Blackstone River Water Quality Monitoring Program
2015/2016 Sampling Seasons Report

Prepared for

Karla Sangrey, Director

Upper Blackstone Water Pollution Abatement District

50 Route 20

Millbury, MA 01527-2199

Prepared by

Dr. Paula L. Sturdevant Rees

Massachusetts Water Resources Research Center

209 Agricultural Engineering Building

250 Natural Resources Way

University of Massachusetts

Amherst, MA 01003

May 2017

Acknowledgements

The UMass Amherst Water Resources Research Center (WRRC) wishes to thank the staff of both the Upper Blackstone Water Pollution Abatement District (Upper Blackstone) and the Narragansett Bay Commission (NBC). Funding for the work was provided by the Upper Blackstone under the oversight of Karla Sangrey. Upper Blackstone laboratory staff assist with sampling collection, run several of the laboratory analyses on collected samples, and generously share their laboratory space on sampling days. Special thanks go to Upper Blackstone staff Deb LaVergne, Denise Prouty, Cindy D'Alessandro, and Sharon Lawson. NBC coordinates their riverine sampling with our crews, enabling co-collection of samples for comparison, and shares their results. Special thanks goes to NBC staff Christine Comeau, Bekki Songolo, jeff Tortorella, and Sara Nadeau. The support of Normandeau Associates for periphyton sampling is also greatly appreciated, including Mark Hutchins, Don Mason, Bob Helmers, Joel Derry, and Lisa Ferrisi. The UMass Dartmouth (UMD) School for Marine Science and Technology (SMAST) lab completes analysis of the nitrogen series. Special thanks go to UMD staff Sara Sampieri Horvet and director David Schlezinger. Travis Drury led WRRC fieldwork and sample analysis with the assistance of Derek Smith. Without the support of these organizations and individuals this work would not be possible.

Authors: Dr. Paula L. Sturdevant Rees and Travis Drury
Massachusetts Water Resources Research Center

Available on line at: http://wrrc.umass.edu/research/wrrc-projects

Suggested citation:
Massachusetts Water Resources Research Center. *Blackstone River Water Quality Monitoring Program 2015/2016 Sampling Season Report*. MaWRRC, Amherst, MA. February 2017.

Table of Contents

List of Figures

List of Tables

Blackstone River Water Quality Monitoring Program
2015 and 2016 Field Seasons

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 the Upper Blackstone along the mainstem of the Blackstone River between April and November in 2015 and 2016. 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 2012-2016 are also presented. Additional details of periphyton and macroinvertebrate sampling are available under separate cover from Normandeau Associates[1]. 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 the Upper Blackstone's monitoring program are publicly available by request (email: tdrury@umass.edu) or via download through the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI, www.cuahsi.org) Hydrologic Information System (HIS) database and servers (his.cuahsi.org), which are sponsored by the National Science Foundation.

2.0 Background

The Blackstone River watershed encompasses an area of approximately 480 mi^2 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

[1] Blackstone River 2015 Periphyton and Benthic Macroinvertebrate Study Final Report (Normandeau Associates, Inc., 2016); Blackstone River 2016 Periphyton 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 402nd 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 (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, the 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. The 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 Upper Blackstone's wastewater treatment plant effluent. The Upper Blackstone's routine river monitoring program provides a multi-year data record over the period 2012 – 2016.

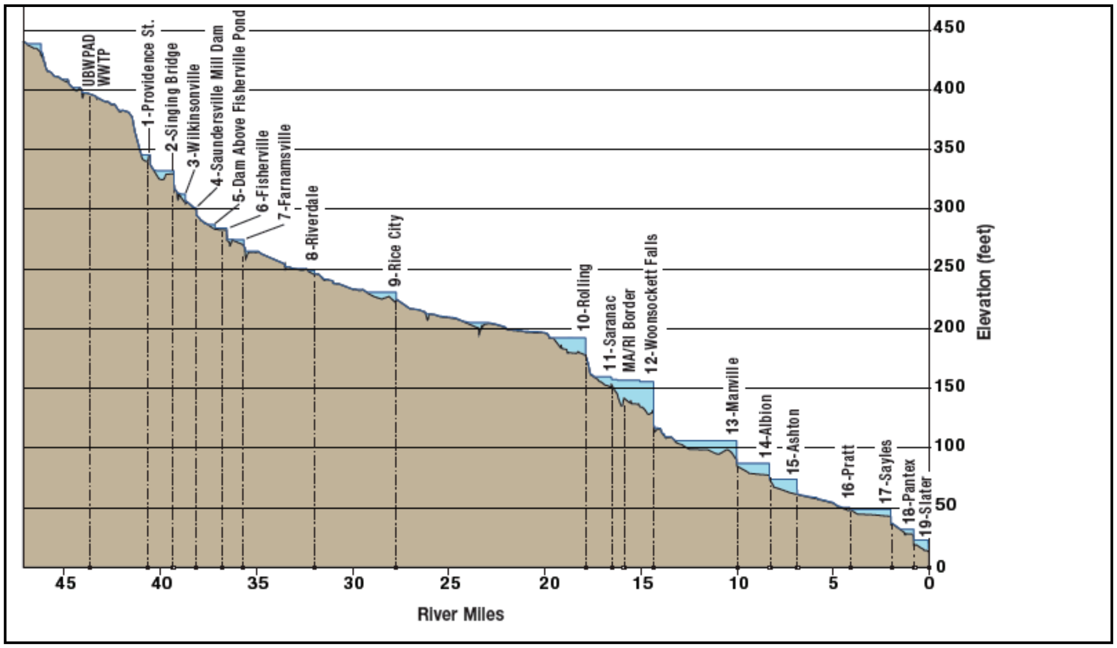


Figure 1: River elevation profile

Table 1: WWTFs in the Blackstone River watershed

WWTP	Receiving Waters	2016 Average Daily Flow (MGD)
Upper Blackstone	Blackstone River	28.8
Woonsocket	Blackstone River	4.9
Grafton	Blackstone River	1.6
Northbridge	Blackstone River	0.88
Burrillville	Branch River	0.86
Uxbridge	Blackstone River	0.84
Hopedale	Mill River	0.38
Douglas	Mumford River	0.19
Upton	West River	0.15

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 Confluence	22.0	Uxbridge WWTF
46.4	Worcester CSO	17.8	Tupperware Dam
44.4	UBPWAD 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		

The Upper Blackstone's routine river monitoring program data indicate that total nitrogen, total phosphorus, and algal growth in the river as measured by chlorophyll-a are decreasing. While the UBWPAD's monitoring program has always followed strict sample collection and analysis procedures, the 2015 and 2016 sampling seasons were the first conducted under a QAPP approved by MassDEP. UMass worked closely with MassDEP's data quality managers and scientists to finalize the QAPP. Having the approved QAPP in place allows MassDEP to use the data in the agency's future watershed assessments.

3.0 Blackstone Water Quality Sampling Program

In 2015 and 2016, 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. Normandeau Associates also conducted one macroinvetebrate survey during the summer of 2015. Sampling locations were selected based on several criteria, in order to:

- Provide reference data for the river above and below the confluence with the Upper Blackstone's effluent channel;
- Correspond with locations monitored by MassDEP in 2008;
- Correspond with long-term monitoring locations maintained by NBC;
- Build upon the 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 the Upper Blackstone's monitoring program, the data collected as part of this water quality-monitoring program are generally denoted "UMass", "2015 data" or "2016 data" in graphs and tables to avoid potential confusion with 1) the location where the Upper Blackstone effluent enters the Blackstone River and 2) the river monitoring location immediately downstream of this confluence. A brief overview of the 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 Quality Assurance Plan (approved by MassDEP in June 2015), 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 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.

Table 3: Blackstone River 2015 and 2016 sampling sites

Site ID#	Site Name	Lat	Lon	River Mile[2]	HSPF Reach[2]	Sampling Details[3]
[1]RSMD	Slater Mill Dam, Pawtucket, RI	41.877	-71.382	0.0	200	N
[1]R116	Rte 116 Bikepath Bridge, Pawtucket, RI	41.938	-71.434	6.3	228	N
[1]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 gage 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	--	PM
W1258	Central Cemetery, Millbury, MA	42.194	-71.766	42.7	392	NPM
UBWPAD2	New Confluence site, shifted downstream	42.206	-71.781	44.6	402	NP
W0680[4]	New Millbury St bridge, Worcester, MA	42.228	-71.787	45.2	414	NPM
UPS1	~500 meters downstream of McKeon Rd, Worcester, MA	42.242	-71.808	NA	NA	M
Mumford	100 meters downstream of confluence with Gilboa Brk, Uxbridge, MA	42.084	-71.695	NA	NA	M

1 Locations of co-sampling with NBC

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

3 Sampling Types: N = 9 sites, nutrients & chlorophyll-a 1 event/month; P = 4 sites, Periphyton event/month July - Sept; M = 5 sites, Macroinvertebrates, 1 event in August 2015.

4 W0680 is located between the Worcester CSO discharge and UBWPAD2.

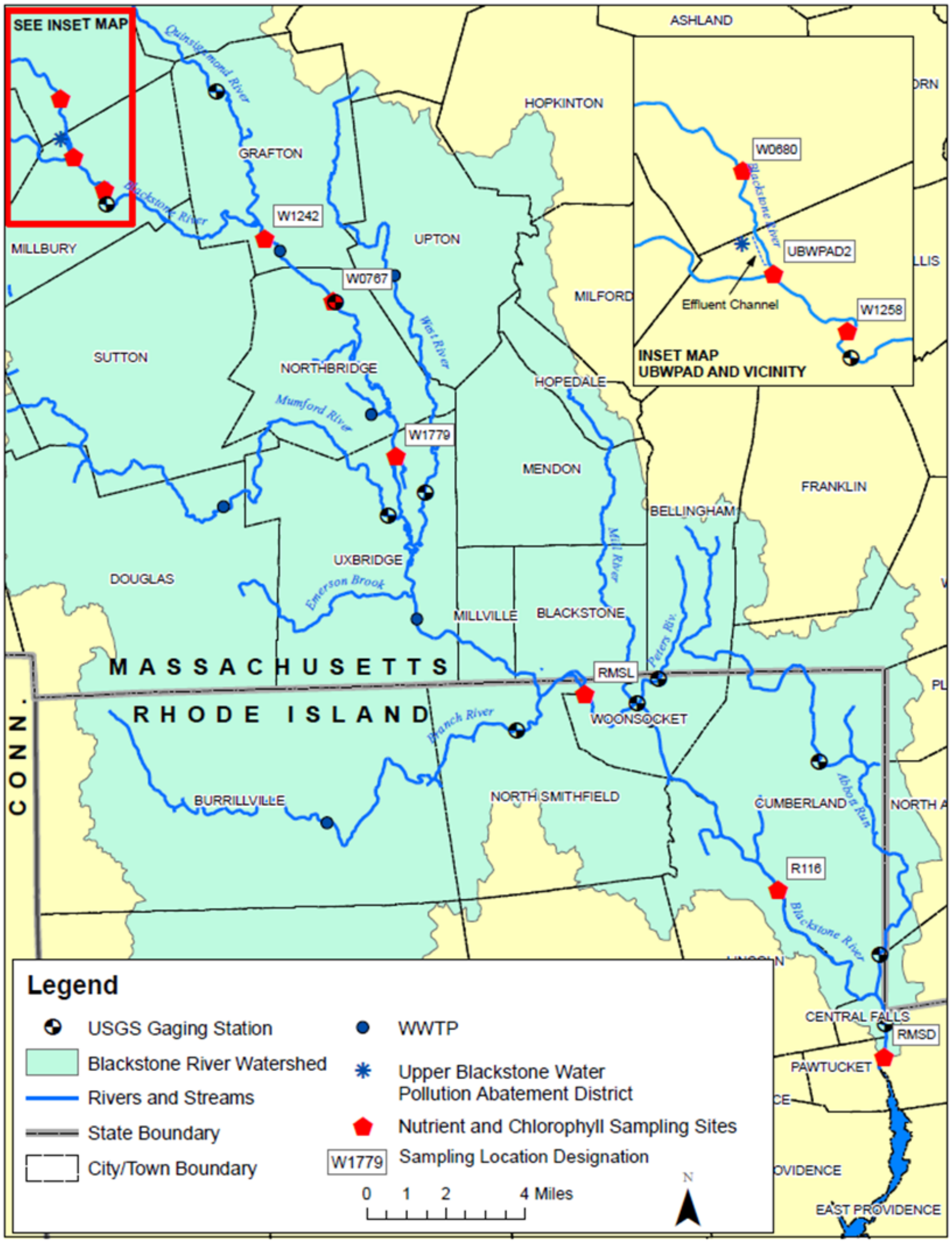


Figure 2: Blackstone River 2015 and 2016 Nutrient and Chlorophyll-a sampling sites

3.2 Sampling Dates and Data Collected

Sampling dates for the nutrient, chlorophyll-a, and periphyton monitoring program are summarized in Table 4 for 2015 and Table 5 for 2016. The macroinvertebrate sampling, not listed in the tables, occurred in August 2015.

Table 4: 2015 river nutrient and periphyton sampling dates

SITE	29-April, 2015 [a]	27-May, 2015 [a]	24-June, 2015 [a]	22-July, 2015 [a]	23-24 July, 2015 [b]	17-18 August, 2015 [b]	19-August, 2015 [a]	8-9 September, 2015[b]	16-September, 2015 [a]	15-October, 2015 [a]	12-November, 2015 [a]
RSMD	X[c]	X[c]	X[c]	X[c]			X[c]		X[c]	X[c]	X[c]
R116	X[c]	X[c]	X[c]	X[c]			X[c]		X[c]	X[c]	X[c]
RMSL	X[c]	X[c]	X[c]	X[c]			X[c]		X[c]	X[c]	X[c]
W1779	X[c]	X[c]	X[c]	X[c]			X[c]		X[c]	X[c]	X[c]
W0767	X[c]	X[c]	X[c]	X[c]			X[c]		X[c]	X[c]	X[c]
W1242	X[c]	X[c]	X[c]	X[c]			X[c]		X[c]	X[c]	X[c]
DEPOT					X[d]	X[d]		X[d]			
W1258	X[c]	X[c]	X[c]	X[c]	X[d]	X[d]	X[c]	X[d]	X[c]	X[c]	X[c]
UBWPAD2	X[c]	X[c]	X[c]	X[c]	X[d]	X[d]	X[c]	X[d]	X[c]	X[c]	X[c]
W0680	X[c]	X[c]	X[c]	X[c]	X[d]	X[d]	X[c]	X[d]	X[c]	X[c]	X[c]

Notes: [a] Nutrient + chlorophyll-a monthly sampling dates
[b] Periphyton sampling dates
[c] Full set of nutrients and chlorophyll-a data collected at this site/date
[d] Periphyton, XLM and limited nutrient data collected at this site/date
X - Data collection completed

Table 5: 2016 river nutrient and periphyton sampling dates

SITE	27-April, 2016 [a]	25-May, 2016 [a]	22-June, 2016 [a]	6 - 7 July, 2016 [b]	20-July, 2016 [a]	17-August, 2016 [a]	30 – 31 August, 2016 [b]	14-September, 2016 [a]	14-15 September, 2016[b]	13-October, 2016 [a]	9-November, 2016 [a]
RSMD	X[c]	X[c]	X[c]		X[c]	X[c]		X[c]		X[c]	X[c]
R116	X[c]	X[c]	X[c]		X[c]	X[c]		X[c]		X[c]	X[c]
RMSL	X[c]	X[c]	X[c]		X[c]	X[c]		X[c]		X[c]	X[c]
W1779	X[c]	X[c]	X[c]		X[c]	X[c]		X[c]		X[c]	X[c]
W0767	X[c]	X[c]	X[c]		X[c]	X[c]		X[c]		X[c]	X[c]
W1242	X[c]	X[c]	X[c]		X[c]	X[c]		X[c]		X[c]	X[c]
DEPOT				X[d]			X[d]		X[d]		
W1258	X[c]	X[c]	X[c]	X[d]	X[c]	X[c]	X[d]	X[c]	X[d]	X[c]	X[c]
UBWPAD2	X[c]	X[c]	X[c]	X[d]	X[c]	X[c]	X[d]	X[c]	X[d]	X[c]	X[c]
W0680	X[c]	X[c]	X[c]	X[d]	X[c]	X[c]	X[d]	X[c]	X[d]	X[c]	X[c]

Notes: [a] Nutrient + chlorophyll-a monthly sampling dates
[b] Periphyton sampling dates
[c] Full set of nutrients and chlorophyll-a data collected at this site/date
[d] Periphyton, XLM and limited nutrient data collected at this site/date
X - Data collection completed

Samples collected for nutrient analysis are analyzed for total ammonia nitrogen (TAM), total nitrite-nitrate nitrogen (NO23), 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), Tables 6 and 7. Additional water samples are collected for analysis of chlorophyll-a and TP during the week of periphyton sampling if it did not coincide with routine nutrient sampling weeks. Samples collected at the three sites co-sampled with NBC are also analyzed for dissolved nutrients. Samples are analyzed at UBWPAD's laboratory, NBC's laboratory, the UMass Environmental Analysis Laboratory (EAL), and/or the UMass Dartmouth (UMD) laboratory depending on the parameter and sampling date as described below.

In 2015, the process of transitioning from the UBWPAD laboratory began. Duplicate aliquots were sent to UMD beginning in June 2015 for the nitrogen series. Similarly, duplicate aliquots were sent to EAL starting in April 2015 for TP. Two additional benefits were realized through this transition. Lower detection limits resulted in a decreased number of "non-detect" analysis results. In addition, the method for TDN and TN analysis at UMD is more aligned with that of the NBC lab, based on direct measurement of TDN and particulate organic nitrogen (PON) rather than requiring analysis for TKN. Throughout 2015, samples continued to be analyzed at the UBWPAD laboratory in order to better understand possible impacts of the change in labs on interpretation of historical trends. In 2016, the nitrogen series and TP were no longer run at the UBWPAD lab but they continued to analyze for TSS, TOP, and DOP.

Table 6: 2015 river sampling program analytes and laboratories

Parameter	UBWPAD	NBC	EAL	UMD
Dissolved Ammonia (dTAM)	Apr – Nov 3 RI Sites	Apr – Nov 3 RI Sites	--	Jun – Nov All sites
Total Ammonia (TAM)	Apr – Nov All sites	--	--	--
Dissolved Nitrite/Nitrate (dNO23)	Apr – Nov 3 RI Sites	Apr – Nov 3 RI Sites	--	Jun – Nov All sites
Total Nitrite/Nitrate (NO23)	Apr – Nov All sites	--	--	--
Dissolved Kjeldahl Nitrogen (dTKN) – 3 RI Sites	Apr – Nov All sites	--	--	--
Total Kjeldahl Nitrogen (TKN)	Apr – Nov All sites	--	--	--
Total Dissolved Nitrogen (TDN)	--	Apr – Nov 3 RI Sites	--	Jun – Nov All sites
Total Nitrogen (TN)	--	Apr – Nov 3 RI Sites	--	--
Particulate Organic Nitrogen (PON)	--	--	--	Jun – 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	--	Apr – Nov 3 RI Sites	--
Total Phosphorus (TP)	Apr – Nov All sites	--	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	--

Table 7: 2016 river sampling program analytes and laboratories

Parameter	UBWPAD Lab	NBC Lab	UMass EAL	UMD Lab
Dissolved Ammonia (dTAM)	--	Apr – Nov 3 RI Sites	--	Apr – Nov All sites
Total Ammonia (TAM)	--	--	--	--
Dissolved Nitrite/Nitrate (dNO23)	--	Apr – Nov 3 RI Sites	--	Apr – Nov All sites
Total Nitrite/Nitrate (NO23)	--	--	--	--
Dissolved Kjeldahl Nitrogen (dTKN) – 3 RI Sites	--	--	--	--
Total Kjeldahl Nitrogen (TKN)	--	--	--	--
Total Dissolved Nitrogen (TDN)	--	Apr – Nov 3 RI Sites	--	Apr – Nov All sites
Total Nitrogen (TN)	--	--	--	--
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 2015 and 2016 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 ~4,000 cfs[2] 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 ~85 cfs[3] at Woonsocket, RI, providing conditions that promote the growth of algal 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 2015 and 2016 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 and stream temperature conditions in Section 4.3. Section 4.4 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 2015 - 2016 are highlighted due to their potential influence on the subsequent sampling season results. The five 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 8. The 2015 sampling season was preceded by the second snowiest winter on record, while the winter prior to the 2016 sampling season was in the lower third of observed snow totals (84th highest accumulation out of 124 seasons).

2 A flow of 4,000 cfs is exceeded ~1% of the time at the Woonsocket stream gaging station

3 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

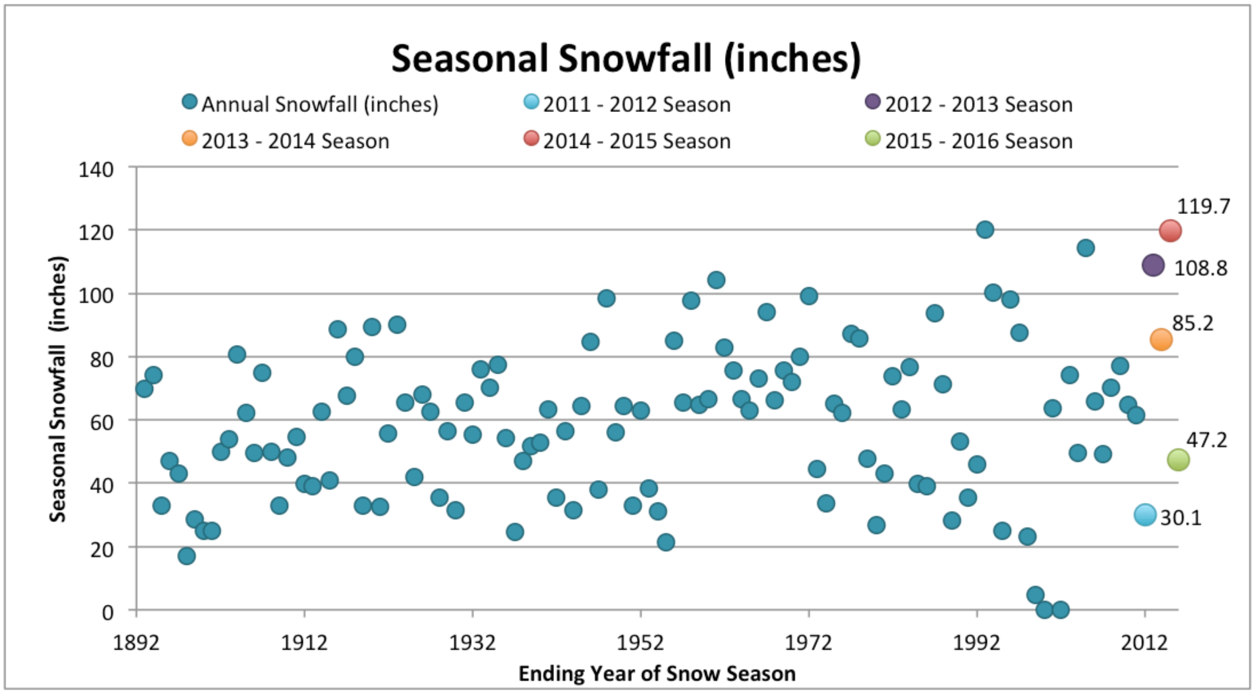


Figure 3: Seasonal snowfall (inches) in Worcester from 1893 through 2016, inclusive (Note: year plotted is end of snow season)

Table 8: Snowfall totals since winter of 2011-2012

	Snow (in)	**Rank in 123 years of record (1 = snowiest)**
Winter 2011 - 12	30.1	111th
Winter 2012 – 13	108.8	4th
Winter 2013 – 14	85.2	19th
Winter 2014 – 15	119.7	2nd
Winter 2015 – 16	47.2	84th

Air temperature data for Worcester are available from the NWS starting in 1948; however, published normal monthly data are based on the 30-year period from 1981 to 2010. 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, 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, 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 for each statistic, 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 winter and spring of 2014 – 2015 was cooler than normal, other than an unseasonably warm May 2015. Temperatures throughout that summer were slightly above normal and late fall was warm. The winter of 2016 continued the pattern of unusually warm temperatures. While Spring 2016 temperatures were average for the region, temperatures from July through September tended to be warmer than normal.

Monthly average temperature data since 1948 are summarized on Figure 5 as a boxplot, with the data for 2015 and 2016 highlighted in blue and red, respectively. 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 the 1.5 time 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 monthly temperature boxplots emphasize how cool the winter of 2015 was, with all months experiencing average temperatures below the lower quartile of observed data, as well has how warm the subsequent summer, fall, and winter were, with most months from July 2015 through March 2016 experiencing average monthly temperatures above the upper quartile.

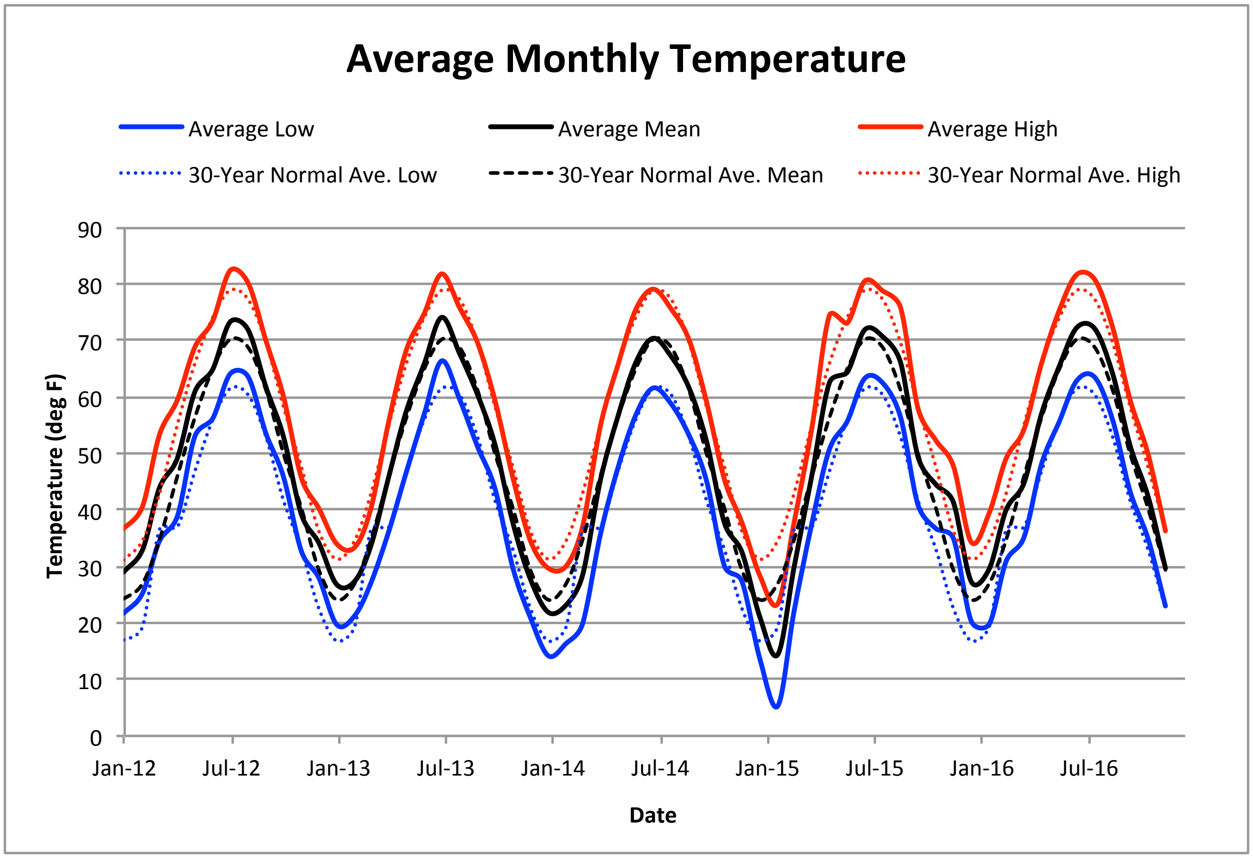


Figure 4: Average monthly low, mean, and high temperature values observed since 2012

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 on-line: www.ncdc.noaa.gov/cdo-web/datasets#GHCND

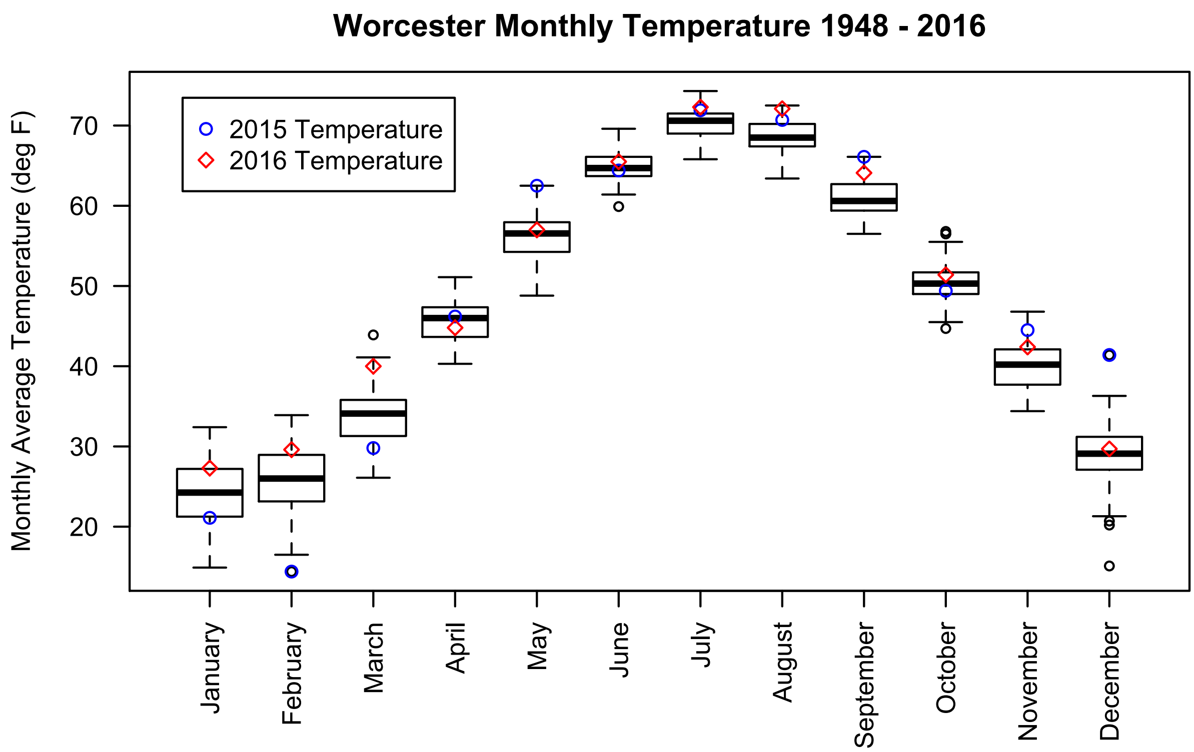


Figure 5: Worcester monthly temperatures 1948 - 2016

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. Accumulations in 2015 and 2016 were nearly identical and in the lower half of observed values. 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, however, conditions since routine sampling began have been on the drier side except for 2014. Of these five years, precipitation totals in 2015 and 2016 were the lowest of the period 2012 - 2016.

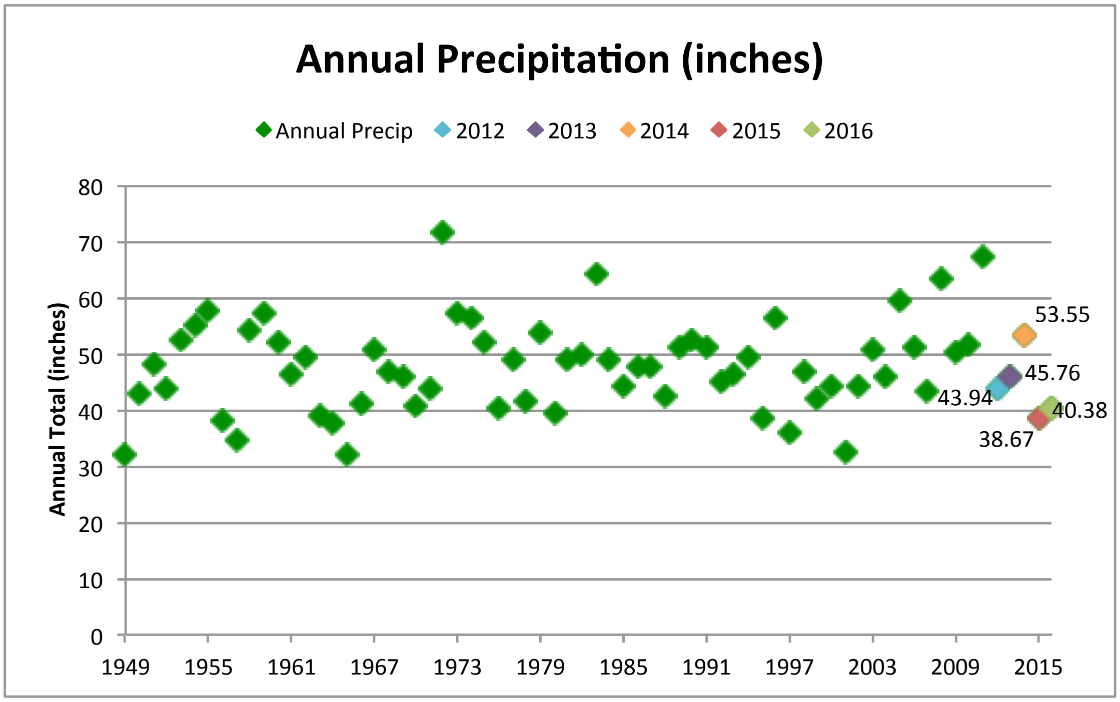


Figure 6: Annual precipitation (inches) in Worcester since 1949

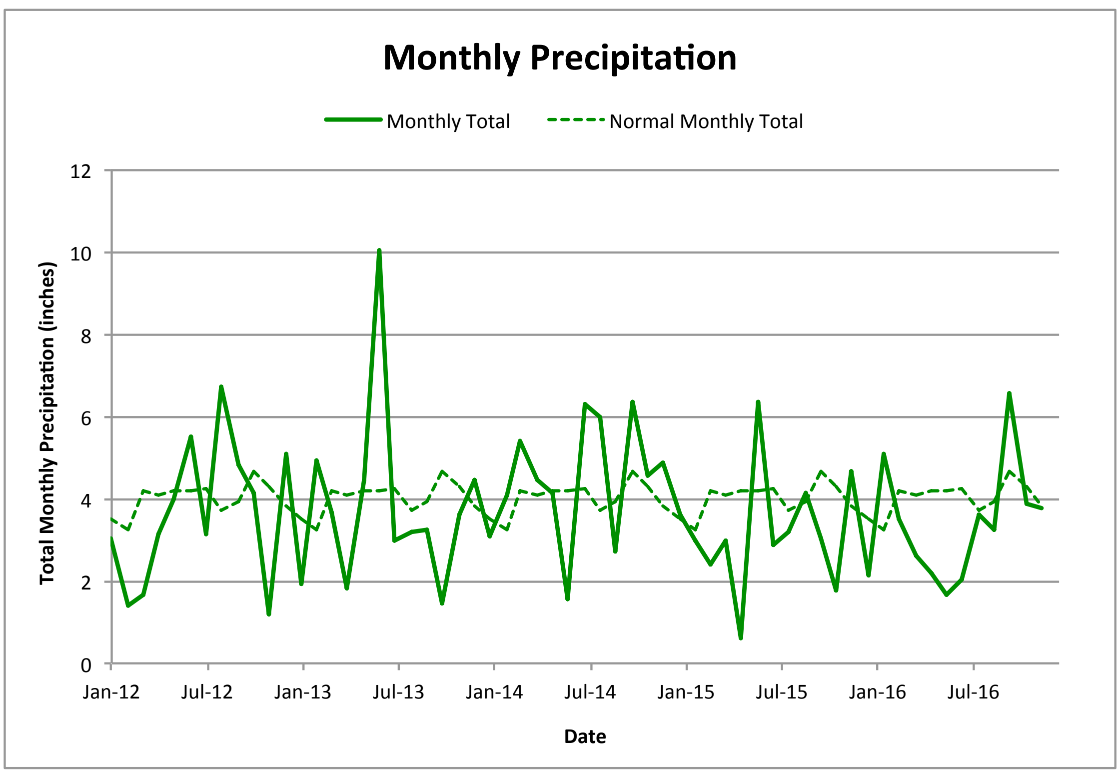


Figure 7: Monthly precipitation totals 2012-2016 compared to normal monthly totals
Notes: Observed totals for each month (solid line) are compared to the normal for the month (dashed lines) based on NWS monthly data for Worcester from 1981 – 2010.

Monthly precipitation totals since 1949 for Worcester are summarized using boxplots on Figure 8. Data for 2015 and 2016 are highlighted in blue and red, respectively. Rainfall totals from March through May 2015 were either at or below the lower quartile of observed values. While June 2015 was very wet, July through December tended to be dry, typically near or below the median observed value for the month. Precipitation totals in January, April, May, June, and July of 2016 were all below the lower quartile of data observed since 1949. Precipitation increased in the late summer through fall of 2016, with several significant daily rainfall events, however except for October monthly rainfall totals remained near the median of historic values. Additional monthly precipitation condition data for the 2015 and 2016 sampling years compared to the NWS 30-year normal are provided in the appendix.

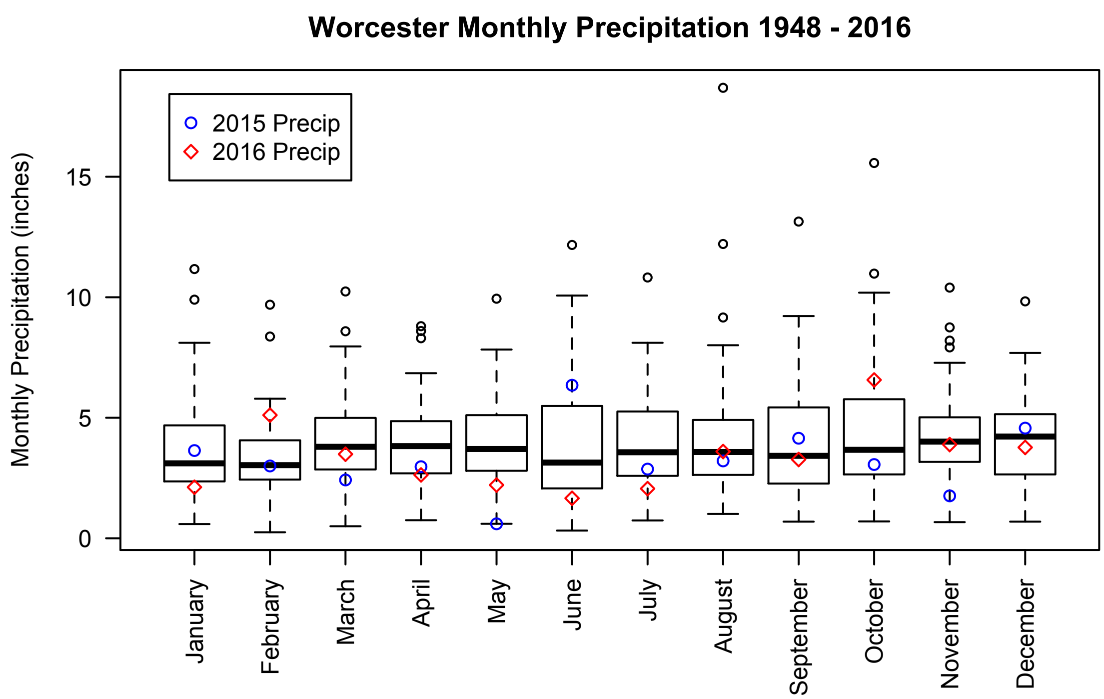


Figure 8: Worcester monthly precipitation 1948 - 2016

Daily precipitation data as measured at the Worcester Airport are plotted on Figure 9 for 2015 and Figure 10 for 2016. The precipitation on sampling dates is highlighted. Cumulative precipitation for the year is also plotted and compared against historical data (50^{th} percentile daily normal for Worcester from 1981 - 2010). Total precipitation was 38.7-inches in 2015 and 40.4 inches in 2016, both below the historical cumulative of 56.5-inches based on historical daily 50^{th} percentile precipitation. Cumulative precipitation throughout the two-year period was below historic normal conditions.

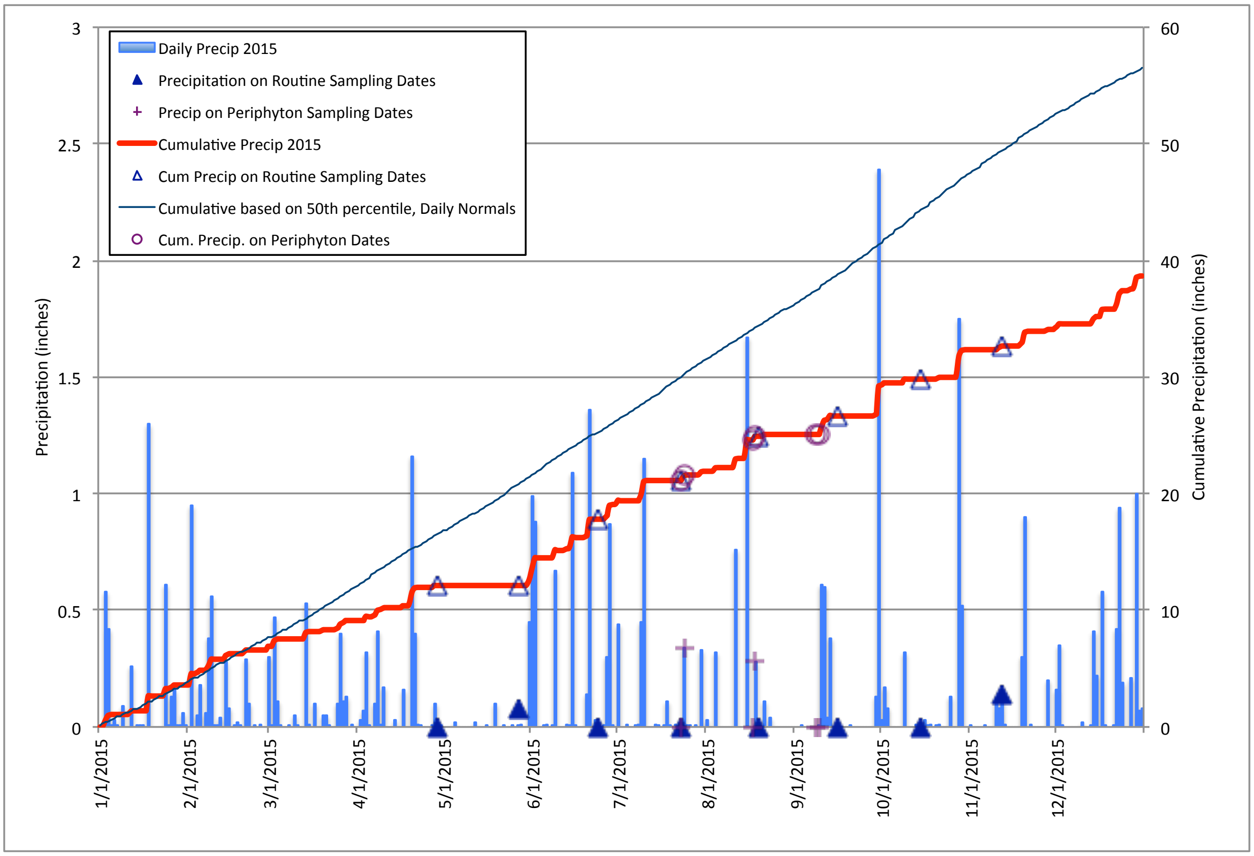


Figure 9: 2015 sampling season daily precipitation at Worcester Airport (KORH) compared against 50^{th} percentile daily normal precipitation

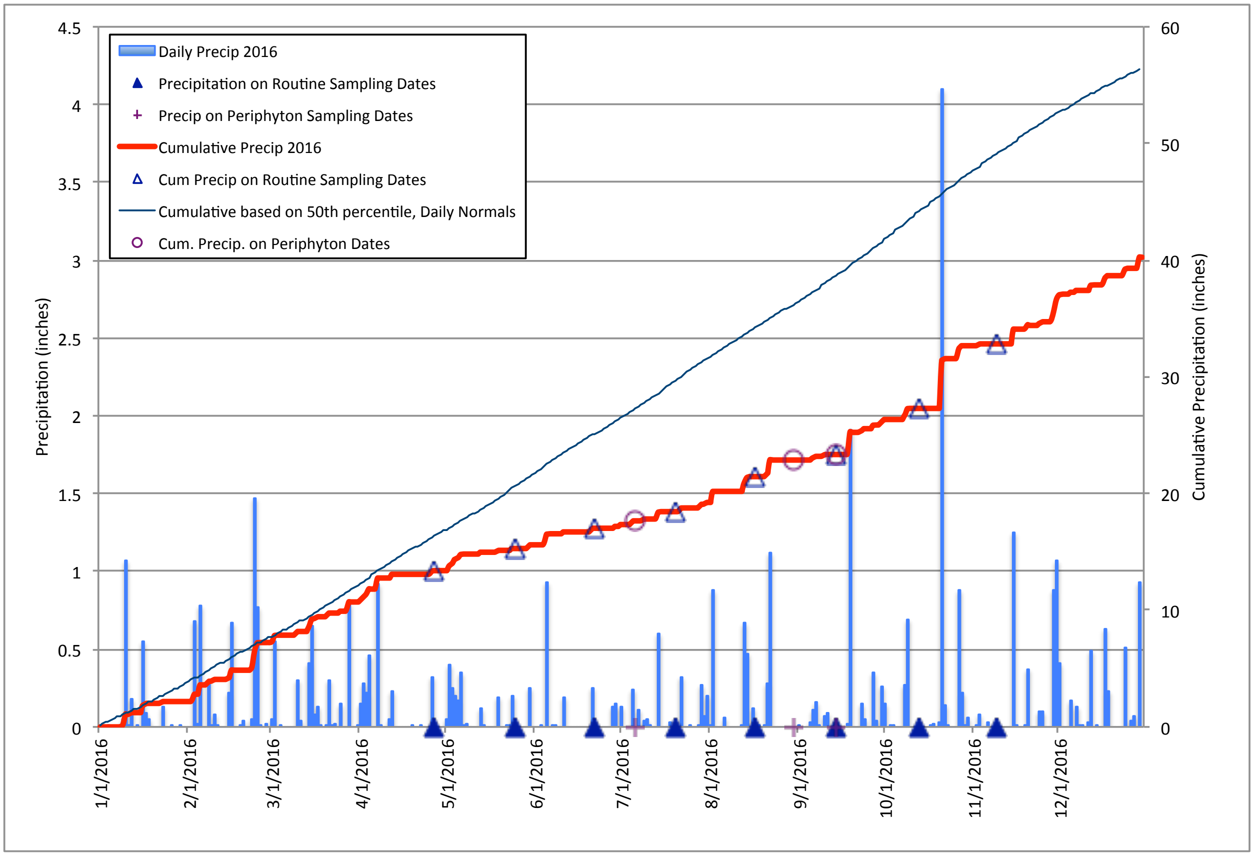


Figure 10: 2016 sampling season daily precipitation at Worcester Airport (KORH) compared against 50th percentile daily normal precipitation

According to monthly water conditions published by the Executive Office of Energy and Environmental Affairs for the Commonwealth of Massachusetts[4], precipitation during Fall 2016 was insufficient to make up for the deficits that began in 2015 (refer to Figure 10). While average streamflows and groundwater levels showed signs of recovery, they continued to be below normal and drought advisories persisted. The 2016 drought as well as the 2017 drought outlook were discussed at a series of meetings hosted by the National Oceanic and Atmospheric Administration (NOAA), the National Integrated Drought Information System (NIDIS), and the Northeast Regional Climate Center (NRCC) in February and March, 2017. Information from these meetings is available on-line (http://www.mass.gov/eea/agencies/dcr/water-res-protection/water-data-tracking/monthly-water-conditions.html).

