Water Quality Report: 2016

Wachusett Reservoir Watershed

March 2017

Massachusetts Department of Conservation and Recreation
Division of Water Supply Protection
Office of Watershed Management

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ABSTRACT

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management manages and maintains a system of watersheds and reservoirs to provide pure water to the Massachusetts Water Resources Authority (MWRA), which in turn supplies drinking water to approximately 2.2 million people and thousands of industrial users in 51 communities. Water quality sampling and watershed monitoring make up an important part of the overall mission of the Division of Water Supply Protection. These activities are carried out by Environmental Quality Section staff at Wachusett Reservoir in West Boylston and at Quabbin Reservoir in Belchertown. This report is a summary of 2016 water quality data from the Wachusett Reservoir tributaries and reservoir. A report summarizing 2016 water quality data from the Quabbin and Ware River watersheds is also available from the Division.

ACKNOWLEDGEMENTS:

This report was prepared by the Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management. Authors are Environmental Analyst Lawrence Pistrang and Aquatic Biologists Jamie Carr and Joy Trahan-Liptak. The sampling station map was produced by GIS analyst Craig Fitzgerald. Internal review and comments were provided by Patricia Austin and Dan Crocker. Steve Sulprizio, Jamie Carr, Joy Trahan-Liptak, David Getman, and Nicole Keleher collected the samples and were responsible for all field measurements. Plankton samples were collected and analyzed by Jamie Carr and Joy Trahan-Liptak. Turbidity analysis was done by Steve Sulprizio with assistance from David Getman. All remaining lab analyses (bacteria, nutrients, other parameters) were done off-site by MWRA staff.

The DCR/DWSP Office of Watershed Management would like to once again thank the staff and management of the MWRA Deer Island Lab for preparing and delivering sample bottles and performing all nutrient and metal analyses during the year. They also thank the MWRA staff at the Southborough Lab for completing all routine and non-routine *E. coli* and fecal coliform analyses during the year.

WATER QUALITY REPORT: 2016
WACHUSETT RESERVOIR AND TRIBUTARIES

1.0 INTRODUCTION

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management manages and maintains a system of watersheds and reservoirs to provide pure water to the Massachusetts Water Resources Authority (MWRA), which in turn supplies drinking water to approximately 2.2 million people and thousands of industrial users in 51 communities.

The Federal Surface Water Treatment Rule requires filtration of all surface water supplies unless numerous criteria are met, including the development and implementation of a detailed watershed protection plan. The Division and the MWRA have a joint waiver from the filtration requirement and continue to aggressively manage the watershed in order to maintain this waiver. Water quality sampling and field inspections help identify tributaries with water quality problems, aid in the implementation of the most recent watershed protection plan, and ensure compliance with state and federal water quality criteria for public drinking water supply sources. Bacterial and nutrient monitoring of the reservoir and tributaries provide an indication of sanitary quality and help to protect public health. Division staff also sample to better understand the responses of the reservoir and its tributaries to a variety of physical, chemical, and biological inputs, and to assess the ecological health of the reservoir and the watershed.

Watershed tributaries and reservoirs comprise the two basic components of the water supply system. Each component requires a specialized program of monitoring activities and equipment suited to their unique characteristics and environmental settings.

Routine water quality samples for bacteria, specific conductance, turbidity, and temperature were collected from nineteen stations on eighteen tributaries. Nutrient samples were collected monthly from ten of these stations. Samples were occasionally collected from additional locations to investigate water quality problems discovered during environmental assessment investigations. Results from all tributary sampling are discussed in Section 3.0.

The Wachusett Reservoir was sampled 1-2 times per week to monitor plankton concentrations, predict potential taste and odor problems, and recommend algaecide treatment as needed. Temperature, pH, dissolved oxygen, chlorophyll *a*, and specific conductance profiles were measured weekly in conjunction with plankton sampling. Quarterly nutrient samples were collected in May, July, October, and December at three depths from three stations. Bacteria samples were collected monthly or more frequently from the reservoir surface to document the relationship between bacteria and roosting populations of waterfowl on the reservoir. Results from all reservoir monitoring efforts are discussed in Section 4.0.

All bacteria, nutrient, specific conductance, turbidity, plankton, precipitation and flow data for the past twenty-nine years are stored in an ACCESS database. All data generated during tributary and reservoir water quality testing in 2016 are discussed in sections 3.1 – 4.4 and are available upon request.

2.0 DESCRIPTION OF MONITORING PROGRAMS

Division staff collected routine water quality samples from nineteen stations on eighteen tributaries and from four stations on the Wachusett Reservoir in 2016. Stations are described in Tables 1 and 2 and sampling locations shown on Figures 1-3 on pages 3-6. Additional stations were sampled to support special studies or potential enforcement actions. Some samples were analyzed by Division staff including 711 turbidity samples and 179 reservoir phytoplankton samples. A total of 1360 physiochemical measurements (temperature and specific conductance) were done in the field at tributary stations, with another 50 water column profiles (temperature, specific conductance, dissolved oxygen, percent oxygen saturation, chlorophyll *a*, and pH) recorded from the reservoir. A total of 1400 bacteria samples were collected and delivered to the MWRA Southborough laboratory for either *E. coli* or fecal coliform analysis, and 146 samples were collected and shipped to the MWRA Deer Island laboratory for 1221 analyses of nutrients and other parameters.

2.1 TRIBUTARY MONITORING

Each tributary station was visited weekly or every other week throughout the entire year, although samples were not collected at some stations during low flow or no-flow conditions in the summer months. Temperature and specific conductance were field measured with a YSI Professional Plus conductivity meter. Discrete samples were collected for analysis of *E. coli* and measurement of turbidity. All *E. coli* samples were delivered to the MWRA Southborough Lab for analysis. Turbidity samples were analyzed at the DCR West Boylston Lab using a HACH 2100N meter.

Nutrient samples were collected monthly from ten stations (shown in Table 1) and analyzed at the MWRA Deer Island Lab for total phosphorus, ammonia, nitrate-nitrogen, nitrite-nitrogen, total Kjeldahl nitrogen, total organic carbon, total suspended solids, and UV-254. Reactive phosphorus (orthophosphate) samples were collected monthly and UV-254 samples were collected weekly from the Stillwater and Quinapoxet Rivers. All sample collections and analyses were done according to Standard Methods for the Examination of Water and Wastewater 22^{nd} Edition. Depth was recorded manually or using automated depth sensors at seven of the nutrient stations and flow calculated using rating curves developed and updated by Division Environmental Quality staff. Daily flow in Gates Brook and the Stillwater and Quinapoxet Rivers was obtained from continuous recording devices installed by the USGS, although no valid data were collected at the Gates Brook station after a four inch rain event on October 21 completely reconfigured the stream channel and buried the water quality probe. Repairs to the gaging station and the resumption of data collection are anticipated to occur in spring 2017.

Precipitation data from the NOAA weather station in Worcester and the USGS stations on the Stillwater River in Sterling and the Quinapoxet River in Holden were collected daily to help interpret water quality changes and determine if these were impacted by precipitation events.

All water quality data, flow data, and precipitation data are now regularly uploaded to both an ACCESS database and an Aquarius database, and reviewed and interpreted with the assistance of environmental analyst/database specialist Daniel Crocker.

Figure 1: Wachusett Watershed Tributary Sampling Stations

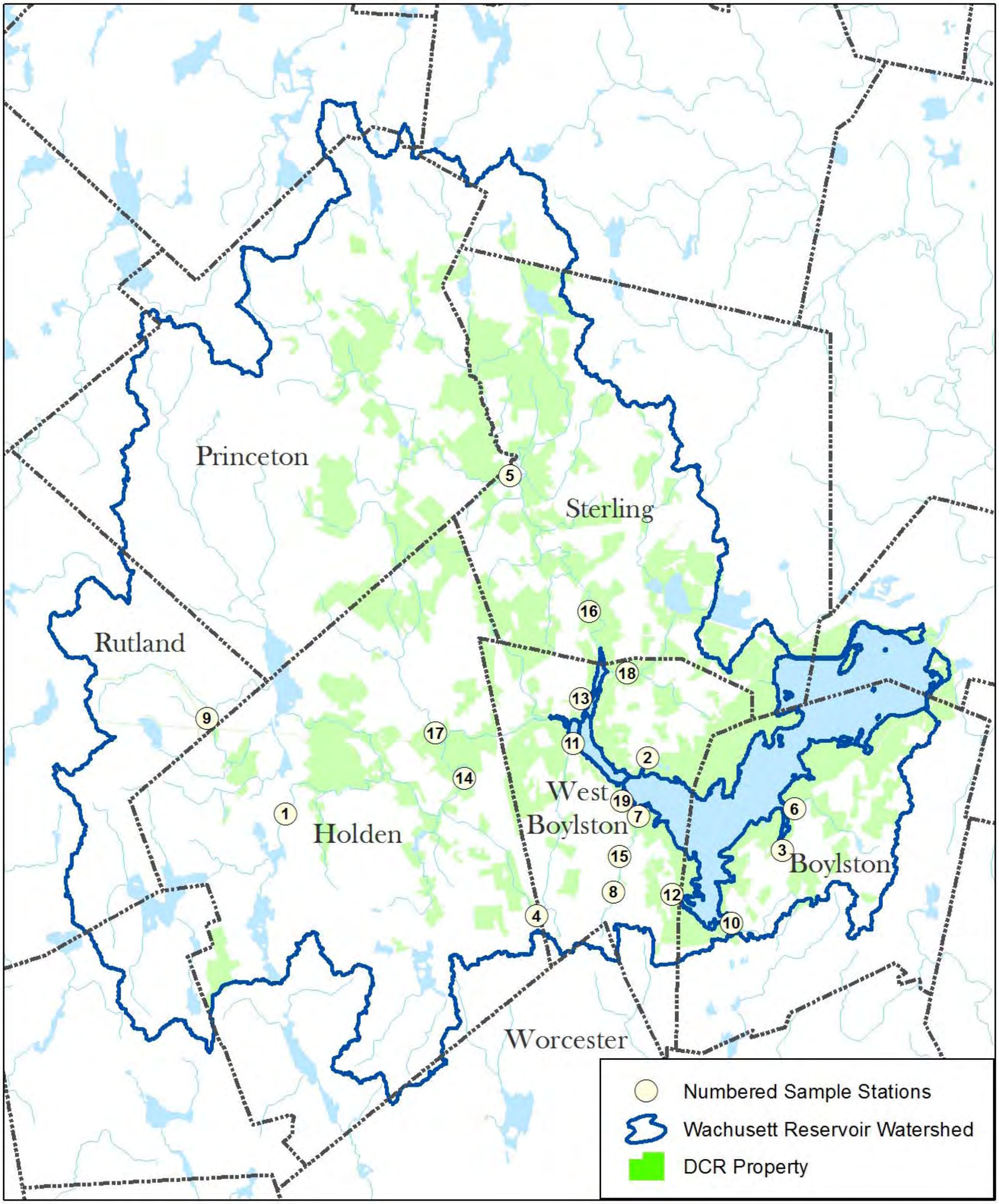


Table 1: Wachusett Tributary Sampling Stations (2016)

STATION	LOCATION	FREQUENCY
1. Asnebumskit Brook (Princeton)	upstream of Princeton Street, Holden	BW
2. Beaman Pond Brook (2)	Route 110, W. Boylston (homes)	BW
3. Boylston Brook	Route 70, Boylston	W
4. Cook Brook (Wyoming)	Wyoming Street, Holden	BW
5. East Wachusett Brook (140)	Route 140, Sterling	BW
6. French Brook (70)	Route 70, Boylston	W, M
7. Gates Brook (1)	Gate 25, West Boylston	W, M*
8. Gates Brook (4)	Pierce Street, West Boylston	W
9. Jordan Farm Brook	Route 68, Rutland	BW
10. Malagasco Brook	West Temple Street, Boylston	W, M
11. Malden Brook	Thomas Street, West Boylston	W, M
12. Muddy Brook	Route 140, W West Boylston	W, M
13. Oakdale Brook	Waushacum Street, West Boylston	BW
14. Quinapoxet River (Canada Mills)	Canada Mills, Holden	W*, M*
15. Scarlett Brook	Worcester Street, West Boylston	W
16. Stillwater River (SB)	Muddy Pond Road, Sterling	W*, M*
17. Trout Brook	Manning Street, Holden	BW, M
18. Waushacum Brook (Prescott)	Prescott Street, West Boylston	W, M
19. West Boylston Brook	Gate 25, West Boylston	W, M

W = weekly (bacteria, temperature, specific conductance, turbidity)
W* = weekly (bacteria, temperature, specific conductance, turbidity, and UV-254)
BW = biweekly (bacteria, temperature, specific conductance, turbidity)
M = monthly (nutrients) with weekly flow
M* = monthly (nutrients) with continuous flow

2.2 RESERVOIR MONITORING

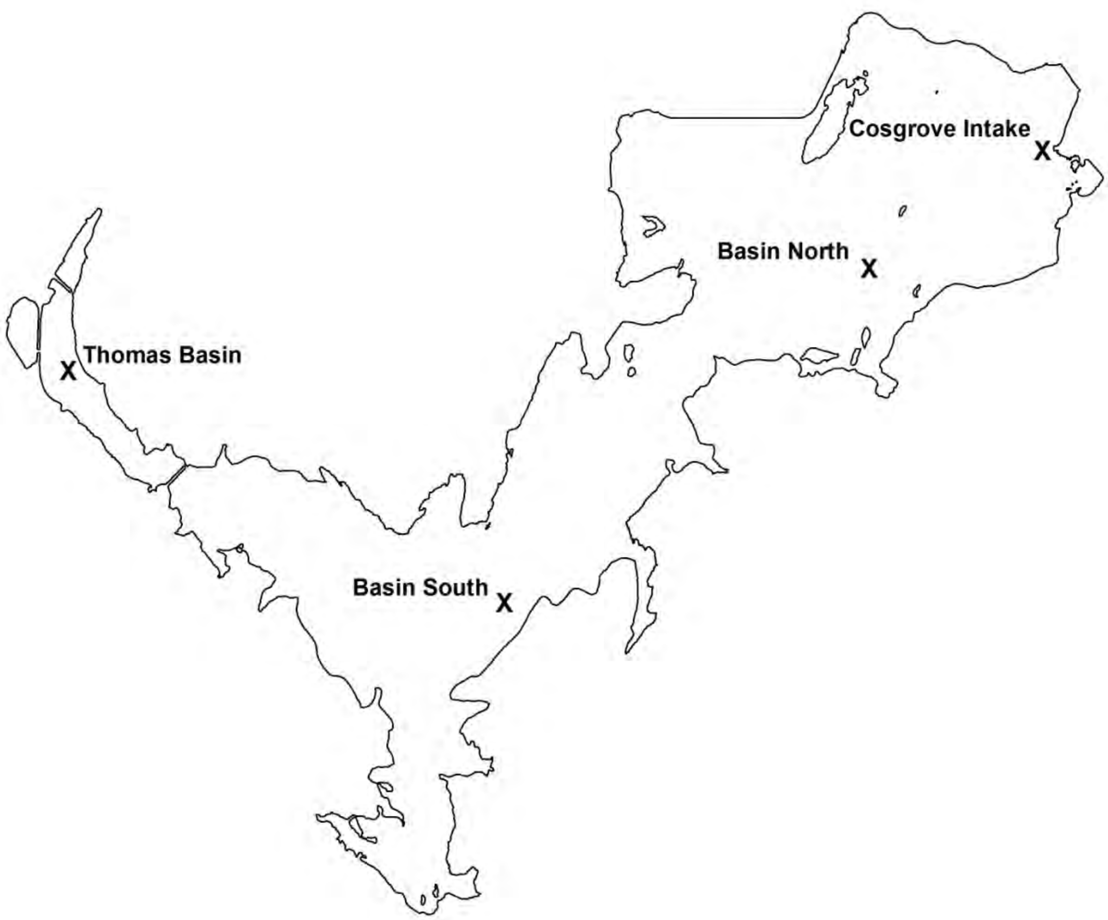
Temperature, specific conductance, chlorophyll *a*, dissolved oxygen concentration and percent saturation, and pH water column profiles were recorded weekly during stratified conditions at Station 3417 (Basin North) in conjunction with routine plankton monitoring. A full panel of nutrient samples was collected quarterly (May, July, October, December) at Station 3417 (Basin North), Station 3412 (Basin South) and Thomas Basin (See Table 2 and Figure 2 on the following page for locations). At each nutrient station, samples were collected from the epilimnion, metalimnion, and hypolimnion and analyzed for nitrate-nitrogen, ammonia-nitrogen, total Kjeldahl nitrogen, total phosphorus, silica, UV-254, and alkalinity. All samples were analyzed at the MWRA Lab at Deer Island (see Section 4.0 for complete discussion). Water column profiles were also recorded at each station during each nutrient sampling event.

Table 2: Wachusett Reservoir Sampling Stations (2016)

STATION	LOCATION	FREQUENCY
A. 3409 (Reservoir)	adjacent to Cosgrove Intake	W
B. 3417 (Reservoir – Basin North)	mid reservoir by Cunningham Ledge	W, Q
C. 3412 (Reservoir – Basin South)	mid reservoir off Scar Hill Bluffs	Q
D. Thomas Basin (Reservoir)	Thomas Basin	Q

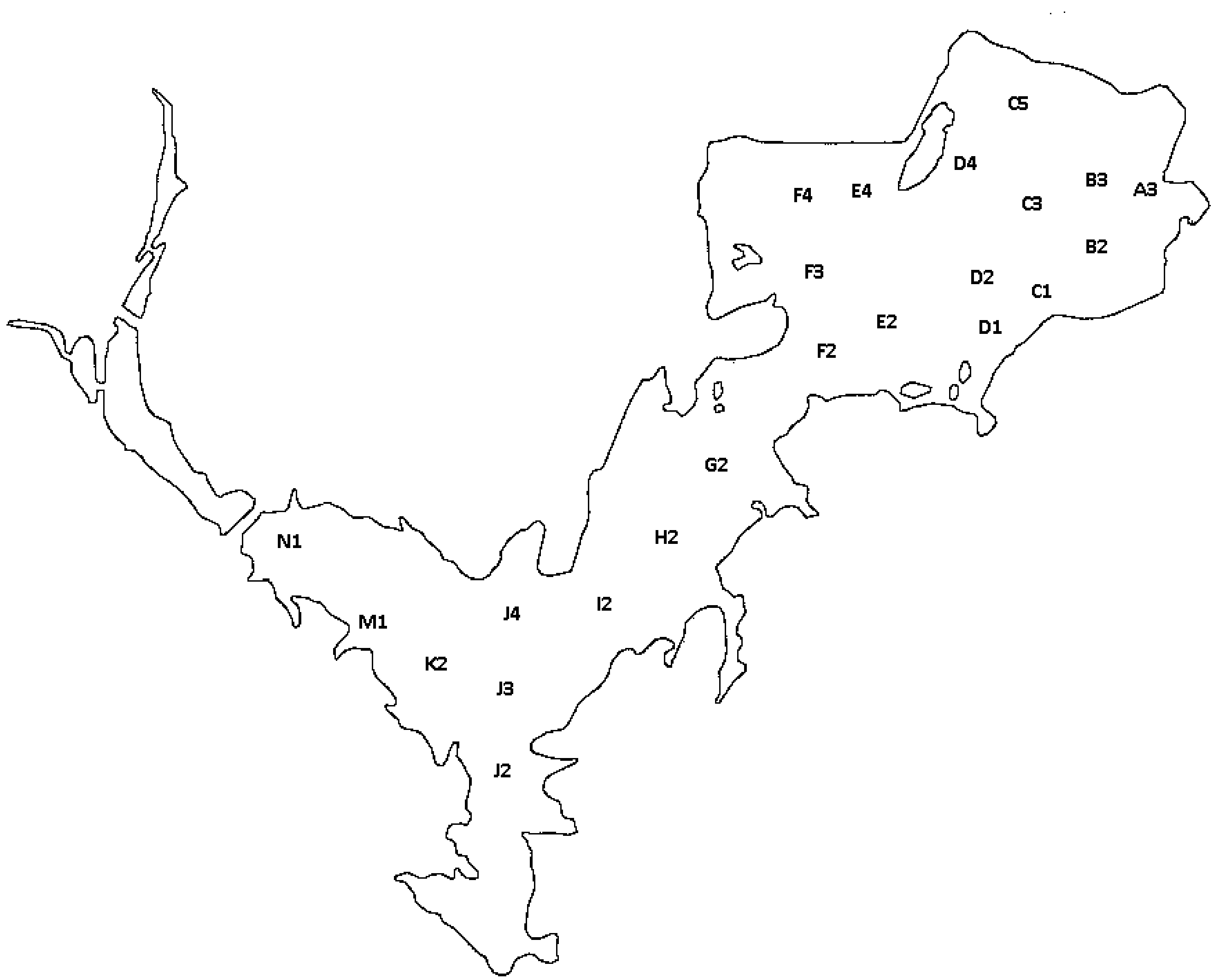
W = weekly (temperature, conductivity, plankton, and water column profiles at Cosgrove or 3417)
Q = quarterly (plankton, profiles, nutrients)

Figure 2: Reservoir Nutrient and Phytoplankton Sampling Stations



MWRA personnel collected a regulatory fecal coliform sample seven times per week from the John J. Carroll Water Treatment Plant at Walnut Hill in Marlborough. Division staff collected bacteria samples (fecal coliform January through May, *E. coli* June through December) twice in early January and late April, once per month though August, and then weekly for the remainder of the year from 23 reservoir surface stations shown below. Additional midweek samples were collected from mid-October through early November to document the impacts of an intensified bird harassment effort. No samples were collected from mid-January through mid-April due to ice cover.

Figure 3: Reservoir Transect Stations



3.0 RESULTS OF TRIBUTARY MONITORING PROGRAM

3.1 BACTERIA

The Massachusetts Class A surface water quality standards use *E. coli* as an indicator organism. The statutory limit is "a geometric mean not to exceed 126 *E. coli* colonies per 100 mL and with no single sample to exceed 235 colonies per 100 mL". The geometric mean of 126 colonies per 100 mL was only exceeded at a single station (Gates Brook 4) in 2016, the same as in 2015. The limit had been exceeded at Gates Brook 4 in 2010, at both Gates Brook 4 and Gates Brook 6 in 2011, and at Gates Brook 4, Gates Brook 6, and Oakdale Brook in 2012, but no stations had exceeded the geometric mean standard in 2013 or 2014 (Table 3).

All samples from Beaman Pond Brook, Cook Brook, and Trout Brook contained less than 235 MPN per 100 mL in 2016. Muddy Brook contained less than 235 MPN per 100 mL in 2015. Trout Brook and Waushacum Brook met this standard in 2014, and Cook Brook, Trout Brook, East Wachusett Brook, and Waushacum Brook met the standard in 2013. Every station had exceeded the single sample limit of 235 MPN per 100 mL in 2010, 2011, and 2012.

Table 3: *E. coli* (MPN/100 mL) in Wachusett Tributaries

STATION	GMEAN (2013)	GMEAN (2014)	GMEAN (2015)	GMEAN (2016)	%>235 (2013)	%>235 (2014)	%>235 (2015)	%>235 (2016)
Asnebumskit (Princeton)	40	52	105	54	10.0%	20.0%	38.1%	24.0%
Beaman Pond Brook 2	34	33	60	16	9.7%	6.7%	10.0%	**0.0%**
Boylston Brook	72*	26	48	40	24.2%	12.8%	18.8%	15.6%
Cook Brook (Wyoming)	18	34	26	22	**0.0%**	20.0%	15.8%	**0.0%**
East Wachusett (140)	11	19	26*	21	**0.0%**	8.0%	15.0%	4.6%
French Brook (70)	23	41	53	61*	4.0%	12.0%	14.6%	19.2%
Gates Brook (1)	26	31	39	37	14.0%	10.0%	15.2%	10.2%
Gates Brook (4)	90	110	**184**	**131**	28.0%	28.0%	39.1%	24.5%
Jordan Farm Brook	18	40	86*	18	4.4%	12.0%	35.3%	6.7%
Malagasco Brook	18	27	40	48*	6.0%	6.0%	14.3%	10.2%
Malden Brook	20	28	31	33	2.0%	6.0%	7.1%	6.1%
Muddy Brook	20	28	30	68*	2.0%	4.0%	**0.0%**	22.5%
Oakdale Brook	40	31	57	57	12.2%	12.0%	9.5%	20.0%
Quinapoxet River (C.Mills)	27	36	54*	49	4.0%	8.0%	9.5%	12.2%
Scarlett Brook	35	38	27	55*	12.0%	10.0%	14.3%	16.3%
Stillwater River (SB)	30	32	78*	50	6.0%	6.0%	21.4%	12.2%
Trout Brook	12	23	29*	15	**0.0%**	**0.0%**	19.1%	**0.0%**
Waushacum (Prescott)	19	34	42	53*	**0.0%**	**0.0%**	9.5%	25.0%
West Boylston Brook	56	82	50	80	14.0%	22.0%	16.7%	24.5%

*highest annual geometric mean (2007-2016)

Bacteria samples collected from the tributary stations during 2016 contained a wide range of *E. coli* concentrations, from less than 10 MPN/100mL in approximately fifteen percent of all samples to a high of 24,200 MPN/100mL in Malagasco Brook during a midsummer rainstorm. As in previous years, many of the highest concentrations were recorded during or following rain events of 0.20" or more. Nineteen of the twenty-five samples that exceeded 1000 MPN/100mL were collected during or immediately following wet weather. Only six samples that exceeded 1000 MPN/100mL were collected during dry weather, all from three stations during the summer and fall when flows were reduced and any contaminants present would have been concentrated.

Annual geometric mean concentrations of *E. coli* over the past four years appear to show a general trend towards declining water quality. This cannot be conclusively linked to specific pollution events or sources such as sewer releases, impacts from wildlife or domestic animals, or improper storage of manure because weekly concentrations of bacteria and annual statistics can vary greatly due to fluctuations in water temperature and in the amount, frequency, and timing of precipitation events. Annual variations in flow can also impact annual statistics. It is important to use care when comparing yearly data and usually better to look for longer term trends when assessing water quality, but some preliminary observations and conclusions can be made.

Annual geometric mean concentration of *E. coli* seems to be increasing at most stations. Geometric means at seven stations in 2016 were higher than during the previous year, even though *E. coli* concentrations in 2015 were uncharacteristically high at most locations (Table 3). Geometric means in 2016 were higher than the four year average geometric mean at 13 of 19 stations (Table 4). Annual geometric means at Malagasco and Scarlett Brooks were the highest recorded since the early 1990s, and were the highest ever recorded at French, Muddy, and Waushacum Brooks (Table 3). This was the third year in a row that French Brook recorded an historic high concentration. Both Muddy and Waushacum Brooks reached an historic maximum for the second year in a row.

