Water Quality Report: 2015

Wachusett Reservoir Watershed

March 2016

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

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 2015 water quality data from the Wachusett Reservoir tributaries and reservoir. A report summarizing 2015 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 Lawrence Pistrang, Environmental Analyst, and Jamie Carr, Aquatic Biologist. The sampling station map was produced by GIS analyst Craig Fitzgerald using the most recent data. Internal review was provided by Patricia Austin and John Scannell. Steve Sulprizio, Jamie Carr, Joy Trahan-Liptak, David Getman, and Daniel Crocker collected the samples and were responsible for all field measurements. Plankton samples were analyzed by Jamie Carr and Joy Trahan-Liptak. Turbidity analysis was done by Steve Sulprizio, David Getman, Daniel Crocker, or Patricia Austin. All other lab analyses (bacteria, nutrients, and metals) were performed by MWRA staff. John Scannell is the Regional Director of the Wachusett/Sudbury Operational Section and Jonathan Yeo is the Director of the Division of Water Supply Protection

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

WATER QUALITY REPORT: 2015
WACHUSETT RESERVOIR AND TRIBUTARIES

1.0 INTRODUCTION

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

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

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

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

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

All bacteria, nutrient, specific conductance, turbidity, plankton, precipitation and flow data for the past twenty-eight years are stored in an AQUARIUS database. All data generated during tributary and reservoir water quality testing in 2015 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 2015. 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 651 turbidity samples and 136 reservoir phytoplankton samples. A total of 1,244 physiochemical measurements (temperature and specific conductance) were done in the field at tributary stations, with another 40 water column profiles (temperature, specific conductance, dissolved oxygen, percent oxygen saturation, chlorophyll *a*, and pH) recorded on the reservoir. A total of 1,012 bacteria samples were collected and delivered to the MWRA Southborough laboratory for either *E. coli* or fecal coliform analysis, and approximately 200 samples were collected and shipped to the MWRA Deer Island laboratory for about 1,400 analyses of nutrients and other parameters.

2.1 TRIBUTARY MONITORING

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

Nutrient samples were collected monthly from ten stations (shown in Table 1) and analyzed at the MWRA Deer Island Lab for total phosphorus, ammonia, nitrate-nitrogen, nitrite-nitrogen, total Kjeldahl nitrogen, total organic carbon, total suspended solids, and UV-254. Reactive phosphorus samples were collected monthly from the Stillwater and Quinapoxet Rivers. All sample collections and analyses were conducted 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 DCR Environmental Quality staff. Daily flow in Gates Brook and the Stillwater and Quinapoxet Rivers was obtained from continuous recording devices installed by the USGS.

Precipitation data from NOAA weather stations in Worcester and Fitchburg, from the USGS stations on the Stillwater River in Sterling and the Quinapoxet River in Holden, from the MWRA rain gage in Clinton, and from a DCR rain gage in West Boylston were collected daily to help interpret water quality changes and determine if these were impacted by precipitation events.

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

Figure 1: Wachusett Watershed Tributary Sampling Stations

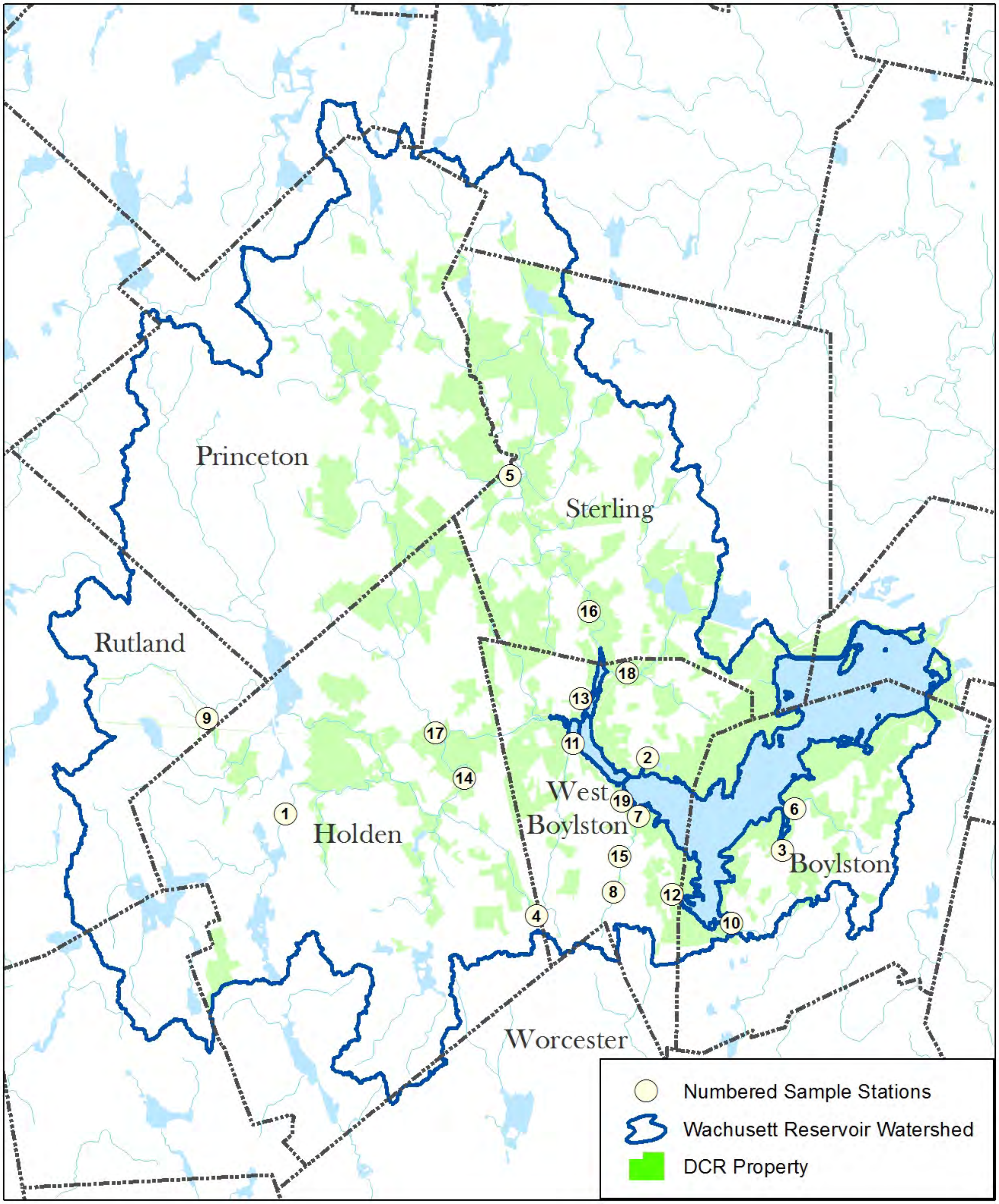


Table 1: Wachusett Tributary Sampling Stations (2015)

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

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

2.2 RESERVOIR MONITORING

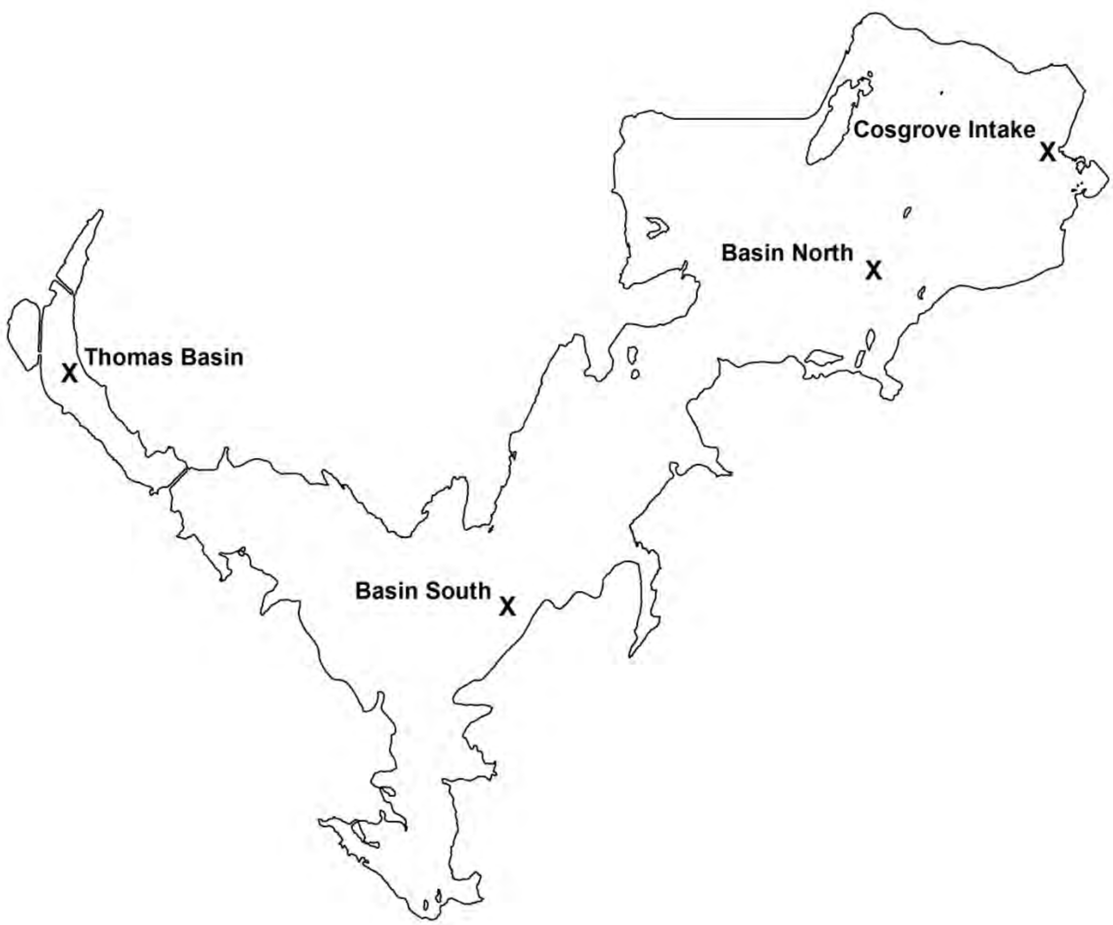
Temperature, specific conductance, chlorophyll *a*, dissolved oxygen concentration and percent saturation, and pH water column profiles were recorded weekly during stratified conditions at Station 3417 (Basin North) in conjunction with routine plankton monitoring. A full panel of nutrient samples was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

Table 2: Wachusett Reservoir Sampling Stations (2015)

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

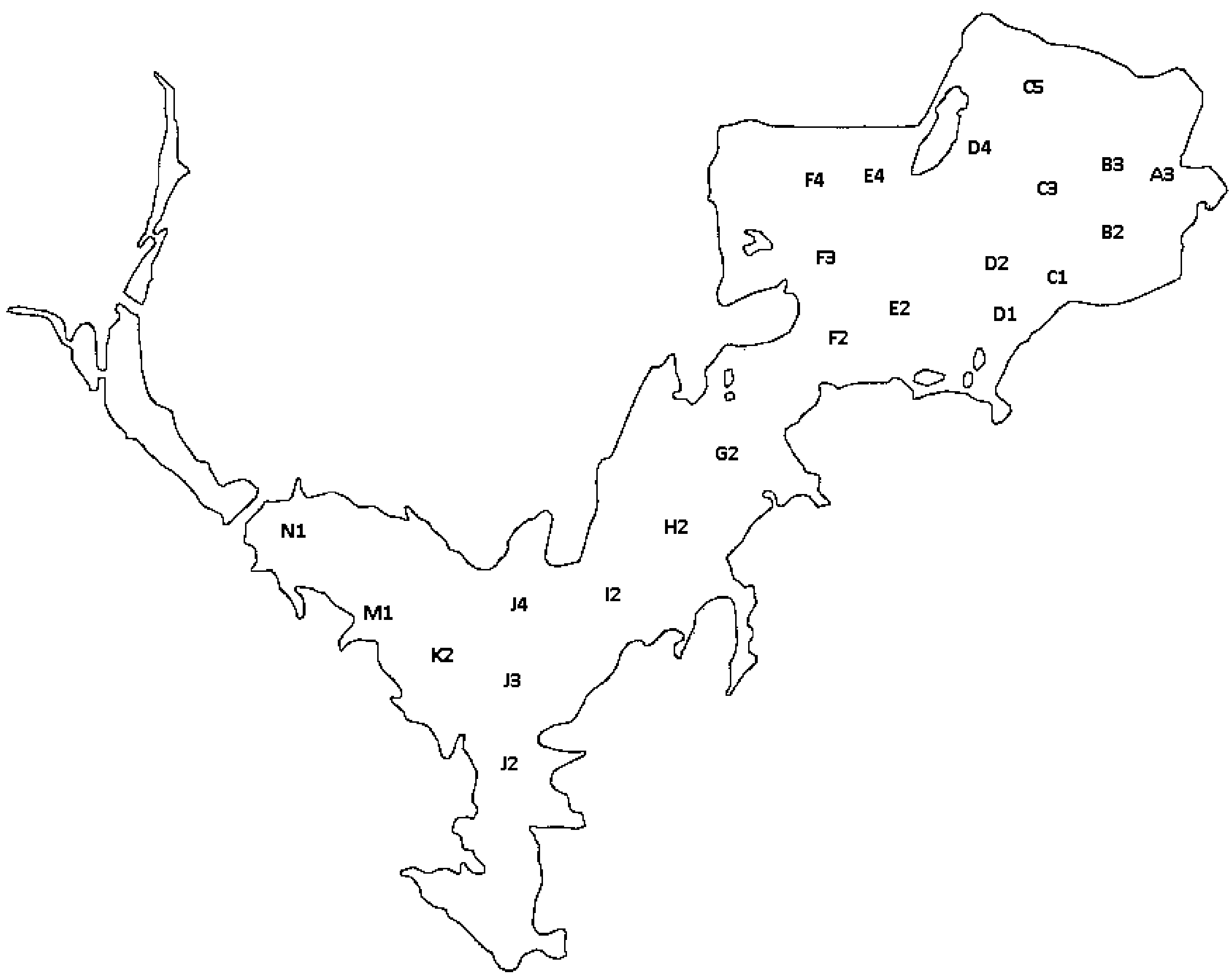
W = weekly (temperature, conductivity, plankton, and water column profiles at Cosgrove or 3417)
Q = quarterly (plankton, profiles, nutrients)

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. Fecal coliform samples were collected by Division staff from 23 reservoir surface stations (Figure 3) once or twice per month.