[4] http://www.mass.gov/eea/agencies/dcr/water-res-protection/water-data-tracking/monthly-water-conditions.html

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 tables 9 and 10 for all nutrient, chlorophyll-a, and periphyton sampling dates in 2015 and 2016, respectively. Most routine sampling in 2015 occurred on days without precipitation, although significant rainfall (>0.5 inches) occurred during the week prior to sampling in June, August, and September. No rainfall occurred on routine sampling days in 2016, however rainfall totals >0.5 inches did occur in the week prior to routine sampling in August and October. 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 stream flow conditions on the sampling days. This issue is addressed further in the next sections.

Table 9: Day-of and antecedent precipitation on routine sampling dates in 2015

	Precipitation in Worcester, MA (NWS Station KORH)- inches			
Sampling Date	**Day Of**	**1-day Prior**	**Total over 3-days Prior**	**Total over 7-days Prior**
29 April [a]	0.0	0.10	0.10	0.11
27 May [a]	T[b]	0.00	T	T
24 June [a]	0.0	0.03	1.39	1.53
22 July [a]	0.0	0.01	0.01	0.12
19 August [a]	0.0	0.28	0.28	1.95
16 September [a]	0.0	0.00	0.38	1.63
15 October [a]	0.0	0.00	0.01	0.33
12 November [a]	0.14	0.08	0.20	0.20

Notes: [a] Nutrient + chlorophyll-a monthly sampling dates
[b] T = trace, defined as 0.001 inches

Table 10: Day-of and antecedent precipitation on routine sampling dates in 2016

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
27 April [a]	0.00	0.32	0.32	0.32
25 May [a]	T[b]	0.20	0.20	0.39
22 June [a]	T	0.25	0.25	0.25
20 July [a]	0.00	0.00	0.30	0.63
17 August [a]	0.00	0.12	0.59	1.26
14 September [a]	0.0	0.0	0.09	0.33
13 October [a]	T	0.00	0.00	0.96
9 November [a]	T	0.00	0.03	0.11

Notes: [a] Nutrient + chlorophyll-a monthly sampling dates
[b] T = trace, defined as 0.001 inches

4.2 Flow Conditions

Flow conditions during the 2015- and 2016-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, at which time small adjustments to the data, particularly for very high or low flows, may be made based on the most up-to-date field quality control data. 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 11 as a boxplot, with the data for 2015 and 2016 highlighted in blue and red, respectively. Data for the USGS gauge at Woonsocket, RI, collected since March 1929, are similarly presented on Figure 12. Both the 2015- and 2016-sampling years were characterized by low flows at Millbury and Woonsocket during most months. Monthly average flows rose above median historical values during only a few times, including January 2015, April 2015, June 2015, and February 2016 at Millbury. Flows were particularly low in 2016 at Millbury, with monthly average flows falling below the lower quartile of historical values except in February and October. Flows also fell below the lower quartile of historical values in March, June, July, August and September 2016 at Woonsocket. Record low monthly flows were set in November 2015 and May, June, and July 2016 at Millbury, as well as in September 2015 at Woonsocket, Table 11.

Monthly flow data for 2015 and 2016 are provided in tabular format in the appendix, along with percent normal data compared to the long-term monthly average.

Table 11: Mean monthly flows in 2015 and 2016 compared to median, mean, and minimum

Millbury (cfs)	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
2015 Monthly Qave	*328*	*130*	*164*	*96*	*60*	*72*	*96*	*75*
2016 Monthly Q_{av}	*169*	***112***	***67***	***49***	*59*	*48*	*115*	*114*
Median 2002 - 2016	275	156	136	96	76	79	134	152
Average 2002 - 2016	273	169	171	111	98	107	161	163
Minimum 2002 - 2016	95	**112**	**67**	**49**	53	47	75	75
Woonsocket (cfs)	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
2015 Monthly Qave	*1655*	*402*	*537*	*308*	*118*	***95***	*324*	*333*
2016 Monthly Qave	*1096*	*602*	*237*	*129*	*126*	*96*	*434*	*457*
Median 1930 - 2016	1326	843	460	245	232	230	312	524
Average 1930 - 2016	1434	878	649	340	307	323	461	665
Minimum 1930 – 2016	461	303	137	120	72	**95**	196	127

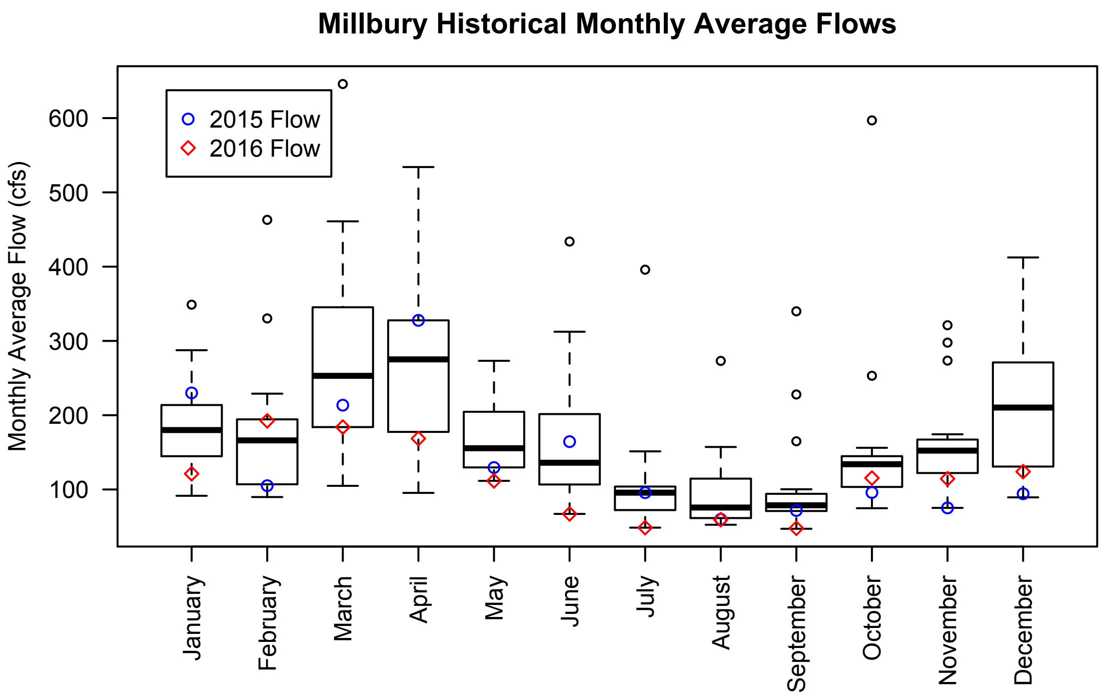


Figure 11: Millbury, MA, USGS gaging station historical monthly average flows

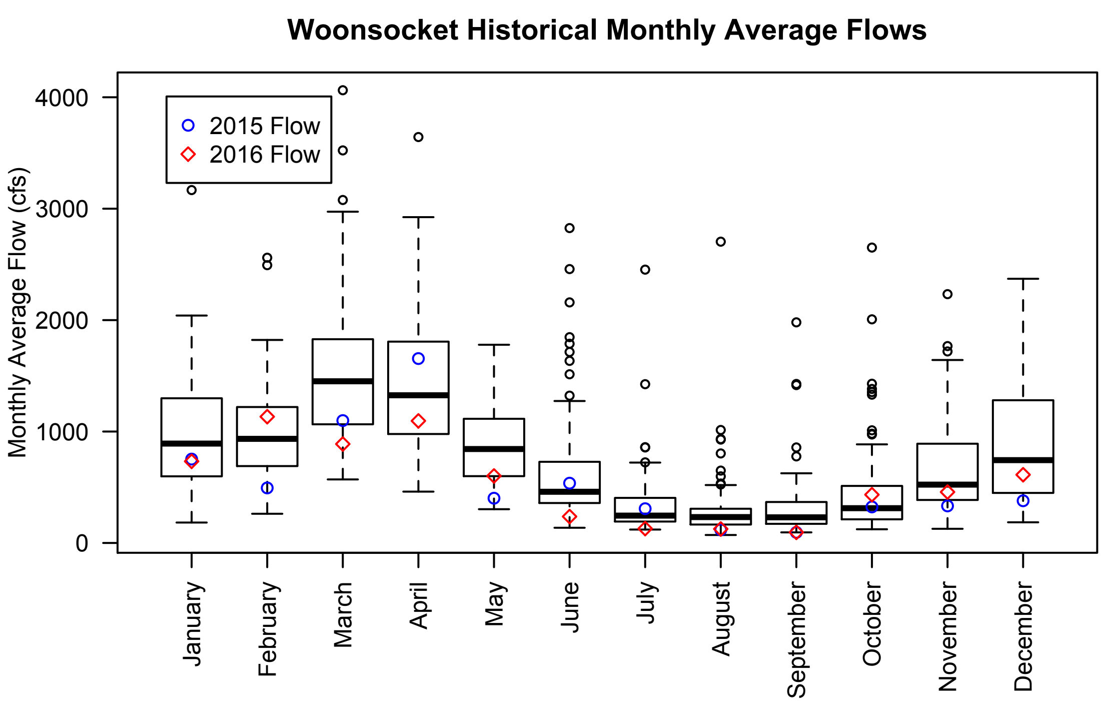


Figure 12: Woonsocket, RI, USGS gaging station historical monthly average flows

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 – 2016), 7Q10 flow has not been officially computed for the Millbury gage 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) fell below 7Q10 conditions over several days during two periods at Woonsocket in 2015 and one period in 2016, corresponding with the September periphyton and routine sampling dates. Average 7-day flows were also below 7Q10 conditions at Millbury during the September 2016 periphyton and routine sampling dates. 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 12 summarizes the minimum 7Q flows observed at Millbury since routine sampling began.

Mean daily stream flows measured at Millbury and Woonsocket are compared to historic mean daily flows on figures 13 and 14 for the 2015-sampling season and on figures 15 and 16 for the 2016-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 most of the 2015 and 2016 sampling season, and that the September events were sampled during flows at or below 7Q10 conditions. Daily flows were also below average historic conditions on most sampling dates. Two exceptions are the July and August 2015 periphyton sampling events, discussed further below, and the June 2016 routine sampling date. Tables 13 and 14 provide 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 13 and 14 are unique and, in some instances, very different for a given month.

Table 12: Minimum 7day average flows at Millbury by year since routine sampling began

Year	Minimum 7Q (cfs)
2012	49
2013	51
2014	47
2015	42
2016	37
7Q10 Estimate	38

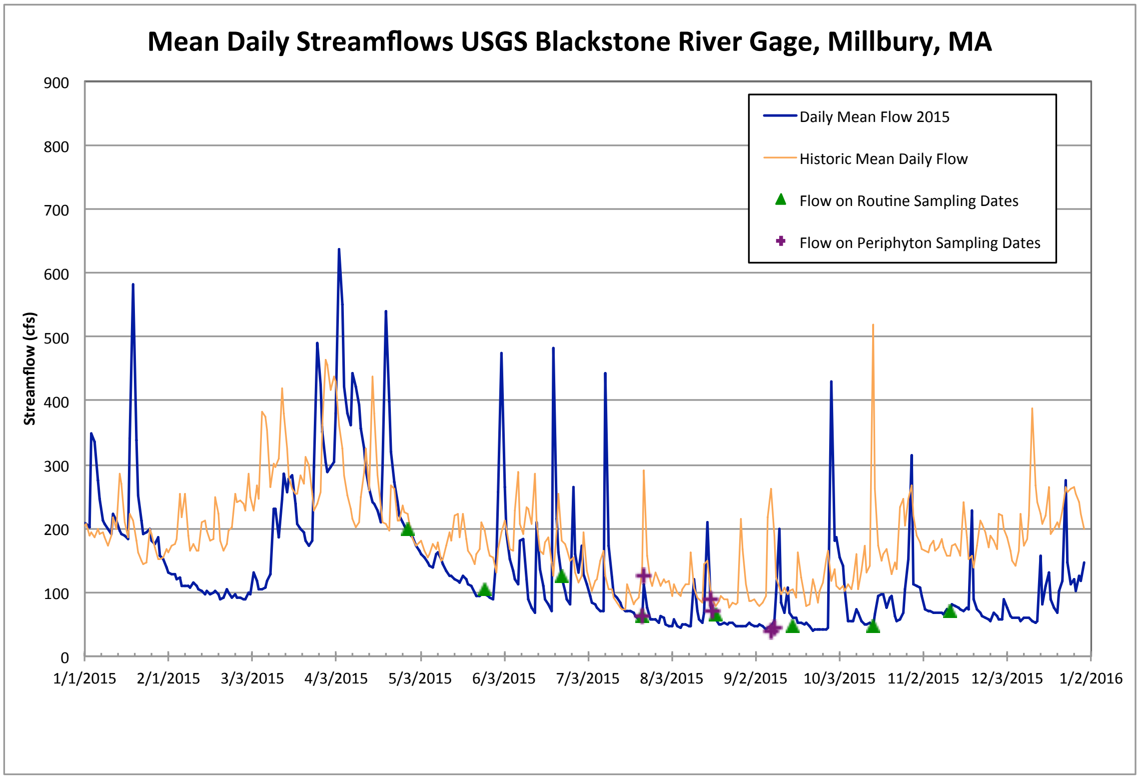


Figure 13: 2015 mean daily streamflows at USGS Millbury, MA gauge
(Notes: Historical Mean Daily Flow data through 2014)

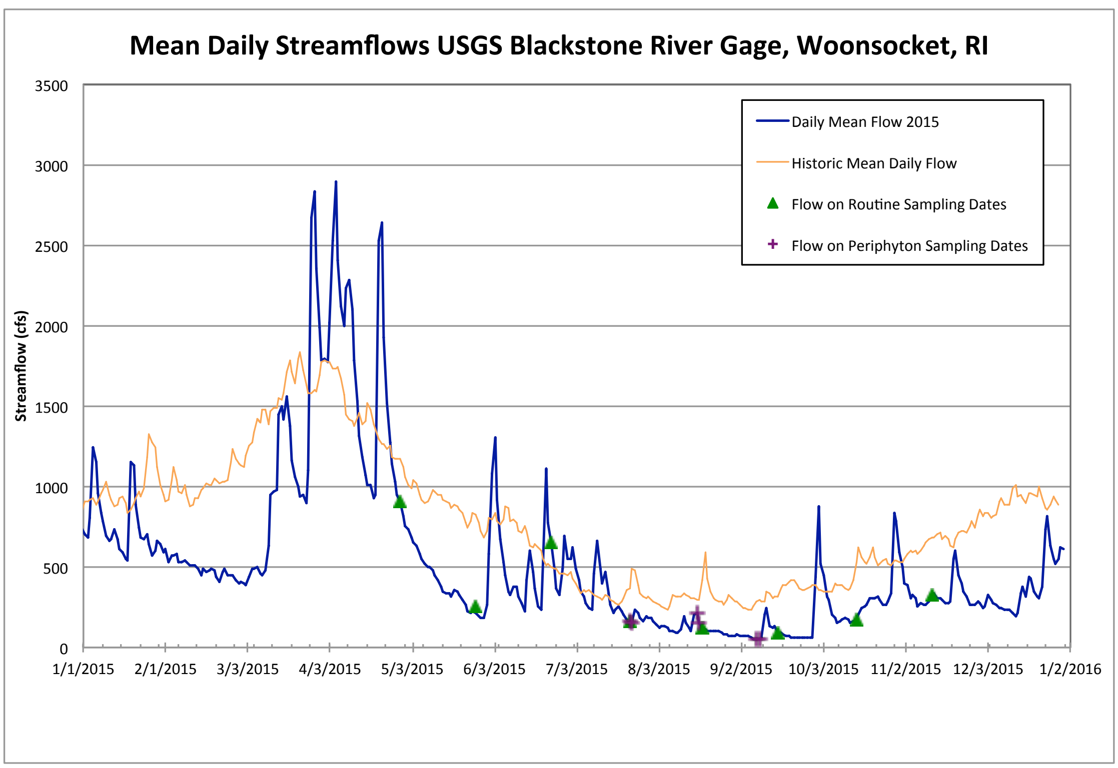


Figure 14: 2015 mean daily streamflows at USGS Woonsocket, RI gauge
(Notes: Historical Mean Daily Flow data through 2014)

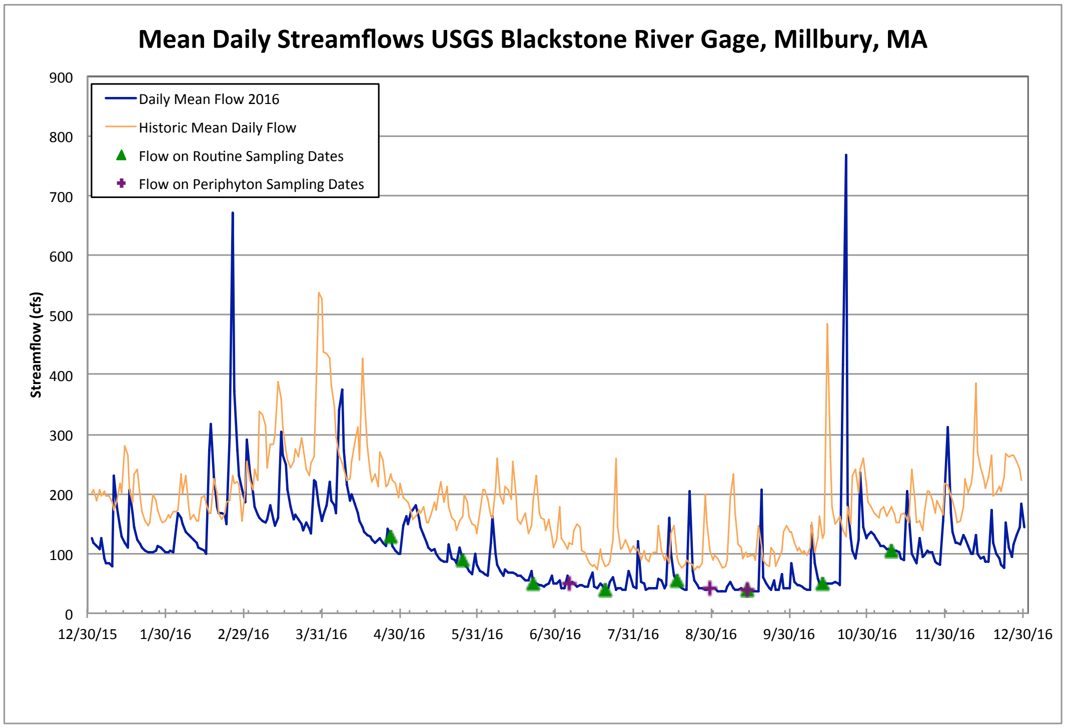


Figure 15: 2016 mean daily streamflows at USGS Millbury, MA gauge
(Notes: Historical Mean Daily Flow data through 2015)

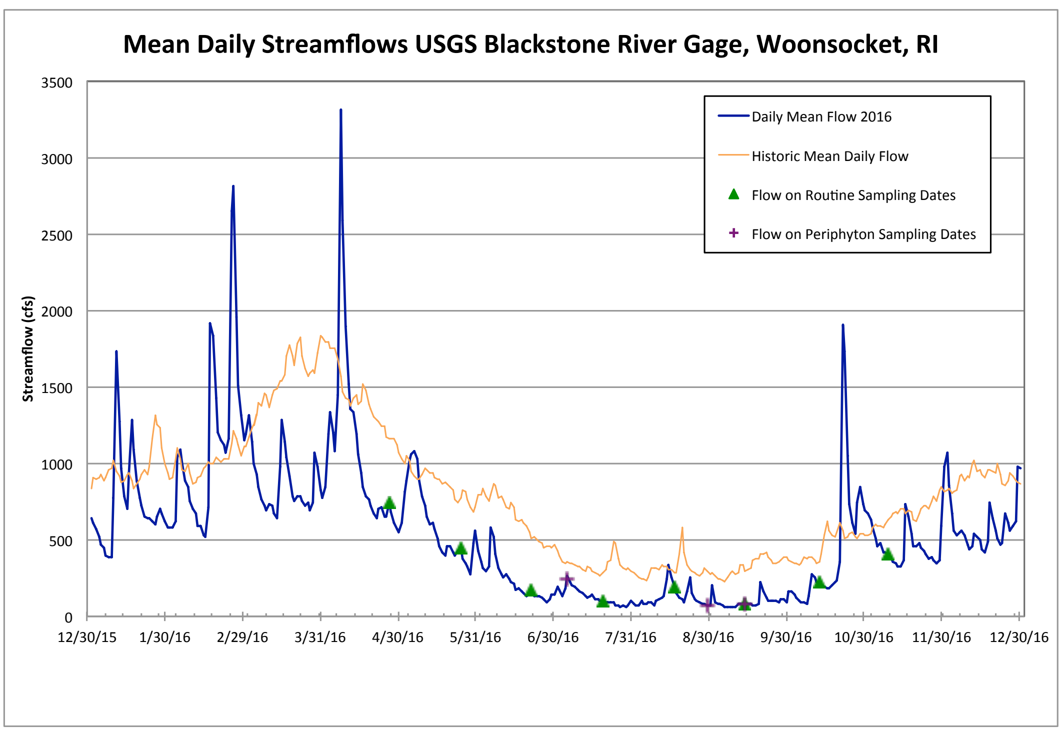


Figure 16: 2016 mean daily streamflows at USGS Woonsocket, RI gauge
(Notes: Historical Mean Daily Flow data through 2015)

Table 13: Routine sampling day-of flow conditions 2015

Sampling Date	Woonsocket, RI – USGS Station 01112500			Millbury, MA – USGS Station 01109730		
	2015 Mean Daily Q (cfs)	[1]Historic Mean Daily Q (cfs)	% of normal	2015 Mean Daily Q (cfs)	[1]Historic Mean Daily Q (cfs)	% of normal
29 April [a]	906	1170	77%	199	222	90%
27 May [a]	259	822	32%	104	197	53%
24 June [a]	650	504	129%	127	181	70%
22 July [a]	177	357	50%	57	93	61%
19 August [a]	126	413	31%	57	78	73%
16 September [a]	96	316	30%	59	106	56%
15 October [a]	176	531	33%	47	520	9%
12 November [a]	325	682	48%	71	156	46%

Notes: [a] Nutrient + chlorophyll-a monthly sampling dates
[b] Periphyton sampling dates
[1] Historic Mean Daily Q (cfs) based on data through 2014

Table 14: Routine sampling day-of flow conditions 2016

Sampling Date	Woonsocket, RI – USGS Station 01112500			Millbury, MA – USGS Station 01109730		
	2016 Mean Daily Q (cfs)	[1]Historic Mean Daily Q (cfs)	% of normal	2016 Mean Daily Q (cfs)	[1]Historic Mean Daily Q (cfs)	% of normal
27 April [a]	744	1160	64%	128	232	55%
25 May [a]	448	773	58%	88	162	54%
22 June [a]	170	512	33%	51	188	27%
20 July [a]	101	281	36%	40	78	51%
17 August [a]	197	289	68%	54	94	57%
14 September [a]	80	299	27%	38	94	40%
13 October [a]	222	360	62%	49	125	39%
9 November [a]	409	633	65%	104	178	58%

Notes: [a] Nutrient + chlorophyll-a monthly sampling dates
[b] Periphyton sampling dates
[1] Historic Mean Daily Q (cfs) based on data through 2015

4.3 Stream Temperatures and Other In-Situ Data Availability

In-situ monitoring of water temperature, pH, conductivity, and dissolved oxygen (DO) concentration and percent saturation was conducted during the 2012 – 2014 periphyton surveys. In 2014 and 2015, in-situ measurements were collected during routine monthly sampling for nutrients, but were discontinued at the UMass sampling sites in 2016[5]. Limited continuous stream temperature data are available from the USGS gaging station located at Millville, MA (01111230) from 2013 through May 2016. These data were utilized to calculate mean monthly water temperature, Table 15.

Table 15: Mean monthly water temperature, USGS Millville stream gauge

Month	Average stream temperature (°F)					
	2008	**2012**	**2013**	**2014**	**2015**	**2016**
June	--	--	69.1	69.7	67.8	--
July	--	--	76.9	75.2	74.5	--
August	--	--	71.7	71.5	75.5	--
September	--	--	--	68.0	69.1	--

4.4 Environmental Condition Summary

Both the 2015 and 2016 sampling years were characterized by warmer and drier than normal summer and fall conditions. However, a colder, wetter winter preceded the 2015 sampling season. Snow accumulations during the winter of 2014 – 2015 are the second highest on record since 1892. The spring of 2015 was generally cool through April, followed by warmer than normal temperatures from August through the end of the year and low snowfall during the winter of 2015 - 2016. Total annual precipitation, nearly identical in 2015 and 2016, was at the lower end of the historical data for Worcester available since 1949. Snowfall was relatively low during the winter of 2015 – 2016, setting the stage for drought conditions that occurred in 2016. Minimum average monthly flow records of 112, 67, and 49 cfs were set in May, June, and July, respectively, at the USGS Millbury gaging site. While storm events did occur during the 2015 and 2016 sampling seasons, routine sampling primarily occurred on days of falling or level flow in both years.

[5] In-situ measurements at the 3 RI co-sampled sites are collected by NBC staff and provided to UMass

5.0 Upper Blackstone Effluent

The Upper Blackstone facility seasonal permits for total phosphorus (TP) and total nitrogen (TN) are listed in Table 16[6]. The Upper Blackstone operates the facility 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 17 shows the actual effluent TN and TP average annual concentrations since 2006, while Table 17 summarizes TP and TN effluent concentrations by season[7], corresponding to the permit limits, since 2012. Figure 18 shows the nutrient loading from the 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 - 2016. The nutrient loads to the river have decreased significantly since 2009. The loads have been even lower since 2013 when the Upper Blackstone began implementing interim measures, which focused on optimizing the plant's Biological Nutrient Removal (BNR) process. The percent reduction in TN and TP effluent loads compared to performance prior to 2009 (2006-2008) is summarized in Table 18. The total annual load of nitrogen from the Upper Blackstone's facility has been reduced by about 60% from nearly 1.2 million pounds per year in 2006 to about 4999,000 ponds in 2015, and 476,000 pound in 2016. The annual reduction in phosphorus load to the river is even more dramatic at about 88% in 2015 and 80% in 2016, from more than 160,000 pounds per year in 2006 to less than 20,000 pounds in 2015 and less than 34,000 pounds in 2016.

Table 16: Upper Blackstone 2008 permit limits

Total Phosphorus (mg/L)[1]	
Apr – Oct (summer)	0.1[2]
Nov – Mar (winter)	1.0
Total Nitrogen (mg/L)	
May – Oct (summer)	5.0
Nov – Apr (winter)	Report

Notes: [1] Upper Blackstone effluent limits are typically listed in mg/L. The conversion is 1 mg/L = 1000 ppb.
[2] The 0.1 mg/L total phosphorus limit is a 60-day rolling average limit.

[6] 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.

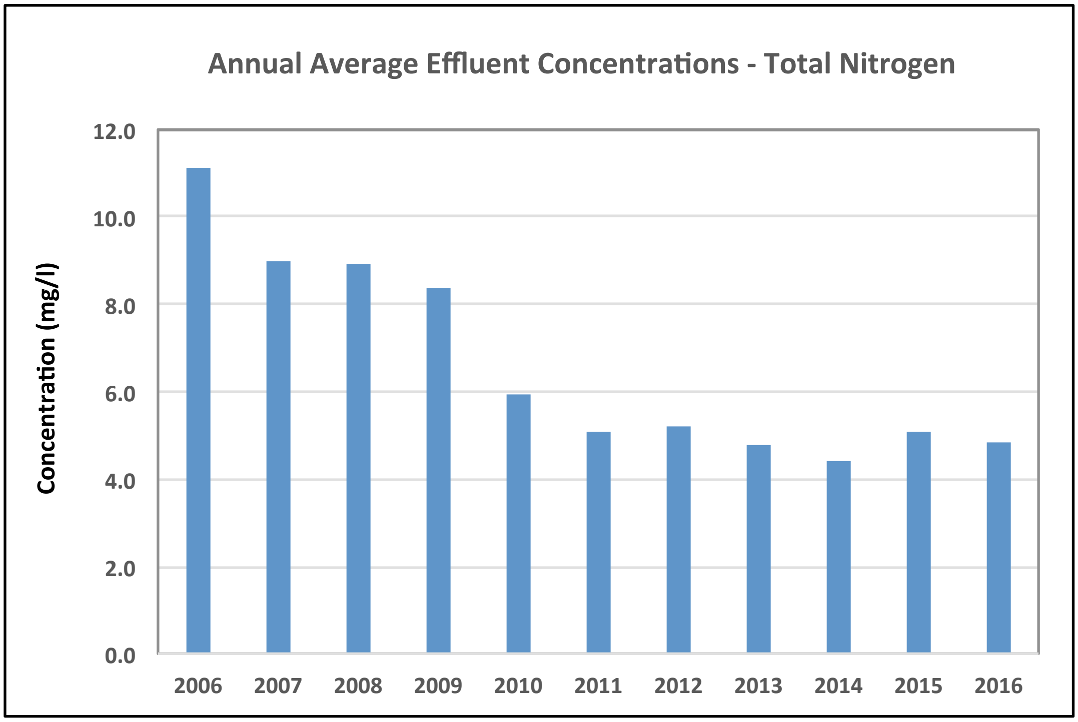
[7] TP 'summer' performance is based on the average of available data for a given year between April 1st and October 31st; TP 'winter' performance is based on the average of available data between November 1st the prior year and March 31st of the year. TN 'summer' performance is based on the average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

Table 17: Upper Blackstone average permit season TP and TN effluent concentrations

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

Table 18: Percent reduction in TN and TP effluent loads compared to plant performance 2006-2008

Year	TN	TP
2012	62%	78%
2013	61%	89%
2014	63%	84%
2015	57%	88%
2016	58%	80%



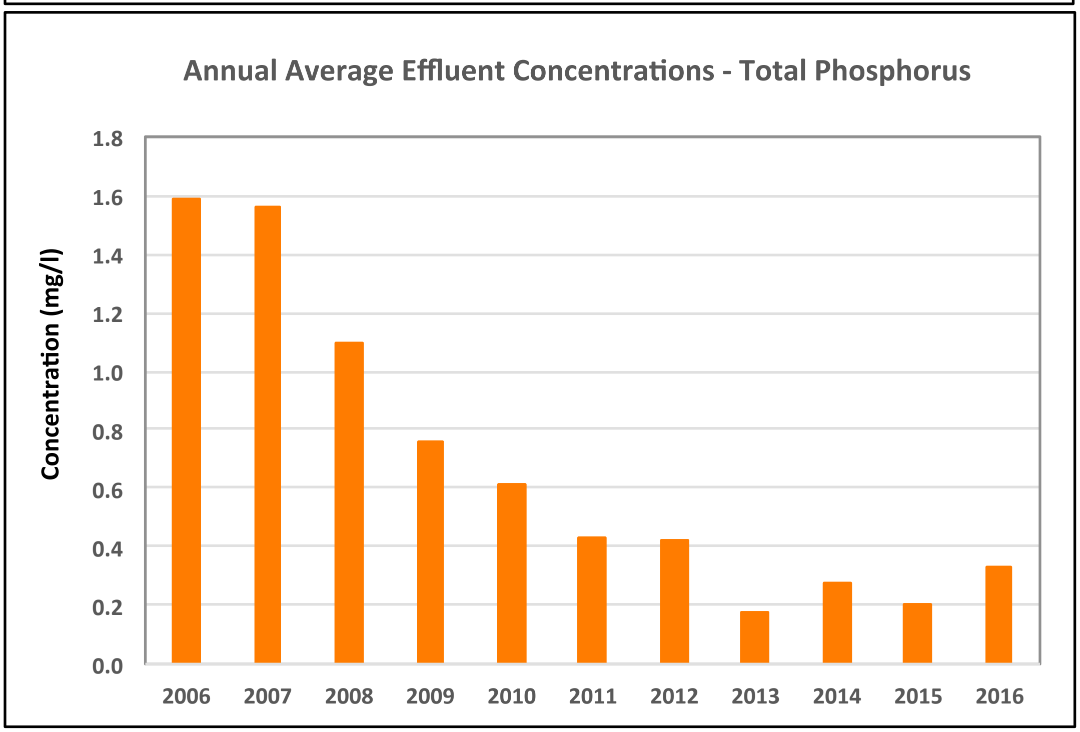
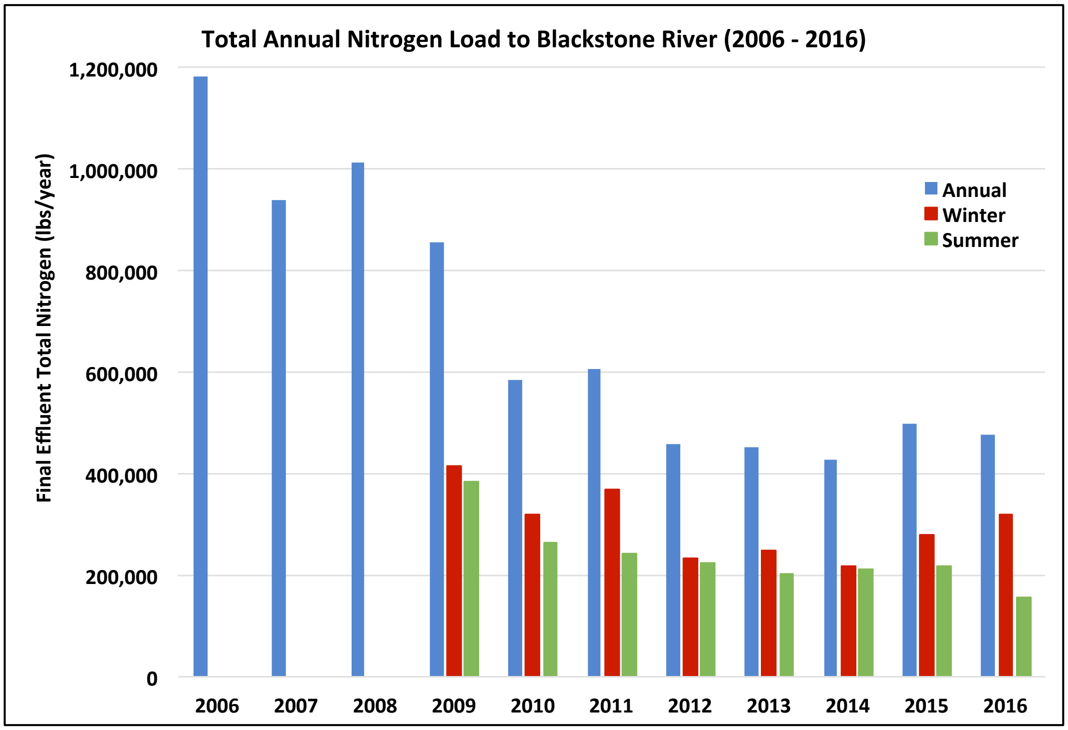


Figure 17: Annual average effluent total nitrogen and total phosphorus concentrations 2006 - 2016 (Stream data are reported as ppb in this report. To compare effluent and stream data, note that 1 mg/L = 1000 ppb.)



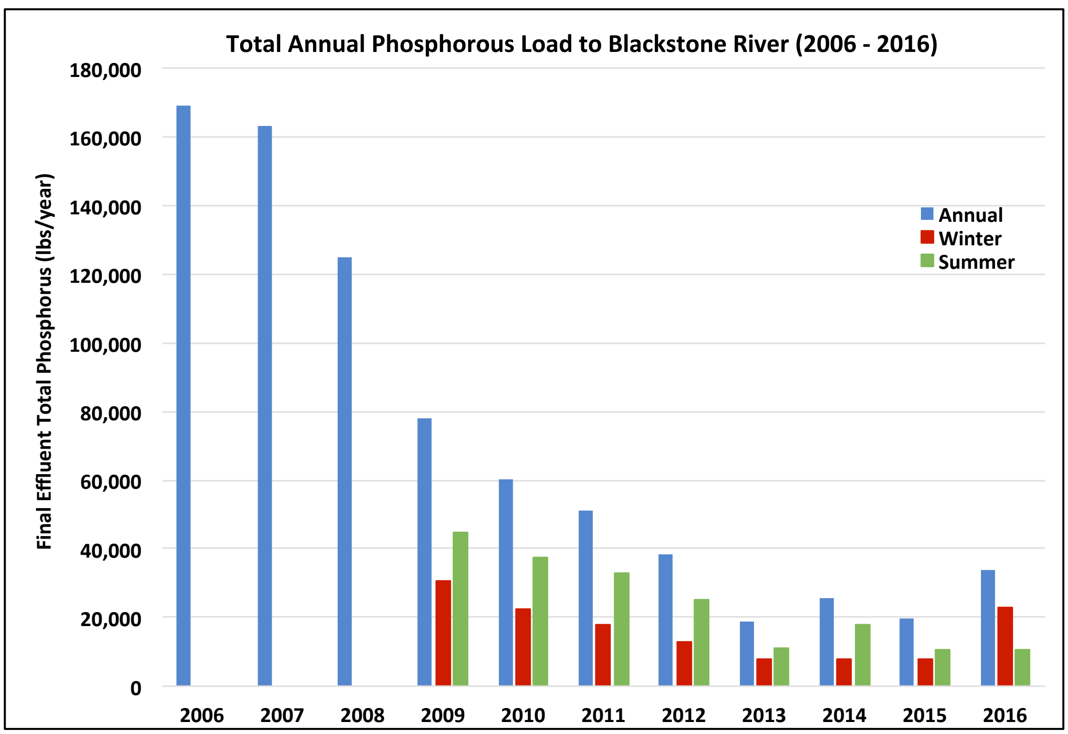
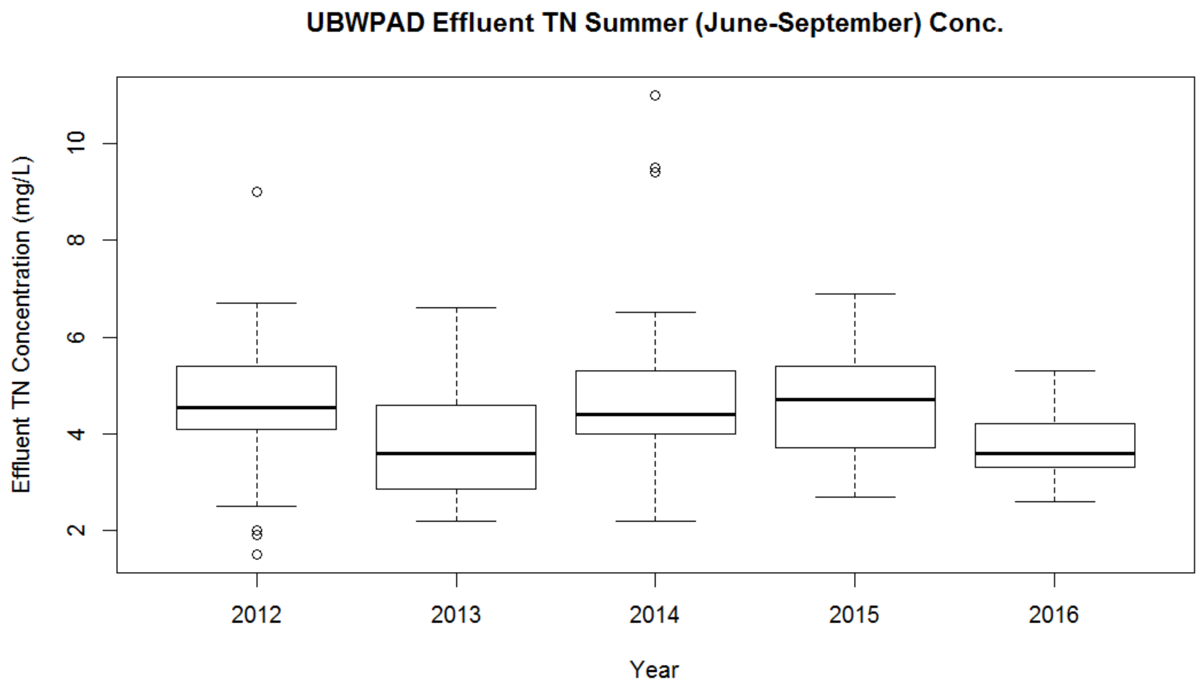


Figure 18: Total annual, winter permit, and summer permit total nitrogen and total phosphorus loads to the Blackstone River 2006 - 2016

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 - 2016 were utilized to calculate the daily average concentration and load from June through September, Table 19. A boxplot of the daily data from June through September each year is shown on Figure 19 for concentrations and Figure 20 for loads from 2012 – 2016. 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. 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, and 2016 but larger variability in 2012 and 2014. Time series plots of effluent TP and TN characteristics, as well as flow, are included in the appendix for 2015 and 2016.

Table 19: Average of the daily effluent nutrient characteristics during the June – September growing season in 2006 to 2016

Year	Effluent TP		Effluent TN	
	June – Sep Ave. Daily Conc. (mg/L)	**June – Sep Ave. Daily Load (lb/d)**	**June – Sep Ave. Daily Conc. (mg/L)**	**June – Sep Ave. Daily Load (lb/d)**
2006	1.7	403	NA	NA
2007	2.1	424	8.3	1687
2008	1.5	421	8.0	2178
2009	0.9	238	7.8	2090
2010	1.0	209	6.1	1180
2011	0.4	139	4.2	1300
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	1050
2016	0.2	38	3.8	680



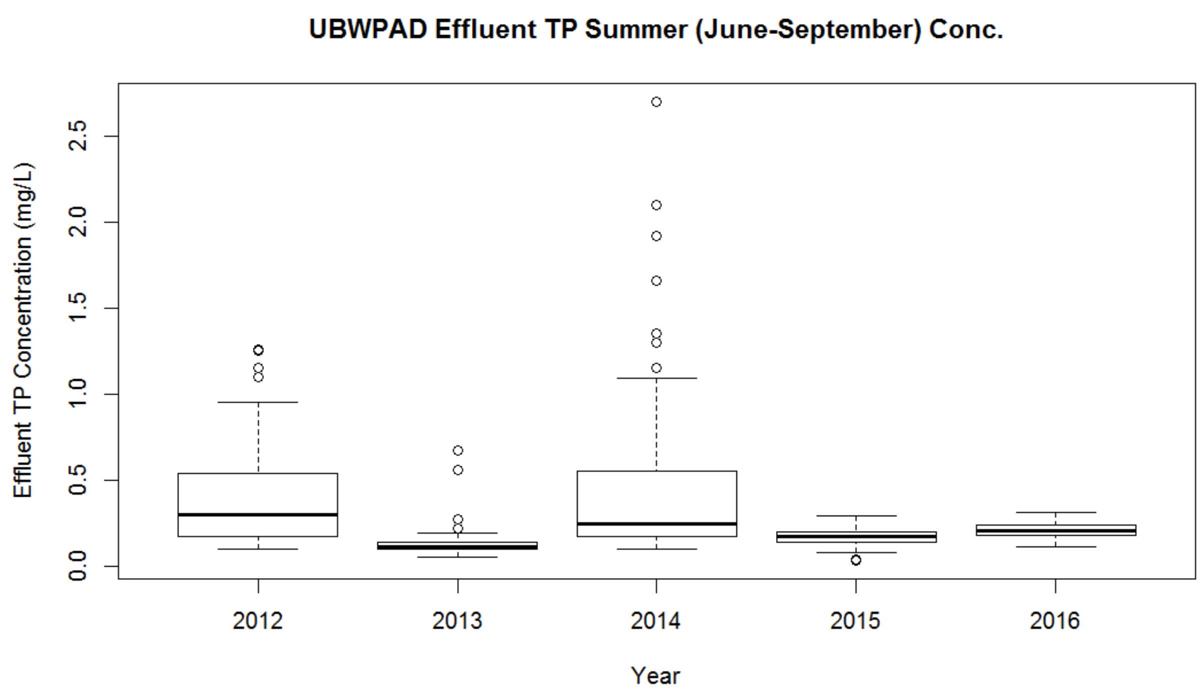
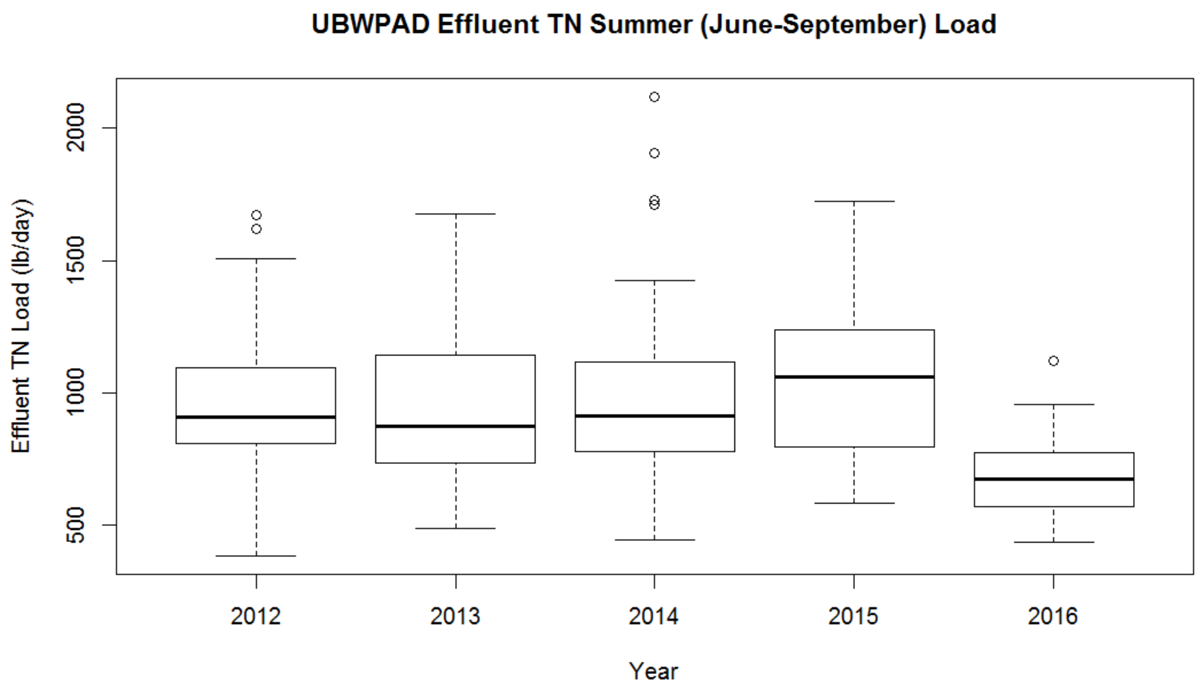


Figure 19: UBWPAD daily effluent TN and TP concentrations by year from June - September



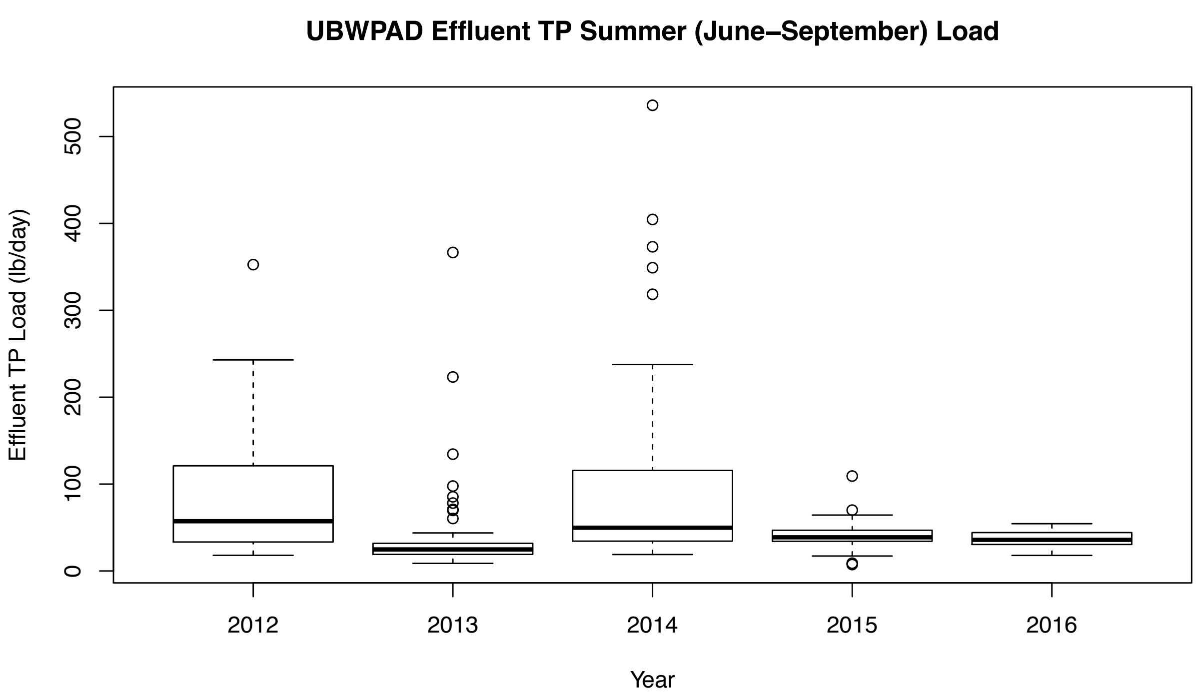


Figure 20: UBWPAD daily effluent TN and TP loads to the river by year from June - September

The Upper Blackstone's effluent discharge can account for a large percentage of the flow that exits the headwaters of the watershed, providing 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 each year are summarized in Table 20. Non-effluent volumes, or the difference between measured streamflow and reported effluent flow, are summarized in Table 21. This difference represents the "natural flow" volume in the river at the Millbury gage. The effluent contributions in 2016 were about 63% of the summer (June – August) flows in the river at Millbury, the highest on record since routine monitoring by the Upper Blackstone began.

