Water Quality Report: 2017

Wachusett Reservoir Watershed

March 2018

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

Table of Contents

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 2017 water quality data from the Wachusett Reservoir tributaries and reservoir. A report summarizing 2017 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, Max Nyquist, David Getman, Dan Crocker, and Lawrence Pistrang collected the samples and were responsible for field measurements. Steve Sulprizio was responsible for the development of stage-discharge relationships and flow monitoring. Modeling efforts and database development were led by Dan Crocker. Turbidity analysis was done by Steve Sulprizio with occasional assistance from David Getman and Pat Austin. Plankton samples were collected and analyzed by Jamie Carr, Joy Trahan-Liptak, and Max Nyquist. 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 non-bacterial analyses during the year. They also thank the MWRA staff at the Southborough Lab for completing all routine and non-routine *E. coli* analyses during the year and for arranging the transportation of weekly UV-254 samples to Deer Island.

WATER QUALITY REPORT: 2017
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 and total suspended solids 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 April, 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, total suspended solids, specific conductance, turbidity, plankton, precipitation and flow data for the past 30 years are stored in an ACCESS database. All data generated during tributary and reservoir water quality testing in 2017 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 764 turbidity samples from tributaries and 176 phytoplankton samples from the reservoir. A total of 1544 physiochemical measurements (temperature and specific conductance) were done in the field at tributary stations, with another 48 water column profiles (temperature, specific conductance, dissolved oxygen, percent oxygen saturation, chlorophyll *a*, and pH) recorded from the reservoir. A total of 1507 bacteria samples were collected and delivered to the MWRA Southborough laboratory for *E. coli* analysis, and 260 were collected and shipped to the MWRA Deer Island laboratory for 1512 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. 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 22nd 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 for eight months after a four inch rain event in October 2016 completely reconfigured the stream channel and buried the water quality probe. Repairs to the gaging station were completed in June 2017 and depth measurements have been collected since that time, but a new stage-discharge relationship has not yet been developed.

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 routinely uploaded to an ACCESS database, and reviewed and interpreted with the assistance of environmental analyst/database specialist Daniel Crocker.

Figure 1: Wachusett Watershed Tributary Sampling Stations

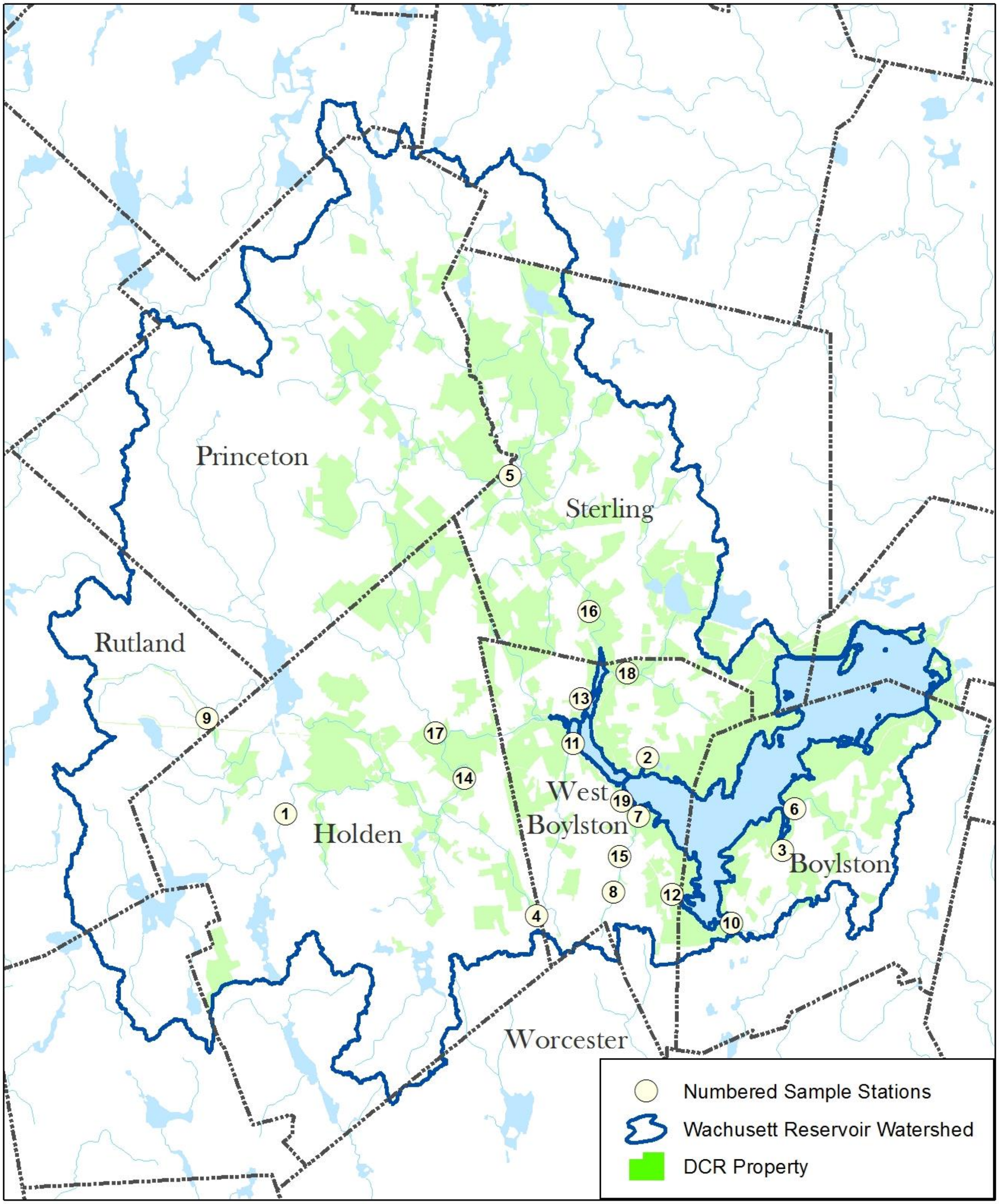


Table 1: Wachusett Tributary Sampling Stations (2017)

STATION	LOCATION	FREQUENCY
1. Asnebumskit Brook (Princeton)	upstream of Princeton Street, Holden	2M
2. Beaman Pond Brook (2)	Route 110, W. Boylston (homes)	2M
3. Boylston Brook	Route 70, Boylston	W
4. Cook Brook (Wyoming)	Wyoming Street, Holden	2M
5. East Wachusett Brook (140)	Route 140, Sterling	2M
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	2M
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	2M
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	2M, 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, UV-254)
2M = twice per month (bacteria, temperature, specific conductance, turbidity)
M = monthly (nutrients, TSS) with weekly flow
M* = monthly (nutrients, TSS) with continuous flow

2.2 RESERVOIR MONITORING

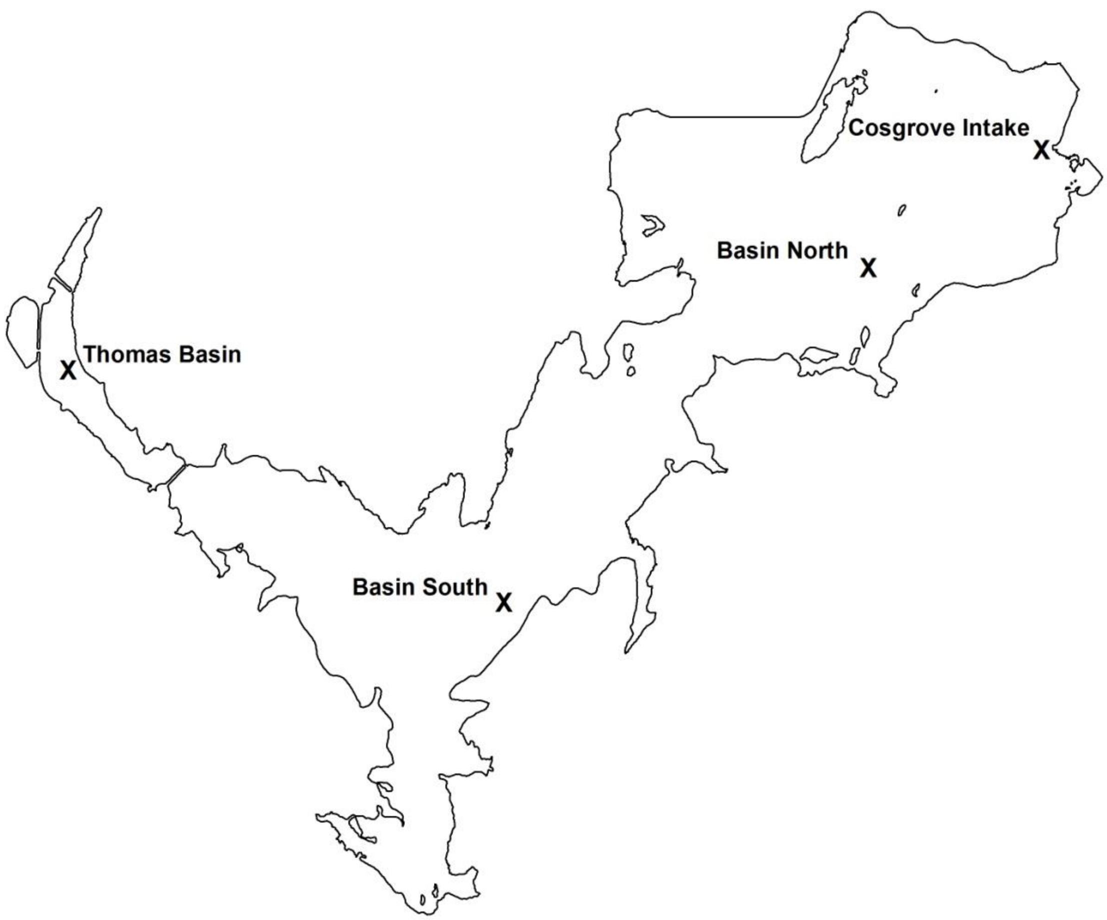
Temperature, dissolved oxygen concentration and percent saturation, specific conductance, chlorophyll *a*, and pH water column profiles were recorded weekly during stratified conditions at Station 3417 (Basin North) in conjunction with routine plankton monitoring. A full panel of nutrient samples was 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 4.3 for complete discussion). Water column profiles were also recorded at each station during each nutrient sampling event.

Table 2: Wachusett Reservoir Sampling Stations (2017)

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

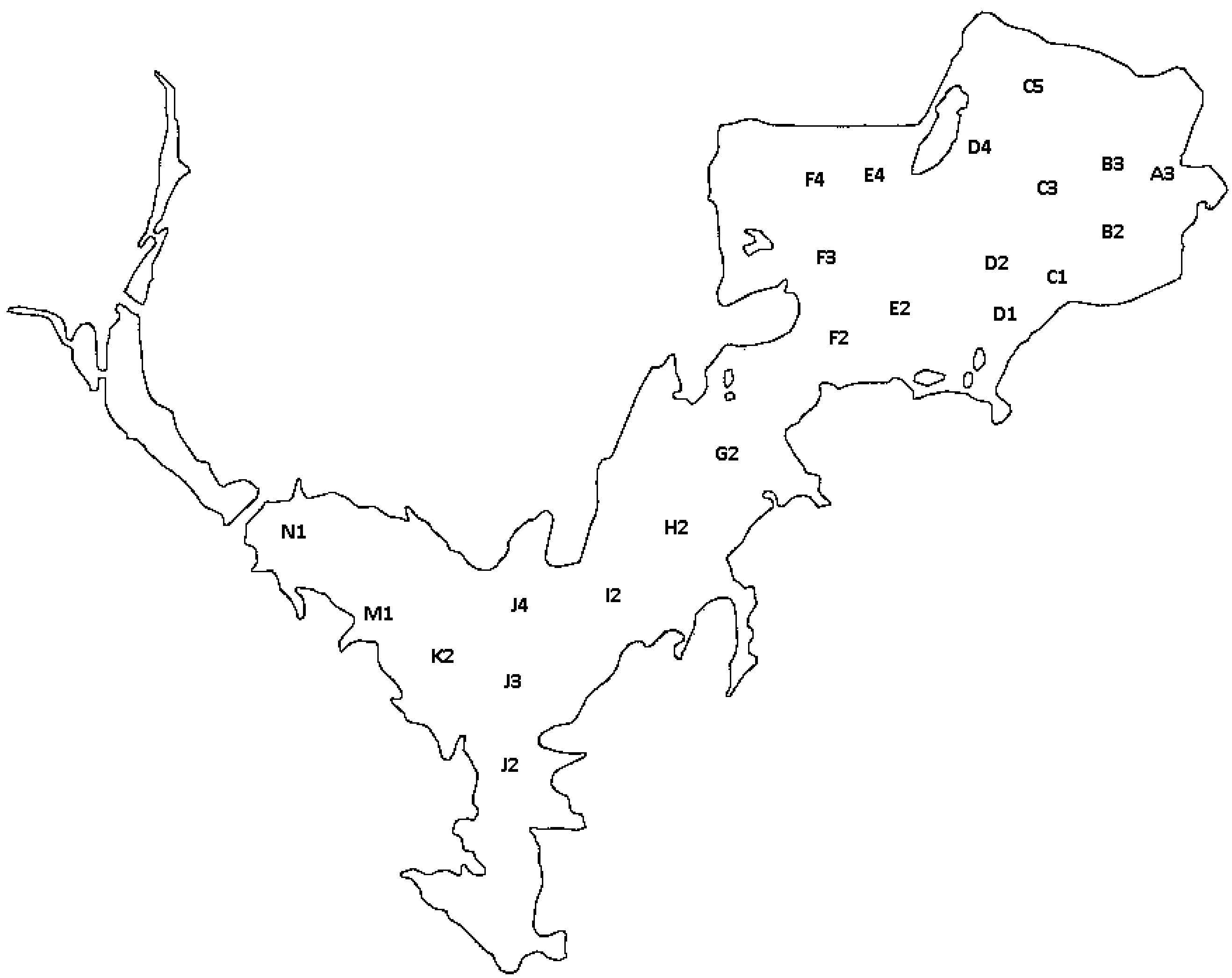
W = weekly (temperature, conductivity, plankton, and water column profiles at Cosgrove or 3417)
Q = quarterly (plankton, profiles, nutrients)

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 *E. coli* samples weekly in January, twice in February and March, once per month in April though early September, and then weekly again for the remainder of the year from 23 reservoir surface stations shown below. Additional midweek samples were collected from late November through mid-December to document the impacts of an intensified bird harassment effort. Unlike many previous years there were no periods of ice cover during 2017 that prevented sample collection.

Figure 3: Reservoir Transect Stations



3.0 RESULTS OF TRIBUTARY MONITORING PROGRAM

3.1 BACTERIA

The Massachusetts Class A surface water quality standards utilize *E. coli* as an indicator organism. The statutory limits are "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 standard was exceeded at a single station (Gates Brook 4) during 2017, 2016, and 2015, and did not exceed any station in 2014 (Table 3). There were, however, only a few stations that met the single sample limit of 235 MPN per 100 mL in 2014-2016, and every station sampled exceeded this standard in 2017. It is very difficult for tributary water quality to meet the single sample standard, even in those with undeveloped watersheds. There can be dramatic fluctuations in bacteria concentrations due to precipitation events and variable flow conditions even without human-related sources of contamination.

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

STATION	GMEAN (2014)	GMEAN (2015)	GMEAN (2016)	GMEAN (2017)	%>235 (2014)	%>235 (2015)	%>235 (2016)	%>235 (2017)
Asnebumskit (Princeton)	52	105	54	46	20.0%	38.1%	24.0%	11.5%
Beaman Pond Brook 2	33	60	16	63	6.7%	10.0%	**0.0%**	25.0%
Boylston Brook	26	48	40	22	12.8%	18.8%	15.6%	2.5%
Cook Brook (Wyoming)	34	26	22	41	20.0%	15.8%	**0.0%**	11.5%
East Wachusett (140)	19	26*	21	17	8.0%	15.0%	4.6%	3.9%
French Brook (70)	41	53	61*	54	12.0%	14.6%	19.2%	14.0%
Gates Brook (1)	31	39	37	48	10.0%	15.2%	10.2%	10.0%
Gates Brook (4)	110	**184**	**131**	**172**	28.0%	39.1%	24.5%	45.1%
Jordan Farm Brook	40	86*	18	43	12.0%	35.3%	6.7%	8.3%
Malagasco Brook	27	40	48*	43	6.0%	14.3%	10.2%	14.0%
Malden Brook	28	31	33	36	6.0%	7.1%	6.1%	4.0%
Muddy Brook	28	30	68*	39	4.0%	**0.0%**	22.5%	4.0%
Oakdale Brook	31	57	57	38	12.0%	9.5%	20.0%	15.4%
Quinapoxet River (C.Mills)	36	54*	49	56*	8.0%	9.5%	12.2%	8.0%
Scarlett Brook	38	27	55*	52	10.0%	14.3%	16.3%	14.0%
Stillwater River (SB)	32	78*	50	45	6.0%	21.4%	12.2%	12.0%
Trout Brook	23	29*	15	20	**0.0%**	19.1%	**0.0%**	2.4%
Waushacum (Prescott)	34	42	53*	30	**0.0%**	9.5%	25.0%	2.0%
West Boylston Brook	82	50	80	87	22.0%	16.7%	24.5%	22.0%

*highest annual geometric mean (2006-2017)

Bacteria samples collected from the tributary stations during 2017 contained a wide range of *E. coli* concentrations, from less than 10 MPN/100mL in approximately eleven percent of all samples to a high of 24,000 MPN/100mL in West Boylston Brook during November. As in previous years, most of the highest concentrations were recorded during or following rain events of 0.20” or more. Nineteen of the twenty samples that exceeded 1000 MPN/100mL were collected during or immediately following wet weather. Only a single sample that exceeded 1000 MPN/100mL was collected during dry weather, a February sample from West Boylston Brook that was likely reflective of raccoon activity.

Annual geometric mean concentrations of *E. coli* over the past four years do not show a clear and uniform trend although there are some indications that water quality may be declining. Increases in annual geometric mean concentrations 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 carefully compare yearly data and is usually better to look for longer term trends when assessing water quality, but some preliminary observations and conclusions can be made.

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

STATION	2017 GEOMETRIC MEAN	5 YEAR MEAN	10 YEAR MEAN
Asnebumskit (Princeton)	46	59	53
Beaman 2	63	41	53
Boylston Brook	22	42	36
Cook Brook (Wyoming)	41	28	25
East Wachusett (140)	17	19	19
French Brook (70)	54	46	39
Gates Brook (1)	48	36	35
Gates Brook (4)	172	137	138
Jordan Farm Brook	43	41	35
Malagasco Brook	43	35	31
Malden Brook	36	30	32
Muddy Brook	39	37	30
Oakdale Brook	38	45	55
Quinapoxet River (C.Mills)	**56**	44	43
Scarlett Brook	52	41	41
Stillwater River (SB)	45	47	46
Trout Brook	20	20	20
Waushacum (Prescott)	30	36	31
West Boylston Brook	87	71	71

Annual geometric mean concentration of *E. coli* does remain at historically elevated levels at most stations. Geometric means at eight stations in 2017 were higher than the previous year, even though *E. coli* concentrations in 2016 were uncharacteristically high at most locations (Table 3). Geometric means in 2017 remain higher than the five year average geometric mean at 12 of 19 stations (Table 4), and annual geometric mean at the Quinapoxet River (Canada Mills) was the highest ever recorded. The combined geometric mean of 784 samples collected from 19 stations in 2017 was 46 MPN/100mL, slightly lower than in 2015 and 2016 (48 MPN/100mL) but still higher than the average annual combined geometric mean from these locations over the past ten years.

This decline in water quality as measured by bacteria was not observed at every sampling location. Annual geometric means in Asnebumskit Brook (Princeton Street), other than during 2015, have been nearly unchanged for the past ten years and are considerably lower than recorded in 2006 and before. Water quality in East Wachusett Brook and Trout Brook has also been relatively consistent in recent years with annual geometric means of 15 to 29 MPN/100mL.

Wet weather samples continue to contain much more bacteria than dry weather samples. Table 5 compares 2017 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)	36	72	17.6%	22.2%	0.0%	33.3%
Beaman 2	50	89	8.3%	0.0%	16.7%	37.5%
Boylston Brook	15	34	31.8%	16.7%	4.6%	0.0%
Cook Brook (Wyoming)	26	103	17.6%	11.1%	5.9%	22.2%
East Wachusett (140)	11	39	29.4%	11.1%	0.0%	11.1%
French Brook (70)	44	73	6.7%	0.0%	6.7%	25.0%
Gates Brook (1)	37	71	6.7%	5.0%	3.3%	20.0%
Gates Brook (4)	133	256	0.0%	0.0%	35.5%	60.0%
Jordan Farm Brook	30	79	6.7%	11.1%	6.7%	11.1%
Malagasco Brook	32	68	20.0%	10.0%	10.0%	20.0%
Malden Brook	29	51	20.0%	5.0%	0.0%	10.0%
Muddy Brook	42	36	13.3%	10.0%	3.3%	5.0%
Oakdale Brook	22	104	29.4%	0.0%	5.9%	33.3%
Quinapoxet River (C.Mills)	54	60	3.3%	10.0%	0.0%	20.0%
Scarlett Brook	33	102	10.0%	5.0%	3.3%	30.0%
Stillwater River (SB)	36	62	6.7%	5.0%	3.3%	25.0%
Trout Brook	15	31	29.2%	11.8%	0.0%	5.9%
Waushacum (Prescott)	30	29	13.3%	25.0%	0.0%	5.0%
West Boylston Brook	60	149	6.7%	0.0%	16.7%	30.0%
ALL WACHUSETT TRIBS	35	67	13.8%	8.1%	6.6%	20.8%

*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 almost always higher than those of dry weather samples (Table 5). Impacts from rain events are often more obvious in subbasins with substantial areas of impervious surfaces or large agricultural operations, but 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 2017 show the average wet weather geometric mean to be less than twice as high as the average dry weather geometric mean, although samples above the Massachusetts single sample statutory limit of 235 MPN/100mL remain nearly three times 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 continued to show 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 in 2017 were twice as likely to exceed the statutory limit of 235 MPN/100mL as dry weather samples from the other three seasons. Wet weather samples collected during the fall in 2017 exceeded the statutory limit much more often than during the other seasons (Table 6).