This decline in water quality as measured by bacteria was not observed everywhere. Annual geometric means in Asnebumskit Brook (Princeton Street), other than in 2015, have been nearly unchanged for the past ten years and are considerably lower than recorded in 2006 and before. Water quality in Trout Brook has also been relatively consistent with annual geometric means of 12 to 29 MPN/100mL. Cook Brook bacteria concentrations have shown more variability but the annual geometric mean in 2016, the four year average, and the ten year average were nearly identical. Data from Jordan Farm Brook, other than in 2015, shows a clear improvement in water quality, and Beaman Pond Brook recorded an historic low annual geometric mean in 2016.

Source elimination may not be responsible for some of the apparent improvements described above. Sample collection in 2014, 2015, and 2016 was reduced to every other week at some stations including all four stations with improved water quality. Drought conditions in 2015 and 2016 greatly reduced stream flow during much of the summer and fall and further decreased sample numbers. Bacteria concentrations tend to be highest during this time of year, so the lack of samples could have artificially lowered the annual geometric mean. The 12 samples collected from Beaman Pond Brook in 2016 and the 15 samples collected from Jordan Farm Brook are not enough to make conclusive statements about apparent water quality improvements.

Table 4: *E. coli* Trends (MPN/100 mL) in Wachusett Tributaries

STATION	2016 GEOMETRIC MEAN	4 YEAR MEAN	10 YEAR MEAN
Asnebumskit (Princeton)	54	63	54
Beaman 2	16	36	50
Boylston Brook	40	47	36
Cook Brook (Wyoming)	22	25	25
East Wachusett (140)	21	19	18
French Brook (70)	61	45	35
Gates Brook (1)	37	33	35
Gates Brook (4)	131	129	130
Jordan Farm Brook	18	41	32
Malagasco Brook	48	33	29
Malden Brook	33	28	32
Muddy Brook	68	37	28
Oakdale Brook	57	46	55
Quinapoxet River (C.Mills)	49	42	40
Scarlett Brook	55	39	39
Stillwater River (SB)	50	48	43
Trout Brook	15	20	20
Waushacum (Prescott)	53	37	30
West Boylston Brook	80	67	69

The combined geometric mean of 711 routine samples collected from 19 stations on 18 tributaries during 2016 was 48 MPN/100mL, the highest recorded in the past decade. The combined geometric mean of 630 routine samples in 2015 was also 48 MPN/100mL. Annual combined geometric mean from these locations has been as low as 26 MPN/100mL but has averaged 38 MPN/100mL since 2008.

Although drought conditions can lead to the loss of flow in smaller tributaries and the collection of fewer samples during the summer and fall (resulting in better annual water quality), it can also lead to the concentration of existing contaminants in larger streams and rivers and a subsequent decline in annual water quality. Conclusive statements about water quality trends based on a comparison of yearly data are not appropriate without an in-depth analysis of seasonal and precipitation factors that extend over many years, along with a complete assessment of potential threats. A long-term in-depth analysis of water quality is beyond the scope of this annual report but will be the basis for a thirty year summary report (1988-2017) that will look for ongoing trends, changes related to specific watershed protection efforts including sewer expansion, and water quality impacts linked to seasonal patterns or precipitation events. Publication of this report is expected in 2019.

Regardless of number of samples collected or the timing, frequency, and magnitude of precipitation events, it is clear that water quality is almost always negatively impacted by unmanaged stormwater. Table 5 compares wet weather and dry weather metrics in Wachusett Watershed tributaries.

Table 5: Impacts of Rainfall on *E. coli* Concentrations (MPN/100 mL) in Wachusett Tributaries

STATION	GMEAN DRY	GMEAN WET	% <10 DRY	%<10 WET	%>235 DRY	%>235 WET
Asnebumskit (Princeton)	65	21	9.5%	25.0%	23.8%	25.0%
Beaman 2	19	7	30.0%	50.0%	0.0%	0.0%
Boylston Brook	24	126	31.8%	10.0%	9.1%	30.0%
Cook Brook (Wyoming)	22	19	25.0%	33.3%	0.0%	0.0%
East Wachusett (140)	26	5	15.8%	100.0%	5.3%	0.0%
French Brook (70)	40	150	9.4%	6.7%	6.3%	46.7%
Gates Brook (1)	27	71	27.3%	0.0%	3.0%	25.0%
Gates Brook (4)	91	277	3.0%	0.0%	15.2%	43.8%
Jordan Farm Brook	21	9	41.7%	66.7%	8.3%	0.0%
Malagasco Brook	38	79	9.1%	12.5%	6.1%	18.8%
Malden Brook	26	55	12.1%	0.0%	3.0%	12.5%
Muddy Brook	62	84	18.2%	12.5%	21.2%	25.0%
Oakdale Brook	76	13	9.5%	75.0%	23.8%	0.0%
Quinapoxet River (C.Mills)	40	75	12.1%	0.0%	6.1%	25.0%
Scarlett Brook	46	83	15.2%	12.5%	12.1%	25.0%
Stillwater River (SB)	39	84	15.2%	0.0%	12.1%	12.5%
Trout Brook	17	8	14.3%	50.0%	0.0%	0.0%
Waushacum (Prescott)	40	96	18.2%	6.7%	18.2%	40.0%
West Boylston Brook	56	167	15.2%	6.3%	21.2%	31.3%
ALL WACHUSETT TRIBS	39	78	15.9%	11.1%	10.9%	25.1%

*wet weather samples collected during or within 24 hours of >0.20" rainfall

The geometric mean and percentage of samples greater than 235 MPN/100mL of wet weather samples are much higher than those of dry weather samples at 12 of the 19 stations (Table 5). The remaining seven stations appear to have better water quality during wet weather than during dry weather, but this is likely an artifact of sampling due to the limited number of storm events during 2016. In each case only four or fewer wet weather samples were collected. Impacts from rain events are usually more obvious in subbasins with large areas of impervious surfaces or substantial agricultural operations, but recent improvements in stormwater management throughout the watershed appear to have reduced some of the negative effects. The geometric means of wet weather samples from some stations in 2012 were more than 20 times higher than geometric means of dry weather samples. Wet weather geometric means at stations in 2015 averaged five times higher than comparable dry weather geometric means, with the greatest differences noted at stations located in areas of dense residential development or agricultural activity. Data for all tributaries in 2016 show the average wet weather geometric mean to be only twice as high as the average dry weather geometric mean. Samples above the Massachusetts single sample statutory limit of 235 MPN/100mL remain more than twice as likely during wet weather than during dry weather. Additional efforts are necessary to address the remaining stormwater issues in the watershed.

Tributary water quality often shows clear seasonal differences. Bacteria concentrations tend to be lowest in the winter and spring (December through May), much higher in the summer (June through August), and often remain elevated during the fall (September through November). This is true for samples collected during dry weather as well as those collected during or following a storm event. Dry weather summer samples are nearly five times more likely to exceed the statutory limit of 235 MPN/100mL than dry weather winter samples. Wet weather samples collected during the summer are more than ten times more likely than wet weather winter samples to exceed the statutory limit (Table 6).

Table 6: Impacts of Season and Precipitation on *E. coli* in 2016

	# OF SAMPLES	% SAMPLES <10 MPN/100mL	% SAMPLES >235 MPN/100mL
ALL SAMPLES			
winter	142	20.4%	5.6%
spring	205	27.3%	4.4%
summer	179	3.4%	35.2%
fall	185	6.5%	14.6%
DRY SAMPLES			
winter	111	20.7%	5.4%
spring	126	34.1%	2.4%
summer	132	4.5%	23.5%
fall	135	5.9%	11.1%
WET SAMPLES			
winter	31	19.4%	6.5%
spring	79	16.5%	7.6%
summer	47	0.0%	68.1%
fall	50	8.0%	24.0%

Bacteria concentrations tend to be lowest during the winter and spring months (December through May) with wet weather geometric means about 2-5 times higher than dry weather geometric means (Table 7), although wet weather and dry weather geometric means have been unusually similar during the winter and spring of both 2015 and 2016. Summer concentrations are generally much higher, either due to low flow conditions that concentrate pollutants or large storm events that increase source loading, but wet weather geometric means remain about 2-5 times higher than dry weather geometric means. The wet weather geometric mean in 2016 was five times higher than the dry weather geometric mean. Fall concentrations are much more variable and dependent upon the amount and timing of precipitation. Differences between wet weather geometric mean and dry weather geometric mean are usually much more pronounced in the fall than in other seasons (as much as 19 times higher), although this was not the case in 2016. The geometric mean of wet weather fall samples was less than twice as high as dry weather fall samples.

Table 7: Seasonal Effect on *E. coli* Geometric Mean Concentration (MPN/100 mL)

	WINTER	SPRING	SUMMER	FALL
geometric mean (2010)	19	20	124	59
geometric mean (2011)	23	27	100	39
geometric mean (2012)	24	29	93	42
geometric mean (2013)	17	24	68	25
geometric mean (2014)	20	24	79	48
geometric mean (2015)	20	18	134	50
geometric mean (2016)	24	22	159	60
geometric mean – dry (2010)	17	17	77	41
geometric mean – dry (2011)	18	21	80	24
geometric mean – dry (2012)	20	17	69	29
geometric mean – dry (2013)	19	19	55	26
geometric mean – dry (2014)	15	18	59	35
geometric mean – dry (2015)	18	19	83	38
geometric mean – dry (2016)	22	18	103	51
geometric mean – wet (2010)	47	35	235	255
geometric mean – wet (2011)	74	59	253	466
geometric mean – wet (2012)	108	96	179	300
geometric mean – wet (2013)	8	61	109	23
geometric mean – wet (2014)	47	59	137	149
geometric mean – wet (2015)	29	12	333	280
geometric mean – wet (2016)	34	31	535	94

Numerous possible sources of bacteria and increased likelihood of short-term weather variations make it difficult to interpret changes in water quality parameters over the short term, but reliable data from Wachusett watershed tributaries extend over nearly thirty years and long term trends suggest that conditions at most locations remain stable or have improved. Although concentrations of bacteria are sometimes elevated as in 2016, if tributary flow is reduced the total bacterial load may actually be lower than normal.

3.2 FLOW

Flow monitoring has been done at a number of locations throughout the watershed for more than two decades using both manual and automated measurements. The USGS was responsible for the development and maintenance of stage/discharge relationships at these sites, but occasional shifts to stream channels plus an extended period with very infrequent field visits led to questions about the accuracy of the data. The USGS continues to operate three stations using continuous monitoring, but responsibility for all other sites was transferred to the Division towards the end of 2011.

Manual measurements of stream depth are made weekly at seven stations using visual observation of staff gages. Six stations have been monitored for many years; documentation of flow in Trout Brook began in 2014. Direct measurement of flow at a range of depths is usually done several times during the year using a FlowTracker handheld acoustic Doppler velocity meter to develop and calibrate accurate stage-discharge relationships. Reliable stage-discharge relationships at five stations allow the use of easily acquired stream depths to quickly estimate flow, although stage-discharge relationships at Muddy Brook and Trout Brook remain under development and estimates of flow for these tributaries is not available.

Three other stations utilize continuous monitoring equipment maintained by the USGS to collect and transmit real time data every 10-15 minutes. Continuous data from the Stillwater and Quinapoxet Rivers have been collected since 1994. Stage data from Gates Brook were collected manually from 1994 until December 2011 when a flow monitoring sensor was installed. Continuous monitoring equipment now collects and transmits real time data every ten minutes, although installation of a new bridge prevented measurements for four months in 2014 and a major storm in October 2016 altered the channel and buried the water quality probe. The downstream control structure needs to be reconstructed and data collection apparatus repaired. Real time flow data will be unavailable at this site until the work is completed and a new stage-discharge relationship developed, although the USGS has generated estimated flow data for the final two months of 2016.

Table 8: Daily Flow Rate and Monthly and 2016 Annual Discharge Volume in Wachusett Tributaries

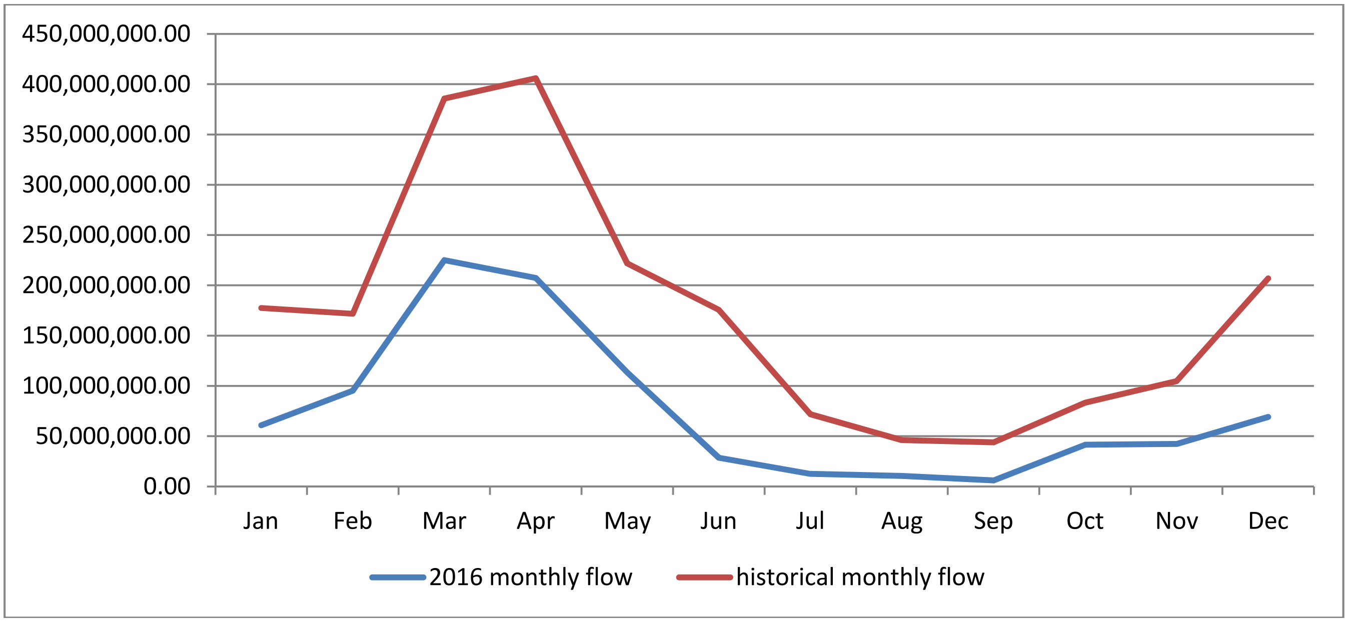
	day max	day min	day mean	month max total	month min total	yearly total
QUINAPOXET	197 cfs	1.5 cfs	28.9 cfs	225 million ft^3	6.0 million ft^3	912 million ft^3
STILLWATER	358 cfs	0.61 cfs	28.0 cfs	192 million ft^3	2.4 million ft^3	887 million ft^3
GATES	29 cfs	0.52 cfs	3.3 cfs	13.0 million ft^3	3.2 million ft^3	*87 million ft^3
WAUSHACUM	55.6 cfs	0.14 cfs	6.1 cfs	71.2 million ft^3	437,400 ft^3	205 million ft^3
W. BOYLSTON	3.4 cfs	0.06 cfs	0.30 cfs	3.8 million ft^3	147,700 ft^3	10.3 million ft^3
MALAGASGO	7.5 cfs	0.07 cfs	0.81 cfs	10.3 million ft^3	255,400 ft^3	26.5 million ft^3
MALDEN	13.3 cfs	0.51 cfs	2.0 cfs	29.8 million ft^3	1.7 million ft^3	84.2 million ft^3
FRENCH	35.8 cfs	0.01 cfs	3.3 cfs	50.2 million ft^3	154,800 ft^3	116 million ft^3

*10 months only

Daily flows vary widely at all locations and illustrate the need for regular and frequent flow monitoring (Table 8). Daily flows in the tributaries ranged from near zero to more than 350 cfs. Mean daily flows are usually 1-5 cfs in most tributaries but much higher in the two rivers. Continuous depth measurements using HOBO water level data loggers should provide much better information in 2017 and beyond and will include information from storm events. Preliminary data collection has been very successful and protocols have been developed that may allow monitoring of flow even during very cold weather in winter.

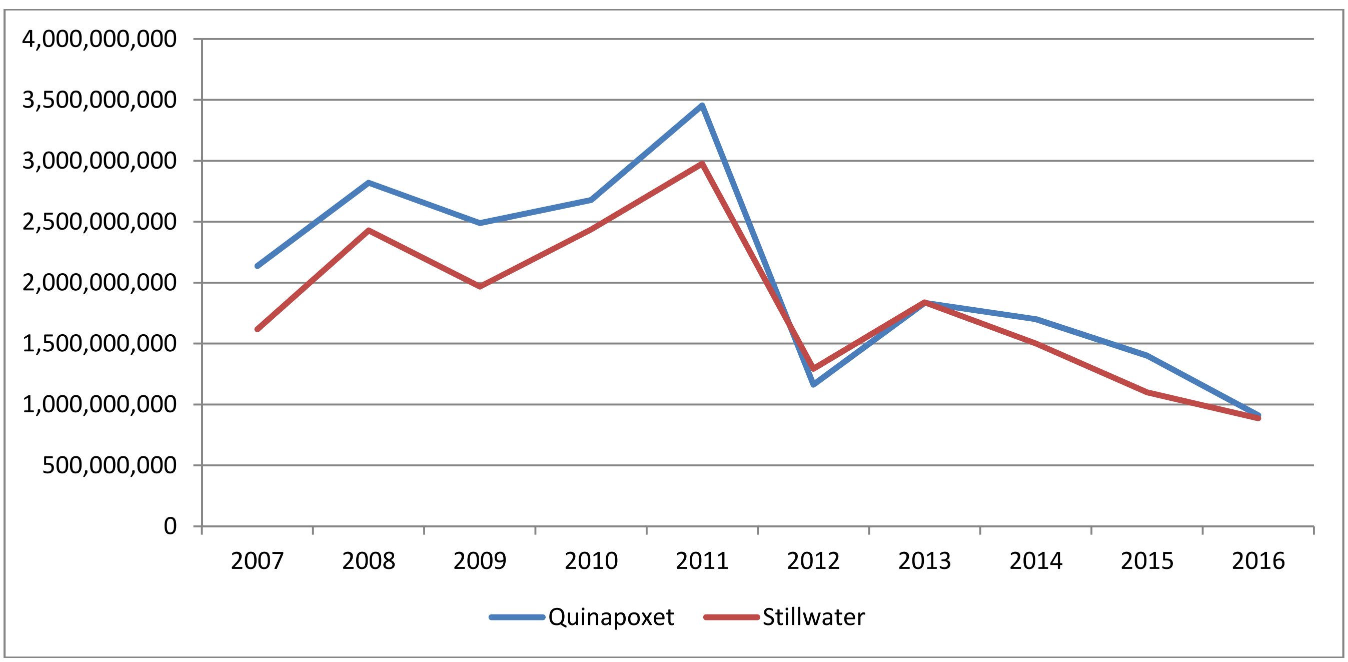
Lower than normal flow volumes were recorded from most tributaries throughout 2016 due to below average annual rainfall amounts.

Figure 4: Monthly Flow in the Quinapoxet and Stillwater Rivers (cubic feet)



Total annual flow has been below normal for the past five years as illustrated below.

Figure 5: Annual Flow in the Quinapoxet and Stillwater Rivers (cubic feet)



3.3 NUTRIENTS

Samples for nitrate-nitrogen, nitrite-nitrogen, ammonia, total Kjeldahl nitrogen, total phosphorus, total organic carbon, total suspended solids, and UV-254 were collected monthly from ten tributary stations with available flow data and analyzed at the MWRA Deer Island Lab using methods with low detection limits. Orthophosphate samples and UV-254 samples were collected weekly from the Quinapoxet and Stillwater Rivers. Samples were preserved according to standard methods.

High concentrations of nitrates can cause significant water quality problems including dramatic increases in aquatic plant growth and changes in the plants and animals that live in aquatic environments. High concentrations eventually lead to changes in dissolved oxygen and temperature. Excess nitrates can become toxic to warm-blooded animals at very high concentrations (10 mg/L) or higher) but never reach these values in the Wachusett watershed. Sources of nitrates include runoff from agricultural sites and fertilized lawns, failing on-site septic systems, atmospheric deposition, and some industrial discharges.

Annual mean nitrate-nitrogen concentrations in the ten tributaries ranged from 0.019 mg/L NO_3-N to 1.22 mg/L NO_3-N (Table 9), with individual measurements from below detection to 1.38 mg/L NO_3-N. Nitrate concentrations in West Boylston Brook are higher than in other brooks but considerably lower than they were ten years ago. Concentrations in Gates Brook continue to decline as well.

Table 9: Nitrate-Nitrogen Annual Mean Concentrations – Wachusett Tributaries (mg/L)

STATION	Muddy	French	Gates	Malagas	Malden	Waush	W. Boyl	Still	Quin	Trout
ave2016	0.139	0.153	0.76	0.615	0.443	0.022	1.20	0.122	0.208	0.097
ave2015	0.134	0.093	0.79	0.704	0.534	0.053	1.25	0.155	0.291	0.107
ave2014	0.135	0.167	0.86	0.583	0.443	0.045	1.14	0.136	0.251	n/s
ave2013	0.144	0.159	0.92	0.709	0.550	0.040	1.39	0.163	0.259	n/s
ave2012	0.098	0.127	0.80	0.489	0.432	0.036	1.17	0.140	0.222	n/s
ave2011	0.089	0.154	0.93	0.426	n/s	n/s	1.09	0.156	0.185	n/s
ave2010	0.105	0.135	1.01	0.634	0.471	n/s	1.57	0.156	0.256	n/s
ave2009	0.072	0.105	1.03	0.504	0.403	n/s	1.25	0.122	0.196	n/s
ave2008	0.132	0.071	1.04	0.513	0.452	n/s	1.69	0.146	0.321	n/s
ave2007	0.113	0.094	1.10	0.735	0.423	n/s	2.05	0.178	0.325	n/s

Ammonia was detected in all tributaries with most annual mean concentrations comparable to those recorded during the previous nine years (Table 10). Historic lows were seen in Muddy Brook, French Brook, Malden Brook, Waushacum Brook, Trout Brook, and the Stillwater and Quinapoxet Rivers.

Table 10: Ammonia-Nitrogen Annual Mean Concentrations – Wachusett Tributaries (mg/L)

STATION	Muddy	French	Gates	Malagas	Malden	Waush	W. Boyl	Still	Quin	Trout
ave2016	0.060	0.018	0.013	0.012	0.005	0.010	0.016	0.006	0.010	0.006
ave2015	0.078	0.041	0.015	0.029	0.016	0.023	0.021	0.011	0.021	0.012
ave2014	0.067	0.034	0.014	0.015	0.009	0.025	0.049	0.012	0.017	n/s
ave2013	0.065	0.051	0.008	0.013	0.006	0.014	0.014	0.007	0.012	n/s
ave2012	0.069	0.045	0.007	0.014	0.011	0.019	0.013	0.008	0.012	n/s
ave2011	0.066	0.039	0.005	0.016	n/s	n/s	0.022	0.010	0.015	n/s
ave2010	0.061	0.120	<0.005	0.010	0.010	n/s	0.012	0.011	0.014	n/s
ave2009	0.077	0.068	0.005	0.018	0.017	n/s	0.015	0.015	0.015	n/s
ave2008	0.068	0.061	0.008	0.014	0.025	n/s	0.014	0.012	0.013	n/s
ave2007	0.079	0.112	0.009	0.015	0.024	n/s	0.039	0.017	0.016	n/s

Total Kjeldahl nitrogen is the sum of ammonia-nitrogen plus organically bound nitrogen but does not include nitrate-nitrogen or nitrite-nitrogen. Analysis for total Kjeldahl nitrogen began in 2015. The highest annual mean concentrations were recorded from French, Malagasco, Waushacum, and Trout Brooks (Table 11). The highest individual measurement in 2016 was from French Brook in June.

Table 11: Total Kjeldahl Nitrogen Mean/Max/Min Concentrations – Wachusett Tributaries (mg/L)

STATION	Muddy	French	Gates	Malagas	Malden	Waush	W. Boyl	Still	Quin	Trout
ave2016	0.227	0.356	0.210	0.342	0.218	0.361	0.188	0.266	0.288	0.310
ave2015	0.252	0.391	0.148	0.351	0.231	0.281	0.174	0.206	0.290	0.257
max2016	0.533	0.723	0.454	0.641	0.488	0.571	0.429	0.502	0.536	0.458
max2015	0.518	0.672	0.276	0.642	0.511	0.376	0.307	0.300	0.785	0.285
min2016	<0.01	0.181	0.121	<0.01	<0.01	0.168	0.103	0.136	0.195	0.117
min2015	0.106	0.255	<0.10	<0.10	0.106	0.135	<0.10	0.160	0.161	0.229

Nitrite-nitrogen was rarely detected. The highest recorded concentration was only 0.007 mg/L and only four of the 120 samples collected in 2016 contained more than the detection limit of 0.005 mg/L.

Phosphorus is an important nutrient, and the limiting factor controlling algal productivity in Wachusett Reservoir. Sources of phosphorus include fertilizers, manure, and organic wastes in sewage. Water Quality Criteria established by the EPA recommend a concentration of no more than 0.05 mg/L of total phosphorus in tributary streams in order to prevent accelerated eutrophication of receiving water bodies. Concentrations measured in ten Wachusett tributaries during 2016 ranged from less than 0.005 mg/L to 0.086mg/L total P, with annual mean concentrations from 0.017 mg/L to 0.038 mg/L (Table 12). All annual mean concentrations were comparable to the previous eight years. Only 10% of the 120 samples collected in 2016 exceeded the recommended maximum concentration of 0.05 mg/L. Half of those were collected on a single day in February following a rain event of more than two inches and the others were collected in June, July, and August following a day of thunderstorms.