Figure 3: Reservoir Transect Stations



3.0 RESULTS OF TRIBUTARY MONITORING PROGRAM

3.1 BACTERIA

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

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

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

STATION	GMEAN (2015)	GMEAN (2014)	GMEAN (2013)	GMEAN (2012)	%>235 (2015)	%>235 (2014)	%>235 (2013)	%>235 (2012)
Asnebumskit (Princeton)	105	64	40	45	38	23	10	24
Beaman Pond Brook 2	60	33	34	48	10	7	10	19
Boylston Brook	48	26	72*	33	19	13	24	17
Cook Brook (Wyoming)	26	34	18	21	16	20	0	10
East Wachusett (140)	26*	19	11	18	15	8	0	6
French Brook (70)	53*	41	23	38	15	12	4	14
Gates Brook (1)	33	31	26	29	10	10	14	10
Gates Brook (4)	**165**	110	90	**225***	34	28	28	51
Jordan Farm Brook	86*	40	15	19	35	12	4	6
Malagasco Brook	40*	27	18	25	14	6	6	8
Malden Brook	31	28	20	27	7	6	2	10
Muddy Brook	30*	28	20	20	0	4	2	2
Oakdale Brook	57	31	40	**143***	10	12	12	41
Quinapoxet River (C.Mills)	54*	36	27	37	10	8	4	8
Scarlett Brook	27	38	35	50*	14	10	12	22
Stillwater River (SB)	78*	32	30	42	21	6	6	10
Trout Brook	29*	23	12	16	19	0	0	2
Waushacum (Prescott)	42*	34	19	23	10	0	0	4
West Boylston Brook	50	82	56	54	17	22	14	14

*highest annual geometric mean (2006-2015)

Bacteria samples collected from the tributary stations during 2015 contained a wide range of *E. coli* concentrations, from less than 10 MPN/100mL in approximately fifteen percent of all samples to a high of 130,000 MPN/100mL in Gates Brook following a midwinter sewer release. In previous years, many of the highest concentrations were recorded during or following rain events of 0.20” or more, and this was the case again in 2015. Twenty-one of twenty-eight samples that exceeded 1000 MPN/100mL (not including the additional samples taken following sewer releases in January and November) were collected during or immediately following wet weather from sixteen different sites. Only seven samples that exceeded 1000 MPN/100mL were collected during dry weather, most during the summer and fall when flows were reduced, and many at locations with known or suspected wildlife presence.

Rain events are clearly linked to poor water quality and the difference between dry weather and wet weather samples can be seen in Table 4. Annual geometric mean of all dry weather samples is less than one third the annual geometric mean of wet weather samples. The percentage of wet weather samples with concentrations greater than 235 MPN/100mL was more than five times higher than the percentage of dry weather samples. Only half as many wet weather samples had concentrations below 126 MPN/100mL as did dry weather samples.

Table 4: Impacts of Rainfall on *E. coli* Concentrations (MPN/100 mL) in Wachusett Tributaries

	dry 2015	wet* 2015	dry 2008-2014	wet* 2008-2014
annual geometric mean (MPN/100mL)	35	131	19 - 31	54 - 148
% samples <126 MPN/100mL	80	41	82 - 92	45 - 66
% samples >235 MPN/100mL	8	41	3 - 10	20 - 41

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

Impacts from rain events are often much more significant in subbasins with large areas of impervious surfaces or agricultural operations, but recent improvements in stormwater management throughout the watershed appear to have reduced some of the negative effects. The geometric means of wet weather samples from some stations in 2012 were as much as twenty-three times higher than geometric means of dry weather samples. Wet weather geometric means at stations in 2015 averaged only five times higher than their comparable dry weather means (Table 5), with the greatest differences noted at stations located in areas of dense residential development (Cook Brook, Scarlett Brook) or agricultural activity (Jordan Farm Brook).

Unlike previous years, all stations exhibited a clear difference between dry weather and wet weather bacteria concentrations (Table 5). Water quality at all stations was worse during wet weather than during dry weather.

Table 5: Impacts of Rainfall on *E. coli* Concentrations (MPN/100 mL) by Tributary Station
(DRY AND WET GEOMETRIC MEAN, PERCENTAGE OF DRY AND WET SAMPLES >235 MPN/100 mL)

	dry geomean	wet geomean	% dry>235	% wet>235
Asnebumskit Brook (Princeton)	77	231	26.7%	66.7%
Beaman Pond Brook 2	53	68	0.0%	20.0%
Boylston Brook	33	142	8.3%	50.0%
Cook Brook (Wyoming)	14	100	7.7%	33.3%
East Wachusett Brook (140)	14	97	0.0%	50.0%
French Brook (70)	38	207	6.1%	50.0%
Gates Brook (1)	24	121	6.1%	25.0%
Gates Brook (4)	155	211	27.3%	62.5%
Jordan Farm Brook	33	515	18.2%	67.0%
Malagasco Brook	32	100	5.9%	50.0%
Malden Brook	27	56	2.9%	25.0%
Muddy Brook	26	57	0.0%	0.0%
Oakdale Brook	40	141	0.0%	33.3%
Quinapoxet River (Canada Mills)	42	144	2.9%	37.5%
Scarlett Brook	19	144	5.9%	50.0%
Stillwater River (SB)	71	117	17.6%	37.5%
Trout Brook	17	109	6.7%	50.0%
Waushacum Brook (Prescott)	32	122	2.9%	37.5%
West Boylston Brook	36	202	11.8%	37.5%

Annual *E. coli* concentrations from 2015 did appear to show a trend towards declining water quality, with nine of nineteen tributary stations reporting their highest annual geometric mean in the past ten years (Table 3). Overall geometric mean of 620 routine samples collected from nineteen stations on eighteen tributaries during 2015 was 47 MPN/100mL. This was the highest overall geometric mean in many years, but number of sample stations and total number of samples collected in 2015 were less than in previous years and a direct comparison may not be appropriate. French Brook and Jordan Farm Brook had their highest ever annual geometric mean for the second consecutive year, however, and sixteen of nineteen stations were above the average of the previous ten years, so it is important to look for a potential cause or causes of the apparent decline in water quality.

Variable water quality can be caused by fluctuations in either pollutant inputs or weather conditions, including changes in the timing, frequency, and magnitude of precipitation events. Irregular weather appears to be increasing due to climate change. There is no evidence of increased inputs of bacteria, but weather conditions in 2015 were unusual. Heavy snowfall in February prevented collection of samples at a time when concentrations tend to be low. Total rainfall for the year (38.67”) was the lowest since 2001 and many tributaries had low flow in the summer and fall. Low flow concentrates contaminants including bacteria. The sporadic sampling during the winter and concentration of bacteria during the summer are the likely causes of the poor dry weather metrics illustrated in Table 4.

Tributary water quality often shows clear seasonal differences during both dry and wet weather (Table 6). Bacteria concentrations tend to be lower in the winter and spring months (December through May), with wet weather concentrations about 2-5 times higher than dry weather concentrations. Wet weather and dry weather geometric means were remarkably similar during the winter and spring of 2015, however. Summer concentrations are generally much higher, either due to low flow conditions that reduce dilution or large storm events that increase source loading, and wet weather concentrations are about 2-3 times higher than dry weather concentrations. Wet weather concentrations in 2015 were four times higher than dry weather concentrations. Fall concentrations are variable and dependent upon the amount and timing of precipitation. Differences between wet weather and dry weather concentrations are usually much more pronounced in the fall than in other seasons, and this was again true in 2015.

Table 6: Seasonal Effect on *E. coli* Concentrations (MPN/100 mL)

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

Numerous possible sources of bacteria and increased likelihood of short-term weather variations make it difficult to interpret changes in water quality parameters over the short term and it is generally more informative to examine long term trends in water quality. Reliable data from Wachusett watershed tributaries extend over more than twenty years and long term trends suggest that conditions at most locations remain stable or have improved. The next detailed assessment of long term trends should be published in early 2019.

3.2 FLOW

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

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

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. Flow data from Gates Brook were collected manually from 1994 until December 2011 when a flow monitoring sensor was installed. Installation of a new bridge over Gates Brook prevented flow measurements for four months in 2014 but a new stage-discharge relationship has been developed.

Table 7: Daily Flow (cfs) and Monthly and Annual Flow Volume (cf) in Wachusett Tributaries

	day max	day min	day mean	month max total	month min total	yearly total
QUINAPOXET	467 cfs	2.2 cfs	45.3 cfs	527 million ft^3	11 million ft^3	1.4 billion ft^3
STILLWATER	438 cfs	1.7 cfs	33.6 cfs	374 million ft^3	8.2 million ft^3	1.1 billion ft^3
GATES	123 cfs	0.8 cfs	3.3 cfs	21.2 million ft^3	3.5 million ft^3	103 million ft^3
WAUSHACUM	36.0 cfs	0.1 cfs	5.1 cfs	99.1 million ft^3	746,064 ft^3	210 million ft^3
W. BOYLSTON	1.4 cfs	0.07cfs	0.3 cfs	3.8 million ft^3	277,664 ft^3	11.1 million ft^3
MALAGASGO	2.9 cfs	0.08 cfs	0.5 cfs	8.5 million ft^3	265,680 ft^3	20.1 million ft^3
MALDEN	10.0 cfs	0.4 cfs	2.3 cfs	27.1 million ft^3	1.1 million ft^3	86.1 million ft^3
FRENCH	13.9 cfs	0.00 cfs	2.4 cfs	35.1 million ft^3	300,370 ft^3	112 million ft^3

Daily and monthly flows varied widely at all locations and illustrate the need for regular and frequent flow monitoring (Table 7). Daily flows in the tributaries ranged from near zero to more than 450 cfs. Mean daily flows are usually 1-5 cfs in most tributaries but much higher in the two rivers.

Problems with ice buildup and beaver dams were noted during the year at the Quinapoxet River gage. The maximum daily flow and total yearly flow volume are likely much greater than indicated in Table 7.

A large January storm produced a USGS estimated flow in excess of 200 cfs in Gates Brook but this was likely due to equipment error or problems with sediment deposits near the depth sensor and the value has been removed from the data set. Data impacted by ice at French and Malden were also removed.

Lower than normal flow volumes recorded from most tributaries during 2015 are due to below average annual rainfall amounts.

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. Depth measurements were taken at seven stream stations to determine flow using rating curves developed by the USGS or by Division Environmental Quality staff. Daily flow was monitored in the Stillwater and Quinapoxet River and in Gates Brook using continuous USGS recording devices. All data are available upon request.

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 0.053 mg/L NO_3-N to 1.25 mg/L NO_3-N (Table 8), with individual measurements from below detection to 1.41 mg/L NO_3-N. Nitrate concentrations in West Boylston Brook are higher than in other brooks but considerably lower than they were 5-10 years ago. Concentrations in Gates Brook continue to decline.

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

STATION	Muddy	French	Gates	Malagas	Malden	Waush	W. Boyl	Still	Quin	Trout
ave2015	0.134	0.093	0.786	0.704	0.534	0.053	1.25	0.155	0.291	0.107
ave2014	0.135	0.167	0.86	0.583	0.443	0.045	1.14	0.136	0.251	n/s
ave2013	0.144	0.159	0.92	0.709	0.550	0.040	1.39	0.163	0.259	n/s
ave2012	0.098	0.127	0.80	0.489	0.432	0.036	1.17	0.140	0.222	n/s
ave2011	0.089	0.154	0.93	0.426	n/s	n/s	1.09	0.156	0.185	n/s
ave2010	0.105	0.135	1.01	0.634	0.471	n/s	1.57	0.156	0.256	n/s
ave2009	0.072	0.105	1.03	0.504	0.403	n/s	1.25	0.122	0.196	n/s
ave2008	0.132	0.071	1.04	0.513	0.452	n/s	1.69	0.146	0.321	n/s
ave2007	0.113	0.094	1.10	0.735	0.423	n/s	2.05	0.178	0.325	n/s

Nitrite-nitrogen was rarely detected during routine sampling. Only two of the 110 samples collected in 2015 contained more than the detection limit of 0.005 mg/L. Ammonia was detected in all tributaries with most annual mean concentrations comparable to those recorded during the previous five years (Table 9).

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

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

Total Kjeldahl nitrogen is the sum of ammonia-nitrogen plus organically bound nitrogen but does not include nitrate-nitrogen or nitrite-nitrogen. Analysis for total Kjeldahl nitrogen began in 2015. Highest mean values were recorded from French and Malagasco Brooks (Table 10). The highest individual measurement was from the Quinapoxet River in September.

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

STATION	Muddy	French	Gates	Malagas	Malden	Waush	W. Boyl	Still	Quin	Trout*
ave2015	0.252	0.391	0.148	0.351	0.231	0.281	0.174	0.206	0.290	0.257
max2015	0.518	0.672	0.276	0.642	0.511	0.376	0.307	0.300	0.785	0.285
min2015	0.106	0.255	<0.10	<0.10	0.106	0.135	<0.10	0.160	0.161	0.229

*two samples only

Phosphorus is an important nutrient, and the limiting factor controlling algal productivity in Wachusett Reservoir. Sources include fertilizers, manure, and organic wastes in sewage. EPA Water Quality Criteria recommend a concentration of no more than 0.05 mg/L total phosphorus in tributary streams in order to prevent accelerated eutrophication of receiving water bodies. Concentrations measured in ten Wachusett tributaries during 2015 ranged from 0.009 mg/L to 0.094 mg/L total P, with annual mean concentrations from 0.015 mg/L to 0.050 mg/L (Table 11). All annual concentrations were comparable to the previous eight years. Only ten samples exceeded the recommended maximum concentration of 0.05 mg/L (compared to seventeen in 2012) and half were collected from Trout Brook during low flow conditions between May and September.

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

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

Total suspended solids are those particles suspended in a water sample retained by a filter of 2μm pore size. These particles can be naturally occurring or might be the result of human activities. Total suspended solids in Wachusett tributaries ranged from <5.0 mg/L to 22 mg/L, but only five of 110 samples contained more than the detection limit. Total suspended solids are not considered a parameter of concern except during storm events when measurements in excess of 100 mg/L are not uncommon.