Table 20: Historical variations in the % of flow at Millbury[1] comprised of plant effluent

Year	June – August	June - September
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%

Note: [1] Calculated as the reported daily effluent flow divided by the measured daily streamflow at Millbury, converted to a percentage, and averaged over the indicated time period

Table 21: Relative contributions by volume (million gallons) June – August

Year	Millbury Q	Effluent	Difference
2003	10,289	3,649	6,640
2004	5,285	2,634	2,651
2005	6,061	2,950	3,111
2006	9,637	2,989	6,648
2007	5,237	2,266	2,971
2008	8,111	2,877	5,235
2009	13,911	3,557	10,354
2010	4,757	2,156	2,601
2011	11,239	2,867	8,372
2012	6,088	2,398	3,690
2013	12,238	3,115	9,123
2014	4,447	2,278	2,169
2015	6,306	2,575	3,730
2016	3,463	2,003	1,460

6.0 Sampling Season Data for 2015/2016

Routine monitoring was conducted monthly from April to October for nutrients and chlorophyll-a at nine in-stream locations. River water quality conditions are summarized in this section by presenting the TP, TN, and chlorophyll-a results. Flow data for each sampling date were available from two USGS gauging sites, located at Millbury, MA and Woonsocket, RI, as summarized in Section 4.2. Observed sampling day flows at Millbury and Woonsocket were utilized to provide flow estimates at each sampling location based on the simulation results from the HSPF model developed for the Blackstone River (UMass and CDM, 2008).

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. Further analyses were conducted by looking at flow-adjusted concentrations.

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 22 summarizes how the sampling events since 2012 were categorized by flow condition. Sampling date "low" flow conditions are summarized for the 2012 through 2016 sampling season, as well as for historical data that were similarly categorized by flow conditions, on Figure 21. 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 flow conditions on sampling days since routine monitoring began in 2012 occurred during the 2014 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 22: 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 (RI)[1] D (MA)	A
2013	A	D (RI)[1] A (MA)	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

Notes: [1] Flow conditions on sampling dates during these months were too disparate to be classified as the same condition

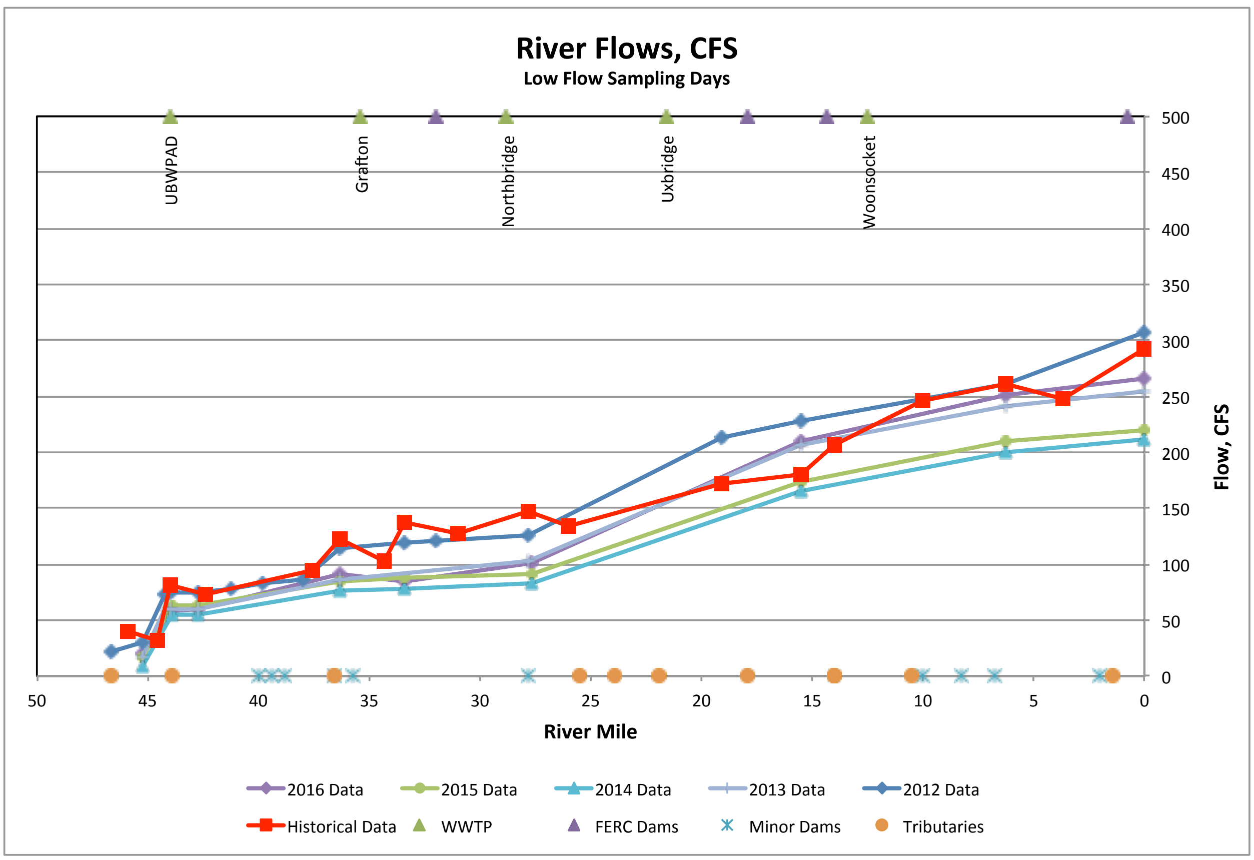


Figure 21: Comparison of average flow conditions on sampling date by year, sorted for sampling dates categorized as "low flow"

Periphyton sampling was conducted three times during summer low flow conditions in both 2015 and 2016. The four sampling locations were all located in Massachusetts, including one upstream of the confluence with the Upper Blackstone effluent channel, and three downstream locations. Periphyton scrapings were analyzed for chlorophyll-a content as well as periphyton species and area coverage. Periphyton chlorophyll-a data are presented in this report. A complete report on periphyton data is available under separate cover from Normandeau Associates.

6.1 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 analysis for trend based on flow-weighted concentration data. Flow-weighted concentration trend analyses are presented for TP, TN, and chlorophll-a in section 6.1.4. Additional information on nitrogen and phosphorus subspecies, as well as laboratory QAQC data, is available upon request.

6.1.1. Total Phosphorus

Available TP concentration data for the Blackstone River since 1996 are summarized in Figure 22 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 on line in 2009 are less variable and are lower than historical concentrations. Upgrades to the plant have translated to improved river conditions.

The mean summer (June – September) TP concentration at each sampling location in the Blackstone River is shown on Figure 23 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 2015 in yellow and 2016 in light blue. In 2014, the 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. The 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.

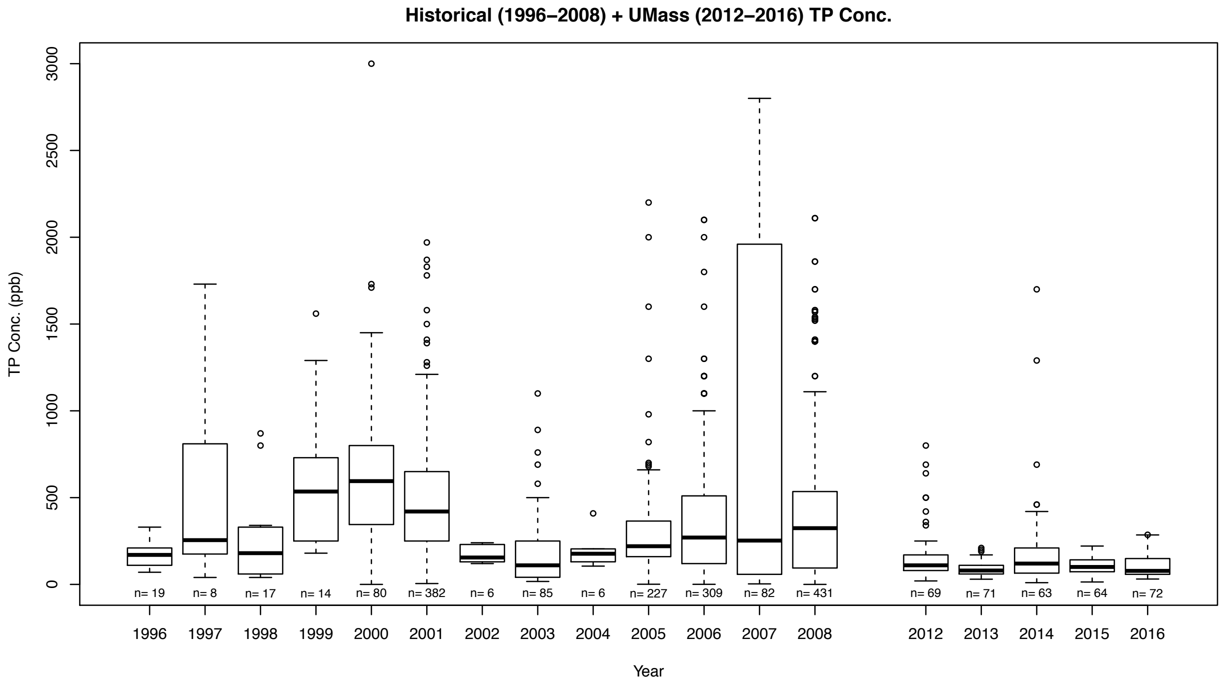
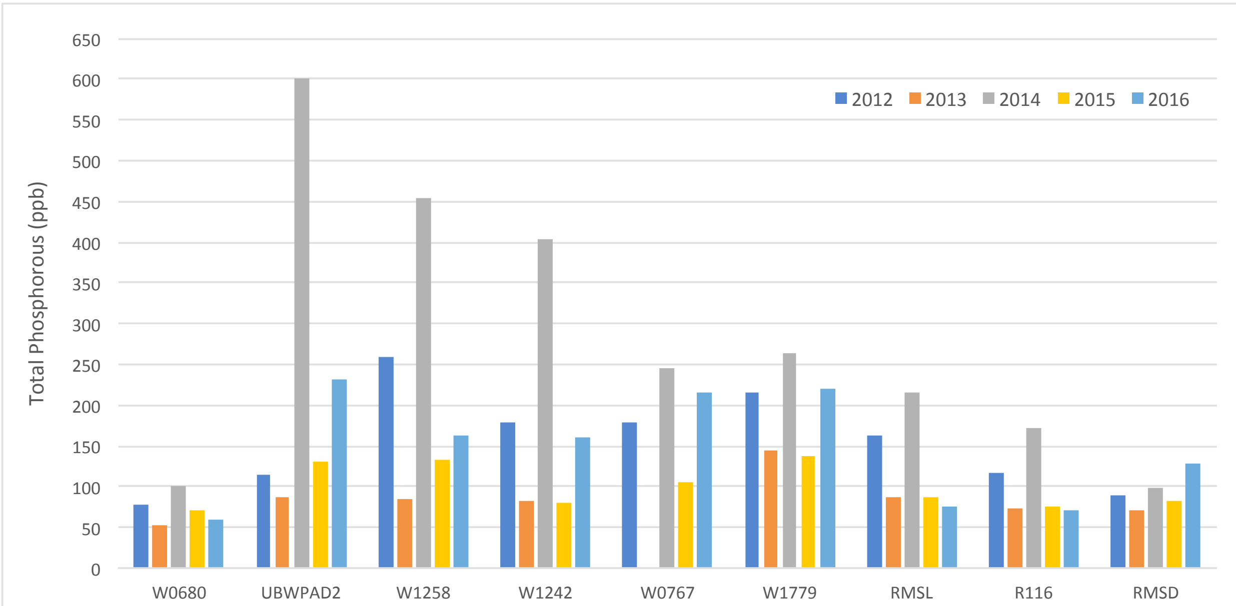


Figure 22: TP concentrations observed in the river 1996 – 2008 and 2012 – 2016



TP (ppb)	*W0680*	*UBWPAD2*	*W1258*	*W1242*	*W0767*	*W1779*	*RMSL*	*R116*	*RMSD*
2012	76.7	115.0	260.0	178.0	178.0	216.0	162.5	117.5	90.0
2013	52.5	87.5	85.0	82.5	NA	145.0	87.5	72.5	70.0
2014	99.8	600.3	453.3	403.3	246.0	264.0	215.3	172.5	98.0
2015	71.0	130.3	133.0	80.8	105.5	137.3	86.0	76.0	82.3
2016	59.8	230.5	163.3	161.3	214.5	221.0	76.0	70.3	128.8

Figure 23: 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 24, with sites plotted from the headwaters (left) to outlet (right) as above. Average concentrations for 2015 (grey) and 2016 (blue/red) are highlighted for both "low" flow (open circles) and all data (solid diamonds), regardless of flow conditions. Average concentrations during "low" and all flow conditions are very similar in both 2015 and 2016 due to the number of sampling dates characterized as low flow (Table 22). It should be noted that data collection at the UBWPAD 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 2015 and 2016 mainly fell within the interquartile range of values observed since 2012 at all sampling sites. Average TP concentrations during low flow conditions in 2012 – 2016 are compared to historical concentrations during similar conditions in Figure 25, 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. These data provide further indication that the Upper Blackstone's efforts are translating into reductions in stream TP levels even in the driest conditions.

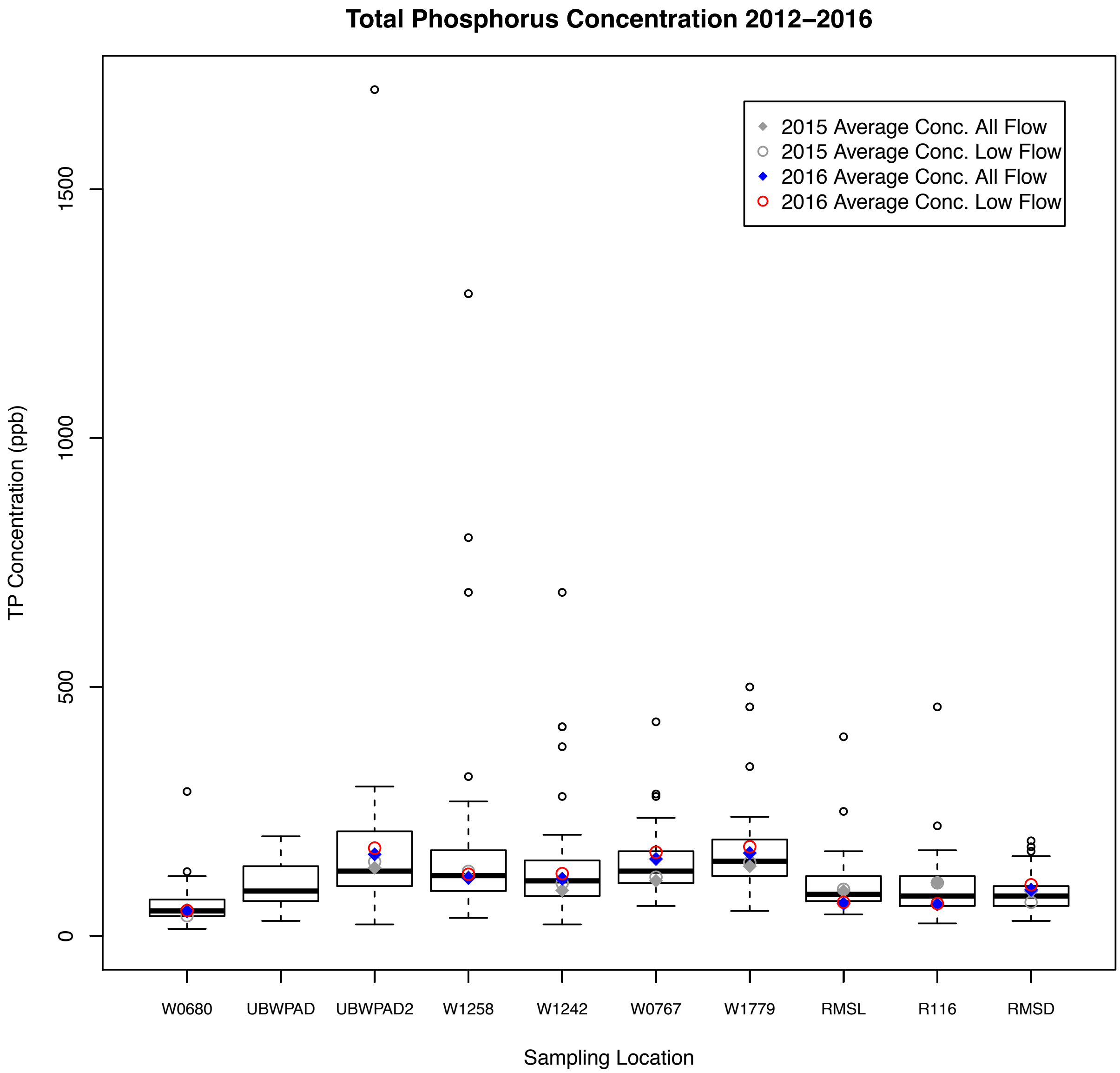


Figure 24: TP concentrations by site from 2012 - 2016

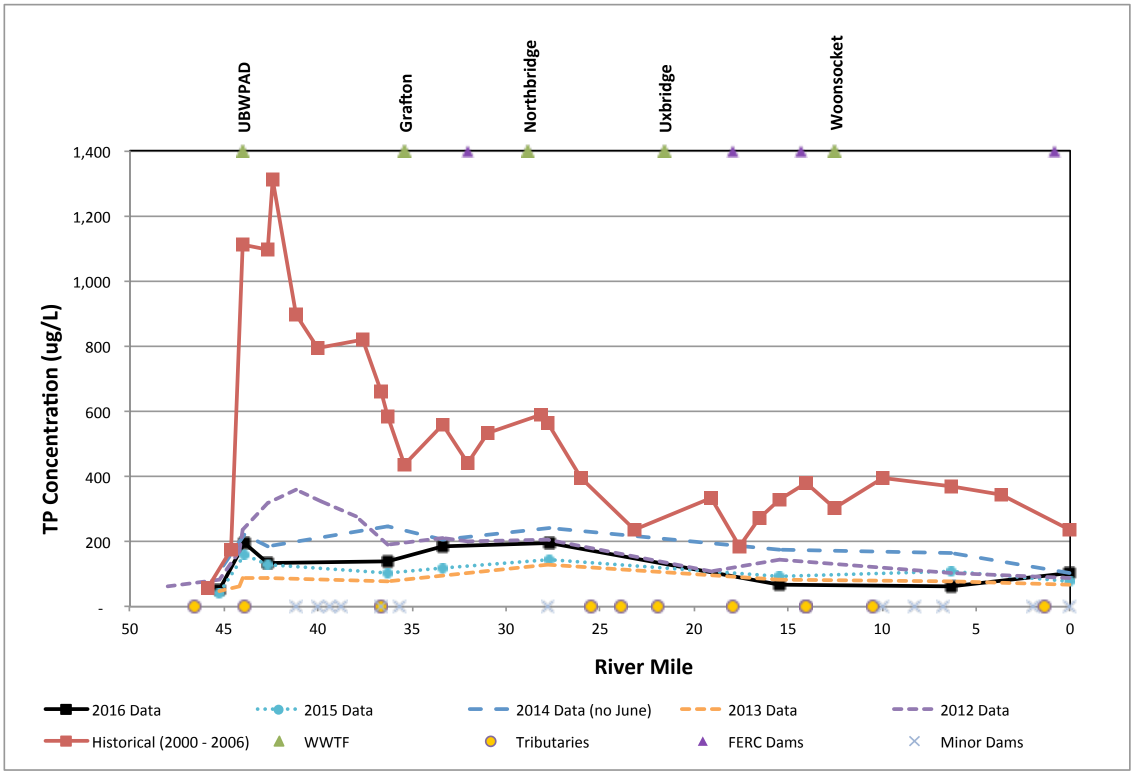


Figure 25: Along stream TP concentrations on low flow days

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 26. Data for all sampling locations along the river are grouped by year. There is a large reduction in TP loads (versus concentrations) in the river since Upper Blackstone upgrades came on line 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 27, with data for 2015 and 2016 highlighted as before. Loads associated with "low" flow sampling events in both 2015 and 2016 were below the median of observed values at all sites. In 2015, sampling in the RI portion of the river (RMSL, R115, and RMSD) resulted in some high loads on "average" days, consistent with the concentration data and resulting in higher than median average loads across all flow conditions. Along stream average TP loads during low flow conditions summarized by year and site, Figure 28, further indicate the on-going improvements in the river and for receiving waters.

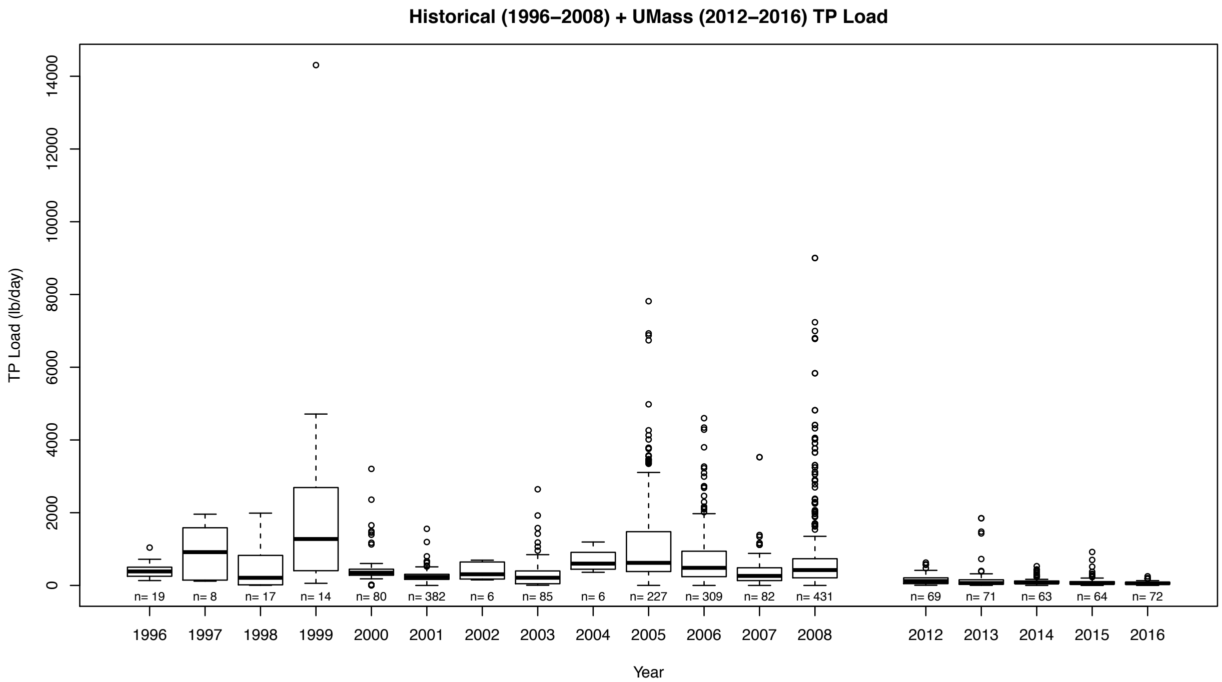


Figure 26: Summary of TP loads observed in the river 1996 – 2008 and 2012 - 2016

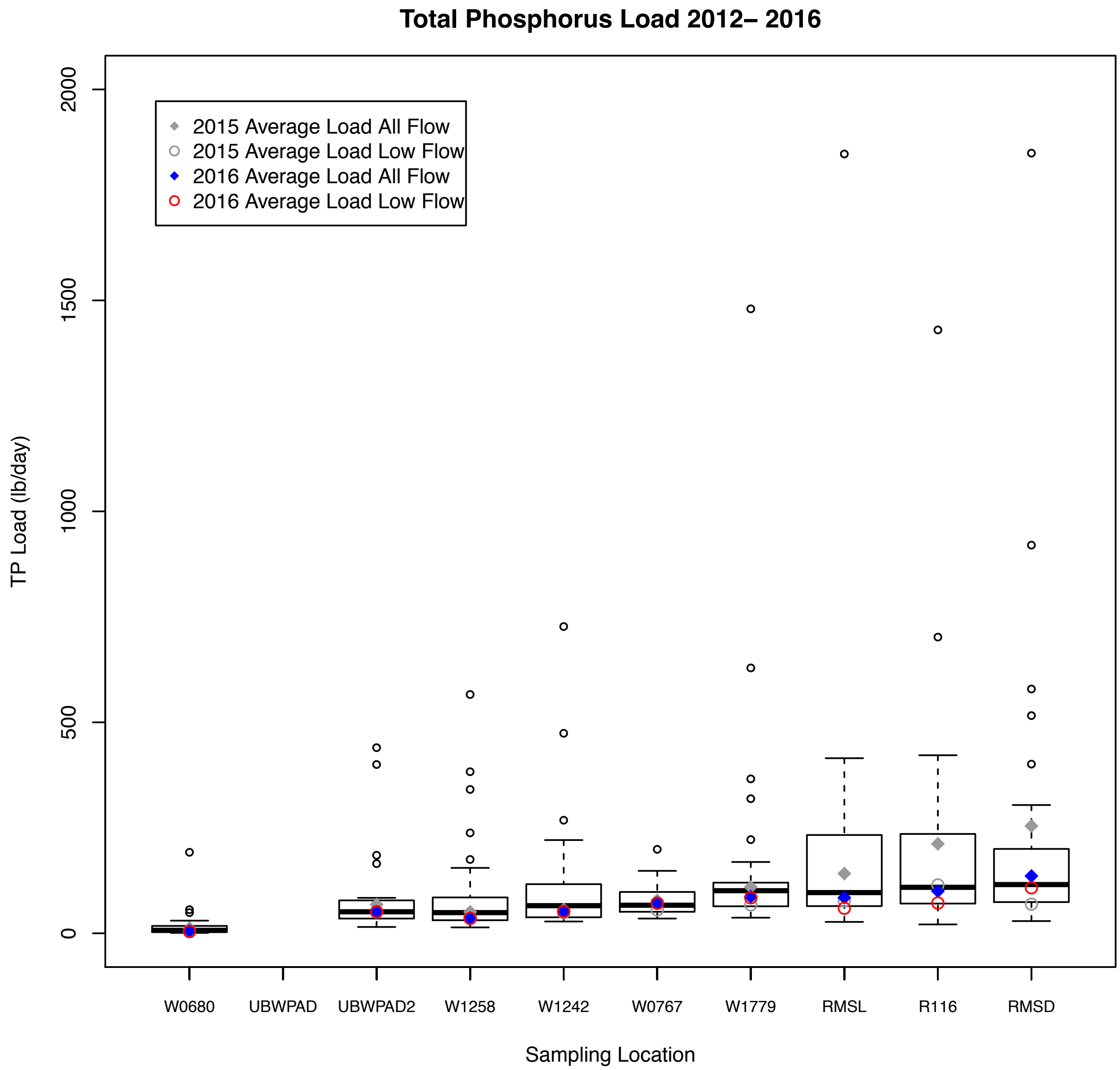


Figure 27: TP load data by site from 2012 - 2016

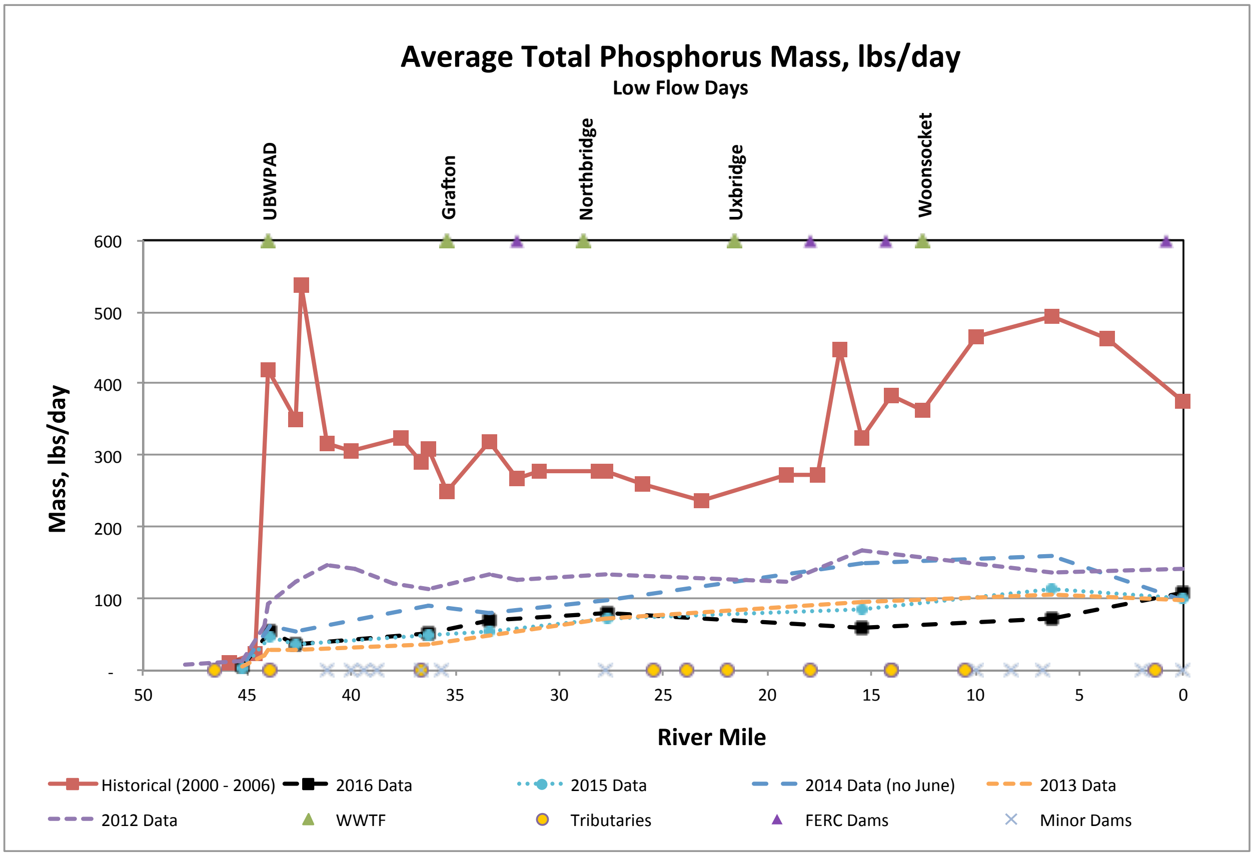


Figure 28: Along stream TP loads on low flow days

6.1.2. Total Nitrogen

Available TN concentration data for the Blackstone River since 1996 are summarized in Figure 29. Fewer extreme have occurred since the Upper Blackstone's plant upgrades came online in 2009, and the overall variability of in-stream concentrations has been reduced even thought the median TN concentration has not changed very much pre- and post-upgrade. The 2008 permit limits reduced TN effluent concentrations by 40% during summer months. Trends in TN are discussed further below.

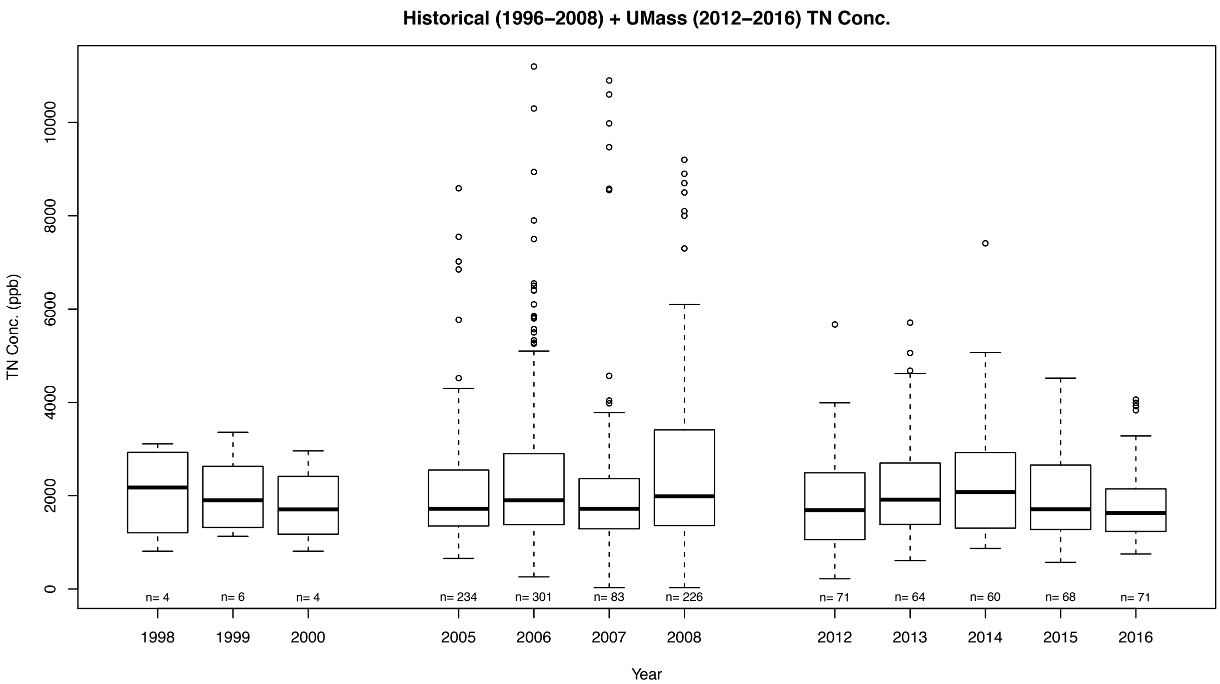
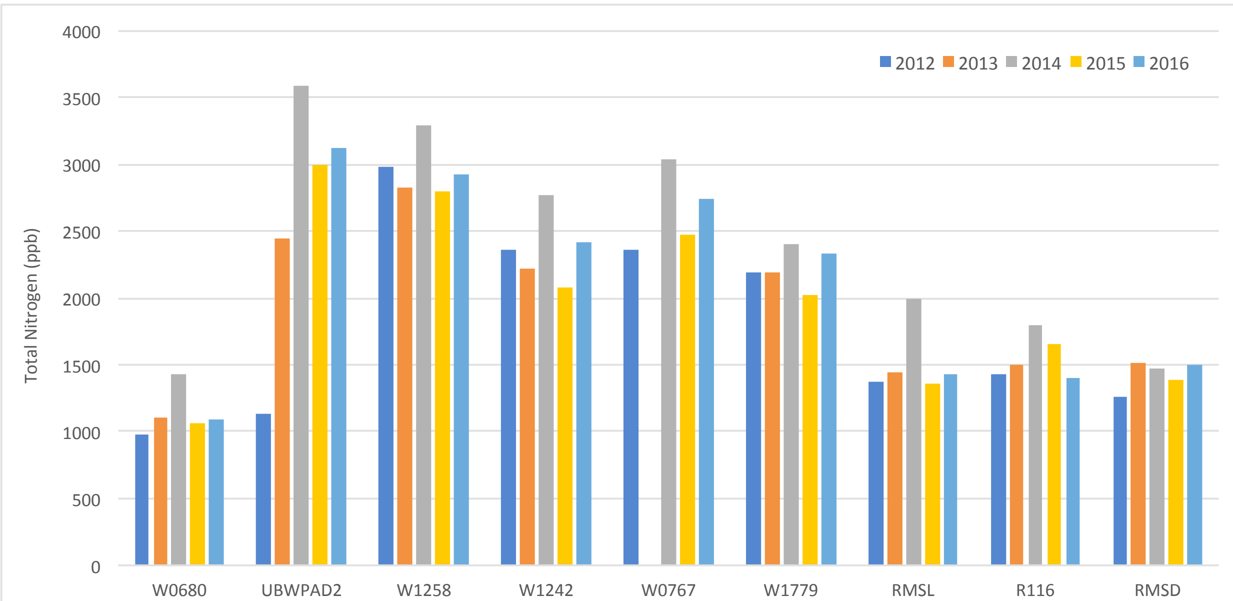


Figure 29: Summary of TN concentrations observed in the river 1996 – 2008 and 2012 - 2016

The mean summer (June – September) TN concentration at each sampling location in the Blackstone River is shown on Figure 30 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 2015 in yellow and 2016 in light blue. As noted above, in 2014 the 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. The 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 the Upper Blackstone's effluent channel, 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.



TN (ppb)	*W0680*	*UBWPAD2*	*W1258*	*W1242*	*W0767*	*W1779*	*RMSL*	*R116*	*RMSD*
2012	983.3	1127.5	2976.0	2366.0	2366.0	2184.0	1368.0	1432.0	1264.0
2013	1102.5	2440.0	2820.0	2225.0	NA	2192.5	1440.0	1497.5	1507.5
2014	1433.3	3590.0	3292.5	2763.8	3041.3	2399.8	1990.0	1801.3	1473.5
2015	1068.8	2993.3	2791.5	2083.8	2466.5	2018.0	1352.8	1653.8	1383.5
2016	1087.5	3120.0	2925.0	2420.0	2742.5	2332.5	1427.5	1407.5	1500.0

Figure 30: Mean summer (June – September) TN concentrations observed by site 2012 - 2016

The full range of TN concentrations observed at each site since 2012 is summarized in Figure 31, with sites plotted from the headwaters (left) to outlet (right) as above. Average concentrations for 2015 (grey) and 2016 (blue/red) are highlighted for both "low" flow (open circles) and all data (solid 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 concentrations in 2015 and 2016 fell within the interquartile range of values observed since 2012 at all sampling sites except for R116, where the average of TN concentrations sampled during low flow conditions was slightly above the interquartile range. Average concentrations in

2015 were higher than in 2016, as evidenced by the grey solid triangle and open circle (2015 data) falling above the solid blue diamond and open red circle (2016 data) in Figure 31. Average TN concentrations during low flow conditions in 2012 – 2016 are compared to historical concentrations during similar conditions in Figure 32, 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. The along stream low flow data suggest that TN concentrations in the river have improved.

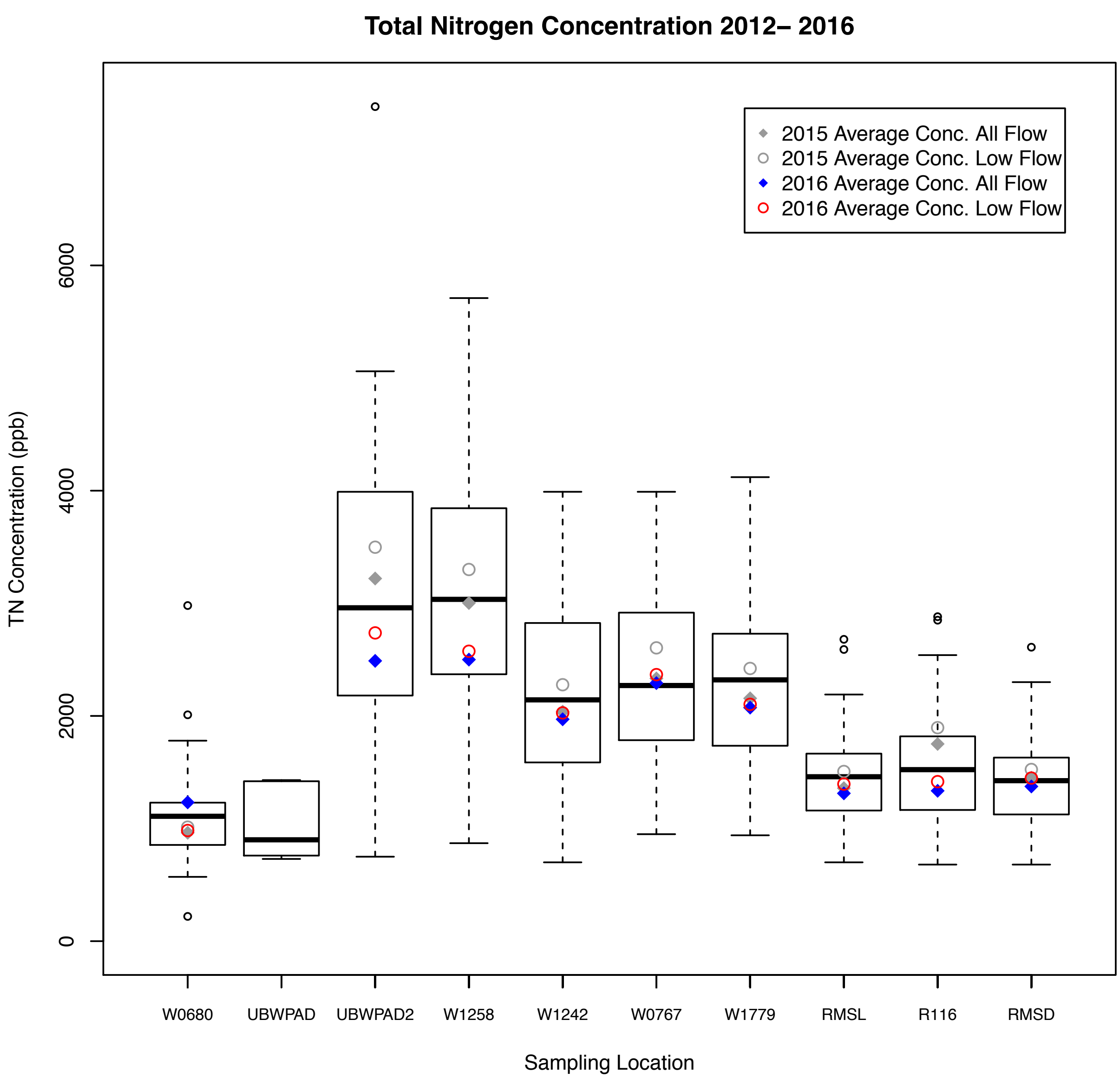


Figure 31: TN concentrations by sampling location from 2012 - 2016

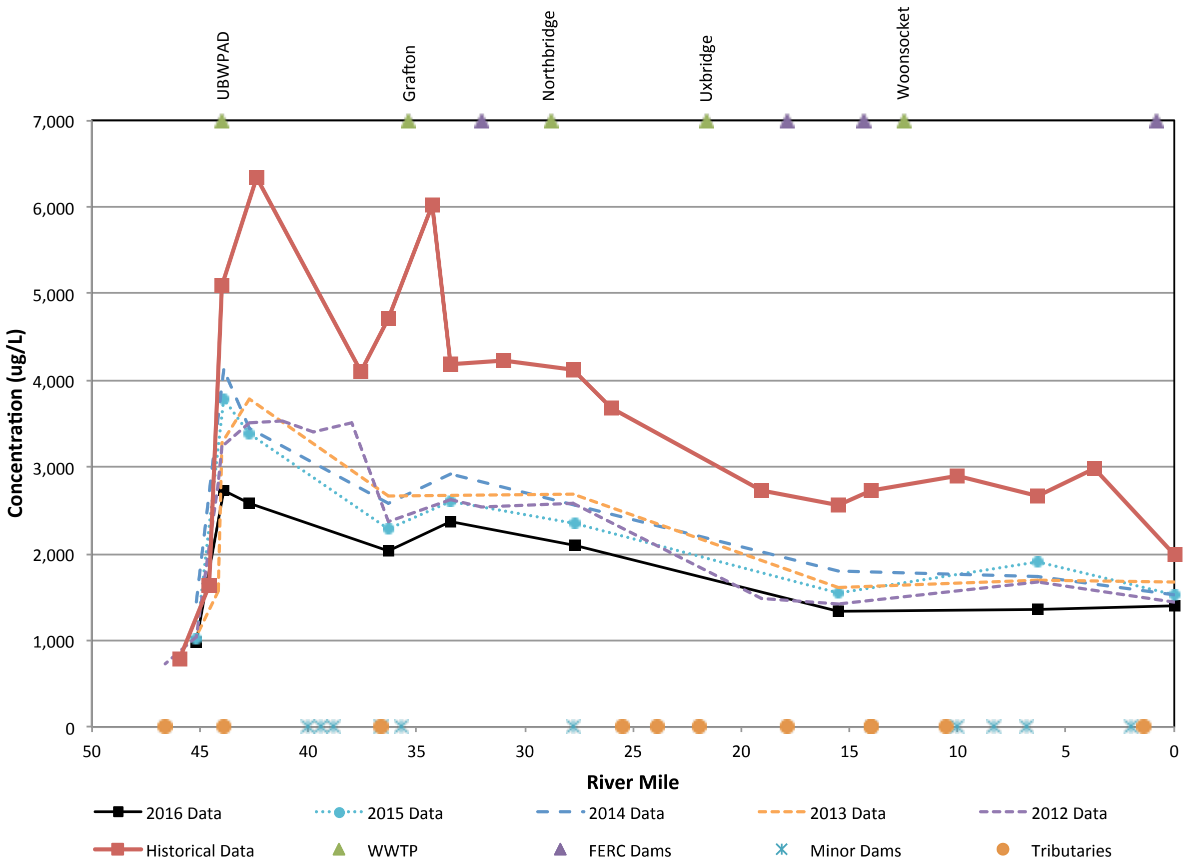


Figure 32: Along stream TN concentrations on low flow days

Estimates of TN loads since 1996 in the Blackstone River are summarized in Figure 33. 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 upgrades were on-line in 2009. The interquartile range of observed TN loads from 2012 through 2016 are smaller than from 1999 through 2008. In addition, the interquartile ranges for years 2012 - 2016 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 34, with data for 2015 and 2016 highlighted as before. Loads associated with "low" flow sampling events in both 2015 and 2016 were below the median of observed values at all but one site. Average TN loads across all flow conditions were elevated in 2015 at some locations compared to historic data. While the interquartile range (body of box) of TN concentrations tended to decrease downstream, TN loads increase. This increase is more pronounced for TN than observed for TP and is explored further below.