Table 12: Total Phosphorus Annual Mean Concentrations – Wachusett Tributaries (mg/L)

STATION	Muddy	French	Gates	Malagas	Malden	Waush	W. Boyl	Still	Quin	Trout
ave2106	0.020	0.029	0.017	0.025	0.019	0.026	0.018	0.019	0.021	0.038
ave2015	0.018	0.032	0.015	0.038	0.024	0.022	0.021	0.019	0.024	0.050
ave2014	0.019	0.031	0.025	0.034	0.025	0.025	0.037	0.018	0.020	n/s
ave2013	0.021	0.032	0.017	0.027	0.018	0.023	0.019	0.015	0.017	n/s
ave2012	0.027	0.049	0.025	0.044	0.028	0.029	0.035	0.023	0.027	n/s
ave2011	0.024	0.036	0.017	0.042	n/s	n/s	0.044	0.019	0.017	n/s
ave2010	0.015	0.055	0.013	0.026	0.019	n/s	0.016	0.016	0.017	n/s
ave2009	0.017	0.033	0.017	0.045	0.030	n/s	0.022	0.012	0.013	n/s
ave2008	0.013	0.038	0.020	0.055	0.027	n/s	0.035	0.016	0.024	n/s
ave2007	0.015	0.041	0.018	0.027	0.020	n/s	0.025	0.021	0.073	n/s

Total suspended solids are those particles suspended in a water sample retained by a filter of 2μm pore size. These particles can be naturally occurring or might be the result of human activities. Total suspended solids in Wachusett tributaries ranged from <5.0 mg/L to 46.5 mg/L, but only 14 of 120 samples contained more than the detection limit and all were collected during or shortly after a rain event. Total suspended solids are not considered a parameter of concern except during storm events when measurements in excess of 100 mg/L are not uncommon.

Total organic carbon (TOC) and UV-254 measure organic constituents in water, and are a useful way to predict precursors of harmful disinfection byproducts. TOC in the tributaries ranged from 1.08 to 22.5 mg/L, with an overall mean of 4.73 mg/L, similar to 2015 and about 10% lower than 2014. The highest concentrations were again recorded from Malagasco and Trout Brooks, with the lowest concentrations from Malden Brook and West Boylston Brook.

Measurements of UV-254 were comparable to TOC measurements. Organic compounds such as tannins and humic substances absorb UV radiation and there is a strong correlation between UV absorption and organic carbon content. The highest UV-254 readings were from Malagasco Brook and Trout Brook, and the lowest were from Malden Brook and West Boylston Brook.

Reactive phosphorus (orthophosphate) samples were collected monthly from the Stillwater and Quinapoxet Rivers to determine if conditions were conducive to the growth of the invasive diatom *Didymosphenia geminate* (Didymo). Blooms of Didymo are unlike other algal blooms because they have been associated with nutrient-poor waters and many blooms have occurred in stream habitats generally considered pristine. While Didymo was formerly considered to have narrow ecological tolerances, it has now been found in streams that exhibit a wide range of chemical characteristics. Didymo is capable of growing throughout most of the year in streams with low to high nitrate-nitrogen concentrations and a wide range of water temperatures, but still occurs most frequently in waters with low concentrations of reactive phosphorus.

Concentrations of reactive phosphorus in 2016 ranged from 0.0012 mg/L to 0.0167 mg/L, with annual average values of 0.0076 mg/L (Stillwater River) and 0.0094 mg/L (Quinapoxet River). Annual metrics were all lower than those recorded over the previous three years. This suggests that conditions are optimal for the presence of Didymo and monitoring efforts should be continued.

Loading estimates for nitrate-nitrogen, ammonia, nitrite-nitrogen, total Kjeldahl nitrogen, total organic carbon, total phosphorus, and total suspended solids in the Stillwater and Quinapoxet Rivers were calculated by multiplying daily flow (cu ft) by concentration (mg/L), multiplying by a unit conversion factor for daily load in kilograms, and then summing all daily totals to obtain an annual load based on monthly sampling (Table 13). Concentrations measured on the most recent previous sampling date were used for the calculations. Nutrient loading estimates did not address short term changes in flow and concentration that occurred during storm events. Almost all samples collected for nitrite-nitrogen and total suspended solids contained concentrations less than the detection limit and limited loading information for those parameters was developed.

Table 13: Annual Nutrient Loading – Wachusett Tributaries (kg)

STATION	NO3	NH3	TKN	TOC	TP
Quinapoxet	5446	224	7587	134,619	581
Stillwater	2807	128	7762	118,933	691

Annual loads of all parameters in the Quinapoxet River were less than in 2015. This was also true for ammonia and nitrate in the Stillwater River, but loads of total Kjeldahl nitrogen, total organic carbon, and total phosphorus all increased in 2016. Differences in estimated loads are usually the result of changes in flows rather than in concentrations, but flows were reduced in 2016. Any increases in annual concentrations should be investigated.

Annual loads from Gates Brook were not calculated due to a lack of flow data measured during the final two months of the year and problems with estimated flow data generated by the USGS.

Time-series loading estimates for nutrients and sediment were generated from flow data and monthly concentrations using the FLUX software program. Input data were analyzed using regression options that best matched sample data distribution to compute solute flux over the period of interest. Concentration and load estimates were calculated on a daily time step and then analyzed for residuals so that stratification schemes could be tested for improving model performance. Any outliers that unreasonably influenced load estimates were removed.

Nutrient loads generated by the FLUX software program for most parameters were similar to those estimated using the less rigorous methods described above. Annual total suspended solids estimates seem to show the most variability, not surprising as most samples contained concentrations below the detection limit. Monthly sampling at times greatly overestimated or greatly underestimated total suspended solids loads when compared to FLUX estimates (Table 14).

Table 14: Annual Nutrient Loading (FLUX estimate vs monthly samples) – Wachusett Tributaries (kg)

STATION	PARAMETER	FLUX 2015	MONTHLY 2015	FLUX 2016	MONTHLY 2016
Quinapoxet	total inorganic N	9916	12,334	6287	5670
Stillwater	total inorganic N	4776	5691	3961	2935
Quinapoxet	total N	21,109	24,060	13,460	13,257
Stillwater	total N	10,248	11,264	10,181	10,697
Quinapoxet	total phosphorus	900	801	595	581
Stillwater	total phosphorus	598	533	594	691
Quinapoxet	TSS	138,468	114,000	92,068	112,577
Stillwater	TSS	92,380	107,500	114,886	179,760

Total nitrogen concentrations in the Stillwater River are nearly unchanged over the past five years, but estimated total nitrogen load has trended lower (Figure 6) due to the reduction in annual stream flow during the lengthy drought. Inorganic nitrogen concentrations in the Stillwater River appeared to increase during the same period, but flow remains the key driver and loads of inorganic nitrogen decreased (Figure 7). Both total phosphorus (Figure 8) and total suspended solids exhibited a reduction in both concentrations and loads. The same patterns were observed in the Quinapoxet River for total nitrogen, inorganic nitrogen, total phosphorus, and total suspended solids

Figure 6: Stillwater River Total Nitrogen Load (kg) and Concentration (mg/L)

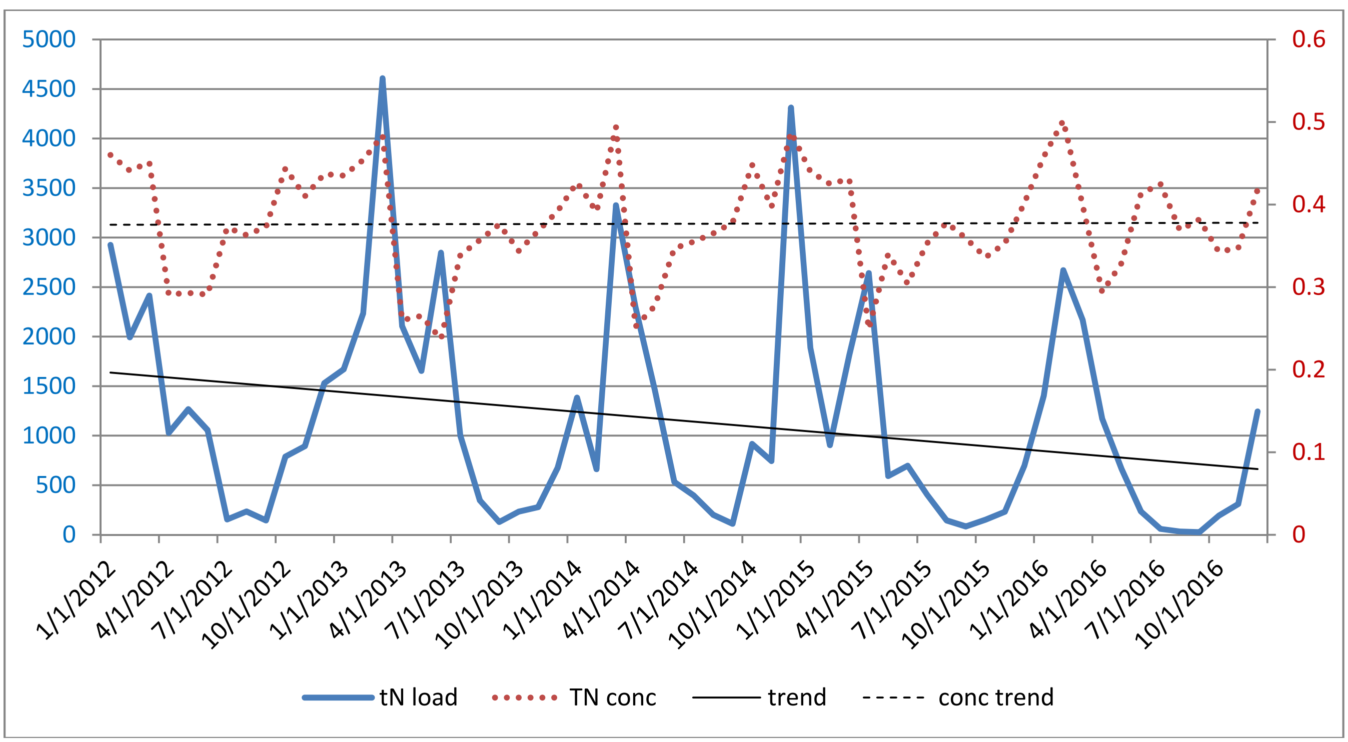


Figure 7: Stillwater River Total Inorganic Nitrogen Load (kg) and Concentration (mg/L)

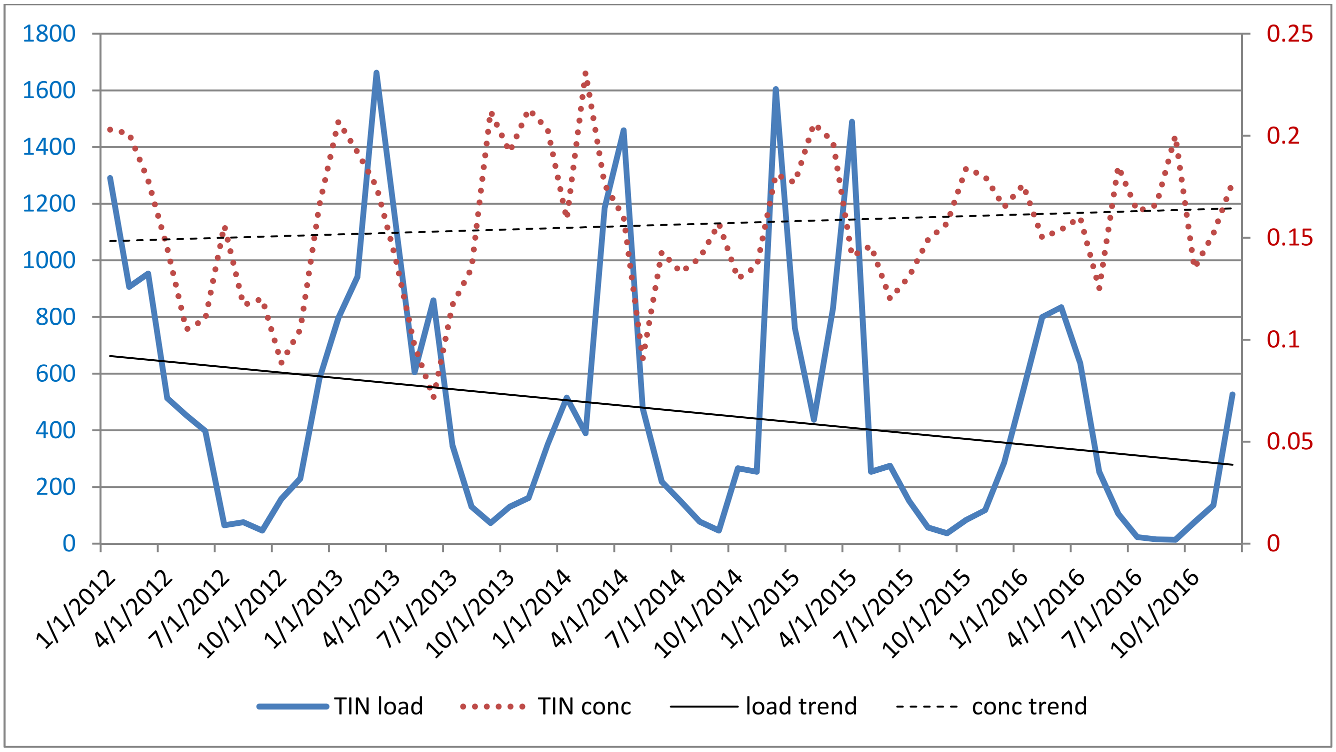
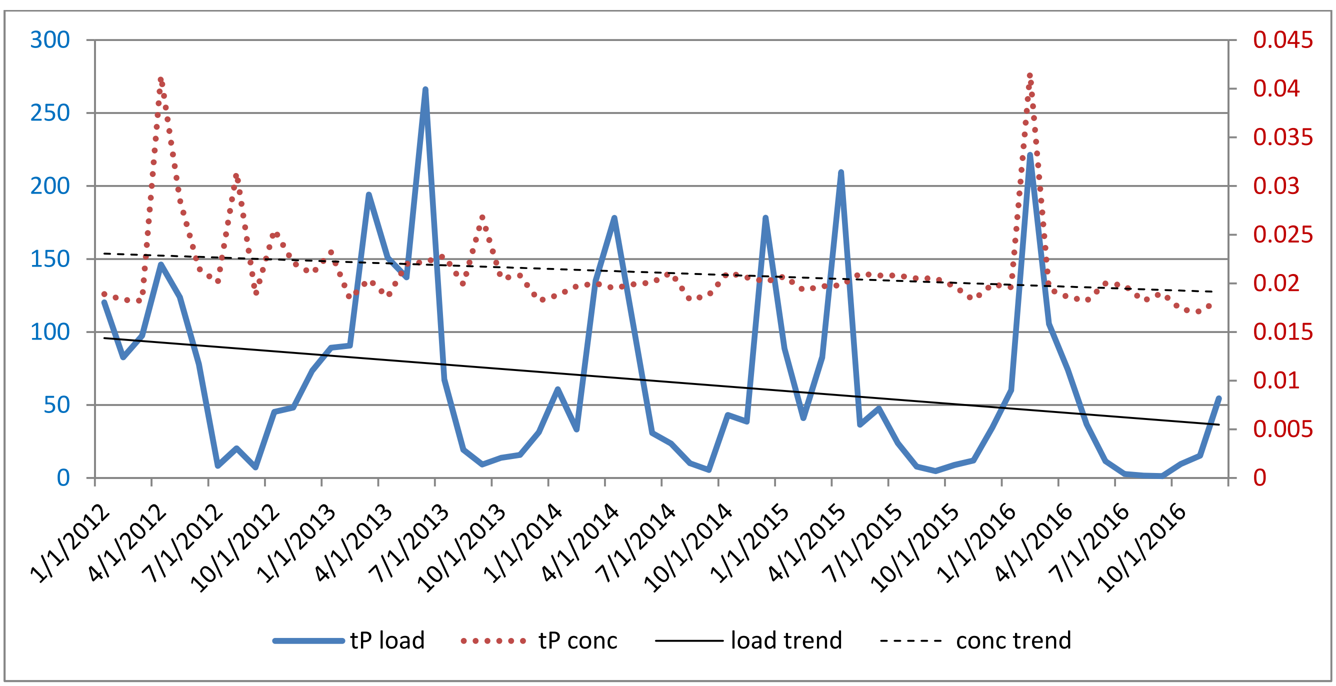


Figure 8: Stillwater River Total Phosphorus Load (kg) and Concentration (mg/L)



Samples from the Stillwater River collected in 2015 and 2016 usually contained more organic nitrogen than inorganic nitrogen (60:40). Forms of nitrogen in the Quinapoxet River were evenly divided over the past two years (50:50) although there was a slight shift towards organic nitrogen in 2016.

Figure 9: Stillwater River Nitrogen Load (% of inorganic and organic forms)

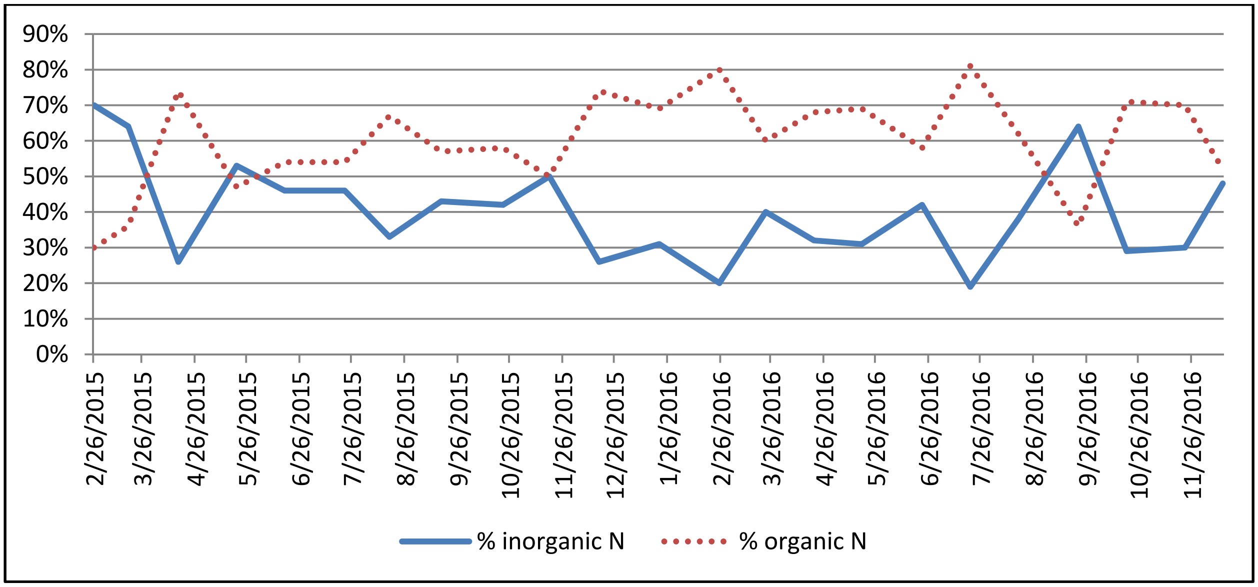
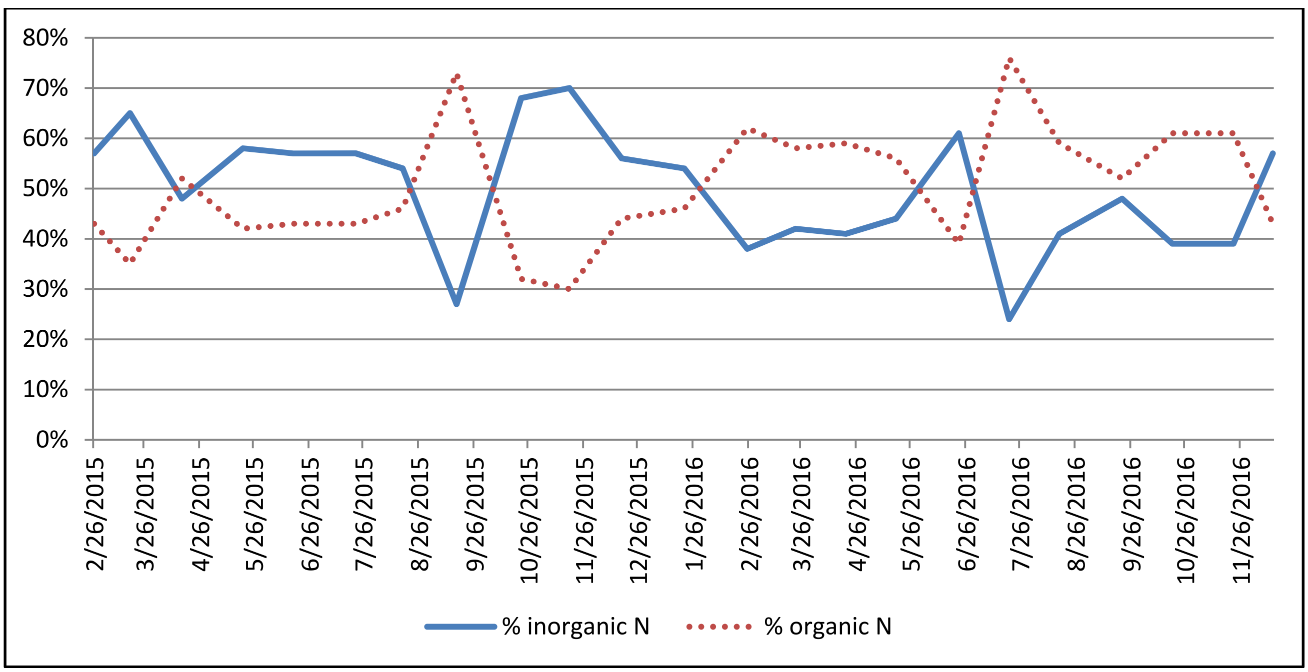


Figure 10: Quinapoxet River Nitrogen Load (% of inorganic and organic forms)



3.4 SPECIFIC CONDUCTANCE

Fresh water systems contain small amounts of mineral salts in solution. Specific conductance is a measure of the ability of water to carry an electric current, dependent on the concentration and availability of these ions. Elevated conductivity levels indicate contamination from stormwater or failing septic systems, or can be the result of watershed soil types.

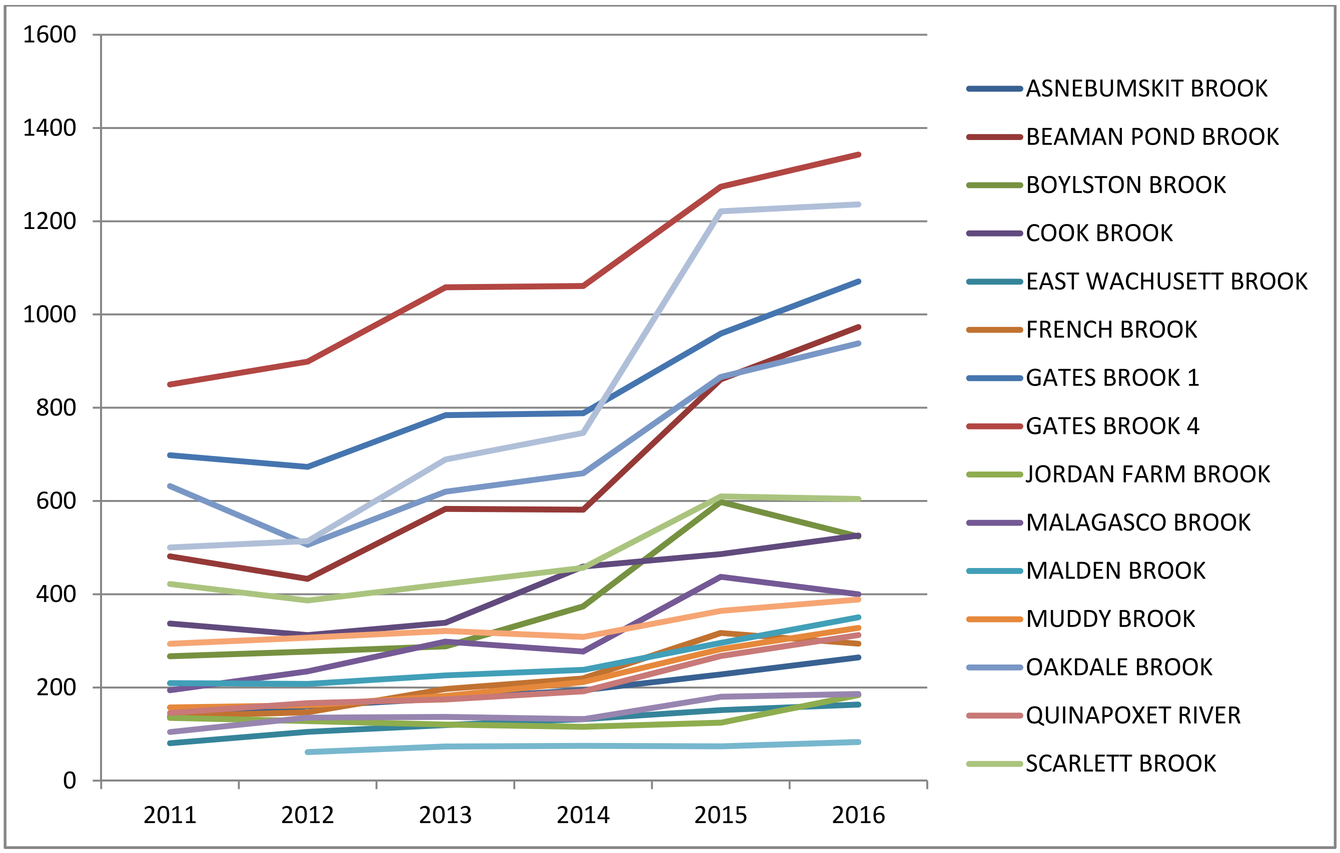
Specific conductance was measured weekly or biweekly at all nineteen tributary stations. Values of less than 100 μmhos/cm were recorded in three quarters of all samples from Trout Brook (19 of 25) but nowhere else. Measurements greater than 1000 μmhos/cm were recorded in 82% of samples from West Boylston Brook and the two stations on Gates Brook, but only in 3% of samples from all other stations. The three highest recorded values (2152 μmhos/cm, 3499 μmhos/cm, 3913 μmhos/cm) were measured at West Boylston Brook and two stations on Gates Brook following a mixed precipitation event in mid-December. Some but not all of the other samples with high specific conductance were collected during summer storm events or during low flow conditions.