Total organic carbon (TOC) and UV-254 measure organic constituents in water, and are a useful way to predict precursors of harmful disinfection byproducts. TOC in the tributaries ranged from 1.18 to 16.2 mg/L, with an overall mean of 4.41 mg/L, down about ten percent from the previous year. The highest concentrations were again recorded from French and Malagasco Brooks, with consistently elevated values as well from the new sample location on Trout Brook. The lowest concentrations were from Gates Brook and West Boylston Brook. There were also some very low readings from Malden and Muddy Brooks in the late part of the year.

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 Gates Brook and West Boylston Brook.

Loading estimates for nitrate-nitrogen, ammonia, total Kjeldahl nitrogen, total phosphorus, and total organic carbon in the Stillwater and Quinapoxet Rivers and in Gates Brook were calculated by multiplying daily flow (cu ft) by concentration (mg/L), multiplying by a unit conversion factor for daily load in kilograms, and then summing all daily totals to obtain an annual load (Table 12). Concentrations measured on the most recent previous sampling date were used for the calculations. Nutrient loading estimates did not address short term changes in flow and concentration that occurred during storm events.

Nutrient loading estimates had also been made in the past for five tributaries where flow is monitored weekly (Table 12). Daily flow (cu ft) based on the most recent previous weekly measurement was multiplied by the most recent previously measured concentration (mg/L) and then by a unit conversion factor to give load in kilograms. No loading estimates were made in 2015 due to an unfortunate delay in the compilation of flow data and because stage-discharge relationships for Muddy Brook and Trout Brook remain under development. Previous estimates did not address short term changes in flow and concentration that took place during storm events.

Estimated loads in 2015 were comparable to estimates from the previous four years. Differences in estimated loads are likely due to changes in flows rather than in concentrations.

Samples were also collected monthly for nitrite-nitrogen and total suspended solids, but most results were less than the detection limit and no useful loading information was developed.

Table 12: Annual Nutrient Loading – Wachusett Tributaries (kg)

STATION	NO_3-N	NO_3-N	NH_3-N	NH_3-N	TKN	total P	total P	TOC	TOC
	2015	2011-14	2015	2011-14	2015	2015	2011-14	2015	2011-14
French	n/a	283-987	n/a	91-177	n/a	n/a	67-139	n/a	13k-29k
Gates	2406	2159-4978	43	18-48	420	53	63-100	6,642	6.6k-14k
Malagasco	n/a	497-1051	n/a	17-45	n/a	n/a	28-110	n/a	10k-28k
Malden	n/a	1159-1441	n/a	21-42	n/a	n/a	61-76	n/a	8.7k-15k
Quinapoxet	11,301	7608-16k	1033	436-1031	11,726	801	774-1681	167,431	126k-352k
Stillwater	5,091	5948-13k	600	371-546	5,573	533	723-1587	117,128	127k-352k
Waushacum	n/a	303-558	n/a	51-136	n/a	n/a	130-185	n/a	25k-44k
W. Boylston	n/a	254-636	n/a	3-17	n/a	n/a	7.4-35	n/a	542-1784

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

Nutrient loads generated by the FLUX software program (Table 13) were similar to those estimated using less rigorous methods (Table 12). FLUX estimated inorganic nitrogen loads were slightly less for all three tributaries, while FLUX estimated total phosphorus was slightly more. Annual total suspended solids estimated by FLUX for the Quinapoxet River were slightly more than previously estimated, while FLUX estimates for the Stillwater River were slightly higher. FLUX estimates for total suspended solids in Gates Brook were nearly four times larger than earlier estimates.

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

STATION	PARAMETER	FLUX 2015	MONTHLY SAMPLING 2015
Quinapoxet	total inorganic N	10,090	12334
Stillwater	total inorganic N	3943	5691
Gates Brook	total inorganic N	2429	2449
Quinapoxet	total phosphorus	874	801
Stillwater	total phosphorus	599	533
Gates Brook	total phosphorus	122	53
Quinapoxet	total suspended solids	132,655	114,000
Stillwater	total suspended solids	89,679	107,500
Gates Brook	total suspended solids	39,550	9300

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. More than three quarters of all measurements from Trout Brook were below 80 μmhos/cm and all were below 100 μmhos/cm; only nine measurements from all other stations in the watershed were as low. Values greater than 800 μmhos/cm were recorded in 91% of samples from West Boylston Brook and the two stations on Gates Brook, but only in 5% of samples from all other stations. The maximum recorded value (2604 μmhos/cm) was measured at a station on Gates Brook following a mixed precipitation event in mid January.

Annual median specific conductance ranged from a low of 73.5 μmhos/cm (Trout Brook) to a high of 1,275 μmhos/cm (Gates Brook 4). All but two annual medians were the highest in the past five years and historic high medians were recorded at eleven stations. Although this suggests a serious decline in water quality, it is much more likely that this was the result of much lower than normal annual rainfall (37.8”) which reduced tributary flow and increased concentrations of mineral salts.

3.5 TURBIDITY

Routine weekly samples were collected from all tributary stations throughout the year, with individual measurements from 0.17 NTU to 13.2 NTU. The eighteen samples with turbidity of 6.0 NTU or higher were collected almost exclusively from Muddy Brook which historically has contained elevated amounts of fine particulate matter. Single samples with turbidity measurements of more than 6.0 NTU were also collected from Asnebumskit, Cook, and Jordan Farm Brooks during a storm event in June. Annual median values ranged from 0.28 NTU in Cook Brook to 5.16 NTU in Muddy Brook. Overall watershed mean of 1.32 NTU (median of 0.82 NTU) was the lowest of the past five years.

Storm events continued to have a negative impact on turbidity, with a watershed median of 1.01 NTU for all wet weather samples but a median of only 0.78 NTU for dry weather samples.

3.6 STORMWATER SAMPLING

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

3.7 SPECIAL STUDIES

Monitoring of potential short term and long term water quality impacts from forest management activities continues. Monitoring of short term impacts consists of monthly sampling at active logging sites above and below stream crossings when flow is present or during storm events. Five sites with eleven stream crossings were visited to collect water quality samples and establish baseline conditions, although not all had flow during all occasions.

The long term monitoring project collects data at a control site and an active site for a ten year period before, during, and following completion of forestry operations. Two years of data have now been collected. 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 historical reservoir tributary stations during the spring of 2012 and 2014. All 2012 samples have been sorted, identified, and counted; 2014 samples are still being processed. Sampling at the same stations is planned for 2016. 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 report.

Approximately 100,000 gallons of raw sewage was reported to have leaked from a pumping station in West Boylston on Woodland Street in late January. The broken pipe could not be immediately repaired and sewage haulers were used to provide bypass pumping. The release was directed into a large adjacent retention pond and then removed.

Flow from the spill traveled through a series of wetlands adjacent to I-190 before reaching Gates Brook and it was hoped that much or all of the release was contained in the retention pond and the wetlands. The spill appeared to be smaller than originally estimated and there was no immediate threat to the Wachusett Reservoir. Bacteria samples were collected from locations close to the spill and along Gates Brook, with some concentrations in excess of 100,000 MPN/100mL. Additional samples helped track the passage of bacterial contamination towards the reservoir. The maximum recorded concentration at Gates Brook (1) was 520 MPN/100mL, less than what can be seen during summer storm events.

Additional samples were collected throughout the brook until mid February when concentrations returned to pre-release levels.

There was a second sewage release in West Boylston in November. A broken pipe released about 4,000 gallons from a manhole on Worcester Street in the early morning. Samples were collected upstream and downstream once the incident was reported, although Division staff were not contacted immediately. The pipe was repaired quickly and only limited impacts to water quality were detected.

4.0 RESULTS OF RESERVOIR MONITORING PROGRAM

4.1 FECAL COLIFORM

Bacterial transect samples were collected from 23 surface stations on the reservoir beginning in late April after ice melted. Samples were collected monthly, twice monthly, or weekly throughout the year to document the relationship between seasonal bacteria variations and visiting populations of gulls, ducks, geese, and other waterfowl. Data were also used to judge the effectiveness of bird harassment activities. Sample locations were shown previously on Figure 3 and all data are included in Table 14.

Table 14: 2015 Wachusett Reservoir Fecal Coliform Transect Data (colonies/mL)

	4/22	5/20	6/10	7/15	8/14	9/16	10/1	10/20	10/26	11/4	11/9	11/16	11/23	11/30	12/7	12/15
A-3	0	0	1	1	0	7	1	0	0	0	0	0	0	0	0	0
B-2	0	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0
B-3	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0
C-1	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	1
C-3	0	1	0	0	0	2	0	3	1	0	0	0	1	0	0	1
C-5	0	1	1	0	0	5	0	0	1	1	0	0	0	0	0	1
D-1	1	0	0	0	0	0	1	1	1	0	1	4	0	0	0	0
D-2	0	0	0	0	1	0	0	2	0	0	1	**12**	2	1	0	0
D-4	0	0	0	0	0	1	3	2	1	0	0	2	0	0	0	0
E-2	1	2	0	0	1	1	0	3	**10**	**13**	2	3	1	0	0	1
E-4	0	1	0	1	0	2	6	2	1	0	0	1	0	0	0	0
F-2	1	0	0	0	0	1	0	1	2	3	1	1	1	0	0	0
F-3	0	1	0	0	2	1	0	4	4	1	3	2	0	0	1	6
F-4	1	0	0	0	0	1	1	4	2	0	0	0	0	1	0	0
G-2	0	0	0	0	0	0	4	3	1	0	0	0	2	4	1	3
H-2	2	0	0	0	6	n/s	2	0	1	1	0	2	0	2	0	2
I-2	0	0	0	0	1	1	3	0	2	0	1	5	2	1	1	1
J-2	0	0	1	0	0	0	1	1	0	0	0	0	3	1	1	4
J-3	0	0	0	0	0	0	0	0	3	0	0	4	2	**10**	1	4
J-4	0	0	0	0	1	1	1	0	1	0	2	9	**43**	**25**	**82**	**70**
K-2	0	0	0	0	0	0	**36**	1	3	0	1	9	9	**12**	6	2
M-1	2	6	0	0	0	5	**29**	0	0	0	0	7	1	0	4	0
N-1	1	0	0	0	3	3	4	0	0	1	2	3	0	2	1	5

Ice cover was present into April and most waterfowl had dispersed before open water was present in the spring. Fecal coliform concentrations remained low throughout the reservoir until the beginning of October when elevated concentrations were noted at the south end of the reservoir. Slightly elevated concentrations were observed near mid reservoir at the end of that month. Concentrations began to increase at the end of November at the south end of the reservoir where gulls traditionally roost and remained high through the end of the year. The source of a high count in a sample collected adjacent to the intake in September remains uncertain, although it could be related to a rain event 36 hours earlier.

Fecal coliform 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 fecal coliform criteria for drinking water require that a minimum of ninety percent of all source water samples contain less than 20 CFU/100mL. All but one of 363 samples collected at Walnut Hill contained less than the standard, with a single concentration of 21 CFU/100mL recorded following a rain event in September. Most samples contained 0 CFU/100mL. The Division has put considerable time and effort into implementing a rigorous bird harassment program, and the results in 2015 again proved to be very effective at maintaining low numbers of both birds and bacteria

4.2 WATER COLUMN CHARACTERISTICS

4.2.1 FIELD PROCEDURES

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

The multiprobe used by the Division to measure water column profiles is a "MiniSonde 5" paired with a "Surveyor 4" water quality logging and data display system manufactured by Hydrolab Corporation (now part of the Hach Company located in Loveland, Colorado). These instruments are routinely charged and calibrated during the field season. At the conclusion of field work, data recorded by the logging system is downloaded as an Excel spreadsheet.

In 2011, the multiprobe was upgraded to measure chlorophyll *a* with the addition of a fluorometer, and this has proved to be a valuable tool for detecting aggregations of phytoplankton at depth. Chlorophyll *a* is the most abundant photosynthetic pigment in algae composing the phytoplankton community and the amount of chlorophyll *a* measured in a sample serves as a surrogate for total phytoplankton biomass.

Preliminary calibrations of the fluorometer were conducted based on comparisons to chlorophyll *a* concentrations measured in duplicate samples submitted to MWRA laboratory staff at Deer Island. Refinement of the initial calibrations is ongoing. During *in situ* measurements the relative intensity of the fluorometry signal has been extremely useful in pinpointing the depths with the greatest density of phytoplankton, allowing them to be targeted for sampling.

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 depth of the Quabbin interflow layer needs to be resolved, 0.5 meter depths are measured within that range.

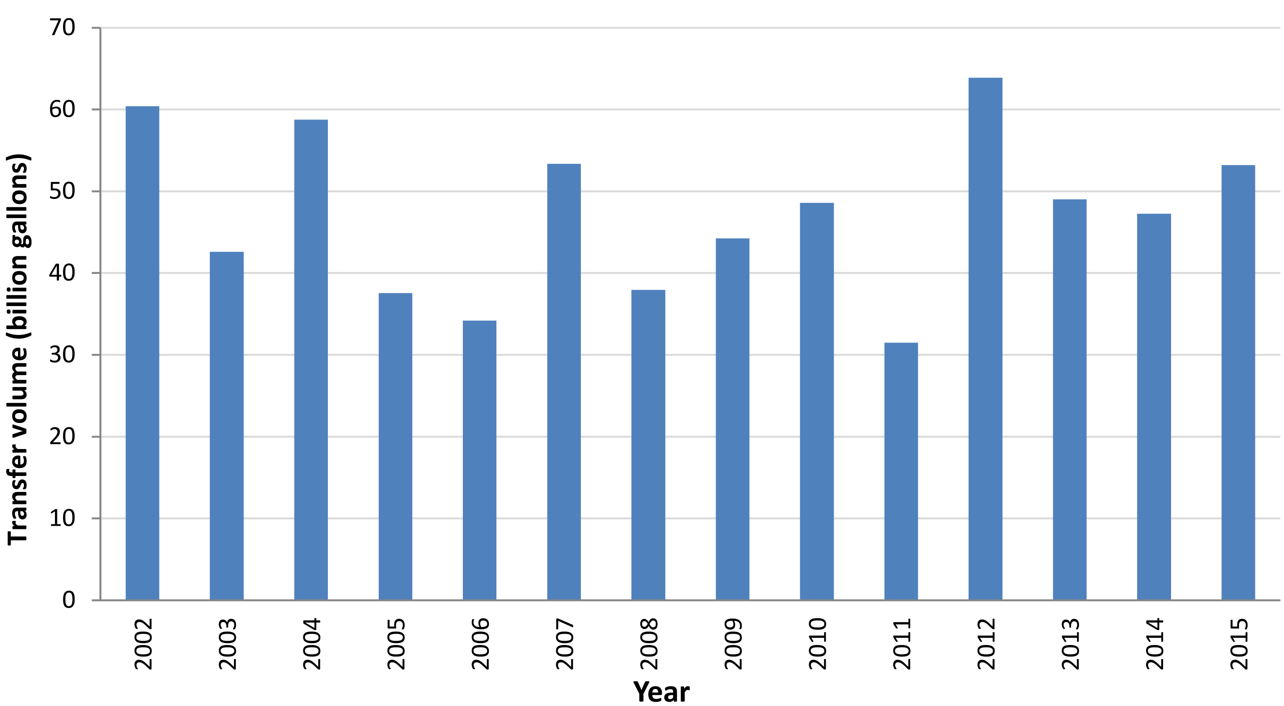
Water column profile data has been collected from various locations in Wachusett Reservoir using a multiprobe sonde since 1988. Data collected from 1988 through 1996 was collected in the field and recorded by hand in a series of 3 logbooks. Beginning in 1998, data was transferred electronically from the probe/handpiece to a computer, a practice which has continued to the present day. The process of synthesizing the electronic data for nearly 800 reservoir profiles into a single format has begun, which should enable the analysis of long term trends soon. Additional data entry is still needed to expand the electronic record back to 1988.