Table 6: Impacts of Season and Precipitation on *E. coli* in 2017

	# OF SAMPLES	% SAMPLES <10 MPN/100mL	% SAMPLES >235 MPN/100mL	GEOMETRIC MEAN
ALL SAMPLES				
winter	162	19.8%	6.8%	28
spring	213	16.0%	7.0%	29
summer	210	5.2%	14.8%	69
fall	195	6.7%	19.5%	70
DRY SAMPLES				
winter	86	19.8%	5.8%	25
spring	157	19.7%	4.5%	26
summer	122	8.2%	10.7%	54
fall	107	6.5%	5.6%	45
WET SAMPLES				
winter	76	19.7%	7.9%	32
spring	56	5.4%	14.3%	41
summer	88	1.1%	20.5%	97
fall	88	6.8%	36.4%	119

Numerous possible sources of bacteria and the increased likelihood of short-term weather variations due to climate change make it difficult to interpret fluctuations in water quality parameters over the short term. Drought conditions as experienced in 2015 and 2016 can reduce flow in smaller tributaries to the point where few (or no) samples are collected during the summer and fall when water quality tends to be worse. This can result in an apparent improvement in annual water quality statistics. Low flow can also lead to the concentration of existing contaminants in larger streams and rivers, however, with a decline in annual water quality. Conclusive statements about water quality trends based on a comparison of yearly data are clearly 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 reliable data from Wachusett watershed tributaries extend over nearly thirty years and 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.

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 and 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. These measurements were supplemented during 2017 by continuous depth recordings using HOBO water level data loggers. 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 are not yet 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 was reconstructed, the data collection apparatus repaired, and a new stage-discharge relationship has been developed. The USGS generated estimated flow data for eight months when the relationship was unavailable.

Continuous monitoring has shown that daily flows vary widely at all locations and demonstrates the need for regular and more frequent flow monitoring. Daily mean flows in the tributaries can differ by more than two orders of magnitude, and instantaneous flow varies even more dramatically (Table 7). Continuous stage measurements using HOBO water level data loggers captures information from storm events that previously were missed by weekly monitoring efforts. Preliminary data collection using HOBOs has been very successful and protocols have been developed that allow monitoring of stage even during very cold weather during the winter.

Table 7: Daily Flow Rate and Monthly and 2017 Annual Discharge Volume in Wachusett Tributaries

tributary	QUIN	STILL	GATES	WAUSH	WBOYL	MALAG	MALDEN	FRENCH
max instantaneous flow (cfs)	689	1040	103	85.24	50.40	32.06	55.30	72.97
max daily mean flow (cfs)	592	710	44.80	72.47	10.8	29.54	54.03	40.30
min daily mean flow (cfs)	2.25	2.08	0.70	0.27	0.04	0.05	0.77	0.06
mean daily flow (cfs)	51.67	52.16	4.44	9.64	0.55*	2.00	5.27	4.35
max month discharge (1000 cf)	453,367	336,018	24,990	91,234	6,753*	38,921	74,625	36,056
min month discharge (1000 cf)	20,572	16,044	3,218	1,202	231	204	2,794	298
mean month discharge (1000 cf)	134,870	136,702	11,537	24,354	1,433*	5,066	13,325	11,027
annual discharge (1,000,000 cf)	1,618	1,640	138.4	292.2	17.2*	60.79	159.9	132.3

*weekly data used to calculate due to lack of available HOBO data from West Boylston Brook during January-July

Annual precipitation returned to historic levels in 2017 following two years of drought conditions (Figure 4) which resulted in increases in annual discharge in all tributaries (Figures 5-6).

Figure 4: Annual Precipitation in Wachusett Watershed (inches)

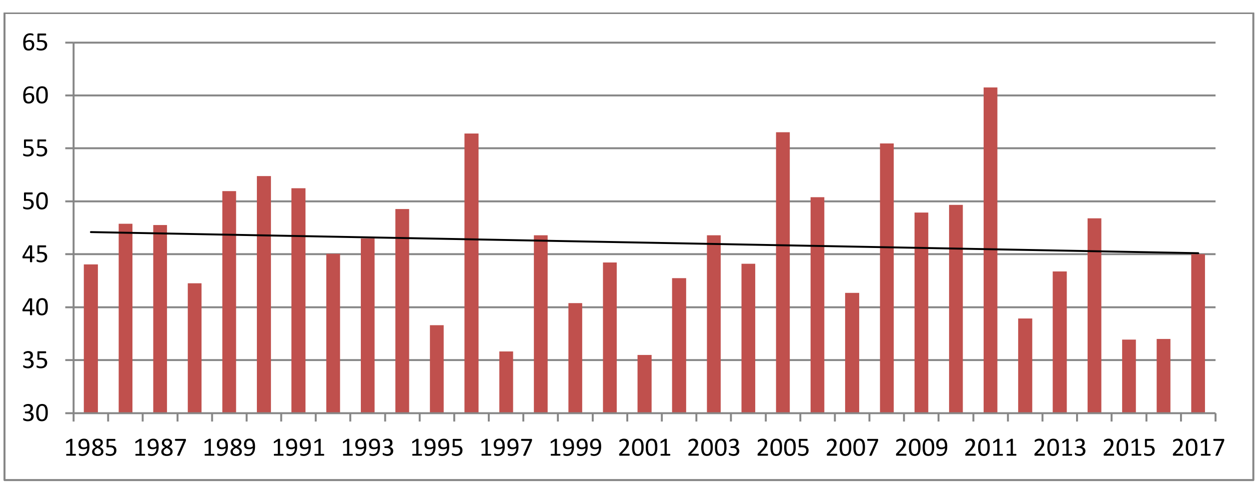


Figure 5: Annual Discharge in the Quinapoxet and Stillwater Rivers (cubic feet)

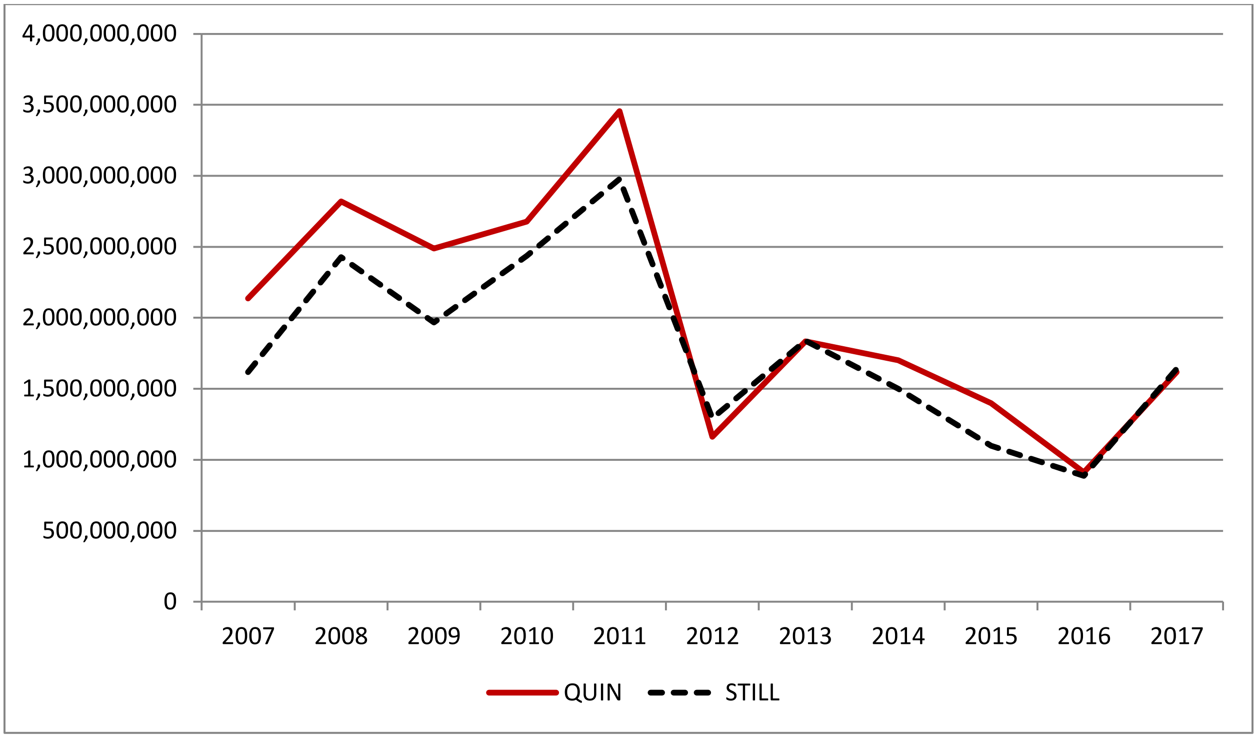
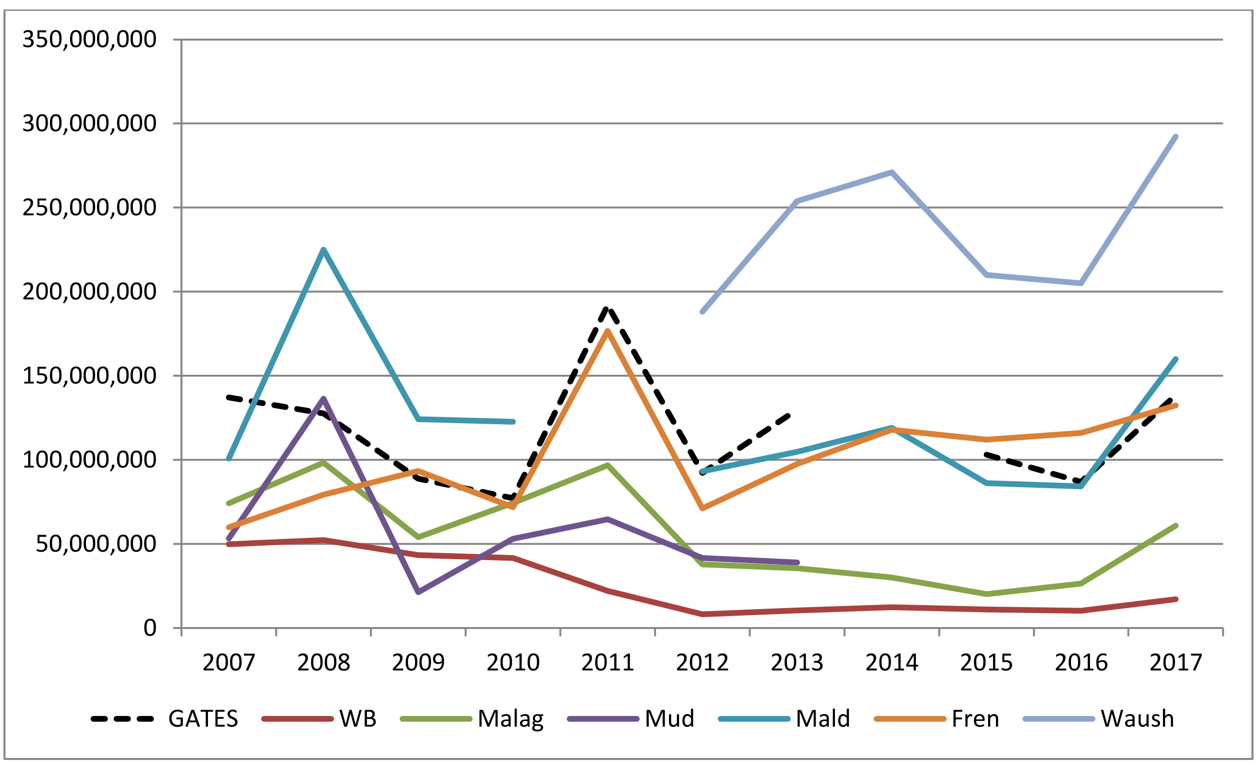
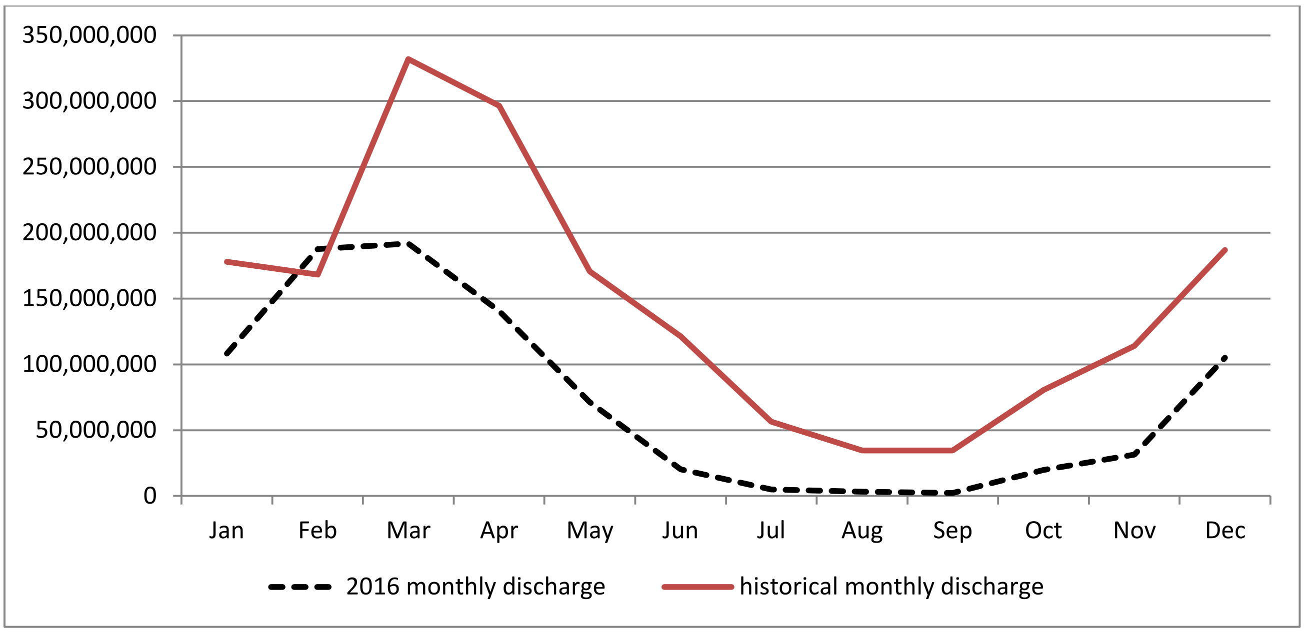


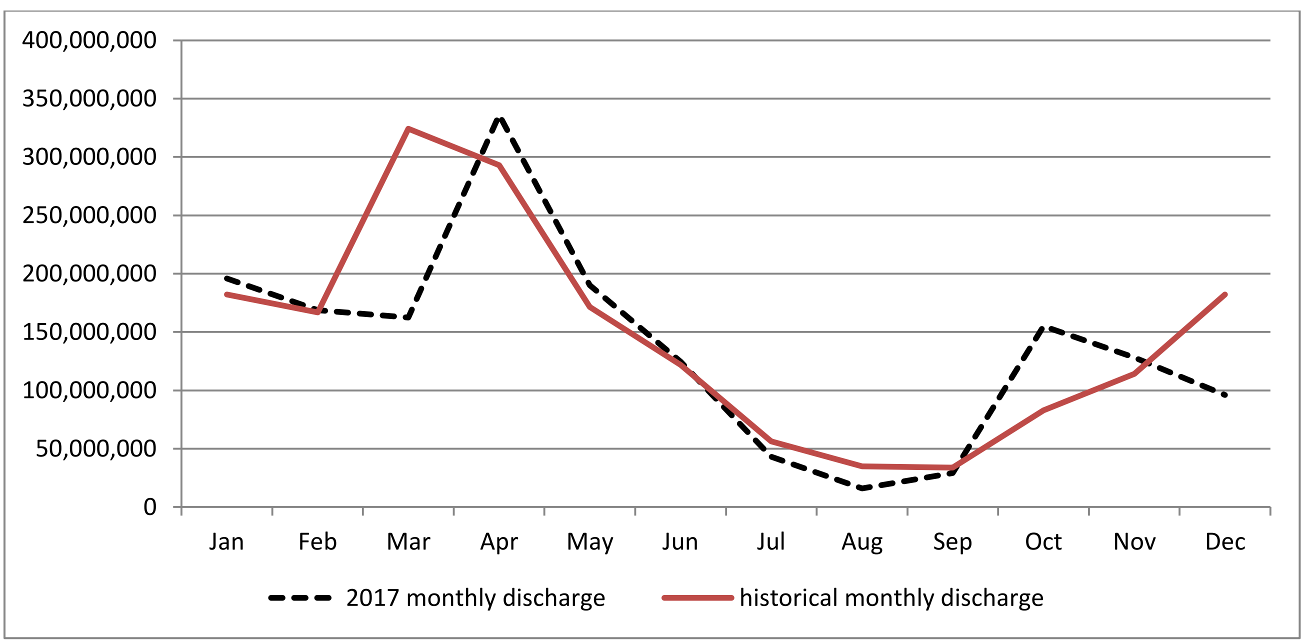
Figure 6: Annual Discharge in Smaller Wachusett Tributaries (cubic feet)



Monthly discharge volumes from the Stillwater and Quinapoxet Rivers throughout 2016 were lower than normal due to annual rainfall amounts well below the annual mean. Although annual precipitation returned to historic levels in 2017 and total discharge volumes increased, only spring (April-June) and late fall (October-November) monthly discharge volumes were above the historical mean in the Stillwater River (Figure 7). All other months remained below the historical mean.

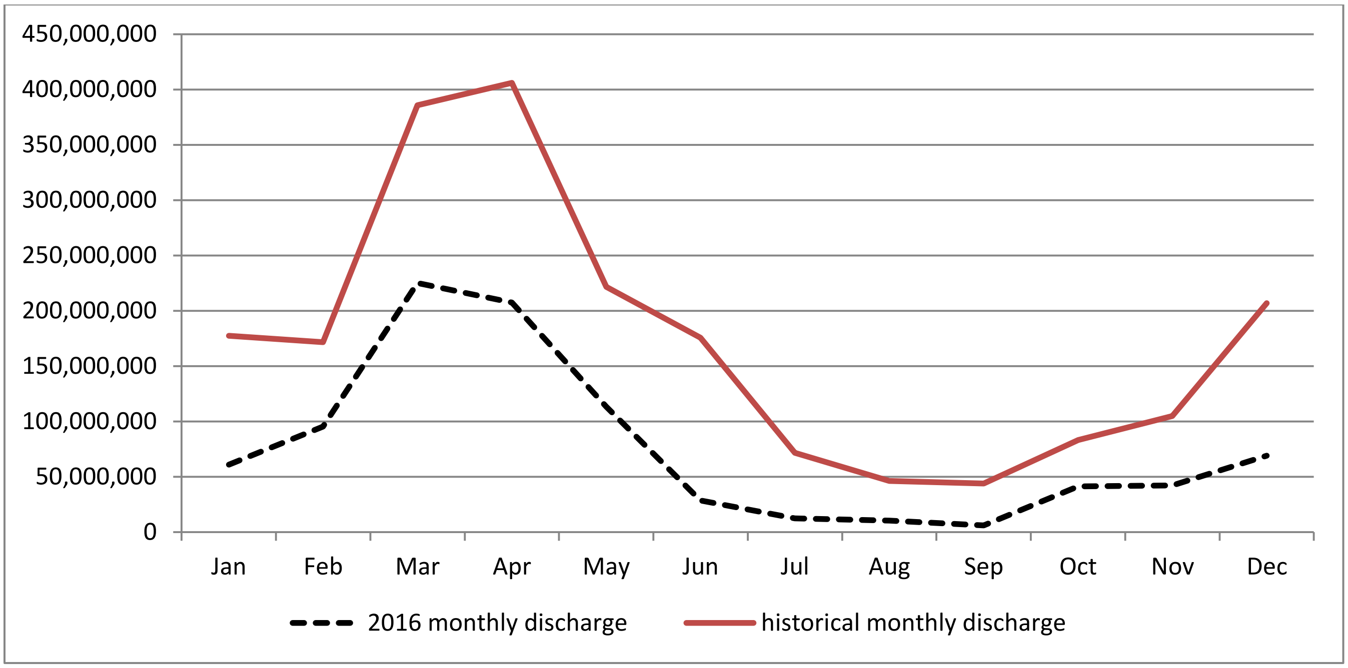
Figure 7: Monthly Discharge in the Stillwater River (cubic feet) 2016–2017

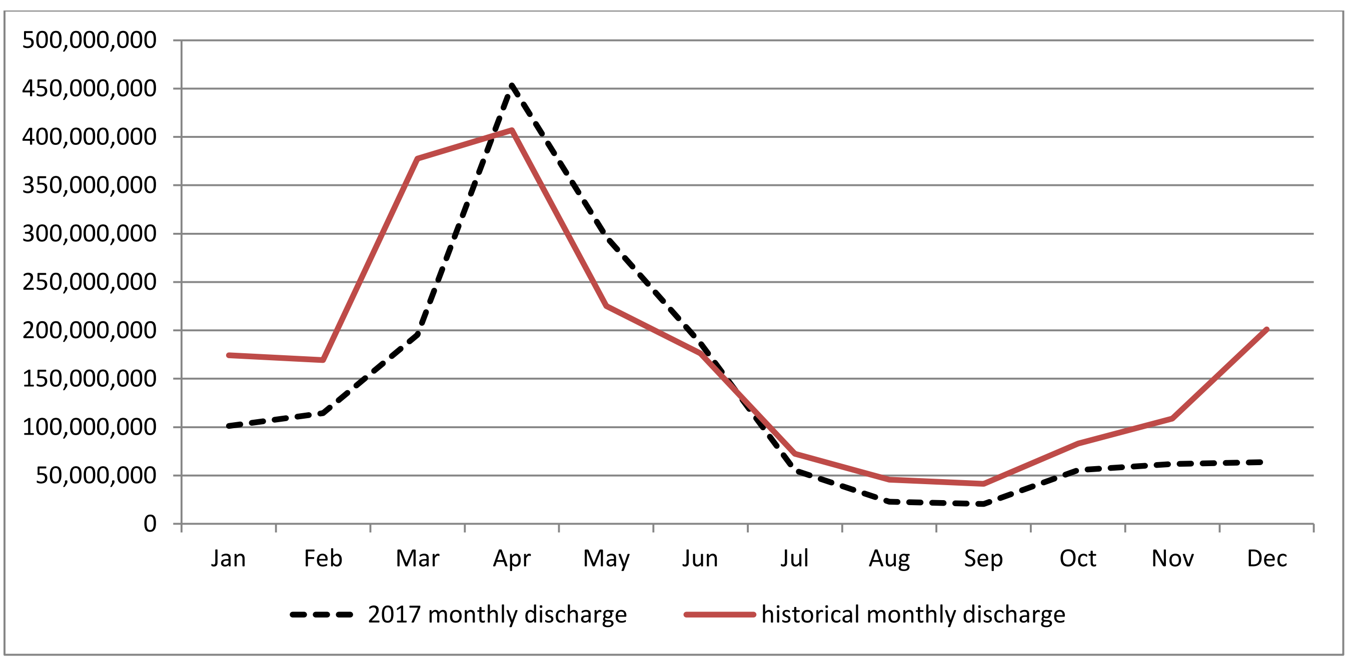




Spring discharge volumes were above the historical mean in the Quinapoxet River during 2017 but fall discharge volumes remained below historical means (Figure 8) due to the fact that much of the fall precipitation was captured in the drought-impacted Quinapoxet Reservoir at the headwaters of the river and not released downstream.