Table 15: Annual Median Specific Conductance in Wachusett Tributaries (μmhos/cm)

STATION	2011	2012	2013	2014	2015	2016
Asnebumskit (Princeton)	135.9	159.8	176.7	193.9	228.1	264.4
Beaman 2	481.4	432.8	583	581	861	973
Boylston Brook	266.8	276.7	288.0	374.0	598	524
Cook Brook (Wyoming)	337.0	312.5	338.7	459.3	486.2	526
East Wachusett (140)	80.5	104.9	119.1	131.8	151.5	163.3
French Brook (70)	138.0	146.7	196.9	219.6	317.0	293.8
Gates Brook (1)	698	673	784	788	959	1071
Gates Brook (4)	850	899	1058	1061	1274	1343
Jordan Farm Brook	134.8	127.8	120.3	115.6	124.3	183.7
Malagasco Brook	194.0	234.5	298.4	277.0	437.4	400.1
Malden Brook	209.1	207.5	226.0	237.7	295.6	350.5
Muddy Brook	157.1	161.5	182.0	211.5	282.1	327.9
Oakdale Brook	632	506	620	659	866	938
Quinapoxet River (C.Mills)	145.3	166.5	174.3	191.5	267.5	312.4
Scarlett Brook	421.8	386.6	421.8	456.6	610	604
Stillwater River (SB)	104.6	135.4	136.9	132.0	180.0	185.8
Trout Brook	n/s	61.1	73.2	74.8	73.5	82.8
Waushacum (Prescott)	293.5	306.5	321.1	308.2	364.4	388.6
West Boylston Brook	500	514	689	746	1221	1236
WACHUSETT TRIBS MEAN	**321.1**	**305.9**	**358.3**	**379.9**	**505**	**535**

Annual median specific conductance ranged from a low of 82.8 μmhos/cm in Trout Brook to a high of 1343 μmhos/cm at Gates Brook 4. All but three annual medians were the highest in the past six years and historic high medians were recorded at 14 stations (Table 15). Figure 11 illustrates the steady increase in annual median specific conductance. Although this suggests a serious decline in water quality, it is at least in part the result of much lower than normal annual rainfall over the past two years which reduced tributary flows and increased concentrations of mineral salts, although a clear trend is emerging. This will be investigated in depth as part of a 30- year summary report.

Figure 11: Five Year Increase in Annual Median Specific Conductance in Wachusett Tributaries



3.5 TURBIDITY

Routine weekly samples were collected from all tributary stations throughout the year, with individual measurements from 0.13 NTU to 49 NTU. The 25 samples with turbidity of 5.0 NTU or higher were predominantly collected from Muddy Brook (15 samples) which historically has contained elevated concentrations of fine particulate matter. Samples with high turbidity from Muddy Brook were collected during both dry and wet weather. Eight other samples with turbidity in excess of 5.0 NTU were collected from six tributaries during storm events throughout the year, and single samples with elevated turbidity were collected from French Brook during dry weather in June and July.

Annual median values ranged from 0.27 NTU in Cook Brook to 3.63 NTU in Muddy Brook. Annual mean values ranged from 0.28 NTU in Cook Brook to 5.5 NTU in Muddy Brook. Overall watershed median of 0.69 NTU and mean of 1.29 NTU were the lowest of the past six years.

Storm events continued to have a negative impact on turbidity, with a watershed median of 0.84 NTU for all wet weather samples (mean of 1.86 NTU) and a median of only 0.65 NTU for dry weather samples (mean of 1.05 NTU). Not all sampling locations are impacted equally by storm events. Tributaries with very low or very high annual turbidity and ones that were dry for a portion of the year and had only a few samples collected during storm events did not exhibit much difference between median wet weather and median dry weather samples. Only very small differences were observed between wet weather and dry weather samples from the Quinapoxet River as well.

Table 16: Annual Mean and Median Turbidity in Wachusett Tributaries (NTU)

STATION	MEAN	DRY MEAN	WET MEAN	MEDIAN	DRY MEDIAN	WET MEDIAN
Asnebumskit (Princeton)	1.14	0.96	2.07	0.76	0.76	1.15
Beaman 2	0.53	0.55	0.44	0.52	0.53	0.44
Boylston Brook	0.92	0.72	1.36	0.71	0.62	0.96
Cook Brook (Wyoming)	0.28	0.28	0.31	0.27	0.28	0.25
East Wachusett (140)	0.47	0.48	0.39	0.49	0.50	0.41
French Brook (70)	1.93	1.76	2.31	1.25	1.09	1.44
Gates Brook (1)	0.57	0.39	0.96	0.37	0.34	0.47
Gates Brook (4)	0.89	0.66	1.36	0.63	0.51	0.87
Jordan Farm Brook	0.51	0.49	0.61	0.51	0.55	0.35
Malagasco Brook	0.82	0.58	1.31	0.61	0.58	0.96
Malden Brook	0.52	0.45	0.66	0.43	0.41	0.51
Muddy Brook	5.5	4.71	7.1	3.63	3.63	3.64
Oakdale Brook	0.43	0.42	0.48	0.34	0.34	0.37
Quinapoxet River (C.Mills)	1.00	0.94	1.12	0.91	0.91	0.95
Scarlett Brook	1.38	0.82	2.54	0.75	0.70	0.86
Stillwater River (SB)	0.75	0.69	0.88	0.68	0.64	0.73
Trout Brook	0.60	0.60	0.58	0.54	0.54	0.53
Waushacum (Prescott)	2.04	1.85	2.45	1.96	1.96	1.79
West Boylston Brook	1.09	0.75	1.81	0.67	0.72	0.57
WACHUSETT TRIBS MEAN	**1.29**	**1.05**	**1.86**	**0.69**	**0.65**	**0.84**

3.6 STORMWATER SAMPLING

Stormwater sampling is done to supplement routine monthly nutrient sampling and more accurately estimate total annual loading, but remains on hiatus until a sampling needs assessment is completed.

3.7 SPECIAL STUDIES

Monitoring of potential short term and long term water quality impacts from forest management activities continues. Monitoring of short term impacts consists of monthly sampling at proposed and active logging sites above and below stream crossings when flow is present or during storm events. Nearly 100 visits were made to eight sites (16 stream crossings) to collect water quality samples, establish baseline turbidity, and monitor water quality during active logging and the installation and removal of stream crossings, although not all sites had flow during all occasions.

The long term forestry monitoring project collects data at a control site and an active site for a ten year period before, during, and following completion of forestry operations. Three years of data have now been collected and a preliminary report summarizing results to date should be completed in June 2017. The study includes monthly dry weather discrete grab sampling and quarterly storm event monitoring using automatic samplers. Parameters monitored are flow, pH, temperature, dissolved oxygen, turbidity, total suspended solids, total organic carbon, ammonia, nitrate, nitrite, and total phosphorus.

Macroinvertebrate samples were collected at more than twenty historic reservoir tributary stations during the spring of 2012, 2014, and 2016. All 2012 samples have been sorted, identified, and counted, while 2014 and 2016 samples are still being processed. Information obtained from these recent samples will be compared with historic long term macroinvertebrate data from the same locations and will be presented in a future water quality report.

High concentrations of bacteria were detected in West Boylston Brook in early February 2016. A series of samples were collected upstream and along various branches of the tributary and the likely source identified as an agricultural operation that had caused problems in the past. Bacteria concentrations dropped but were higher than normal for the year and should be investigated further.

Very high concentrations of bacteria in French, Muddy, Gates, and Waushacum Brooks recorded during a storm event at the end of June were investigated further. Follow-up samples collected the next day also contained elevated concentrations of bacteria. No clear source was identified. Concentrations declined at some locations but remained elevated at others throughout the summer and remain a concern.

4.0 RESULTS OF RESERVOIR MONITORING PROGRAM

4.1 FECAL COLIFORM

Bacterial transect samples were collected from 23 surface stations on the reservoir twice in January before the reservoir was covered with ice. Sampling resumed in mid-April after ice melted. Samples were collected monthly, twice monthly, or weekly throughout the remainder of the year to document the relationship between seasonal bacteria variations and visiting populations of gulls, ducks, geese, and other waterfowl. Supplemental samples were collected in late October during intensive all-reservoir harassment efforts to illustrate time-sensitive changes in bacteria and judge the immediate effectiveness of nightly bird harassment. Sample locations were shown previously on Figure 3 and data are presented in Table 17, although not all supplemental sampling data are included.

Table 17: 2016 Wachusett Reservoir Bacteria Transect Data (MPN/100 mL)

	1/6	1/15	4/13	4/28	5/12	6/16	7/20	8/19	9/2	9/9	9/14	9/21	9/28	10/12	10/17	10/24	11/2	11/10	11/18	11/25	12/1	12/8	12/14	12/20	12/28
A-3	0	0	0	0	0	0	0	1	1	2	2	0	0	1	1	3	0	1	0	1	2	0	0	0	1
B-2	0	0	1	0	0	0	1	3	2	1	0	1	0	1	1	1	1	1	2	2	0	2	1	0	0
B-3	0	0	4	0	0	0	0	2	0	0	1	2	2	0	2	**11**	0	0	3	4	0	2	0	0	1
C-1	0	0	1	0	0	0	0	4	1	1	1	1	0	0	0	3	0	1	0	1	5	1	1	1	0
C-3	0	0	7	0	0	0	0	4	2	2	0	0	1	0	0	3	0	0	1	0	1	1	0	0	0
C-5	0	0	5	0	0	0	0	3	1	6	2	1	1	0	0	2	0	1	0	0	0	1	1	0	1
D-1	0	0	2	0	0	0	0	2	0	0	1	5	0	0	2	4	5	1	1	5	6	1	0	0	0
D-2	0	0	4	1	0	0	1	3	0	3	0	0	1	1	0	4	4	4	7	0	7	0	0	0	0
D-4	0	0	9	0	0	0	0	3	3	1	0	0	1	0	0	4	0	1	0	0	4	5	0	1	0
E-2	0	0	4	1	0	0	1	5	5	3	1	1	0	0	1	9	3	0	6	2	6	0	0	0	1
E-4	0	0	0	0	0	0	0	1	4	1	1	0	1	1	4	6	1	2	3	0	2	5	0	0	1
F-2	1	1	5	1	0	1	0	1	1	4	1	0	0	0	0	5	0	0	3	3	3	4	1	1	2
F-3	2	0	5	1	0	2	2	0	5	7	1	2	5	4	6	4	2	1	1	6	2	2	3	0	**14**
F-4	0	0	2	1	0	0	0	3	9	4	3	2	1	0	4	6	0	0	0	0	2	**14**	0	0	0
G-2	6	6	2	0	0	0	0	0	0	3	1	2	0	0	1	6	0	2	2	0	3	1	0	3	3
H-2	3	4	0	0	0	0	0	0	**22**	2	2	0	0	1	0	5	1	1	3	0	4	4	6	**14**	6
I-2	9	**32**	0	0	0	0	0	3	**22**	1	0	0	0	0	0	**15**	0	n/s	1	0	1	0	4	7	6
J-2	**17**	**14**	0	0	0	1	1	0	2	0	2	0	1	0	0	4	0	1	0	1	1	3	**12**	5	**19**
J-3	**45**	**33**	1	0	0	0	0	0	1	0	0	2	1	0	0	7	1	4	0	**22**	**12**	6	**18**	**53**	**29**
J-4	**106**	**73**	1	0	0	0	0	1	1	0	0	1	0	**14**	3	**11**	4	0	0	**21**	4	**22**	**25**	**101**	**83**
K-2	**50**	**32**	0	0	0	0	1	0	0	0	0	0	1	1	3	9	0	0	0	7	**14**	**24**	**19**	**31**	**41**
M-1	9	**33**	0	0	0	0	1	0	0	0	0	0	0	1	0	**12**	1	2	0	3	7	**31**	4	**29**	**29**
N-1	**29**	**31**	1	1	1	0	0	0	1	0	0	0	1	1	1	6	2	0	3	6	4	5	**14**	**19**	**41**

Very high concentrations of bacteria were recorded in January at the south end of the reservoir where birds typically spend the night. Ice cover was present from February into April and most waterfowl had dispersed before open water was present in the spring. Bacteria concentrations remained low at almost all stations until the beginning of October when elevated concentrations were noted at scattered locations throughout the reservoir. Concentrations began to increase at the end of November at the south end of the reservoir and remained high through the end of the year. Concentrations during the last two weeks of the year were very high (50-100 MPN/100mL) and comparable to that seen in January.

Bacteria samples were collected seven days per week by MWRA staff from the John J. Carroll Water Treatment Plant at Walnut Hill in Marlborough. EPA's criteria for drinking water require that a minimum of ninety percent of all source water samples contain less than 20 MPN/100mL. All of the 366 samples collected at Walnut Hill contained less than the standard. Most samples did not contain any detectable bacteria. The Division has put considerable time and effort into implementing a rigorous bird harassment program, and the results in 2016 continued to prove that the efforts are very effective at maintaining low numbers of both birds and bacteria.

4.2 WATER COLUMN CHARACTERISTICS

4.2.1 FIELD PROCEDURES

Division staff routinely record water column profiles in Wachusett Reservoir for the following hydrographic parameters: temperature, specific conductance, dissolved oxygen concentration, percent oxygen saturation, chlorophyll *a*, and hydrogen ion activity (pH). This involves use of a field instrument known as a multiprobe to record data starting at the surface and then recording repeated measurements as the instrument is gradually lowered to the bottom. Measurements are recorded at one meter intervals, except during periods of isothermy and mixing (generally November through March) when intervals of two or three meters are adequate to characterize the water column.

In recent years, the multiprobe used by the Division to measure water column profiles is a "MiniSonde 5" paired with a "Surveyor 4" water quality logging and data display system manufactured by Hydrolab Corporation (now part of the Hach Company located in Loveland, Colorado). Early in 2016, a Yellow Springs Instrumentation (YSI) EXO2 Sonde was acquired. The YSI sonde collects the same suite of parameters and adds capability to measure phycocyanin/blue green algae and total dissolved solids. During the 2016 field season, both probes were used, often simultaneously, to compare measurements recorded by the more familiar older technology to the new and less familiar. In general, parameters were comparable and after August the YSI probe was predominantly used. Probes were routinely charged and calibrated during the field season. At the conclusion of field work, data recorded by the logging system is downloaded as an Excel spreadsheet.

The capability to now measure phycocyanin/blue green algae *in situ* during reservoir profiles will be a valuable tool for detecting densities of cyanobacteria within the reservoir. As was the case when the ability to measure chlorophyll *a* was added to the program in 2011, an increase in technology may result in an increase in algae densities reported because the depth at which a maximum density occurs can be identified and sampled.

4.2.2 THERMAL STRATIFICATION

Typical of most deep lakes and reservoirs in the temperate region, Wachusett Reservoir becomes thermally stratified in summer. The development of stratification structure usually begins in late April or early May when increasing solar radiation and atmospheric warming cause a progressive gain of heat in surficial waters. Stratification is most pronounced during summer when the water column is characterized by three distinct strata: a layer of warm, less dense water occupying the top of the water column (epilimnion), a middle stratum characterized by a thermal gradient or thermocline (metalimnion), and a stratum of cold, dense water at the bottom (hypolimnion). This thermal structure is weakened in fall as heat from the upper portion of the water column is lost to the increasingly cold atmosphere. In late October or early November, the last vestiges of stratification structure are dispersed by wind-driven turbulence and the entire water column is mixed and homogenized in an event known as fall turnover.

Profile measurements recorded during the period of thermal stratification are important for many reasons, including the following: (1) to monitor phytoplankton growth conditions and detect growth of potential taste and odor causing organisms associated with discrete strata of the water column (see section on phytoplankton), (2) to track the progress of the Quabbin interflow through the Wachusett basin during periods of water transfer, and (3) to monitor water quality within each stratum and determine appropriate depths for vertically stratified nutrient sampling.

Profiles are measured weekly during the stratification period at Basin North/Station 3417 in conjunction with plankton monitoring (see section 4.2.4). Profiles are collected less frequently outside of the peak season, but are still typically collected twice per month as long as the reservoir is not frozen. Samples are typically collected at 1 meter intervals, with an additional 0.5 meter surface sample also recorded. In situations where layers of water are well mixed, samples may be collected every 2 meters. In cases where aggregations of algae are suspected, or the precise depth of the Quabbin interflow layer needs to be resolved, 0.5 meter depths are measured within that range.

Water column profile data has been collected from various locations in Wachusett Reservoir using a multiprobe sonde since 1988. Data collected from 1988 through 1996 was collected in the field and recorded by hand in a series of 3 logbooks; this data was entered into a spreadsheet in 2016. This will allow the historic data to be combined with profile data collected right up to and including present samples. A database is currently being developed that will allow for tracking and analysis of Wachusett Reservoir profile data.

4.2.3 THE QUABBIN INTERFLOW IN WACHUSETT RESERVOIR

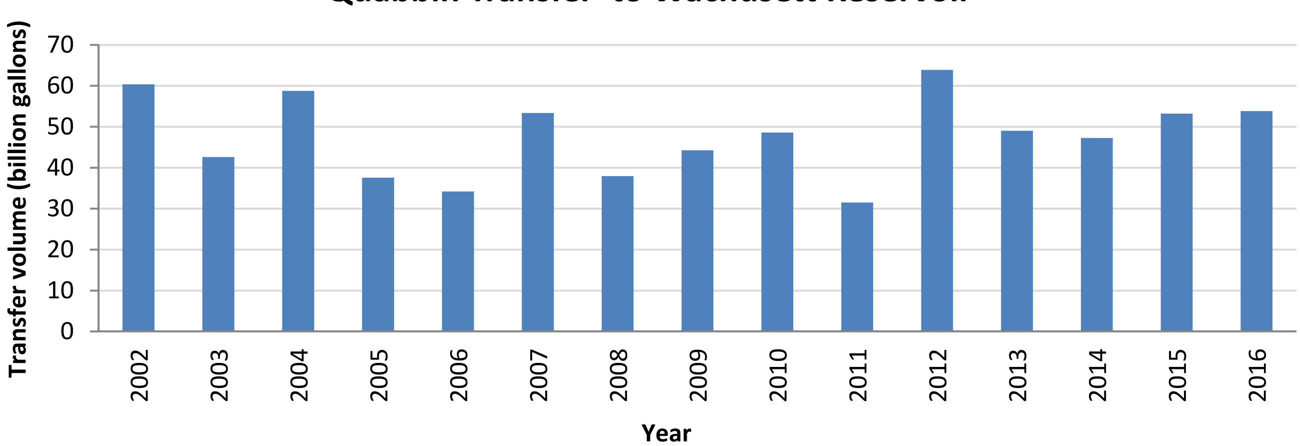
The transfer of water from Quabbin to Wachusett Reservoir via the Quabbin Aqueduct has a profound influence on the water budget, profile characteristics, and hydrodynamics of Wachusett Reservoir. In a typical season, the amount of water transferred from Quabbin to Wachusett ranges from 50-100% of the volume of the Wachusett Reservoir. The period of peak transfer rates generally occurs from June through November. However, at any time of the year, approximately half of the water in the Wachusett basin is derived from Quabbin Reservoir.

The peak transfer period overlaps the period of thermal stratification in Wachusett and Quabbin Reservoirs. Water entering the Quabbin Aqueduct at Shaft 12 is withdrawn from depths of 13 to 23 meters in Quabbin Reservoir. These depths are within the hypolimnion of Quabbin Reservoir where water temperatures typically range from only 9 to 13° C from June through October. This deep withdrawal from Quabbin is colder and denser relative to epilimnetic waters in Wachusett Reservoir. However, due to a slight gain in heat from mixing as it passes through Quinapoxet Basin and Thomas Basin, the transfer water is not as cold and dense as the Wachusett hypolimnion. Therefore, Quabbin water transferred during the period of thermal stratification flows conformably into the metalimnion of Wachusett where water temperatures and densities coincide.

The term ‘interflow’ describes this metalimnetic flow path for the Quabbin transfer that, once fully developed, generally occupies the Wachusett water column from roughly 6 to 16 meters in depth. Interflow water quality is distinctive from ambient Wachusett water in having a low specific conductivity characteristic of Quabbin Reservoir. Multiprobe measurements of conductivity readily distinguish the Quabbin water within Wachusett Reservoir. The interflow penetrates through the main basin of Wachusett Reservoir (from the Route 12 Bridge to Cosgrove Intake) in about 3 to 5 weeks depending on the timing and intensity of transfer from Quabbin. The interflow essentially connects Quabbin inflow to Cosgrove Intake in a “short circuit” with limited mixing with ambient Wachusett Reservoir water.

In 2016, the Quabbin transfer was transferring water almost continuously from the middle of May through December; limited transfer also occurred during January - April. A total volume of 53.8 billion gallons (203,816,498 cubic meters) was delivered to Wachusett via the Quabbin aqueduct during 2016. This is equivalent to 90.1% of the volume of Wachusett Reservoir (59.8 billion gallons). This is in line with the average volume of water transferred within a typical year (Figure 12).

Figure 12
Quabbin Transfer to Wachusett Reservoir



4.2.4 SEASONAL PATTERNS IN PROFILE MEASUREMENTS

Thermal stratification of the water column and the presence of the Quabbin interflow are the major determinants of vertical gradients and patterns recorded in profile measurements. Profiles depicting water column characteristics on June 16, August 25, October 5, and December 6 (Figures 13-16) show how hydrographic parameters change with depth from early in the stratification period through fall turnover when mixing homogenizes the entire basin volume and restores equilibrium conditions with the atmosphere.

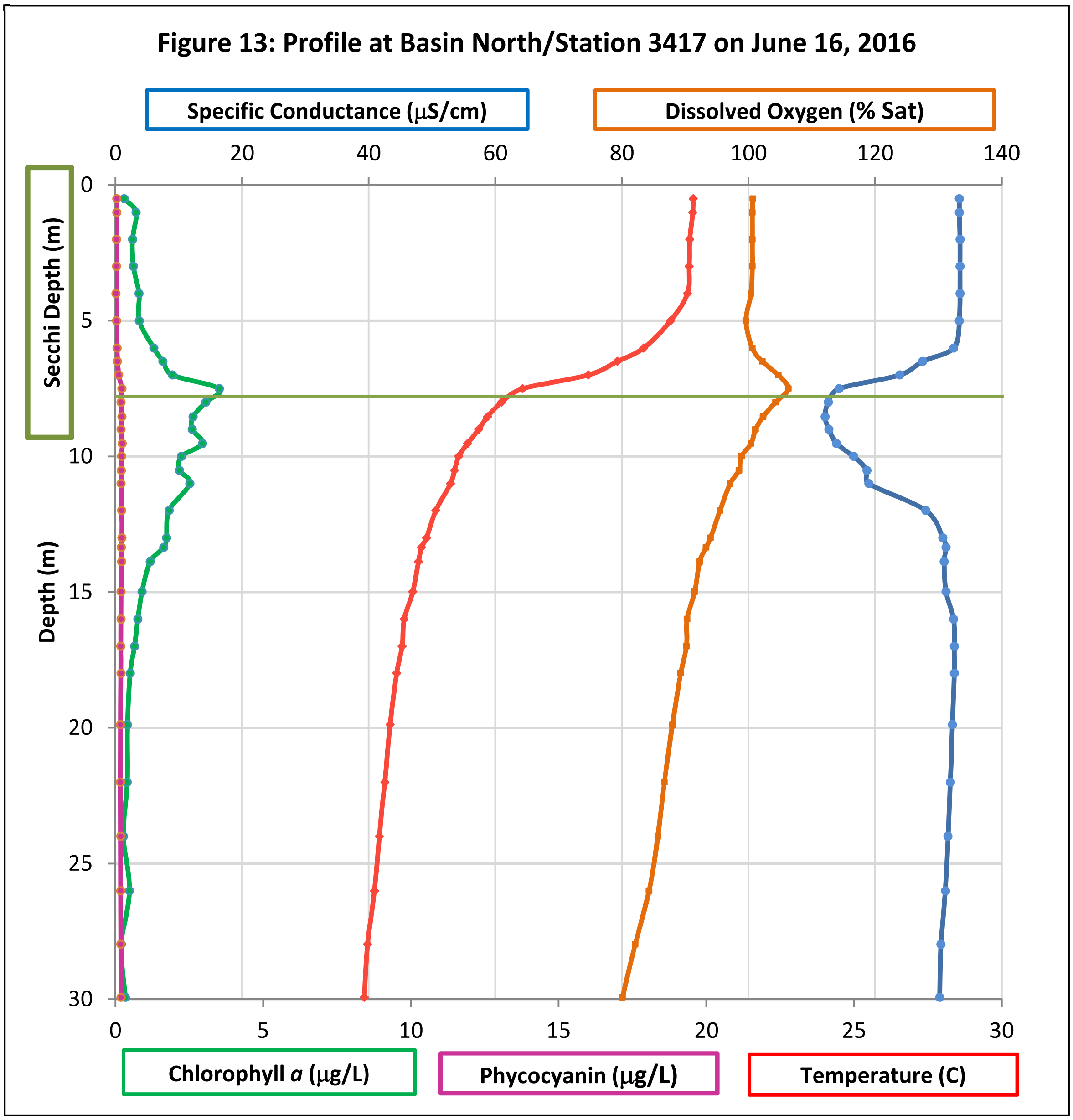
General trends in water column temperature and dissolved oxygen concentrations during the stratification period can be discerned in these profiles. Specifically, temperatures change in the epilimnion and metalimnion, but temperatures in the hypolimnion remain between 8 and 10° C throughout the summer. Dissolved oxygen values remain near 100% saturation in the epilimnion most of the year due to this stratum being exposed to the atmosphere and mixing due to wind-induced turbulence. In contrast, saturation values in the hypolimnion decline progressively due to microbial decomposition processes and the isolation of these strata from the atmosphere. The supply of oxygen at depth cannot be replenished until thermal structure is dissipated and turnover occurs. However, dissolved oxygen in the hypolimnion remains sufficient (typically >4.5 mg/L), even throughout the fall, to provide suitable habitat for cold water salmonids that inhabit the reservoir.

Hydrogen ion activity (pH) in Wachusett Reservoir is determined ultimately by the exchange of inorganic carbon between the atmosphere and water (carbon dioxide-bicarbonate-carbonate buffering). Generally, pH values in Wachusett Reservoir are unremarkable, ranging from around neutral (pH=7) to slightly acidic (pH=6). Specific patterns of pH distribution vertically in the water column and seasonally over the year are mainly determined by the opposing processes of photosynthesis and respiration, but are not depicted in Figures 13 through 16 since this parameter typically exhibits only minor fluctuations.

Specific conductance (conductivity) profiles in Wachusett Reservoir reflect the interplay between native water contributed from the Wachusett watershed and water transferred from Quabbin Reservoir. The Quinapoxet and Stillwater Rivers are the two main tributaries to Wachusett Reservoir and are estimated to account for approximately 75 percent of annual inflow from the reservoir watershed. Measurements of conductivity in these rivers generally range between 60 and 240 uS/cm with an average value between 125 and 150 uS/cm. In contrast, the average conductivity value of Quabbin water is approximately 40 uS/cm.