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.

Figure 4: Quabbin Transfer to Wachusett Reservoir



The term ‘interflow’ describes this metalimnetic flow path for the Quabbin transfer that, once fully developed, generally occupies the Wachusett water column from 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 flow path of Quabbin water within Wachusett Reservoir. The interflow penetrates through the main basin of Wachusett Reservoir (from the Route 12 Bridge to Cosgrove Intake) in about 3 to 5 weeks depending on the timing and intensity of transfer from Quabbin. The interflow essentially connects Quabbin inflow to Cosgrove Intake in a “short circuit” with limited mixing with ambient Wachusett Reservoir water.

In 2015, the Quabbin transfer was continuously transferring water from late April through December; limited transfer also occurred in early January and mid-March. A total volume of 53.2 billion gallons (201,353,529 cubic meters) was delivered to Wachusett via the Quabbin aqueduct during 2015. This is equivalent to 89% of the volume of Wachusett Reservoir (59.8 billion gallons). This is in line with the average volume of water transferred within a typical year (see Figure 4 on previous page).

4.2.4 SEASONAL PATTERNS IN PROFILE MEASUREMENTS

Thermal stratification of the water column and the presence of the Quabbin interflow are the major determinants of vertical gradients and patterns recorded in profile measurements. Profiles depicting water column characteristics on June 25, August 27, October 6, and November 15 (Figures 5-8) 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 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 5 through 8 since this parameter typically exhibits only minor fluctuations.

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

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

Interflow penetration at Basin North/3417 was first observed on June 4, becoming established as a defined layer by June 25 (Figure 5), as revealed by the conductivity profile. This indentation in the conductivity profile intensifies (extends to lower conductivity values) over the period of transfer as water in the interior of the interflow undergoes less mixing with ambient reservoir water at the boundaries of the interflow stratum. The epilimnion occupied the top 6 meters of the water column on this date and had reached a temperature of 22.8° C. Epilimnetic dissolved oxygen measured 104% saturation on this date due to photosynthetic activity by phytoplankton. No discernible peak in chlorophyll *a* concentration was observed on this date; phytoplankton samples collected in conjunction with this profile revealed only moderate densities.

The interflow continued to become more fully established, remaining as a discrete layer through the summer months. On August 27, the “bulge” in the conductivity profile (Figure 6) shows the typical mid-summer configuration of the fully established interflow with a thickness of eight meters present between depths of 6.5 and 14 meters. Conductivity reached minimum values of around 80 uS/cm at a depth of 9.5 meters. The epilimnion still occupied the top six meters of the water column with a temperature of 24.8° C. The steep gradient in temperature and density between the epilimnion and interflow can be seen in this profile where the temperature decreases 7° C between depths of 5 and 7 meters. Although a modest spike in chlorophyll *a* concentration at depth was observed in early August, it had dissipated by the end of the month.

The epilimnion began steadily losing heat in mid-September. By October 6 (Figure 7), heat losses and wind energy had eroded the thermocline downward. The interflow was still clearly visible as a distinct layer only days prior, but this profile reveals that the metalimnetic interflow had begun mixing with the epilimnion. At this point, the change to lower specific conductivity values is a gradual decline between 9 and 13.5 meters. Dissolved oxygen remained near saturation in the epilimnion, but had declined to a low of 54% saturation in the hypolimnion. Phytoplankton activity was minimal at this time and the chlorophyll *a* profile was comprised of low values throughout the water column.

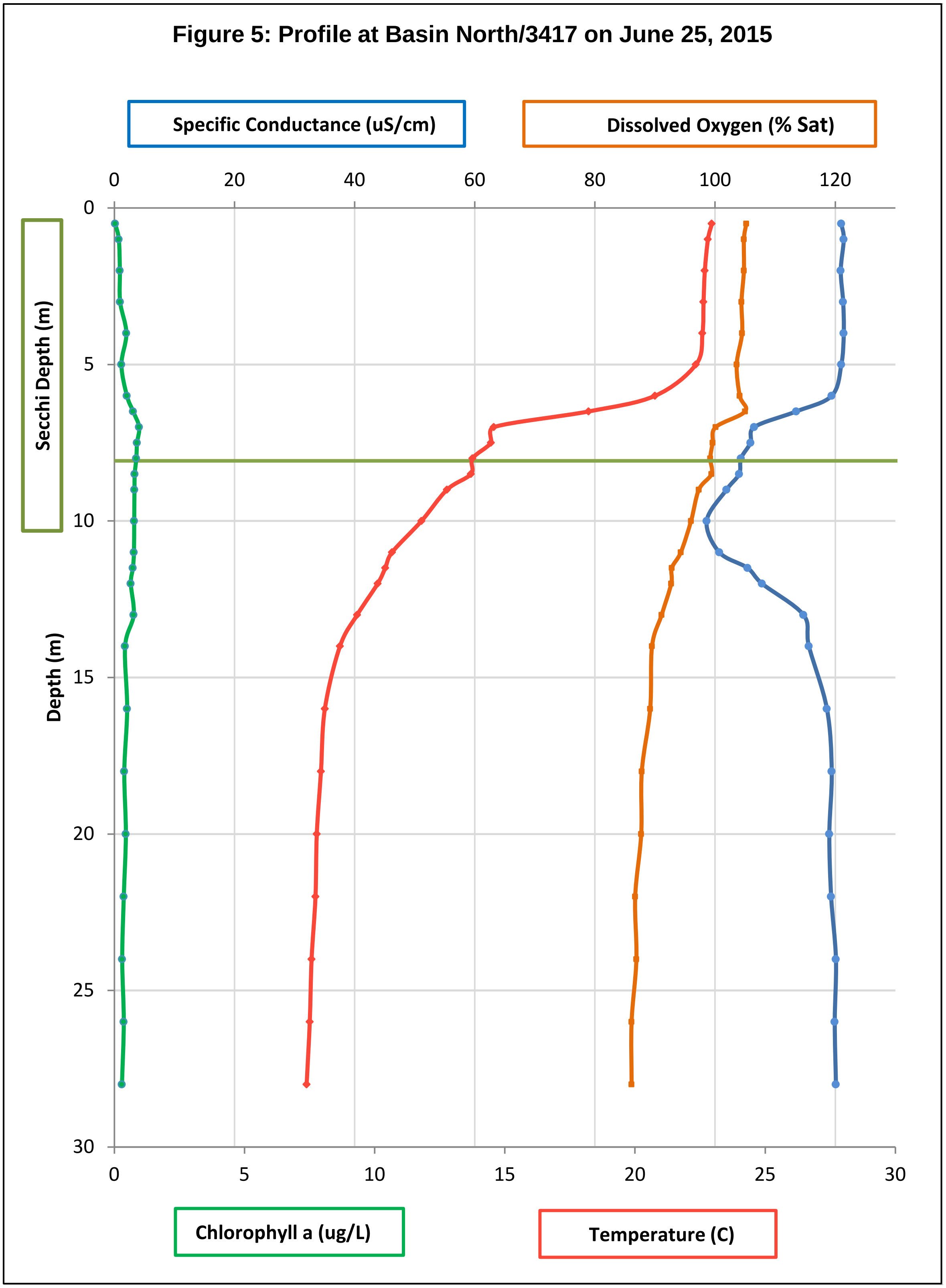


Figure 5: Profile at Basin North/3417 on June 25, 2015
Specific Conductance (uS/cm)
Dissolved Oxygen (% Sat)
0
20
40
60
80
100
120
Secchi Depth (m)
Depth (m)
0
5
10
15
20
25
30
0
5
10
15
20
25
30
Chlorophyll a (ug/L)
Temperature (C)

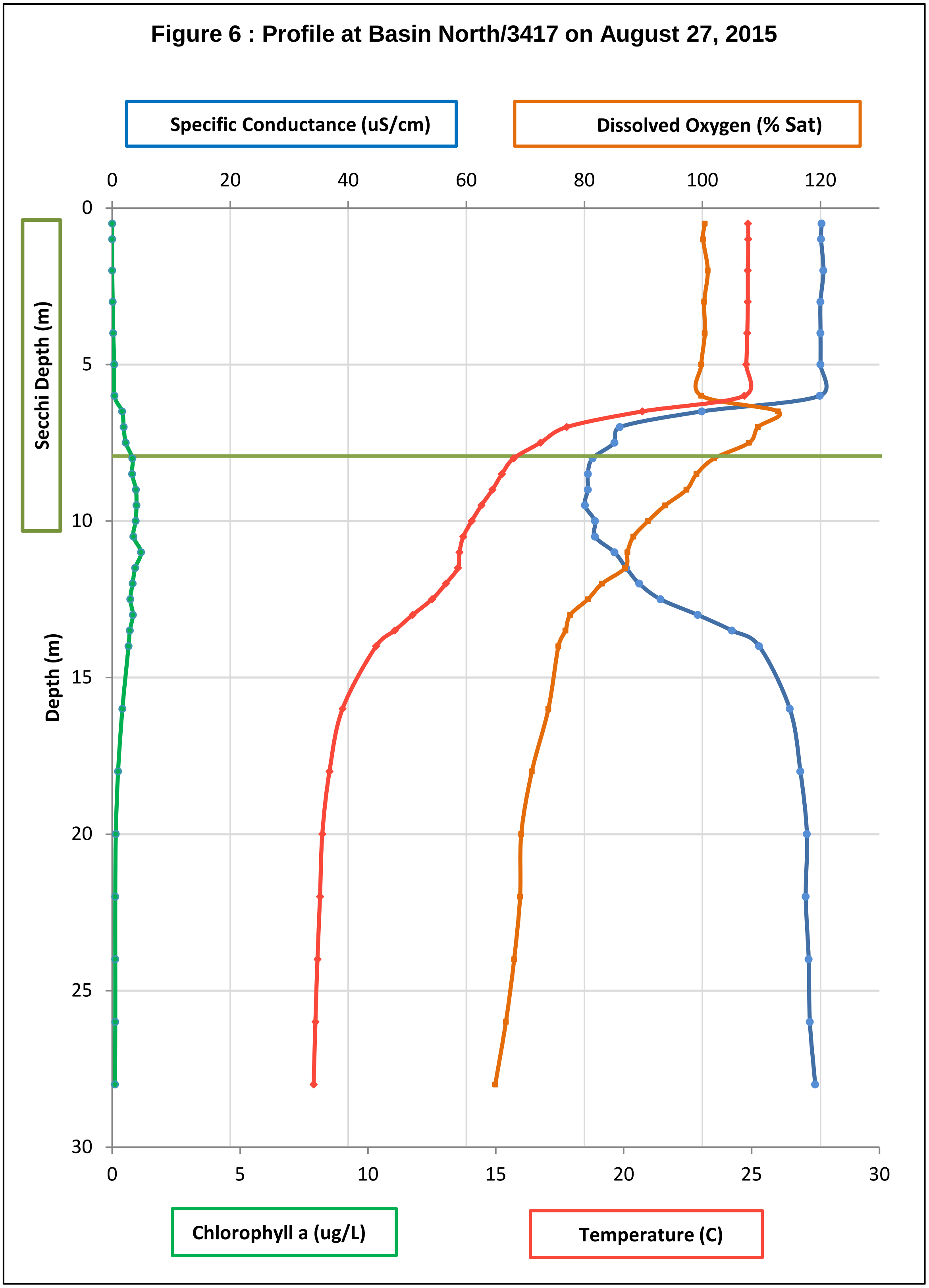


Figure 6 : Profile at Basin North/3417 on August 27, 2015
Specific Conductance (uS/cm)
Dissolved Oxygen (% Sat)
0
20
40
60
80
100
120
0
5
10
15
20
25
30
Secchi Depth (m)
Depth (m)
0
5
10
15
20
25
30
Chlorophyll a (ug/L)
Temperature (C)