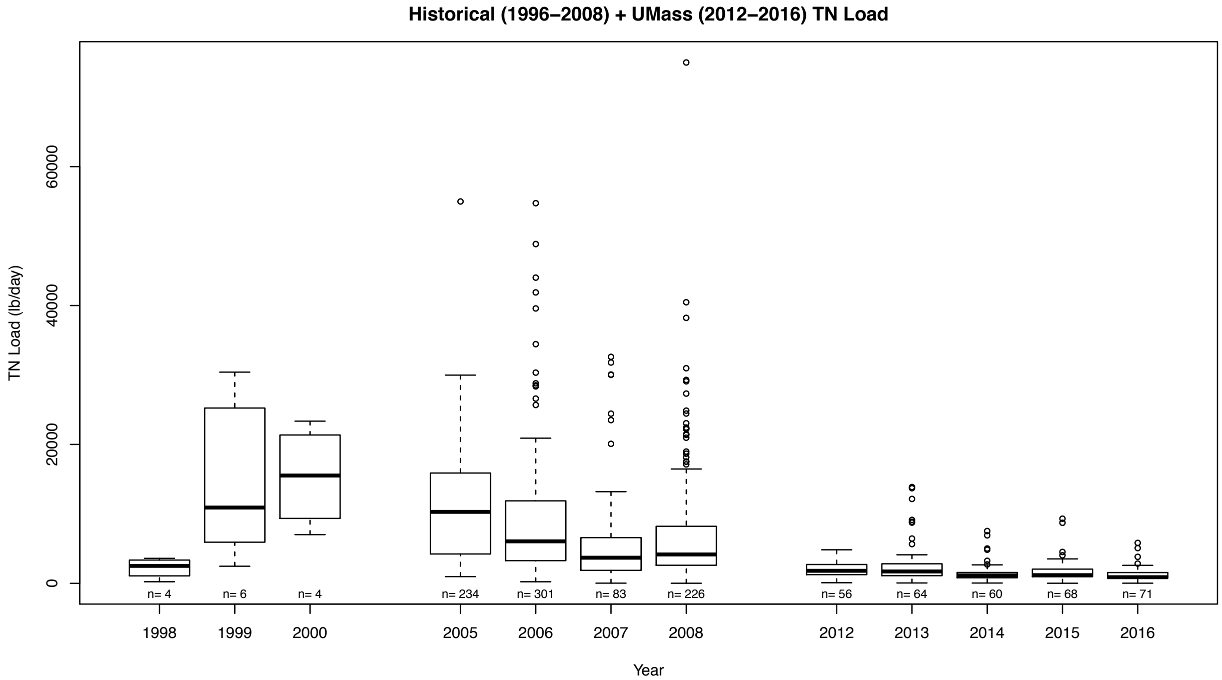


Figure 33: TN loads observed in the river 1996 – 2008 and 2012 - 2016

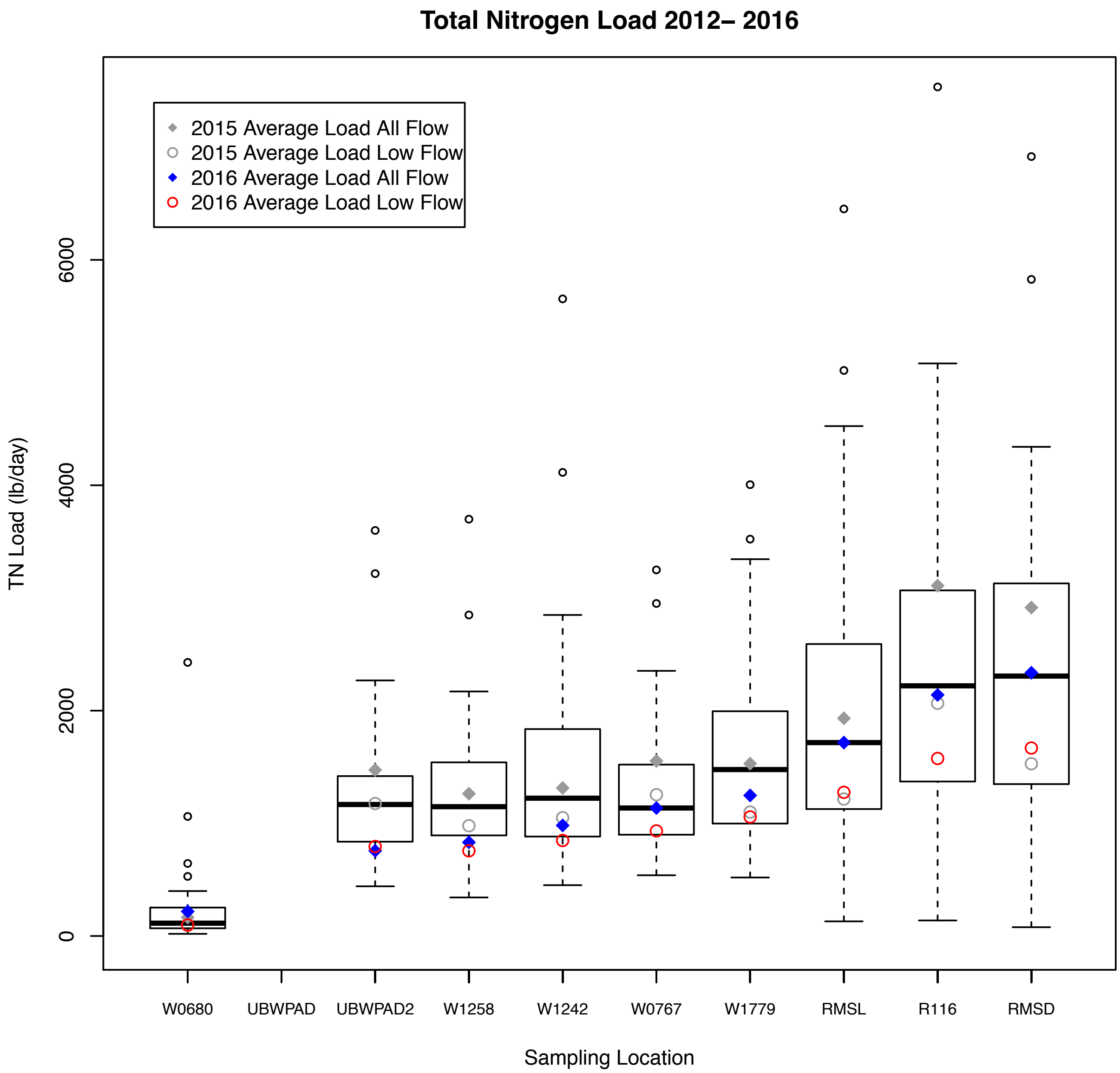


Figure 34: TN load data by sampling location 2012 - 2016

Along stream average TN loads during low flow conditions, as summarized by year and site, Figure 35, further indicate on-going improvements in the river and for receiving waters. The average TN load on low flow days in 2016 was lower than observed from 2012 through 2015, as well as compared to historic data, at almost all sampling locations.

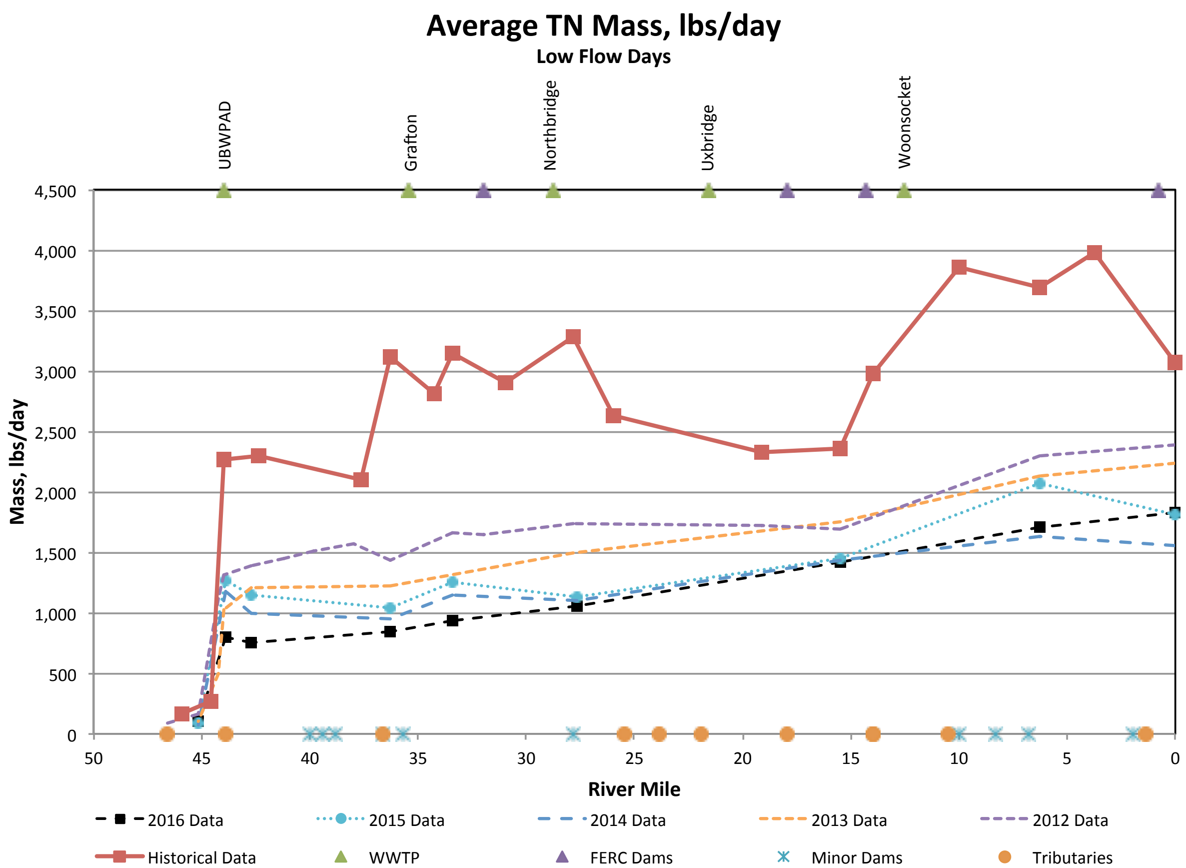


Figure 35: Along stream TN loads on low flow days

6.1.3. Chlorophyll-a

Chlorophyll-a concentrations observed during the summer months (June – September) since 2012 are summarized by year in Figure 36. The same data are summarized by site in Figure 37. Summertime chlorophyll-a levels were elevated in 2016 compared to other years at MA sampling locations but much closer to median observed values at the three sampling sites located in RI. Data for 2015 were more reflective of average conditions across the sites. The mean summer (June – September) Chlorophyll-a concentration for each year and sampling location on the Blackstone River is summarized on Figure 38. Data are clustered by sampling site, plotted from the headwaters (left) to the outlet (right). Chlorophyll-a concentrations tend to increase in the downstream direction, as water is retained in and then exits from impoundments.

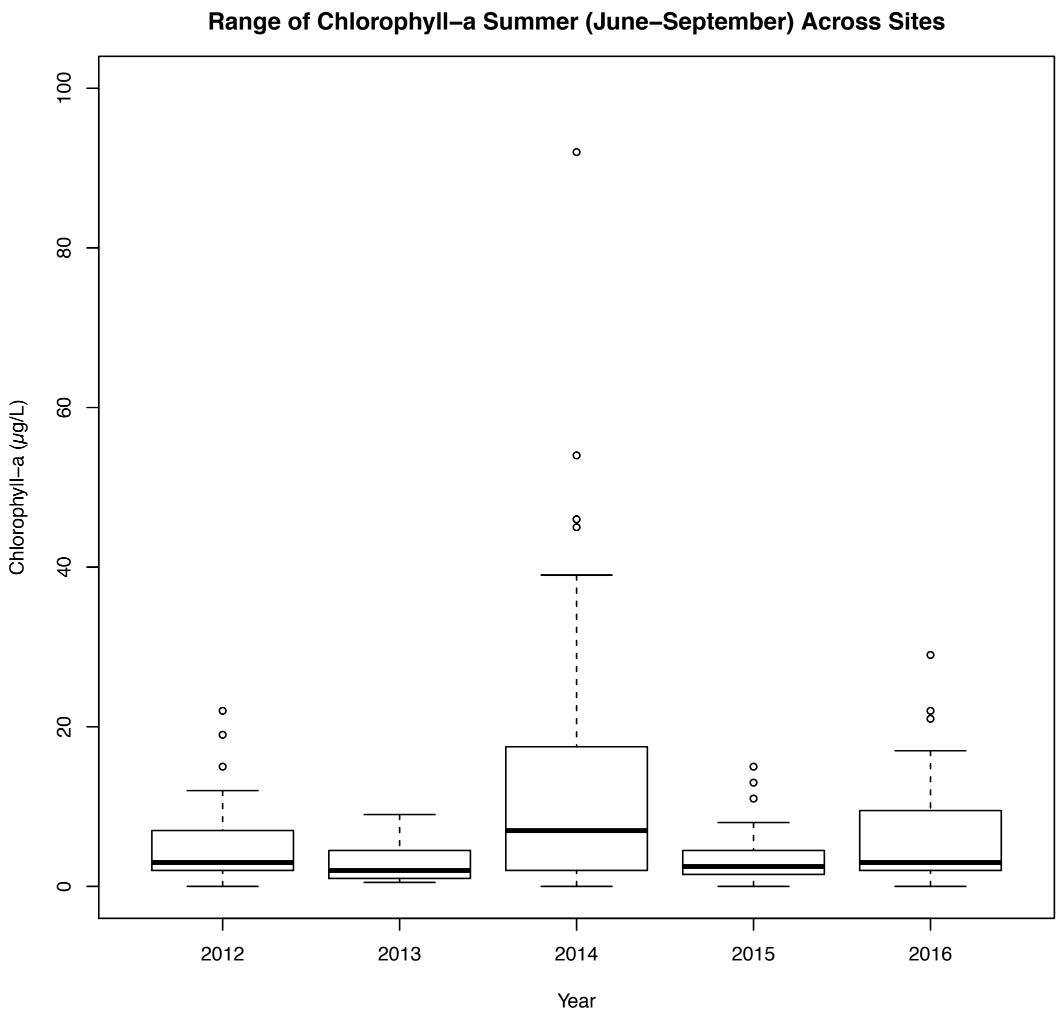


Figure 36: Chlorophyll-a concentrations observed during June, July, August and September since 2012, summarized by year

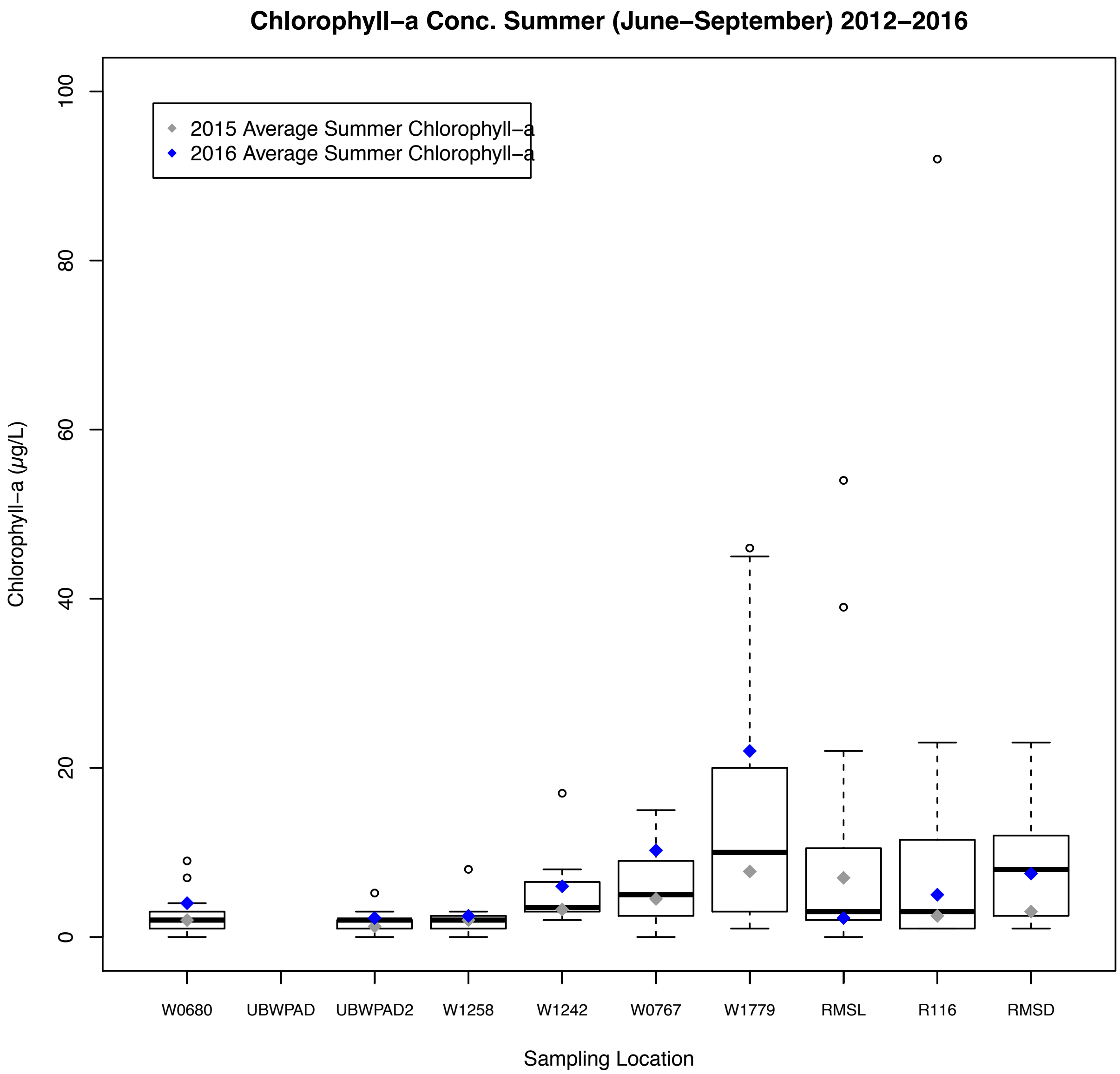
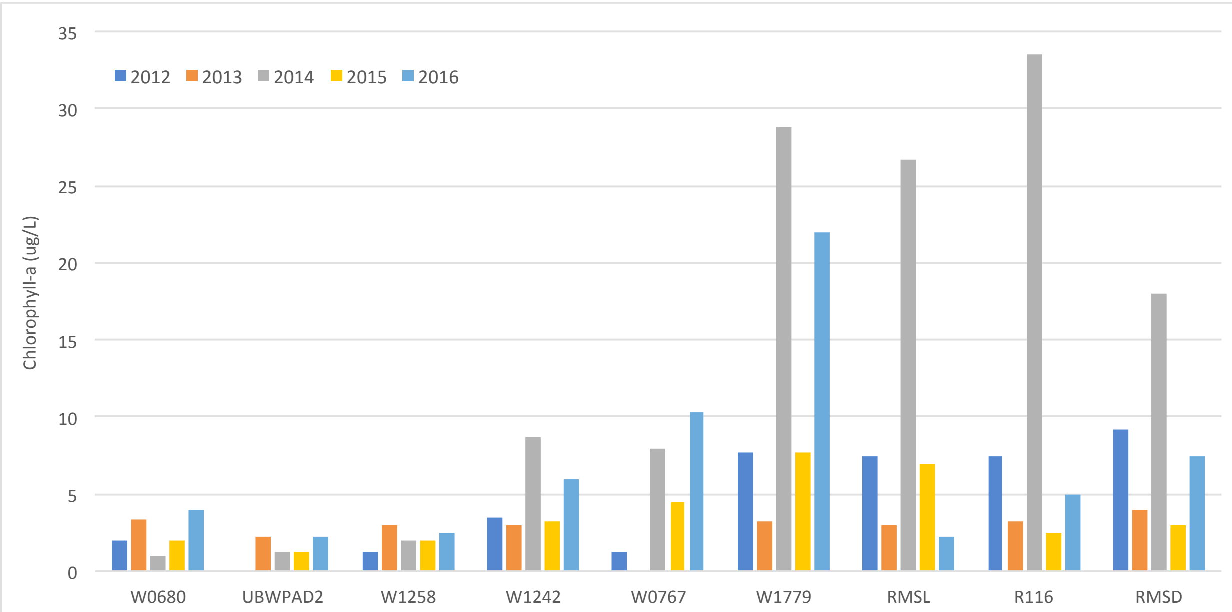


Figure 37: Chlorophyll-a concentrations observed during June, July, August and September since 2012, summarized by sampling location



Chl-a (ug/L)	*W0680*	*UBWPAD 2*	*W1258*	*W1242*	*W0767*	*W1779*	*RMSL*	*R116*	*RMSD*
2012	2.0	NA	1.3	3.5	1.3	7.8	7.5	7.5	9.3
2013	3.3	2.2	3.0	3.0	NA	3.3	3.0	3.3	4.0
2014	1.0	1.3	2.0	8.8	8.0	28.8	26.8	33.5	18.0
2015	2.0	1.3	2.0	3.3	4.5	7.8	7.0	2.5	3.0
2016	4.0	2.3	2.5	6.0	10.3	22.0	2.3	5.0	7.5

Figure 38: Mean summer (June – September) Chlorophyll-a concentrations by site 2012 - 2016

Average and maximum Chlorophyll-a concentrations during low flows in 2012 – 2016 are compared to historical concentrations during similar conditions in Figures 39 and 40. These figures indicate similar trends, with 2015 data falling in the middle of data collected since 2012, and 2016 data falling at the high end along portions of the river in MA but at the low end in RI. The highest average and maximum Chlorophyll-a concentrations observed since 2012 at most sampling locations occurred in 2014.

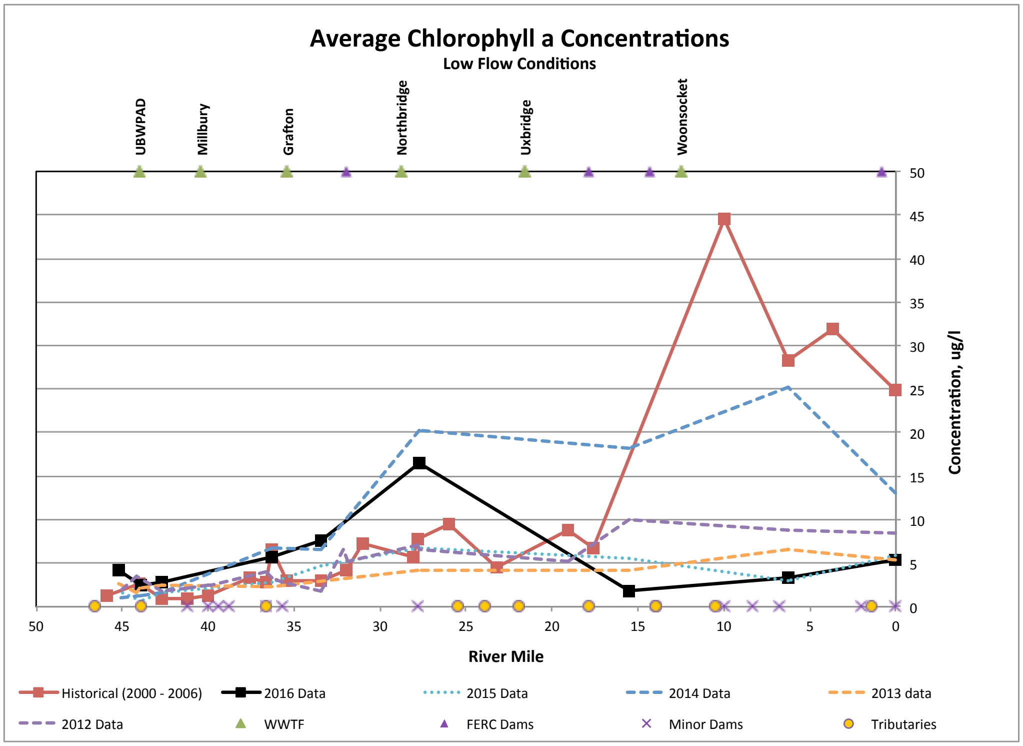


Figure 39: Along stream average Chlorophyll-a levels on low flow days

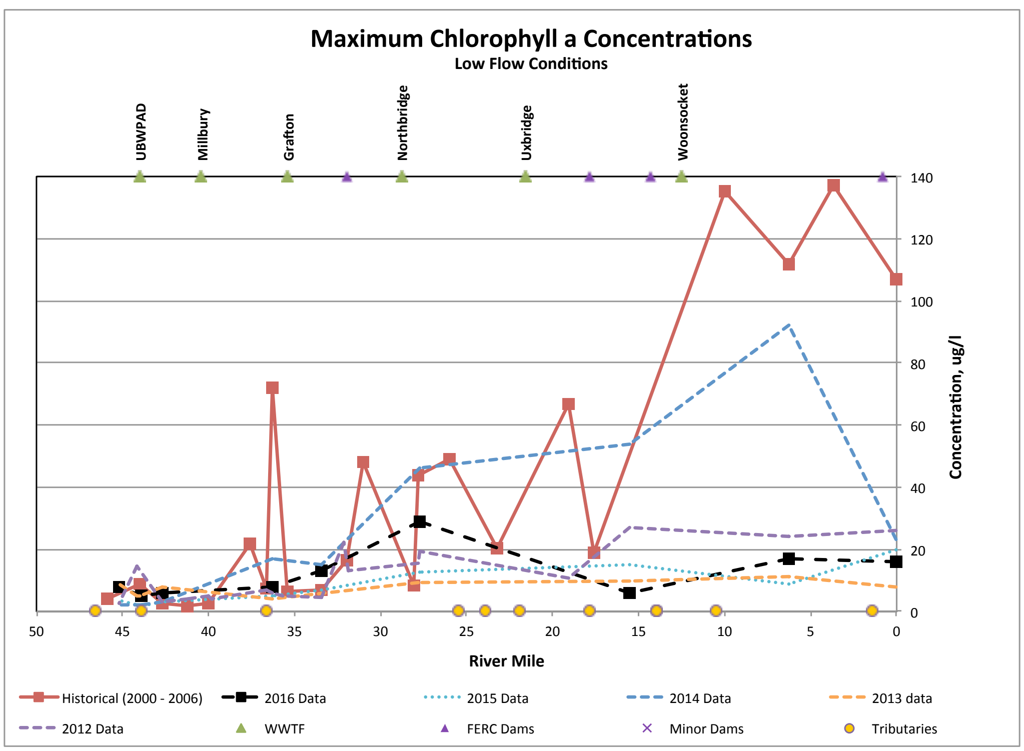


Figure 40: Along stream maximum Chlorophyll-a levels on low flow days

A combination of factors, including temperature, exposure to sunlight, flow, and nutrient availability on the days preceding routine sampling, likely contribute to the observed year-to-year differences in water column chlorophyll-a. The years 2014, 2015, and 2016 were all characterized by low flow conditions, particularly on the days when routine samples were collected. River flows on routine sampling days during the years 2014 and 2016 were slightly lower than in 2015 along the MA portions of the river, while along the RI portions of the river, 2014 sampling day flows were a bit lower than in 2015 and 2016. TP and TN levels were highest in 2014. While TN levels in 2016 were consistently lower than in 2015, TP levels were higher in 2016 than 2015 along the MA portions of the river (and lower along the RI portions). Summer temperatures were warmer in 2016 than either 2015 or 2014. In addition, the summer followed a particularly warm spring. Conversely, the winter of 2014/2015 and spring of 2015 were atypically cool. The dry conditions, particularly along the MA portions of the river, followed by a warm spring and hot summer, are likely the major factors contributing to the elevated chlorophyll-a levels in MA and low levels in RI observed in 2016. The cold winter and spring may have somewhat suppressed chlorophyll-a levels in 2015.

6.1.4. 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 complete the analysis at all sampling locations except for W0767. The Mann-Kendall analysis becomes more robust as more data become available. The analysis found:

- Statistically significant decreasing trends in TP flow-weighted concentration at the state-line sampling site RMSL and the Route 122, Grafton, sampling location W1242. These sites exhibited seasonal decreasing trends in TP at the 95% and 90% significance level, respectively.
- Statistically significant seasonal decreasing trends in TN at the 95% significance level at three sampling locations: Central Cemetery in Millbury, MA (W1258); Route 122, Grafton (W1242) and below Rice City Pond at Hartford Street in Uxbridge, MA (W1779). If data are blocked monthly, instead of just seasonally, there is also a significant decreasing trend in flow-weighted TN concentration at the state-line sampling site RMSL at the 95% significance level.

- A statistically significant decreasing trend in seasonal flow-weighted chlorophyll-a concentration at the 90% significance level at one site, the New Millbury Street Bridge sampling location in Worcester, MA (W0680), upstream of the confluence. If data are blocked monthly, instead of just seasonally, there is also a significant decreasing trend in flow-weighted chlorophyll-a concentration at the Central Cemetery sampling location (W1258), downstream of the confluence. The monthly flow-adjusted decreasing trends at both W0680 and W1258 are significant at the 95% significance level.

6.2 Periphyton Sampling

Normandeau Associates conducted periphyton sampling at four sites in July, August, and September of 2015 and 2016. Three sampling sites (UBPWAD[8], W1258, and Depot) are located in areas where the MassDEP conducted its periphyton sampling in 2008 (MassDEP and Beskins, 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.

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 (4) parallel transects in riffle/run areas were collected. Transects were spaced at least 5 meters apart and were selected to maintain habitat uniformity. Three (3) sub-samples were collected from three (3) 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^2. The value reported for each composite is the average of three (3) 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 (6) aliquots, or the average of the two composite samples.

Normandeau has conducted periphyton sampling at all four sites since 2012. Periphyton results are presented in Figure 41 and Table 23, including the 2008 MassDEP data. In 2014, 2015, and 2016, water column samples were collected at the time of periphyton sampling and analyzed for TP and chlorophyll-a, Table 24. Periphyton levels in 2016 were the highest observed since sampling began except at the most upstream site, W0680, which is located above the confluence with the Upper Blackstone's effluent channel, Figures 41 and 42. The most elevated levels occurred

[8] 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.

downstream from the confluence, at the UBWPAD site. MassDEP utilizes 200 mg/m^2 as the target maximum periphyton chlorophyll-a level in rivers. Data collected in 2012 through 2015 fall below this target level, but all of the periphyton samples collected at the UBWPAD sampling location, the July sample at Depot, and the September sample at W1258 fell above this target level in 2016. The 2014-periphyton samples also tended to be high compared to other years, particularly at W0680. Timing of maximum levels during the summer season varies from year-to-year and site-to-site, Table 23 and Figure 43.

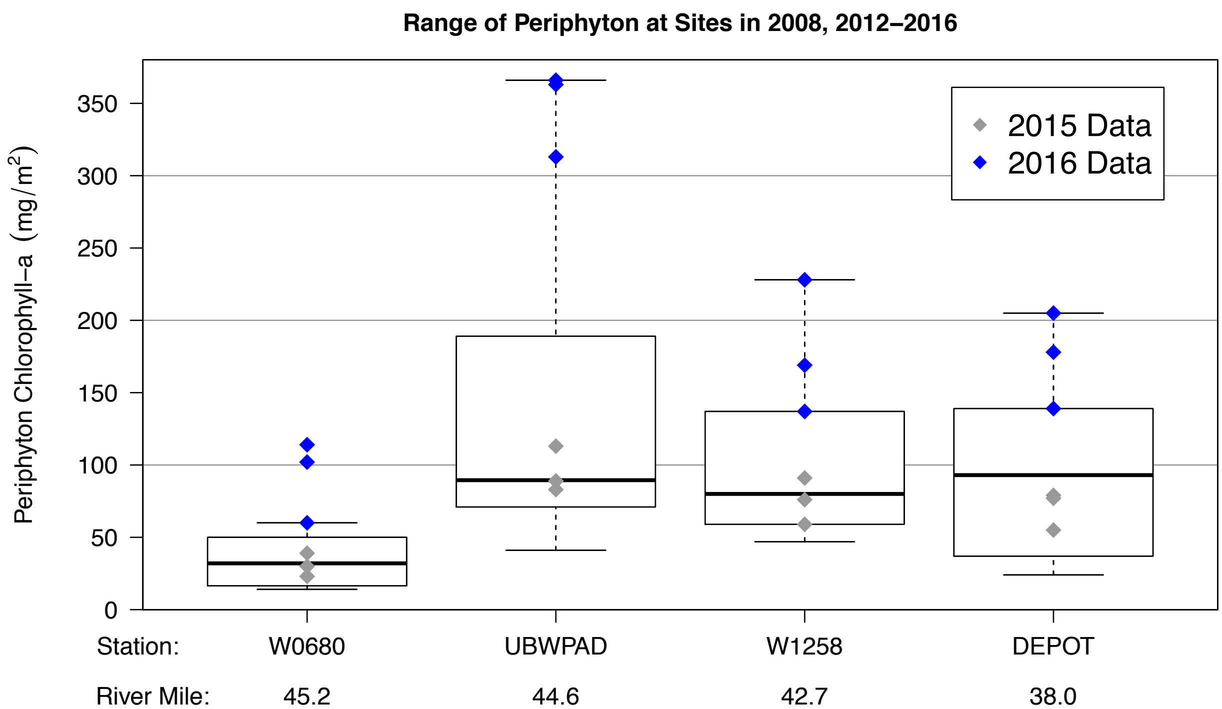


Figure 41: Range of periphyton at sampling sites in 2008, 2012 - 2016

Table 23: Available periphyton data for the Blackstone River

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

Notes: [a] Data collected by MassDEP (MassDEP and Beskins, 2009)
[b] In 2013, periphyton was sampled twice in July, once in early July and once in late July

Table 24: Available water column Chlorophyll-a and TP data week of periphyton sampling

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

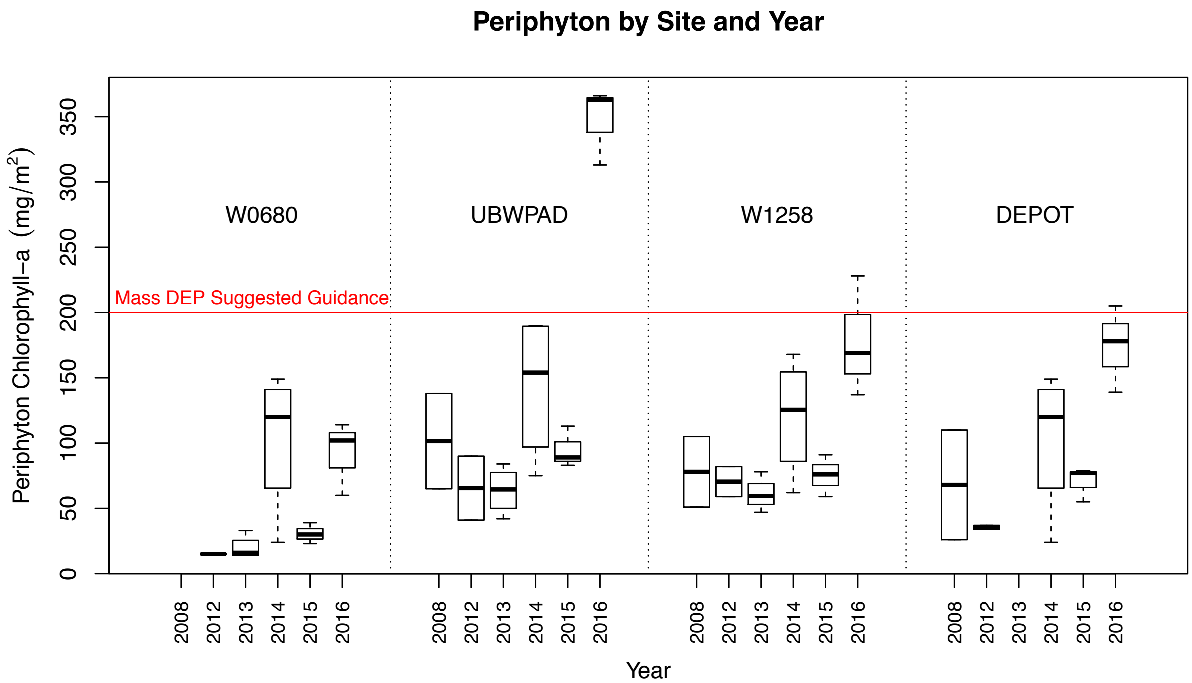


Figure 42: Summary of available periphyton data by sampling site and year

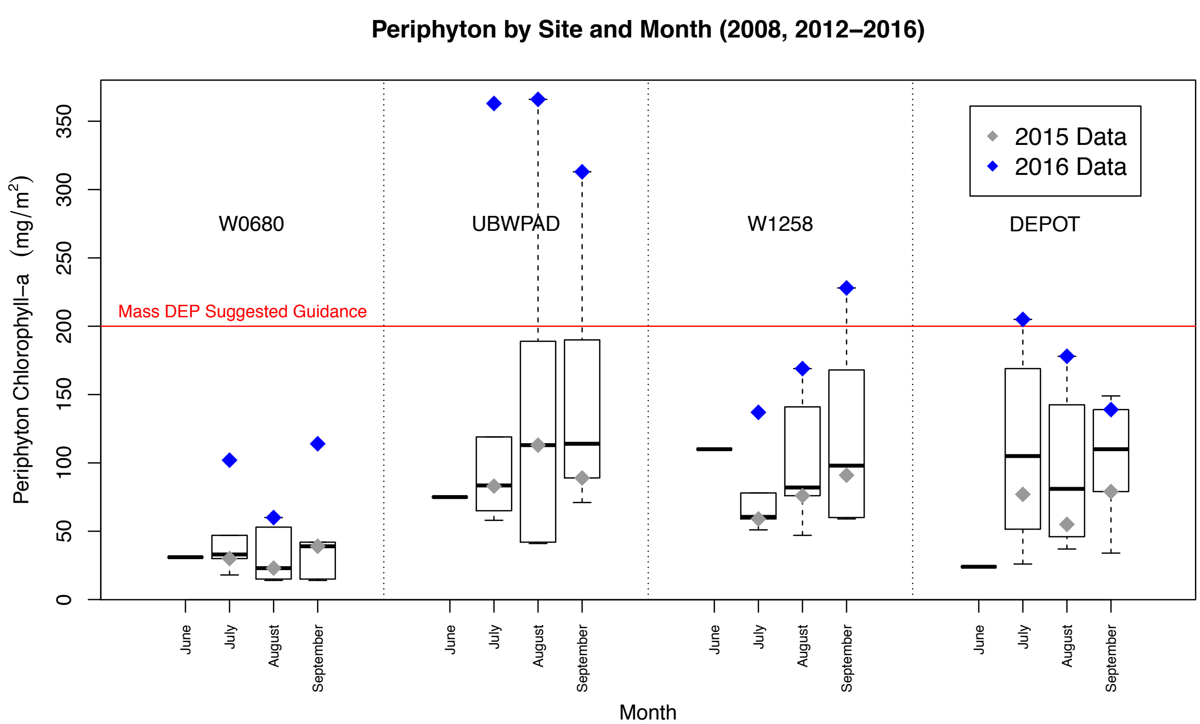


Figure 43: Periphyton concentrations by sampling site and month 2008 and 2012 - 2016

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. Their guidance utilizes three times (3x) the median average monthly flow as the criteria for potential scour. Table 25 summarizes the 3x median average monthly flow values for the USGS Millbury gauge. 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)[9]. In 2016 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.
- 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.

In summary, periphyton sampling decisions are made with respect to these suggested metrics, weather forecasts, and personnel availability.

[9] 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 2016. These values shift slightly each year, as new data are added and the values updated.

Table 25: Monthly mean daily summer discharge (cfs) for USGS Millbury gauge

(Period of Record mean daily value = 127 cfs; 3x = 381 cfs)

Year	Jun	Jul	Aug	Sep
2002[a]	NA	54.2	55.6	72.2
2003	302.6	96.2	124.6	100.3
2004	80.1	98.2	88.1	164.9
2005	106.7	136.1	63.1	78.7
2006	312.4	103.0	75.7	73.9
2007	136.1	77.3	52.5	54.3
2008	114.2	151.3	143.1	227.9
2009	145.9	395.9	157.2	79.4
2010	114.3	60.9	65.9	47.1
2011	201.5	92.9	273.1	339.9
2012	135.9	67.8	104.6	88.0
2013	433.8	104.9	85.2	81.8
2014	80.2	76.7	67.7	70.3
2015	164.4	95.7	59.9	71.7
2016	**67.1**	**48.6**	59.4	47.8
Average[b]	171.1	110.6	98.4	106.5
Median[b]	136.0	95.7	75.7	78.7
3xMedian[b]	408.0	287.1	227.1	236.1
Minimum[b]	**67.1**	**48.6**	52.5	47.1

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

[b] Summary calculations based on data through 2016

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 26. No exceedences occurred in either 2014 or 2016, but in 2015, two days in June, one day in July, and one day in September rose above this level. Figure 44 summarizes flow conditions in 2015 during the two-week periods prior to periphyton sampling relative to 3x the median of monthly daily flows and an instantaneous flow value of 250 cfs, both of which are more restrictive than conditions suggested by the MassDEP guidance. In addition, a line representing 3x the median period of record daily flow is included on the figure. For comparison purposes, Figure 45 summarizes the flow conditions similarly for 2016. Similar figures for earlier years are provided in the appendix. The 3x median values included on all figures are calculated based on the daily flows from 2002 – 2016 for consistency purposes. However, it should be noted that the actual criteria used each sampling season varies slightly. For instance, the criteria utilized during the 2016-sampling season were based on data from 2002 through 2015, as data for 2016 were not available. The values listed in Table 25 will be the criteria utilized for the 2017 sampling season.

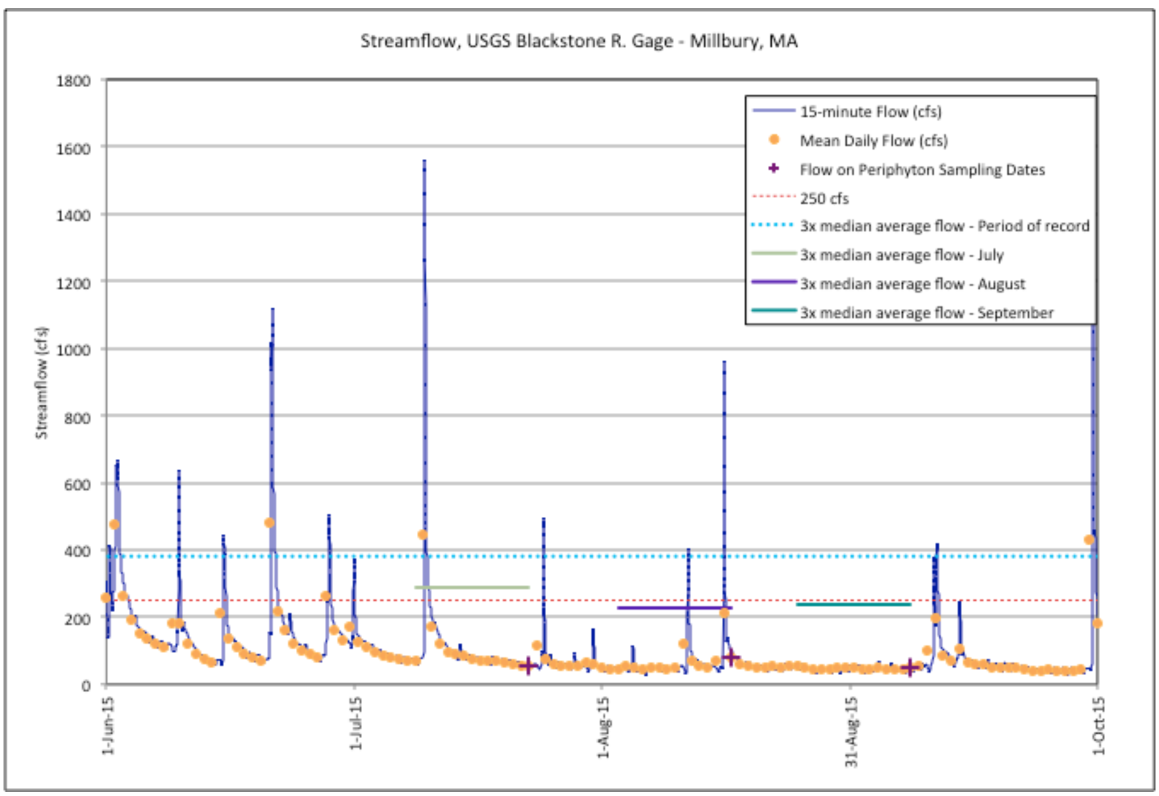


Figure 44: Summary of 2015 flows relative to periphyton sampling

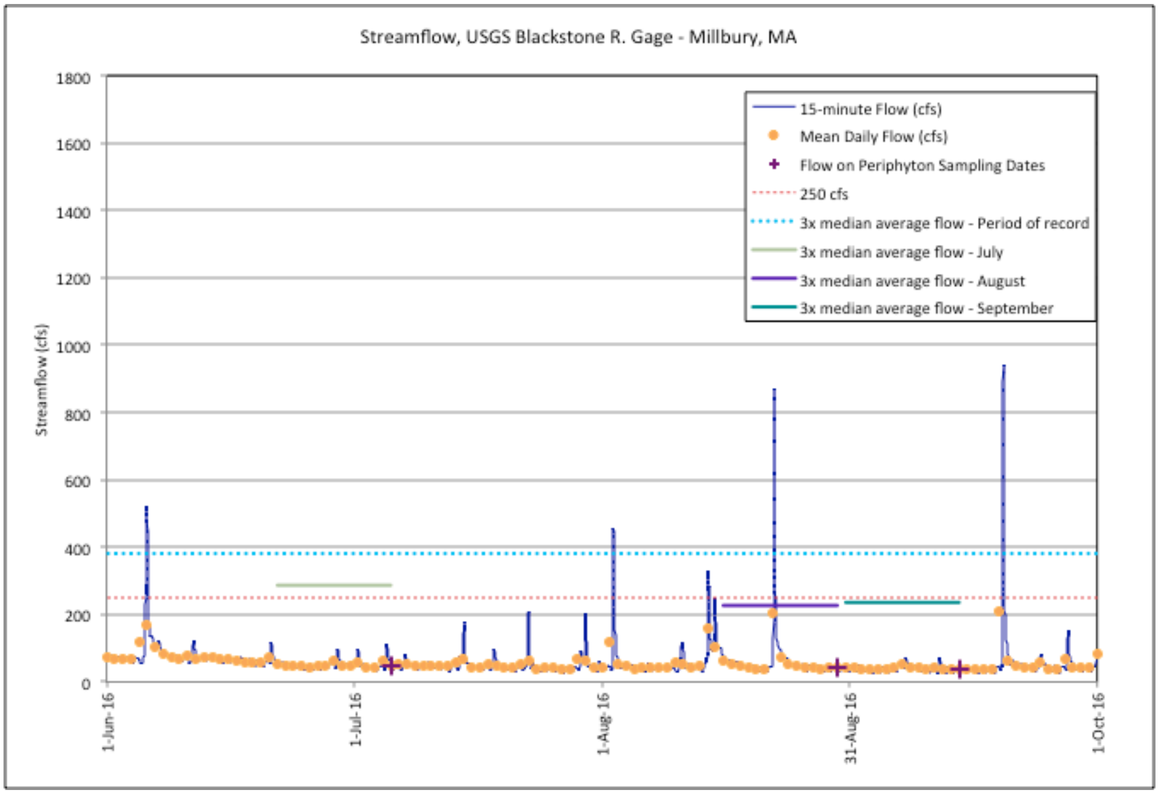


Figure 45: Summary of 2016 flows relative to periphyton sampling

Table 26: Number of days mean daily flow at Millbury exceeded 3x the period of record median

Year	Jun	Jul	Aug	Sep
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

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 27 for 2015. Although 2015 was overall dry, it was difficult to meet the ideal dry weather – low flow criteria. Key observations include:

- July 2015 sampling occurred 13 days after mean daily flows rose to ~450 cfs and instantaneous values were close to 1600 cfs.
- August 2015 sampling occurred on the 17th, two days after 1.67 inches of rain fell on August 15th, on top of 0.76 inches that had fallen August 11th. Instantaneous flows rose above 950 cfs the day before sampling.