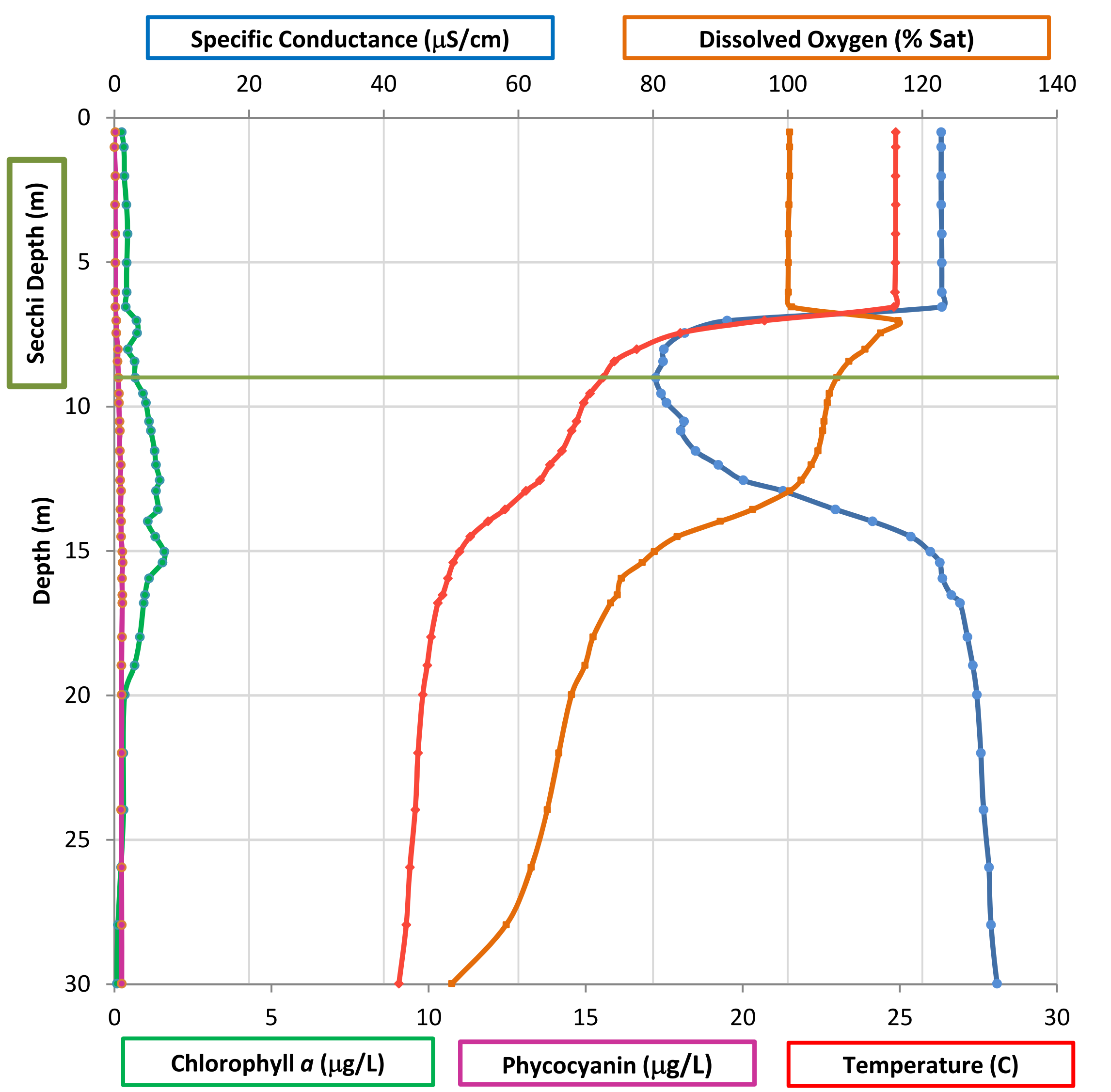
During periods of isothermy and mixing (November through March), conductivity values throughout the main Wachusett basin typically range from 75 to 145 uS/cm depending on the amount of water received from Quabbin the previous year. During the summer stratification period the Quabbin interflow is conspicuous in profile measurements as a metalimnetic stratum of low conductivity.

Interflow penetration at Basin North/3417 was first observed on June 2, becoming established as a defined layer by June 16 (Figure 13), as revealed by the conductivity profile. This indentation in the conductivity profile intensifies (extends to lower conductivity values) over the period of transfer as water in the interior of the interflow undergoes less mixing with ambient reservoir water at the boundaries of the interflow stratum. The epilimnion occupied the top 6 meters of the water column on this date and had reached a temperature of 22.8° C. Epilimnetic dissolved oxygen measured 104% saturation on this date due to photosynthetic activity by phytoplankton. No discernible peak in chlorophyll *a* concentration was observed on this date; phytoplankton samples collected in conjunction with this profile revealed only moderate densities.



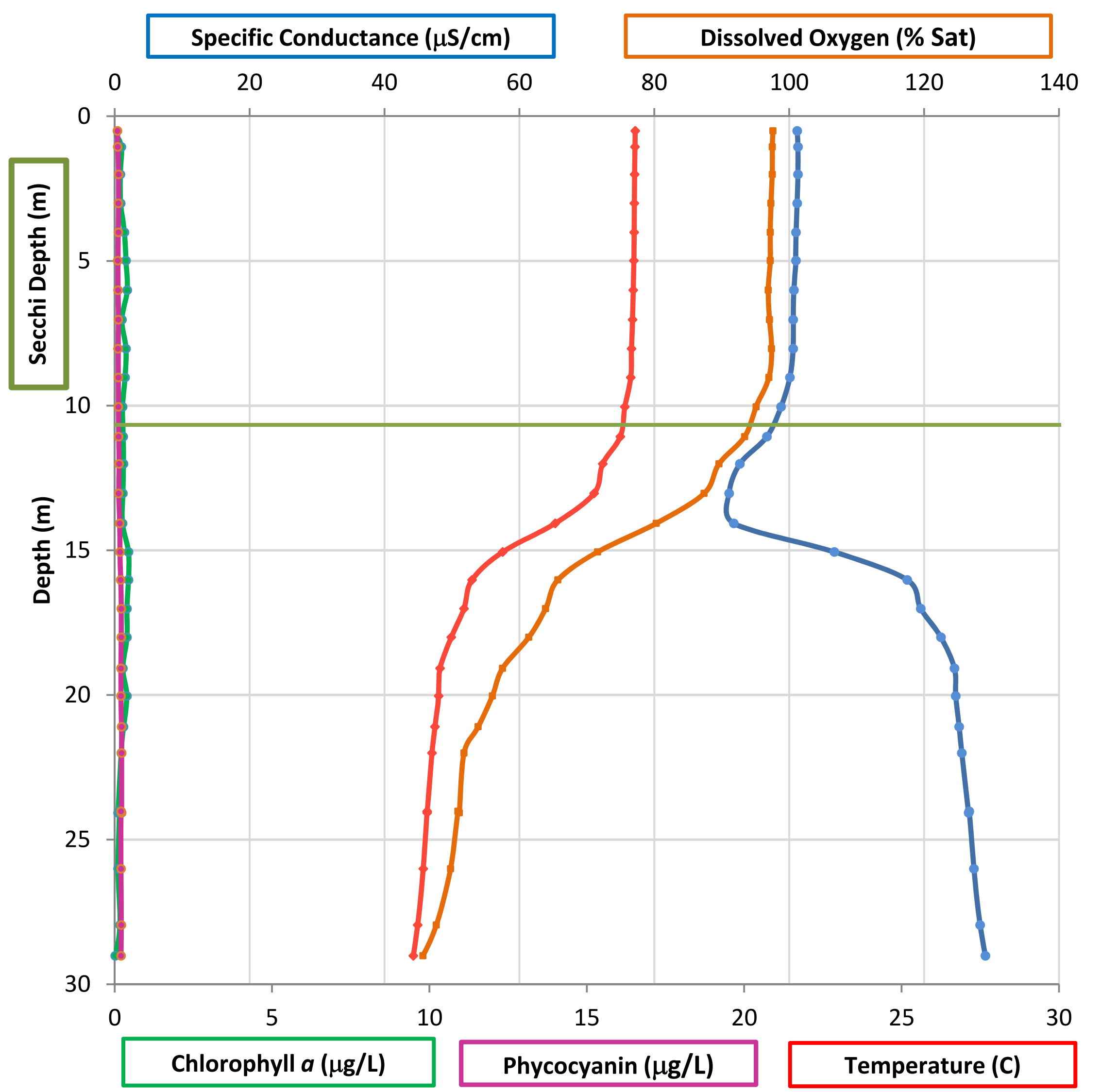
The interflow continued to become more fully established, remaining as a discrete layer through the summer months. On August 25, the “bulge” in the conductivity profile (Figure 14) shows the typical mid-summer configuration of the fully established interflow with a thickness of eight meters present between depths of 6.5 and 14 meters. Conductivity reached minimum values of around 80 uS/cm at a depth of 9.5 meters. The epilimnion still occupied the top six meters of the water column with a temperature of 24.9° C. The steep gradient in temperature and density between the epilimnion and interflow can be seen in this profile where the temperature decreases 8° C between depths of 6.5 and 8 meters. Although a modest spike in chlorophyll *a* concentration at depth was observed in early August, it had dissipated by the end of the month.

Figure 14: Profile at Basin North/Station 3417 on August 25, 2016

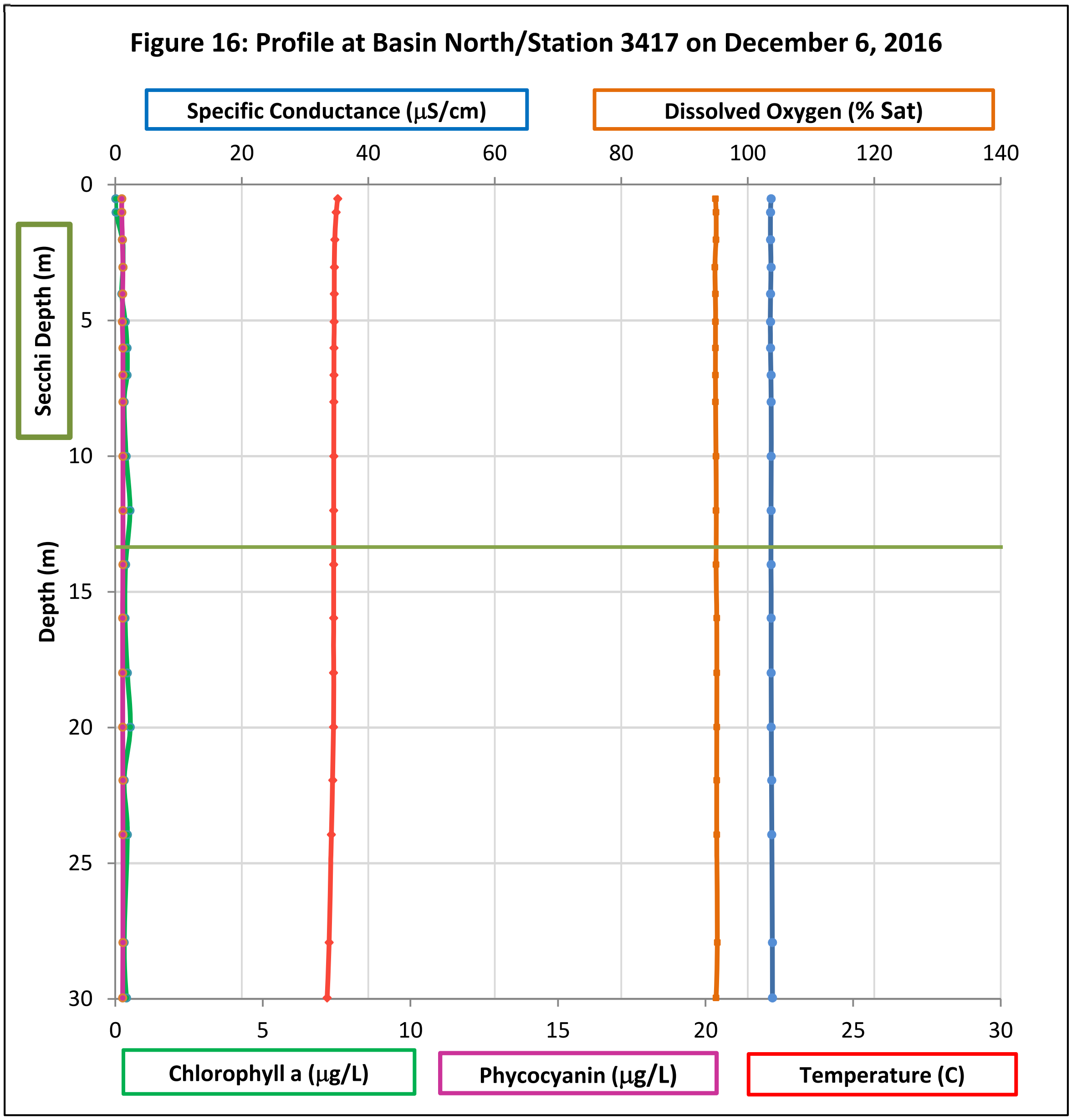


The epilimnion began steadily losing heat in mid-September. By October 5 (Figure 15), heat losses and wind energy had eroded the thermocline downward. The interflow was still clearly visible as a distinct layer only one week prior, but this profile reveals that the metalimnetic interflow had begun mixing with the epilimnion. At this point, the change to lower specific conductivity values is a gradual decline between 10 and 14 meters. Dissolved oxygen remained near saturation in the epilimnion, but had declined to a low of 46% saturation in the hypolimnion. Phytoplankton activity was minimal at this time and the chlorophyll *a* profile was comprised of low values throughout the water column.

Figure 15: Profile at Basin North/Station 3417 on October 5, 2016



A profile recorded on December 6 (Figure 16) documents the complete breakdown of the stratification structure and reveals that turnover is complete. This profile shows the water column was isothermal, with a difference of less than 0.5° C from the surface to the bottom (7.5° C - 7.2° C). Fall turnover exposes the entire basin volume to the atmosphere, thereby replenishing dissolved oxygen concentrations throughout the water column. Conductivity values were constant at 104 uS/cm throughout the water column. Also noteworthy is the Secchi disk depth recorded in association with this profile, as the depth of 13.4 m (43.8 feet) is the highest Secchi disk depth transparency ever recorded at Wachusett Reservoir.



4.3 NUTRIENTS

4.3.1 FIELD PROCEDURES

Nutrient dynamics in Wachusett Reservoir were documented through a program of quarterly sampling as follows: at the onset of thermal stratification (May), in the middle of the stratification period (July), near the end of the stratification period (October), and during a winter period of mixis before ice cover (December). Samples were collected at three main monitoring stations consisting of Basin North/Station 3417, Basin South/Station 3412, and Thomas Basin (Figure 2).

Grab samples were collected in the epilimnion, metalimnion/interflow, and hypolimnion during the period of thermal stratification and near the top, middle, and bottom of the water column during mixis. Water column profiles of temperature, dissolved oxygen, and specific conductance were measured with a multiprobe and evaluated in the field to determine depths for metalimnetic/interflow samples.

Quarterly sampling continued to be performed in collaboration with MWRA staff at the Deer Island Central Laboratory, who provided sample containers and were responsible for all sample analysis. Details of sampling protocol are provided in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics (Worden and Pistrang, 2003).

Modifications to the quarterly sampling program have consisted only of a lower minimum detection limit for total Kjeldahl-nitrogen (reduced to 0.05 mg/L from previous limits of 0.2 and 0.6 mg/L) and the addition of UV254 absorbance (in 2000) to the suite of parameters being measured. Measurement of UV absorbance at a wavelength of approximately 254 nanometers serves as a relative assay of the concentrations of organic compounds dissolved in the water.

4.3.2 RESULTS OF NUTRIENT ANALYSES

The nutrient database for Wachusett Reservoir established in the 1998-99 year of monthly sampling and subsequent quarterly sampling through 2015 is used as a basis for interpreting data generated in 2016. Most results from quarterly nutrient sampling in 2016 were within historical ranges, with the exception being UV254 measurements and two new record lows in hypolimnetic nitrate values. New record lows for UV254 were observed at seven out of nine stations in 2016, including all except Thomas Basin surface and mid depth stations. The record lows were recorded in the October and December samples, with most values at or below historic minima at Basin North and Basin South from October through December. These values corresponded with new record Secchi disk depth recorded on December 6, 2016 (discussed in section 4.4.3). Overall nutrient concentrations for 2016 range from near average to below average (see Table 18) and the complete 2016 reservoir nutrient results in Appendix A). New record lows for hypolimnetic nitrate values were recorded at Basin South in July and Basin North in December.

The patterns of nutrient distribution in 2016 quarterly samples correspond closely to those documented in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics (Worden and Pistrang, 2003). These patterns consist most importantly of the following: (1) seasonal and vertical variations with low epilimnetic concentrations in summer resulting from phytoplankton uptake, and conversely, higher concentrations accumulating in the hypolimnion due to microbial decomposition of sedimenting organic matter, (2) interannual fluctuations in nutrient concentrations and parameter intensities occurring across the system as a result of the divergent influences of the Quabbin transfer and the Wachusett watershed with temporary lateral gradients becoming pronounced for nitrate, silica, UV254, and conductivity, either increasing or decreasing downgradient of Thomas Basin depending on the dominant influence.

Nutrient monitoring has been ongoing at Wachusett Reservoir since 1998. Methods of collection and methods of analysis have remained constant throughout this period of time. All reservoir nutrient data has been synthesized into a single format and is in the process of being incorporated into a single database that will allow for the management and analysis of over 5,600 nutrient results collected over the 19 year time period.

Reference Cited:

Worden, David and Larry Pistrang. 2003. Nutrient and Plankton Dynamics in Wachusett Reservoir: Results of the MDC/DWM's 1998-2002 Monitoring Program, a Review of Plankton Data from Cosgrove Intake, and an Evaluation of Historical Records. Metropolitan District Commission, Division of Watershed Management.

Table 18 - Wachusett Reservoir Nutrient Concentrations:
Comparison of Ranges from 1998-2015 Database[1] to Results from 2016 Quarterly Sampling [2]

Sampling Station[3]	Ammonia (NH_3; ug/L)		Nitrate (NO_3; ug/L)		Silica (SiO_2; mg/L)		Total Phosphorus(ug/L)		UV254 (Absorbance/cm)	
	1998-2015	2016	1998-2015	2016	1998-2015	2016	1998-2015	2016	2000-2015	2016
Basin North/3417 (E)	<5 - 16	<5 - 6	<5 - 176	<5 - 32	0.59 - 4.62	1.08 - 2.17	<5 - 17	<5 - 6	0.032 - 0.089	**0.029** - 0.050
Basin North/3417 (M)	<5 - 51	<5 - 7	<5 - 180	<5 - 43	0.77 - 4.67	1.46 – 2.44	<5 - 20	<5 - 8	0.032 - 0.102	**0.029** - 0.052
Basin North/3417 (H)	<5 - 41	5 - 36	33 - 225	**30** - 80	1.27 - 5.06	1.73 – 3.45	<5 - 19	5 - 8	0.032 - 0.084	**0.030** - 0.051
Basin South/3412 (E)	<5 - 15	<5 - 7	<5 - 176	<5 - 38	0.56 - 4.58	1.19 – 2.29	<5 - 20	<5 - 6	0.031 - 0.101	**0.028** - 0.054
Basin South/3412 (M)	<5 - 39	<5 - 9	<5 - 184	<5 - 45	0.95 - 4.80	1.39 – 2.51	<5 - 22	<5 - 6	0.032 - 0.128	**0.031** - 0.058
Basin South/3412 (H)	<5 - 44	7 - 24	35 - 224	**19** - 72	1.64 - 4.78	1.87 – 3.42	<5 - 37	5 - 8	0.036 - 0.111	**0.032** - 0.055
Thomas Basin (E)	<5 - 18	<5	<5 - 201	<5 - 71	0.62 - 7.44	1.22 – 3.02	<5 - 27	<5 - 11	0.026 - 0.305	0.028 - 0.100
Thomas Basin (M)	<5 - 27	<5 - 8	<5 - 213	<5 - 68	0.88 - 7.36	1.39 – 3.20	<5 - 29	<5 - 10	0.026 - 0.334	0.028 - 0.098
Thomas Basin (H)	<5 - 57	<5 - 9	<5 - 236	<5 - 112	0.92 - 7.39	1.68 – 5.92	<5 - 29	<5 - 15	0.027 - 0.345	**0.026** - 0.229

Notes: (1) 1998-2015 database composed of 1998-99 year of monthly sampling and subsequent quarterly sampling through December 2015, except for measurement of UV254 initiated in 2000 quarterly sampling

(2) 2016 quarterly sampling conducted May, July, October, and December

(3) Water column locations are as follow: E = epilimnion/surface, M = metalimnion/middle, H = hypolimnion/bottom

(4) Numbers in bold indicate new record values

4.4 PLANKTON

4.4.1 FIELD PROCEDURES

Plankton monitoring consists of three tasks conducted from a boat: measurement of water column profiles (see section 4.2.4), measurement of Secchi disk transparency, and grab sampling. This work is generally conducted at Basin North/Station 3417 during periods of the year lacking ice cover when boats are on the water. Basin North/Station 3417 is representative of the deepest portion of the basin and is outside the area adjacent to Cosgrove Intake where copper sulfate is applied on the infrequent occasions when "taste and odor" organisms attain problematic densities. The catwalk behind Cosgrove Intake is an additional location suitable for plankton grab sampling. Seiche effects or turbulence from water withdrawals can destabilize stratification boundaries and obscure associated phytoplankton distribution patterns at Cosgrove Intake during summer. However, samples collected from the catwalk during the late-November through early-April period of mixis are adequately representative of the main basin. Samples collected at Cosgrove Intake under stratified conditions may not be representative of any other location, but are informative as to plankton densities in close proximity to the intake.

Monitoring frequency is twice a week (usually Monday and Thursday) from May through September when episodes of rapid population growth of taste and odor organisms have occurred in the past, and typically weekly (ice permitting) outside of that period. During the annual stratification period, samples are typically collected near the middle of the epilimnion at a depth of three meters as well as at or near the interface between the epilimnion and metalimnion (typically at a depth of six or seven meters). Additional samples are often collected where profile measurements reveal elevated chlorophyll *a* values. Additionally, surface samples are collected in summer months to monitor for increased densities of the Cyanophyte *Anabaena,* which may accumulate at the surface. During the period of mixis, collection of samples at two depths (3 and 6 meters) generally suffices, but other samples are collected as needed. Samples are collected using a Van Dorn Bottle and kept in a cooler until they are returned to the laboratory for concentration and microscopic analysis. Secchi disk transparency is recorded in association with Basin North samples as an approximate measure of the amount of particulates, mostly plankton, suspended in the water column.

During the stratification period, sampling is focused where profile measurements show a spike in dissolved oxygen concentration, chlorophyll *a* concentration, or phycocyanin, as appropriate. Peaks in these parameters are indicative of photosynthetic activity associated with a phytoplankton bloom or aggregation within a specific stratum of the water column. Additional grab samples are collected at the precise depth where spikes are indicated. Motile colonial Chrysophytes such as *Chrysosphaerella*, *Dinobryon* and Synurophytes such as *Synura* are known to produce subsurface blooms in Wachusett Reservoir and are generally the most potent taste and odor taxa encountered. The aggregation stratum that these organisms have historically preferred is often between 6 and 8 meters, coincident with the steep temperature gradient at the interface between the epilimnion and the metalimnetic interflow (see Section 4.2.3). However, in recent years, chlorophyll *a* maxima have been documented at depth, with targeted sampling revealing aggregations of these organisms inhabiting the middle or even lower portion of the interflow layer.

MWRA and DCR have analyzed the historical phytoplankton data and established a treatment consideration level for each taste and odor taxa. Once this level is reached, monitoring frequency is increased and action is considered.

4.4.2 CONCENTRATION AND MICROSCOPIC ANALYSIS OF PHYTOPLANKTON

Prompt acquisition and distribution of information on phytoplankton densities is critical for agency decisions on the need for additional sampling or algaecide applications to avoid taste and odor problems. The method of sand filtration for concentration of phytoplankton samples has long been in use by the Division because it enables relatively rapid analysis of samples while subjecting organisms to minimal damage or distortion. The specific method used is documented in Standard Methods Twelfth Edition (1965, pages 669-671). The method entails gravity filtration of sample water through a layer of fine sand. The concentrated sample and sand is gently washed with waste filtrate water in a beaker to detach organisms from the sand grains and promptly decanted after the sand has been allowed to settle. A known quantity of the concentrated sample is then analyzed microscopically using quantitative techniques.

Phytoplankton taxa in concentrated samples are enumerated using a Sedgewick-Rafter (S-R) Cell which enables phytoplankton densities to be quantified. Each concentrated sample is mixed to homogenize the sample and then 1 ml of the sample is withdrawn with a pipette and placed into the S-R Cell. Initial inspection of phytoplankton within the S-R Cell is accomplished with a stereozoom microscope capable of magnification from 7X to 45X. Use of this instrument to scan the entire S-R Cell is important to detect colonies of certain motile taxa present at low densities such as *Synura*, colonies floating against the underside of the cover such as *Anabaena,* or to view large colonies such as *Uroglenopsis*. Analysis of surface samples collected in summer is typically limited to scanning unless *Anabaena* is detected at densities sufficient to warrant enumeration using a compound microscope (see below).

Scanning of the entire S-R Cell enables colonial “taste and odor” organisms to be identified and quantified at very low densities. Colonies observed in the S-R Cell using the stereozoom microscope are quantified by counting the number of colonies and then measuring their average diameter using a compound microscope (see below). This information, along with the known concentration factor arising from sand filtration, is used to calculate and express densities of colonial “taste and odor” organisms as Areal Standard Units (ASUs).

After the scanning procedure described above, microscopic analysis of phytoplankton samples is next performed with a Zeiss Axio Imager A2 compound microscope at a magnification of 200X using either bright field or phase-contrast illumination. Approximately 15 minutes are allowed for the phytoplankton to settle to the bottom of the S-R Cell before enumeration. Phytoplankton is enumerated in a total of ten fields described by an ocular micrometer. The area of the ocular field is determined by calibration with a stage micrometer and the fields are selected for viewing at approximately 0.5 cm intervals across the length of the S-R Cell. If the initial count of ten fields reveals that known taste and odor organisms are present in densities approaching treatment consideration thresholds, up to forty additional fields are recorded for the density of that particular organism in order to increase the precision of the count.