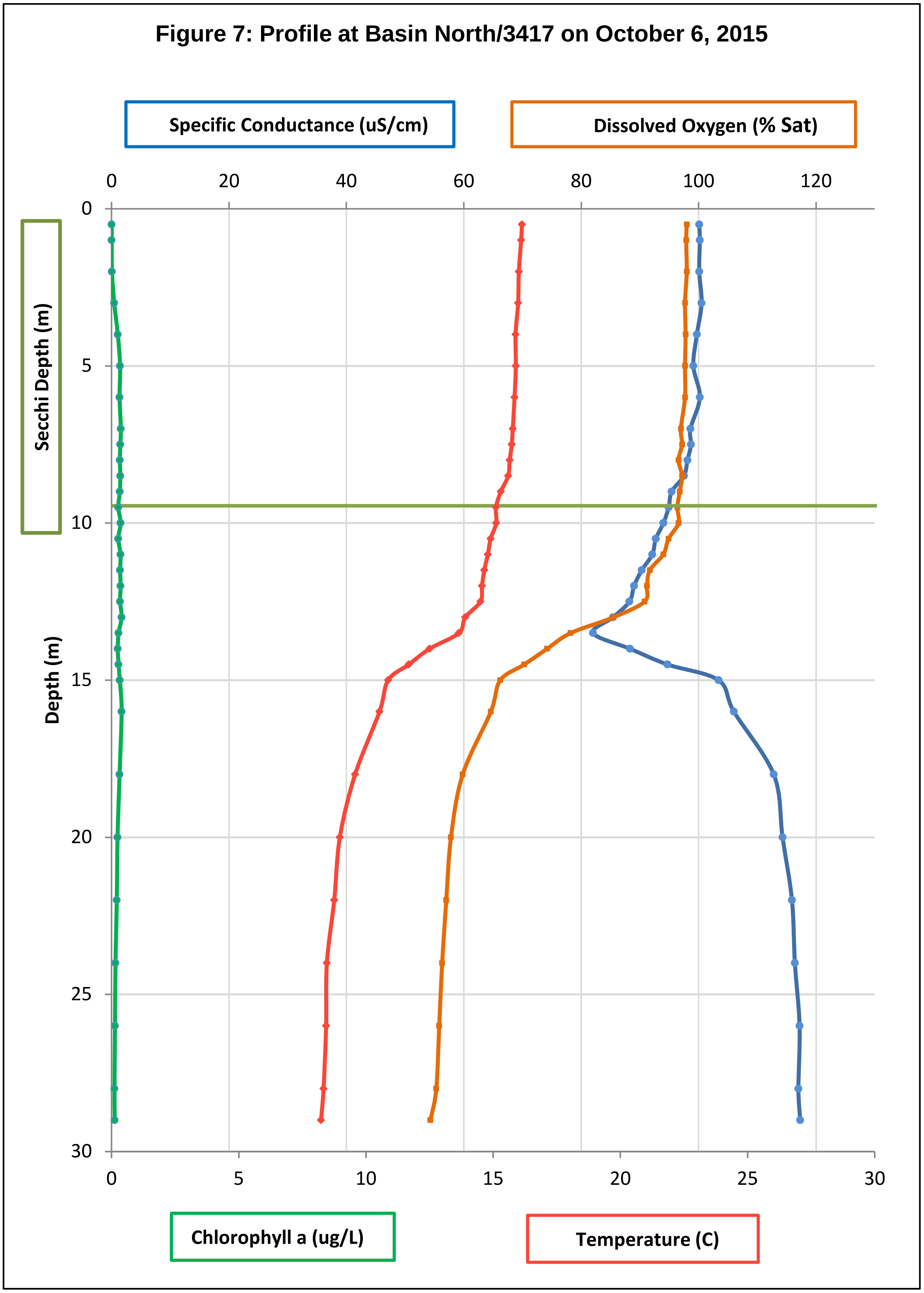


Figure 7: Profile at Basin North/3417 on October 6, 2015
Specific Conductance (uS/cm)
Dissolved Oxygen (% Sat)
0
20
40
60
80
100
120
Secchi Depth (m)
Depth (m)
0
5
10
15
20
25
30
Chlorophyll a (ug/L)
Temperature (C)

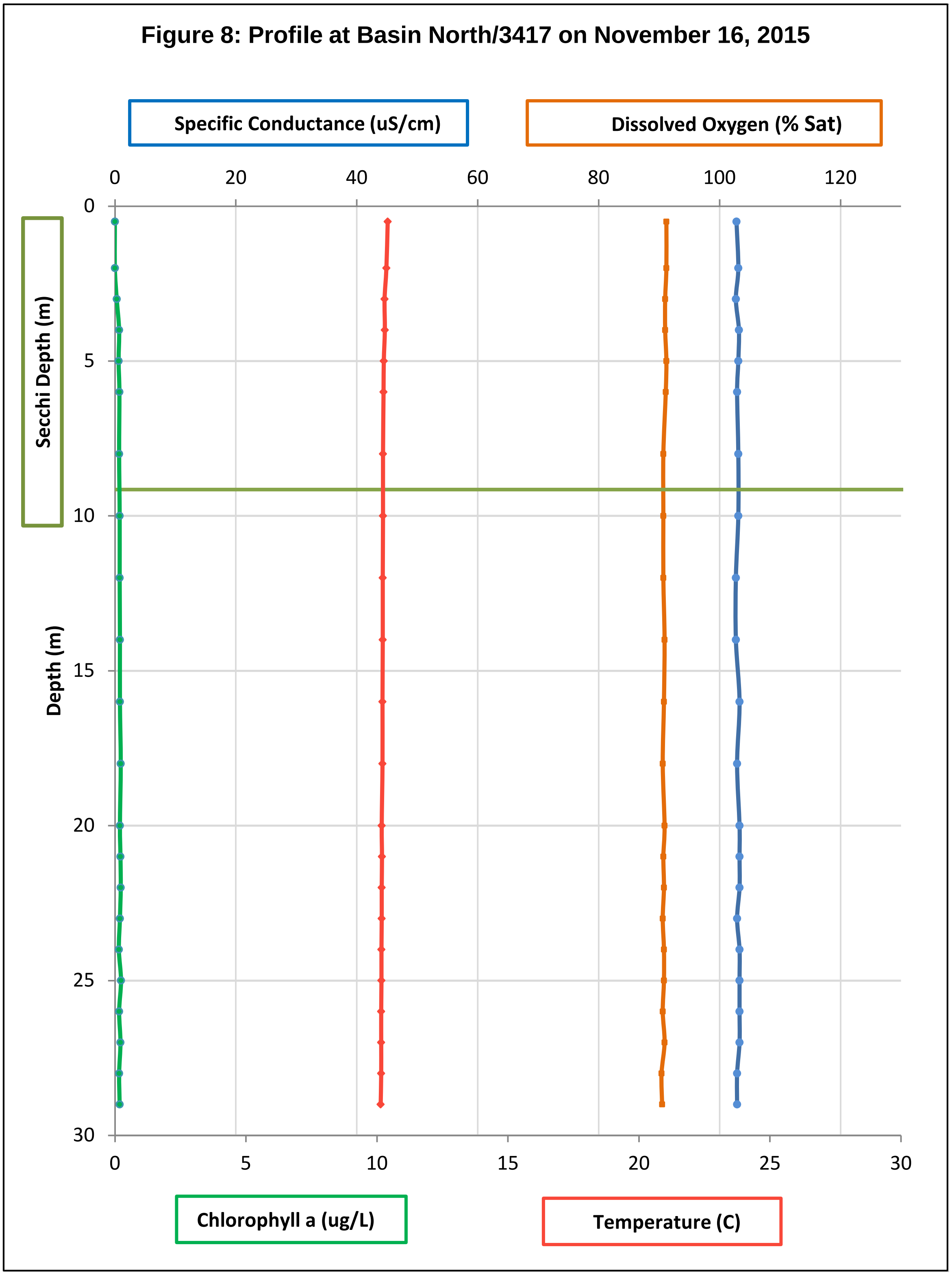


Figure 8: Profile at Basin North/3417 on November 16, 2015
Specific Conductance (uS/cm)
Dissolved Oxygen (% Sat)
0
20
40
60
80
100
120
Secchi Depth (m)
Depth (m)
0
5
10
15
20
25
30
0
5
10
15
20
25
30
Chlorophyll a (ug/L)
Temperature (C)

One month later, a profile recorded on November 16 (see Figure 8 on the previous page) 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 only 0.3° C from the surface to the bottom (10.4° C-10.1° 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 103 uS/cm throughout the water column.

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. Sampling protocol, chain-of-custody documentation, and sample delivery were similar to those established during the 1998-99 year of study. Details of sampling protocol have been 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 2014 is used as a basis for interpreting data generated in 2015. The results from quarterly nutrient sampling in 2015 document concentrations that were all within historical ranges, with the exception of one measurement. At the Basin South station on July 23, the Nitrate result collected at mid depth from the metalimnion measured below the detection limit of 0.005 mg/L, which was the first time a Nitrate sample from this location was below the detection limit. Overall nutrient concentrations for 2015 range from near average to below average (Table 15). The Quabbin transfer from April through December likely influenced the generally low nutrient results observed in the October and December samples. Complete 2015 reservoir nutrient results can be found in Appendix A.

The patterns of nutrient distribution in 2015 quarterly samples correspond closely to those documented in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics (Worden and Pistrang, 2003). These patterns consist most importantly of the following: (1) seasonal and vertical variations with low epilimnetic concentrations in summer resulting from phytoplankton uptake, and conversely, higher concentrations accumulating in the hypolimnion due to microbial decomposition of sedimenting organic matter, (2) interannual fluctuations in nutrient concentrations and parameter intensities occurring across the system as a result of the divergent influences of the Quabbin transfer and the Wachusett watershed with temporary lateral gradients becoming pronounced for nitrate, silica, UV254, and conductivity, either increasing or decreasing downgradient of Thomas Basin depending on the dominant influence.

Nutrient monitoring has been ongoing at Wachusett Reservoir since 1998. Methods of collection and methods of analysis have remained constant throughout this period of time. All reservoir nutrient data has been synthesized into a single format contained within a single spreadsheet, and the process of analyzing more than 4,200 nutrient results collected over this 18 year time period will begin soon.

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 15: Wachusett Reservoir Nutrient Concentrations (Ranges from 1998-2014 Database [1] Compared To 2015 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)	
	1998-2014	2015	1998-2014	2015	1998-2014	2015	1998-2014	2015	2000-2014	2015
Basin North/3417 (E)	<5 - 16	5	<5 - 176	<5 - 66	0.59 - 4.62	1.43 - 2.70	<5 - 17	<5 - 15	0.032 - 0.089	0.036 - 0.064
Basin North/3417 (M)	<5 - 51	<5 - 7	<5 - 180	21 - 90	0.77 - 4.67	2.26 - 3.08	<5 - 20	5 - 11	0.032 - 0.102	0.037 - 0.069
Basin North/3417 (H)	<5 - 41	<5 - 25	33 - 225	42 - 116	1.27 - 5.06	2.41 – 4.06	<5 - 19	8 - 11	0.032 - 0.084	0.037 - 0.065
Basin South/3412 (E)	<5 - 15	<5	<5 - 176	<5 - 82	0.56 - 4.58	1.47 – 2.81	<5 - 20	5 - 14	0.031 - 0.101	0.036 - 0.066
Basin South/3412 (M)	<5 - 39	<5 - 6	6 - 184	<5 - 107	0.95 - 4.80	1.69 – 3.17	<5 - 22	<5 - 10	0.032 - 0.128	0.035 - 0.072
Basin South/3412 (H)	<5 - 44	<5 - 27	35 - 224	42 - 142	1.64 - 4.78	2.32 – 3.98	<5 - 37	7 - 10	0.036 - 0.111	0.036 - 0.071
Thomas Basin (E)	<5 - 18	<5	<5 - 201	<5 - 31	0.62 - 7.44	1.77 – 2.67	<5 - 27	7 - 14	0.026 - 0.305	0.035 - 0.067
Thomas Basin (M)	<5 - 27	<5	<5 - 213	8 - 35	0.88 - 7.36	1.83 - 2.86	<5 - 29	5 - 10	0.026 - 0.334	0.038 - 0.065
Thomas Basin (H)	<5 - 57	<5	<5 - 236	14 - 36	0.92 - 7.39	1.87 – 3.04	<5 - 29	8 - 10	0.027 - 0.345	0.034 - 0.051

Notes: (1) 1998-2014 database composed of 1998-99 year of monthly sampling and subsequent quarterly sampling through December 2014, except for measurement of UV254 initiated in 2000 quarterly sampling

(2) 2015 quarterly sampling conducted May, July, October, and December

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

4.4 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 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 (Secchi and profiles are not recorded at this location). 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 present right at the intake.

Monitoring frequency is generally weekly in early spring, fall, and winter, and 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. 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 as an approximate measure of the amount of particulates, mostly plankton, suspended in the water column.

During the stratification period, sampling is focused where profile measurements show a spike in dissolved oxygen concentration and/or a spike in chlorophyll *a* concentration. 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 Division staff have analyzed the historical phytoplankton data and established a treatment consideration level for each taste and odor taxa. Once this level is reached monitoring frequency is increased and action is considered.

4.4.2 CONCENTRATION AND MICROSCOPIC ANALYSIS OF PHYTOPLANKTON

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

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

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

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

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

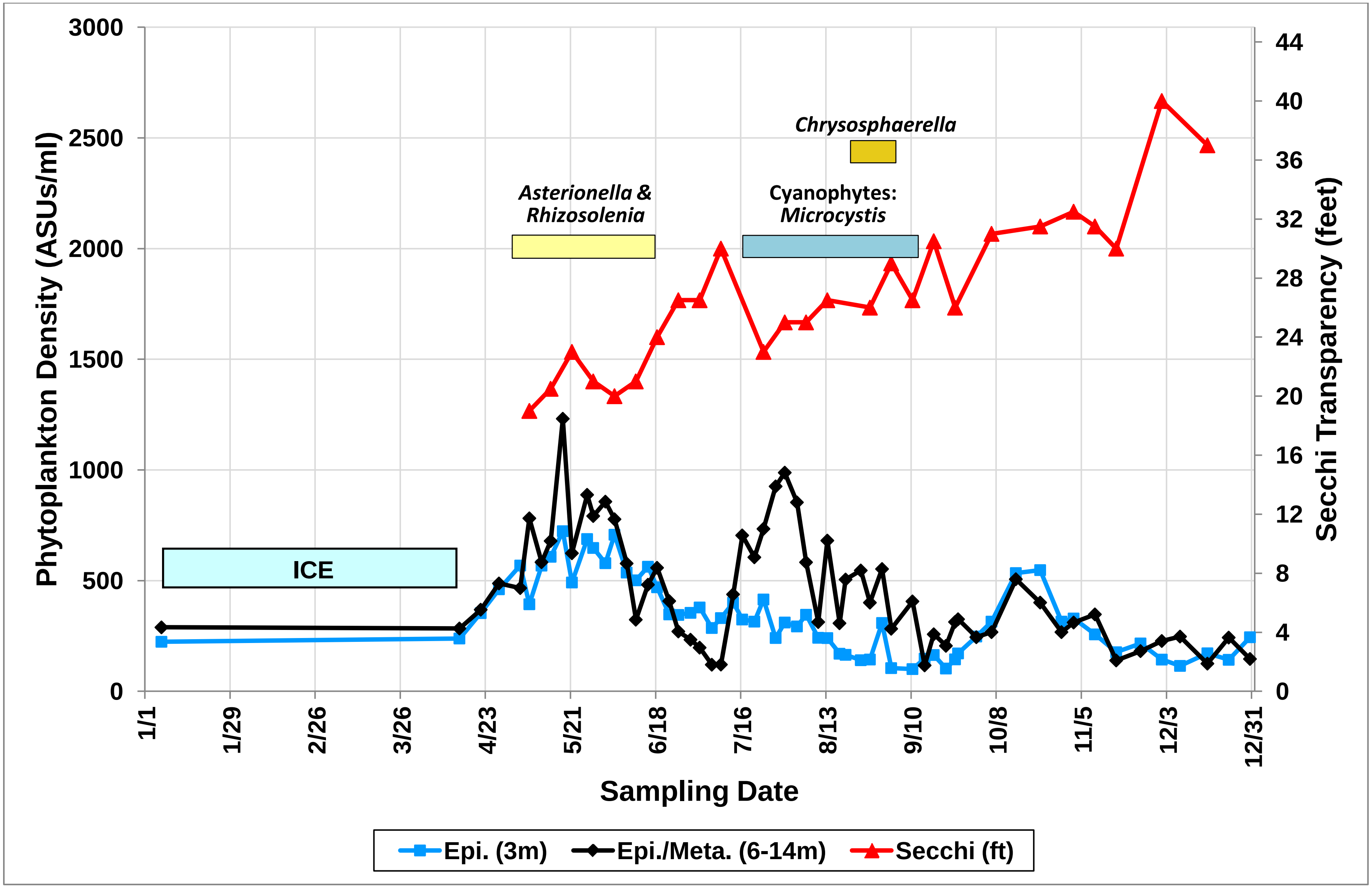
4.4.3 PHYTOPLANKTON MONITORING RESULTS

After an initial phytoplankton sample was collected on January 6, 2015, the reservoir iced over and the sampling program did not resume until April 14th. Monitoring after ice out in April 2015 revealed low overall densities of less than 240 ASU/mL. Diatoms dominated early in the spring, continuing a steady increase until mid-May (Figure 9). At that time *Asterionella* and *Urosolenia/Rhizosolenia* comprised 75% of the total phytoplankton and a maximum total phytoplankton value for the season of 1,231 ASU/mL was recorded. (This taxa has been referred to in previous documents as *Rhizosolenia* due to this program predating taxonomic revision to *Urosolenia*. For continuity, the original names are maintained.)Historically, high spring diatom levels are common and have not resulted in any taste or odor impacts to drinking water quality.