Based on these flow conditions, it is possible that scour contributed to lower periphyton levels in July and August of 2015. While it is unlikely that scour directly impacted the September 2015 sampling event, if scour did occur prior to the August 17th sampling event, there may have been insufficient time for full re-growth. Normandeau Associates, who conducted the sampling, did not note any evidence of scour in the field in either July or August. Additional figures and tables for 2012, 2013, 2014 and 2016 are provided in the appendix. Lower flow conditions were associated with periphyton sampling during these years.

Nutrient levels in the stream may influence periphyton growth, however similar in-stream TP concentrations can have very different corresponding periphyton concentrations, Figure 46, 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 vertical line are characterized by similar water column TP concentrations on the day of periphyton sampling, but are characterized by different periphyton chlorophyll-a concentrations. Mean summertime (June – September) TN and TP concentrations (earlier Figures 23 and 30) 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 since routine sampling began in 2012 occurred in 2014, however the highest observed periphyton chlorophyll-a concentrations were observed in 2016. Nutrient availability is only one of several environmental conditions that may impact periphyton growth.

Table 27: 2015 periphyton sampling antecedent rain and discharge conditions

2015 Date	Daily Precipitation, Worcester, MA (inches)	Mean Daily Discharge (cfs) – Millbury, MA	Peak Daily Discharge (cfs) – Millbury, MA
July 16	0.00	75	87
July 17	T	70	81
July 18	0.11	71	87
July 19	T	70	82
July 20	0.00	67	74
July 21	0.01	62	69
July 22	0.00	57	66
July 23	0.00	55	60
August 10	0.00	48	56
August 11	0.76	121	403
August 12	0.00	70	90
August 13	0.00	57	70
August 14	0.00	52	59
August 15	1.67	69	859
August 16	0.00	211	961
August 17	0.00	79	94
September 1	0.00	51	60
September 2	0.00	47	56
September 3	T	47	56
September 4	0.00	51	70
September 5	0.00	47	63
September 6	0.00	43	52
September 7	0.00	45	59
September 8	0.00	48	61

Note: [a] Periphyton sampling dates are shaded

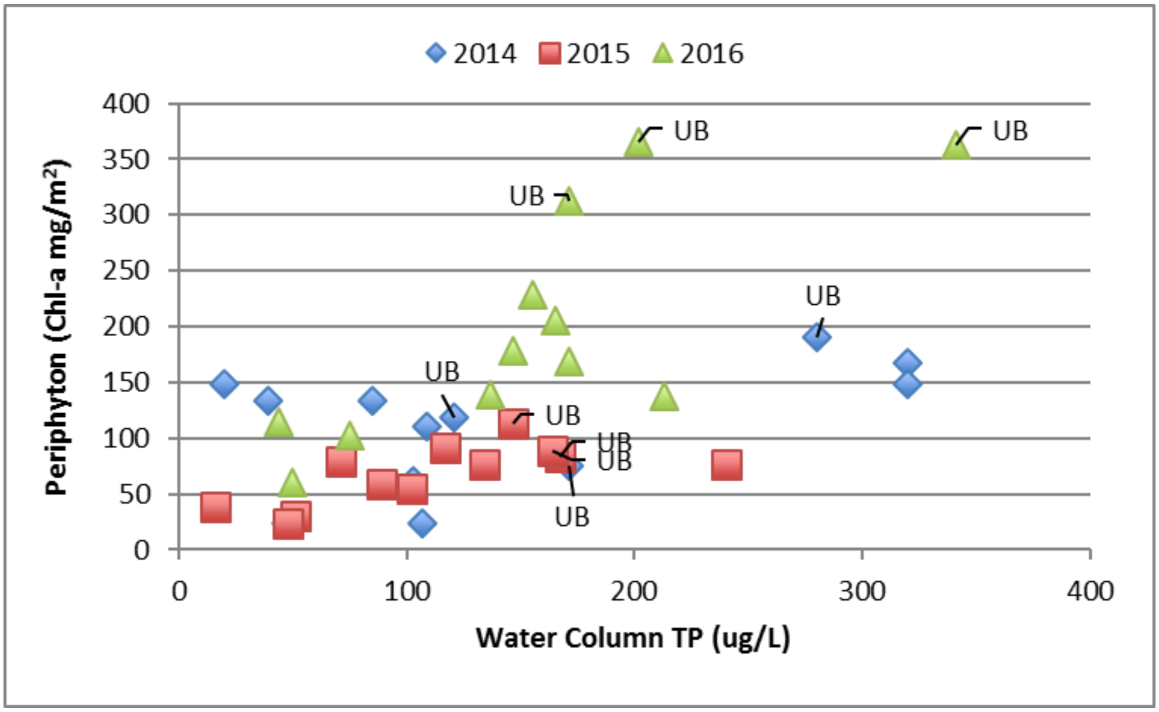


Figure 46: Measured periphyton chlorophyll-a concentrations in 2014, 2015 and 2016 plotted against water column TP concentration (*UB = UBWPAD periphyton monitoring location)

In addition to streamflow and nutrients, other environmental factors that influence water column chlorophyll-a levels – particularly exposure to sunlight and stream temperatures – may strongly influence periphyton growth and partially account for monthly and annual variability. Low summer stream flows result in shallower water depths and greater penetration of sunlight to the river bottom, where periphyton grows. Monthly mean daily discharge for the months of July, August and September 2016 were the lowest observed during months for which corresponding periphyton data are available (2008, 2012 – 2016). These dates (July, August, and September 2016) also correspond with the highest periphyton chlorophyll-a values on record for the UBWPAD, W1258, and Depot street periphyton sampling locations.

Shallow depths also tend to result in elevated water temperatures. Temperatures in June, July and August were warmer in 2016 than 2015. In addition, the summer of 2016 followed a particularly warm spring. Conversely, air temperatures preceding the 2015 sampling season were atypically cool, with below normal temperatures from November 2014 through March 2015. While it is logical that warmer air temperatures translate to warmer water temperatures, particularly when water depths are shallow, water temperature data are not available for comparison.

In summary, the dry conditions, low flows and associated shallow water depths, warm winter through summer air temperatures, and elevated TP levels along the MA portions of the river all likely contributed to the elevated periphyton levels observed during the summer of 2016. Three factors likely repressed observed periphyton growth in 2015 – flow conditions preceding sampling, the cold winter/cooler spring temperatures, and lower in-stream nutrient concentrations.

7.0 Summary

The Upper Blackstone has conducted water quality monitoring and periphyton sampling since 2012 to track the impacts of the plant upgrades and effluent on river quality. This report presents the 2015 and 2016 field data. In addition, sufficient data now exist to examine trends in water quality, and to evaluate potential impacts of flow, temperature, and effluent concentrations on in-stream river water quality. Review of the sampling results indicates:

- The winter of 2014 – 2015 was unusually cold and snowy, resulting in the second largest accumulation of snow since 1892. The cold winter was followed by a cool spring.
- In contrast, Fall 2015 through March 2016 was an unusually warm period, followed by a warm summer.
- Precipitation totals in both 2015 and 2016 were well below normal. The Blackstone River watershed experienced abnormally dry- to moderate-drought conditions from the start of the 2016 calendar year through most of the fall of 2016.
- Summer 2016 was the driest summer season sampled to date by the Upper Blackstone's routine monitoring program (2012 – 2016) and was also drier than during 2008, the year of the most recent monitoring by MassDEP for both water column nutrient and periphyton data. Record low monthly flows at Millbury were set in May, June and July. 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.
- Calculations suggest that approximately 65% of the river flow at Millbury from June through September 2016 was comprised of effluent contributions to river flow. This is the highest summer sampling season contribution observed since routine monitoring began in 2012.
- Comparing plant performance prior to 2009 (2006-2008) to performance in calendar year 2015, the total nitrogen load to the Blackstone River from the Upper Blackstone was reduced by 57% and the total phosphorus load was reduced by 88%. Data for 2016 were similar, with reductions of 59% and 78%, respectively, for TN and TP over pre-upgrade conditions.
- Effluent average summertime (June - September) TN and TP daily loads in 2016 were the lowest observed since plant upgrades went on-line in 2010. Boxplots of the daily effluent TN and TP concentrations from June – September, summarized by year from 2012 - 2016, suggest that day-to-day variability was less in 2016 than in the prior years since routine monitoring began in 2012.
- Upper Blackstone facility average April – October permit season TP effluent concentration was similar in 2016, 2015 and 2013, but the average November – March permit season TP effluent concentration in 2016 was double that of prior years.

- Despite the low flow conditions, average water column TP and TN concentrations in 2015 and 2016 mainly fell within the interquartile range of values observed since 2012 at all sampling sites; they were below median levels at several sites.
- TP and TN loads observed in the river that were associated with "low" flow sampling events were below the median of observed values at almost all sites in both 2015 and 2016.
- Summertime chlorophyll-a concentrations in the river were elevated in 2016 compared to other years at MA sampling locations, but much closer to median observed values at the three sampling sites located in RI. Data for 2015 were more reflective of average in-stream conditions observed from 2012 - 2016.
- The highest sampling season average chlorophyll-a concentrations observed in the river since 2012 during low flow conditions occurred in 2014 at most sampling locations, with values ranging from 1 μg/L at the most upstream W0680 sampling site to 25 μg/L at the Rhode Island R116 monitoring location.
- The 2016 sampling season average chlorophyll-a concentrations during low flow conditions at the Massachusetts sampling sites were similar to the 2014 data, but sampling season average low flow chlorophyll-a concentrations at the Rhode Island sampling sites were much lower in 2016 than observed in 2014.
- The maximum chlorophyll-a concentrations observed at each sampling site during routine monitoring from 2012 – 2016 occurred in 2014, ranging from 10 μg/L at the most upstream W0680 sampling site to 92 μg/L at the Rhode Island R116 monitoring location.
- Trends in water quality were evaluated using a seasonal Mann-Kendall test computed on flow-weighted TP, TN, and chlorophyll-a concentration data collected since 2012. Decreasing TP trends were noted when accounting for either season or month at 2 sites (RMSL and W1242). Decreasing TN trends were noted when accounting for either season or month at 4 sites (W1779, W1242, W1258, and RMSL). Decreasing trends in chlorophyll-a were noted when accounting for month at 2 sites (W1258 and W0680).
- Periphyton levels in 2016 were the highest observed since sampling began except at the most upstream site, W0680, which is located above the confluence with the Upper Blackstone's effluent channel
- MassDEP utilizes 200 mg/m^2 as guidance for "nuisance levels" of periphyton based on the literature (MassDEP, 2009; NEIWPCC, 2001). Data collected in 2012 through 2015 fall below this target level, but some of the 2016 data exceed the target level.
- A wide range of periphyton levels can result from similar TP conditions, based on other environmental conditions such as river flow conditions, air and water temperatures, and light penetration.

- The years 2014, 2015, and 2016 were all fairly dry years, with 2014 and 2016 a bit drier than 2015 along the MA portions of the river where periphyton sampling takes place. Observed periphyton concentrations were highest during the 2014 and 2016 sampling seasons.
- The dry conditions, warm winter, spring and summer air temperatures, and elevated TP levels along the MA portions of the river likely all contributed to the elevated periphyton levels observed during the summer of 2016.
- Three factors likely suppressed periphyton growth in 2015 – flow conditions preceding sampling, the cold winter/cooler spring temperatures, and low in-stream nutrient concentrations.

8.0 Future Work

The Upper Blackstone plans to continue water quality monitoring in the Blackstone River in 2017 to track the impacts of reduced nutrient concentrations in UBWPAD plant effluent. Blackstone River data collected in 2015 and 2016 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). The 2015 and 2016 data, in addition to the data from 2012 – 2014, will be publicly available for download through the CUAHSI Hydrologic Information System (HIS) databases and servers (his.cuahsi.org). In addition, the 2016 data will be submitted to MassDEP to supplement the data already submitted for 2014 and 2015.

9.0 References

Barbaro, J.R. and Zariello, P.J. (2006). *A Precipitation-Runoff Model for the Blackstone River Basin, Massachusetts and Rhode Island.* U.S. Geological Survey Scientific Investigations Report 2006-5213.

Chaudhury, R.R., Sobrino, J.A.H., Wright, R.M. and Sreenivas, M. (1998). "Dissolved Oxygen Modeling of the Blacksone River (Northeastern United States)". *Water Resources* (32-8) p2400-2412.

Helsel, D.R. and R.M. Hirsch (2002). *Hydrologic Analysis and Interpretation: Chapter A3 - Statistical Methods in Water Resources.* Techniques of Water-Resources Investigations of the United States Geological Survey. U.S. Geological Survey, Washington, D.C. Available on-line: http://water.usgs.gov/pubs/twri/twri4a3/

Ji, Z.G., Hamrick J.H. and Pagenkopf, J. (2002). "Sediment and Metals Modeling in a Shallow River". *Journal of Environmental Engineering* (128-2) p105-119.

Massachusetts Department of Environmental Protection (MassDEP), 2006. Massachusetts Surface Water Quality Standards, 314 CMR 4.00, Division of Water Pollution Control, 20 p.

Massachusetts Department of Environmental Protection (MassDEP) and Beskins, J. 2009. *Technical Memorandum: Blackstone River Algal Biomass Measured ad Chlorophyll a at Selected Main Stem and Impoundment Stations – 2008*.

Massachusetts Department of Environmental Protection, Division of Watershed Management, Worcester, MA.Chaudhury et al., 1998 and Ji et al., 2002

Moorleghem, C.V., L. Six, F. Degryse, E. Smolders, and R. Merckx (2011). Effect of organic P forms and P present in inorganic colloids on the determination of dissolved P in environmental samples by the diffusive gradient in thin films technique, ion chromatography, and colorimetry, *Analytical Chemistry*, 83, 5317 – 5323.

New England Interstate Water Pollution Control Commission (NEIWPCC), 2001. *The Relationships between Nutrient Concentrations and Periphyton Levels in Rivers and Streams – A Review of Scientific Literature,* prepared by ENSR Corporation, Document Number: 4933-011-400, 60 pp. (http://www.neiwpcc.org/ncreports.asp).

New England Interstate Water Pollution Control Commission (NEIWPCC), 2003. *Collection and Evaluation of Ambient Nutrient Data for Rivers and Streams in New England – Data Synthesis Report – Final Report.* A cooperative effort of NEIWPCC, U.S. EPA – New England, ENSR International, and New England States Regional Technical Advisory Team, September, 2003, 100 pp. (http://www.neiwpcc.org/ncreports.asp).

Parker, G.W., Breault, R.F., Waite, A.M., and Hartman, Elaine, 2011, Time of travel and dispersion of a dye plume in the Blackstone River, Massachusetts and Rhode Island, 2009: U.S. Geological Survey Open-File Report 2011–1284, 13 p. Available by request only.

UMass and CDM. 2005. *Quality Assurance Project Plan for Blackstone River Watershed Assessment Study*. Available upon request.

UMass and CDM. 2008. *Blackstone River HSPF Water Quality Model Calibration Report*. Available upon request.

UMass and CDM. 2011. *Blackstone River HSPF Water Quality Model Calibration Report Addendum*. Available upon request.

U.S. Geological Survey (USGS). 2012. Office of Water Quality Technical Memorandum 2013.01, "Guidance on Methods for Determining the Concentration of Total Nitrogen in Whole-Water Samples", November 30, 2012.

U.S. Environmental Protection Agency (EPA) web page "Water: Monitoring and Assessing Water Quality", http://water.epa.gov/type/rsl/monitoring/, accessed March 27, 2013.

U.S. Environmental Protection Agency (EPA) web page "Water: Monitoring and Assessing Water Quality", http://water.epa.gov/type/rsl/monitoring/ , accessed March 27, 2013.

U.S. Geological Survey (USGS) National Water Quality Assessment Data Warehouse (NAWQA), available on-line at: http://infotrek.er.usgs.gov/apex/f?p=NAWQA:HOME:2964371376043112

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 mm 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 mm pore size glass microfiber filter in the lab. Filtering for chlorophyll-a was conducted at the Upper Blackstone's lab (referred to subsequently as the UBWPAD 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 UBWPAD 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 UBWPAD, 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 xx and xx.

Table 28: Parameters calculated based on lab results

Lab	**Parameter**	**Calculation**[1]
UBPWAD	Total Organic Nitrogen	tON = TKN - TAM
	Dissolved Organic Nitrogen	dON = dTKN - dTAM
	Total Inorganic Nitrogen	TIN = NO23 + TAM
	Dissolved Inorganic Nitrogen	DIN = dNO23 + dTAM
	Total Dissolved Nitrogen	TDN = TAM + NO23
	Total Nitrogen	TN = TKN + NO23
NBC	Dissolved Inorganic Nitrogen	DIN = dNO23 + dTAM
	Dissolved Organic Nitrogen	dON = TDN - DIN
	Dissolved Kjeldahl Nitrogen	dTKN = TDN – dNO23
UMD	Total Nitrogen	TN = TDN + PON

Note: [1] Half the detection limit was utilized in the calculation for parameters and sampling dates below the detection limit.

Table 29: 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 Nitrage Method (1-Reagent)	36.2 ppb / 16.8 ppb
dNO2, NO2	STD Method 18th 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 20th ed., 4500P	8 ppb
TDP	STD Method 20th ed., 4500P	8 ppb
Chl-a	STD Method 20th ed., 10200 H	1 ppb
UMass Dartmouth		
Parameter	**Method**	**Detection Limit**
dTAM	STD Method 20th ed, 4500-NH3-F	1.8 ppb
dNO23	STD Method 18th ed, 4500-NO3-F	7 ppb
TDN	STD Method 218h ed, 4500-Norg	10.8 ppb
POCN	Need to add	

Appendix C: Additional Tables

Table 30: Summary of 2015 and 2016 precipitation in relation to NWS 30-year normal monthly data

	Monthly Precipitation (inches)					
	Worcester, MA (NWS station KORH)			**Worcester, MA (NWS station KORH)**		
	2015	**Normal Month Total[a]**	**% of normal**	**2016**	**Normal Month Total[a]**	**% of normal**
Jan	3.64	3.49	104%	2.12	3.49	61%
Feb	3.00	3.23	93%	5.11	3.23	158%
Mar	2.42	4.21	57%	3.49	4.21	83%
Apr	2.97	4.11	72%	2.63	4.11	64%
May	0.60	4.19	14%	2.21	4.19	53%
Jun	6.35	4.19	152%	1.66	4.19	40%
Jul	2.86	4.23	68%	2.06	4.23	49%
Aug	3.21	3.71	87%	3.60	3.71	97%
Sep	4.15	3.93	106%	3.27	3.93	83%
Oct	3.06	4.68	65%	6.57	4.68	140%
Nov	1.76	4.28	41%	3.89	4.28	91%
Dec	4.65	3.82	122%	3.7	3.82	99%

Notes: [a] Based on data from 1981 – 2010, NWS Normal Monthly Data, available on-line: www.ncdc.noaa.gov/cdo-web/datasets#GHCND

Table 31: Summary of 2015 monthly flow conditions

	Monthly Mean Discharge (cfs)					
	Woonsocket, RI – USGS Station 01112500			Millbury, MA – USGS Station 01109730		
	2015	Ave 1930 – 2016	% normal	2015	Ave 2003 – 2016[a]	% normal
Jan	753	964	78%	230	188	122%
Feb	494	1,007	49%	105	187	56%
Mar	1,098	1,507	73%	214	284	75%
Apr	1,655	1,434	115%	328	273	120%
May	402	878	46%	130	169	77%
Jun	537	669	83%	164	171	96%
Jul	308	340	91%	96	111	86%
Aug	118	307	38%	60	98	61%
Sep	95	323	29%	72	107	67%
Oct	324	461	70%	96	161	60%
Nov	333	665	50%	77	163	47%
Dec	379	896	42%	95	210	45%

Note: [a] Long-term average in July – December based on data from 2002 – 2016.

Table 32: Summary of 2016 monthly flow conditions

	Monthly Mean Discharge (cfs)					
	Woonsocket, RI – USGS Station 01112500			Millbury, MA – USGS Station 01109730		
	2016	Ave 1930 – 2016	% normal	2016	Ave 2003 – 2016[a]	% normal
Jan	733	964	76%	121	188	64%
Feb	1133	1,007	113%	192	187	103%
Mar	888	1,507	59%	184	284	65%
Apr	1096	1,434	76%	168	273	62%
May	602	878	69%	112	169	66%
Jun	237	669	37%	67	171	39%
Jul	129	340	38%	49	111	44%
Aug	126	307	41%	59	98	60%
Sep	96	323	30%	48	107	45%
Oct	434	461	94%	115	161	71%
Nov	457	665	69%	114	163	70%
Dec	612	896	68%	124	210	59%

Note: [a] Long-term average in July – December based on data from 2002 – 2016.

Table 33: Summer monthly mean streamflows (cfs) and water temperatures (deg F)

	Monthly Mean Streamflow (cfs) at Millbury, MA – USGS Station 01109730						
	2008	2011	2012	2013	2014	2015	2016
June	114	202	136	434	80	537	237
July	151	93	68	105	77	308	129
August	143	273	105	86	68	118	126
September	228	340	88	82	70	95	96
	Monthly Mean water temperature (^{o}F) at Milleville, MA - USGS Station 01111230						
	2008	2011	2012	2013	2014	2015	2016
June	NA	NA	NA	69.1	69.7	NA	NA
July	NA	NA	NA	76.9	75.2	NA	NA
August	NA	NA	NA	71.7	71.5	NA	NA
September	NA	NA	NA	NA	68.0	NA	NA

Table 34: 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)

Date	Woonsocket[a]		Millbury[b]		Sampling
	Q (cfs)	7Q (cfs)[c]	Q (cfs)	7Q (cfs)	
8/25/15	99				
8/26/15	96				
8/27/15	85				
8/28/15	83				
8/29/15	73				
8/30/15	73				
8/31/15	70	83			
9/1/15	78	80			
9/2/15	75	77			
9/3/15	69	74			
9/4/15	67	72			
9/5/15	68	71			
9/6/15	62	70			
9/7/15	56	68			
9/8/15	52	64			Periphyton
9/9/15	53	61			Periphyton
9/10/15	66	61			
9/11/15	202	80			
9/16/15	96				Routine
9/17/15	92				
9/18/15	78				
9/19/15	73				
9/20/15	68				
9/21/15	61				
9/22/15	58	75			
9/23/15	59	70			
9/24/15	57	65			
9/25/15	57	62			

9/26/15	59	60			
9/27/15	58	58			
9/28/15	57	58			
9/29/15	59	68			
9/2/16	95				
9/3/16	85				
9/4/16	77				
9/5/16	69				
9/6/16	58				
9/7/16	58				
9/8/16	65	72			
9/9/16	57	67			
9/10/16	65	64			
9/11/16	82	65	43		
9/12/16	86	67	39		
9/13/16	84	71	38		
9/14/16	80	74	38		Routine + periphyton
9/15/16	78	76	37		
9/16/16	77	79	36		
9/17/16	75	80	37	38	
9/18/16	74	79	37	37	
9/19/16	77	78			

Notes: [a] 7Q10 Woonsocket = 85 cfs
[b] 7Q10 Millbury = 38 cfs
[c] 7Q based on average of flow on day listed plus preceding 6 days

Table 35: 2014 periphyton sampling antecedent rain and discharge conditions

2014 Date	Daily Precipitation, Worcester, MA (inches)	Mean Daily Discharge (cfs) – Millbury, MA	Peak Daily Discharge (cfs) – Millbury, MA
June 5	0.35	132	220
June 6	T	115	133
June 7	0.00	102	114
June 8	0.00	92	102
June 9	T	86	98
June 10	T	81	90
June 11	T	75	87
June 12[a]	0.03	73	79
July 16	0.01	159	307
July 17	0.00	82	106
July 18	0.00	63	73
July 19	T	55	66
July 20	0.00	51	60
July 21	0.00	49	56
July 22	0.00	48	55
July 23	0.10	47	54
August 5	0.00	53	65
August 6	T	50	58
August 7	0.16	47	55
August 8	0.00	49	58
August 9	0.00	47	58
August 10	0.00	45	56
August 11	0.00	45	56
August 12	0.00	46	56
September 10	0.00	51	59
September 11	T	52	64

September 12	0.00	52	63
September 13	0.23	60	124
September 14	0.00	63	110
September 15	0.00	54	65
September 16	T	51	59
September 17	0.00	50	60

Note: [a] Periphyton sampling dates are shaded

Table 36: 2016 periphyton sampling antecedent rain and discharge conditions

2016 Date	Daily Precipitation, Worcester, MA (inches)	Mean Daily Discharge (cfs) – Millbury, MA	Peak Daily Discharge (cfs) – Millbury, MA
Jun 29	0.15	62	104
Jun 30	0.00	49	59
July 1	0.13	49	88
July 2	0.00	55	98
July 3	0.00	43	52
July 4	0.00	41	49
July 5	0.24	64	115
July 6	0.00	46	58
August 23	0.00	71	94
August 24	0.00	54	64
August 25	0.00	47	56
August 26	0.00	42	52
August 27	0.00	41	54
August 28	0.00	40	49
August 29	0.00	40	48
August 30	0.00	41	51
September 7	0.16	52	75
September 8	0.01	43	51
September 9	0.00	40	50
September 10	0.07	39	56
September 11	0.09	43	75
September 12	0.00	39	52
September 13	0.00	38	45
September 14	0.00	38	48

Note: [a] Periphyton sampling dates are shaded

Appendix D: Additional Figures

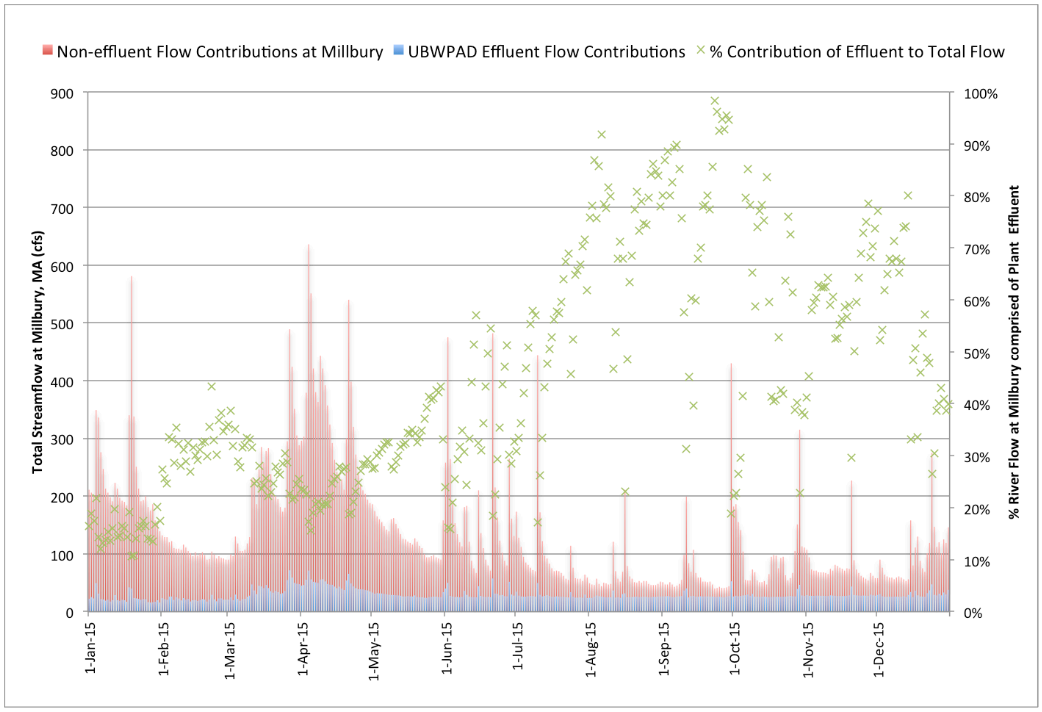


Figure 47: Effluent flow contributions at Millbury, 2015

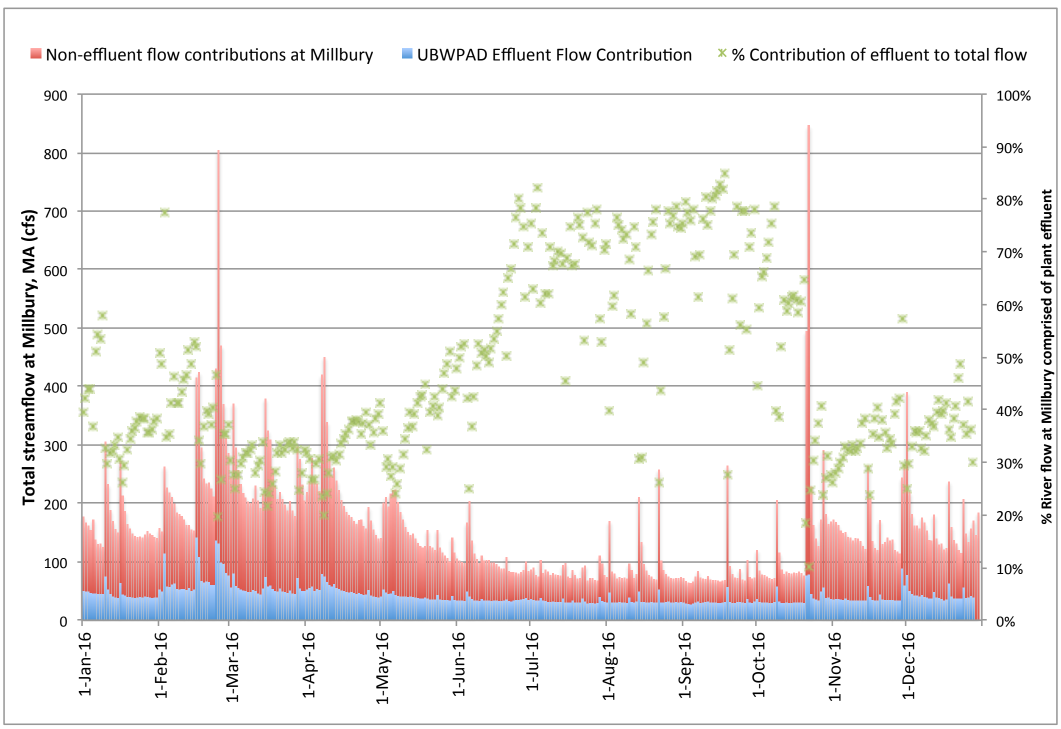
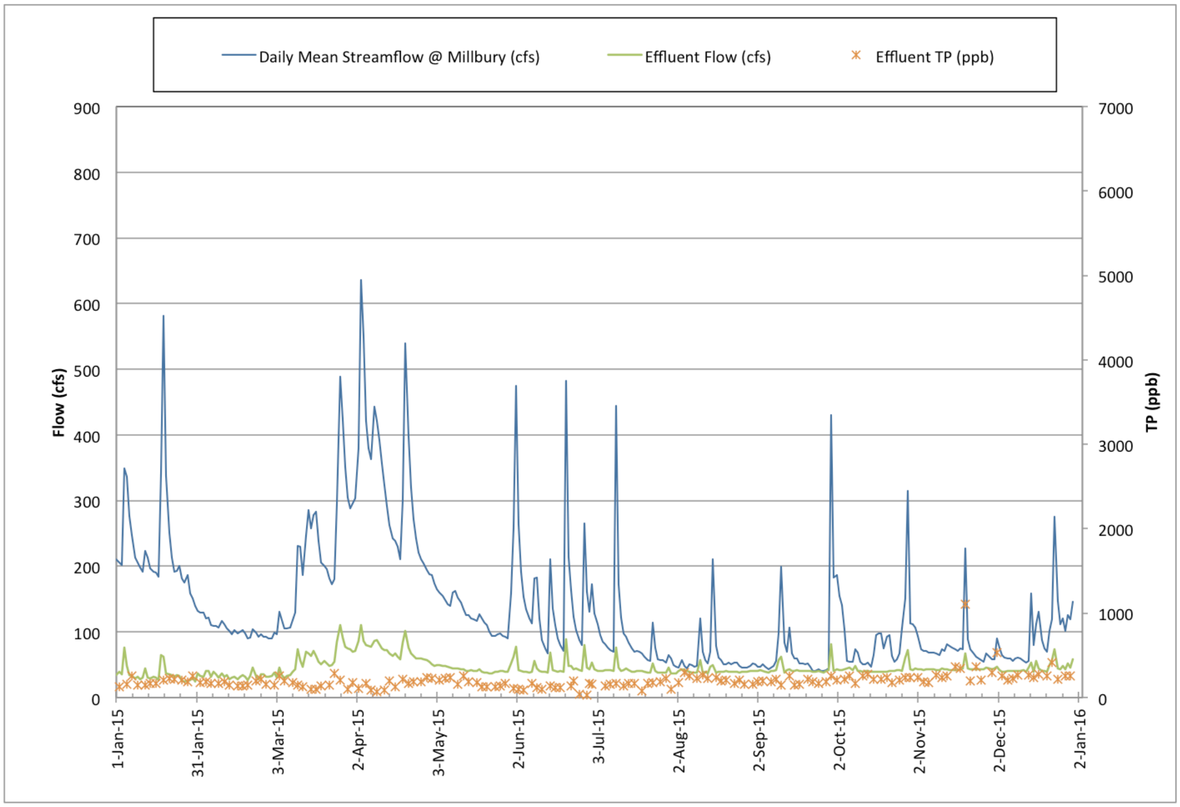


Figure 48: Effluent flow contributions at Millbury, 2016



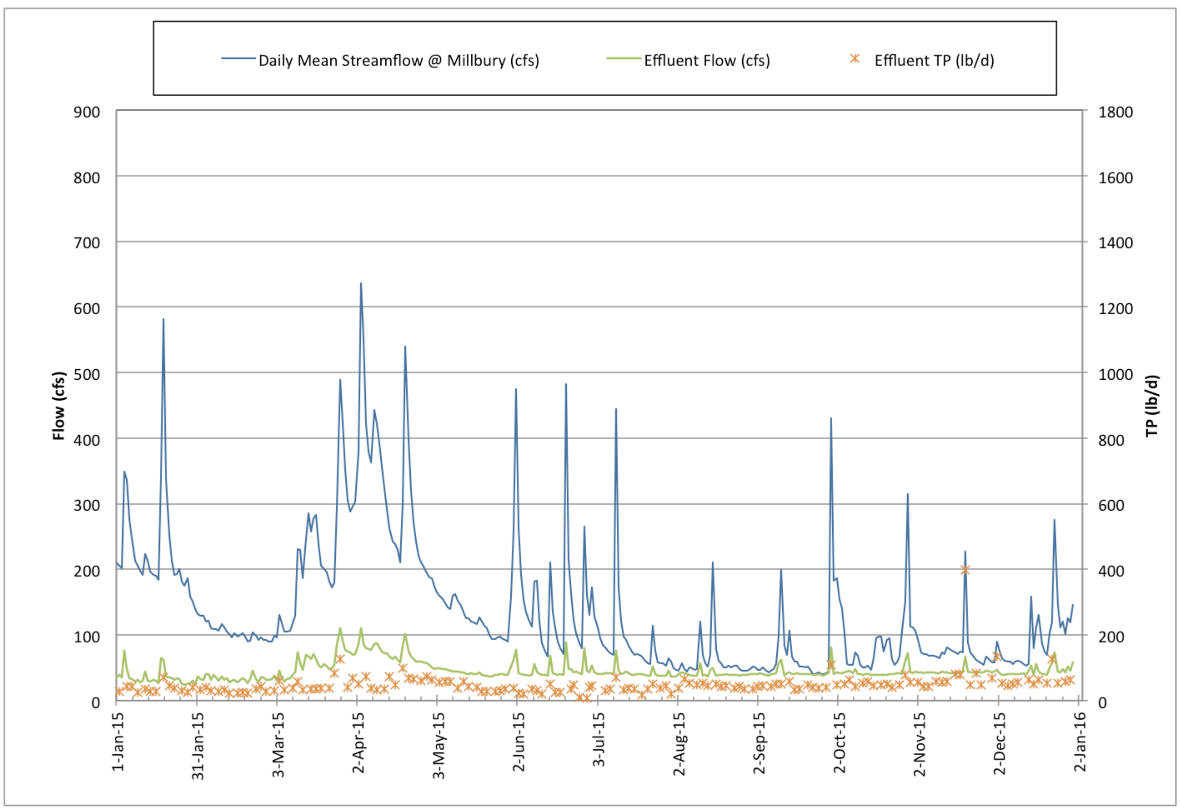
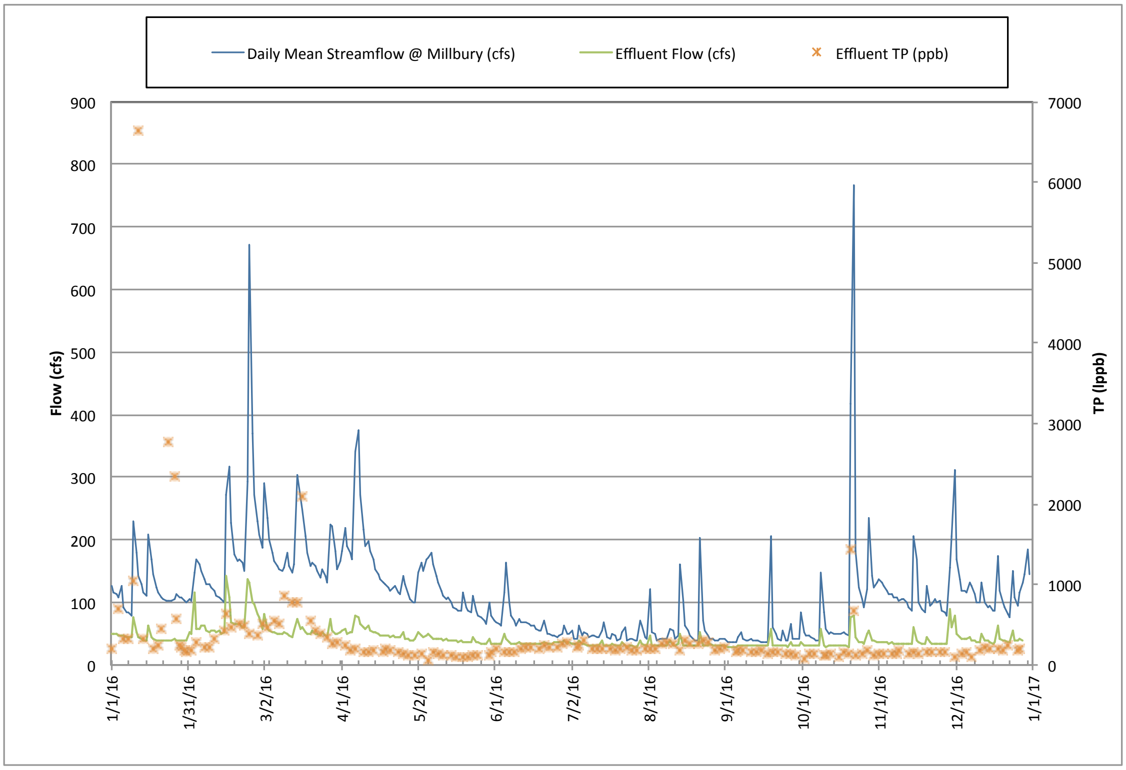


Figure 49: Effluent TP characteristics, 2015



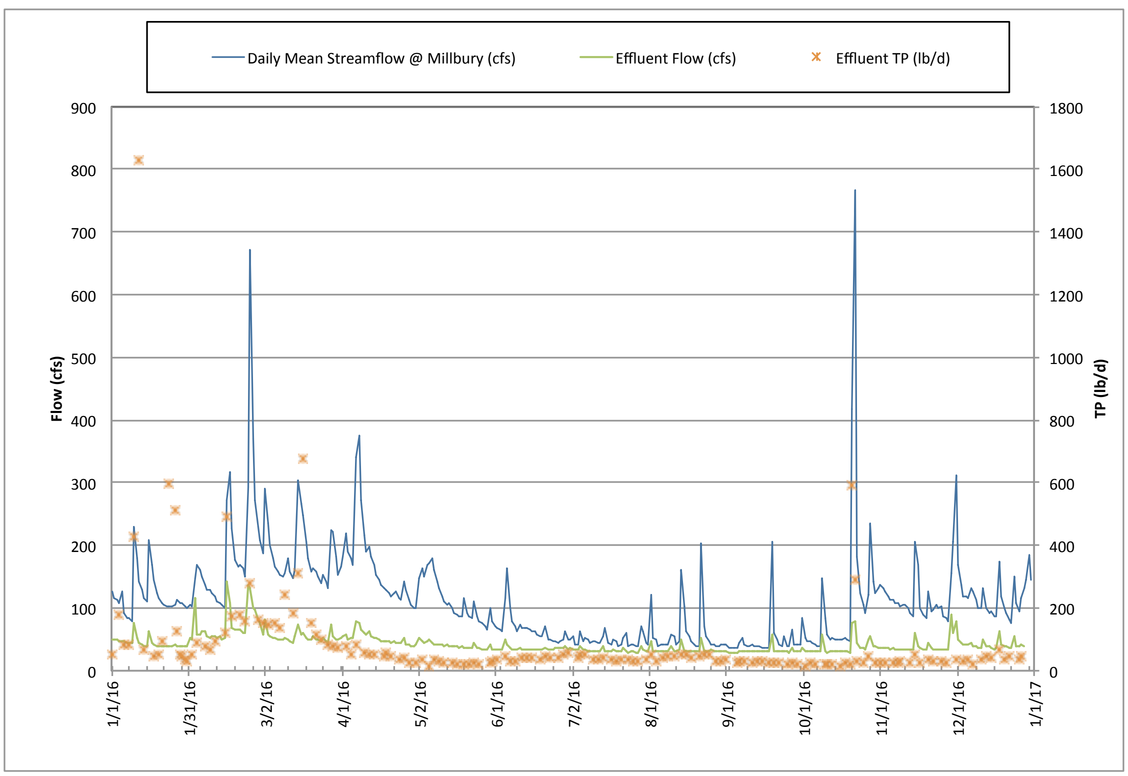


Figure 50: TP effluent characteristics 2016

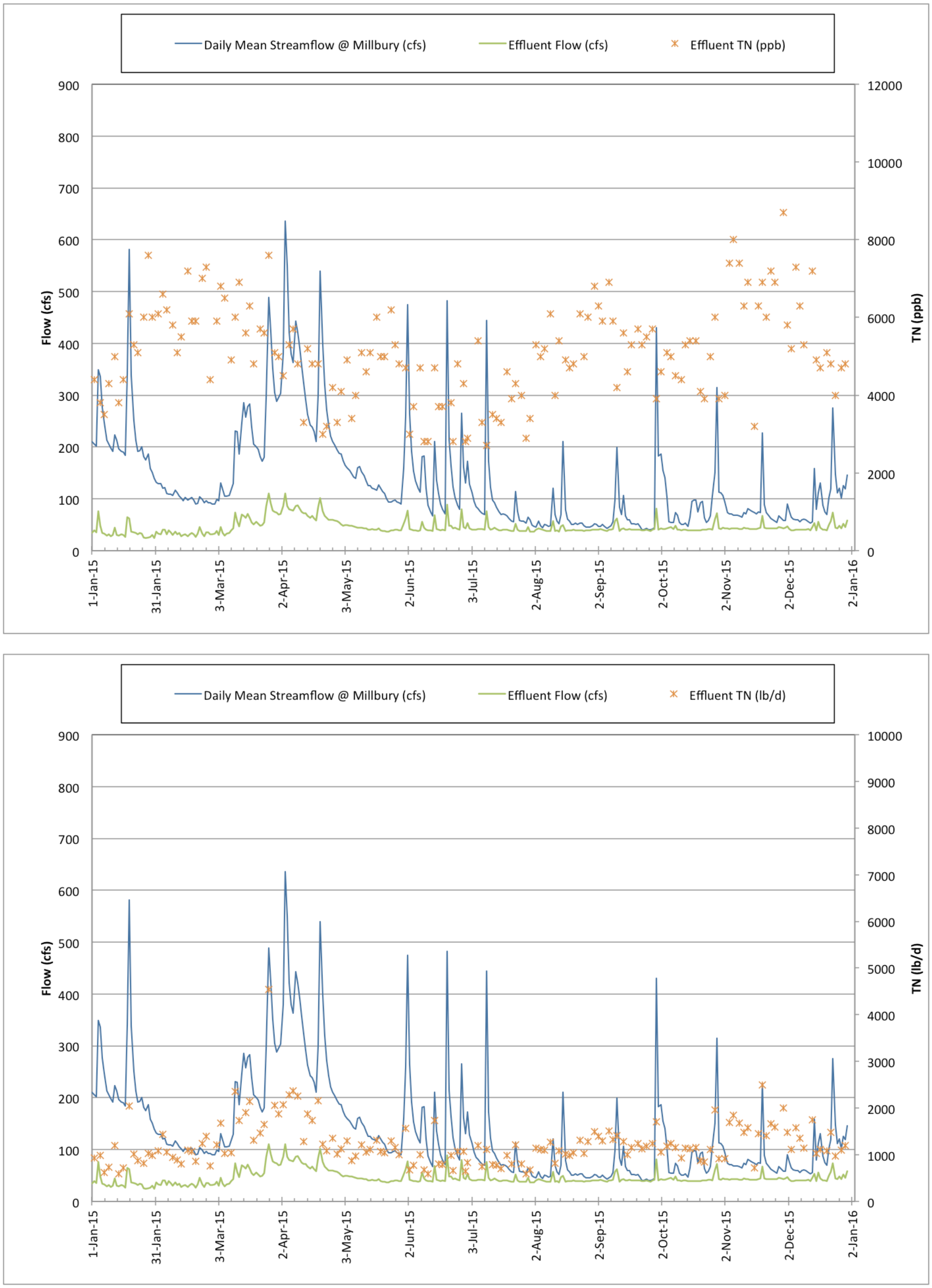
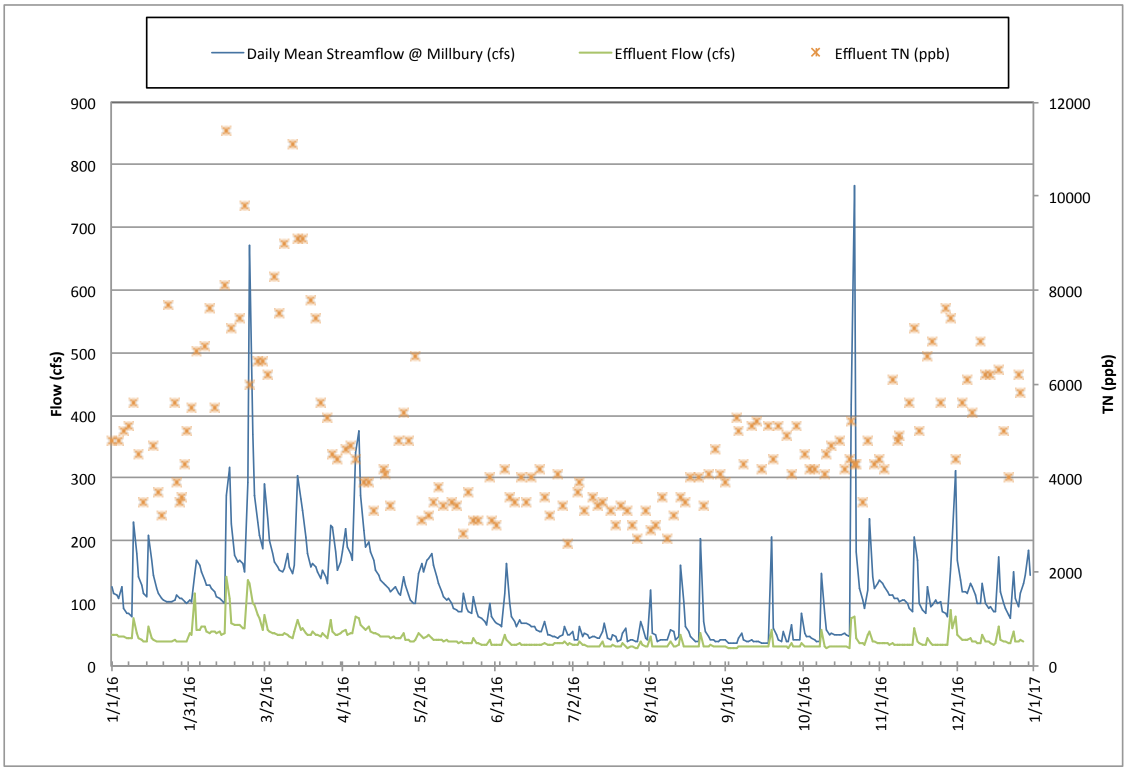