Phytoplankton densities are expressed as Areal Standard Units (ASUs; equivalent to 400 square microns) per milliliter. The area of each specimen viewed in each counting field is estimated using the ocular micrometer (the ocular field is divided into a ten by ten grid, each square in the grid having a known area at 200X magnification). In the case of taxa which form gelatinous envelopes or are enclosed in colonial mucilage, such as *Microcystis*, the area of the envelope is included in the estimate for that specimen. The areal extent of certain colonial taxa, such as the diatoms *Asterionella* and *Tabellaria*, is estimated by measuring the dimensions of one cell and multiplying by the number of cells in the colony. Cell fragments or structures lacking protoplasm, such as lorica of *Dinobryon*, diatom frustules, and thecae of dinoflagellates, are not included.

During the peak season, phytoplankton sample splits are sent weekly to the MWRA lab in Southborough for automated plankton analysis with a Fluid Imaging FlowCAM system. This system is calibrated to recognize and enumerate five taste and odor taxa of interest. Split sample FlowCAM results are useful in comparing results to total densities for taste and odor taxa calculated by Division biologists using sand filtration and microscopic analysis.

4.4.3 PHYTOPLANKTON MONITORING RESULTS

A total of 179 total algae samples were collected and analyzed during the 2016 season. Given that no ice cover was ever established on the main basin during 2016, samples were collected between January 4 and December 27, 2016 without interruption. Overall phytoplankton densities were low in January and into February before beginning to increase due to the typical spring proliferation of diatoms (Figure 17). Densities continued a steady increase until April 11, when the maximum density for the season of 1,561 ASU/mL was recorded. At that time, *Asterionella* was present at 1,279 ASU/mL, comprising 82% of the total density. Historically, high spring diatom levels are common and have not resulted in any taste or odor impacts to drinking water quality.

Densities continued a steady decline from this point forward, reaching a value of 212 ASU/mL on May 19 as Chrysophytes became dominant. A relatively brief period with moderate densities of *Uroglenopsis* lasted until the first week of June before giving way to *Dinobryon* and then *Chrysosphaerella*. *Chrysosphaerella*, a motile Chrysophyte that has caused taste and odor issues in the past when reaching high densities, was observed to aggregate within the interflow at depth beginning in mid June, reaching a peak of 905 ASU/mL at a depth of 10.5 meters at Basin North on June 30. However, the aggregation stratum was particularly narrow, and only a single sample was collected with a count at that density. Samples collected slightly shallower at 7.5 and 9 meters revealed ¼ and ½ the density as the 10.5 meter sample. Additional samples collected at similar depths before and after that sample, paired with *in situ* chlorophyll *a* values recorded with a multiprobe, documented that this organism occupied a limited depth range at an elevated density. *Chrysosphaerella* also followed a trend observed in recent years of slowly decreasing maximum densities observed at continually lower depths until finally abating, with the completion of that pattern observed this year in early August.

Overall phytoplankton densities remained quite low from August until October. *Microcystis* dominated the fall season, with low absolute values of 200 ASU/mL or less dominating the other organisms found at even lower densities.

Chrysophytes and Synurophytes have recently been the most frequently occurring nuisance algae in Wachusett Reservoir. *Dinobryon* was sporadically present at low levels from April through September. *Uroglenopsis* was observed at values greater than 50 ASU/mL for a brief 2 week period in mid May and was observed as present again in October and December. *Synura* was only observed at countable densities a handful of times, most notably in mid June and briefly in late September. *Chrysosphaerella* dynamics were discussed previously.

Anabaena made its usual seasonal appearance in late May, and was found at levels under 10 ASU/mL for most of the year, persisting into the fall. A single peak density for the year of 32 ASU/ml was recorded in a surface sample collected at Cosgrove Intake on July 25.

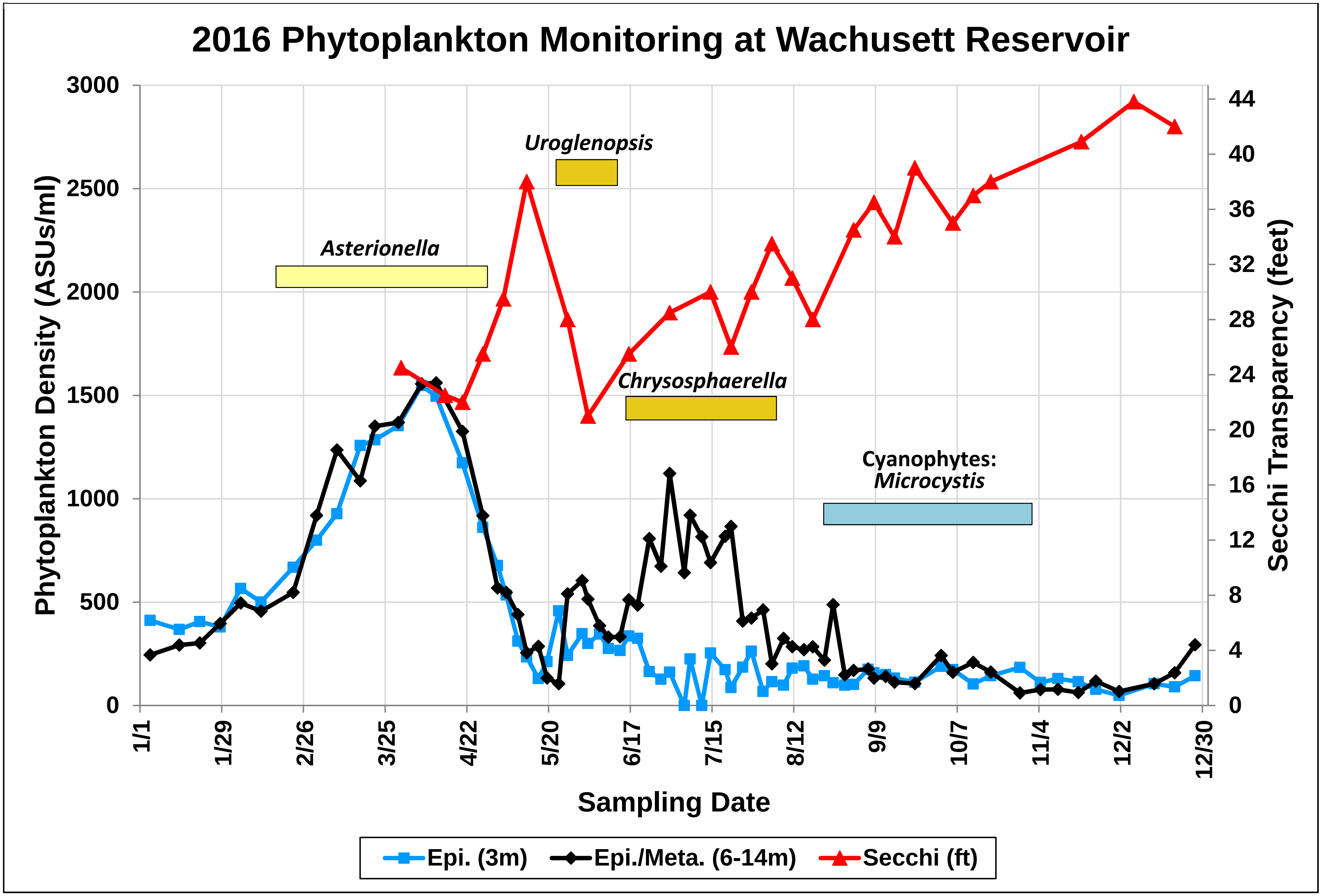
Secchi disk transparency is affected by the phytoplankton dynamics outlined above, as well as the water contributions from the Wachusett watershed and Quabbin transfer. 2016 followed a typical pattern, with early season transparency dictated by phytoplankton density (Figure 15) and watershed inputs. Early season lows of 21 and 22 feet were recorded and a generally increasing trend held from June onward. The Secchi disk depth of 43.8 feet (13.4 meters) recorded on December 6 marked the highest value ever recorded for Wachusett Reservoir, breaking previously held records of 37 feet (2012) and 40 feet (2016) by a comfortable margin. It is worth noting that in early December nutrient levels such as nitrate and total phosphorous were very low, phytoplankton levels were very low, UV254 values were at historic lows, and summer precipitation was so infrequent that a severe drought warning was in place for central Massachusetts for September, October and November (DCR Office of Water Resources 2016). Figure 5 in section 3.2 shows that the total combined flow for the Quinapoxet and Stillwater Rivers was the lowest in the past 10 years. The result was a higher percentage of Quabbin water present in Wachusett in the second half of 2016, even though the Quabbin transfer was typical in volume and duration. The total volume of Quabbin water transferred in 2016 was fractionally higher than 2015, but still 10 billion gallons less than the total transfer in 2012.

Phytoplankton monitoring has been ongoing at Wachusett Reservoir since 1989. Methods of data collection and methods of analysis have remained relatively constant throughout this period of time, although data was recorded in several different electronic formats. All phytoplankton data has been compiled and is being imported into a single database, in order to facilitate future analysis of more than 5,600 samples collected over this 28 year time period.

<u>Reference Cited:</u>

DCR Office of Water Resources. 2016. Massachusetts Drought Declaration Map. Published online at: http://www.mass.gov/eea/images/dcr/watersupply/rainfall/october-2016.jpg.

Figure 17


2016 Phytoplankton Monitoring at Wachusett Reservoir
Phytoplankton Density (ASUs/ml)
Secchi Transparency (feet)
Sampling Date
Asterionella
Uroglenopsis
Chrysosphaerella
Cyanophytes:
Microcystis
3000
2500
2000
1500
1000
500
0
44
40
36
32
28
24
20
16
12
8
4
0
1/1
1/29
2/26
3/25
4/22
5/20
6/17
7/15
8/12
9/9
10/7
11/4
12/2
12/30
Epi. (3m)
Epi./Meta. (6-14m)
Secchi (ft)

4.4.4 WACHUSETT RESERVOIR PHYTOPLANKTON IMAGES

Images shown on the following pages are examples of algae observed in Wachusett Reservoir.

Figure 18
***Bacillarophyceae* (diatoms): *Asterionella,* July 7th 2016, Basin North**

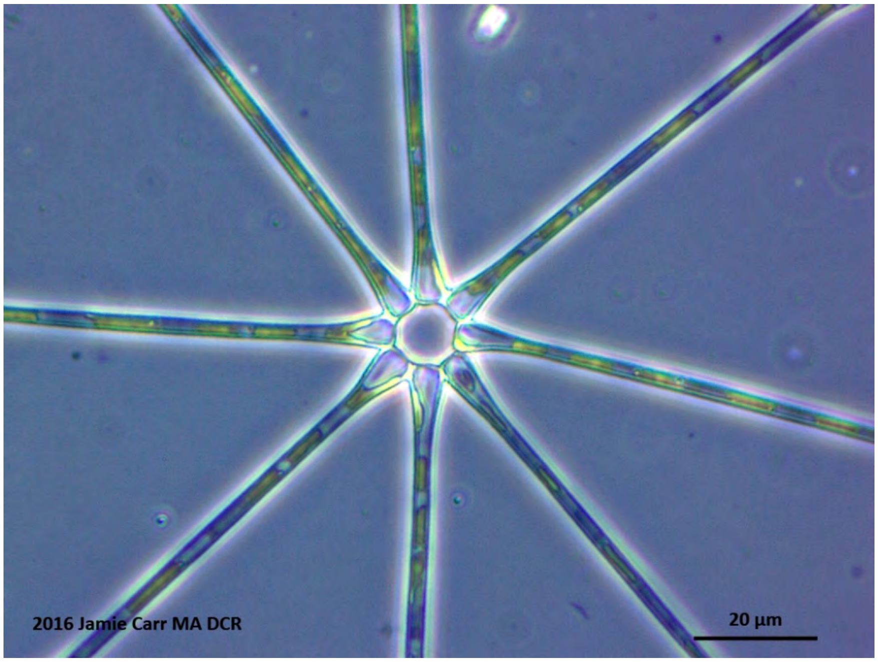


Figure 19
***Bacillarophyceae* (diatoms): *Tabellaria,* August 11th 2016, Basin North**

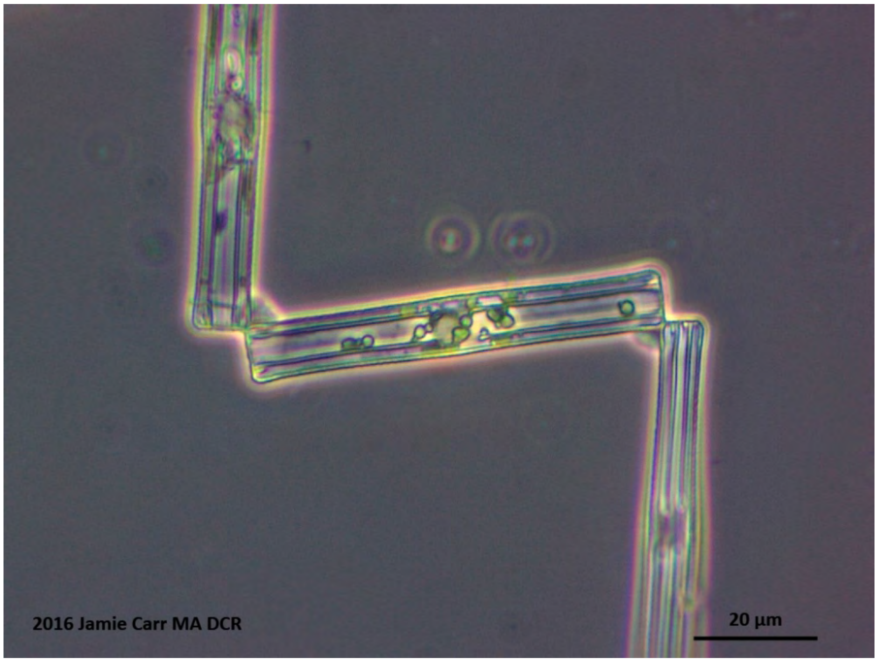


Figure 20
***Chlorophyta* (green algae): *Arthrodesmus*, September 12th 2016, Cosgrove Intake**

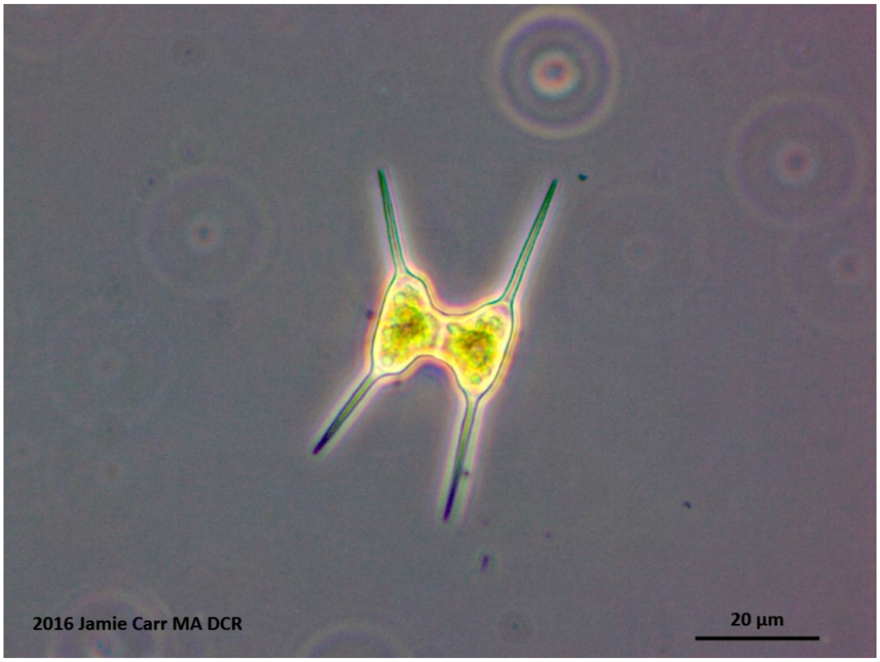


Figure 21
***Chlorophyta* (green algae): *Crucigenia*, July 7th 2015, Basin North**

Figure 22
***Chrysophyta* (golden/golden-brown algae): *Mallomonas*, September 12th 2016, Cosgrove Intake**

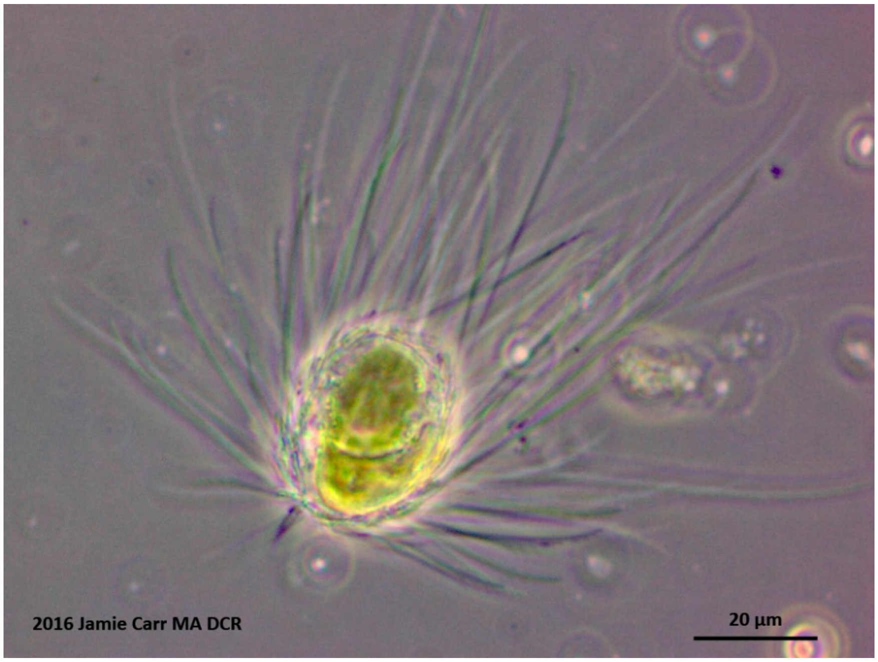
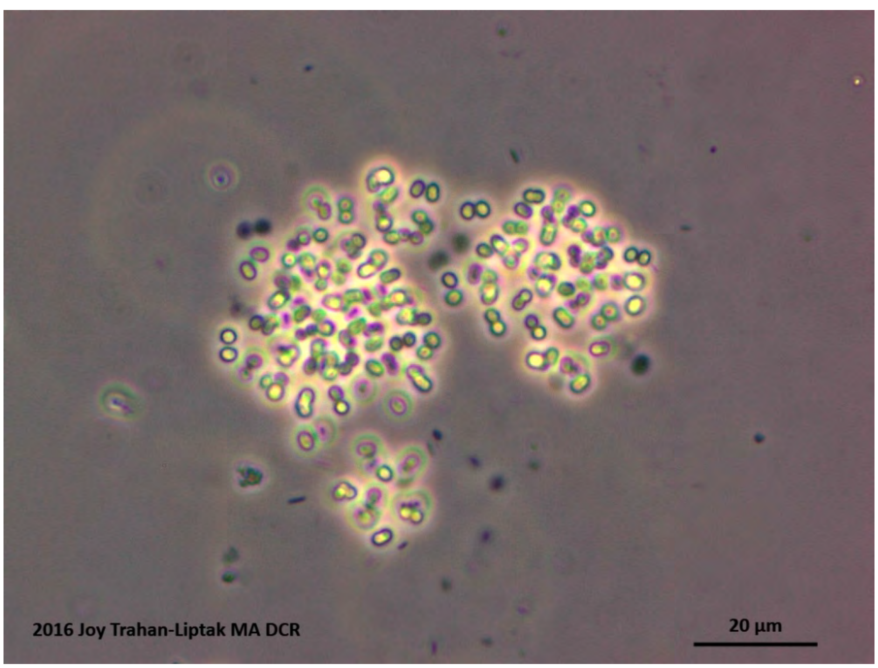


Figure 23
***Cyanophyta* (often called "blue green algae"): *Aphanocapsa*, August 11th 2016, Basin North**



4.5 MACROPHYTES

Non-native aquatic macrophytes (also referred to as aquatic invasive species or AIS) have serious water quality implications including increases in water color, turbidity, phytoplankton growth, and trihalomethane (THM) precursors. These increases result from the function of these plants as nutrient "pumps," extracting nutrients from sediment and releasing them to the water column, mostly as dissolved and particulate organic matter. Non-native, invasive species of macrophytes are known to aggressively displace native vegetation and grow to nuisance densities with the aforementioned impairments to water quality. AIS can be transported to the reservoir system via human or wildlife pathways including, but not limited to; aquarium releases, recreational activity (i.e., fishing and boating equipment), waterfowl movement, and downstream flow. Unless otherwise specified, the non-native species discussed herein have been identified as a threat to water quality and are managed as such.

An update to the 2010 "Aquatic Invasive Species Assessment and Management Plan" was completed in spring of 2016. This document, titled "Wachusett Reservoir Aquatic Invasive Species Summary; Historical Update and Ongoing Actions" summarizes the history and threat of AIS in and around Wachusett Reservoir and addresses future actions.

Table 19: Aquatic Invasive Species in or Around Wachusett Reservoir

Species	Known to be Present in Wachusett Reservoir	Known to be Present in Local Area
Eurasian Milfoil	X	X
Fanwort	X	X
Variable Milfoil	X	X
Brittle Naiad		X
Water Chestnut		X
Brazilian elodea		X
Mudmat	X	
Asian Waterwort	X	

AIS were first recorded in Wachusett Reservoir in the late 1990s and have been actively managed since 2002. Eurasian water-milfoil (*Myriophyllum spicatum*, subsequently referred to as EWM) and *Cabomba caroliniana* (fanwort) are present in several basins of Wachusett Reservoir and are the primary species managed in this system. Variable water-milfoil (*Myriophyllum heterophyllum*, subsequently referred to as VWM) is also present in several areas of the reservoir and is managed on a limited basis. Several minute and cryptic AIS including *Glossostigma cleistanthum* (mudmat) and *Elatine ambigua* (Asian waterwort) have also been documented in the reservoir and are monitored on a routine basis as part of an overall AIS detection and management program.

The following sections of this report provide a brief description of historical infestations and management activities and provide details of management activities undertaken during 2016 and those planned for 2017.

4.5.1 WACHUSETT RESERVOIR INVASIVE MACROPHYTE CONTROL PROGRAM

EWM was first identified in the Wachusett Reservoir system on August 31, 1999. The plants were initially isolated to Stillwater Basin; however, over the next several years, distribution extended southerly, in the direction of water flow, progressing through Oakdale Basin, into Thomas Basin and the upper coves of the Main Basin west of the Route 12/140 causeway in West Boylston. Fanwort followed a similar trend, with the initial discovery of the plant in Stillwater Basin occurring in August 2000.

Figure 24: Locations of 2016 AIS Management in the Wachusett Reservoir system

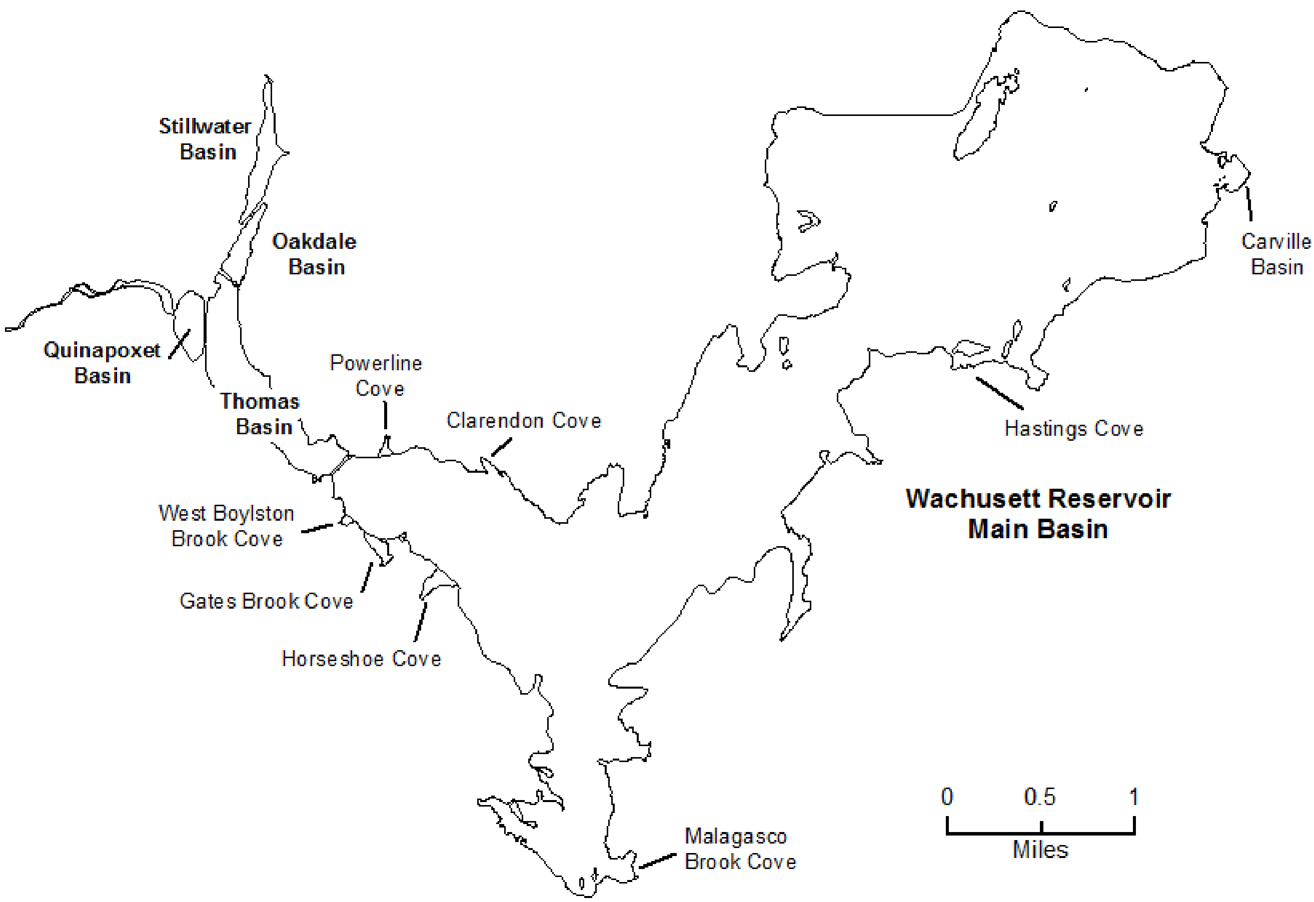
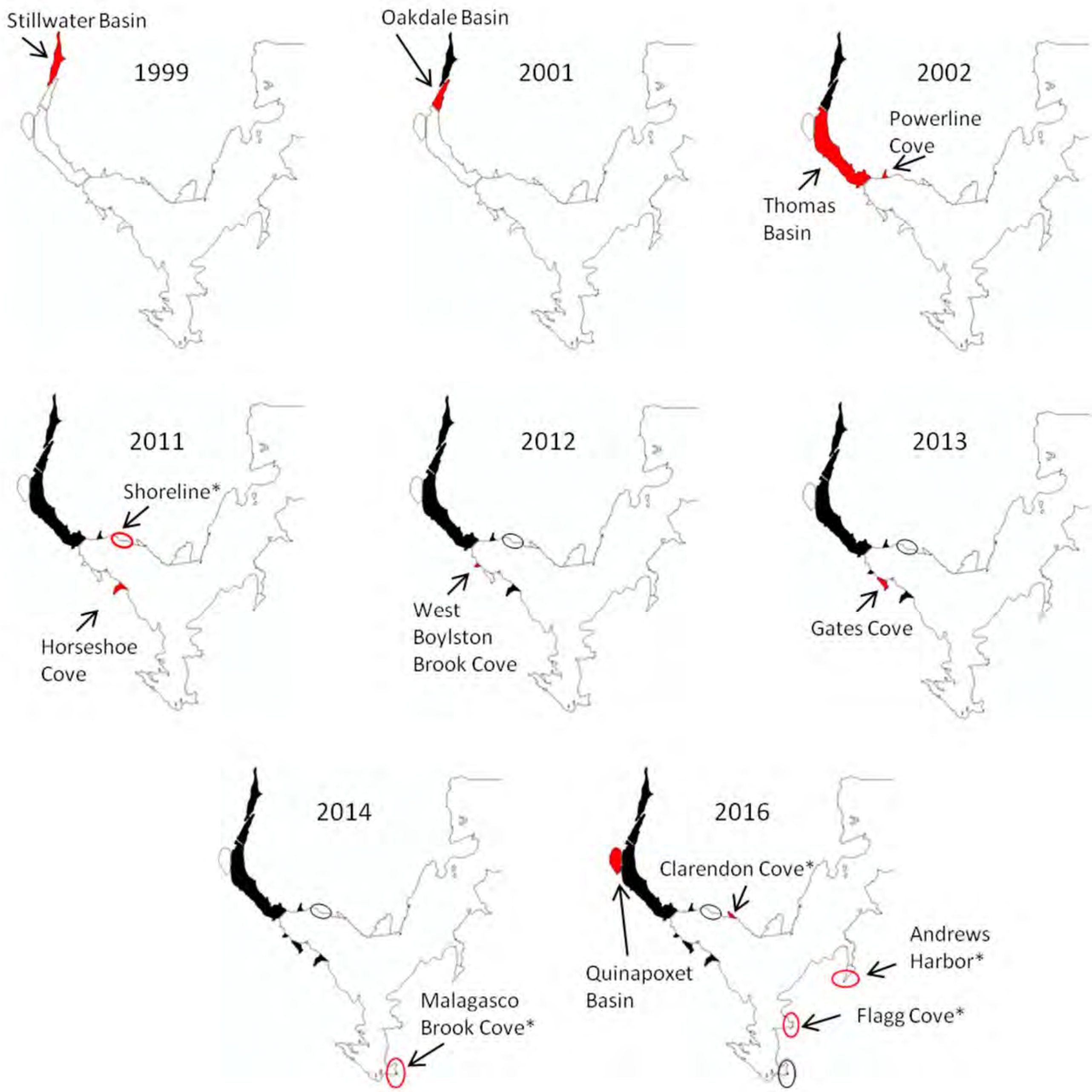


Figure 15: Progression of Eurasian Milfoil distribution in Wachusett Reservoir.