Figure 8: Monthly Discharge in the Quinapoxet River (cubic feet) 2016–2017





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. 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 0.030 mg/L NO_3-N to 1.28 mg/L NO_3-N (Table 8), with individual measurements from below detection to 1.68 mg/L NO_3-N in West Boylston Brook. Nitrate concentrations in West Boylston Brook are higher than in other brooks but are considerably lower than they were ten years ago. Concentrations in Gates Brook continue to decline as well.

Table 8: Nitrate-Nitrogen Annual Mean Concentrations – Wachusett Tributaries (mg/L)

STATION	FRENCH	GATES	MALAG	MALDEN	MUDDY	QUIN	STILL	TROUT	WAUSH	W. BOYL
ave2017	0.110	0.848	0.684	0.488	0.108	0.320	0.134	0.099	0.030	1.28
ave2016	0.153	0.760	0.615	0.443	0.139	0.208	0.122	0.097	0.022	1.20
ave2015	0.093	0.790	0.704	0.534	0.134	0.291	0.155	0.107	0.053	1.25
ave2014	0.167	0.860	0.583	0.443	0.135	0.251	0.136	n/s	0.045	1.14
ave2013	0.159	0.920	0.709	0.550	0.144	0.259	0.163	n/s	0.040	1.39
ave2012	0.127	0.800	0.489	0.432	0.098	0.222	0.140	n/s	0.036	1.17
ave2011	0.154	0.930	0.426	n/s	0.089	0.185	0.156	n/s	n/s	1.09
ave2010	0.135	1.010	0.634	0.471	0.105	0.256	0.156	n/s	n/s	1.57
ave2009	0.105	1.030	0.504	0.403	0.072	0.196	0.122	n/s	n/s	1.25
ave2008	0.071	1.040	0.513	0.452	0.132	0.321	0.146	n/s	n/s	1.69

Ammonia was detected in all tributaries with most annual mean concentrations comparable to those recorded during the previous nine years (Table 9). Historic lows were seen in French Brook, Malden Brook, and the Stillwater River.

Table 9: Ammonia Annual Mean Concentrations – Wachusett Tributaries (mg/L)

STATION	FRENCH	GATES	MALAG	MALDEN	MUDDY	QUIN	STILL	TROUT	WAUSH	W. BOYL
ave2017	0.011	0.008	0.014	0.005	0.078	0.015	0.006	0.008	0.012	0.037
ave2016	0.018	0.013	0.012	0.005	0.060	0.010	0.006	0.006	0.010	0.016
ave2015	0.041	0.015	0.029	0.016	0.078	0.021	0.011	0.012	0.023	0.021
ave2014	0.034	0.014	0.015	0.009	0.067	0.017	0.012	n/s	0.025	0.049
ave2013	0.051	0.008	0.013	0.006	0.065	0.012	0.007	n/s	0.014	0.014
ave2012	0.045	0.007	0.014	0.011	0.069	0.012	0.008	n/s	0.019	0.013
ave2011	0.039	0.005	0.016	n/s	0.066	0.015	0.010	n/s	n/s	0.022
ave2010	0.120	<0.005	0.010	0.010	0.061	0.014	0.011	n/s	n/s	0.012
ave2009	0.068	0.005	0.018	0.017	0.077	0.015	0.015	n/s	n/s	0.015
ave2008	0.061	0.008	0.014	0.025	0.068	0.013	0.012	n/s	n/s	0.014

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 10). The highest individual measurement in 2017 was from Malagasco Brook in July.

Table 10: Total Kjeldahl Nitrogen Mean/Max/Min Concentrations – Wachusett Tributaries (mg/L)

STATION	FRENCH	GATES	MALAG	MALDEN	MUDDY	QUIN	STILL	TROUT	WAUSH	W. BOYL
ave2017	0.358	0.152	0.465	0.202	0.270	0.246	0.224	0.351	0.303	0.174
ave2016	0.356	0.210	0.342	0.218	0.227	0.288	0.266	0.310	0.361	0.188
ave2015	0.391	0.148	0.351	0.231	0.252	0.290	0.206	0.257	0.281	0.174
max2017	0.606	0.268	0.830	0.567	0.406	0.441	0.435	0.515	0.388	0.541
max2016	0.723	0.454	0.641	0.488	0.533	0.536	0.502	0.458	0.571	0.429
max2015	0.672	0.276	0.642	0.511	0.518	0.785	0.300	0.285	0.376	0.307

Nitrite-nitrogen was rarely detected. The highest recorded concentration was only 0.010 mg/L and only two of the 126 samples collected in 2017 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 2017 ranged from less than 0.005 mg/L to 0.119mg/L total P, with annual mean concentrations from 0.015 mg/L to 0.037 mg/L (Table 11). All annual mean concentrations were comparable to the previous nine years. Only six of the 126 samples collected in 2017 exceeded the recommended maximum concentration of 0.05 mg/L. All were collected during or immediately following rain events in June, July, and November.

Table 11: Total Phosphorus Annual Mean Concentrations – Wachusett Tributaries (mg/L)

STATION	FRENCH	GATES	MALAG	MALDEN	MUDDY	QUIN	STILL	TROUT	WAUSH	W. BOYL
ave2017	0.023	0.015	0.037	0.016	0.021	0.017	0.015	0.031	0.020	0.020
ave2016	0.029	0.017	0.025	0.019	0.020	0.021	0.019	0.038	0.026	0.018
ave2015	0.032	0.015	0.038	0.024	0.018	0.024	0.019	0.050	0.022	0.021
ave2014	0.031	0.025	0.034	0.025	0.019	0.020	0.018	n/s	0.025	0.037
ave2013	0.032	0.017	0.027	0.018	0.021	0.017	0.015	n/s	0.023	0.019
ave2012	0.049	0.025	0.044	0.028	0.027	0.027	0.023	n/s	0.029	0.035
ave2011	0.036	0.017	0.042	n/s	0.024	0.017	0.019	n/s	n/s	0.044
ave2010	0.055	0.013	0.026	0.019	0.015	0.017	0.016	n/s	n/s	0.016
ave2009	0.033	0.017	0.045	0.030	0.017	0.013	0.012	n/s	n/s	0.022
ave2008	0.038	0.020	0.055	0.027	0.013	0.024	0.016	n/s	n/s	0.035

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 90.4 mg/L, but only 10 of 126 samples contained more than the detection limit and most 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 can occur.

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 1.05 to 22.5 mg/L, with an overall mean of 5.14 mg/L, about ten percent higher than the overall mean during the drought years of 2016 and 2015 but comparable to 2014. The highest concentrations were again recorded from Malagasco and Trout Brooks, with the lowest concentrations from Malden Brook, Gates 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, Gates Brook, and West Boylston Brook.

Load estimates for ammonia, nitrate-nitrogen, total Kjeldahl nitrogen, total organic carbon, and total phosphorus in Gates Brook and the Stillwater and Quinapoxet Rivers were calculated by multiplying monthly discharge (cu ft), monthly nutrient concentrations (mg/L), and a unit conversion factor to give monthly load in kilograms, and then summing monthly totals to obtain an annual load (Table 12). Mean daily discharges were added to calculate monthly discharge. Nutrient load estimates did not address short term changes in discharge or concentration that occur during storm events. Almost all samples collected for nitrite-nitrogen and total suspended solids contained concentrations less than the detection limit so load estimates for those parameters were not developed.

Table 12: 2017 Nutrient Load Estimates – Wachusett Tributaries (kg)

STATION	Ammonia	Nitrate	TKN	TOC	Total P
Quinapoxet	418	11,002	11,902	208,033	679
Stillwater	196	5,630	10,041	207,788	604
Gates	25	3,486	664	8,880	55

Estimated annual loads of nearly all parameters were considerably higher in 2017 than estimates from 2016 (Table 13). Concentrations of some parameters were higher, some were lower, and some unchanged, but annual discharge was almost twice as much in 2017 than in 2016 and led to much larger loads. Discharge is almost always the primary driver of annual load; concentrations are usually much less important. Annual loads from Gates Brook were not calculated in 2016 due to problems with estimated flow data generated by the USGS.

Table 13: Annual Nutrient Load Estimates 2016 – Wachusett Tributaries (kg)

STATION	Ammonia	Nitrate	TKN	TOC	Total P
Quinapoxet	182	5,260	7,176	122,101	466
Stillwater	147	2,897	7,184	113,730	610

Total phosphorus in the Stillwater River was the only parameter without an estimated increase in annual load in 2017. The slight decline in annual mean concentration (Table 11) was certainly not enough to overcome the effect of a large increase in discharge, yet estimated total phosphorus load remains nearly unchanged. This is likely due to an over-estimate of load in 2016. The February sample was collected during a 2" rain event and the measured total phosphorus concentration was more than five times higher than in any other month. Total discharge in February was more than 20% of the annual discharge. The protocol used for development of a load estimate required that the extremely high concentration that likely was present only for a short storm-related period was applied to one fifth of the total discharge for the year and the resultant annual load estimate was likely much too high.

Time-series loading estimates for nutrients 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 were similar to those estimated using the less rigorous methods described above for most parameters (Table 14), although FLUX generated estimates for total phosphorus were considerably higher.

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

STATION	PARAMETER	FLUX 2016	MONTHLY 2016	FLUX 2017	MONTHLY 2017
Quinapoxet	total inorganic N	6,559	5,442	10,286	11,420
Stillwater	total inorganic N	3,924	3,044	6,022	5,826
Quinapoxet	total N	12,920	12,436	22,594	22,904
Stillwater	total N	9,451	10,081	15,609	15,671
Quinapoxet	total phosphorus	604	466	981	679
Stillwater	total phosphorus	553	610	929	604

Total nitrogen concentrations in the Stillwater River are nearly unchanged over the past six years, but estimated total nitrogen load has trended lower (Figure 9) due to the reduction in annual stream flow during the lengthy drought. Inorganic nitrogen concentrations were more variable over the same period but the overall trend was stable. Flow remains the key driver and loads of inorganic nitrogen decreased over the past six years (Figure 10). Total phosphorus (Figure 11) and total organic carbon (Figure 12) exhibited a reduction in both concentration and load. The same pattern was observed in the Quinapoxet River for total nitrogen, total phosphorus, and total organic carbon. Concentrations of inorganic nitrogen actually increased in the Quinapoxet River while loads decreased (Figure 13).

Figure 9: Stillwater River Total Nitrogen Load (kg) and Concentration (mg/L)

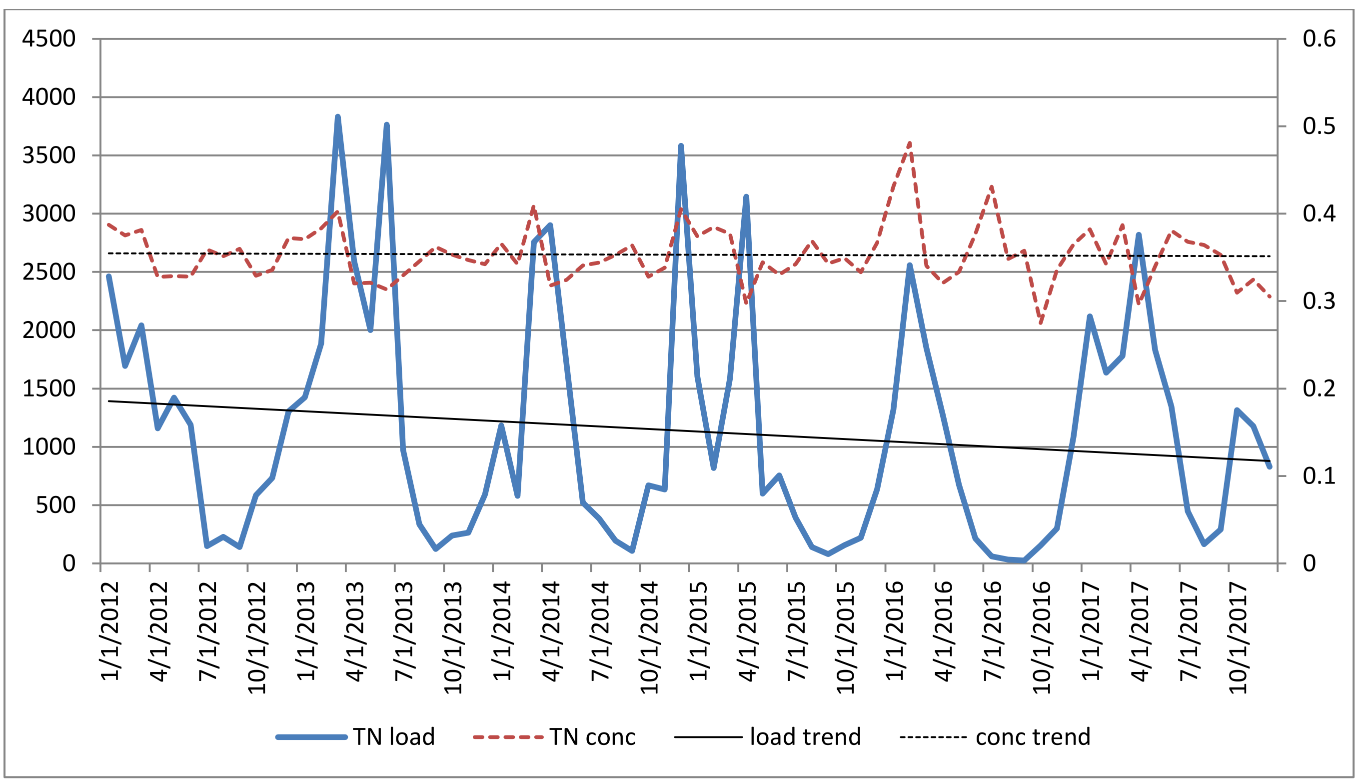


Figure 10: Stillwater River Total Inorganic Nitrogen Load (kg) and Concentration (mg/L)

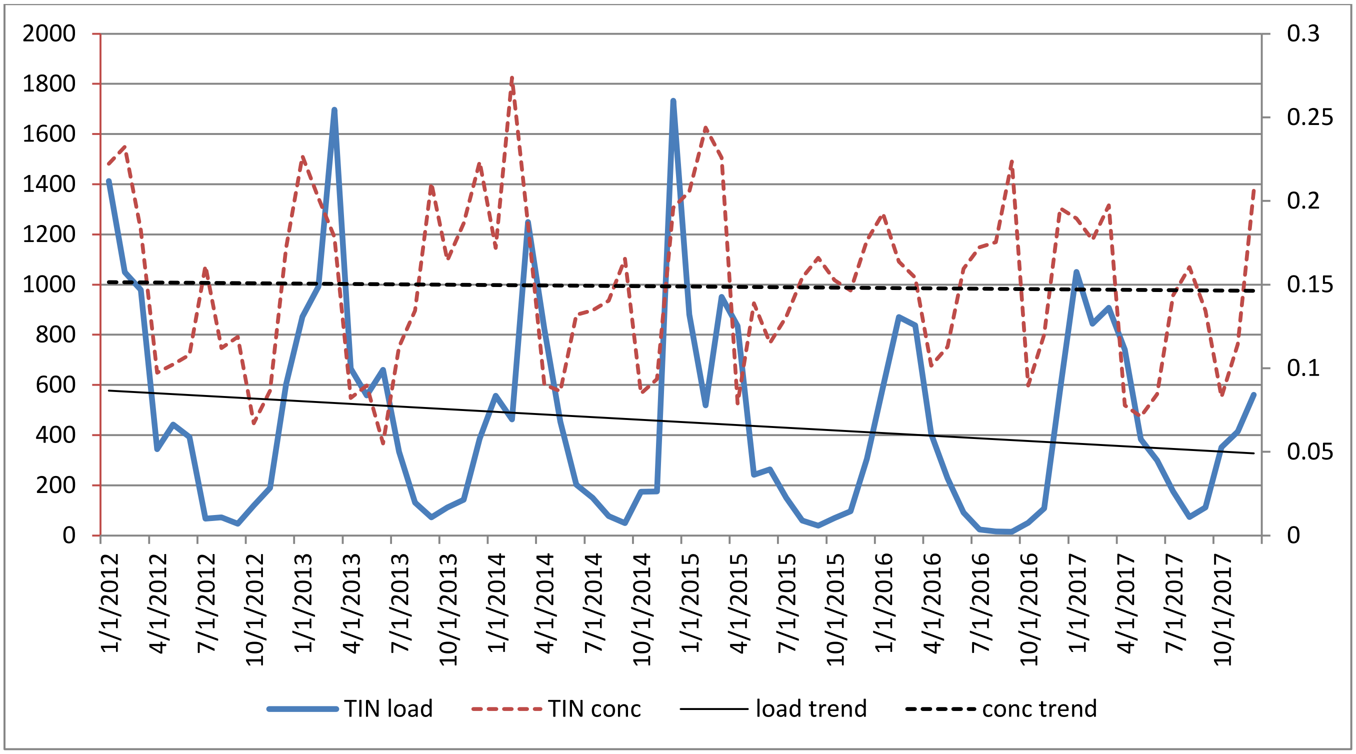


Figure 11: Stillwater River Total Phosphorus Load (kg) and Concentration (mg/L)

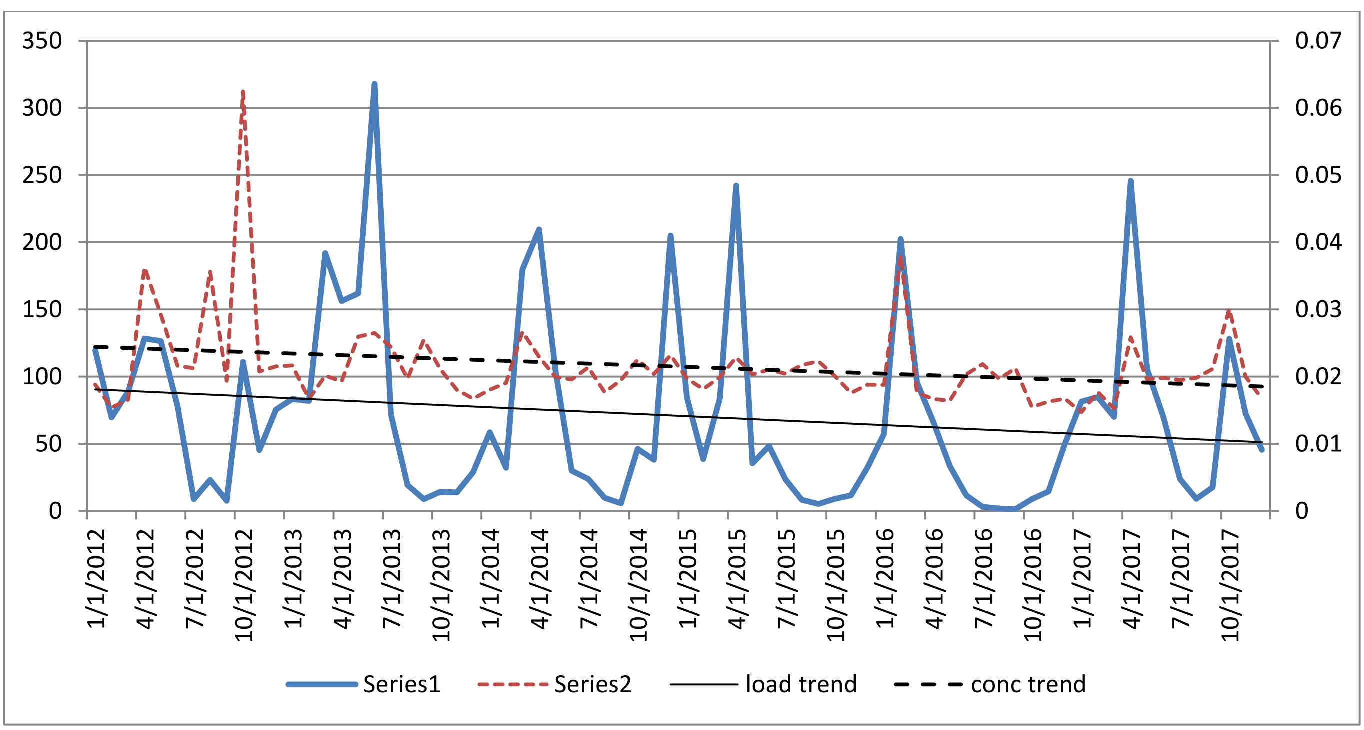


Figure 12: Stillwater River Total Organic Carbon Load (kg) and Concentration (mg/L)