Diatoms remained dominant in reservoir samples until mid-July, when Cyanophyte levels increased within the hypolimnion and at depth. In particular, *Microcystis* was seen at higher than usual densities in samples collected at 7m in depth or greater. This persisted through August 6th, when levels moved below 200 ASU/mL. In addition, the motile Chrysophyte *Chrysosphaerella* was observed to aggregate within the interflow at depth in August. However, the aggregation strata was particularly narrow (<0.5m), and only a single sample was collected with a count approaching treatment consideration levels (504 ASU/mL at 8.75 meters on August 13). Additional samples collected at similar depths before and after that sample, paired with *in situ* chlorophyll *a* values recorded with a multiprobe, lead to the conclusion of a narrow aggregation persisting at a specific depth for a limited time.

Overall phytoplankton densities continued a steady decline from August until October, when mixing of the water column redistributes nutrients and often leads to a brief and mild fall phytoplankton resurgence. *Microcystis* dominated at this time, reaching 400-500 ASU/ml for a brief period in mid October and steadily declining through December, at which time overall phytoplankton densities settled in at 100-200 ASU/ml.

Figure 9: 2015 Phytoplankton Monitoring at Wachusett Reservoir



Chrysophytes and Synurophytes have recently been the most frequently occurring nuisance algae in Wachusett Reservoir. None of these taxa was measured at nuisance levels in 2015. *Dinobryon* was sporadically present at low levels from May through September. *Uroglenopsis* was observed at values below 100 ASU/mL for about a month from late May through early July. *Synura* was only observed at countable densities a handful of times in April, May and August.

Anabaena made its usual seasonal appearance in June, and was found at levels between 7 and 17 ASU/mL for a brief period during June 15-18. It also persisted at low densities into the fall, with low densities below 10 ASU/ml recorded sporadically from May through November.

Secchi disk transparency is affected by the phytoplankton dynamics outlined above, as well as the water contributions from the Wachusett watershed and Quabbin transfer. 2015 followed a typical pattern, when the first measurement recorded as 19 feet in early May increased to over 30 feet by October (Figure 9). This year, however, marked an additional increase in Secchi depth in December. The Secchi disk depth of 40 feet recorded on December 1st marked the highest value ever recorded for Wachusett Reservoir, breaking the previous record of 37 feet recorded in late October 2012. It is worth noting that at that time, nutrient levels such as nitrate and total phosphorous were very low, and phytoplankton levels also were low. The total volume of Quabbin water transferred in 2015 was higher than in 2013 or 2014, but still 11 billion gallons less than the total transfer in 2012, when the last Secchi record was set.

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 synthesized into a single format contained within a single spreadsheet, and the process of analyzing more than 5,300 samples collected over this 27 year time period has begun.

4.4.4 WACHUSETT RESERVOIR PHYTOPLANKTON IMAGES

The six images shown on the following pages are examples of phytoplankton observed in the waters of the reservoir. All images were captured from samples collected during 2015 and are representative of the beauty and diversity of the organisms that live in the Wachusett Reservoir.

FIGURE 10:
***Bacillarophyceae* (diatoms): *Urosolenia/Rhizosolenia,* May 4th 2015, Cosgrove Intake**

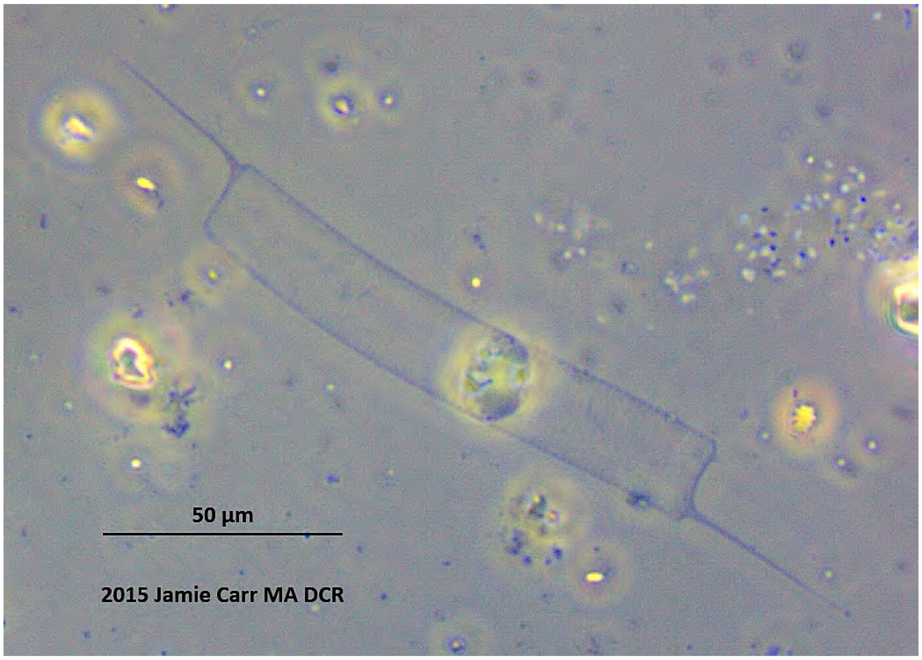


FIGURE 11:
***Bacillarophyceae* (diatoms): *Meridion,* May 4th 2015, Oakdale Brook at Stillwater Basin**

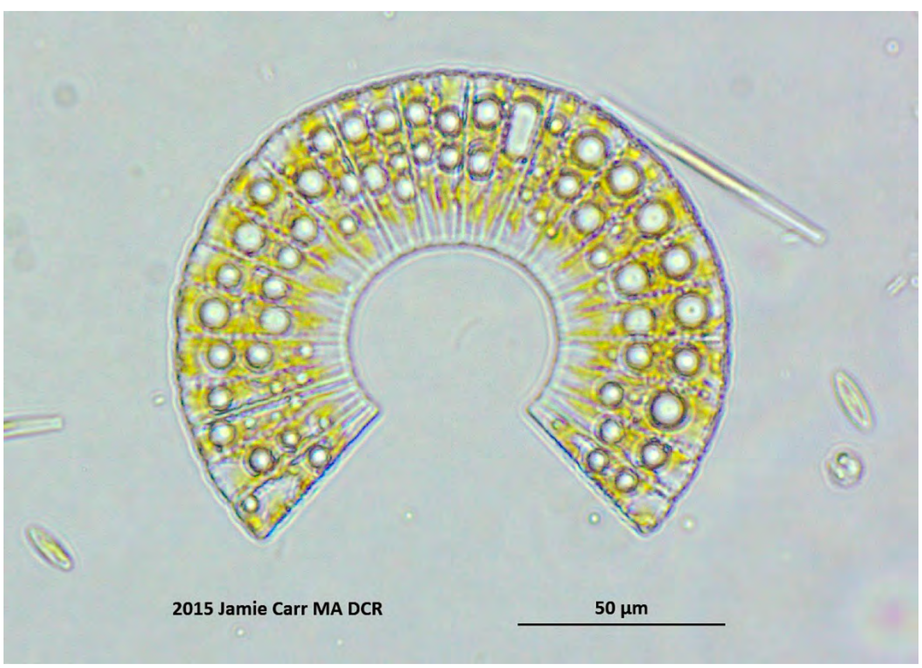


FIGURE 12:
Chlorophyta **(green algae):** ***Nephrocytium*****, August 31st 2015, Cosgrove Intake**

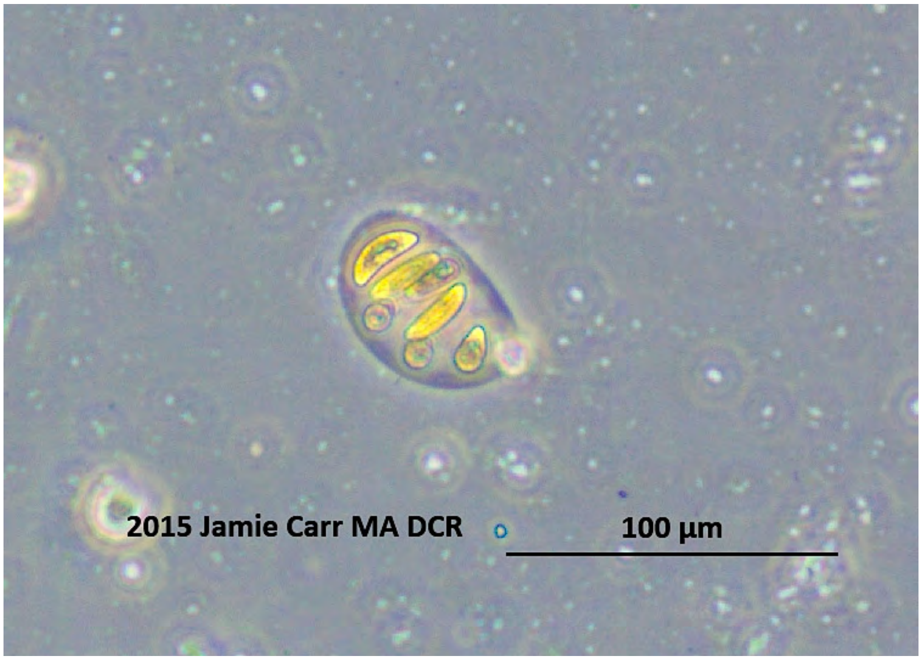


FIGURE 13:
Chlorophyta **(green algae):** ***Spirogyra*****, September 18st 2015, Gates Brook Cove**

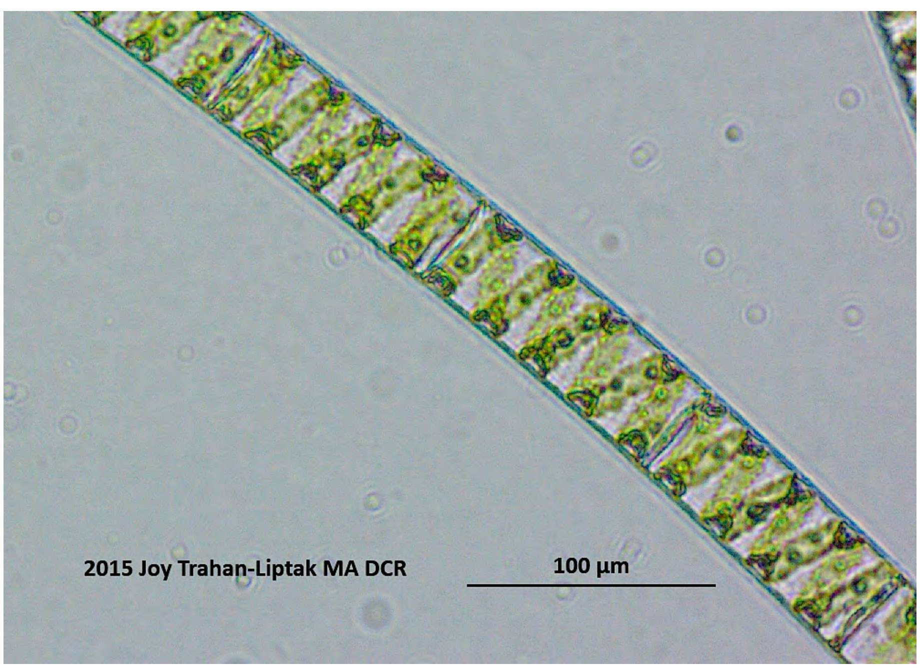
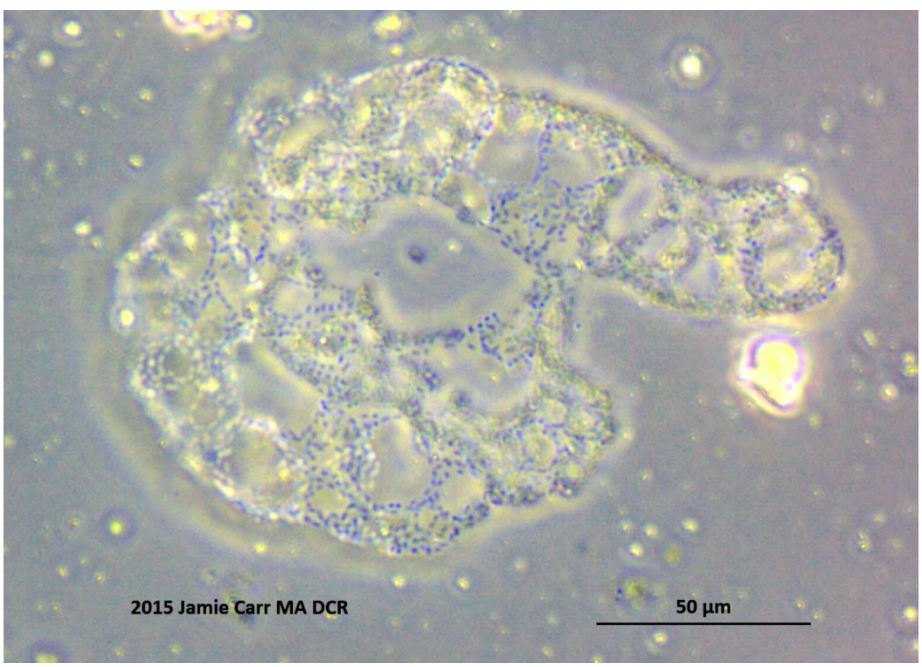


FIGURE 14:
***Chrysophyta* (golden/golden-brown algae): *Mallomonas*, July 27th 2015, Cosgrove Intake**

FIGURE 15:
***Cyanophyta* (often called "blue green algae"): *Microcystis*, July 20th 2015, Cosgrove Intake**



4.5 MACROPHYTES

4.5.1 THE THREAT OF INVASIVE AQUATIC MACROPHYTES

In August of 2001, a pioneering colony of Eurasian watermilfoil (*Myriophyllum spicatum;* referred to subsequently as “EWM”) was observed for the first time in Oakdale Basin, a small basin in the upper reaches of the reservoir system (Figure 16). EWM is a non-native, invasive species of macrophyte known to aggressively displace native vegetation and grow to nuisance densities with associated impairments to water quality. Prior to 2001, this plant was restricted to the uppermost component of the reservoir system, Stillwater Basin, where its distribution has been monitored since 1999.