Red indicates a newly discovered occurrence in that year, black indicates a previous occurrence, an asterisk (*) indicates single plants which were present only in the first year shown but continue to be included in annual monitoring efforts thereafter.

The 2001 expansion of EWM into Oakdale Basin prompted the Division and the MWRA to design and implement an invasive macrophyte control program. This program was initiated in 2002 and continues to the present. Details of control efforts in past years are provided in previous annual reports; however, the main components of this program have been the following:

- deployment and maintenance of floating fragment barriers
- placement of benthic barriers
- hand-harvesting and Diver Assisted Suction Harvesting (DASH)
- routine scouting throughout the reservoir system by the Division aquatic biologists to ensure early detection of pioneering infestations
- immediate removal of pioneer infestations upon detection
- point-intercept vegetation surveys by independent contractors (ESS Group, Inc.)

Removal of EWM and fanwort via hand-harvesting was initiated in Oakdale Basin in 2002. Despite these efforts, EWM and fanwort have gradually spread throughout Thomas Basin, and into several coves of the main basin. As new infestations are identified, these areas are also targeted in annual removal efforts. DASH was first utilized in 2012 and has been continued as an additional control strategy for dense patches of plant growth as a complement to the typical hand-harvesting efforts. An extensive DASH project in Stillwater Basin was initiated in 2013 in an effort to reduce the potential for re-infestation from dense growth in this uppermost basin of the reservoir. These physical control efforts are carried out by MWRA contractors supervised, and at times supplemented, by Division aquatic biologists.

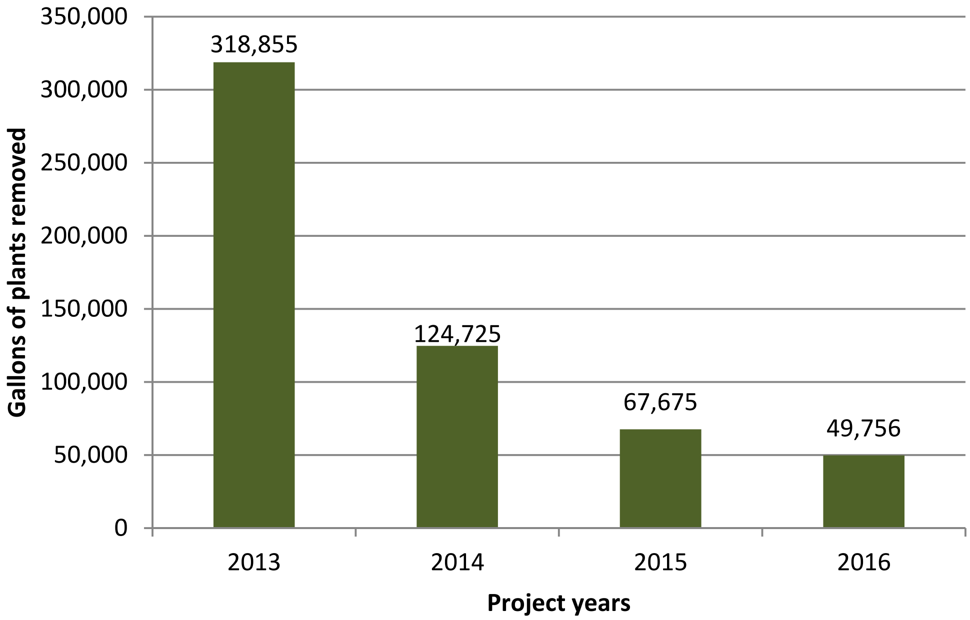
Stillwater Basin

EWM was first identified in Stillwater Basin in 1999 followed by fanwort in 2000. Initially, the density and near 100% coverage of these species in the 34-acre basin caused managers to focus efforts on containing the infestation and preventing further spread downstream by installing fragment curtains and removing downstream pioneer infestations. After several years it became evident that the established populations of EWM and fanwort in Stillwater Basin, provided propagule pressure and an endless supply of potential plant fragments waiting to move downstream. Consequently, a large-scale DASH program targeting EWM, fanwort and VM in this basin was initiated in 2013.

In the project's first season, a total of 322,880 gallons of plant biomass was removed over the course of the six month season. Work has continued through 2016, with the contractor working with multiple DASH units in the basin to perform two full passes of plant removal each year. The total biomass removed has decreased each year, as has the time required to conduct two full passes.

Native plant species have been observed re-colonizing areas previously inundated with invasive species. Pondweed (*Potamogeton*) species including clasping-leaf pondweed (*P. perfoliatus*) and fern-leaf pondweed (*P. robbinsii*) as well as coontail (*Ceratophyllum demersum*), American waterweed (*Elodea canadensis*) and native naiad (*Najas*) species are now common. These observations are encouraging; however, it is anticipated that this will be a long term project with ongoing annual maintenance to reduce the biomass of invasive plants in this basin.

Figure 26: Gallons of Invasive Plants Removed from Stillwater Basin



Oakdale, Thomas, and Main Basin Areas

Hand-harvesting has been conducted by MWRA contractors in Oakdale and Thomas Basins since 2002, with the addition of DASH in 2012. Prior to 2015, the number of invasive plants removed was reported by basin (i.e., a final total for all 175 acres of Thomas Basin), making it difficult to determine if plants were scattered throughout the basins or concentrated in specific areas. It was also difficult to determine if plants were harvested in the same areas year to year or if infestations moved around the basins. In order to identify established beds of target species and track the locations of new occurrences, management areas were broken into smaller zones. Starting in 2015, the numbers of plants removed are reported by zone.

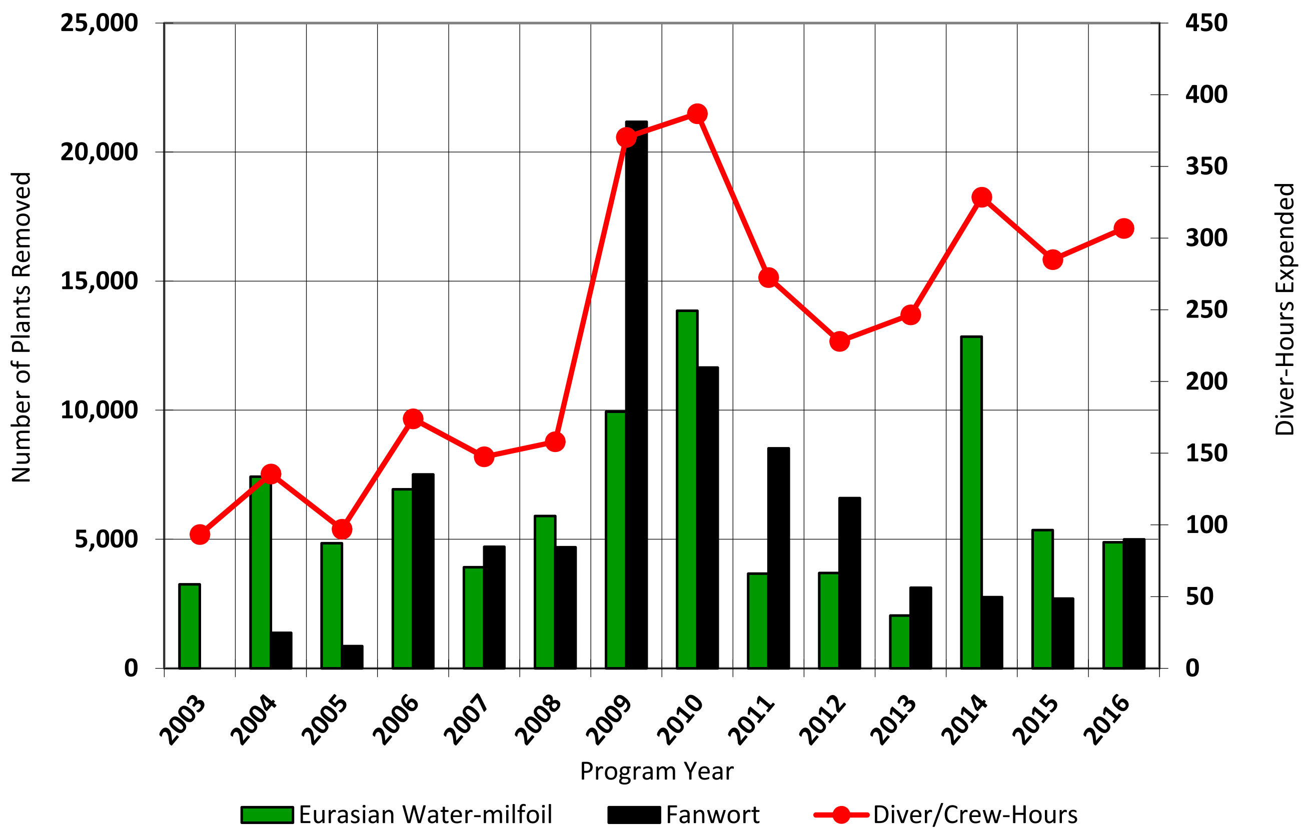
Hand-harvesting and DASH continued in 2016 with a total of 16 days of removal conducted over two phases in July and September. Management activities were guided by pre-harvest surveys conducted by the contractor as well as DCR aquatic biologists. Following the initial removal effort in July, MWRA employed Quality Assurance (QA) divers for 4 days to assess harvest efficiency in select management areas. Data provided by the QA divers in the form of still pictures, video, and survey notes/waypoints indicated that several stands of EWM and fanwort persisted. As a result, the plant-removal contractors were required to conduct an interim harvest event in several zones. The following table presents removal data for the 2016 harvest season, including plants removed by contractors and DCR aquatic biologists.

Figure 27: Fanwort observed by QA divers

Table 20: 2016 Eurasian Milfoil and Fanwort Removal Totals for Oakdale, Thomas, and Main Basin Areas[1]

	Phase 1	DCR	Interim	Phase 2	Total
Dates	July 6 – 15	July 15	Aug 11 – 12	Sept 14 – 26	
# DASH days	4	n/a	n/a	1.5	**5.5**
# Hand-harvest days	7	1	2	7	**16**
# Areas worked/total	31/31	4/31	8 (partial)/31	30/31	
# EWM plants removed	1,095	28	897	2,861	**4,881**
# Fanwort plants removed	1,818	n/a	766	2,409	**4,993**

Figure 28: Invasive Macrophyte Removal Yearly Totals 2003-2016



- In 2002 496.5 diver-hours were expended in removing an estimated 75,000 to 100,000 EWM plants
- 2012-2015 totals include hand-harvesting by divers as well as DASH
- The diver-hour number reported here for 2015 is adjusted to reflect raw data reported to DCR

[1] It should be noted that these totals may conflict with numbers reported elsewhere; however, the numbers presented here are based on DCR's analysis of raw data provided by the contractor and are considered final.

A slight decrease in EWM totals was observed in 2016, with 475 fewer plants pulled than in 2015. The fanwort harvest rose substantially; increasing by 85% to 4,993 plants. This is the greatest number of fanwort plants removed since 2012 and breaks the decreasing trend observed for this species since 2009. Zone data shows that the majority of these fanwort plants were removed from Oakdale Basin Zones 4, 5 and 8 as well as Thomas Basin Zone 4. It is notable that each of these areas (with the exception of Oakdale Zone 8) were included in QA inspections and that the interim harvest subsequently required in these zones yielded 74% more plants than the initial effort. These zones contain large plateau areas where water depths become shallower towards the middle of the basin after an initial drop along the shoreline. These areas may have been overlooked in previous years by divers expecting to find plants directly adjacent to the shoreline. Zone data collected for Thomas Basin indicate that the majority of EWM and fanwort plants are removed from the upper reaches of the basin with a small number of EWM plants removed from coves in the lower portion of the basin.

Despite the use of fragment barriers in infested upper basins (discussed below), some invasive plant fragments reach the main basin of the reservoir. EWM was first detected in Powerline Cove in 2002 and has consistently occurred at low densities since 2009. Fanwort has been detected only in Powerline Cove and only in six out of the last 15 years. EWM has occurred in two additional coves; West Boylston Brook and Gates, since 2012 and 2013, respectively. These areas are routinely surveyed by DCR biologists and contracted divers are directed to remove plants as needed. The overall density of EWM plants in these areas is low; however, soft substrates, especially those found in Gates Brook Cove, provide ideal growing conditions for aquatic plants.

Table 21: Invasive Plants Removed from Main Basin Coves

	Powerline Cove		**West Boylston Brook Cove**	**Gates Cove**
	Fanwort	EWM	EWM	EWM
2002	-	14	-	-
2003	-	0	-	-
2004	-	0	-	-
2005	-	21	-	-
2006	-	18	-	-
2007	1	1	-	-
2008	-	-	-	-
2009	17	59	-	-
2010	7	22	-	-
2011	4	75	-	-
2012	5	103	13	-
2013	-	7	1	60
2014	1	37	14	141
2015	-	51	22	61
2016	-	20	1	104

Outlying Occurrences of Eurasian Water-milfoil

Prior to 2016, Horseshoe Cove and Malagasco Brook Cove contained the furthest known occurrences of EWM in outlying areas of the reservoir. During the whole-reservoir shoreline survey conducted in 2016 (see discussion below), a single stem of EWM was found and removed from Flagg Cove. This survey also identified several new areas which were prioritized for further assessment via snorkel survey. These areas were snorkeled by DCR aquatic biologists and several new locations of EWM growth were identified. In each case, plants were removed in their entirety.

Table 22: Locations of EWM

	Number of EWM Plants Removed			
Location	**2011**	**2012**	**2014**	**2016**
Andrews Harbor	–	–	–	1
Clarendon Cove	–	–	–	1
Flagg Cove	–	–	–	1
Horseshoe Cove	4	6	–	1
Malagasco Brook Cove	–	–	1	–

No plants were discovered in these areas during 2013 or 2015.

Early identification and removal of pioneer plants such as these reduce the risk that these plants will proliferate and become a larger management and budget concern in the future.

Quinapoxet Basin

Quinapoxet Basin is located on the west side of Thomas Basin, separated by a railroad track causeway. Directly upstream of the basin is the Quinapoxet River dam and Shaft One where water transferred from Quabbin Reservoir enters the Wachusett Reservoir system. VWM has been known to exist at great densities in this basin since at least 1989. This infestation was last confirmed in 2013 when DCR aquatic biologists documented dense cover of VWM throughout the 30-acre basin.

DCR aquatic biologists conducted a survey of this basin again in August 2016. VWM continues to persist through the basin and two additional invasive species, EWM and fanwort, were identified. Two moderately dense patches of EWM were present in the northern portion of the basin, with additional EWM plants scattered along the eastern and southern shoreline. Fanwort was isolated to the southern shoreline. As noted elsewhere in this report, these species are already present in downstream locations;

Figure 29: Fragment barrier installed at Quinapoxet Basin railroad bridge.

however, their presence in Quinapoxet Basin represents another potential source of fragments which could easily move downstream via water currents or elsewhere via wildlife vectors.

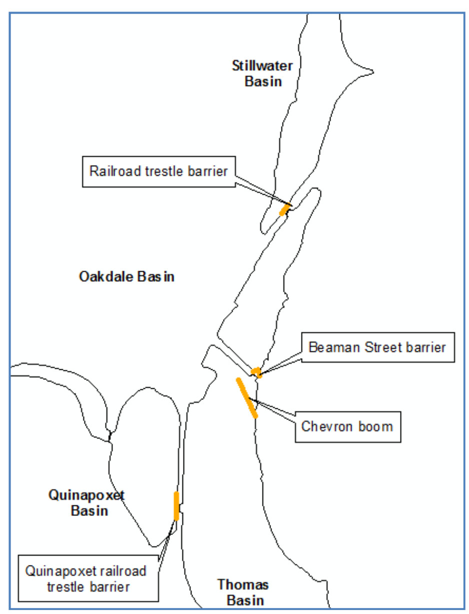
Removal efforts were initiated in September with creation of a boat launching area on the north side of the basin and installation of a fragment curtain at the railroad causeway. DASH was conducted over a one day period in October and approximately 170 EWM plants were removed. Despite thoroughly covering the area where fanwort growth was documented, no fanwort growth was observed by divers in the fall. This area will be added to DCR's routine AIS monitoring locations and removal work will continue as necessary.

Hastings Cove and Carville Basin Variable Water-milfoil

Variable milfoil is present in localized areas throughout the reservoir. In most locations this species occurs at sparse densities; however, in 2013, a localized but dense bed of VWM was identified in the Hastings Cove area of the main basin. Due to the close proximity of this location to the Cosgrove Intake Facility and observations of VWM fragments in the area, the VWM in Hastings Cove has been managed with DASH since 2013. A total of 18,376 plants were removed from an area of only 1/3 of an acre in 2013. In 2016 a total of 3,420 VWM plants were removed which represents an increase from the past two years. The contractor noted that this year's growth pattern appeared to be different, with plants growing slightly deeper than in previous years. This may be attributed to a drawdown of the reservoir water level in early spring which may have allowed deeper light penetration, triggering early season growth of plants at deeper depths.

Reservoir shoreline scouting and snorkel surveys identified several additional areas of VWM. Most of these areas are small and sparse; however, a more dense bed of VWM was identified in Carville Basin, another location in close proximity to the Cosgrove Intake Facility. This area was subsequently added to the DASH work areas and 113 plants were removed in October.

Figure 30: Locations of Fragment Barriers



Fragment Barriers

In addition to the activities summarized above, DCR staff maintained floating fragment barriers at strategic bottleneck locations to restrict the movement of invasive fragments into down gradient portions of the reservoir system. These locations consist of the railroad trestle bridge between Stillwater Basin and Oakdale Basin and the Beaman Street Bridge between Oakdale Basin and Thomas Basin (Figure 17). The floating fragment barriers were initially purchased and deployed at these locations in 2002. Additionally, a 400 foot floating boom has been deployed in a chevron configuration downstream of the Beaman Street bridge and left in place from early spring through late fall in each year since 2012. This boom is positioned at an angle to the shore and to the flow moving under the bridge, such that plant fragments are guided to the shoreline by the boom instead of continuing into Thomas Basin along with the current. Observations of fragments collected in the chevron boom suggest that this boom works well to trap invasive plant fragments. As mentioned above, an additional fragment barrier has been installed at the railroad bridge between Quinapoxet Basin and Thomas Basin to reduce the spread of fragments entering from that basin.

Reservoir-Wide Survey Activities

Whole-reservoir Shoreline Survey and Biovolume Mapping

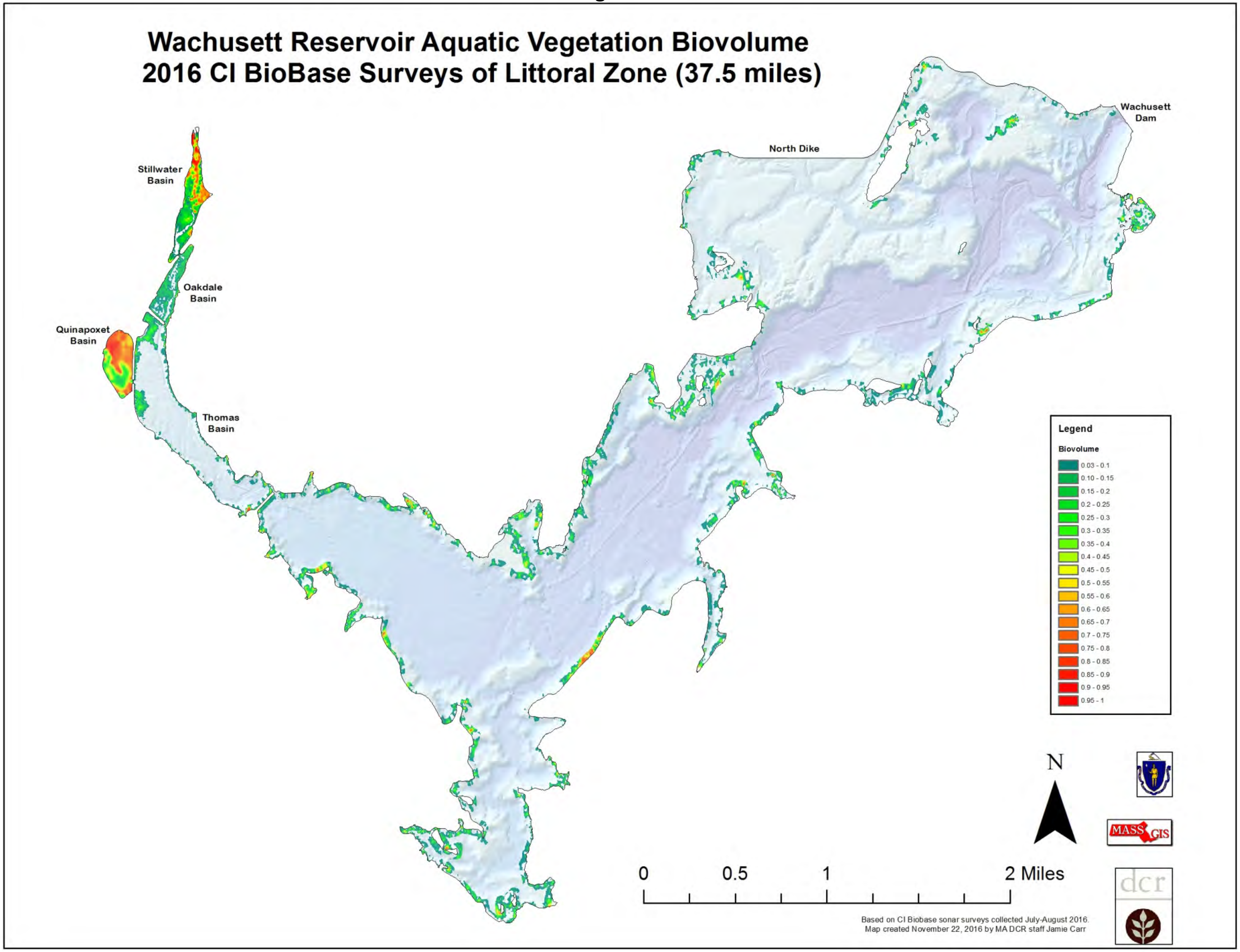
A complete visual survey of the entire littoral zone of Wachusett reservoir was last completed in 2011. The goal of this type of survey is to catch and identify any new infestations of invasive plants before they become well established. Given the amount of time required to complete an entire shoreline survey the goal is that it can be repeated every five years. Doing so also identifies priority areas that are monitored much more frequently in the interim (see section on Outlying Occurrences of EWM above).

In order to facilitate surveys, the reservoir was divided into 13 different zones (See annual report 2011 Figure 9 for map) in order to systematize scouting efforts and ensure that each portion of reservoir shoreline was scouted during the summer growing season. Scouting consisted of slowly patrolling the shoreline by boat, with one person standing on the bow identifying any plant growth and stopping to further examine at anything that could not be readily identified on the first pass. Scouting was conducted on calm days or along leeward shores in order to maintain the best viewing conditions from the boat. A total of 37.5 miles of shoreline (including island shorelines) was surveyed in this effort between July 28th and August 24th.