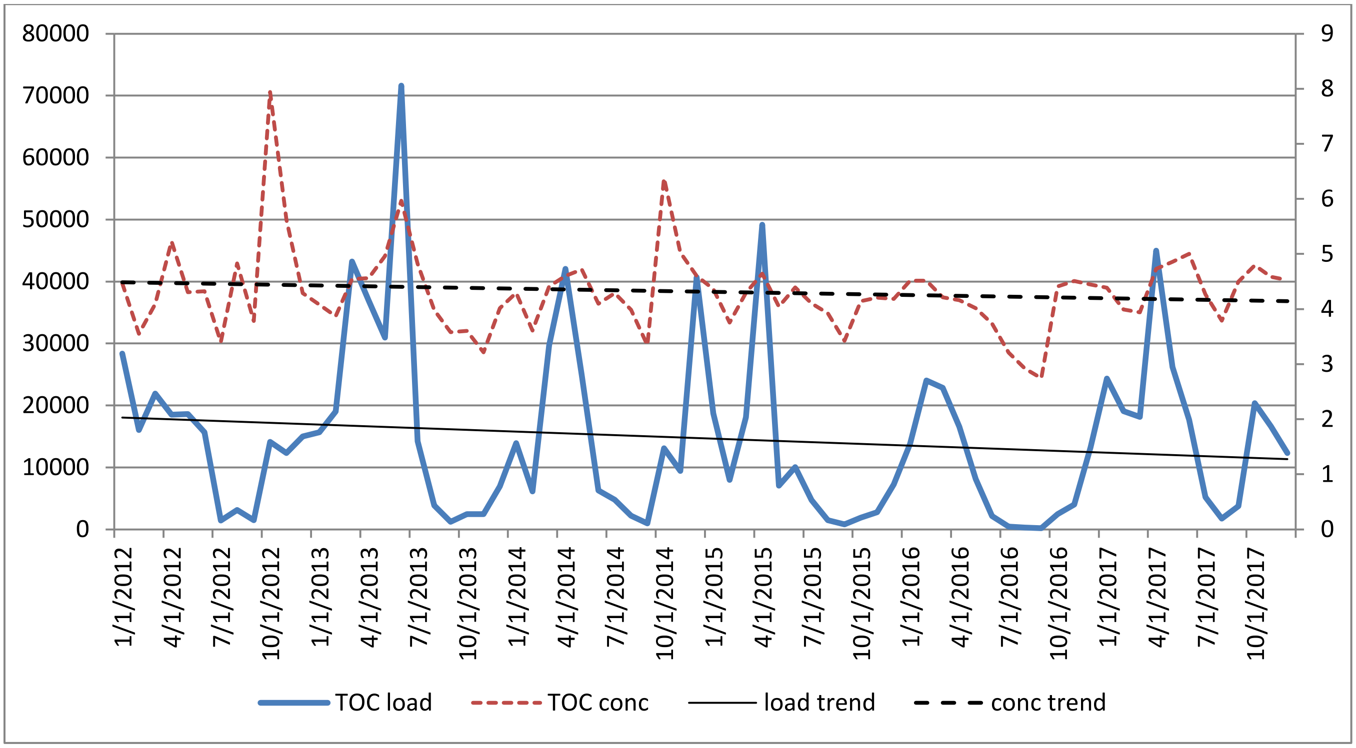
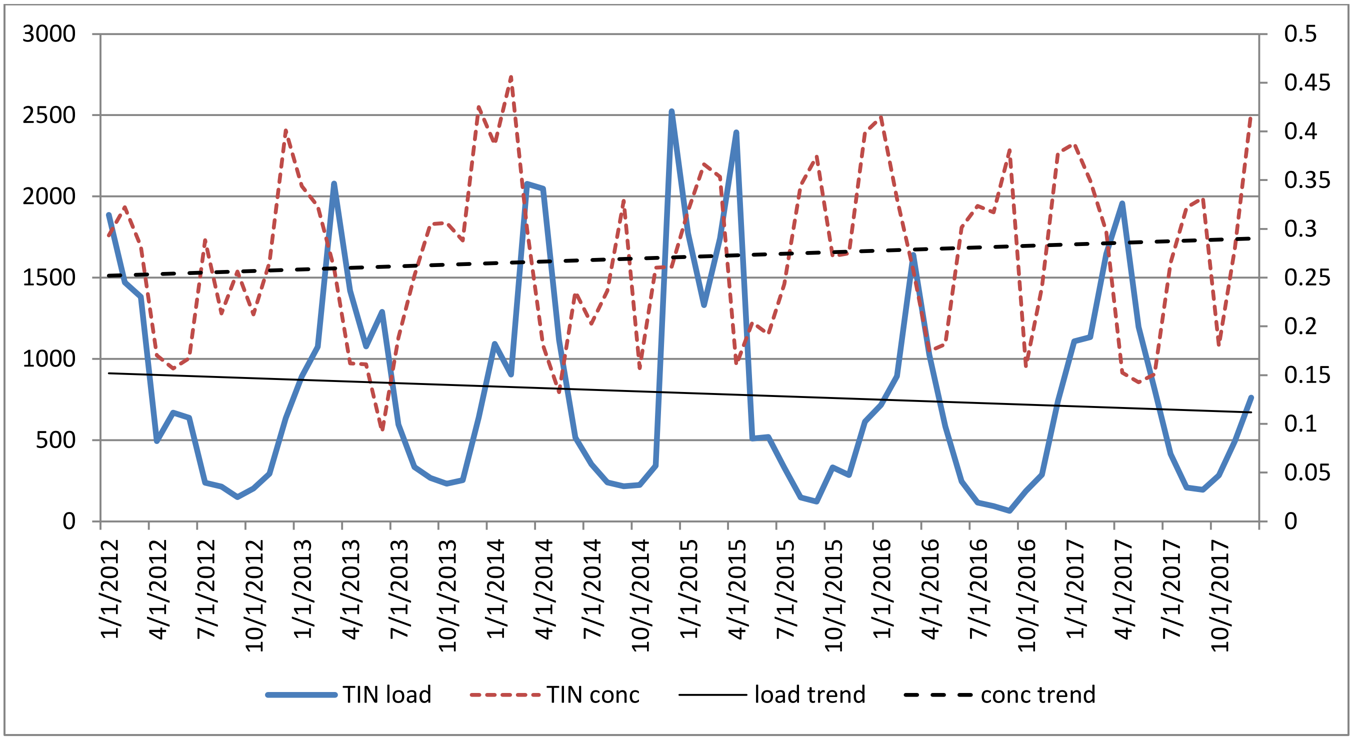


Figure 13: Quinapoxet River Total Inorganic Nitrogen Load (kg) and Concentration (mg/L)



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.

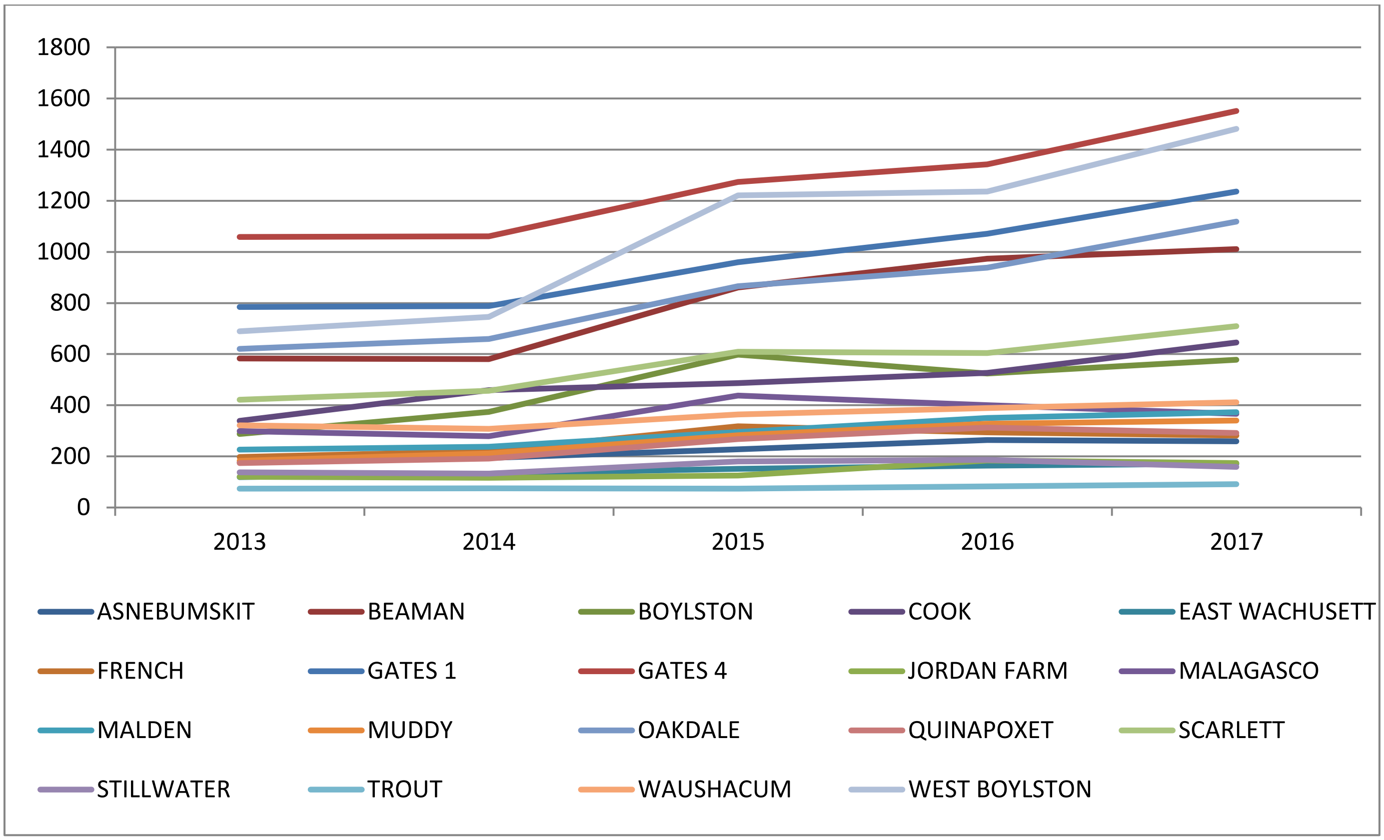
Specific conductance was measured weekly or biweekly at all nineteen tributary stations. Values of less than 100 μmhos/cm were recorded in almost two thirds of all samples from Trout Brook (26 of 41) and on single dates from Jordan Farm Brook and Beaman Brook 2. Measurements greater than 1000 μmhos/cm were recorded in 89% of samples from West Boylston Brook and the two stations on Gates Brook, but in less than 6% of samples from all other stations. Extremely high specific conductance (>1800 μmhos/cm) was observed during the winter and early spring in Scarlett Brook, West Boylston Brook, and the two stations on Gates Brook, and then throughout the summer and fall in West Boylston Brook during low flow conditions. The continued very high measurements in West Boylston Brook suggest an ongoing source of contamination and will be investigated.

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

STATION	2013	2014	2015	2016	2017
Asnebumskit (Princeton)	176.7	193.9	228.1	264.4	258.5
Beaman 2	583	581	861	973	1011
Boylston Brook	288.0	374.0	598	524	578
Cook Brook (Wyoming)	338.7	459.3	486.2	526	645
East Wachusett (140)	119.1	131.8	151.5	163.3	170.6
French Brook (70)	196.9	219.6	317.0	293.8	281.3
Gates Brook (1)	784	788	959	1071	1236
Gates Brook (4)	1058	1061	1274	1343	1551
Jordan Farm Brook	120.3	115.6	124.3	183.7	173.3
Malagasco Brook	298.4	278.6	437.4	400.1	366.3
Malden Brook	226.0	237.7	295.6	350.5	372.3
Muddy Brook	182.0	211.5	282.1	327.9	339.7
Oakdale Brook	620	659	866	938	1119
Quinapoxet River (Canada Mills)	174.3	191.5	267.5	312.4	291.2
Scarlett Brook	421.8	456.6	610	604	709
Stillwater River (Steel Bridge)	136.9	132.0	180.0	185.8	158.7
Trout Brook	73.2	74.8	73.5	82.8	91.7
Waushacum (Prescott)	321.1	307.0	364.4	388.6	412.1
West Boylston Brook	689	746	1221	1236	1482
WACHUSETT TRIBS MEAN	358.3	380.0	505	535	592

2017 annual median specific conductance ranged from a low of 91.7 μmhos/cm in Trout Brook to a high of 1551 μmhos/cm at Gates Brook 4. Twelve annual medians were the highest in the past five years and historic high medians were recorded at 11 stations (Table 14). Elevated specific conductance is not restricted to West Boylston Brook and Figure 11 illustrates the steady increase in annual median specific conductance in nearly all sampled watershed tributaries. Reduced tributary flows and increased concentrations of mineral salts could be a factor, or it might reflect changes in sampling frequency and equipment, although an unidentified source of contamination could also be involved. This will be investigated in depth as part of a 30- year (1988-2017) summary report.

Figure 14: 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 0.12 NTU to 70.5 NTU. The 57 samples with turbidity of 5.0 NTU or higher were predominantly collected from Muddy Brook (29 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. All but one of the other samples with turbidity in excess of 5.0 NTU were collected during or immediately following storm events throughout the year. A single sample with elevated turbidity was collected from Scarlett Brook in February, possible a result of melting snow or parking lot maintenance.

Annual median values ranged from 0.30 NTU in Cook Brook to 5.88 NTU in Muddy Brook. Overall watershed median of 0.79 NTU was slightly higher than the previous year.

Storm events continued to result in an increase in turbidity, with a median of 1.07 NTU for all wet weather samples and a median of only 0.69 NTU for dry weather samples. Not all sampling locations are impacted equally by storm events. Tributaries with very low flow and ones with upstream beaver activity did not exhibit much difference between median wet weather and median dry weather samples, and in some instances showed a decrease in measured turbidity during storm events.

Table 16: Annual, Wet Weather, and Dry Weather Median Turbidity in Wachusett Tributaries (NTU)

STATION	ANNUAL MEDIAN	DRY MEDIAN	WET MEDIAN
Asnebumskit (Princeton)	1.22	1.22	1.58
Beaman 2	0.57	0.53	1.32
Boylston Brook	0.81	0.74	1.00
Cook Brook (Wyoming)	0.30	0.23	0.33
East Wachusett (140)	0.49	0.49	0.64
French Brook (70)	1.20	1.69	1.25
Gates Brook (1)	0.51	0.41	0.66
Gates Brook (4)	1.20	0.71	1.70
Jordan Farm Brook	0.39	0.35	0.70
Malagasco Brook	0.80	0.73	1.28
Malden Brook	0.46	0.42	0.65
Muddy Brook	5.88	4.93	5.95
Oakdale Brook	0.38	0.33	0.49
Quinapoxet River (Canada Mills)	0.85	0.77	1.18
Scarlett Brook	1.09	0.97	1.22
Stillwater River (Steel Bridge)	0.64	0.65	0.72
Trout Brook	0.70	0.58	0.82
Waushacum (Prescott)	1.66	1.74	1.47
West Boylston Brook	0.67	0.55	0.79
WACHUSETT TRIBS MEAN	0.79	0.69	1.07

3.6 STORMWATER SAMPLING

Stormwater sampling is done to supplement routine monthly nutrient sampling and to more accurately estimate total annual loading, but remained on hiatus while a sampling needs assessment was underway. Stormwater sampling at three locations will be resumed in 2018 during events that produce two or more inches of rainfall.

3.7 SPECIAL STUDIES

Staff continues to monitor potential short term and long term water quality impacts from forest management activities. Investigation of short term impacts consists of monthly turbidity monitoring above and below stream crossings prior to and following completion of all activity at logging sites, with more frequent sampling during active forestry or during storm events. A total of 260 visits were made to 25 locations (14 sites) 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. No problems with elevated turbidity were noted during the year.

Long term forestry monitoring involves collection of data at a control site and an active site for at least ten years before, during, and following completion of forestry operations. Four years of data have now been collected and a preliminary report summarizing results to date should be completed in June 2018. 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.

4.0 RESULTS OF RESERVOIR MONITORING PROGRAM

4.1 BACTERIA

Bacterial transect samples (*E. coli*) were collected weekly in January, twice in February and March, once per month in April though early September, and then weekly again for the remainder of the year from the 23 previously established surface stations on the reservoir. Samples were collected to document the relationship between seasonal bacteria variations and visiting populations of gulls, ducks, geese, cormorants, and swans. Additional midweek samples were collected from late November through mid-December to document the impacts of an intensified full-reservoir bird harassment effort. Unlike many previous years there were no periods of ice cover during 2017 that prevented sample collection. Sample locations were shown previously on Figure 3 and data are presented in Table 17.

Table 17: 2017 Wachusett Reservoir Bacteria Transect Data (MPN/100 mL)

Location	Cosgrove	B2	B3	C1	C3	C5	D1	D2	D4	E2	E4	F2	F3	F4	G2	H2	I2	J2	J3	J4	K2	M1	N1
1/4	1	2	2	1	3	1	1	2	0	2	0	2	5	1	3	6	**15**	10	**14**	**78**	**38**	**12**	**14**
1/12	3	0	2	1	3	0	3	1	3	1	**12**	4	**95**	5	4	7	**16**	9	**34**	**45**	**41**	**11**	**25**
1/26	5	1	1	**13**	1	2	1	1	0	2	0	6	4	0	**11**	4	**11**	7	9	**29**	**16**	**29**	**19**
1/31	0	0	1	0	0	0	0	9	1	6	0	0	0	2	3	2	5	4	**25**	**29**	2	**12**	7
2/8	**11**	**14**	**14**	**15**	**27**	5	9	**12**	5	**19**	3	**14**	**12**	3	**16**	2	3	1	2	4	9	5	7
2/28	1	0	1	0	1	0	1	1	0	3	0	5	0	0	**13**	**25**	5	0	1	10	4	1	1
3/8	1	0	0	0	1	0	2	0	0	2	1	4	0	1	10	**31**	10	4	2	**12**	2	3	2
3/21	0	0	1	0	1	0	1	0	0	1	0	1	**18**	0	**41**	**27**	5	0	7	0	0	0	0
4/11	1	0	1	1	0	1	1	0	0	1	1	0	0	0	1	2	3	0	1	6	6	0	2
5/16	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	2	4	4
6/12	0	1	1	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	2
7/12	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
8/9	0	1	0	1	1	4	7	0	1	**22**	0	0	2	0	1	0	2	0	0	0	0	0	0
9/8	0	2	2	2	2	0	0	0	0	0	2	1	**29**	1	2	4	6	1	0	3	1	0	2
9/18	2	3	6	0	4	**11**	5	2	5	0	2	4	**21**	4	5	3	0	0	2	0	1	1	1
9/25	7	1	2	2	0	6	0	4	2	0	6	1	0	1	0	2	1	1	1	1	1	0	0
10/4	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0
10/11	4	2	1	3	1	1	1	4	5	1	4	2	1	2	0	1	**27**	0	3	4	3	4	1
10/18	1	2	1	0	0	1	0	2	1	1	1	2	0	0	0	1	0	0	4	2	0	1	1
10/23	1	0	0	2	1	1	3	0	1	9	1	2	7	0	0	5	0	0	0	2	0	0	0
11/1	6	3	2	7	4	5	4	2	1	**31**	3	**15**	2	7	3	4	7	4	6	**11**	7	**38**	**25**
11/8	3	4	4	2	6	1	1	4	0	5	2	6	1	2	3	2	2	2	1	2	3	1	2
11/15	1	3	1	3	2	1	4	**16**	1	7	3	9	7	**16**	3	2	3	0	0	1	1	1	1
11/21	0	5	1	2	1	1	1	1	**18**	2	1	5	1	2	0	1	0	0	0	0	0	2	1
11/27	1	4	3	3	2	4	4	3	**38**	**27**	**11**	6	6	10	6	3	1	0	0	0	1	0	0
11/29	6	3	5	2	**16**	1	1	9	4	4	8	2	3	9	8	1	3	0	2	5	0	0	0
12/4	1	3	2	1	0	0	2	2	6	**11**	0	3	9	0	2	0	1	3	7	6	3	2	2
12/7	0	1	1	2	2	1	5	2	6	1	4	3	1	2	6	1	3	3	4	3	2	5	3
12/11	1	1	0	3	2	1	0	1	4	**11**	3	2	2	2	0	2	1	0	5	5	2	1	0
12/14	1	3	0	5	4	3	4	4	1	2	2	0	5	1	3	0	0	1	2	3	2	1	1
12/18	2	3	2	3	0	2	9	4	1	3	3	3	**24**	3	3	1	**29**	3	9	4	**12**	**10**	3

full reservoir harassment (11/29-12/14)

High concentrations of bacteria were recorded throughout January at the southern end of the reservoir (where birds typically spend the night) and at a single location near mid-reservoir on the 12th. Elevated concentrations were also noted in early February at multiple locations at mid-reservoir and the north end of the reservoir including at the Cosgrove Intake, although concentrations were considerably lower and exceeded 20 MPN/100mL only at a single sampling station (C3). Elevated concentrations persisted at mid-reservoir through March, but most waterfowl had departed by April as smaller water bodies became free of ice and bacteria concentrations at all reservoir locations were very low.

Bacteria concentrations remained low at almost all stations until the beginning of November with only single samples from mid-reservoir occasionally with elevated concentrations. Concentrations began to increase throughout November but dropped immediately following the initiation of an intensified full-reservoir bird harassment effort. There was a slight rebound in concentrations at mid-reservoir and near the roost in late December once harassment efforts were reduced to normal levels.

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 365 samples collected at Walnut Hill contained less than the standard, with a maximum concentration of 12 MPN/100mL. 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 2017 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*, phycocyanin, turbidity, 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.

A Yellow Springs Instrumentation (YSI) EXO2 multi-parameter sonde was utilized to measure water column profiles during the 2017 field season. The capability to now measure phycocyanin/blue green algae *in situ* during reservoir profiles is a valuable tool for detecting peak densities of algae and cyanobacteria within the reservoir. It does appear that temperature may affect the accuracy of phycocyanin probe readings, especially at the very low levels normally found in the reservoir. This bears further investigation in the future.

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. As of 2017, all historic profile data from 1988-2017 has been compiled into a single format and is now housed in a single database. A custom Shiny/R application called WAVE, developed by UMass and Division staff has been developed and serves to as a portal to view and track data within the database.

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.

The 2017 season marked a notable departure from the typical transfer schedule, as the Quabbin transfer was not initiated in earnest until June 27th. This was the result of several factors. Very low rainfall in the drought year of 2016 lowered the Quabbin Reservoir elevation for the start of 2017. A very wet spring (Figure 15), coupled with the desire to refill Quabbin's capacity, meant that the daily demand was capably met by withdrawing only from Wachusett for the first 6 months of the year. Thus, the Wachusett elevation was between 1 to 3.5 feet higher than normal for April, May, and June, peaking at an elevation of 394.1 on April 10th. Water was transferred almost continuously from June 26th through the end of the year, but the late start resulted in a yearly total that was the lowest since 2011 and the second lowest total in the past 20 years. A total volume of 32.3 billion gallons (122,170,322 cubic meters) was delivered to Wachusett via the Quabbin aqueduct during 2017. This is equivalent to 54.0% of the volume of Wachusett Reservoir (59.8 billion gallons). For comparison, the equivalent of slightly more than 90% of the Wachusett total volume was transferred in 2015 and 2016, when more than 50 billion gallons were transferred each year (Figure 16).