Figure 16: Wachusett Reservoir Invasive Macrophyte Management Areas

The expansion of EWM into Oakdale Basin represented a significant increase in the risk of a potentially rapid and overwhelming dispersal of this plant into the main reservoir basin. The water quality implications of such an event are serious and include increases in water color, turbidity, phytoplankton growth, and trihalomethane (THM) precursors. These increases result from the function of this plant and macrophytes in general as nutrient "pumps," extracting nutrients from sediment and releasing them to the water column, mostly as dissolved and particulate organic matter.

Fanwort (*Cabomba caroliniana*) is another invasive plant that was first discovered as only sporadic individual plants present at the northern end of Stillwater Basin in 1999. Fanwort began to spread into Oakdale Basin in 2004. The spread of fanwort was initially more gradual than that of EWM, but in 2009 it surpassed EWM in total plants before decreasing in the past few seasons. Fragmentation is the most important mode of reproduction and dispersal of these species. Vegetative fragments are generally released at the end of the growing season when the plants undergo senescence. These fragments float for some time before sinking to the bottom and can take root and become established in suitable habitat. Control measures targeting both EWM and fanwort are discussed in the sections that follow.

4.5.2 WACHUSETT RESERVOIR INVASIVE MACROPHYTE CONTROL PROGRAM

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. The main components of this program have been the following: deployment of floating fragment barriers, maintenance of benthic barriers, annual hand-harvesting and DASH (Diver Assisted Suction Harvesting) plant removal efforts, and routine scouting throughout the reservoir system by the Division to ensure early detection of pioneering infestations (details of control efforts in previous years are provided in their respective annual reports). Harvesting efforts initially focused on Oakdale Basin, but both EWM and fanwort have gradually spread throughout Thomas Basin, located directly downstream, so this basin is also targeted in annual removal efforts. Additional removal work is conducted in several coves of the main basin, as needed. DASH was first utilized in 2012 and has been continued as an additional control strategy for dense patches of plant growth as a complement to the typical hand-harvesting efforts. An extensive DASH project in Stillwater Basin was initiated in 2013 in an effort to reduce the potential for re-infestation from dense growth in this uppermost basin of the reservoir.

Oakdale and Thomas Basins

2015 marked the first year of a new three-year contract between MWRA and Aquatic Control Technology (ACT). The scope of this contract was updated from previous versions to ensure that efforts are specifically focused on removing as much of the remaining invasive plant population as possible while providing improved documentation. Additions to the contract included surveys of management areas before each phase of harvesting and division of large management areas into smaller zones to allow for better reporting of removal locations and therefore tracking of EWM and fanwort beds.

A survey of each management area was conducted on July 8th by ACT biologist Brittany Laginhas, accompanied by Division aquatic biologists Jamie Carr and Joy Trahan-Liptak. Observations made during this survey are summarized in Table 16:

Table 16: Summary of Spring Macrophyte Survey Results

Basin	Target Species Observations	Vegetation Community Observations*
Oakdale Basin	12.3 acres of trace to moderate (5 - 40%) EWM growth; 6 individual fanwort plants along the perimeter	Native Naiad (*Najas* sp.) beds were observed frequently, especially in the northern portion of the basin, Coontail (*Ceratophyllum demersum*) was also common along with Pondweed (*Potamogeton*) species. Variable milfoil (*Myriophyllum heterophyllum*, VM) occurred at trace to moderate densities.
Thomas Basin	6.6 acres of mostly trace (5 - 10%) EWM growth	Dominated by VM (defined yet?) interspersed in many areas with growth of Clasping-Leaf pondweed (*Potamogeton perfoliatus*), Fern-Leaf pondweed (*P. robbinsii*), and Slender pondweed (*P. pusillus*).
Powerline Cove	Isolated trace (5%) patch of EWM (3 plants)	Sparse to dense Clasping-leaf pondweed, scattered occurrences of other native species including Waterweed (*Elodea* sp.). Patches of dense VM.
Gates Brook Cove	2.3 acres of trace (5%) EWM growth	Sparse to dense Clasping-leaf pondweed and Coontail.
West Boylston Cove	1 acre of trace (5%) EWM growth	Trace to dense Clasping-leaf pondweed, moderate to dense patches of arrowhead (*Sagittaria* sp.), sparse to moderate occurrences of Waterweed.

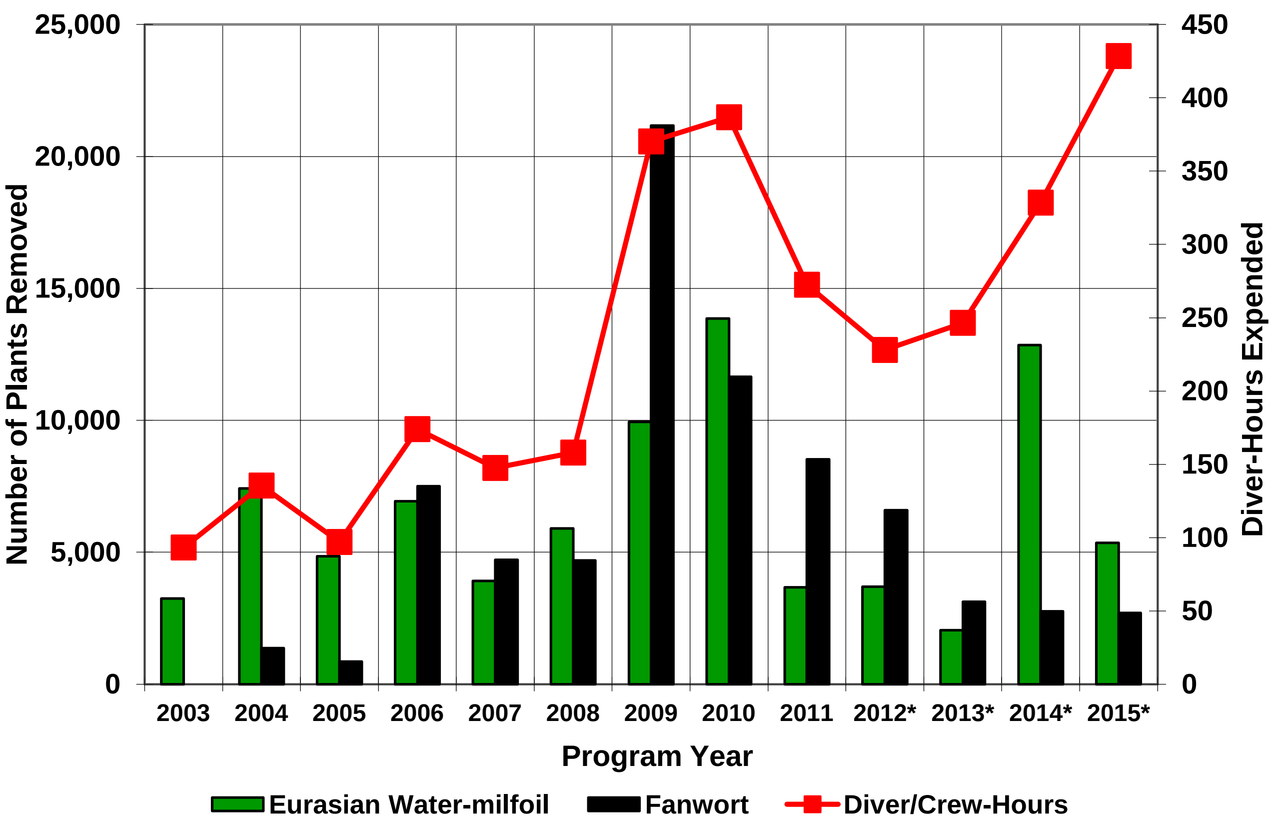
*information based on raw GPS point data provided by ACT

The first plant removal effort in 2015 began on July 13th and extended through to July 17th. This entailed four days with the DASH crew and five days for traditional diver hand-harvesting crews removing plants in Oakdale Basin, Thomas Basin, Powerline Cove, West Boylston Brook Cove, and Gates Brook Cove. A total of 2,632 EWM plants and 1,101 fanwort plants were removed.

The second effort began on September 1st and consisted of 1.5 days of DASH work and six days of diver hand-harvesting, which ended on September 10th. The second hand-harvesting effort was guided by observations of target plant re-growth made during an interim survey conducted by Division aquatic biologists and ACT staff on August 28th. Scouting by ACT's Field Technician during harvesting efforts also guided work, which focused on Oakdale and Thomas Basins, but also included work in Powerline Cove, Gates Cove, and West Boylston Brook Cove. A total of 2,724 EWM plants and 1,597 fanwort plants were pulled during the second effort.

The total number of EWM plants removed in 2015 was 5,356, the total number of fanwort plants removed was 2,698, and the total diver-hours expended were 428.5. The 2015 fanwort totals represent a slight decrease from 2014 harvesting totals, continuing a trend of 6 consecutive years of decreasing fanwort harvest totals (Figure 17). The 2014 EWM count was greatly elevated as compared to the period 2011-2013 but similar to 2010 and was attributed to large expanses of small, immature plants in the Oakdale Basin and the upper end of the Thomas Basin. Totals for EWM decreased in 2015, but remain above harvest totals from 2011 to 2013. In an effort to identify established beds of target species and track the locations of new occurrences, each management area was broken into smaller zones. The number of plants removed from each zone was recorded and this information will be used in the coming years to prioritize management areas and facilitate removal efforts.

Figure 17: Harvesting of Invasive Marcophytes (2003 – 2015)



- *2012-2015 totals include hand harvesting by divers as well as DASH
- In 2002 496.5 diver-hours were expended in removing an estimated 75,000 to 100,000 EWM plants

The post-harvest aquatic plant survey was conducted on October 8th by Matthew Salem and Rebecca Giguere from ACT. As expected, this survey documented an overall increase in non-target plant cover and biomass, with naiad and variable milfoil remaining the dominant species. A few specimens of EWM were observed along the shoreline, but no fanwort was observed.

Main Basin Coves

Despite the use of fragment barriers in infested upper basins (discussed below), some invasive plant fragments reach the main basin of the reservoir. Historically, evidence of this is represented by the occurrence of a small number of plants found in Powerline Cove. This cove is located immediately east of the Route 12 Bridge/Causeway on the northern shoreline of the main basin where power lines span the reservoir. Varying numbers of EWM and fanwort have been detected and removed from this cove over the past 12 years (Table 17). The high annual variation in EWM numbers in Powerline Cove may be related to the overall environmental factors driving growth in the larger basins as well.

TABLE 17: Summary of Harvesting Results in Powerline Cove

	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
EWM	14	0	0	21	18	1	0	59	22	75	103	7	37	51
Fanwort	0	0	0	0	0	1	0	17	7	4	5	0	1	0

Shoreline surveys conducted by Division aquatic biologists have resulted in detection of EWM in several additional main basin coves since 2011 (Table 18). Individual plants or small clusters are removed by DCR biologists and, when densities warrant, the coves are added to the contractor's management areas. Gates Brook Cove has been included in contract management areas since 2013, and West Boylston Brook Cove has been included since 2014. The overall density of EWM plants in these areas is low; however, the soft substrates, especially those found in Gates Brook Cove, provide ideal growth conditions for aquatic plants.

TABLE 18: Summary of EWM Removals in Coves of the Main Basin

	2010	**2011**	**2012**	**2013**	**2014**	**2015**
Horseshoe Cove	0	4	6	0	0	0
W. Boylston Brook Cove	0	0	13	1	14	22
Gates Cove	0	0	0	60	141	61
Malagasco Brook Cove	0	0	0	0	1	0

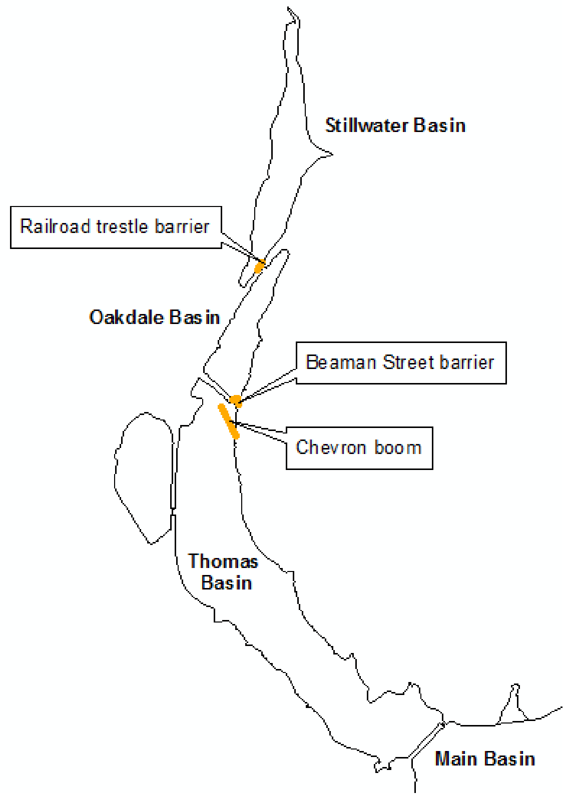
Hastings Cove Variable Milfoil

In 2013, a localized but dense growth of variable milfoil in the Hastings Cove area of the main basin was harvested for the first time. Although there are other large but more sparse occurrences of variable milfoil (*Myriophyllum heterophyllum*, VM) in the main basin, the Hastings Cove infestation represents a discrete, dense source of potential plant fragments and is readily addressed by the plant removal techniques utilized in the main project area. In 2015, only 1,398 variable milfoil plants were removed from Hastings Cove; a marked decrease from the 18,376 plants removed from an area of only 1/3 of an acre in 2013. The time spent on this area also decreased, as the DASH crew spent 96 hours in Hastings Cove in 2013 and 24 hours in 2015 (ACT 2015).