Figure 51: TN effluent characteristics, 2015



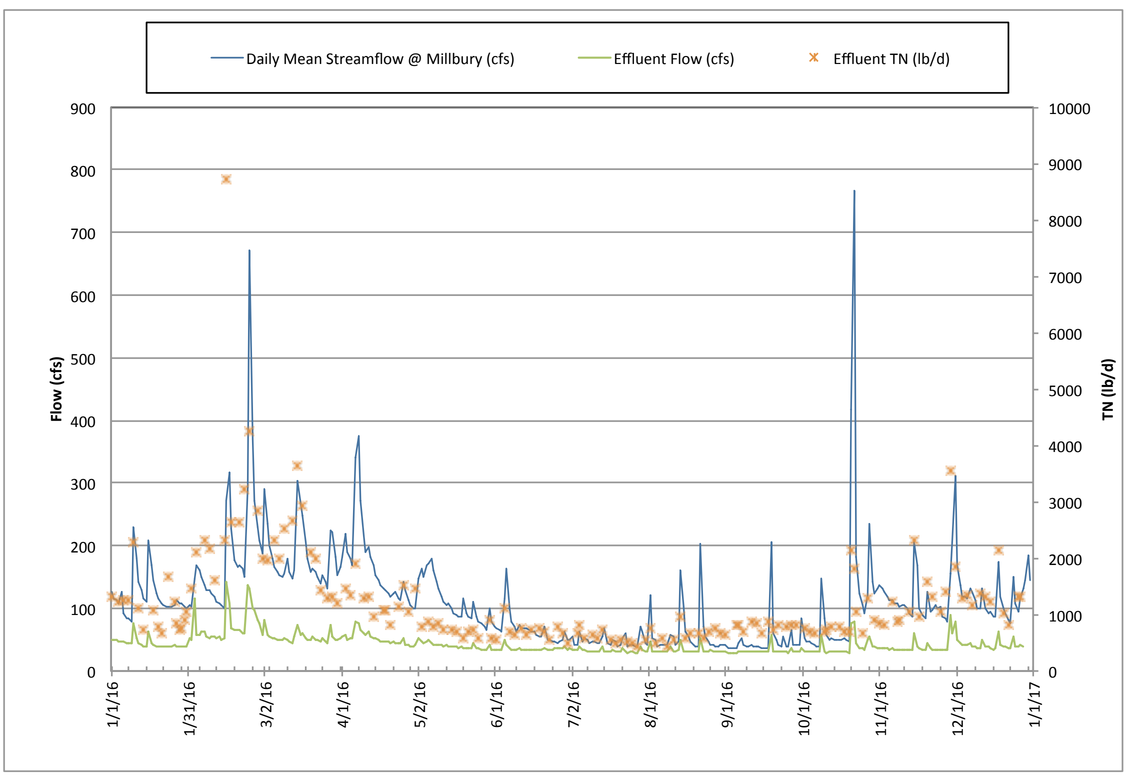


Figure 52: TN effluent characteristics, 2016

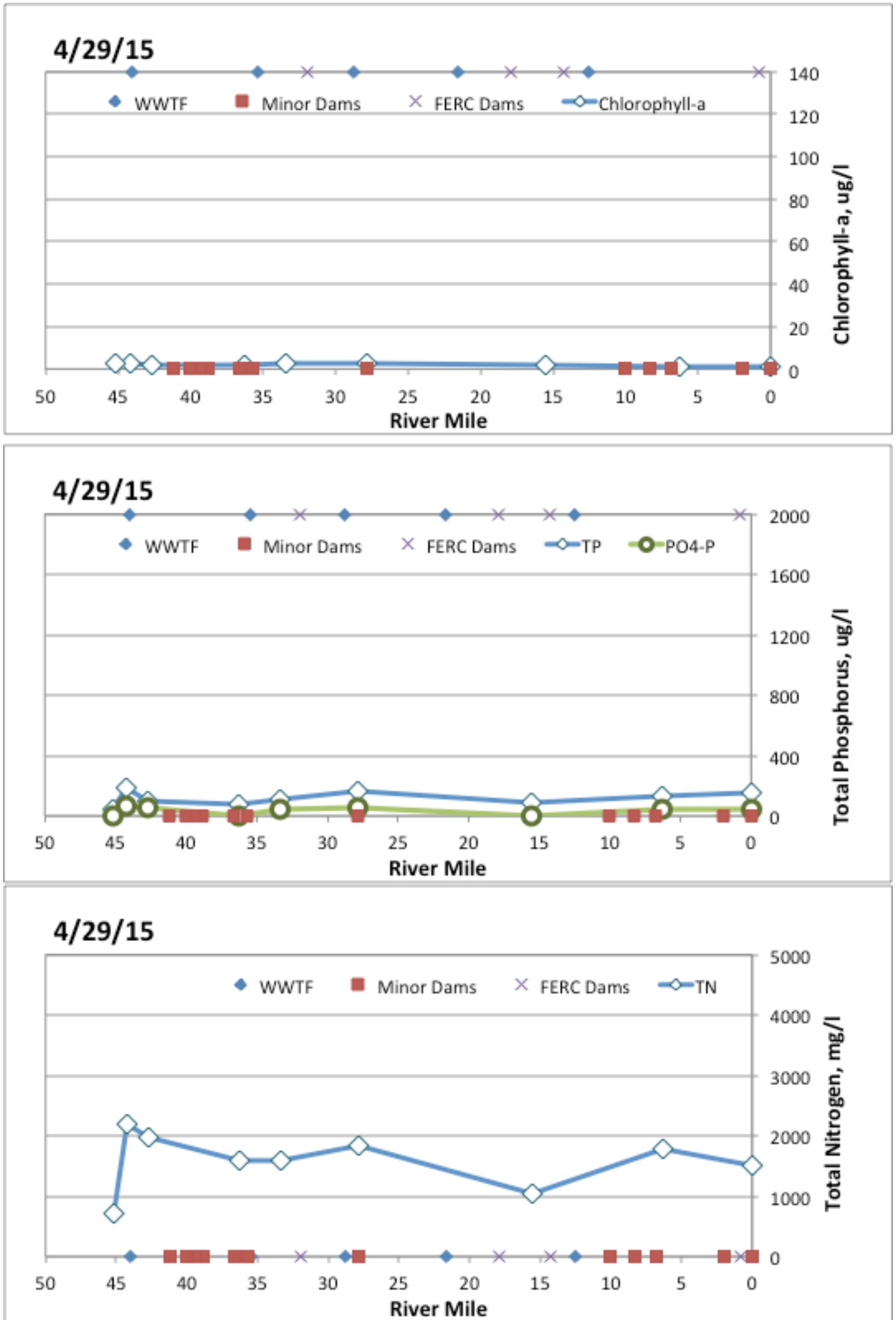


Figure 53: 29 April 2015 along stream concentration plots (Chl-a, TP, TN)

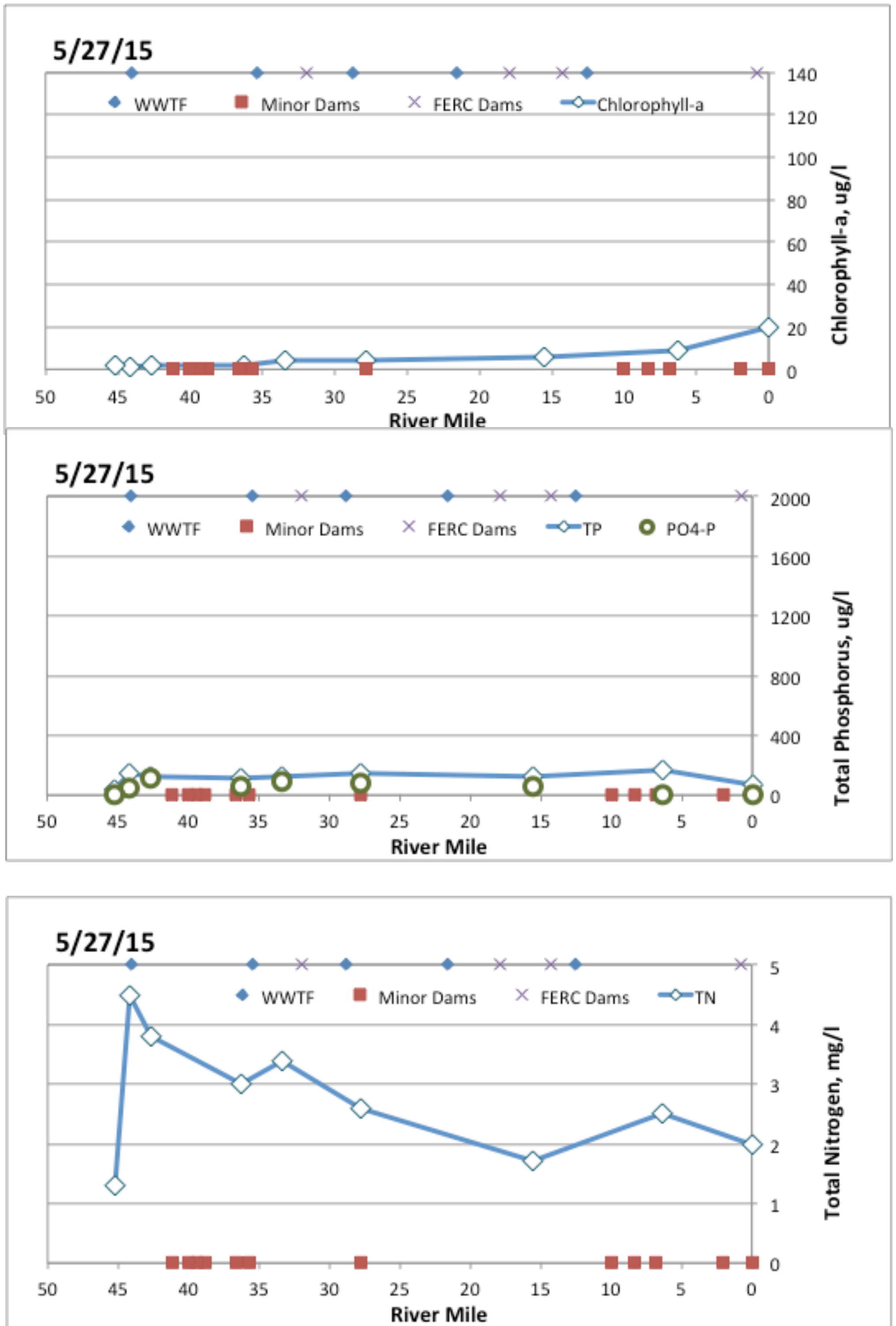


Figure 54: 27 May 2015 along stream concentration plots (Chl-a, TP, TN)

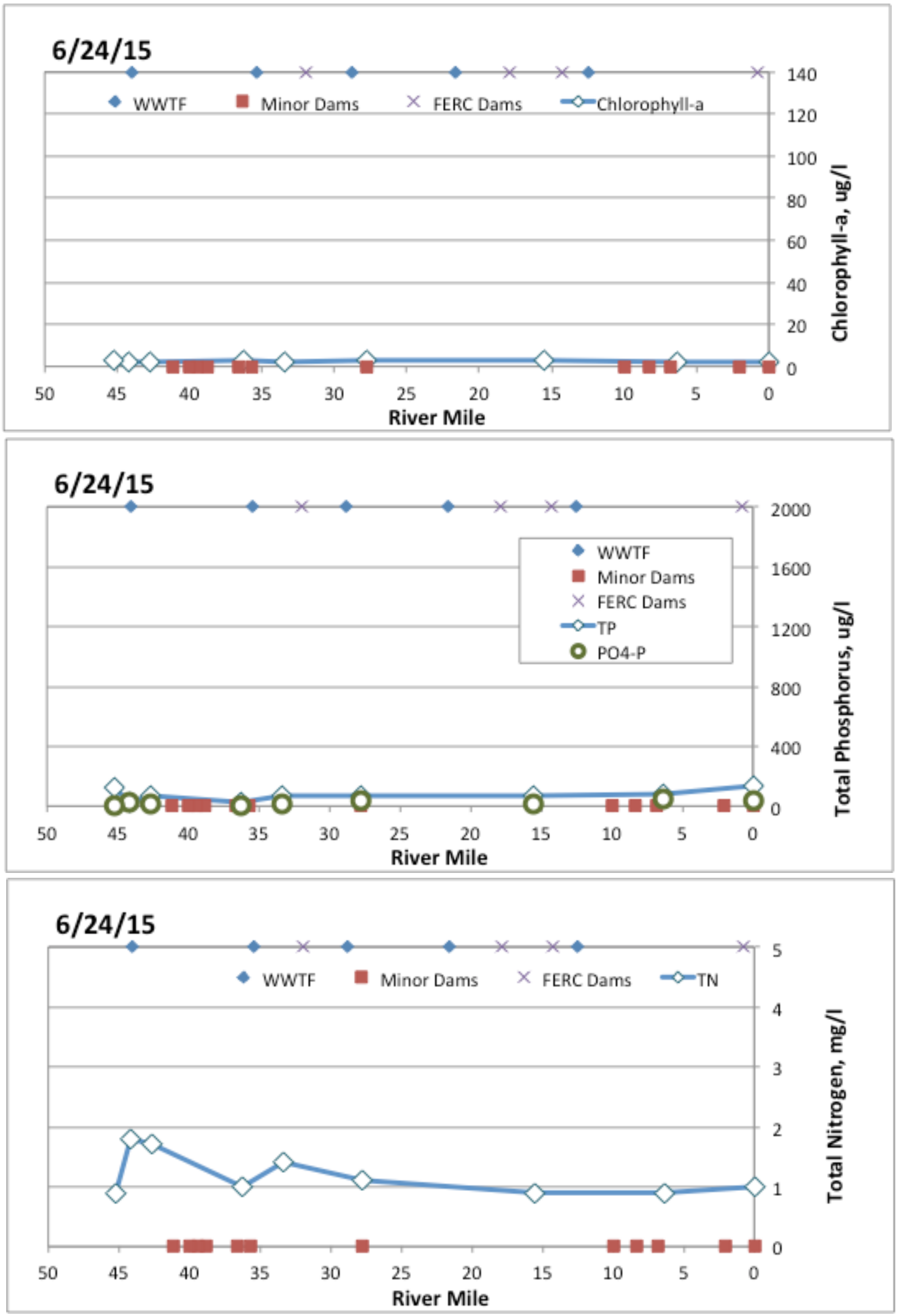


Figure 55: 24 June 2015 along stream concentration plots (Chl-a, TP, TN)

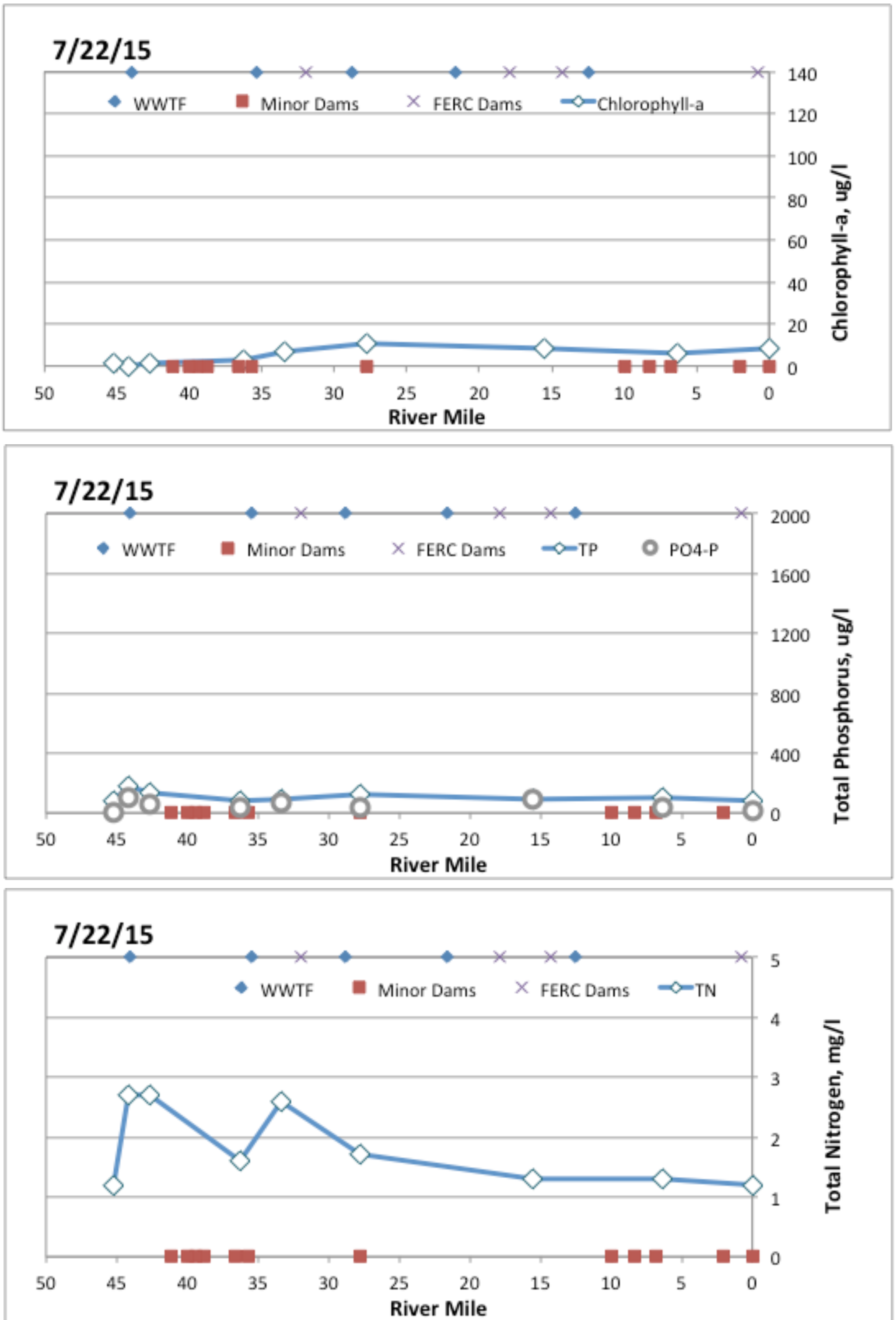


Figure 56: 22 July 2015 along stream concentration plots (Chl-a, TP, TN)

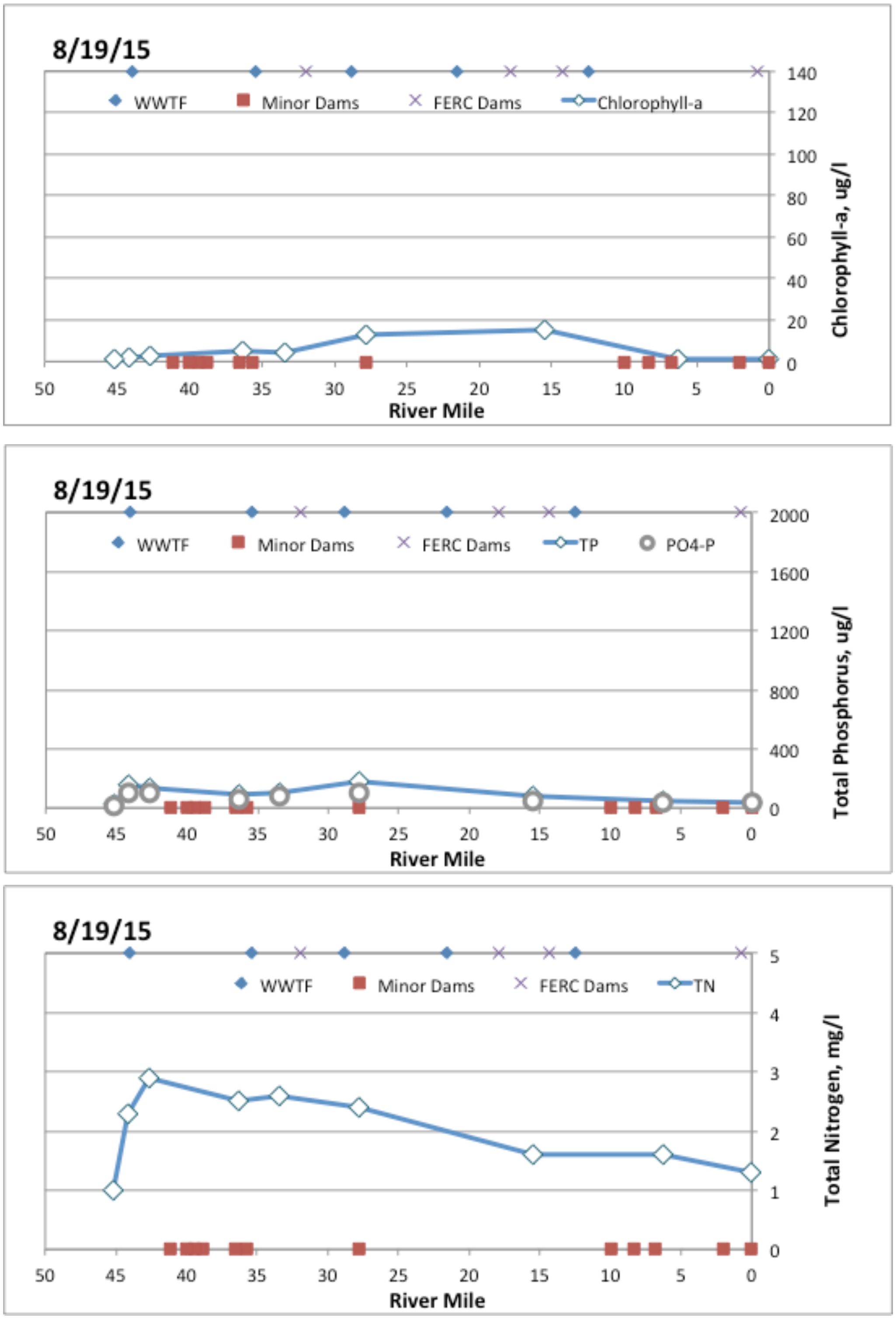


Figure 57: 19 August 2015 along stream concentration plots (Chl-a, TP, TN)

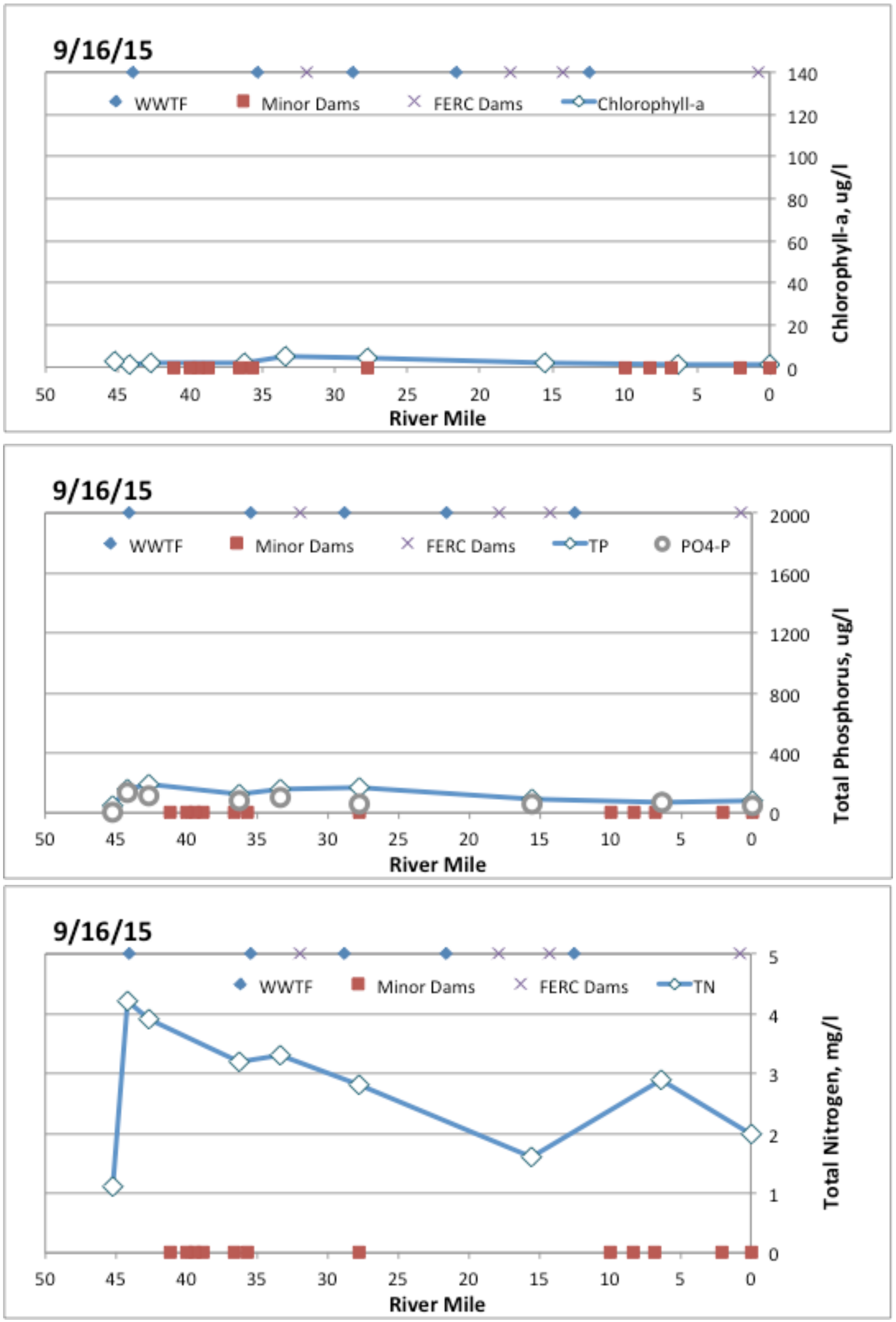


Figure 58: 16 September 2015 along stream concentration plots (Chl-a, TP, TN)

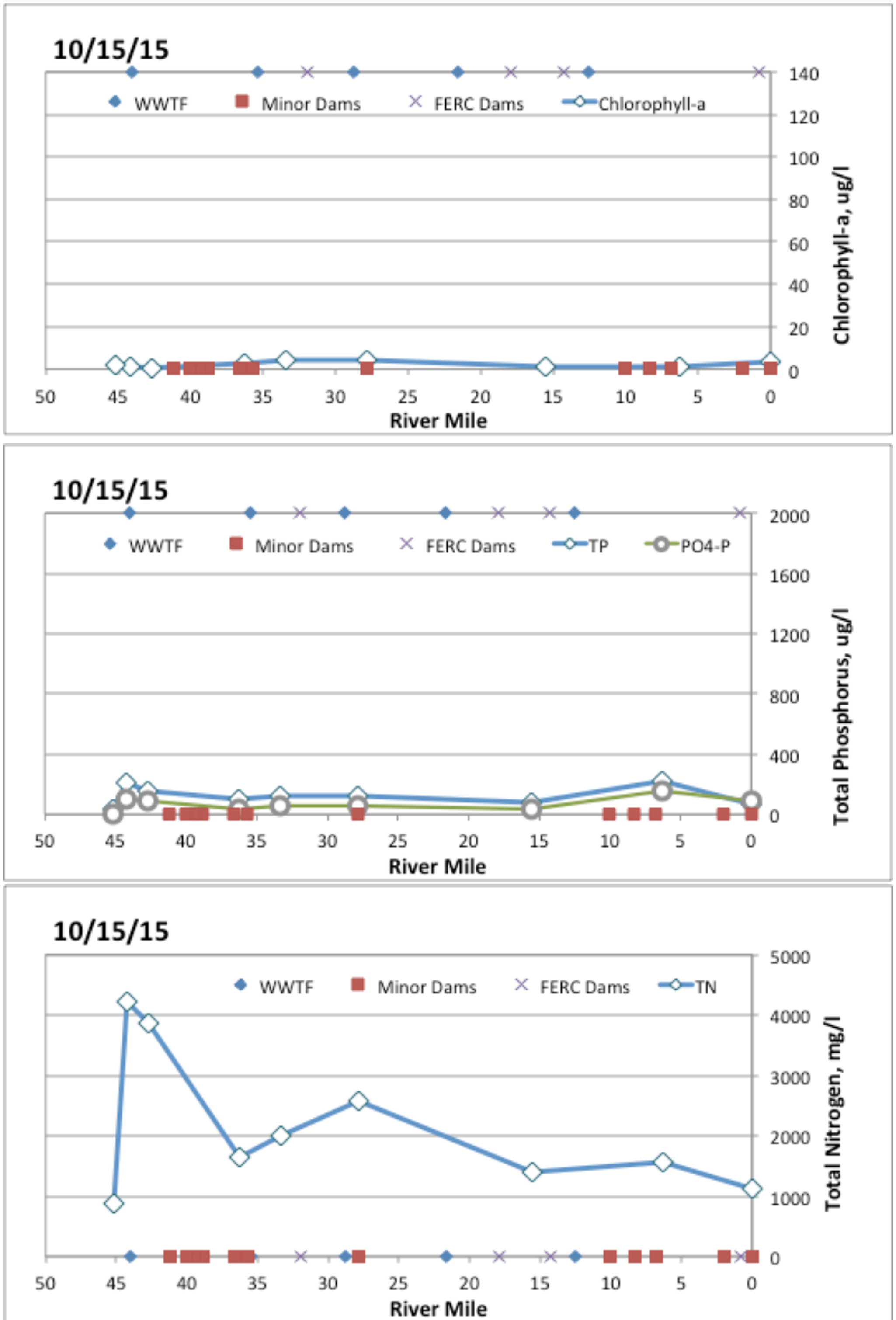


Figure 59: 15 October 2015 along stream concentration plots (Chl-a, TP, TN)

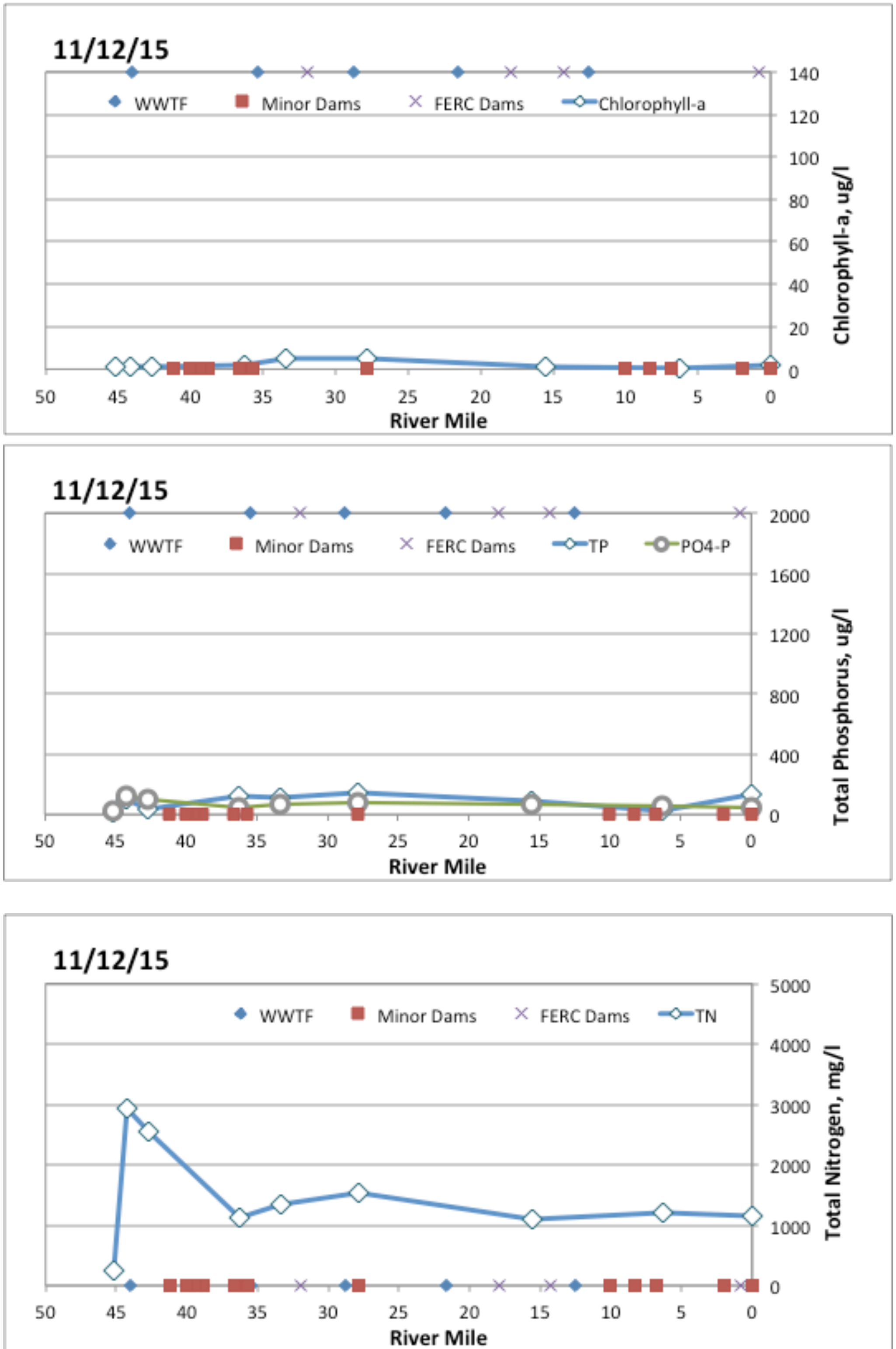
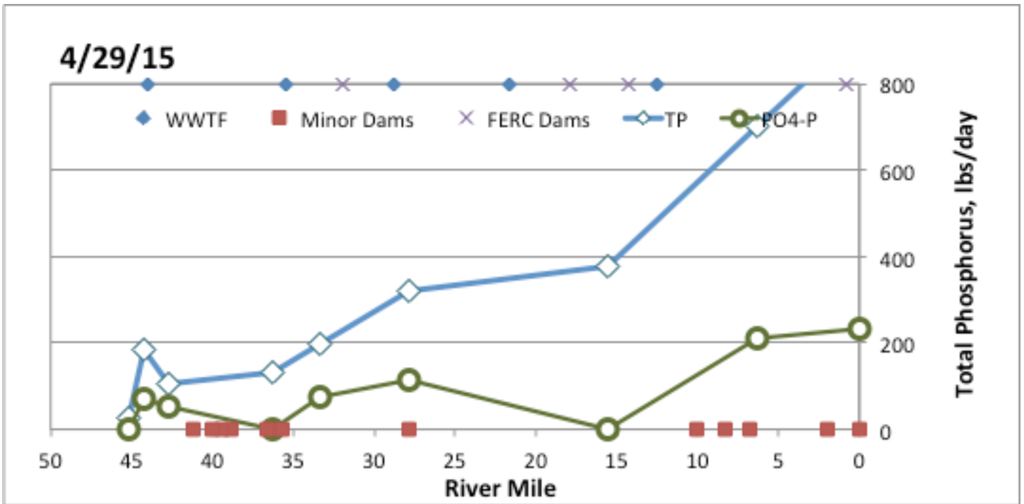


Figure 60: 12 November 2015 along stream concentration plots (Chl-a, TP, TN)



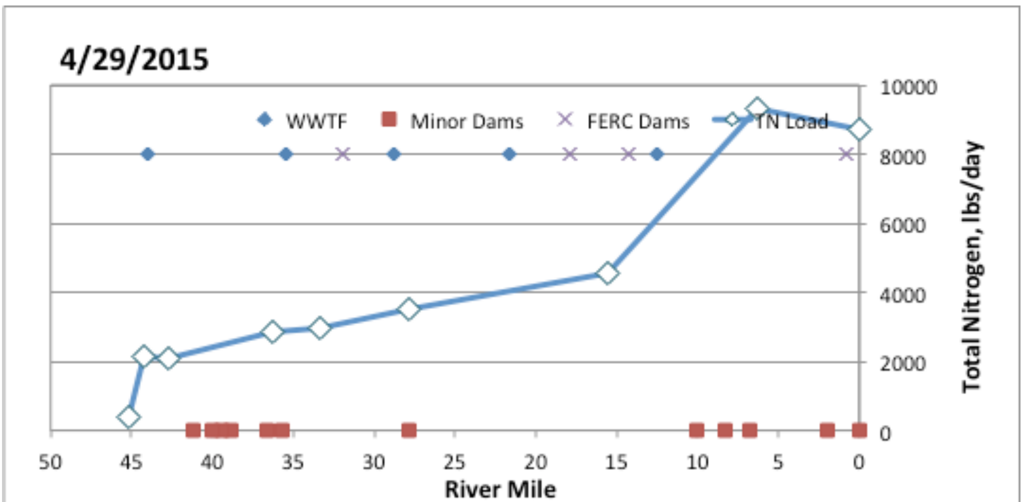
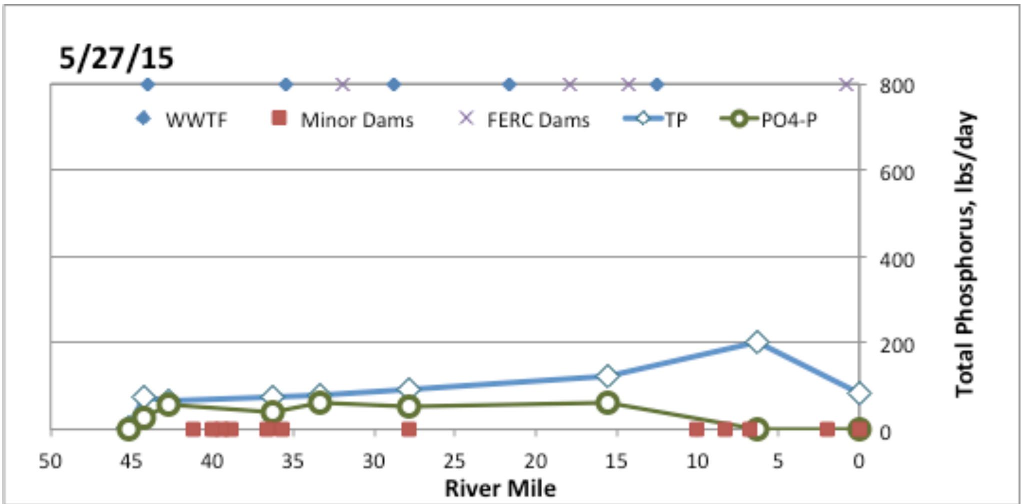


Figure 61: 29 April 2015 along stream load plots (TP, PO4 as P, TN)



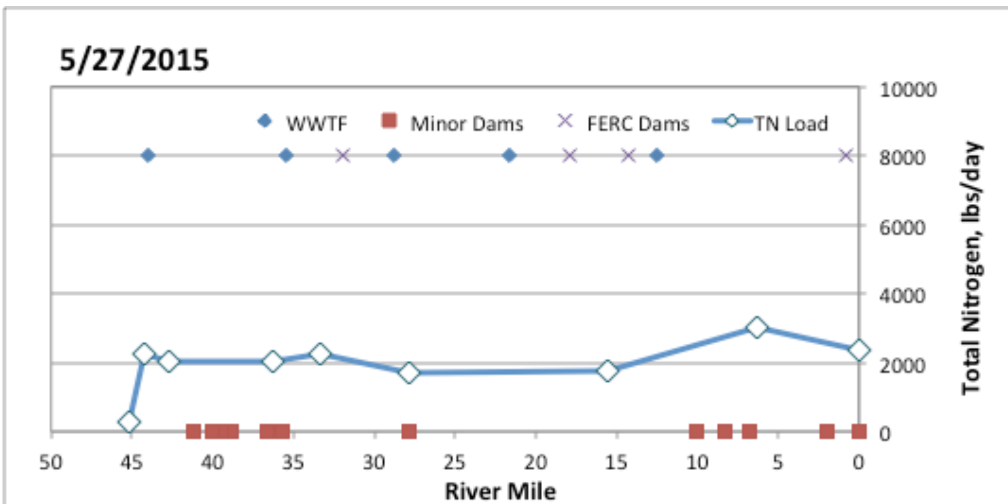


Figure 62: 27 May 2015 along stream load plots (TP, PO4 as P, TN)

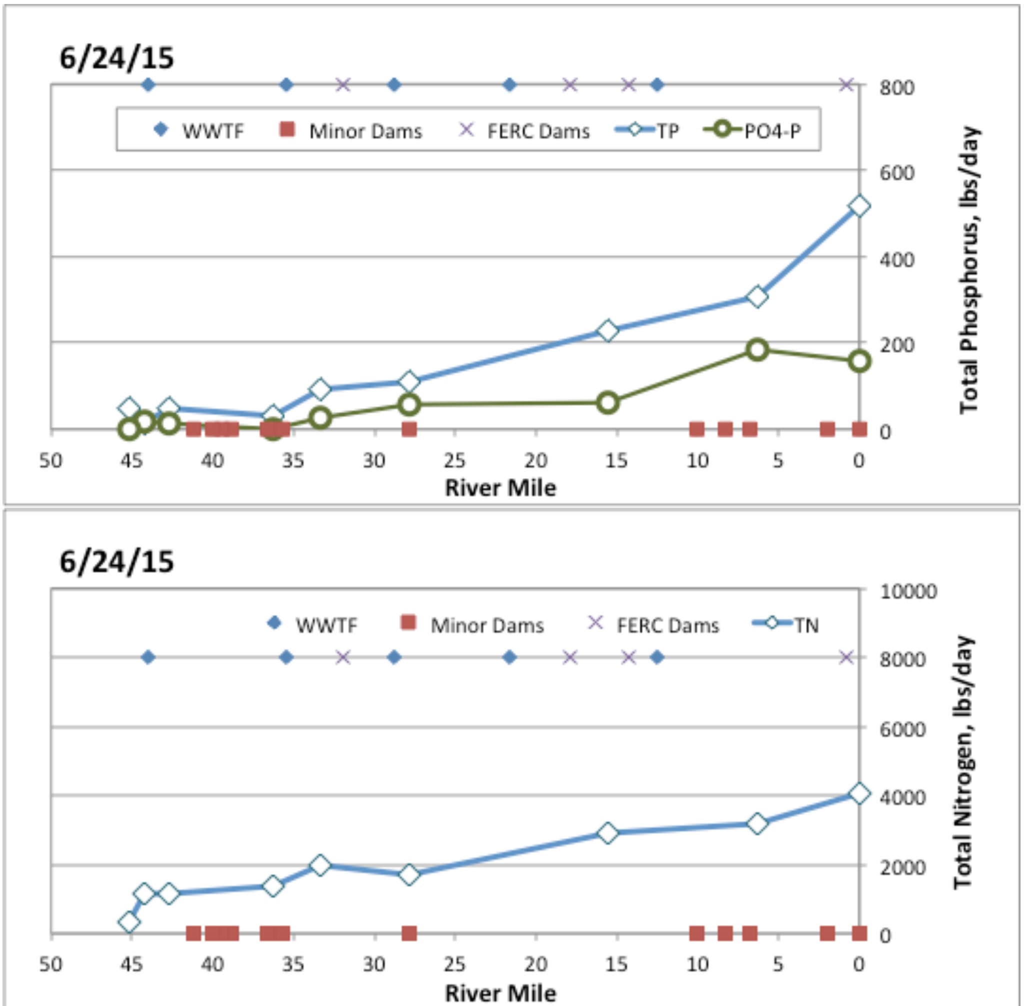
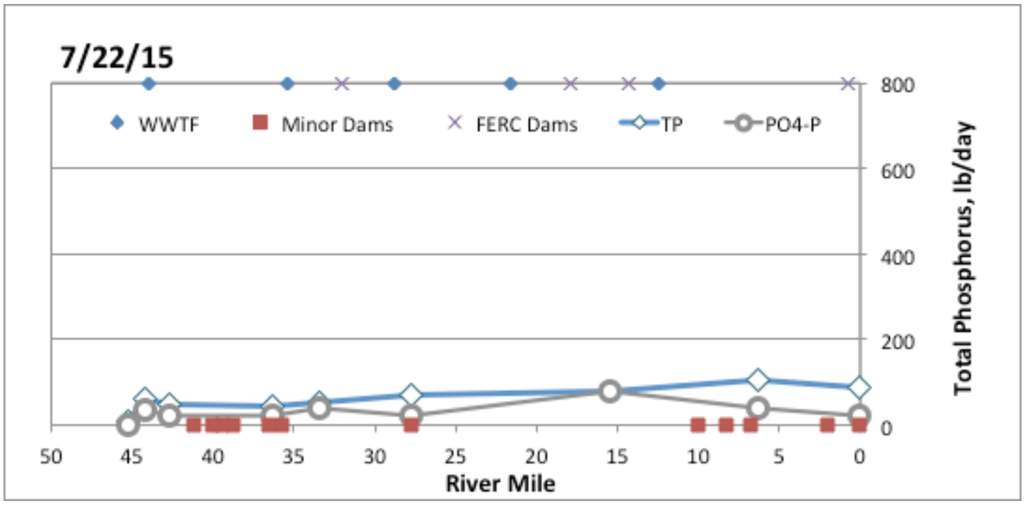