Figure 15: 2017 Monthly Precipitation (inches)

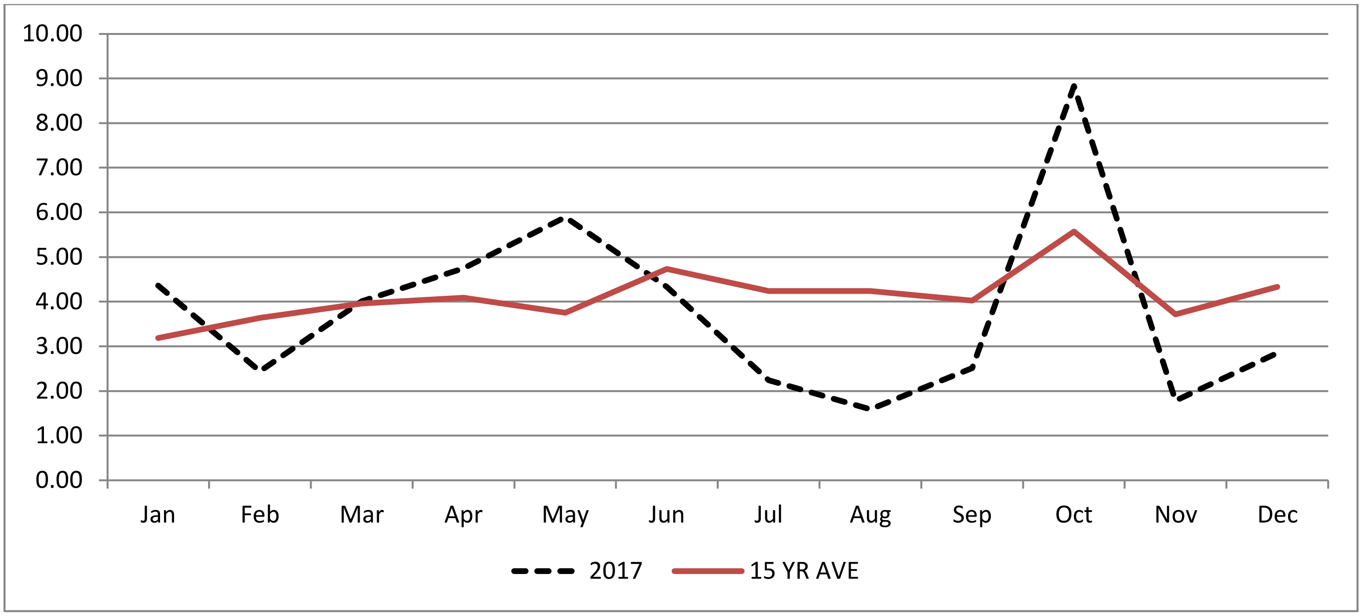
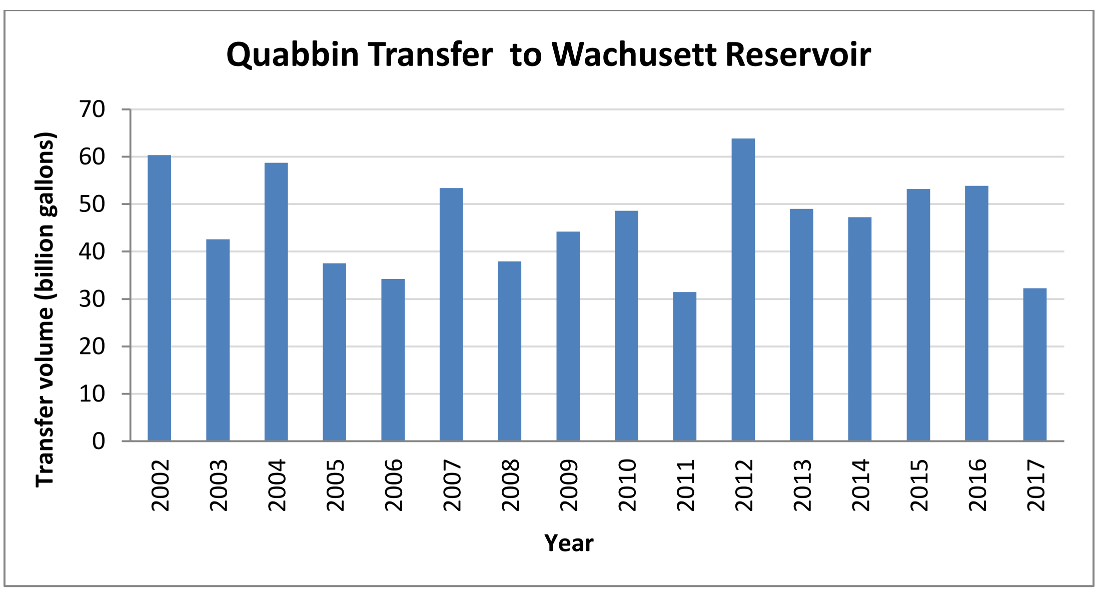


Figure 16: Quabbin Transfers to Wachusett Reservoir



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 recorded in profile measurements. Profiles depicting water column characteristics in July, August, October, and November (Figures 17-20) 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 metalimnion and 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 through the fall, to provide suitable habitat for cold water salmonids such as Lake Trout and Landlocked Salmon that inhabit the reservoir.

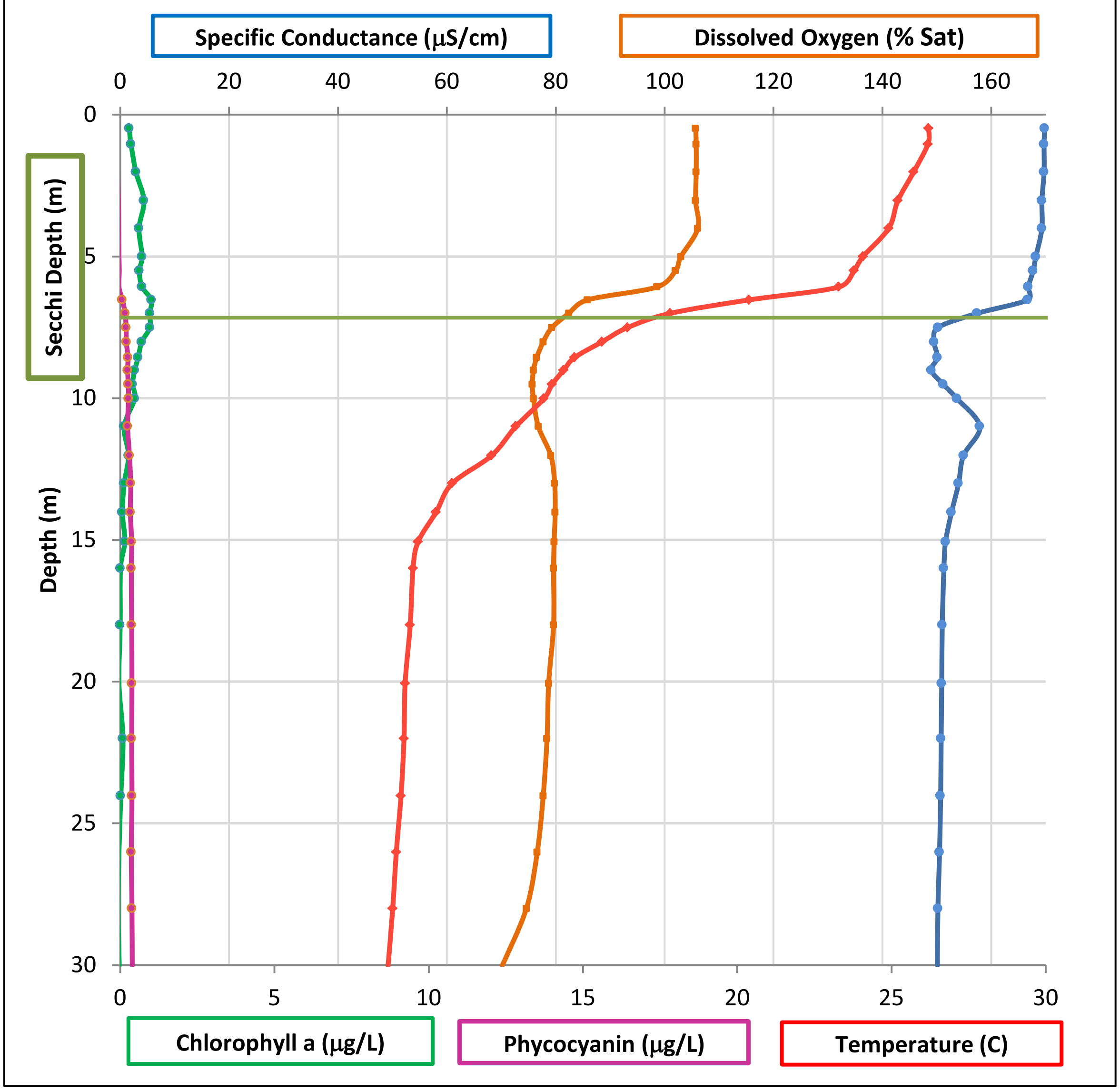
Hydrogen ion activity (pH) in Wachusett Reservoir is determined ultimately by the exchange of inorganic carbon between the atmosphere and water (carbon dioxide-bicarbonate-carbonate buffering). Generally, pH values in Wachusett Reservoir are unremarkable, ranging from around neutral (pH=7) to slightly 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 17 through 20 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 Stillwater and Quinapoxet 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 70 and 300 µS/cm with an average value between 129 and 194 µS/cm. In contrast, the average conductivity value of Quabbin water is approximately 48 µS/cm.

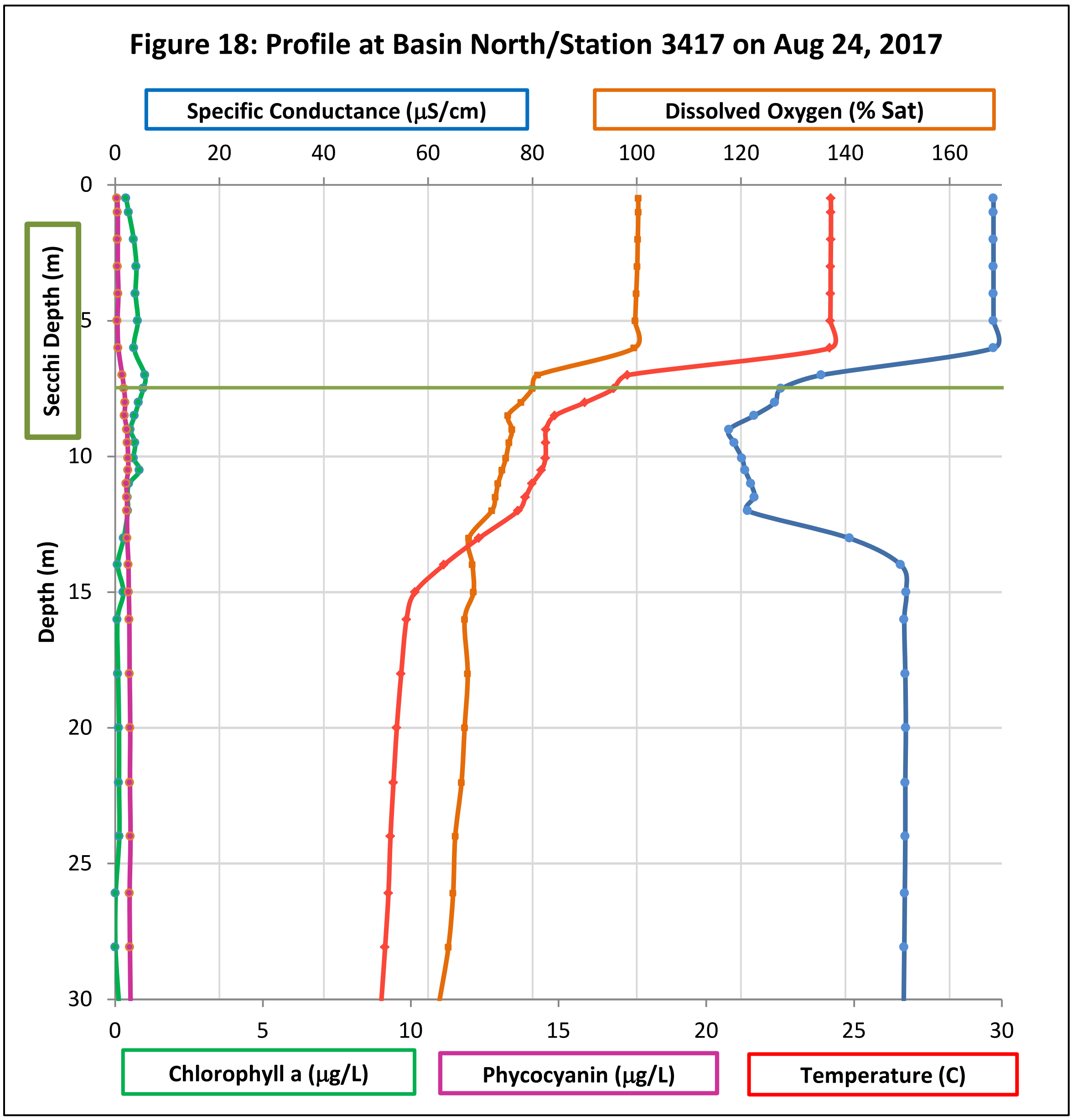
During periods of isothermy (November through March), conductivity values throughout the main Wachusett basin typically range from 75 to 145 µS/cm depending on the amount of water received from Quabbin the previous year. During the summer stratification period the Quabbin interflow is conspicuous in profile measurements as a metalimnetic stratum of low conductivity. Due to the lower than normal Quabbin transfer volume, the specific conductance levels measured in the reservoir in 2017 were the highest on record. A record high specific conductance value for Basin North of 169.8 µS/cm was recorded near the surface on July 19th. Specific conductance values greater than 160 were recorded at the surface at Basin North throughout August. The highest specific conductance readings on record at the Basin South and Thomas Basin monitoring stations occurred in 2017 as well.

Interflow penetration at Basin North/3417 was first observed on July 19 (Figure 17), 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. It is noteworthy that this is about 1 month later than typical for interflow arrival, and that specific conductance values at all depths are higher than typically observed. The epilimnion occupied the top 6 meters of the water column on this date and had reached a temperature of 26.2° C. Epilimnetic dissolved oxygen measured 106% 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.

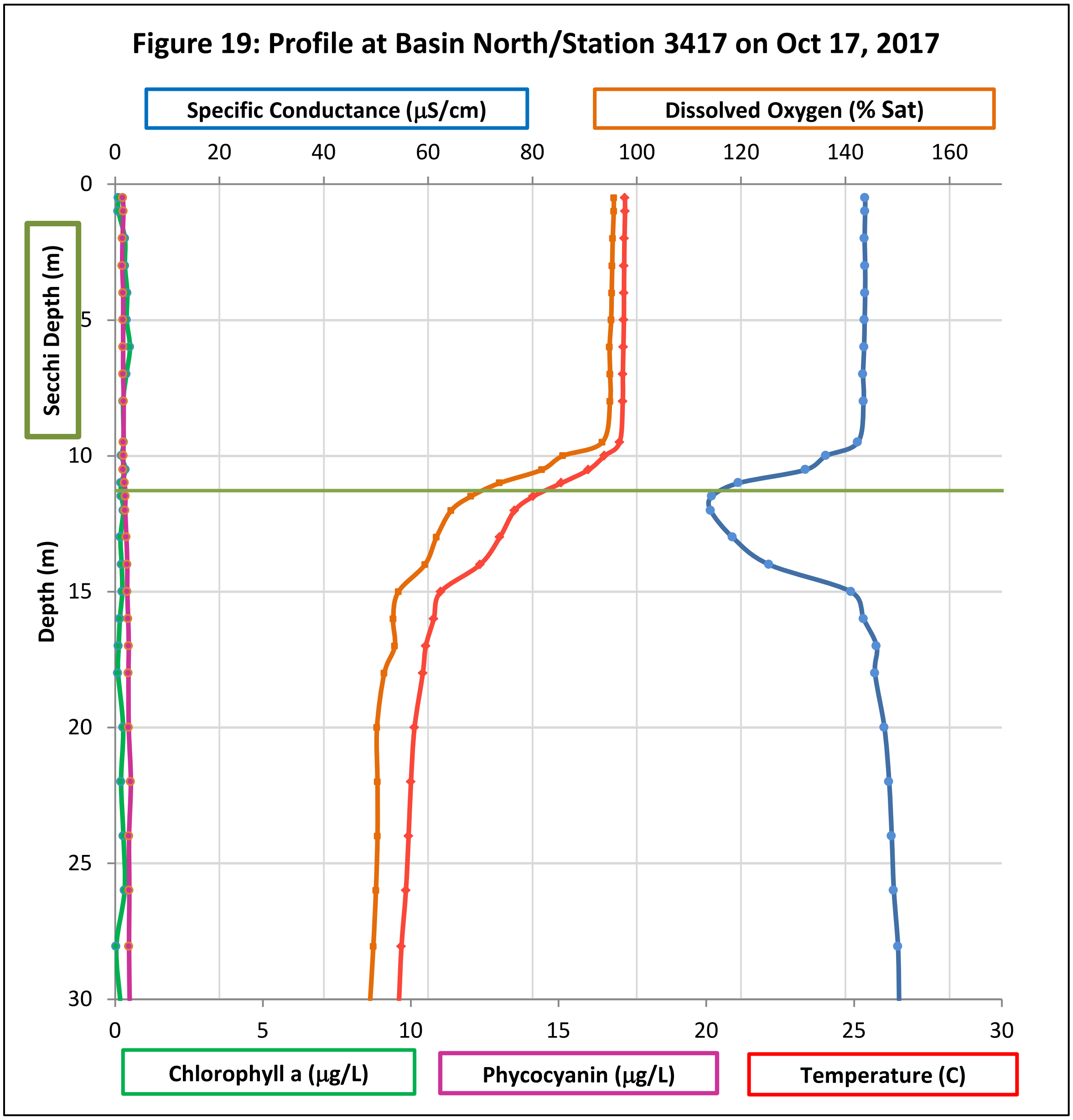
Figure 17: Profile at Basin North/Station 3417 on Jul 19, 2017



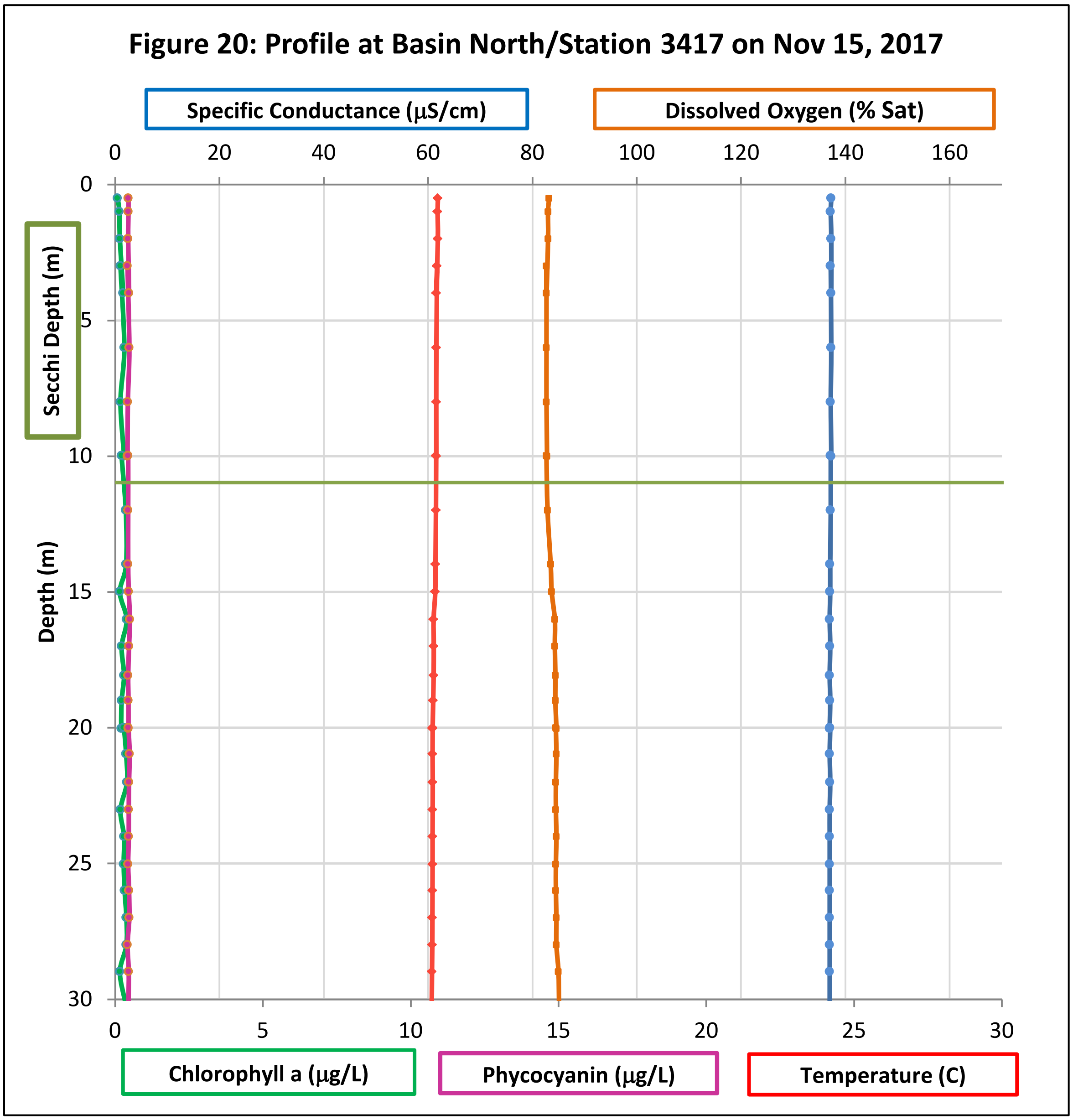
The interflow continued to become more fully established, remaining as a discrete layer through the summer months. On August 24, the “bulge” in the conductivity profile (Figure 18) shows the typical mid-summer configuration of the fully established interflow with a thickness of eight meters present between depths of 6 and 14 meters. Conductivity reached minimum values of around 117 µS/cm at a depth of 9 meters. The epilimnion still occupied the top six meters of the water column with a temperature of 24.2° 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 and 8 meters. Chlorophyll *a* concentrations are again low as was overall phytoplankton density at this time.



Epilimnetic temperatures typically begin to steadily decrease throughout September, however this year the epilimnion did not begin losing heat in earnest until mid-October. By October 17 (Figure 19), heat losses and wind energy had eroded the thermocline downward. The interflow is still clearly visible as a distinct layer, although at this point in the season it is shrinking in size as the top portion is eroded. At this point, the change to lower specific conductivity values is a gradual decline between 9.5 and 15 meters. Dissolved oxygen remained near saturation in the epilimnion, but had declined to a low of 50% 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.



A profile recorded on November 15 (Figure 20) 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 0.2° C from the surface to the bottom (10.9° C – 10.7° 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 137 µS/cm throughout the water column, continuing a trend of higher than normal values. The Secchi disk depth recorded in association with this profile was a robust 11 m (36 feet), slightly less than the peak value (11.4m) recorded at the end of October.



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 2016 is used as a basis for interpreting data generated in 2017. All results from quarterly nutrient sampling in 2017 were within historical ranges. Overall, nutrient concentrations for 2017 are comparable to measurements recorded in recent years (see Table 18 and the complete 2017 reservoir nutrient results in Appendix A).

The patterns of nutrient distribution in 2017 quarterly samples generally followed 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. In 2017, the lack of Quabbin transfer resulted in the Wachusett watershed water quality more heavily influencing reservoir water quality than in a typical year.

