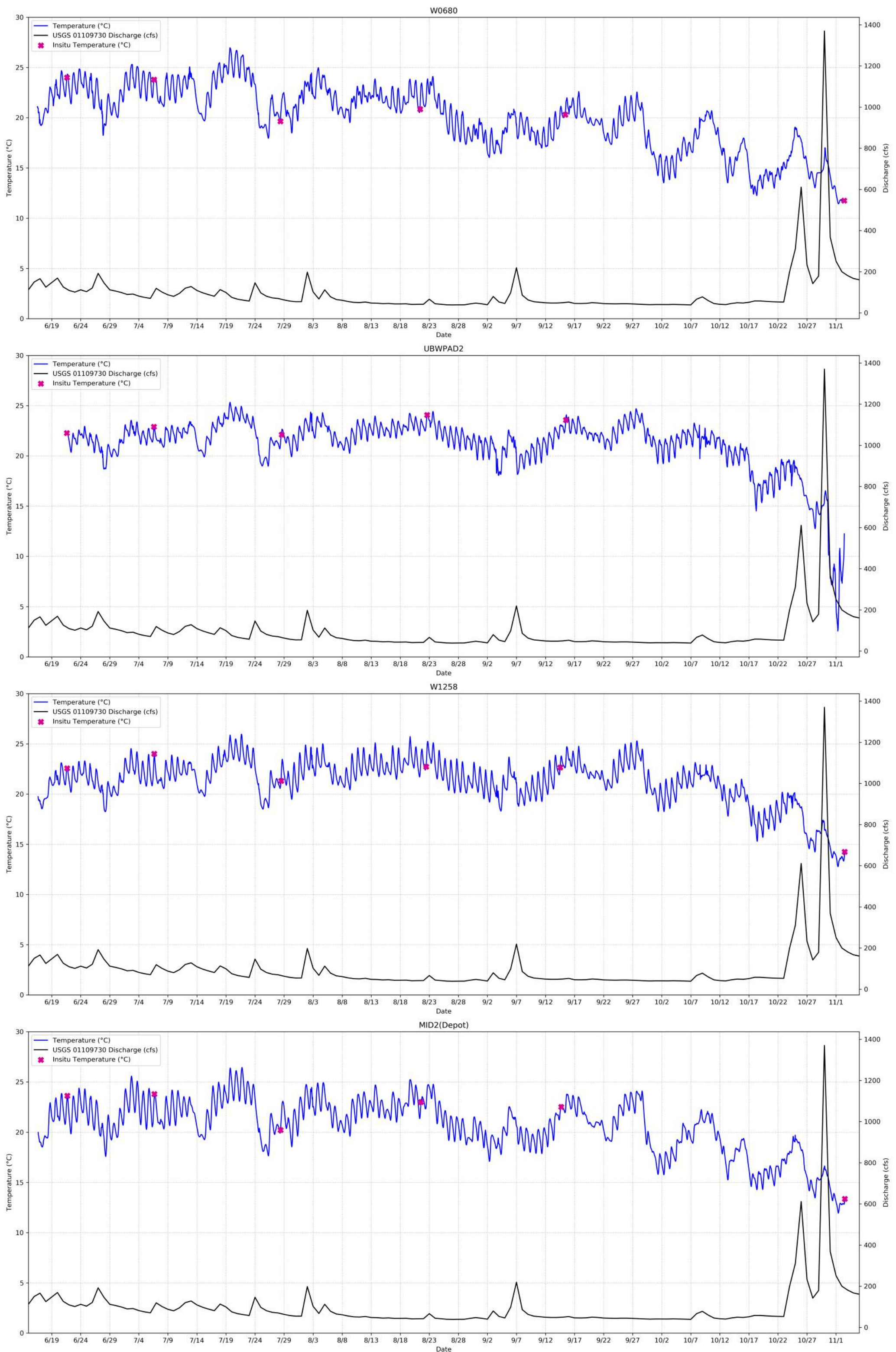




Figure 5:Corrected Dissolved Oxygen Data as % Saturation