Figure 63: 24 June 2015 along stream load plots (TP, PO4 as P, TN)



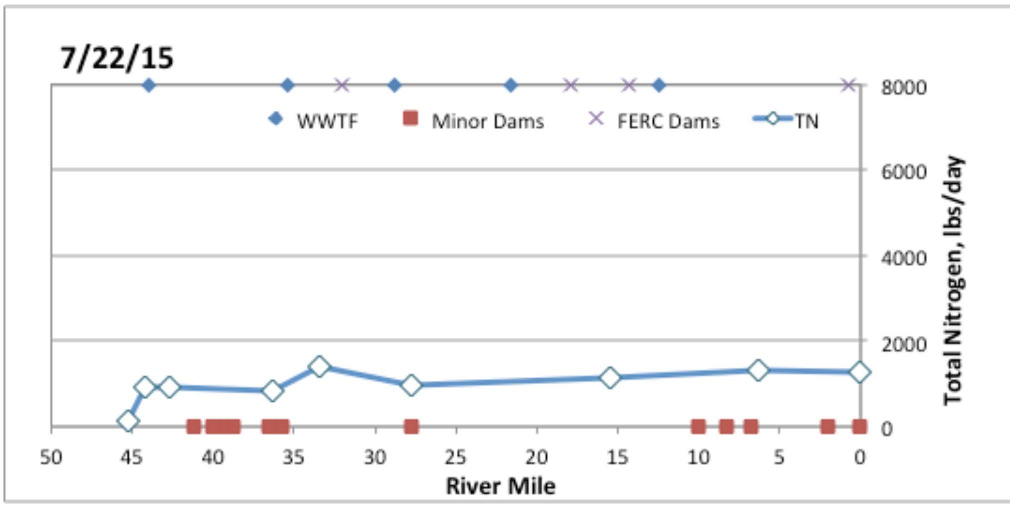


Figure 64: 22 July 2015 along stream load plots (TP, PO4 as P, TN)

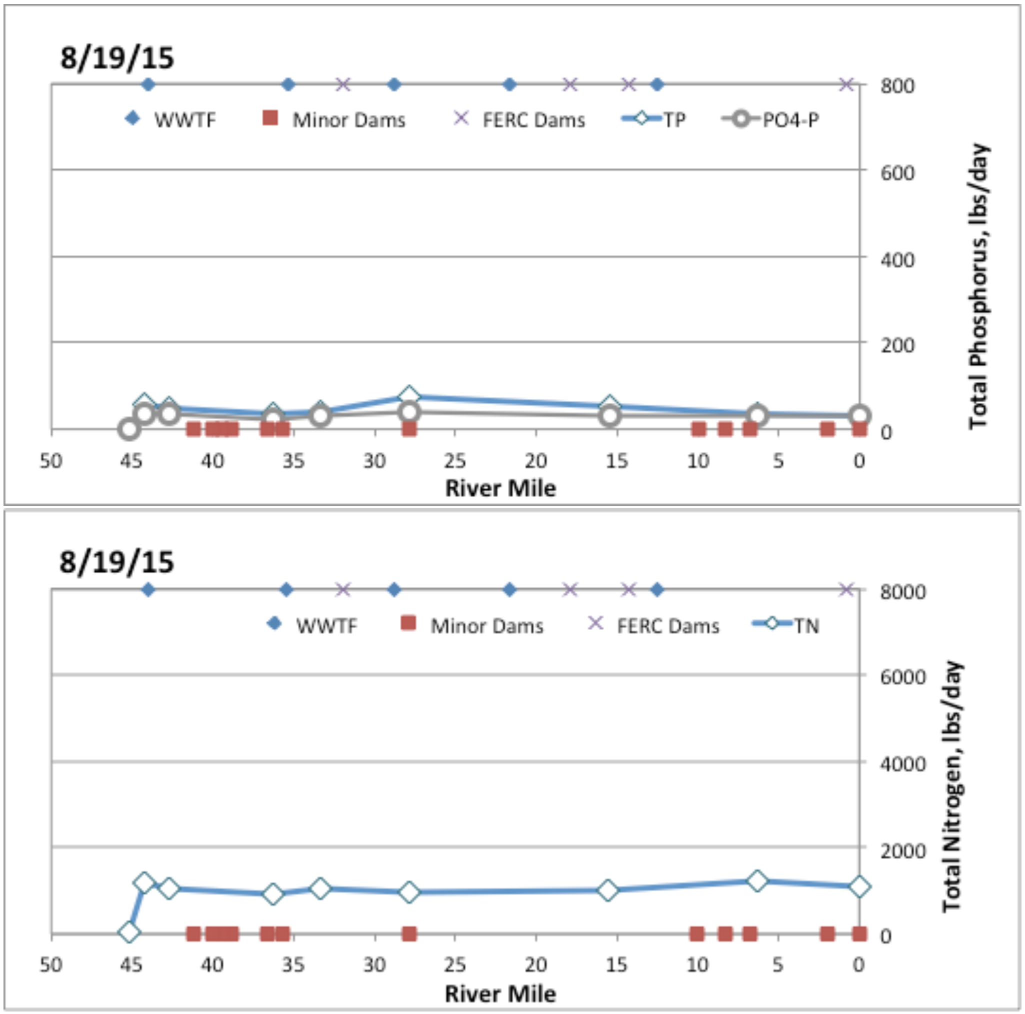


Figure 65: 19 August 2015 along stream load plots (TP, PO4 as P, TN)

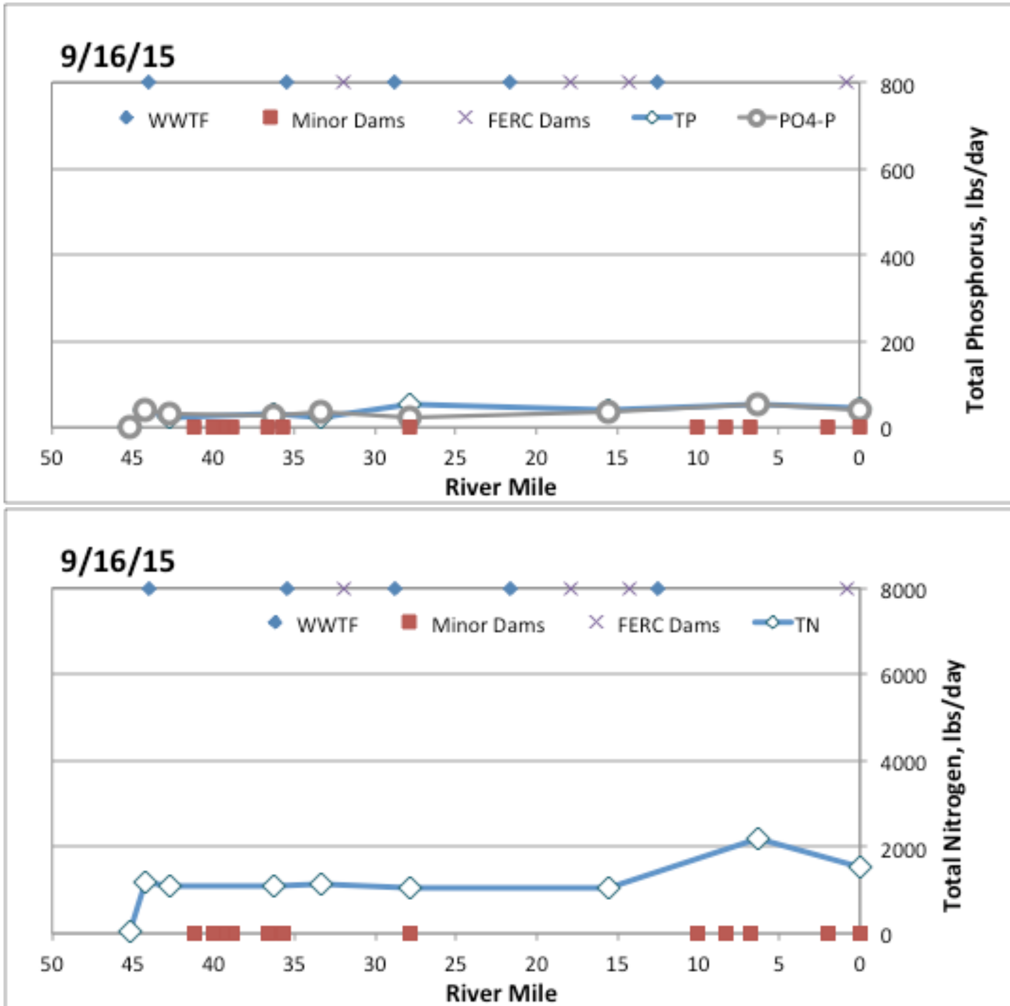
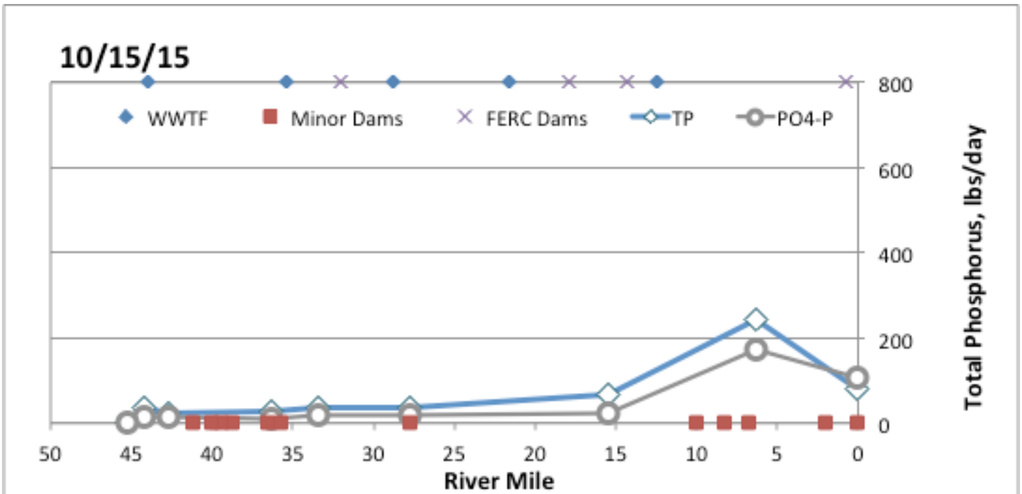


Figure 66: 16 September 2015 along stream load plots (TP, PO4 as P, TN)



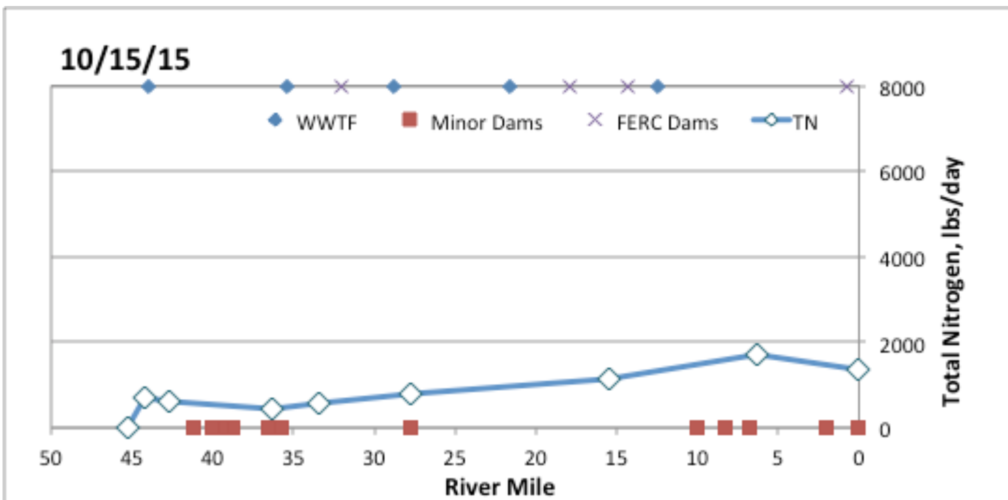


Figure 67: 15 October 2015 along stream load plots (TP, PO4 as P, TN)

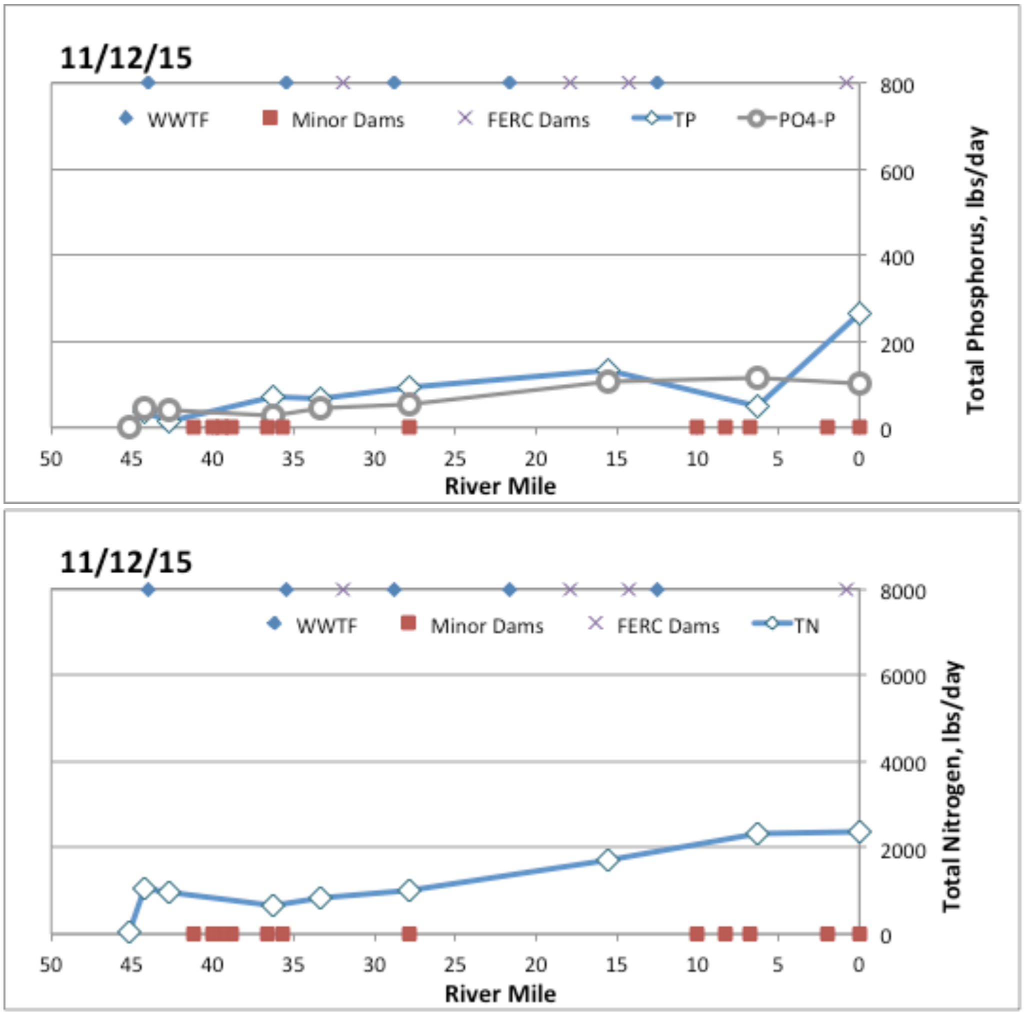


Figure 68: 12 November 2015 along stream load plots (TP, PO4 as P, TN)

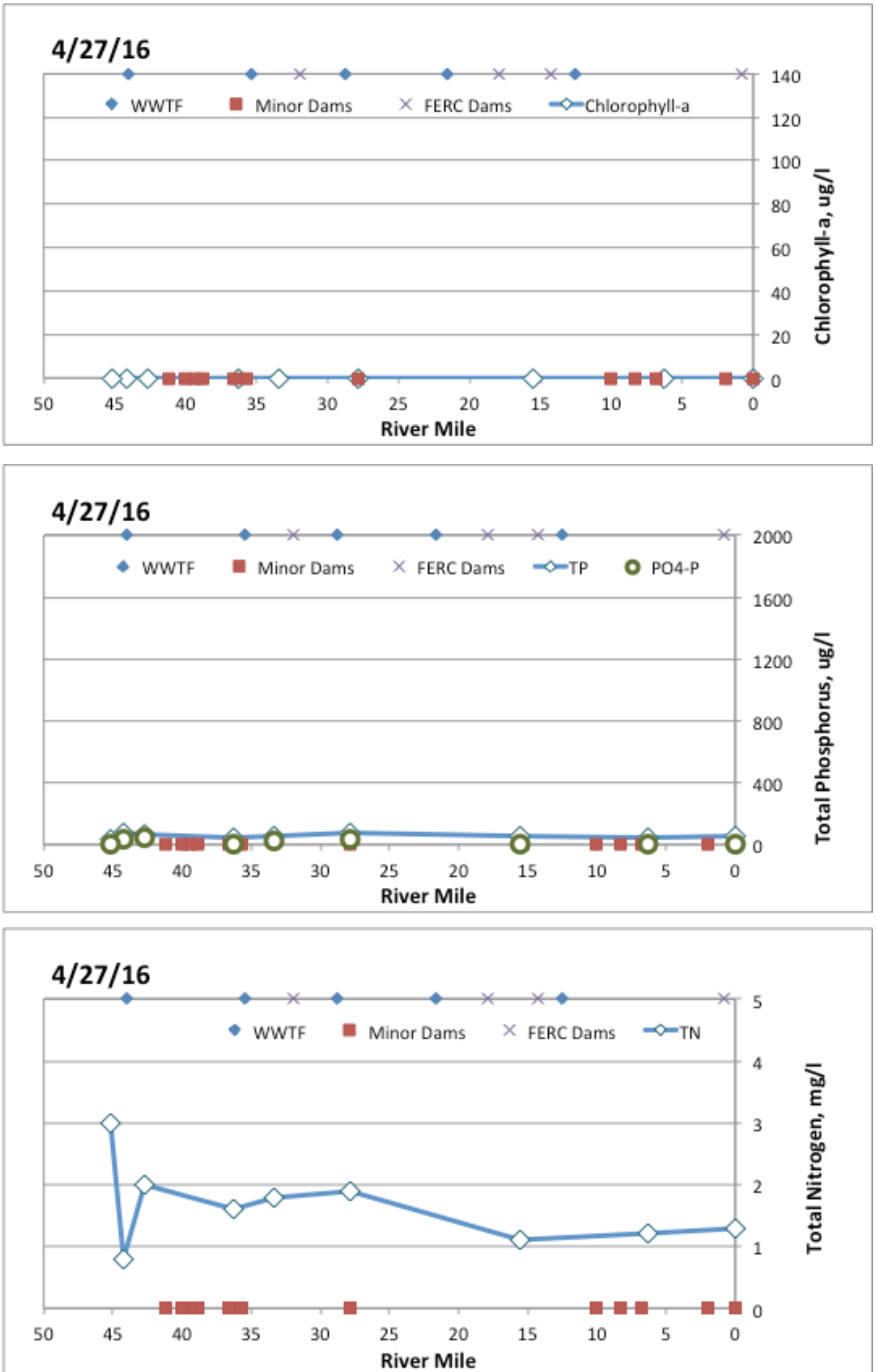


Figure 69: 27 April 2016 along stream concentration plots (Chl-a, TP, PO4 as P, TN)

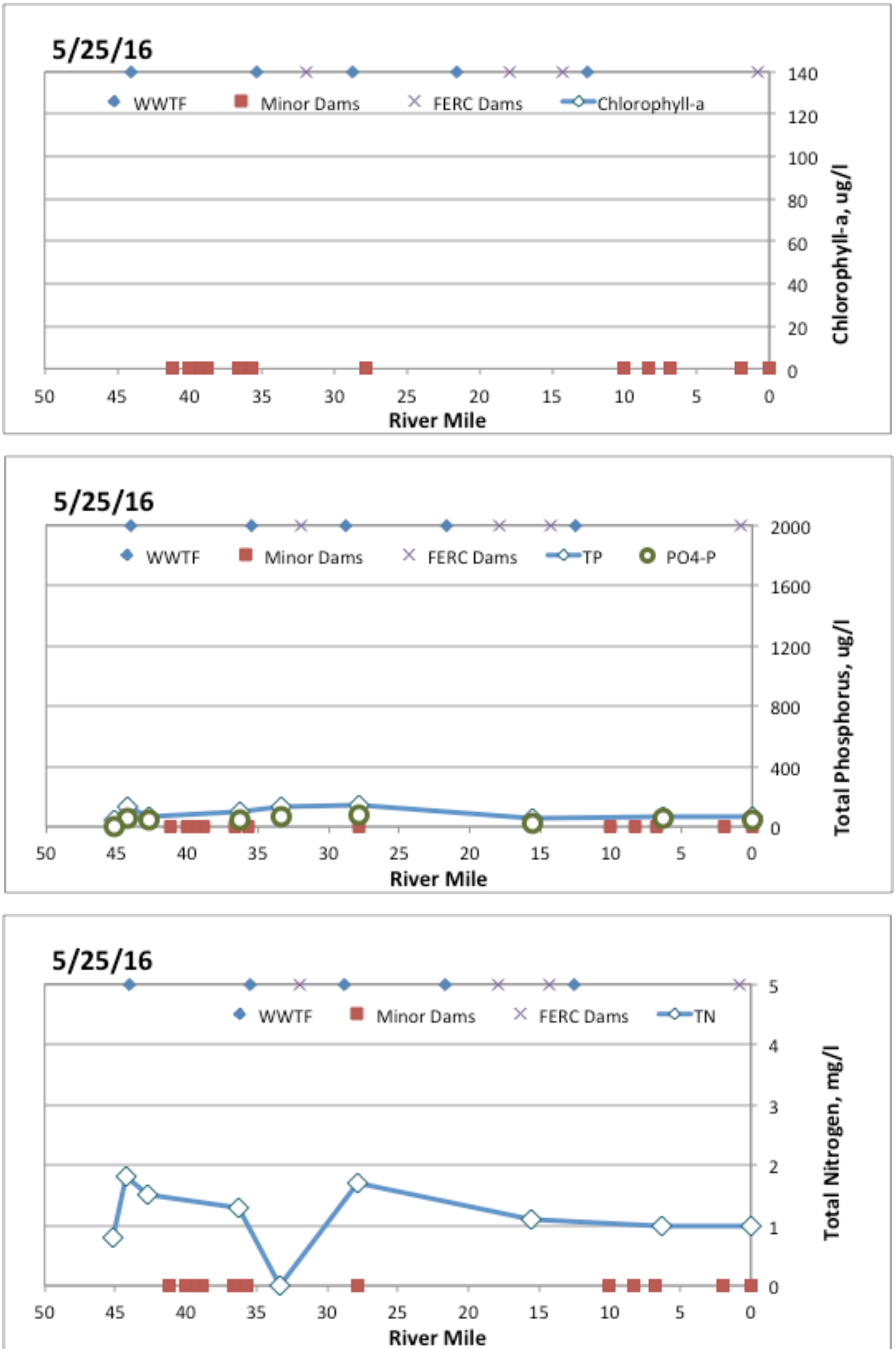


Figure 70: 25 May 2016 along stream concentration plots (Chl-a – no data available, TP, TN)

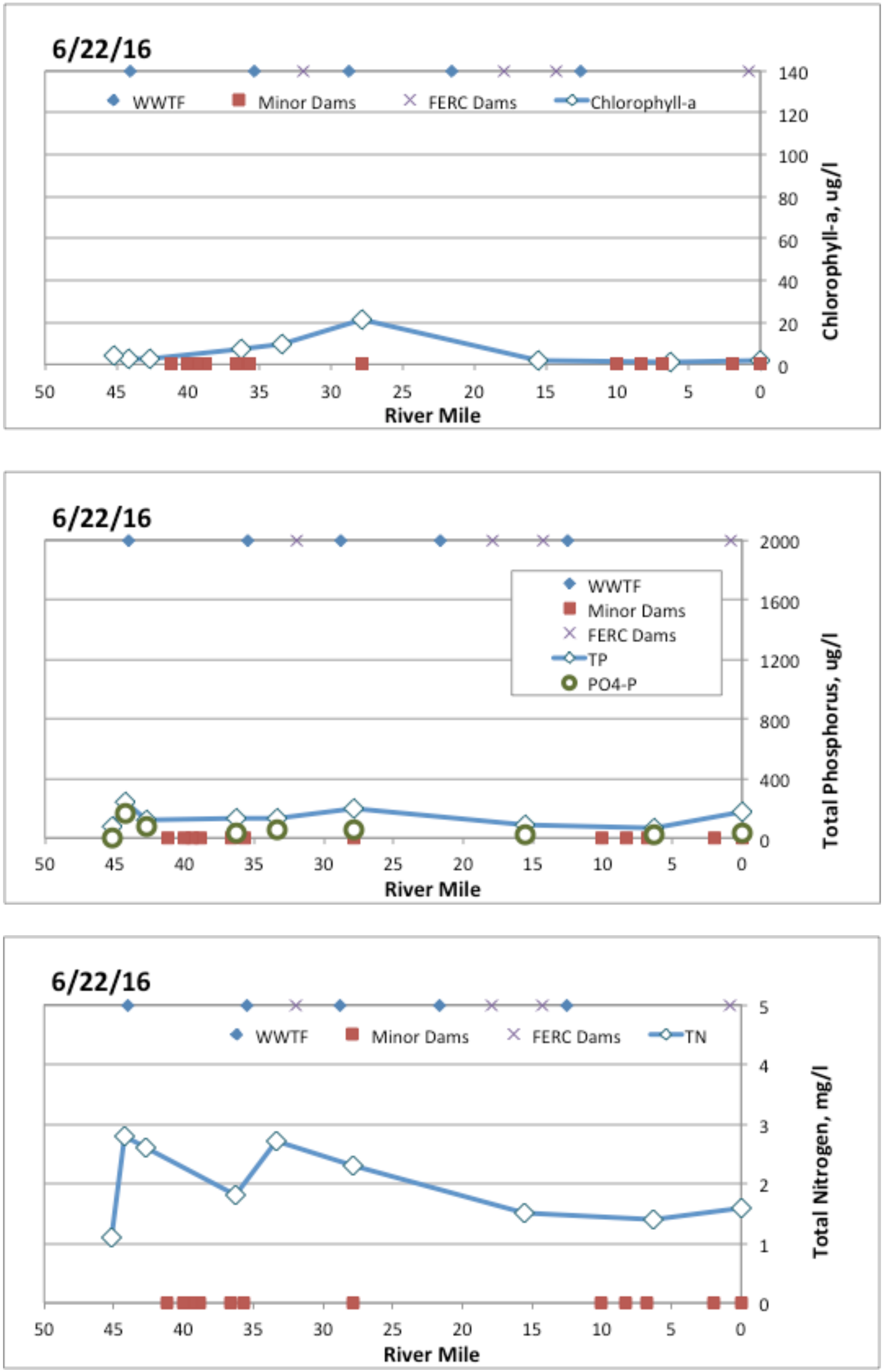


Figure 71: 22 June 2016 along stream concentration plots (Chl-a, TP, PO4 as P, TN)

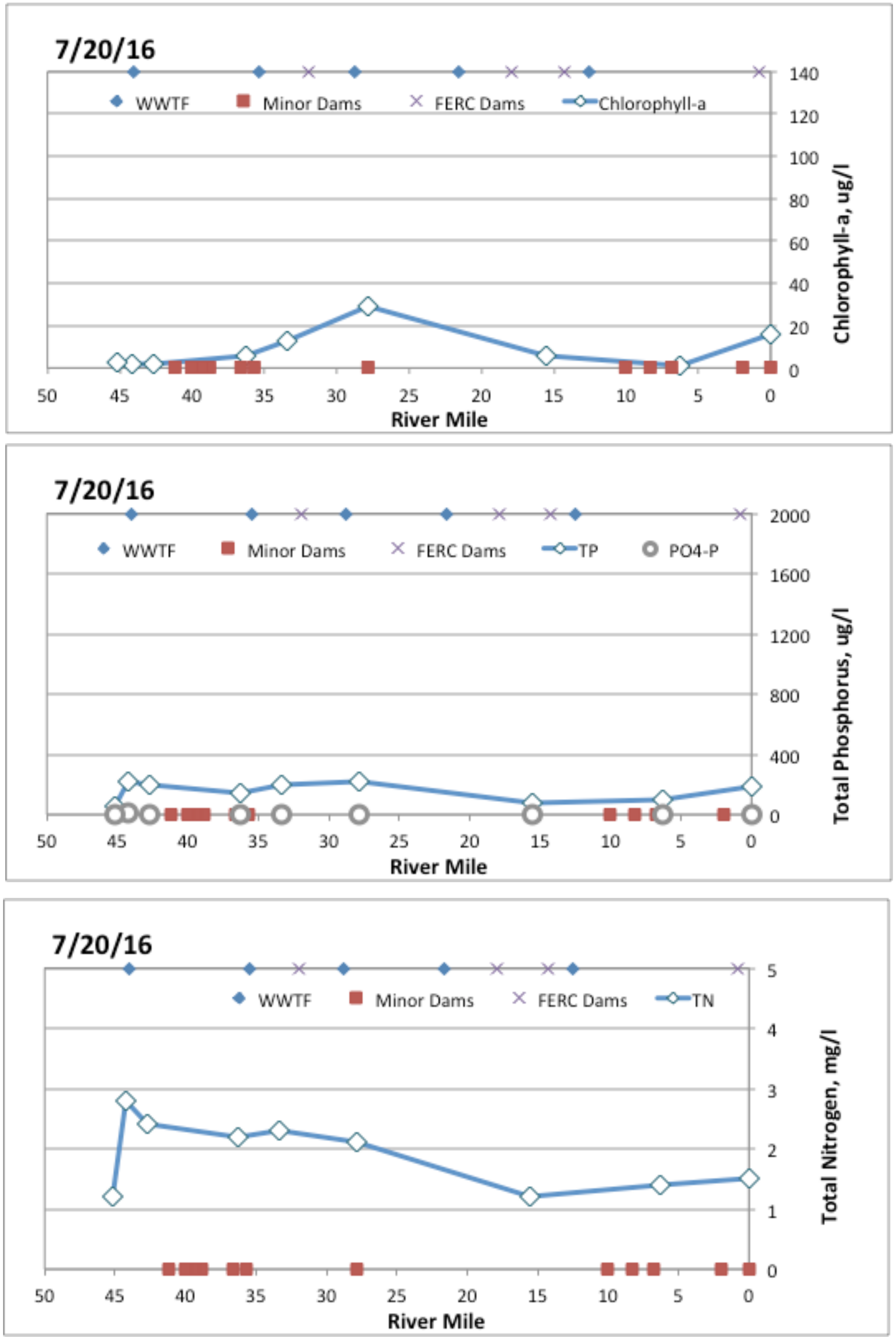


Figure 73: 20 July 2016 along stream concentration plots (Chl-a, TP, PO4 as P, TN)

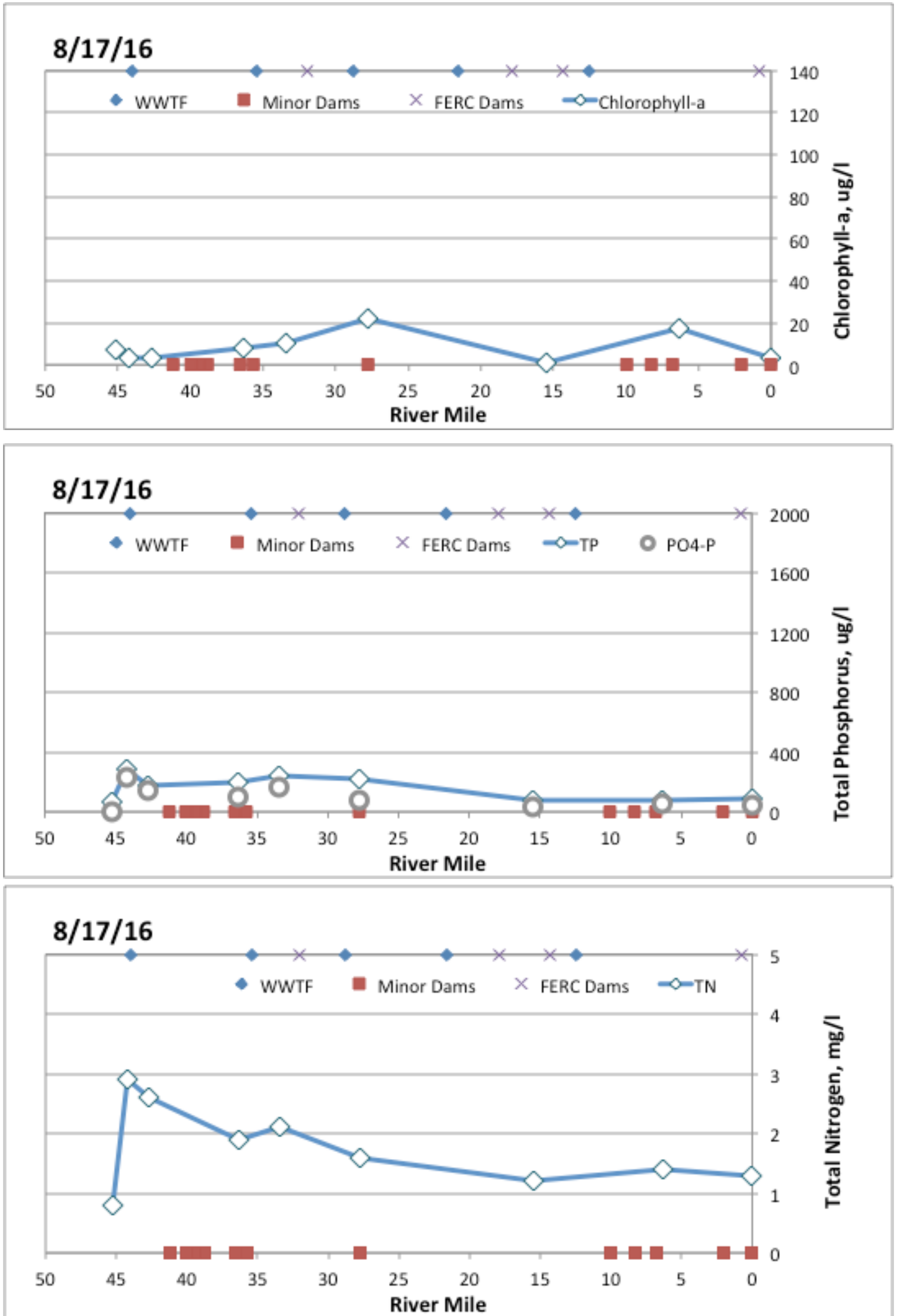


Figure 74: 17 August 2016 along stream concentration plots (Chl-a, TP, PO4 as P, TN)

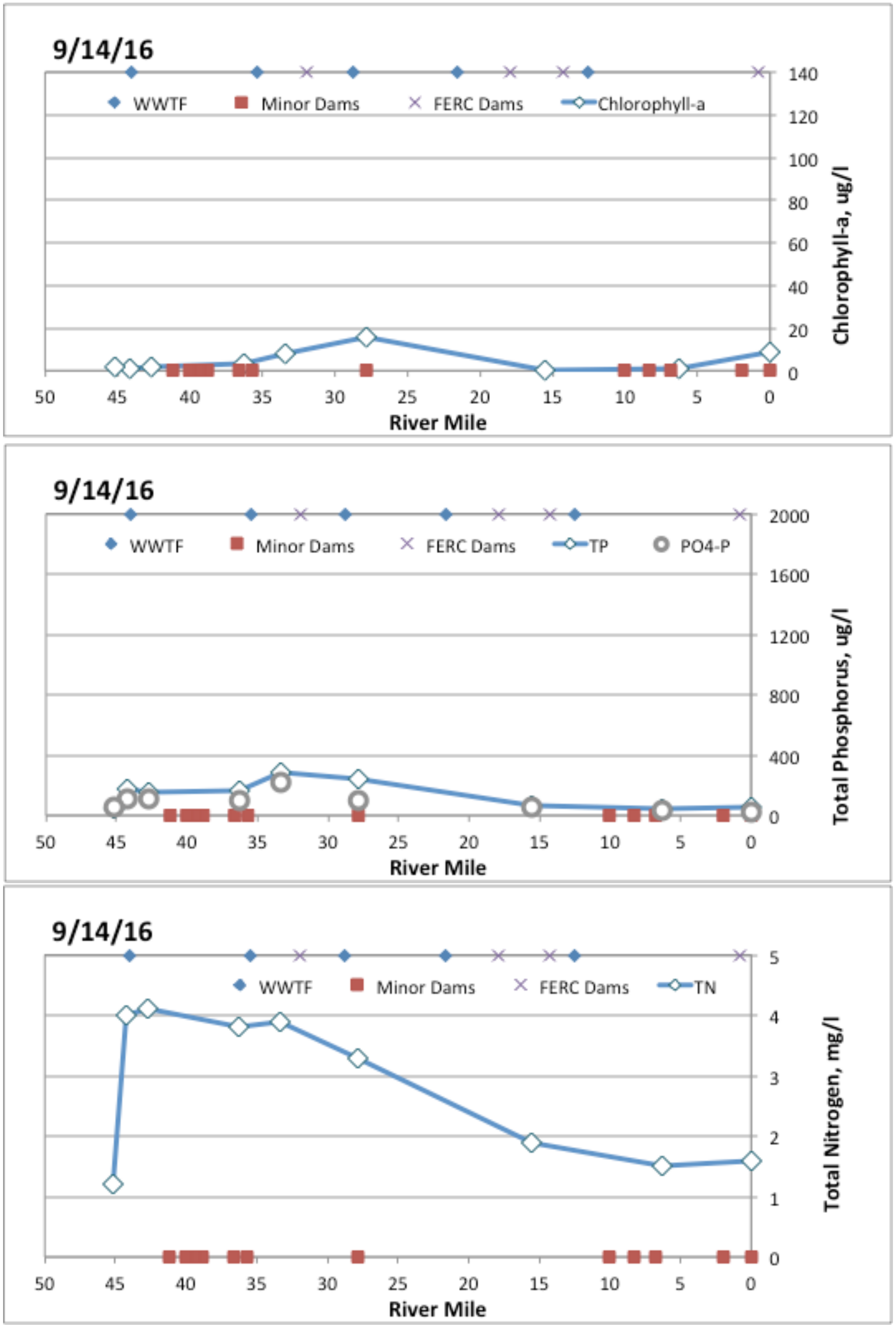


Figure 75: 14 September 2016 along stream concentration plots (Chl-a, TP, PO4 as P, TN)

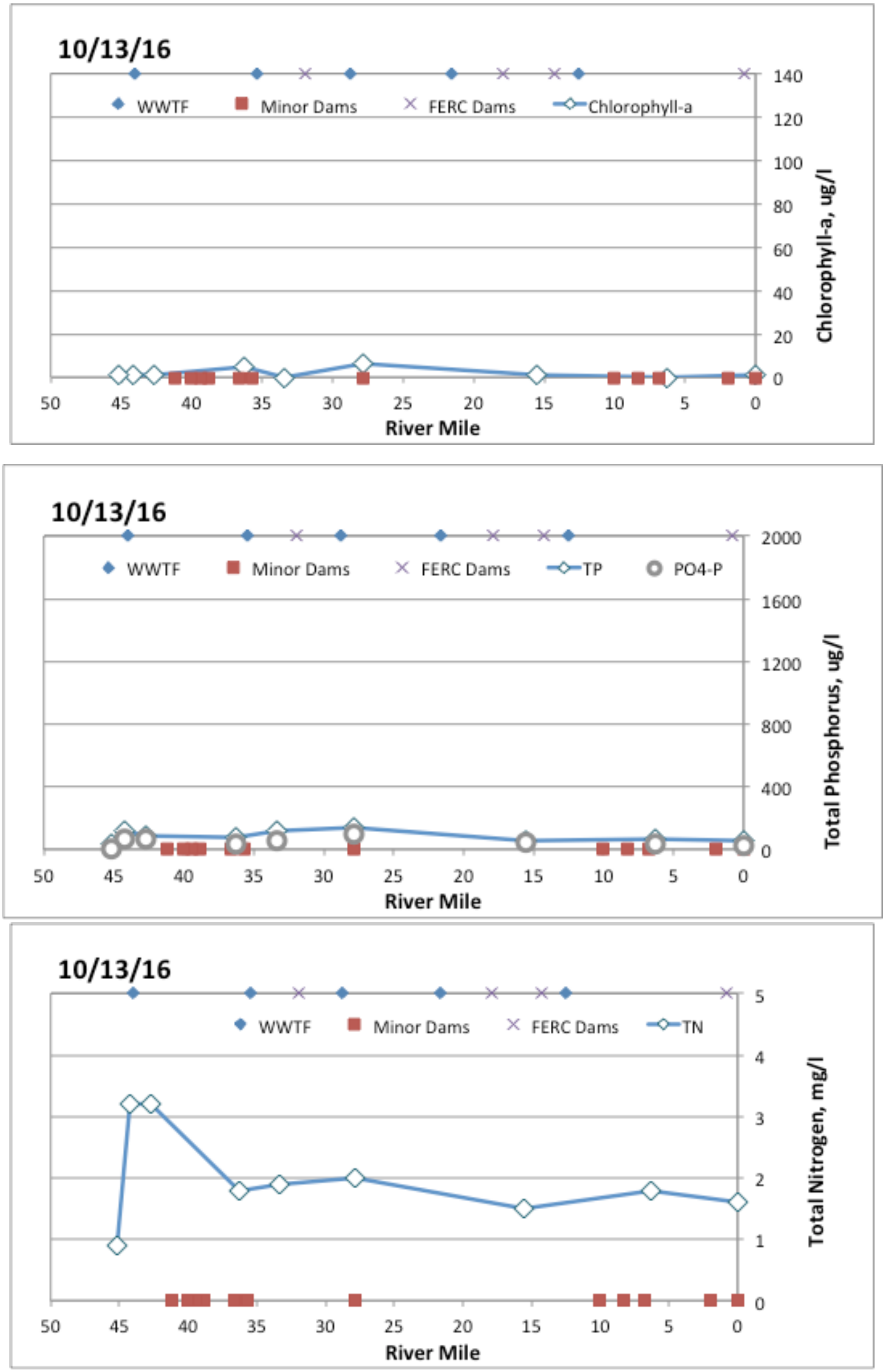


Figure 76: 13 October 2016 along stream concentration plots (Chl-a, TP, PO4 as P, TN)

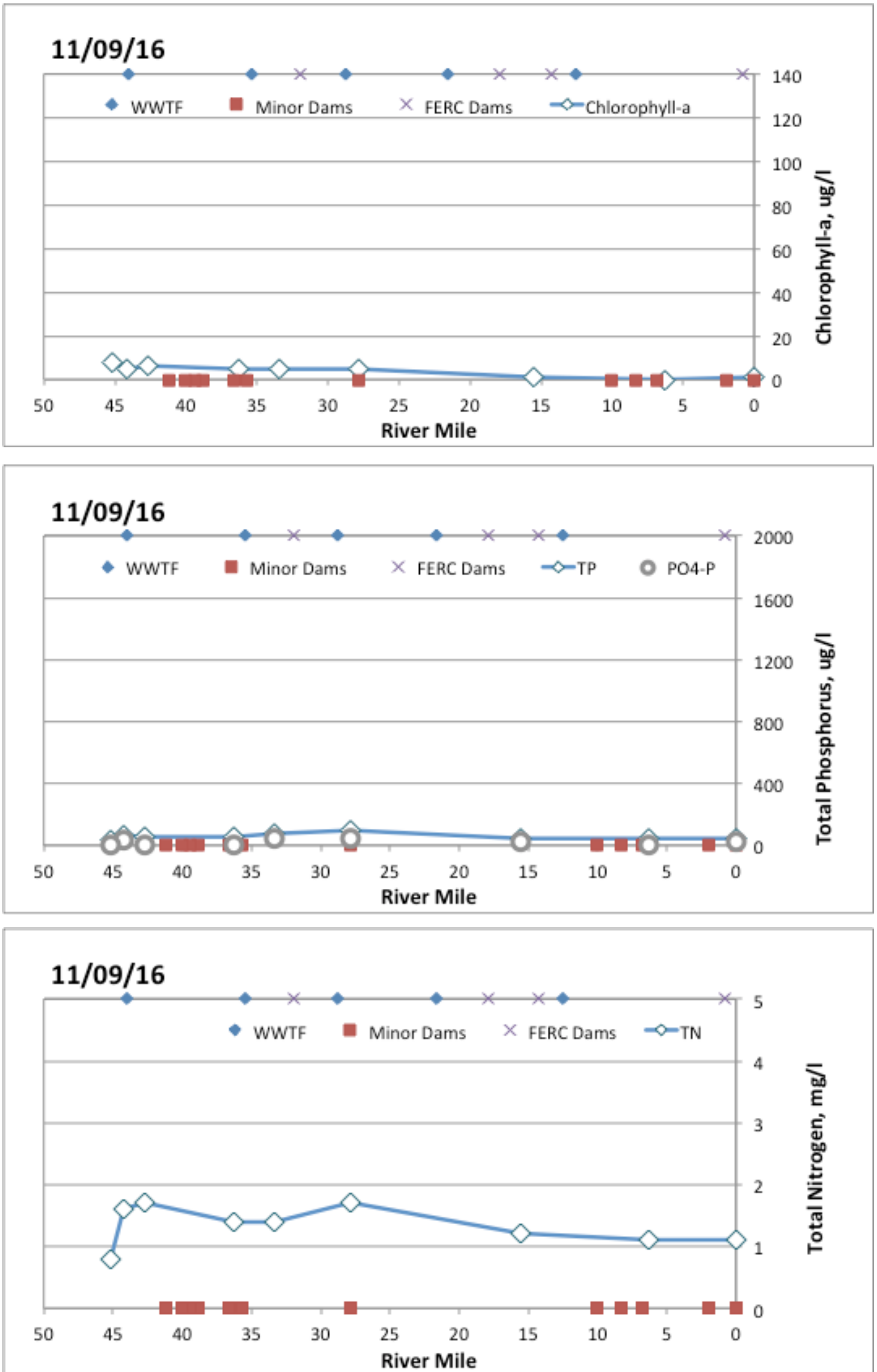


Figure 77: 9 November 2016 along stream concentration plots (Chl-a, TP, PO4 as P, TN)