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 now housed in a single database that will allow for the management and analysis of over 5,300 nutrient results collected over the 20 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 1998-2016 Database[1] to Results from 2017 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)	
	1998-2016	2017	1998-2016	2017	1998-2016	2017	1998-2016	2017	2000-2016	2017
Basin North (E)	<5 - 16	<5 - 9	<5 - 176	<5 - 51	0.59 - 4.62	1.00 - 2.36	<5 - 17	<5 - 7	0.029 - 0.090	0.051 - 0.071
Basin North (M)	<5 - 51	7 - 34	<5 - 180	40 - 56	0.77 - 4.67	2.06 - 2.64	<5 - 20	<5 - 11	0.029 - 0.102	0.045 - 0.096
Basin North (H)	<5 - 41	<5 - 32	30 - 225	44 - 116	1.27 - 5.06	2.12 - 3.83	<5 - 19	<5 - 8	0.030 - 0.084	0.053 - 0.068
Basin South (E)	<5 - 15	<5 - 11	<5 - 176	<5 - 58	0.56 - 4.58	1.00 - 2.53	<5 - 20	<5 - 7	0.028 - 0.102	0.051 - 0.075
Basin South (M)	<5 - 39	5 - 24	<5 - 184	38 - 65	0.95 - 4.80	2.23 - 3.06	<5 - 32	<5 - 11	0.031 - 0.128	0.042 - 0.076
Basin South (H)	<5 - 44	6 - 31	19 - 224	58 - 113	1.64 - 4.78	2.25 - 3.77	<5 - 37	<5 - 9	0.032 - 0.111	0.055 - 0.079
Thomas Basin (E)	<5 - 18	<5 - 8	<5 - 201	<5 - 91	0.62 - 7.44	1.51 - 3.48	<5 - 27	5.1 - 17	0.026 - 0.305	0.051 - 0.186
Thomas Basin (M)	<5 - 27	<5 - 8	<5 - 213	<5 - 91	0.88 - 7.07	1.58 - 3.76	<5 - 29	<5 - 13	0.026 - 0.334	0.051 - 0.188
Thomas Basin (H)	<5 - 57	<5 - 13	<5 - 236	12 - 120	0.92 - 7.39	1.88 - 5.38	<5 - 29	8.4 - 12	0.026 - 0.345	0.034 - 0.154

Notes: (1) 1998-2016 database composed of 1998-99 year of monthly sampling and subsequent quarterly sampling through December 2016, except for measurement of UV254 initiated in 2000 quarterly sampling

(2) 2017 quarterly sampling conducted May, July, October, and December

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

(4) No values were recorded in 2017 outside of the historical range

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 was conducted 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 (See Appendix B for an updated Secchi Disk depth SOP).

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 6X to 50X. 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. The perimeter of the S-R cell is scanned to confirm that phytoplankton are still alive, record presence/absence of taxa, and allow the taxonomist to familiarize themselves with taxa present in the sample before counting. Phytoplankton is then 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 178 total algae samples were collected and analyzed during the 2017 season. Given that no ice cover was ever established on the main basin during 2017, samples were collected between January 4 and December 27 without interruption. Overall phytoplankton densities were low in January and into February before beginning to increase in March during the typical spring proliferation of diatoms (Figure 21). Densities continued a steady increase until the end of March, when the maximum density for the season of 1,482 ASU/mL was recorded. At that time, *Asterionella* was present at 1,228 ASU/mL, comprising 82.9% 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.

In general, total phytoplankton densities continued a steady decline from this point forward, reaching a value of 212 ASU/mL on June 8th. The exception was a brief period in early May with higher than typical densities of *Uroglenopsis,* which quickly decreased but were observed through the end of May. *Anabaena* made its usual seasonal appearance around Father's Day in June, as historical records show the peak for this taxa occurs within a narrow range of dates centered on mid-June. *Ananabaena* was first recorded on June 5th, and higher densities had abated by June 22nd. However, during this time, densities recorded in 2017 were higher than recorded in recent years; reaching a peak of 109 ASU/mL on June 13th after a rapid warming of the reservoir surface temperature was observed. Excepting a single value calculated from a surface scum sample in 2003, this was the first *Anabaena* density recorded in the reservoir greater than 50 ASU/mL since 1996.

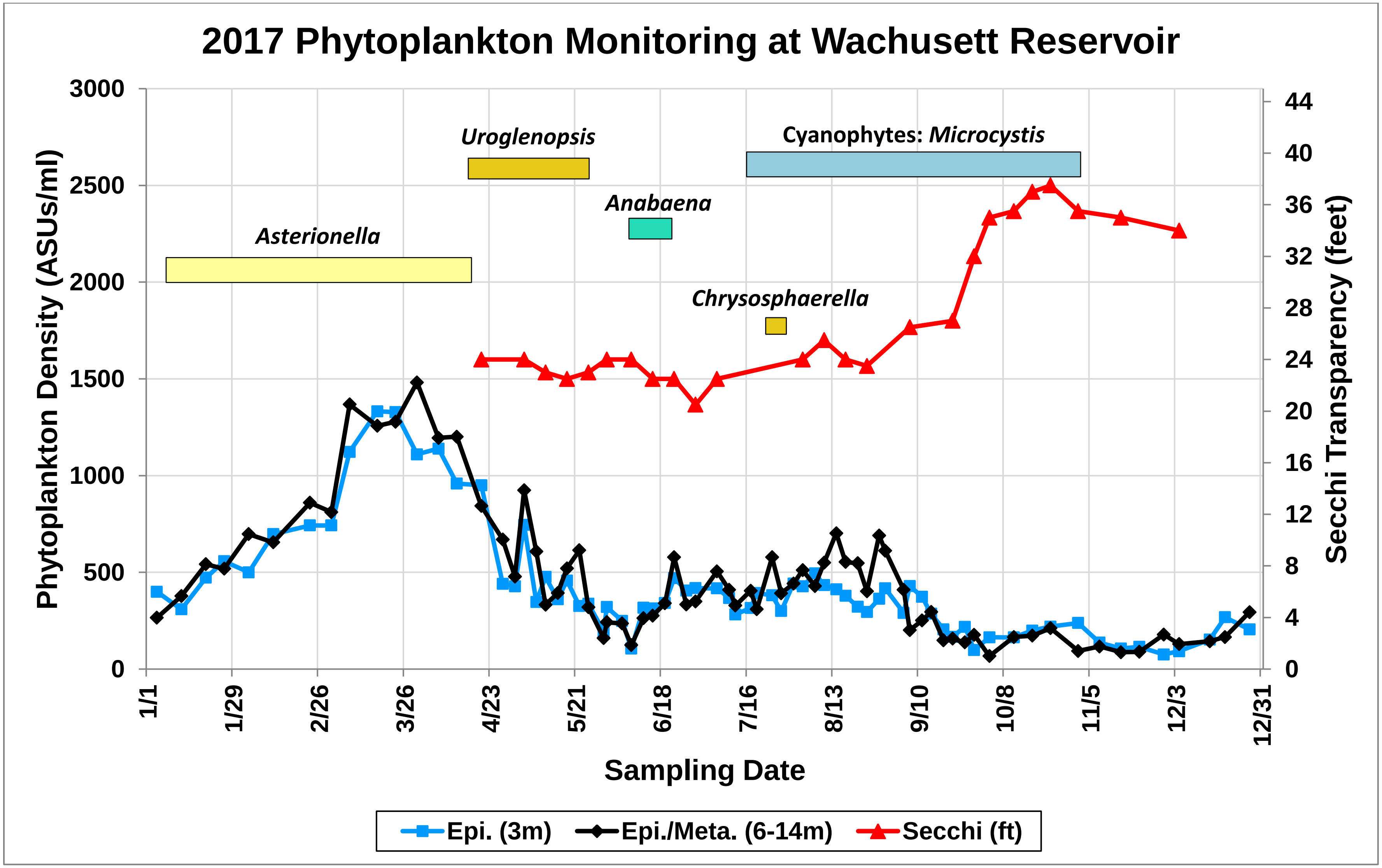
From the end of June onward, densities were generally moderate until decreasing in the middle of September; densities were quite low from that point through the end of the year. Cyanophytes, most notably *Microcystis,* dominated the fall season. *Microcystis* densities were higher than the past two years (although similar to 2015), peaking on August 30th at 376 ASU/mL.

Chrysophytes and Synurophytes have recently been the most frequently occurring nuisance algae in Wachusett Reservoir. As mentioned, *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. *Dinobryon* was typically present at low levels from February through August, but never proliferated and remained well below levels of concern. *Synura* was only observed above the early monitoring trigger of 10 ASU/ml a single time in May. Most notable in its exceedingly late appearance and relative absence was *Chrysosphaerella*, a motile Chrysophyte that typically begins to aggregate within the interflow beginning in mid-June. This appears to be related to the delay in the Quabbin transfer and the interflow arriving at Basin North much later than normal. Additionally, when the interflow did arrive, specific conductance values within the interflow were higher than normal, apparently resulting in less than optimal habitat for *Chrysosphaerella*. The density of this taxa was greater than 50 ASU/mL only once, on July 24th.

Secchi disk transparency is affected by the phytoplankton dynamics outlined above, as well as the water contributions from the Wachusett watershed and Quabbin transfer. As has been mentioned in nutrient and phytoplankton discussions, the wet spring and high percentage of native Wachusett watershed water also affects visibility. 2017 began with a typical pattern (Figure 21), with early season lows of 23 to 24 feet normal for that time of year. However, Secchi disk depths did not increase in earnest until the fall, holding below 27 feet until the end of September, instead of the typical steady increase as the summer progresses. Values increased from that point forward until reaching a maximum recorded depth for the year of a robust 37.5 feet on October 23rd.

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 nearly 5,800 samples collected over this 29 year time period.

Figure 21: Phytoplankton at Wachusett Reservoir



4.4.4 WACHUSETT RESERVOIR PHYTOPLANKTON IMAGES

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

FIGURE 22

***Bacillarophyceae* (diatoms): *Tabellaria,* June 5th 2017, Cosgrove Intake**

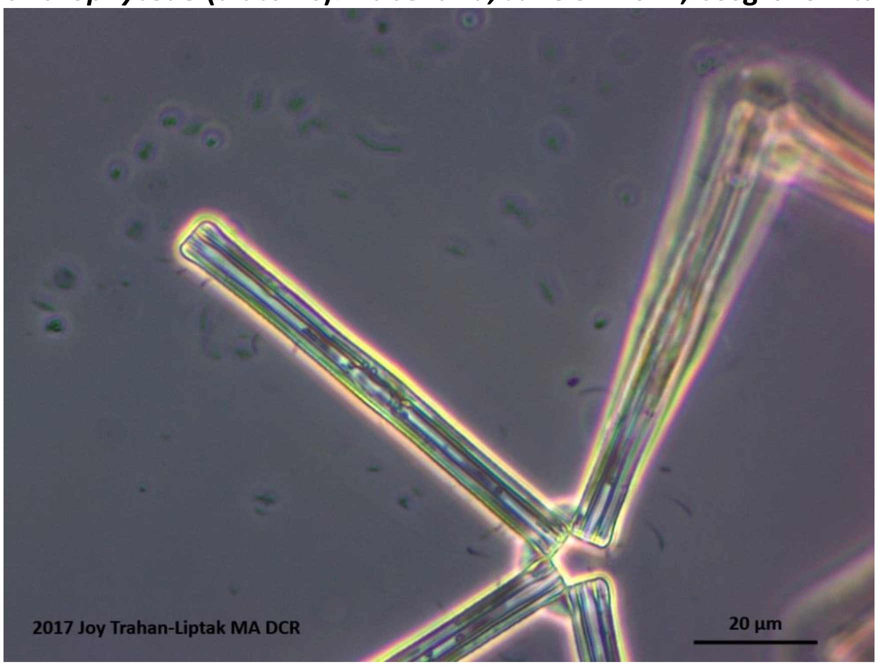


FIGURE 23

***Chlorophyta* (green algae): *Closterium*, April 27th 2017, Basin North**

FIGURE 24

***Chlorophyta* (green algae): *Kirchneriella*, August 30th 2017, Basin North**

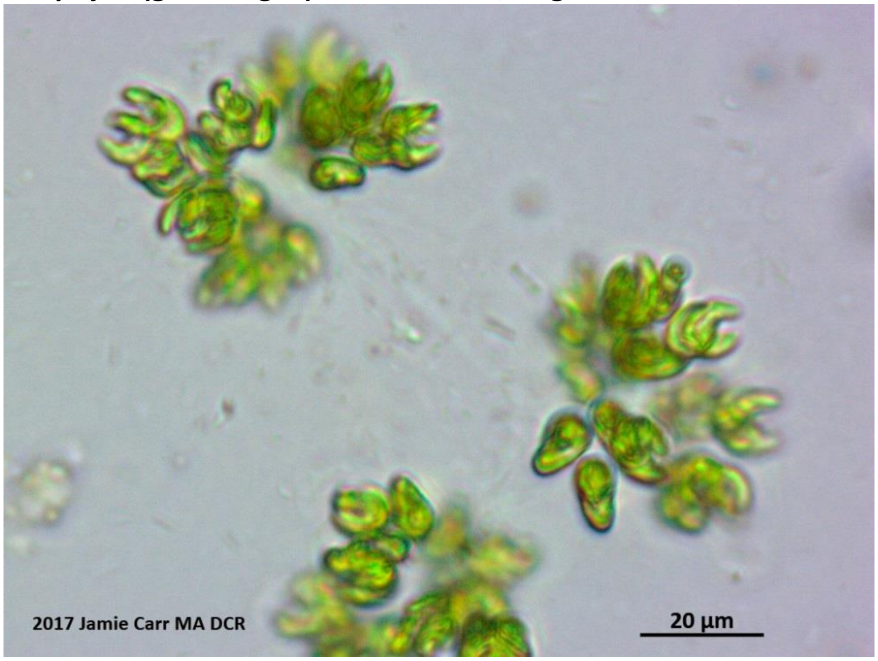


FIGURE 25

***Chrysophyta* (golden/golden-brown algae): *Dinobryon*, June 5th 2017, Cosgrove Intake**

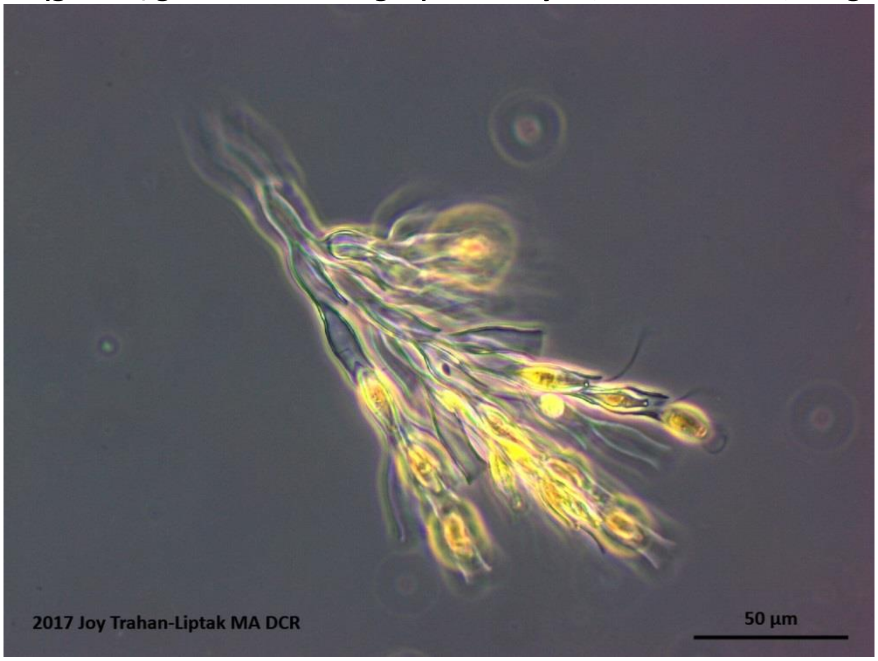


FIGURE 26

***Cyanophyta* (often called "blue green algae"): *Anabaena* June 15th 2017, Cosgrove Intake**

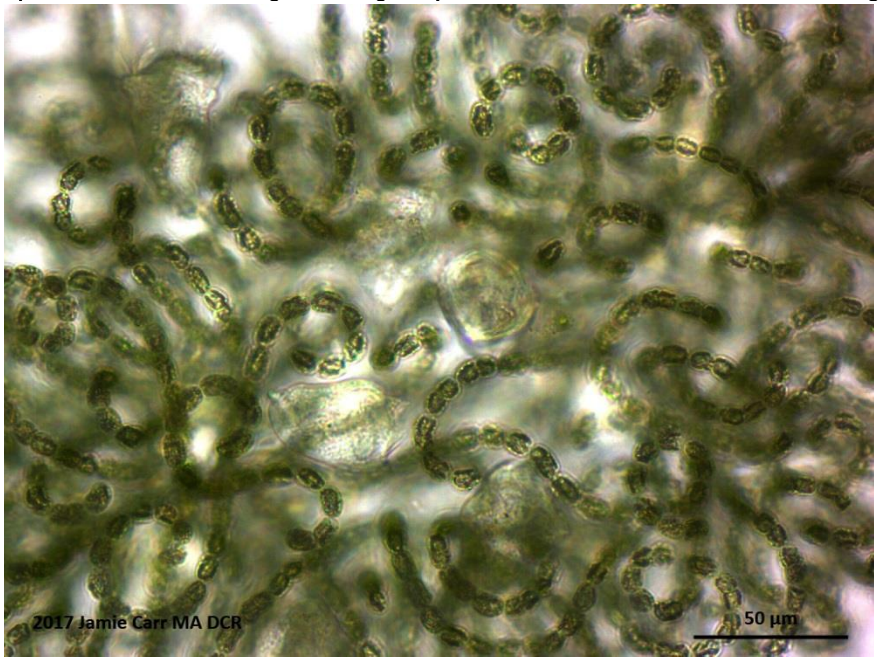
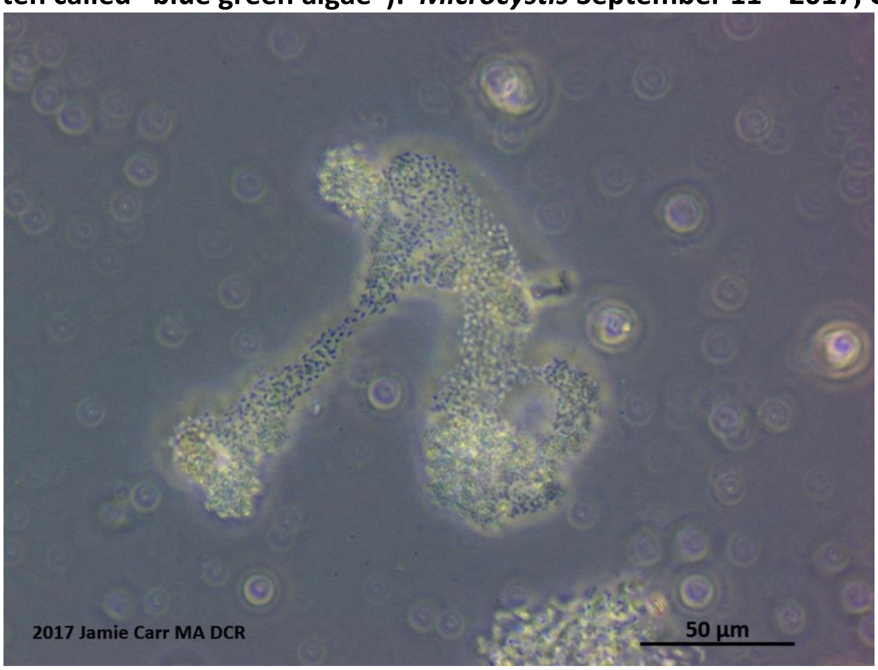


FIGURE 27

***Cyanophyta* (often called "blue green algae"): *Microcystis* September 11th 2017, Cosgrove Intake**



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. It is updated periodically to reflect changes in AIS composition within and in close proximity to the reservoir.

TABLE 19

Aquatic Invasive Species in or Around Wachusett Reservoir

Scientific Name	Common Name	Known to be Present in Wachusett Reservoir	Known to be Present in Local Area
Myriophyllum spicatum	Eurasian water-milfoil (EWM)	x	x
Cabomba caroliniana	Fanwort	x	x
Myriophyllum heterophyllum	Variable water-milfoil (VWM)	x	x
Najas minor	Brittle naiad		x
Trapa natans	Water chestnut		x
Egeria densa	Brazilian elodea		x
Glossostigma cleistanthum	Mudmat	x	
Elatine ambigua	Asian waterwort	x	

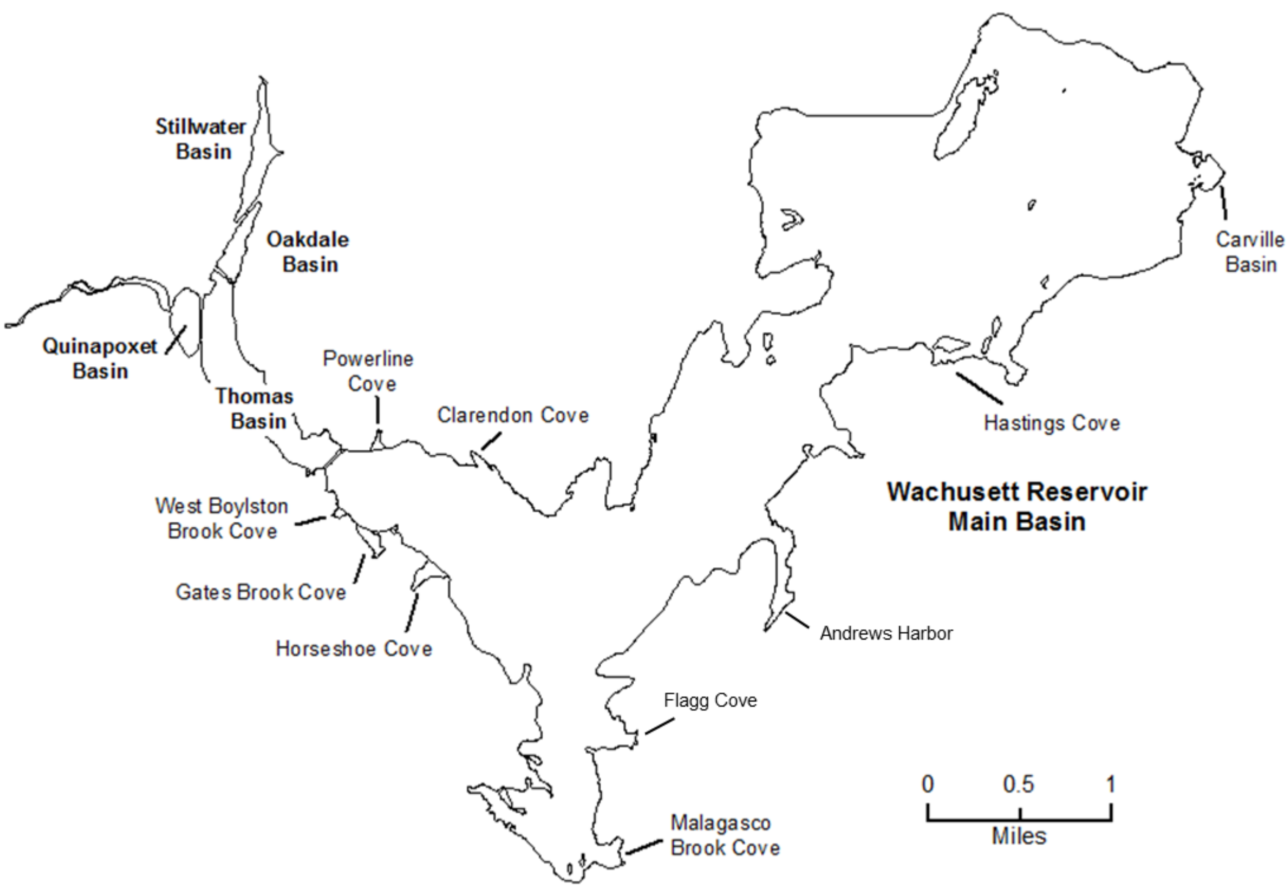
AIS were first recorded in Wachusett Reservoir in the late 1990s and have been actively managed since 2002. Eurasian water-milfoil (*Myriophyllum spicatum*, subsequently referred to as EWM) and *Cabomba caroliniana* (fanwort) are present in several basins of Wachusett Reservoir and are the primary species 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 details of AIS management activities undertaken during 2017 and those planned for 2018.