Additionally, during this year's survey, data was continually collected with a Lowrance® fish finder, such that the sonar logs could be uploaded to CI Biobase software to produce plant biovolume maps for all areas surveyed (Figure 31). This technology interpolates aquatic plant biovolume along the travel route of the boat by using the latitude and longitude recorded in a file and interpretation of the bottom depth and depth to aquatic plant growth. This information is extremely insightful in order to identify aquatic plant biovolume density patterns, measure areas of growth, and identify hotspots and priority areas for further monitoring. Data uploaded to the CI Biobase website was processed, quality checked, and exported to be further processed and assembled into a single map layer in ArcMap 10.3.

Results of the littoral zone survey clearly show that the highest density of aquatic plant growth in Wachusett Reservoir is concentrated in the upper basins, where plant management activities are already underway. These areas provide the best habitat for aquatic plant growth in terms of shallow depth, warmer water temperatures, softer substrates, and higher nutrient inputs. All or most of these attributes are lacking in the majority of the main basin, where the majority of the plant biovolume recorded was comprised of native clasping-leaf pondweed (*Potamogeton perfoliatus*) growth. Areas of dense growth were also observed in smaller coves with stream inputs and in shallow depositional areas within the reservoir.

Figure 31



Wachusett Reservoir Aquatic Vegetation Biovolume
2016 CI BioBase Surveys of Littoral Zone (37.5 miles)
Stillwater Basin
Oakdale Basin
Quinapoxet Basin
Thomas Basin
North Dike
Wachusett Dam
Legend
Biovolume
0.03 - 0.1
0.10 - 0.15
0.15 - 0.2
0.2 - 0.25
0.25 - 0.3
0.3 - 0.35
0.35 - 0.4
0.4 - 0.45
0.45 - 0.5
0.5 - 0.55
0.55 - 0.6
0.6 - 0.65
0.65 - 0.7
0.7 - 0.75
0.75 - 0.8
0.8 - 0.85
0.85 - 0.9
0.9 - 0.95
0.95 - 1
N
0
0.5
1
2 Miles
Based on CI Biobase sonar surveys collected July-August 2016.
Map created November 22, 2016 by MA DCR staff Jamie Carr

Contractor Aquatic Macrophyte Surveys

MWRA contracted with ESS Group, Inc. in 2016 to carry out point-intercept surveys of DCR/MWRA source and emergency reservoirs. These surveys have been conducted on an annual basis since 2013 with a previous survey conducted in 2010. No new AIS were identified in Wachusett Reservoir during the 2016 survey.

Additional AIS Observations

DCR Aquatic Biologists are continually scouting for known AIS in new locations, while at the same time keeping a lookout for any potential new introductions. In recent years, three new non-native aquatic plants were detected in Wachusett Reservoir: Mudmat (*Glossostigma cleistanthum*), Asian waterwort (*Elatine ambigua*), and Onerow yellowcress (*Rorippa microphyla*). Information and review of each of these species was presented in the 2014 Annual report (MA DCR 2015). Field observations conducted in 2015 and 2016 appear to support the early conclusion that these species are not an imminent threat to the water quality or ecological balance of the reservoir and are not candidates for active management at this time.

References Cited:

MA DCR. 2012. Water Quality Report: 2011, Wachusett Reservoir Watershed.
MA DCR. 2015. Water Quality Report: 2014, Wachusett Reservoir Watershed.
ESS Group, Inc. 2016. Aquatic Macrophyte Surveys, MWRA/DCR Source and Emergency Reservoirs.

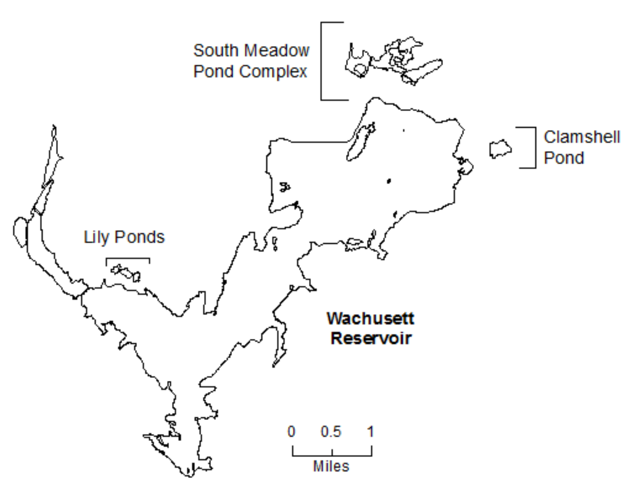
4.5.2 SUPPLEMENTAL INVASIVE MACROPHYTE CONTROL ACTIVITIES

Additional activities were conducted in 2016 outside of the Wachusett Reservoir in conjunction with the main components of the in-reservoir invasive control program. Details of these activities are presented below.

Infestations in Close Proximity to Wachusett Reservoir

AIS have been discovered in several local ponds in recent years (Figure 32). Although technically outside of the Wachusett Reservoir watershed, two of these ponds/complexes have been identified as potential sources of invasive species due to their close proximity to the reservoir. The potential for transfer of invasive species present in these water bodies to the reservoir by waterfowl or bait buckets necessitates special management and monitoring efforts. Management of the following ponds is on-going.

Figure 32: Locations of Local Ponds



South Meadow Pond Complex

In August of 2010, the invasive macrophyte hydrilla (*Hydrilla verticillata*) was discovered in South Meadow Pond in the Town of Clinton. The South Meadow Pond complex (which includes South Meadow Pond West and East as well as Coachlace and Mossy Ponds) is located only about 1,970 feet (600 m) north of Wachusett Reservoir. Within a month of the discovery of hydrilla in the South Meadow Pond complex, DCR and the MWRA collaborated on response efforts and implemented a program to suppress hydrilla biomass, hiring a contractor to implement a control plan and apply herbicides. The treatment and monitoring program has continued through 2016.

Annual reductions in pre-treatment tuber density were realized with no tubers observed in 2015. Pre-treatment tuber density increased in 2016, particularly at stations in the west basin of South Meadow Pond and in the east basin close to the boat launch. The following is an excerpt of the contractor's report summarizing their findings in regards to tubers:

> After a consistent decreasing trend in tubers from 2010-2014 and no tubers observed in 2015, some were found during this year's sampling. While still relatively low, the average tuber density was the highest since 2012 and is concerning from a management perspective. Since substantial Hydrilla growth was observed in 2015 when no tubers were found, it's unlikely that there were actually no tubers present that year, but just that the tuber density was low enough that the discrete sampling methods missed finding them. The observations in 2016 do indicate that tuber density is increasing and that the management program is not adequately controlling the plant growth prior to tuber production. Much of the increase may be due to the late timing of treatment in 2015, but it will also be important to carry through on some changes in timing and herbicide choice. (SOLitude Lake Management 2016)

Approximately 23 acres of hydrilla were treated over all four basins of the pond complex on July 13, 2016. VWM was also treated in approximately seven acres. The post-management survey of the South Meadow Ponds complex showed 'minor' re-growth of hydrilla along South Meadow Road and in the southwest portion of Mossy Pond. The plant population of a 3-acre cove of Coachlace Pond was observed to shift from dense VWM to 95% cover of hydrilla.

DCR aquatic biologists conducting a spring survey of the South Meadow Pond Complex observed extensive growth of an additional invasive species; curly-leaf pondweed (*Potamogeton crispus*, CLPW). This species initiates growth early in the spring before many other aquatic plant species and senesces in early summer after producing turions. It is therefore likely that CLPW has been present in the complex for a period of time, but was not observed due to surveys timed for mid-summer. Despite efforts to have this newly identified infestation managed via herbicides upon detection in 2016, treatment was not possible before the plants naturally senesced. Treatment for this species is anticipated in early spring 2017.

<u>References Cited:</u>

SOLitude Lake Management. 2016. Final Report for 2016 Aquatic Plant Management, South Meadow Pond. Prepared for Massachusetts Department of Conservation and Recreation Lakes and Ponds Program.

Clamshell Pond

Clamshell Pond is located approximately 1,300 ft (400 m) from the Wachusett Reservoir shoreline, east of Cosgrove Intake. The pond is bordered by land owned by DCR, the Town of Clinton (Rauscher Farm Conservation Area), a homeowners association, and two private property owners. Two records (in separate databases) of two invasive species in Clamshell Pond were recently discovered: Water Chestnut (*Trapa natans*) and Brazilian Elodea (*Egeria densa*). Both records were recorded in 2008 by Dr. Robert Bertin of Holy Cross. In June 2016, DCR aquatic biologists, with assistance from DCR Lakes and Ponds, conducted assessments of Clamshell Pond and determined that both water chestnut and Brazilian elodea were present.

Figure 33 Water Chestnut Plant

Figure 34: Brazilian Elodea

Water chestnut was observed at low densities around the perimeter of the pond. It was determined that management of water chestnut would be possible via hand-harvesting by two DCR biologists using a canoe. Following communication with the Clinton Conservation Commission, harvesting took place on June 24th and 28th when a total of 874 rosettes were removed and August 31st when an additional 30 rosettes were removed for a season total of 904 rosettes.

Brazilian elodea was found in more than 70% of the pond with dense growth most common. This invasive species is uncommon in Massachusetts (reported in less than 20 locations state-wide) and is likely the result of an aquarium release. Although the historical record and extent of growth indicate that this species has likely been present within the pond for some time, and may have expanded to its maximum extent, it remains a water quality threat to Wachusett Reservoir. As a result, DCR plans to work with the surrounding property owners to develop a management plan to reduce the potential for spread of this species to the reservoir and other area water bodies.

Lily Ponds

The 'Lily Ponds' consist of three small water bodies locally referred to as West, Middle, and East Lily Pond. The ponds are located in West Boylston approximately 500 feet to the north of Wachusett Reservoir, are fed via overland flow and groundwater seepage, and are not directly connected to the reservoir by surface flow. These water bodies are accessed via Wachusett Reservoir Gate 28 and are popular fishing and bait collection areas. The ponds are also frequented by ducks, geese, and wading birds. Surveys of the Lily Ponds conducted by DCR Aquatic Biologists as part of their assessment of ponds in the Wachusett Watershed in August 2015 revealed the presence of *Najas minor* (European/Brittle Naiad) in each of the three ponds as well as EWM in Middle Lily Pond. The ponds were closed to fishing upon discovery of the infestation due to public's use of the ponds for fishing and bait collection and management of the ponds via herbicides was initiated in fall 2015.

Surveys of the ponds carried out in 2016 found that both EWM and brittle naiad was reduced in each pond; however, these plants were still present at low densities and were managed with a single herbicide treatment on August 29th. Observations show that herbicide treatments have reduced the distribution and density of EWM and brittle naiad in the Lily Ponds; however, annual monitoring and maintenance will likely be ongoing. As biomass continues to decrease, spot treatments, hand-harvesting, and other methods intended to target small infestations may be recommended.

<u>Reference Cited:</u>

SOLitude Lake Management. 2016. 2016 Year-End Report, Lily Ponds. Prepared for Massachusetts Department of Conservation and Recreation Lakes and Ponds Program.

Watershed Pond Assessments

As time allows, DCR Aquatic Biologists conduct surveys of water bodies within the Wachusett Reservoir Watershed and in close proximity to the reservoir. These baseline surveys are used as screening tools for non-native aquatic vegetation and to inform watershed and reservoir managers regarding non-native plant infestations that have the potential to spread to Wachusett Reservoir. Water bodies are selected based on their-proximity to the reservoir, size, public access, and known presence of invasive vegetation based on historical data (Table 23).

Table 23: Wachusett Reservoir Area Ponds Surveyed in 2016 for Non-native Aquatic Vegetation

Name	Town	Proximity to Wachusett Reservoir (miles)*	Acres	Number of Invasive Vegetation Species Observed	Year management initiated
Clamshell Pond	Clinton	0.25	24.3	2	2016
Eagle Lake	Holden	4.89	58.2	1	n/a
Lily Pond East $^{\alpha}$	West Boylston	0.21	4.7	1	2015
Lily Pond Middle $^{\alpha}$	West Boylston	0.21	7.5	2	2015
Lily Pond West $^{\alpha}$	West Boylston	0.26	4.3	1	2015
Lancaster Mill Pond	Clinton	0.04	23.3	1	n/a
Maple Spring Pond	Holden	8.74	40.4	1	n/a
South Meadow Pond Complex $^{\alpha}$	Clinton/Lancaster	0.3	130	3	2010
Stump Pond	Holden	4.97	28.2	1	n/a

* number of miles to closest reservoir shoreline location
$^{\alpha}$ surveyed as part of an ongoing management program

Surveys were primarily conducted by paddling a canoe throughout the littoral zone. Observations of the aquatic vegetation community including species composition and densities were made visually through the water surface or by periodic use of a throw rake to collect plants from the bottom substrates. These data were recorded in a field notebook along with corresponding GPS waypoints for later entry into Excel spreadsheets and/or GIS. When feasible, photographs of observed organisms and of the general area are also taken to document findings.

4.5.3 PLANS FOR INVASIVE PLANT CONTROL EFFORTS IN 2017

The invasive nature of AIS necessitates a long-term commitment to annual control efforts in the upper reaches of the Wachusett Reservoir system if their dispersal into the main basin is to be prevented. To meet this challenge, DCR and the MWRA continue to work collaboratively to sustain annual control efforts and refine the control program as necessary.

Next year, during the 2017 growing season, plans call for a resumption of intensive management in Oakdale and Thomas Basins as well as the main basin coves. Starting in 2017, DASH will be utilized as the primary removal technique in all management areas. As usual, surveys will be utilized to direct harvest efforts; however, these assessments will be undertaken solely by DCR aquatic biologists who will also guide contractor efforts and manage data collection throughout the project. The large scale Stillwater Basin DASH project is scheduled to resume again at the beginning of June 2017 for another full season of intensive harvesting.

Associated with harvesting efforts, DCR aquatic biologists will continue systematic scouting for invasive macrophytes throughout the reservoir system to identify and target any pioneering specimens found in new locations. The single stems of EWM found in 2016, as far west as Andrews Harbor, are concerning and these areas, as well as priority locations identified during the shoreline survey, will be monitored to determine if spread is occurring and to evaluate if any potential management actions are prudent.

The following is a brief list of activities carried out related to AIS:

- Coordinate with AIS contractors for access, monitor progress, direct work
- Monitor efficacy of herbicide treatments in area ponds
- Install and maintain floating fragment barriers
- Conduct surveys of areas of interest (Stillwater, Oakdale, Thomas, main basin coves)
- Conduct annual surveys of local water bodies
- Respond to any new AIS discoveries as appropriate
- Inspect all boats accessing the reservoir and collect decontamination forms

4.6 FISH

Fish are an important component of the reservoir ecosystem and knowledge of fish population dynamics in the reservoir is important to understanding the Wachusett Reservoir food web and its impacts upon drinking water quality. Fisheries work in the reservoir has primarily consisted of historical angler creel surveys, conducted in 1979, 1980 and 1998. More recent angler creel surveys conducted in 2011 and 2012 show that the species most frequently caught by anglers have changed over the past 30 years, and that this likely reflects changes in the fish community composition over this time period. It is hoped that an angler creel survey will be conducted for Wachusett Reservoir during the 2017 season as well, pending availability of resources. Further study to learn more about the current population status, life history, and sustainable yield of Lake Trout (*Salvelinus namaycush*) in the Wachusett Reservoir was recommended due to their presence as the top cold water predator in the reservoir food chain and the absence of information about their population (Carr 2015).

Historically, actual sampling of fish in Wachusett Reservoir has been sporadic and infrequent due to a lack of available resources. In 2014, MA DFW and MA DCR partnered to initiate a tagging study of lake trout in Wachusett Reservoir similar to an ongoing effort for Quabbin Reservoir. This project involves setting gill nets to capture lake trout moving onto their shallow spawning areas after dark in the fall, weighing and measuring each fish caught, inserting a passive integrate transponder (PIT) tag, and releasing the fish. In subsequent years, if a lake trout is recaptured, the PIT tag will identify that specific fish and changes in weight and length can be recorded. As more fish are tagged in subsequent years, more fish will be recaptured and more information will be gained.

To date 338 lake trout have been captured during the 2014, 2015, and 2016 fall sampling efforts. A total of 293 individual lake trout have been tagged and released. Thirteen fish that had been tagged and released previously have been recaptured (3 fish have been recaptured twice). Twenty-nine fish were either released without being tagged, harvested for collection of otoliths to aid in future age analysis, or considered mortalities.

To date, 77% of lake trout captured in Wachusett Reservoir have been males, and 23% have been females. It is believed that male lake trout are caught more frequently in gill nets when spawning because they spend more time making multiple passes of the spawning are searching for females. Females are believed to move onto the spawning area to spawn without lingering and thus are less likely to be captured.

Figure 35 A captured lake trout is measured before being tagged

Figure 36 PIT tag used for tagging lake trout

<u>Reference Cited:</u>

Carr, Jamie. 2015. Wachusett Reservoir Creel Survey Report: Survey Years 2011 and 2012. Massachusetts Department of Conservation and Recreation, Division of Watershed Management.

5.0 SAMPLING PLAN FOR 2017

The Wachusett watershed sampling program for 2017 follows protocols used during previous years. Temperature, specific conductance, *E. coli*, and turbidity will be measured weekly or biweekly at nineteen stations on eighteen tributaries during dry and wet weather. Additional sampling will be done as needed to help locate occasional sources of contamination. Samples will also be collected to support potential enforcement actions required by other Division staff. Nutrient samples will be collected monthly from ten tributary stations with available flow data and samples for orthophosphate and UV-254 will continue to be collected weekly from the Stillwater and Quinapoxet Rivers.

The routine sampling program provides data on the effects of storm events on tributary water quality using detailed precipitation data from stations within or near the watershed. Additional stormwater sampling will be done to obtain data on specific storm types (length, intensity, and season) following an evaluation and assessment of existing information . Samples during 'extreme' storm events will be collected when possible to support UMASS modeling efforts.

Understanding watershed hydrology is a necessary part of any water quality monitoring program. A continuation of the hydrology monitoring program is planned for 2017. Precipitation data from NOAA weather stations in Worcester and from the USGS stations on the Stillwater River in Sterling and the Quinapoxet River in Holden will be collected daily. Snow pack measurements and calculation of snow-water equivalent amounts will be done regularly during the winter months throughout the watershed. All data will be regularly uploaded into the existing database.

Depth will be recorded at seven stations and flow calculated using rating curves developed by Division staff and refined using Aquarius software tools. Depth measurements will be collected continuously using HOBO water level data loggers that have been installed within custom designed enclosures that should allow winter measurements. Additional locations may be added to increase our understanding of flow throughout the watershed. Flow measurements will be taken at several times throughout the year to correct or improve existing rating curves. Daily flow in Gates Brook and the Stillwater and Quinapoxet Rivers will be obtained from continuous recording devices installed by the USGS.

Sampling at all active logging operations will continue with turbidity samples collected above and below each proposed stream crossing during dry and wet weather prior to the start of any activity to establish baseline conditions, during the installation of all temporary bridges or pole crossings, regularly throughout active logging operations, and after all activity has ceased. Sampling will also occur where timber harvesting is taking place within fifty feet of a stream or steep slopes are present. Summary reports will be produced for each location once active operations are complete and post-cutting monitoring has ended.

Monitoring to assess impacts of active forest management will continue. The monitoring effort utilizes paired subbasin sampling at and near a single forestry site in the Wachusett watershed. Sampling includes monthly dry weather grab sampling and quarterly storm event monitoring using automatic samplers for turbidity, total suspended solids, total organic carbon, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, and total phosphorus. Documentation of tributary flow and precipitation amounts and intensity will also be done. Data will be used to estimate nutrient loading and will be compared to loading estimates from other subbasins across the Wachusett watershed to determine if Division forestry management methods prevent measurable impacts upon stream water quality. A summary report that covers the first three years of the study will be completed in June 2017.

Temperature, dissolved oxygen, pH, and conductivity profiles will be measured weekly from the reservoir at Basin North/Station 3417 in conjunction with weekly or twice weekly plankton monitoring. More frequent profiles will be collected when necessary to document changing conditions in the reservoir. Samples for nitrate-nitrogen, ammonia-nitrogen, total Kjeldahl nitrogen, total phosphorus, and total silica will be collected quarterly at Basin North/Station 3417, Basin South/Station 3412, and Thomas Basin using standard methodologies used in the past.

Movement of water and contaminants through the reservoir remains the focus of significant interest. Sampling of the reservoir surface will continue on a regular basis. Monthly, biweekly, or weekly bacterial transect sampling will be done during ice-free periods to help further understand the effect of avian populations and water movement on fecal coliform levels throughout the reservoir.

A comprehensive analysis of water quality sampling over the past three decades is expected to be completed during 2017. This could result in small scale or potentially significant changes to the water quality sampling program in 2018 and beyond, and will be discussed in detail in the 2017 Wachusett Reservoir Watershed Water Quality Report.

APPENDIX A:

Results of Quarterly Nutrient Sampling:
Total Phosphorus (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	05/04/16	07/13/16	10/05/16	12/06/16
MD25	Basin North (E)	0.005	0.006	<0.005	0.006
MD61	Basin North (M)	0.006	0.008	<0.005	0.005
MD62	Basin North (H)	0.005	0.008	0.005	0.005
MD26	Basin South (E)	0.006	0.005	<0.005	0.006
MD63	Basin South (M)	0.005	0.007	<0.005	<0.005
MD64	Basin South (H)	0.006	0.007	0.005	0.008
MD27	Thomas Basin (E)	0.011	0.005	<0.005	0.010
MD65	Thomas Basin (M)	0.008	0.009	<0.005	0.010
MD66	Thomas Basin (H)	0.011	0.008	<0.005	0.015

Results of Quarterly Nutrient Sampling:
Ammonia NH_3 (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	05/04/16	07/13/16	10/05/16	12/06/16
MD25	Basin North (E)	0.006	0.006	<0.005	0.006
MD61	Basin North (M)	0.007	<0.005	<0.005	0.005
MD62	Basin North (H)	0.008	0.036	0.017	0.005
MD26	Basin South (E)	0.007	<0.005	<0.005	<0.005
MD63	Basin South (M)	<0.005	<0.005	0.008	0.009
MD64	Basin South (H)	0.012	0.008	0.024	0.007
MD27	Thomas Basin (E)	<0.005	<0.005	<0.005	<0.005
MD65	Thomas Basin (M)	<0.005	<0.005	0.008	<0.005
MD66	Thomas Basin (H)	0.007	<0.005	<0.005	0.009

Results of Quarterly Nutrient Sampling:
Nitrate NO_3 (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	05/04/16	07/13/16	10/05/16	12/06/16
MD25	Basin North (E)	0.033	<0.005	<0.005	0.032
MD61	Basin North (M)	0.043	<0.005	<0.005	0.030
MD62	Basin North (H)	0.043	0.056	0.080	0.030
MD26	Basin South (E)	0.038	<0.005	<0.005	0.031
MD63	Basin South (M)	0.045	<0.005	0.012	0.031
MD64	Basin South (H)	0.052	0.019	0.072	0.034
MD27	Thomas Basin (E)	0.071	<0.005	<0.005	0.036
MD65	Thomas Basin (M)	0.068	<0.005	<0.005	0.037
MD66	Thomas Basin (H)	0.112	<0.005	0.012	0.095

Results of Quarterly Nutrient Sampling:
Total Kjeldahl Nitrogen (mg/L; MDL = 0.05 mg/L)

		Sampling Date			
ID	Sampling Station	05/04/16	07/13/16	10/05/16	12/06/16
MD25	Basin North (E)	0.168	0.116	0.144	0.263
MD61	Basin North (M)	0.109	0.105	0.214	0.260
MD62	Basin North (H)	0.141	0.173	0.119	0.212
MD26	Basin South (E)	0.141	0.105	0.119	0.139
MD63	Basin South (M)	0.160	0.175	0.107	0.292
MD64	Basin South (H)	0.148	0.158	0.113	0.389
MD27	Thomas Basin (E)	0.190	<0.100	<0.100	0.623
MD65	Thomas Basin (M)	0.144	0.150	0.129	0.436
MD66	Thomas Basin (H)	0.219	0.150	0.168	0.617

Results of Quarterly Nutrient Sampling:
UV254 (mg/L)

		Sampling Date			
ID	Sampling Station	05/04/16	07/13/16	10/05/16	12/06/16
MD25	Basin North (E)	0.050	0.044	0.029	0.031
MD61	Basin North (M)	0.052	0.043	0.029	0.030
MD62	Basin North (H)	0.049	0.051	0.045	0.030
MD26	Basin South (E)	0.054	0.042	0.028	0.031
MD63	Basin South (M)	0.058	0.039	0.031	0.032
MD64	Basin South (H)	0.055	0.044	0.044	0.032
MD27	Thomas Basin (E)	0.100	0.041	0.028	0.078
MD65	Thomas Basin (M)	0.098	0.032	0.028	0.084
MD66	Thomas Basin (H)	0.135	0.027	0.026	0.229

Results of Quarterly Nutrient Sampling:
Silica (mg/L)

		Sampling Date			
ID	Sampling Station	05/04/16	07/13/16	10/05/16	12/06/16
MD25	Basin North (E)	2.170	1.080	1.400	1.800
MD61	Basin North (M)	2.440	1.650	1.460	1.840
MD62	Basin North (H)	2.560	2.960	3.450	1.730
MD26	Basin South (E)	2.290	1.190	1.340	1.920
MD63	Basin South (M)	2.510	1.390	1.700	2.020
MD64	Basin South (H)	2.600	1.870	3.420	2.020
MD27	Thomas Basin (E)	2.880	1.220	1.400	3.020
MD65	Thomas Basin (M)	2.840	1.390	1.360	3.200
MD66	Thomas Basin (H)	3.600	1.680	1.770	5.920

Results of Quarterly Nutrient Sampling:
Alkalinity (mg/L)

		Sampling Date			
ID	Sampling Station	05/04/16	07/13/16	10/05/16	12/06/16
MD25	Basin North (E)	6.02	6.36	6.04	5.44
MD61	Basin North (M)	6.06	5.54	5.62	5.70
MD62	Basin North (H)	5.82	6.66	6.96	5.66
MD26	Basin South (E)	6.34	6.58	5.72	5.72
MD63	Basin South (M)	5.96	6.28	5.42	5.62
MD64	Basin South (H)	6.06	6.70	6.68	5.66
MD27	Thomas Basin (E)	8.04	6.62	5.86	5.50
MD65	Thomas Basin (M)	7.90	5.08	5.74	5.22
MD66	Thomas Basin (H)	7.98	4.48	5.16	6.14