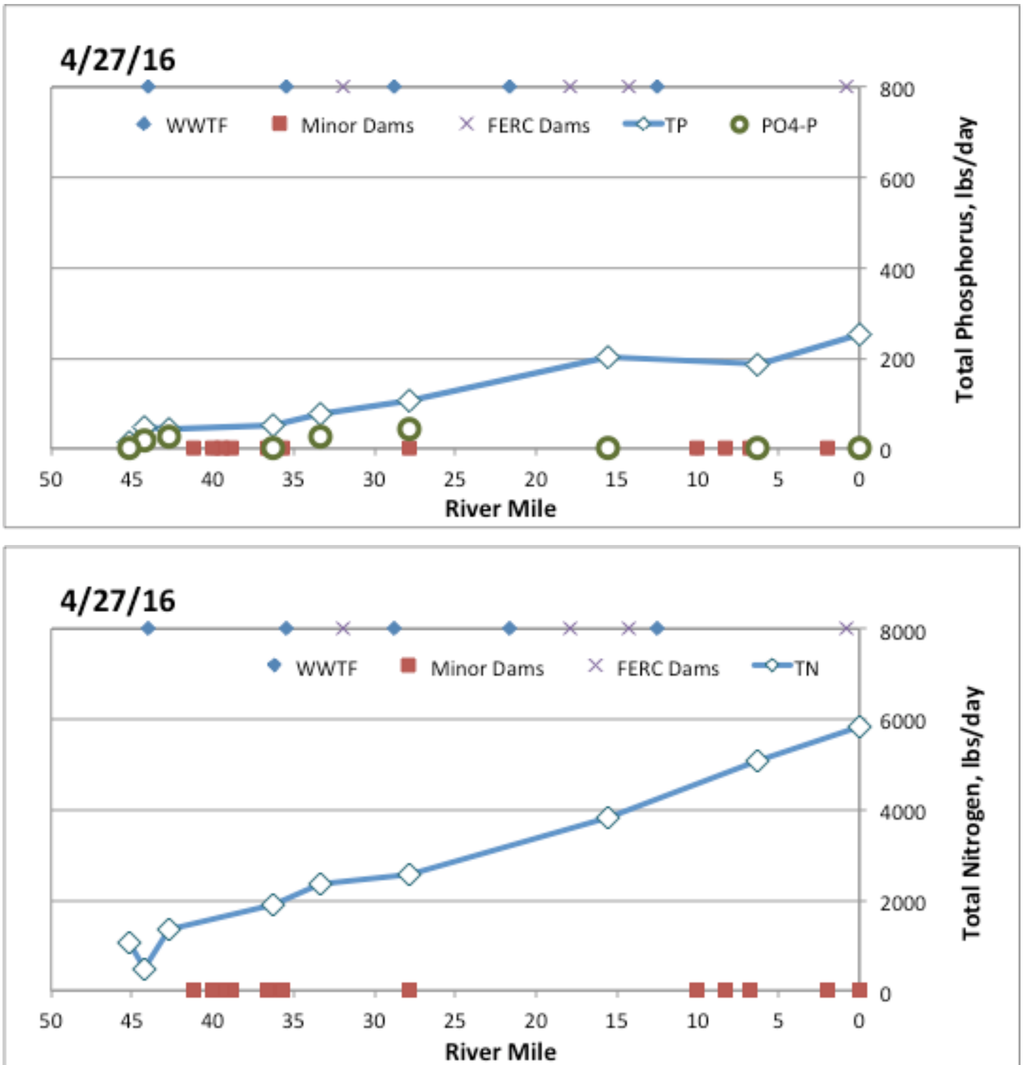


Figure 78: 25 May 2016 along stream load plots (TP, PO4 as P, TN)

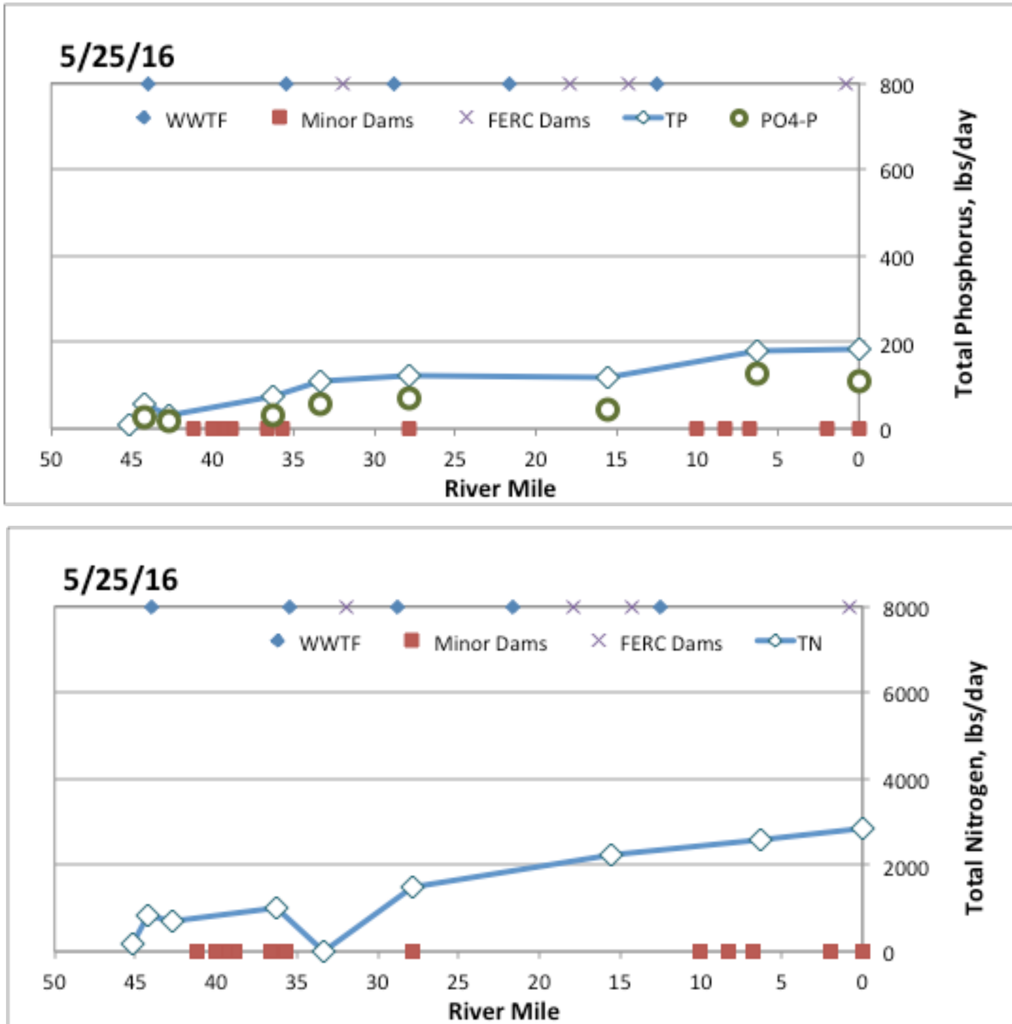
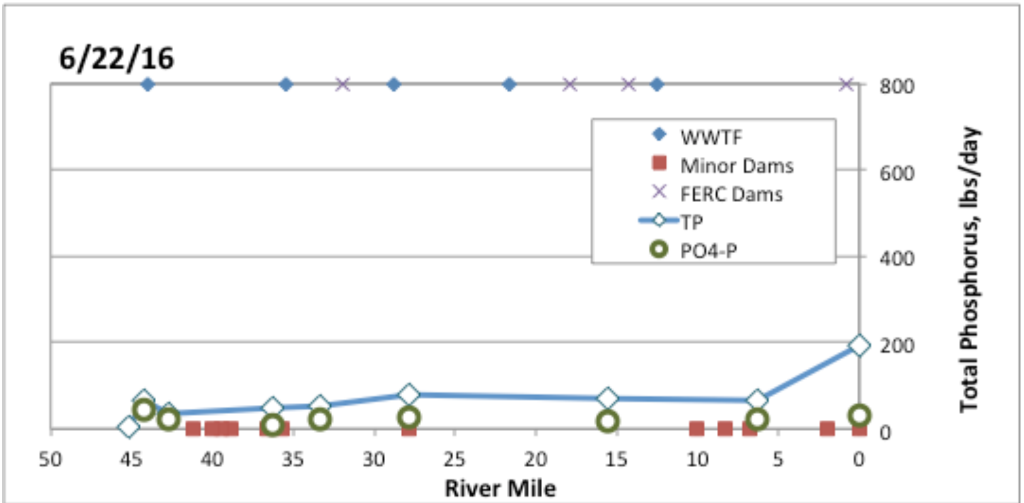


Figure 79: 25 May 2016 along stream load plots (TP, PO4 as P, TN)



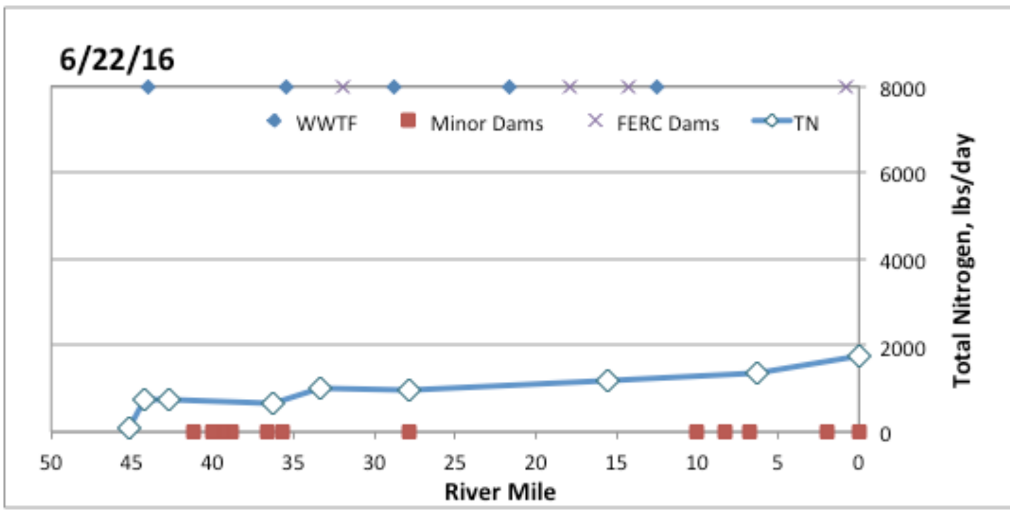
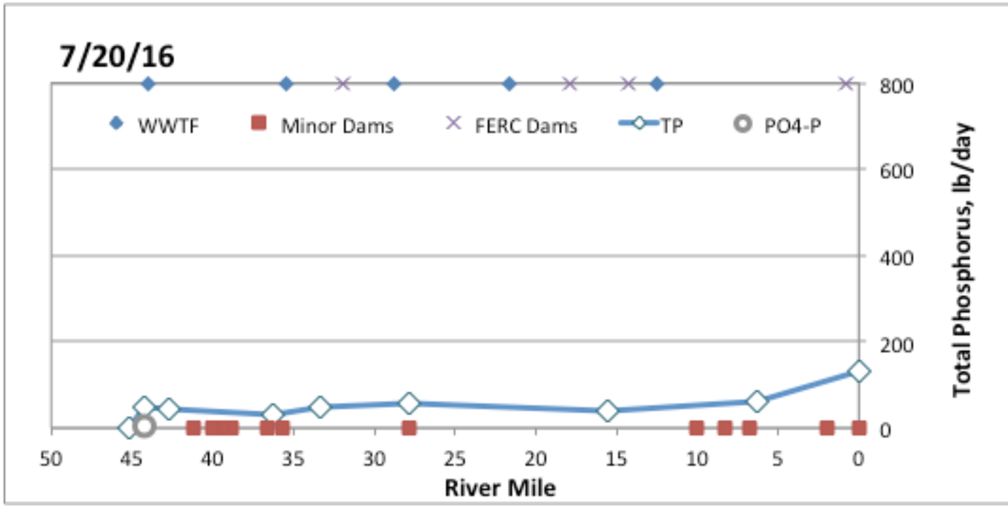


Figure 80: 22 June 2016 along stream load plots (TP, PO4 as P, TN)



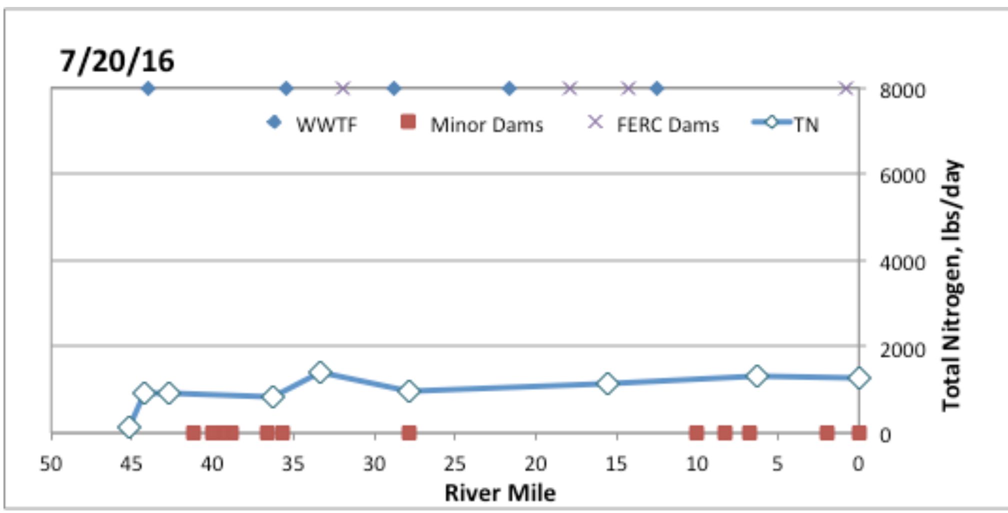


Figure 81: 20 July 2016 along stream load plots (TP, PO4 as P, TN)

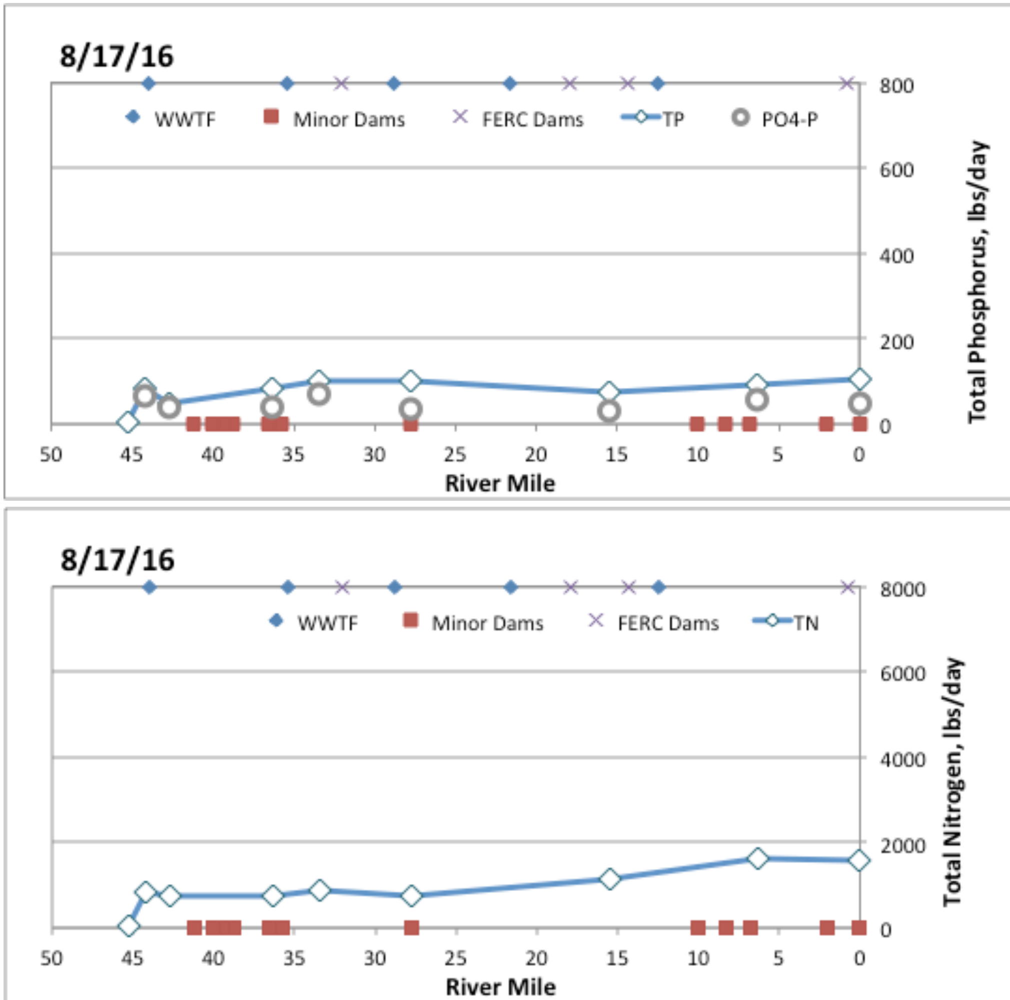


Figure 82: 17 August 2016 along stream load plots (TP, PO4 as P, TN)

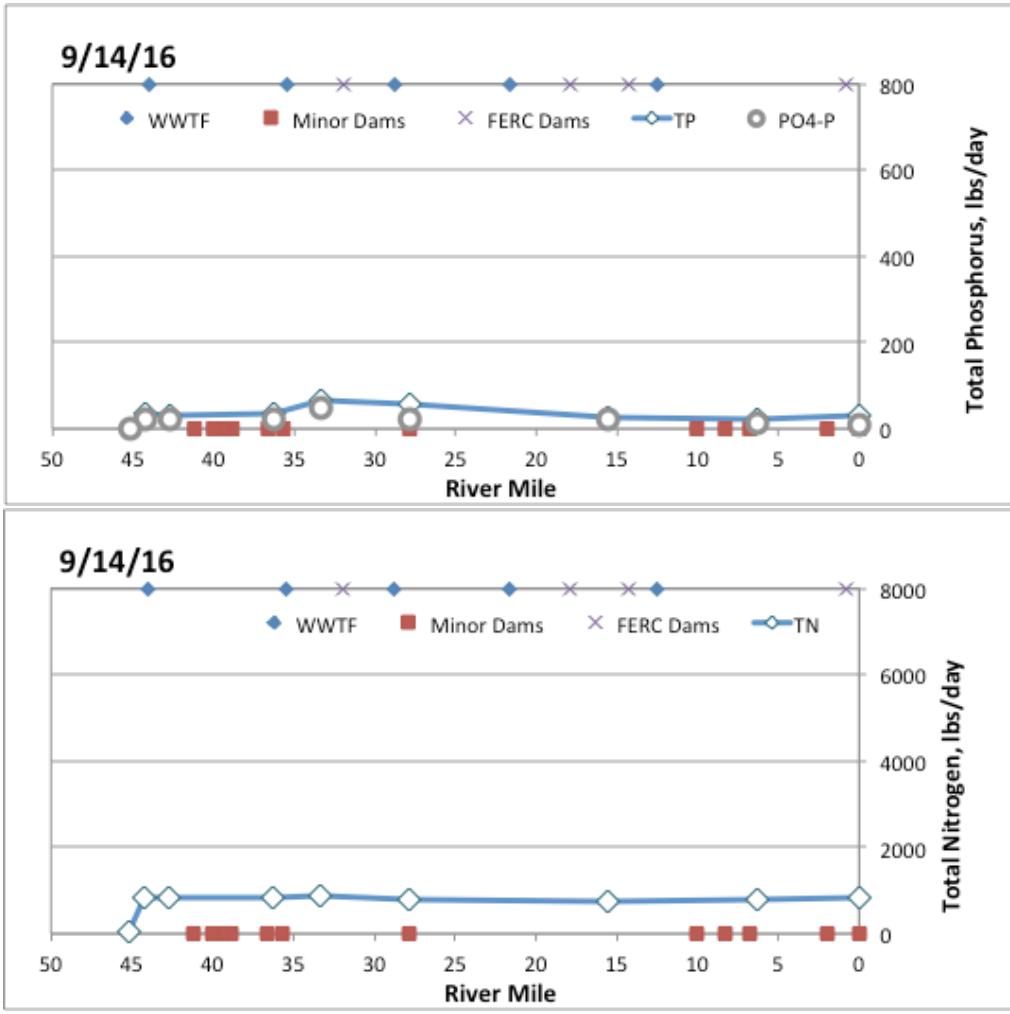


Figure 83: 14 September 2016 along stream load plots (TP, PO4 as P, TN)

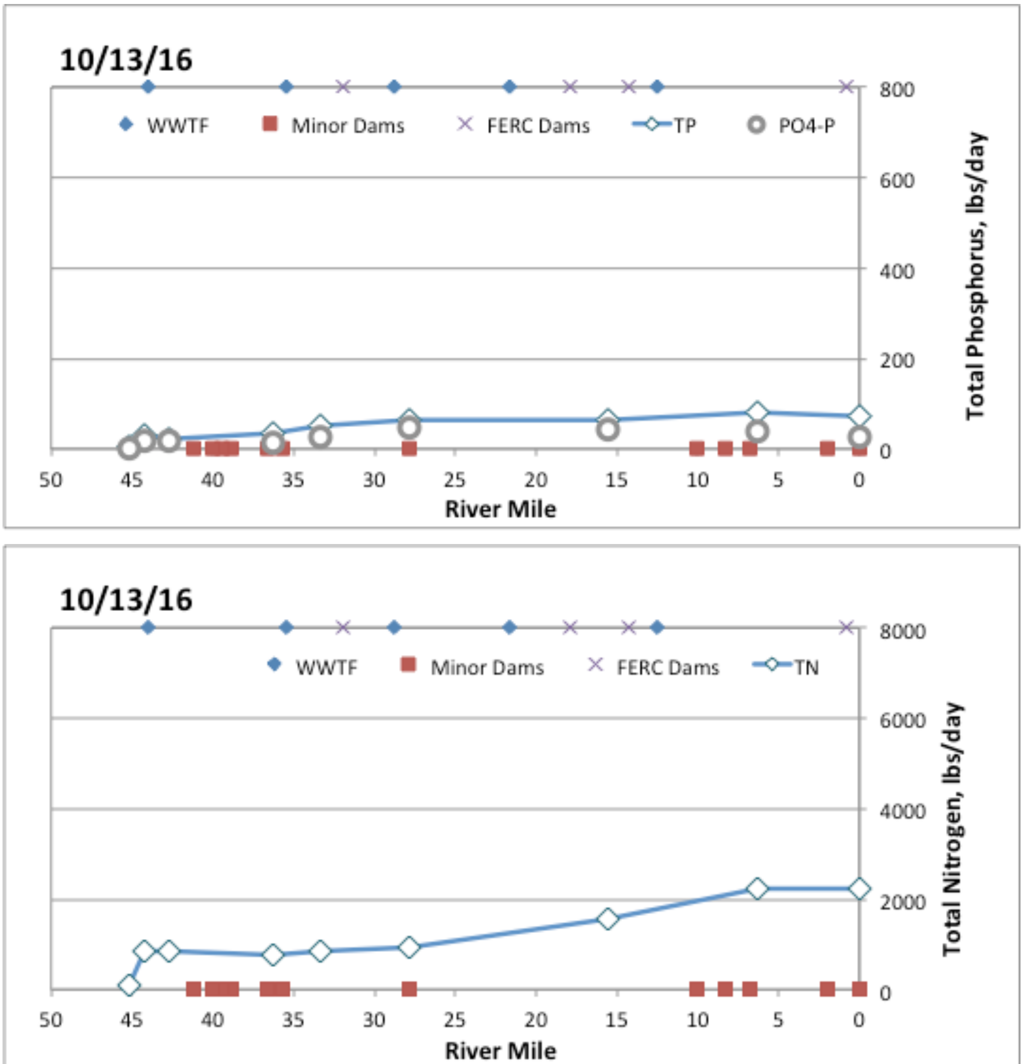


Figure 84: 13 October 2016 along stream load plots (TP, PO4 as P, TN)

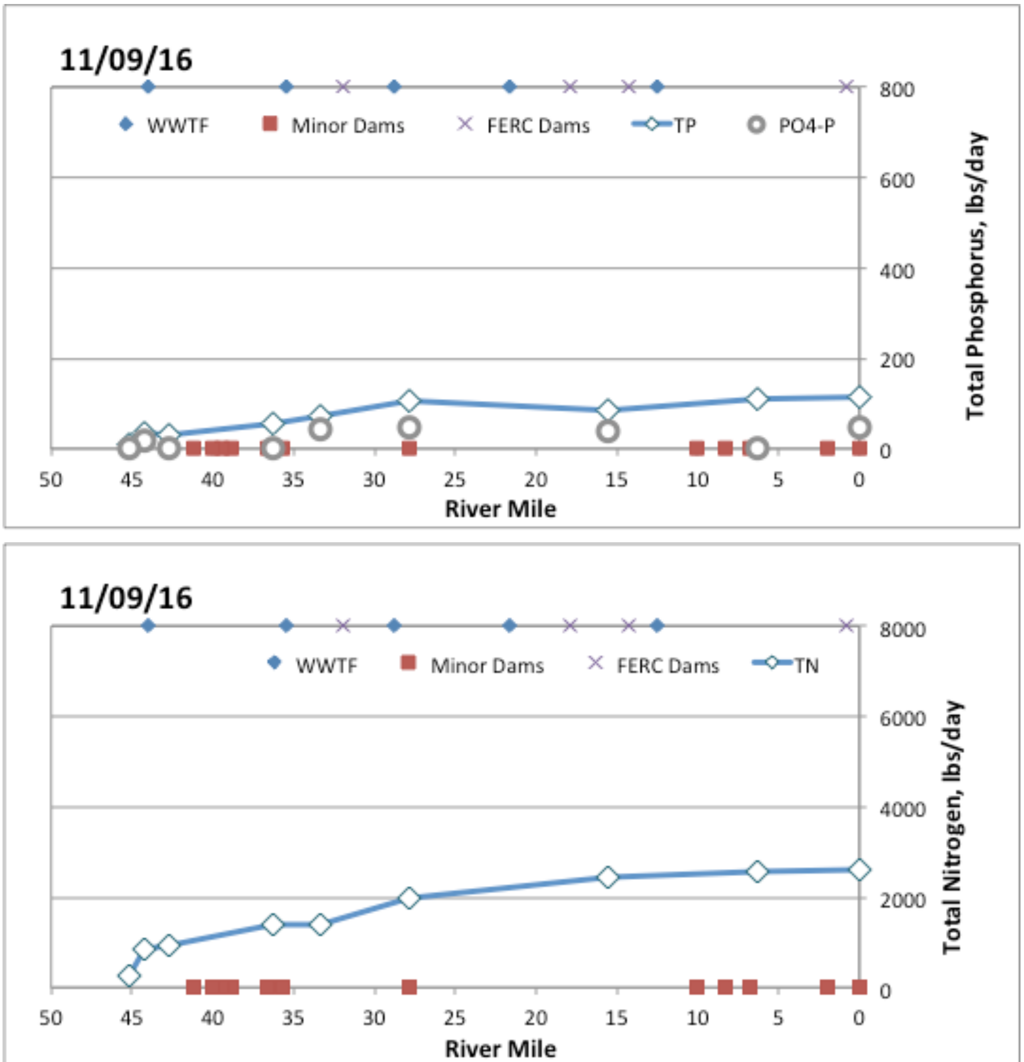


Figure 85: 9 November 2016 along stream load plots (TP, PO4 as P, TN)

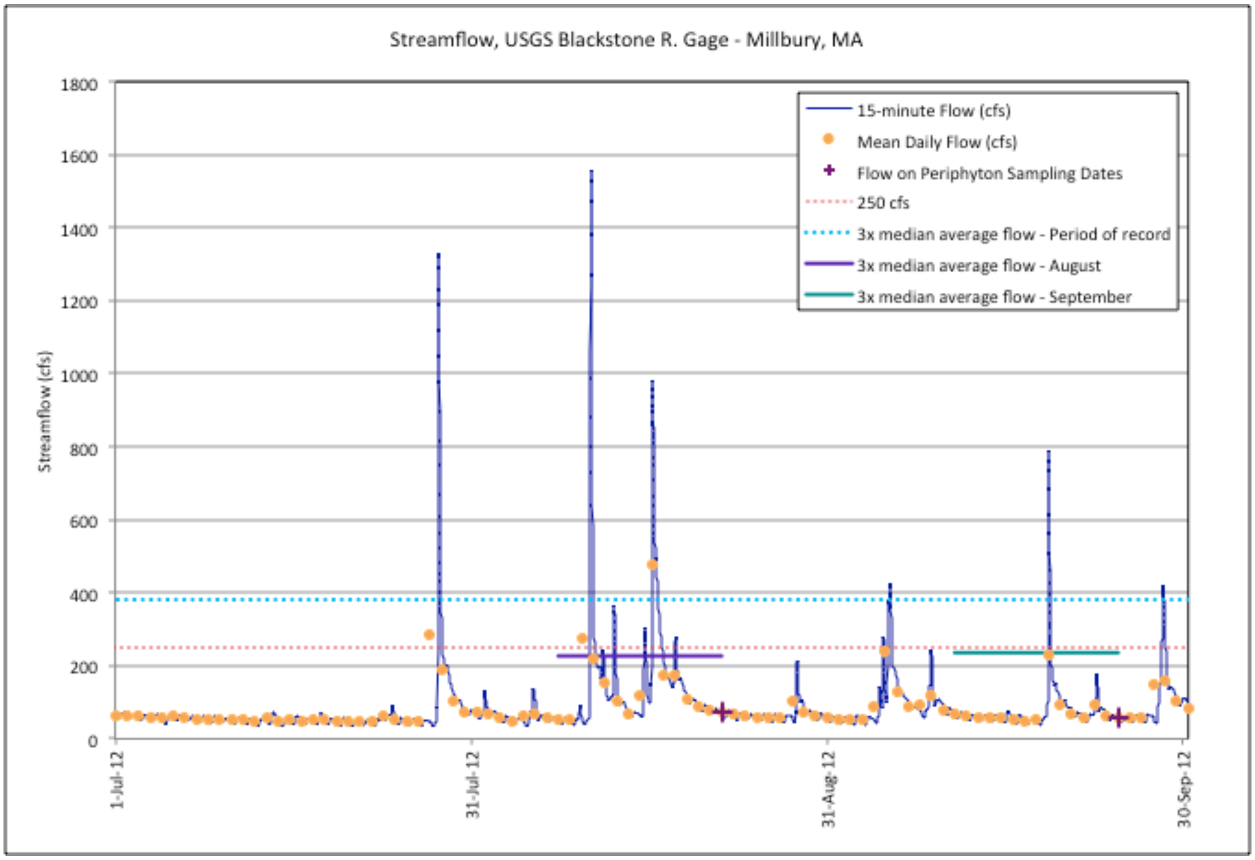


Figure 86: Summary of 2012 flows relative to periphyton sampling
(3x median values based on daily data from 2002 – 2016 for consistency)

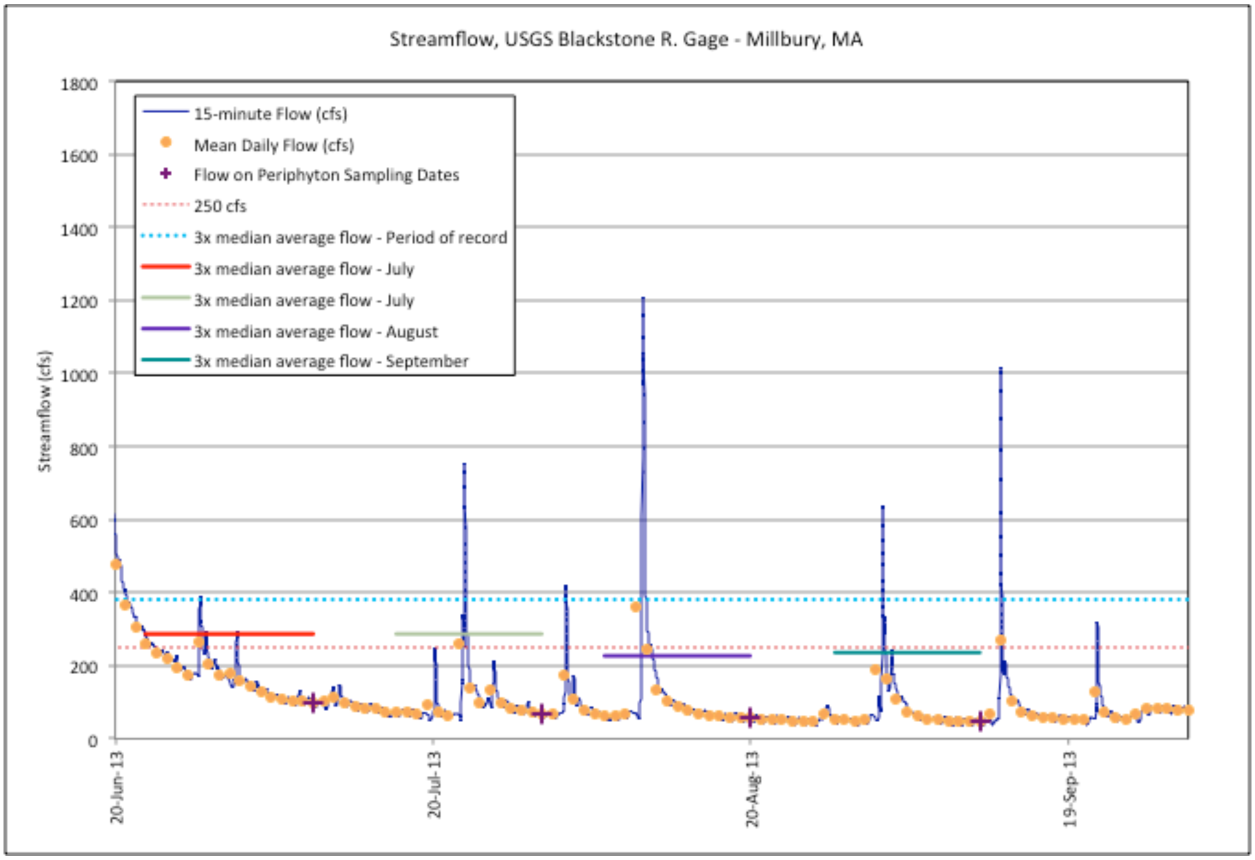


Figure 87: Summary of 2013 flows relative to periphyton sampling
(3x median values based on daily data from 2002 – 2016 for consistency)

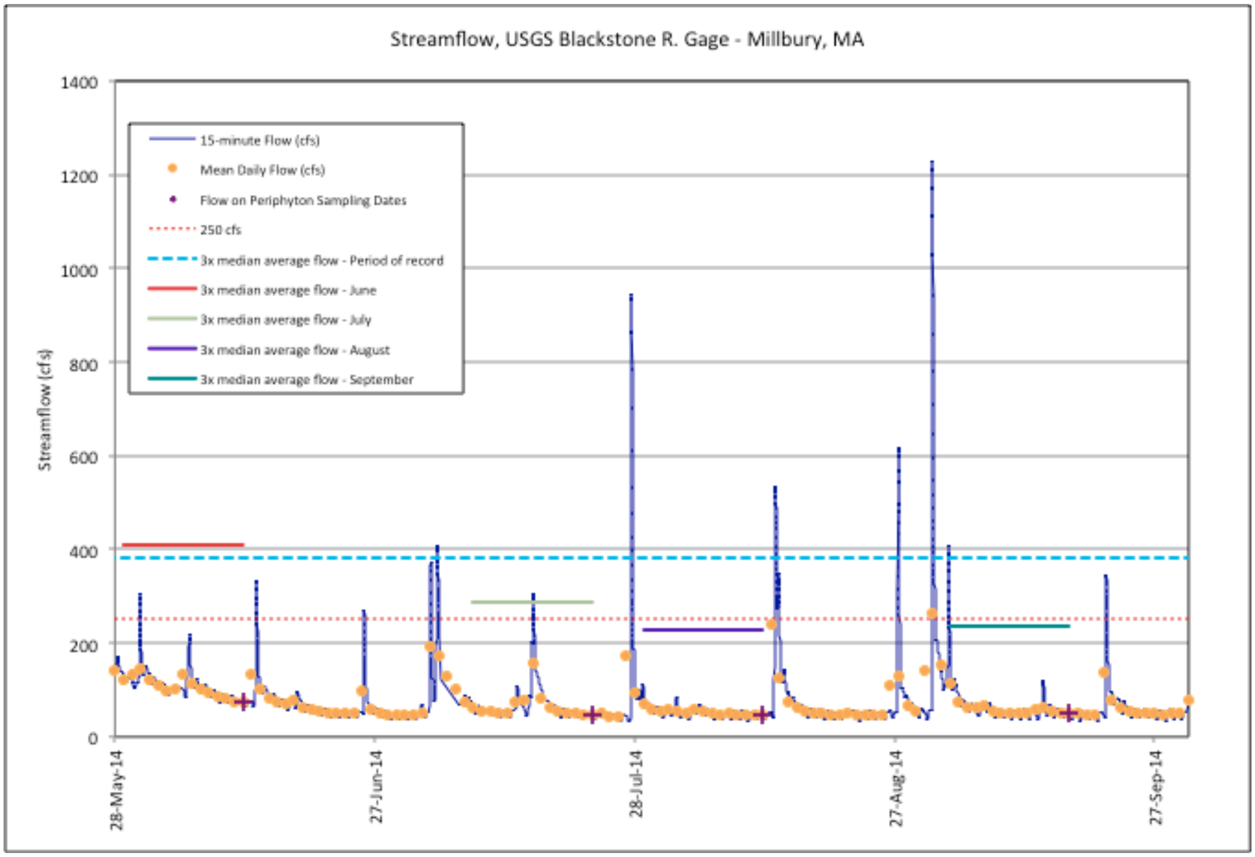


Figure 88: Summary of 2014 flows relative to periphyton sampling
(3x median values based on daily data from 2002 – 2016 for consistency)

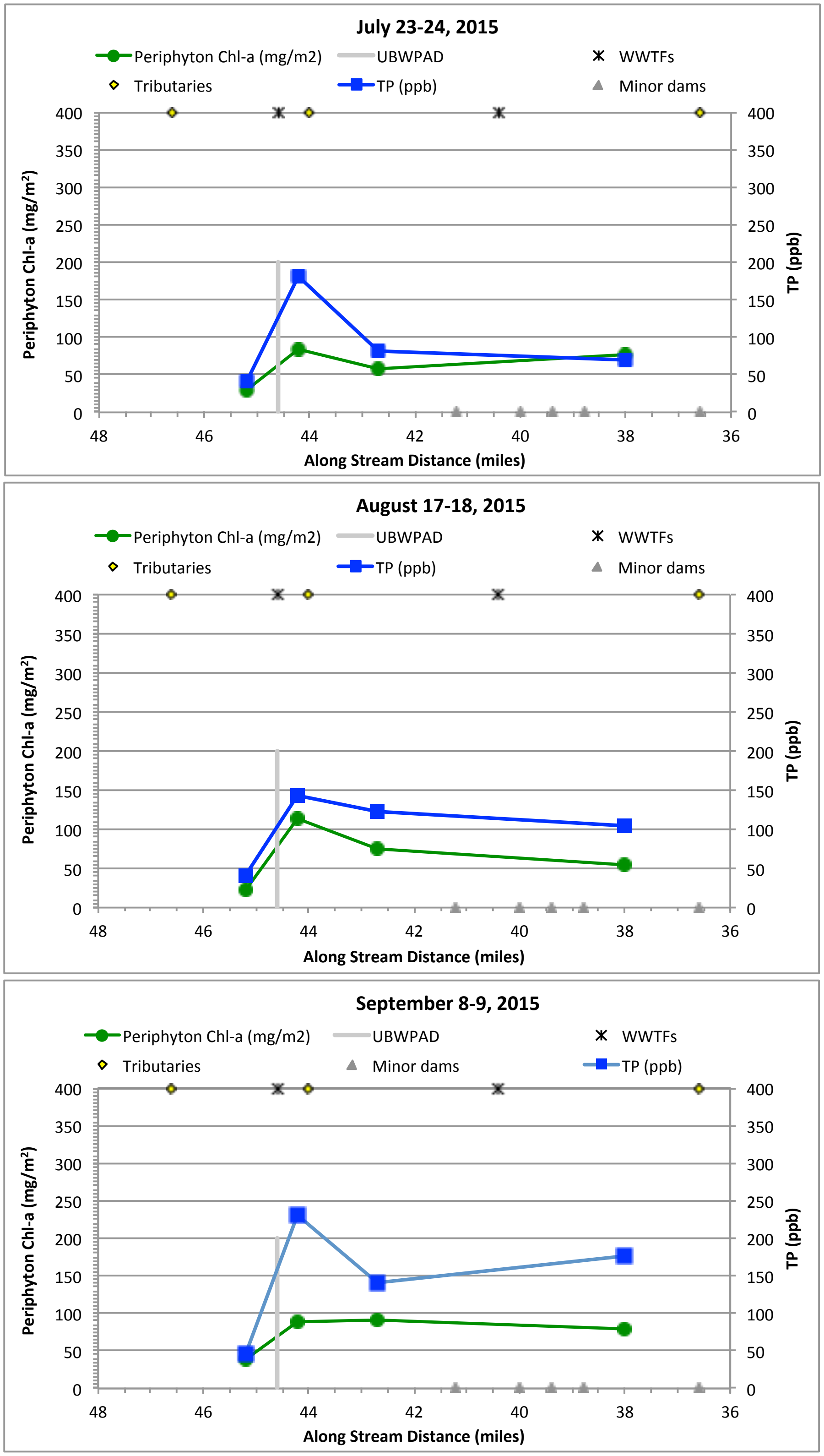


Figure 89: Periphyton along stream plots for individual sampling events, 2015

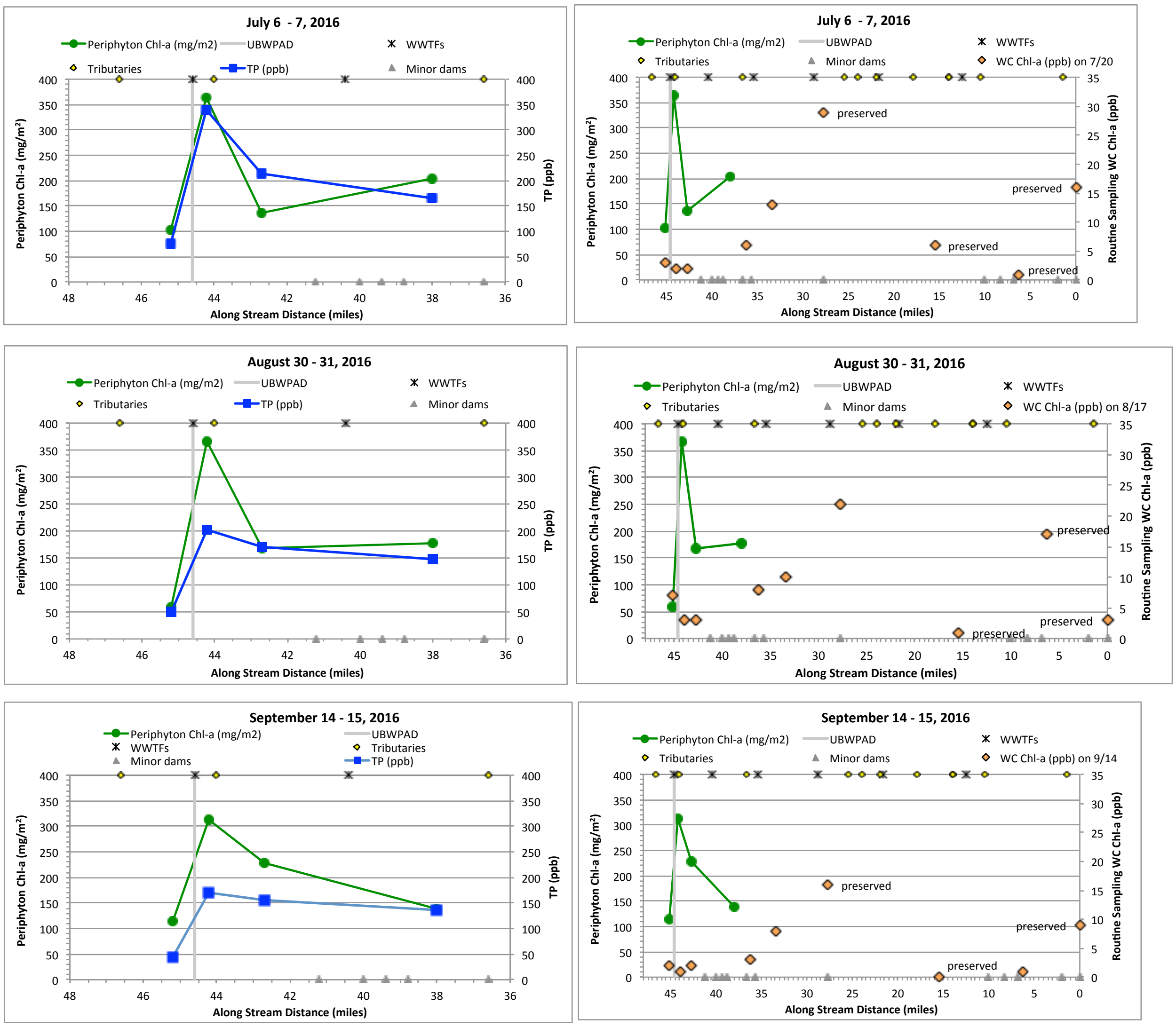


Figure 90: Periphyton along stream plots for individual sampling events, 2016

(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 data as on the left, but also the water column Chl-a data for the routine sampling event occurring in the same month as periphyton sampling.)