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 in August 2000. 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.

FIGURE 28
Locations of 2017 AIS Management in the Wachusett Reservoir system



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 (Figure 28). As new infestations are identified, these areas are also targeted in annual removal efforts. DASH (Diver Assisted Suction Harvesting) 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. Details of control efforts in past years are provided in previous annual reports; however, the main components of this program are as follows:

- deployment and maintenance of floating fragment barriers
- hand-harvesting and Diver Assisted Suction Harvesting (DASH)
- routine scouting within the reservoir and watershed 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.)
- Scouting the entire littoral zone of Wachusett Reservoir every 5 years (completed in 2012 and 2016)

The following sections provide information on specific management activities that took place throughout the Wachusett Reservoir and in surrounding water bodies in 2017.

Stillwater Basin

Invasive Species	First Documented	Management Technique(s)
EWM	1999	• DASH initiated in 2013
Fanwort	2000	
VWM	1990s	

Program Highlights

- 322,880 gallons of plants removed in the first season of DASH
- Steady decrease in invasive plant biovolume in each year
- Native plants recolonizing previously infested areas

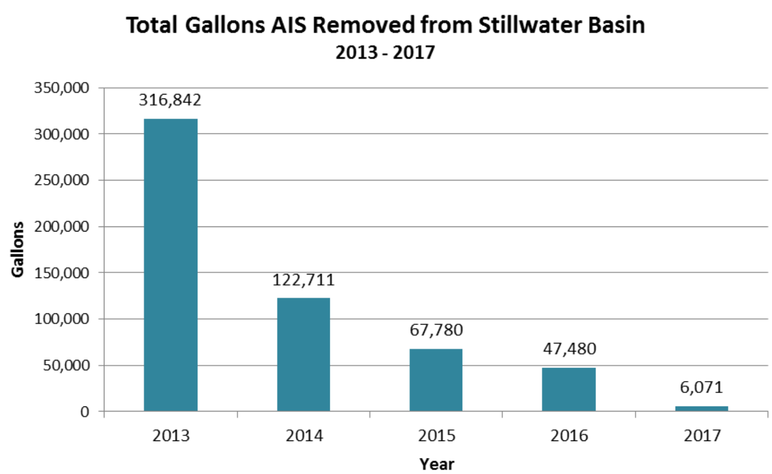
Location of Stillwater Basin

General Management Method

- DASH is conducted between April and November.
- The basin is broken into 3 work zones.
- Each zone covered by DASH efforts twice per year.
- Fragment barriers are utilized to reduce fragment transport.
- Progress is tracked closely with data submitted to DCR and MWRA on a weekly basis.
- Quality Assurance divers track and ensure success of removal efforts on a weekly basis.

2017 Activities

- 6,071 gallons of invasive biomass removed
- Early season high water conditions allowed divers to better reach areas which are typically too shallow for DASH operations. These areas and other 'hot spots' where yearly re-growth was the most dense were targeted first.
- Two full passes of zones 1 and 2 were conducted. Low densities observed in zone 3 allowed for one full and one partial pass.
- Native plants continue to recolonize previously infested area



Future Plans

- Management is anticipated to continue in a similar manner; however, due to the decreases in biomass, level of effort is anticipated to decrease slightly.

Oakdale & Thomas Basins

Invasive Species	First Documented	Management Technique(s)
EWM	1999	• Benthic barrier in Oakdale 2002 • Hand-harvesting since 2002 • Hand-harvesting and DASH combination since 2012
Fanwort	2000	
VWM	Early 1990s	

Program Highlights

- Substantial decrease in EWM and fanwort realized in 2002, the first year of the project
- Year-to-year fluctuations in both EWM and fanwort are common
- In general, plants growing in these two basins exist as single stems or isolated plant beds

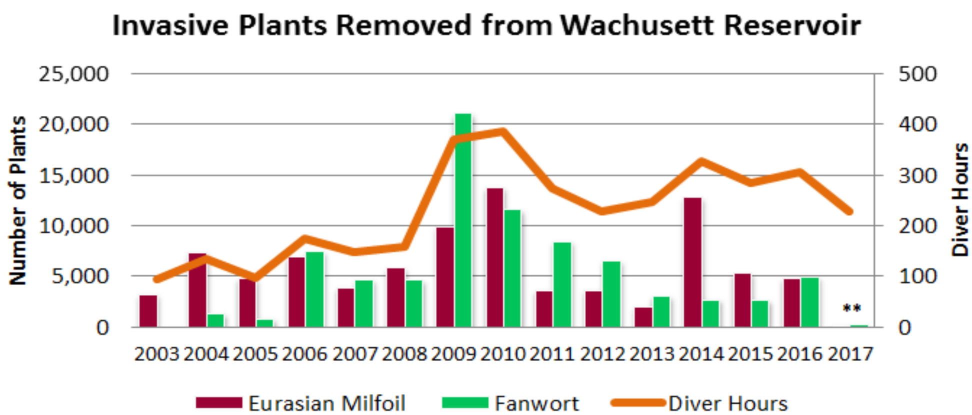
Location of Thomas and Oakdale Basins

General Management Method

- Two harvest rounds are conducted each year – typically one in July and one in September
- Surveys of the basins are conducted prior to each harvest to guide efforts
- Starting in 2015, each basin was broken into smaller units for reporting purposes
- Starting in 2015, quality assurance divers track and ensure success of removal efforts

2017 Activities

- Two complete passes of each basin were conducted; late July/early August and late September
- Over 90% reduction in both EWM and fanwort observed between 2016 and 2017



** Eurasian Milfoil = 84, Fanwort = 237

- *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 numbers reported here for 2015-2017 are adjusted to reflect raw data reported to DCR*

Future Plans

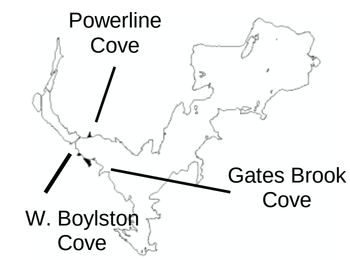
- Management is anticipated to continue in a similar manner in 2018

Main Basin Coves – Powerline, West Boylston Brook, and Gates Brook

Cove	Occurrence	Management Technique(s)
Powerline	EWM: 2002 – present FW: 2007, 2009-2012, 2014	• Hand-harvesting • Hand-harvesting / DASH combination since 2012
Gates Brook	EWM: 2012 – present	
W. Boylston Brook	2012 – 2016	

Program Highlights

- Overall density of invasive plants in these coves is low; however, soft substrates, especially those found in Gates Brook Cove, provide ideal growing conditions for aquatic plants.
- Year-to-year fluctuations in EWM are common
- Fanwort has not been found outside of Powerline Cove



Location of managed main basin coves

General Management Method

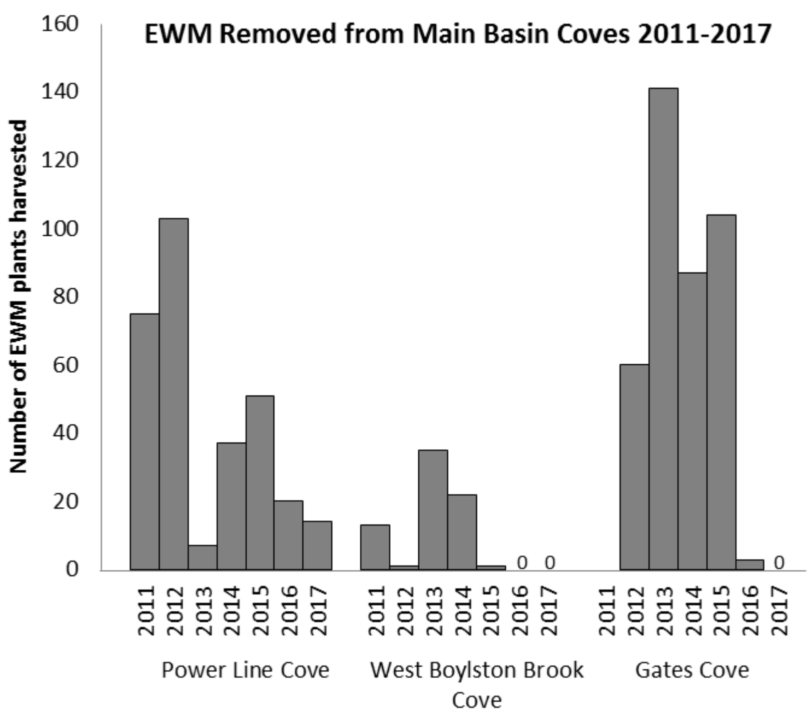
- Schedule and management plan follows that discussed above under Thomas and Oakdale Basins
- Hand-harvesting is the primary removal method with DASH implemented as necessary

2017 Activities

- Limited numbers of plants were present in these areas in 2017 – the lowest totals in all three coves since 2014.
- Gates Brook Cove – Dense, early season growth of native *Elodea* sp. may have contributed to the decrease of EWM in this cove
- West Boylston Brook Cove – No EWM was observed in this cove during 2017
- No fanwort was observed in 2017; most recently one plant was removed from Powerline Cove in 2014.

Future Plans

- Management is anticipated to continue in a similar manner in 2018



Quinapoxet Basin

Invasive Species	First Documented	Management Technique(s)
EWM	2016	• EWM and fanwort DASH since 2016 • VWM DASH removal pilot initiated in 2017
Fanwort	2016	
VWM	1989	

Program Highlights

- Management of EWM and fanwort was initiated immediately following discovery in 2016; total numbers of plants decreased between 2016 and 2017
- VWM is present throughout the basin at great densities (see map of biovolume below)
- A pilot program was conducted in 2017 to assess the feasibility of VWM removal via DASH

Location of Quinapoxet Basin

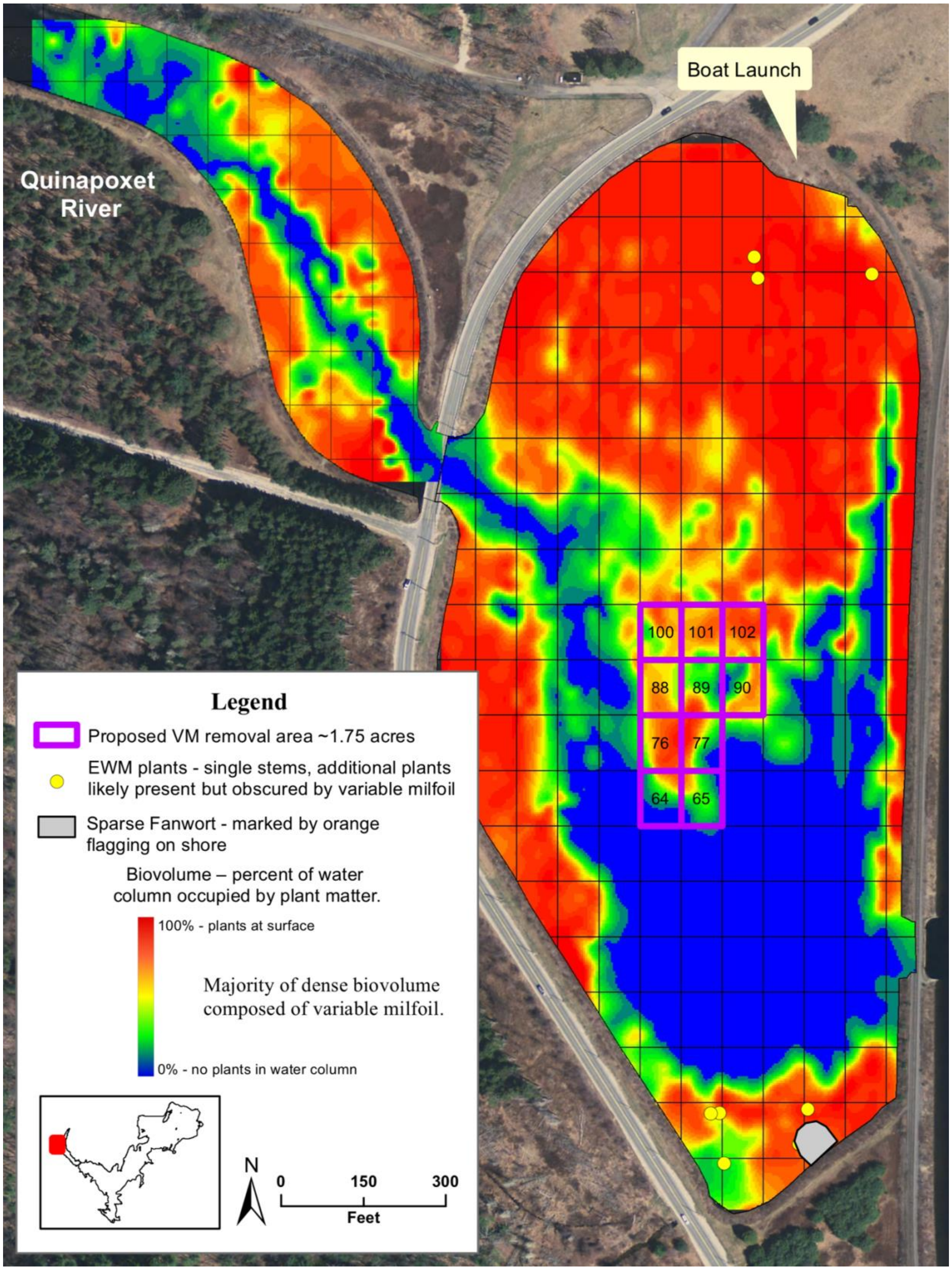
General Management Method

- Surveys of the basin are conducted by DCR biologists to identify the location and extent of AIS to guide removal operations
- Two rounds of DASH are conducted; generally in August and late September
- A fragment barrier is installed on the upstream side of the rail road bridge between Quinapoxet and Thomas Basins to reduce movement of plant fragments to downstream locations

2017 Activities

- EWM distribution and density decreased following the initial year of harvest; 43 EWM plants were removed in 2017 compared to 170 in 2016.
- A total of 95 fanwort plants were removed (it should be noted that early season die-off prevented removal of fanwort during the 2016 season).
- A total of 12,480 VWM plants were removed from a 1.75-acre area of moderate to dense growth over a period of one week and total diver effort of approximately 200 diver-hours. This effort was part of a pilot program to determine the feasibility of VWM removal in this historically infested basin.

Quinapoxet Basin



July 2017 distribution and density (as biovolume) of AIS in Quinapoxet Basin

Future Plans

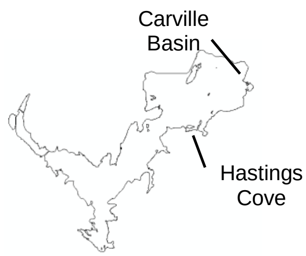
- Management is anticipated to continue in a similar manner in 2018

Hastings Cove and Carville Basin

Invasive Species	VWM First Documented	Management Technique(s)
Hastings Cove	2013	• DASH
Carville Basin	2016	

Program Highlights

- These areas are the closest to the Cosgrove Intake known to contain VWM. Harvesting was initiated in an effort to prevent the spread of these plant beds and to reduce the potential for fragments to migrate downstream and impact the intake works and for spread to the north basin and the shallows.



Location of Carville Basin and Hastings Cove

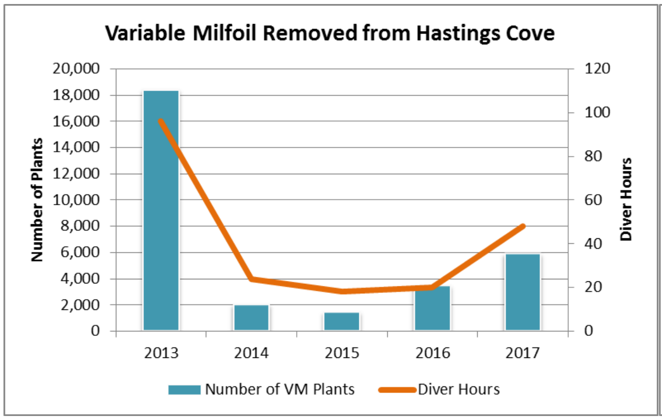
General Management Method

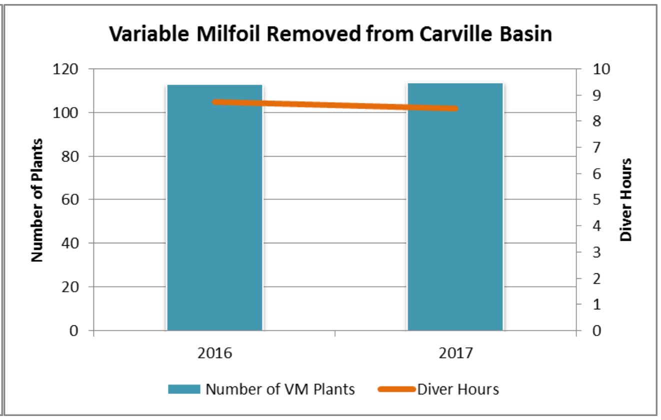
- Schedule and management plan follows that discussed above under Thomas and Oakdale Basins
- DASH is the primary management method with hand-harvesting as necessary

2017 Activities

- Hastings Cove – two rounds of harvesting were necessary due to a larger quantity of VWM plants in 2017. This harvesting resulted in 5,849 VWM plants, an increase of 71% since 2016, possibly due to fluctuating water levels.
- Carville Basin – two days of harvesting were conducted resulting in a removal of 114 plants which was similar to the number removed in 2016
-

Variable Water-milfoil Removal Totals





Future Plans

- Management is anticipated to continue in a similar manner in 2018

Outlying Occurrences of Eurasian water-milfoil

DCR biologists conduct regular surveys of reservoir areas where EWM has been observed and removed in previous years, as well as areas which have been identified as likely to support invasive species. These include areas which are in close proximity to other occurrences of invasive species (both within and nearby the reservoir), areas near roadways or popular fishing areas, and areas where nutrient-rich substrates would provide ideal habitat for new infestations. No new occurrences of EWM or fanwort were documented in 2017.

TABLE 20
Locations of EWM in Outlying Reservoir Areas

	Number of EWM Plants Removed				
Location	**2011**	**2012**	**2014**	**2016**	**2017**
Andrews Harbor	–	–	–	1	–
Clarendon Cove	–	–	–	1	–
Flagg Cove	–	–	–	1	–
Horseshoe Cove	4	6	–	1	–
Malagasco Brook Cove	–	–	1	–	–

2013 and 2015 are not included here as no AIS were observed in these areas during that period.

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.

Additional Management Activities

Contractor Aquatic Macrophyte Surveys

MWRA contracted with ESS Group, Inc. in 2017 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 2017 survey. ESS noted that, following three "…years of increasing density, mudmat bed density declined at more locations (30) than where it was observed to increase (15 locations), including areas of new growth. This marks the first year-over-year decline observed for mudmat at Wachusett Reservoir."

Additional AIS Observations

DCR Aquatic biologists are monitoring for known AIS in new locations and 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 since that time 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.

A genetic study was conducted to confirm the presence of *E. ambigua* in Wachusett Reservoir based on samples collected in 2014. The resulting article published in Rhodora (Rosman et al. 2016) confirmed the identification and a subsequent correction to this article clarified its extent in Wachusett Reservoir (see Appendix C for the errata published in Rhodora, March 2017).

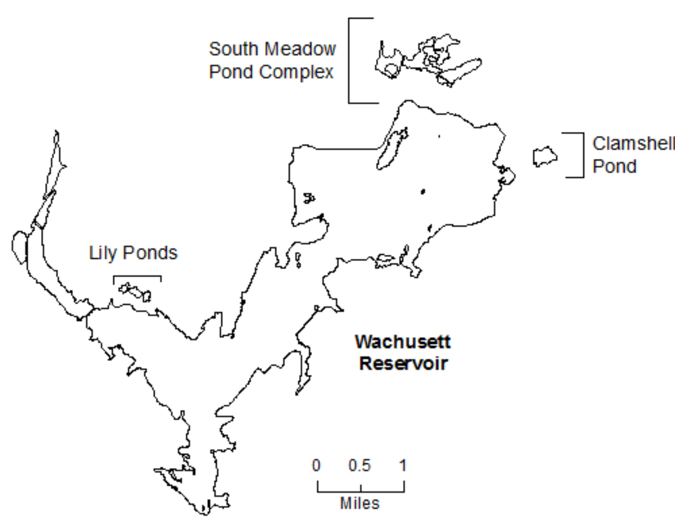
4.5.2 SUPPLEMENTAL INVASIVE MACROPHYTE CONTROL ACTIVITIES

Additional activities were conducted in 2017 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.

Management of AIS outside of Wachusett Reservoir

In recent years AIS have been discovered in several local ponds (Figure 29). 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 29: 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 2017.

Sediment tuber density is measured in several areas of the ponds complex to monitor the effectiveness of treatments. In the initial years of treatment, tuber density was significantly reduced annually, reaching the point where no tubers found during surveys in 2015. In 2016, tuber density increased with an average per-site density of 3.16 tubers/m^2 in South Meadow Pond West and 1.8 tubers/m^2 in South Meadow Pond East (although plants were observed in additional areas, no tubers were reported from Coachlace Pond in 2016 and there are no sampling sites in Mossy Pond).

Based on these results, the contractor recommended a change in treatment methods to include use of endothall, an herbicide that has provided control of hydrilla in New York water bodies. Despite use of this product in 2017, a follow-up survey conducted by DCR biologists showed significant re-growth of hydrilla, necessitating a second treatment. It should be noted that the DCR survey was conducted while the pond complex was undergoing an algae bloom which caused reduced water clarity, obscuring the view of hydrilla in many areas. Therefore, the extent of hydrilla re-growth was likely underestimated. Following these two treatments, tuber densities were higher than those observed in any year since management started. These results are problematic and DCR is working to develop a plan for 2018 that will reverse this trend and continue to protect Wachusett Reservoir from potential infestations.

Two additional submerged invasive aquatic species are present and managed in the South Meadow Ponds complex; Curly-leaf pondweed and VWM. Following a survey conducted by DCR biologists, approximately 23 acres of Curly-leaf Pondweed were treated over all four basins of the pond complex during an early season treatment performed on May 15, 2017. This was the initial year of treatment for this species which was first documented at low densities in the pond in 2015 and increased substantially in 2016. VWM was treated concurrently with hydrilla.

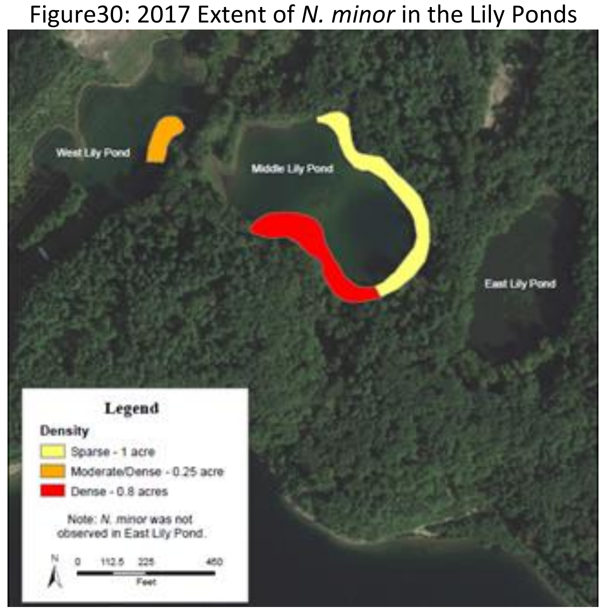
<u>References Cited:</u>

SOLitude Lake Management. 2017. Final Report for 2017 Aquatic Plant Management, South Meadow Pond. Prepared for Massachusetts Department of Conservation and Recreation Lakes and Ponds Program.

Lily Ponds

Two invasive species, *Najas minor* (European/Brittle Naiad) and *Myriophyllum spicatum* (Eurasian Water-milfoil) were identified in the Lily Ponds during 2015. Due to the highly invasive nature of these non-native species, DCR implemented a rapid response and initiated management of these species in the fall of 2015. Management includes closure of the ponds to recreation (i.e., fishing and bait collection) as well as treatment utilizing state-approved and US EPA registered herbicides. The initial treatment of *N. minor* and *M. spicatum* was successful in reducing the biomass of both

Figure30: 2017 Extent of *N. minor* in the Lily Ponds



species within each treated pond (see previous management reports for details). The continuing management plan for these ponds includes annual monitoring for *N. minor*, *M. spicatum* and any other non-native species that may present a threat to the ponds and in turn Wachusett Reservoir.

Several surveys were conducted by DCR Aquatic biologists during the summer of 2017 to assess the effects of the 2016 treatment and determine if additional treatment would be necessary in 2017. During the initial survey in June, neither *N. minor* nor *M. spicatum* was observed in any of the three ponds.

A follow-up survey on August 23rd found growth of *N. minor* present in East and Middle Lily Pond, totaling less than 2 acres (Figure 30). A treatment was scheduled for these two ponds and was conducted on September 1st following notification to the abutting landowner and the Conservation Commission. A post-treatment survey was conducted by DCR biologists who confirmed *N. minor* showed effects of treatment within two weeks and no further treatment was necessary.

<u>Reference Cited:</u>

SOLitude Lake Management. 2017. 2017 Year-End Report, Lily Ponds. 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.

Brazilian elodea was found in more than 70% of the pond with dense growth most common during the initial survey in 2016 and again 2017. This invasive species is uncommon in Massachusetts (reported in less than 20 locations state-wide) and may be 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. DCR has met with the Town of Clinton Conservation Commission and is working with the town through the DCR Partnership Program to develop a management plan to reduce the potential for spread of this species to the reservoir and other area water bodies. A DCR partnership grant was awarded to the town of Clinton in late 2017 and plans are in process for herbicide treatment of Brazilian elodea in 2018.

Based on the low densities of water chestnut present around the perimeter of the pond and the biology of this particular invasive, the most appropriate management of this species is hand-harvesting. Following communication with the Clinton Conservation Commission, the 2016 harvest was conducted by DCR biologists and the 2017 harvest was conducted as a joint effort by DCR biologists and volunteers from the Rauscher Farm Management Subcommittee. This model of volunteer harvesting in cooperation with DCR will continue in future management seasons.

Table 21: Clamshell Pond Water Chestnut Removal

Year	Date(s) of harvest	Total number water chestnut plants removed	Comments
2016	June 24 and 28 August 31	904	Harvest conducted by DCR biologists. Plants were scattered throughout the littoral zone of the pond at trace to sparse density.
2017	August 5 and 31	235	Harvest conducted by DCR biologists and volunteers from the Rauscher Farm Management Subcommittee. Plants were again scattered throughout the littoral zone. Many rosettes were in poor condition and were not rooted.

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 22).

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.

Table 22: Wachusett Reservoir Area Ponds Surveyed in 2017 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

Name	Town	Proximity to Wachusett Reservoir (miles)*	Acres	Number of Invasive Vegetation Species Observed	Year management initiated
Lily Pond East	West Boylston	0.21	4.7	1	2015
Lily Pond Middle	West Boylston	0.21	7.5	2	2015
Lily Pond West	West Boylston	0.26	4.3	1	2015
South Meadow Pond Complex	Clinton/Lancaster	0.3	130	3	2010

* number of miles to closest reservoir shoreline location

4.5.3 PLANS FOR INVASIVE PLANT CONTROL EFFORTS IN 2018

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.

Plans for the 2018 season call for continuation of DASH in all upper basins of the reservoir (Oakdale, Quinapoxet, and Thomas Basins), as well as coves of the main basin. DCR aquatic biologists will continue to conduct surveys and guide contractor harvest efforts as well as manage data collection throughout the project. The large scale Stillwater Basin DASH project is scheduled to resume in June 2018 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 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, maintain, and monitor floating fragment barriers
- Conduct surveys of areas of interest (Stillwater, Oakdale, Thomas, main basin coves)
- Conduct surveys of local water bodies
- Respond to any new AIS discoveries as appropriate
- Inspect all boats, divers, and other in-water equipment or individuals accessing the reservoir and collect decontamination forms
- Keep the Wachusett Watershed Rangers up to date on AIS topics to guide their interactions with recreational users

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. Historic fisheries work in the reservoir consisted of angler creel surveys, conducted in 1979, 1980 and 1998, along with sporadic and infrequent sampling in the reservoir. 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. An angler creel survey was conducted at Wachusett Reservoir during the 2017 angling season, following the recommendation complete one every 5 years (Carr 2015). Results of the 2017 creel survey will be published in a separate report.

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, the absence of information about their population, and their susceptibility to climate change (Carr 2015).

As a result, 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 421 lake trout have been captured during fall sampling efforts between 2014 and 2017. A total of 359 individual lake trout have been tagged and released. Twenty-three fish that had been tagged and released previously have been recaptured (3 fish have been recaptured twice). Thirty-six 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 31: DCR and DFW biologists remove a lake trout from captured in a net (North Dike in background)

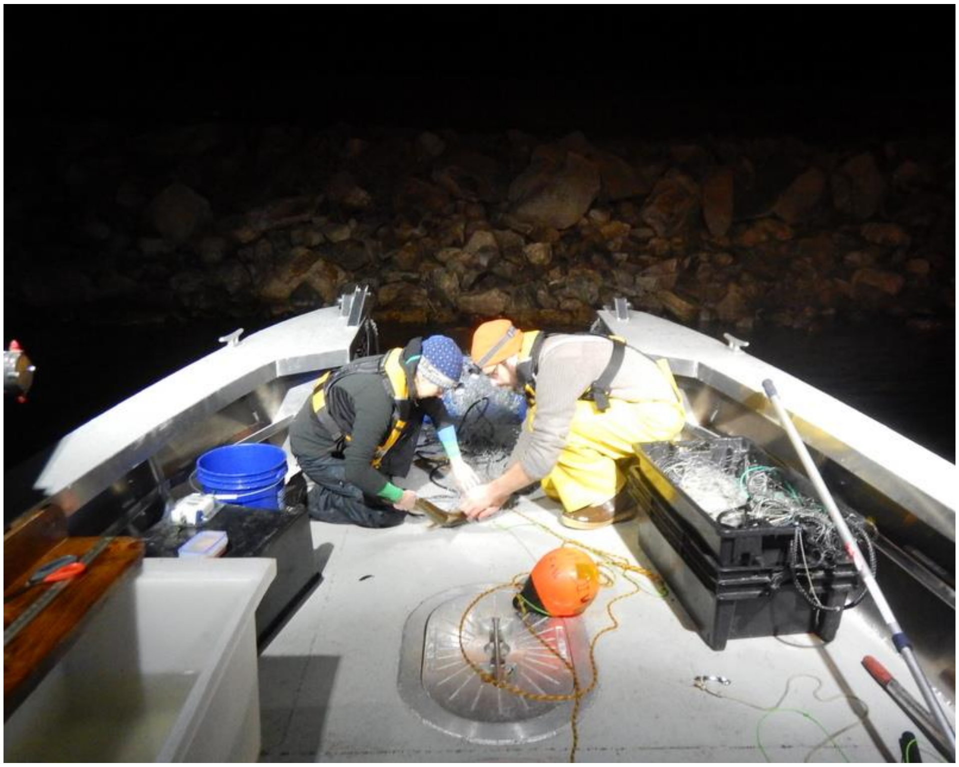


Figure 32: PIT tag used for tagging lake trout

<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 2018

The Wachusett watershed sampling program for 2018 is a modification of the protocol used during previous years. Temperature, specific conductance, *E. coli*, and turbidity will be measured twice per month at 18 stations on 17 tributaries without regard to weather conditions. Sampling of Beaman Pond Brook will be discontinued as flow from this tributary almost never reaches the reservoir. Additional sampling for *E. coli* will be done within 48-72 hours when a result at one of the 18 stations is higher than a predetermined metric. Supplementary samples may also be collected from these stations when specific flow conditions are present that have been under-sampled in the past, or from extra locations to help identify sources of contamination.

Nutrients, total suspended solids, and (new for 2018) chlorides will be sampled monthly from ten tributary stations with available flow data and hopefully a second time each month during previously under-sampled conditions such as low flow during extended drought or periods of high flow caused by snow melt or large precipitation events.

Routine sampling provides some data on the effects of storm events on tributary water quality when samples are collected during or following precipitation. More detailed 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 for a variety of parameters will be collected during extreme precipitation events (>2" of rain) 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 Fitchburg and from the USGS stations on the Stillwater River in Sterling and the Quinapoxet River in Holden will be uploaded daily. Snow pack measurements and calculation of snow-water equivalent amounts will be done regularly during the winter months throughout the watershed and data uploaded into the existing database.

Depth will be recorded at seven stations and flow calculated using rating curves developed by Division staff. Depth measurements will be collected continuously using HOBO water level data loggers that have been installed within custom designed enclosures that allow winter measurements regardless of temperature. 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 four years of the study will be completed in the summer of 2018.

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.

APPENDIX A

Results of Quarterly Nutrient Sampling:

Total Phosphorus (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	5/4/2017	7/19/2017	10/3/2017	12/4/2017
MD25	Basin North (E)	0.005	0.007	0.006	<0.005
MD61	Basin North (M)	0.005	0.011	0.007	<0.005
MD62	Basin North (H)	<0.005	0.008	0.008	<0.005
MD26	Basin South (E)	0.005	0.007	<0.005	0.006
MD63	Basin South (M)	<0.005	0.011	0.006	0.006
MD64	Basin South (H)	<0.005	0.008	0.009	0.006
MD27	Thomas Basin (E)	0.017	0.009	0.005	0.007
MD65	Thomas Basin (M)	0.013	0.010	<0.005	0.008
MD66	Thomas Basin (H)	0.011	0.009	0.008	0.012

Results of Quarterly Nutrient Sampling:

Ammonia NH_3 (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	5/4/2017	7/19/2017	10/3/2017	12/4/2017
MD25	Basin North (E)	0.005	<0.005	<0.005	0.009
MD61	Basin North (M)	0.007	0.034	0.010	0.008
MD62	Basin North (H)	<0.005	0.032	<0.005	0.008
MD26	Basin South (E)	<0.005	<0.005	<0.005	0.011
MD63	Basin South (M)	0.005	0.024	0.012	0.015
MD64	Basin South (H)	0.006	0.031	0.006	0.013
MD27	Thomas Basin (E)	0.008	<0.005	<0.005	<0.005
MD65	Thomas Basin (M)	0.007	0.008	<0.005	0.007
MD66	Thomas Basin (H)	0.013	0.007	<0.005	0.007

Results of Quarterly Nutrient Sampling:

Nitrate NO_3 (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	5/4/2017	7/19/2017	10/3/2017	12/4/2017
MD25	Basin North (E)	0.051	<0.005	<0.005	0.048
MD61	Basin North (M)	0.056	0.052	0.040	0.046
MD62	Basin North (H)	0.052	0.060	0.116	0.044
MD26	Basin South (E)	0.058	0.007	<0.005	0.054
MD63	Basin South (M)	0.065	0.045	0.038	0.055
MD64	Basin South (H)	0.067	0.075	0.113	0.058
MD27	Thomas Basin (E)	0.091	0.007	<0.005	0.042
MD65	Thomas Basin (M)	0.091	0.027	<0.005	0.051
MD66	Thomas Basin (H)	0.120	0.024	0.012	0.082

Results of Quarterly Nutrient Sampling:

Total Kjeldahl Nitrogen (mg/L; MDL = 0.05 mg/L)

		Sampling Date			
ID	Sampling Station	5/4/2017	7/19/2017	10/3/2017	12/4/2017
MD25	Basin North (E)	0.120	0.241	0.159	<0.100
MD61	Basin North (M)	0.128	0.181	0.103	<0.100
MD62	Basin North (H)	0.112	0.227	0.107	<0.100
MD26	Basin South (E)	0.137	0.237	0.119	<0.100
MD63	Basin South (M)	0.178	0.230	0.118	<0.100
MD64	Basin South (H)	0.108	0.271	0.142	<0.100
MD27	Thomas Basin (E)	0.212	0.242	0.114	0.165
MD65	Thomas Basin (M)	0.204	0.247	0.151	0.122
MD66	Thomas Basin (H)	0.198	0.213	0.103	<0.100

Results of Quarterly Nutrient Sampling:

UV254 (mg/L)

		Sampling Date			
ID	Sampling Station	5/4/2017	7/19/2017	10/3/2017	12/4/2017
MD25	Basin North (E)	0.062	0.071	0.051	0.054
MD61	Basin North (M)	0.058	0.096	0.045	0.053
MD62	Basin North (H)	0.056	0.068	0.055	0.053
MD26	Basin South (E)	0.067	0.075	0.051	0.072
MD63	Basin South (M)	0.066	0.074	0.042	0.076
MD64	Basin South (H)	0.062	0.063	0.055	0.079
MD27	Thomas Basin (E)	0.186	0.087	0.051	0.063
MD65	Thomas Basin (M)	0.188	0.072	0.051	0.065
MD66	Thomas Basin (H)	0.154	0.046	0.034	0.126

Results of Quarterly Nutrient Sampling:

Silica (mg/L)

		Sampling Date			
ID	Sampling Station	5/4/2017	7/19/2017	10/3/2017	12/4/2017
MD25	Basin North (E)	2360	994	1590	2100
MD61	Basin North (M)	2240	2640	2250	2060
MD62	Basin North (H)	2230	2790	3830	2120
MD26	Basin South (E)	2410	999	1510	2530
MD63	Basin South (M)	2360	3060	2230	2510
MD64	Basin South (H)	2460	2250	3770	2730
MD27	Thomas Basin (E)	3480	1510	1570	2780
MD65	Thomas Basin (M)	3760	1830	1580	2960
MD66	Thomas Basin (H)	3450	3390	1880	5380

Results of Quarterly Nutrient Sampling:

Alkalinity (mg/L)

		Sampling Date			
ID	Sampling Station	5/4/2017	7/19/2017	10/3/2017	12/4/2017
MD25	Basin North (E)	6.02	7.06	6.52	6.40
MD61	Basin North (M)	6.06	6.98	5.82	6.62
MD62	Basin North (H)	5.90	6.70	6.10	6.34
MD26	Basin South (E)	5.92	7.12	6.76	7.08
MD63	Basin South (M)	6.14	6.54	5.68	6.58
MD64	Basin South (H)	5.98	6.50	6.20	6.52
MD27	Thomas Basin (E)	7.90	7.98	6.70	5.20
MD65	Thomas Basin (M)	7.92	7.88	6.80	5.42
MD66	Thomas Basin (H)	6.56	5.44	4.92	8.10

APPENDIX B

SECCHI DISK DEPTH STANDARD OPERATING PROCEDURES

Below is the MA DCR Division of Water Supply Protection standard operating procedure for collecting a Secchi depth measurement on the Wachusett Reservoir. This procedure should be followed by any analyst responsible for collecting a Secchi depth. The two bullet points below describe the best practices for collecting accurate data.

- The goal is to record an accurate measure of the maximum viewable depth of the Secchi disk as viewed with the unaided eye (if the user normally wears glasses, they should remain on). Do not use sunglasses, an Aquascope view tube, or other polarizing filters to view the disk. Using the shaded side of the boat or the boat motor to reduce glare from the sun on the water's surface is recommended and encouraged.
- If the boat is moving or the current is strong and the disk and tape are at an angle, the analyst should wait and allow the disk to return below them and the tape to straighten out before collecting a measurement. Patience with the tape and viewing may be required depending on conditions.

1. **Prepare the measuring tape –** Unwind 20-40 feet of the measuring tape attached to the Secchi disk. It is easier to lower and raise the tape during measurement collection without the hand crank. Fumbling with the hand crank during sampling increases the risk of losing the disk in the reservoir. To reduce bias, use a tape printed only on one side and turn the tape so the measurements cannot be viewed while lowering the disk.
2. **Get into a viewing position –** Crouch, lie or kneel down towards the surface of the water until the analyst is comfortably positioned approximately 1-2 feet above the water surface.
3. **Lower the Secchi disk into the water –** Pick up the Secchi disk by the measuring tape and begin to slowly lower the disk into the water.
4. **Find the lower bound –** Lower the Secchi disk into the water until it disappears from view. Read the measuring tape where it intersects with the surface of the water to note the lower bound of the Secchi depth and remember this reading.
5. **Find the upper bound –** Slowly raise the Secchi disk until it is visible to note the upper bound of the Secchi depth and note this reading as before. The final value reported for the Secchi depth should be between these upper and lower bound readings.
6. **Find the Secchi depth –** To define the Secchi disk depth, slowly lower the Secchi disk until the disk is just visible. Raise and lower the disk in and out of sight using smaller increments to narrow the window and increase the accuracy of the measurement. Look at the measuring tape where it intersects the water to record the first Secchi depth.
7. **Collect repeat measurements –** Repeat step 6 two more times, so that 3 values have been noted for Secchi depth. If all 3 values are within the upper and lower bounds found in steps 4 and 5, the measurement is complete. If any of these 3 depths are deeper than the lower bound, then repeat steps 4-6 again.
8. **Establish analyst final Secchi depth –** The analyst's final Secchi disc depth is the median of the 3 values recorded in steps 6 and 7.
9. **Multiple analysts –** It is preferred that more than one analyst follow the procedure if time allows in order to serve as a quality check. If this is the case they should discuss and compare values. Analysts typically have median values that closely agree (within 5%). If the values do not agree, the average, or the value of the more experienced analyst may be used as the final Secchi depth at the discretion of the analysts.

APPENDIX C

RHODORA, Vol. 119, No. 977, pp. 56–57, 2017

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CORRECTION

In the recent article "New records of *Elatine ambigua* (Elatinaceae), a nonindigenous North American species" by Rosman et al. (Rhodora 118: No. 974: 2016. pp. 241–242, doi: 10.3119/15-30) the extent of *E. ambigua* in Wachusett Reservoir is described as follows:

A field survey of *Elatine ambigua* conducted in Wachusett Reservoir in Boylston (Worcester County, Massachusetts) found several populations growing within the reservoir. We also observed that *E. ambigua* achieved a much larger population size than many of the other aquatic plant species and dominated most of the shallow areas of the reservoir. Being so abundant, this species clearly limits the growth of native species such as *E. minima*. In Wachusett Reservoir, *E. minima* populations are much smaller both in patch size and in the total number of individuals than the *E. ambigua* populations. At least in this case, it seems that the introduction of *E. ambigua* has negatively impacted some of the native plant populations within the reservoir. Thus, we recommend more extensive studies of this species to elucidate whether it should be considered as an invasive species in the USA.

During subsequent communication with D. H. Les (pers. comm.) he conceded that the use of the phrase "dominated most of the shallow areas of the reservoir" did misrepresent the authors' actual intent, which was to indicate that *Elatine ambigua* dominated in those "several populations" in which it was found rather than to imply that the species occurred throughout the reservoir. Consequently, the Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection (MA DCR; Jamie Carr, jamie.carr@state.ma.us) wishes to clarify the extent of *E. ambigua* documented in the Wachusett Reservoir based on their own extensive surveys.

Since the discovery of this new occurrence by MA DCR in 2014 and DNA identification provided later that same year by Rosman et al., MA DCR aquatic biologists have been monitoring *Elatine ambigua* in Wachusett Reservoir. As a component of an aquatic plant survey of the 60.4 km littoral zone of the reservoir conducted in 2016, MA DCR documented *E. ambigua* growing in isolated dense patches. The extent of the largest patch was 0.016 ha and the total area of all recorded occurrences was 0.03 ha. *Elatine ambigua* occupies 0.03% of shallow areas of the reservoir $\leq$1.5m in depth. Although *E. ambigua* is locally abundant in the few locations where it occurs, native *E. minima* is common throughout the littoral zone of the 1656 ha reservoir and thus its population achieves a far greater size in terms of extent and total number of individuals. MA DCR concurs with the authors that more extensive studies of *E. ambigua* are needed to determine if it impacts native plants and acts invasively in this region.