Fragment Barriers

In addition to the activities summarized above, DCR staff maintained floating fragment barriers at strategic bottleneck locations to restrict the movement of invasive fragments into down gradient portions of the reservoir system. These locations consist of the railroad trestle bridge between Stillwater Basin and Oakdale Basin and the Beaman Street Bridge between Oakdale Basin and Thomas Basin (Figure 18). The floating fragment barriers were initially purchased and deployed at these locations in 2002. Additionally, a 400 foot floating boom was deployed in a chevron configuration downstream of the Beaman Street Bridge and left in place for the entire 2013, 2014 and 2015 seasons. This boom is positioned at an angle to the shore and to the flow moving under the bridge, such that plant fragments are guided to the shoreline by the boom instead of continuing into Thomas Basin along with the current. Observations of fragments collected in the chevron boom suggest that this boom works well to trap invasive plant fragments. The Oakdale trestle boom appeared to function very well to prevent fragments from moving out of Stillwater Basin, while the Beaman Street boom will likely be reconfigured again for 2016 to improve its effectiveness.

FIGURE 18: Locations of Fragment Barriers



Stillwater Basin

The established populations of EWM and fanwort in the uppermost basin of the reservoir, Stillwater Basin, provide propagule pressure and an endless supply of potential plant fragments waiting to move downstream. Surveys in the main basin and the invasive plants found each year in the coves indicate that fragments are reaching and colonizing the main basin. With this in mind, a project was undertaken to begin removal of EWM and fanwort from the Stillwater Basin in 2013.

A contract was procured to begin a DASH plant removal project in the 34 acre Stillwater Basin in May of 2013. Variable milfoil, EWM and fanwort growth covered a significant portion of the basin; in many areas these plants were topped out and plant cover reached 100%. A first pass was performed in an attempt to remove as much of the biomass from as much of the basin as possible with multiple DASH boats working simultaneously to harvest invasive plants. A total of 322,880 gallons of plant biomass was removed over the course of the six month project in 2013. This project was continued in 2014 and 2015, with the contractor working with multiple DASH units in the basin to perform two full passes of plant removal. The 2014 operation lasted from May 12th to November 21st, and removed 128,753 gallons of plants. The 2015 operation lasted from May 4th through October 30th and removed 71,705 gallons of plant material. The reduced biomass harvested in 2015 is encouraging, as is the fact that making two complete attempts at harvesting the entire basin was more feasible to complete within a single season in 2015. For example, in 2014, the first round of harvesting in Zone 2 lasted approximately 38 days, while in 2015, first round harvesting in this zone required 10 less days and the amount of plant material removed decreased overall (Figure 19). Evidence of this is visible in before and after images (Figure 20) and growth of native plants. Clasping-leaf Pondweed (*P. perfoliatus*) and Fern-leaf Pondweed (*P. robbinsii*) were observed re-colonizing areas previously inundated with invasive species in 2014 and 2015. These observations are encouraging; however, it is anticipated that this will be a long term project with ongoing annual maintenance to reduce the biomass of invasive plants in this basin.

FIGURE 19: Plant Removal by DASH in Stillwater Basin Zone 2

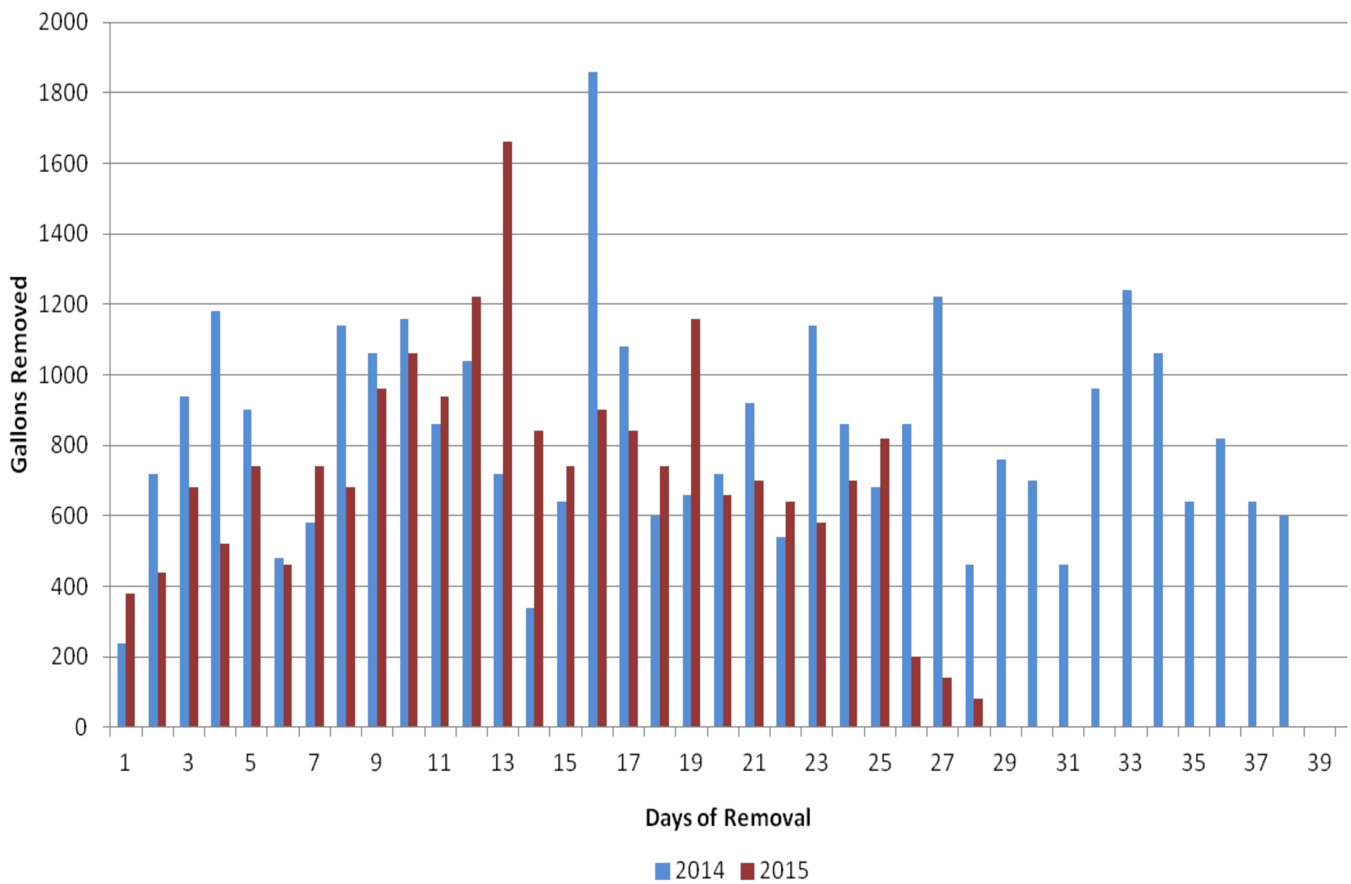


FIGURE 20: Stillwater Basin Zone One Pre-Phase 1 6/24/15 (left), Post-Phase 1, 8/ 7/15 (right).

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

References Cited:

Aquatic Control Technology. 2016. Wachusett Reservoir - Aquatic Invasive Macrophyte Control Program, 2015 Project Completion Report. Prepared for Massachusetts Water Resources Authority.

DCR. 2015. Water Quality Report: 2014, Wachusett Reservoir Watershed.

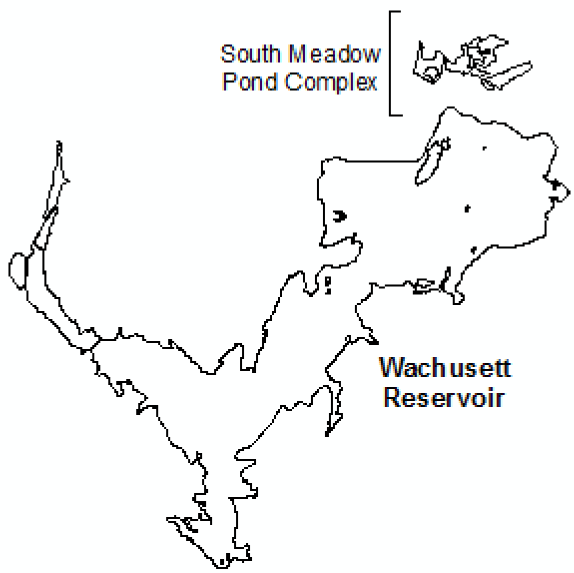
4.5.3 SUPPLEMENTAL INVASIVE MACROPHYTE CONTROL ACTIVITIES

Additional activities were conducted in 2015 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.

4.5.3.1 Hydrilla in the 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 is located only about 1,970 feet (600 m) north of Wachusett Reservoir (Figure 21), thus this infestation is at the doorstep of the reservoir. Even though the South Meadow Pond complex is technically outside the Wachusett watershed, the extremely close proximity of the hydrilla infestation to Wachusett Reservoir and the possible potential for transfer to the reservoir by waterfowl or bait buckets necessitates special management and monitoring efforts.

FIGURE 21



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 the contractor Aquatic Control Technology (ACT) to implement a control plan and apply herbicides. ACT's treatment and monitoring plan went into full swing in 2011, and has continued successfully through 2015. Control of hydrilla has been impressive with only scattered individual plants present for several seasons. Pre-management hydrilla tuber densities of 27.9 tubers/m^2 in 2010 have been incrementally reduced each year and, remarkably, no tubers were found within sampled locations during the pre-treatment or post-treatment surveys in 2015. However, these tuber density results do not indicate that there are no viable tubers present in South Meadow Pond; rather that the density has been reduced to the point that collection is difficult with this sampling protocol. Control of the tuber bank is the key to the long term control of this invasive plant, and management results to this point have been very positive. Despite finding no tubers in 2015, beds of Hydrilla were observed at trace to sparse densities with plants reaching heights just below the surface in approximately 11 acres of the pond complex during surveys in June and July. These areas were treated with an herbicide in August. The post-management survey of the South Meadow Ponds complex showed trace to sparse re-growth of Hydrilla with plant heights of 2-4". ACT reported that native plant growth observed in 2015 was similar to past years; however, an invasive species new to this pond system during the June/July surveys. This species, Curly-leaf Pondweed (*Potamogeton crispus*), was observed in approximately 8 acres of South Meadow Pond at densities from trace to dense (ACT 2015).

References Cited:

Aquatic Control Technology. 2015. Final Report for 2015 Aquatic Plant Management, South Meadow Pond. Prepared for Massachusetts Department of Conservation and Recreation Lakes and Ponds Program.

4.5.3.2 Watershed Pond Assessments

As time allows, Division 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.

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, photographic documentation of observed organisms and of the general area was also taken.

In 2015, a total of 20 ponds within the watershed were surveyed. These water bodies were selected based on their close proximity to the reservoir, size, public access, and known presence of invasive vegetation based on historical data (Table 19).

Non-native aquatic vegetation was documented in 12, or 60%, of the 20 ponds surveyed. The most commonly observed non-native species, occurring in eight water bodies, was Variable Milfoil, a species that has been present within Wachusett Reservoir for several decades. Eurasian Milfoil (Figure 22) and fanwort were each observed in three separate watershed ponds. These species are also present in the upper basins of Wachusett Reservoir and have been managed on an annual basis since the early 2000s (Section 4.5.2). A fourth non-native species that has not been observed in Wachusett Reservoir, European Naiad (*Najas minor* also known as Brittle Naiad), was documented in eight watershed ponds. This species will be discussed further in the following section.

FIGURE 22
Eurasian Milfoil documented in Muddy Pond, Sterling, MA.

A memorandum to update the 2010 Aquatic Invasive Species Assessment and Management Plan is currently in process. This memorandum will update the invasive species found in and around Wachusett Reservoir and its watershed and outline a general strategy for assessing the threat of and addressing newly discovered invasive species.

TABLE 19: Wachusett Watershed Ponds Surveyed in 2015 for Non-native Aquatic Vegetation

Name	Town	Proximity to Wachusett Reservoir (miles)*	Acres	Number of Invasive Vegetation Species Observed
Jellyfish Pond	Boylston	0.03	3.9	0
Pleasant Valley Pond North	West Boylston	0.08	2.0	1
Pleasant Valley Pond South	West Boylston	0.16	2.3	0
Lily Pond East $^{\alpha}$	West Boylston	0.21	4.7	1
Lily Pond Middle $^{\alpha}$	West Boylston	0.21	7.5	2
Lily Pond West $^{\alpha}$	West Boylston	0.26	4.3	1
Lampson Brook Pond	West Boylston	1.17	0.8	0
Carrolls Pond	West Boylston	1.28	1.5	0
Edwards Pond	West Boylston	1.29	0.9	0
Muddy Pond	Sterling	1.31	25.8	2
French Brook Pond	Boylston	2.14	10.4	0
The Quag	Sterling	2.27	34.7	2
West Waushacum Pond	Sterling	2.39	118.2	2
Landfill Pond	Holden	2.74	3.3	0
Trout Brook Pond	Holden	4.29	0.6	0
Unionville Pond	Holden	5.41	20.0	2
Chaffin Pond	Holden	7.59	83.9	2
Bryant Pond	Holden	8.07	7.5	2
Dawson Pond	Holden	8.57	24.6	2
Maple Spring Pond	Holden	8.74	40.4	1

* number of miles to closest reservoir shoreline location

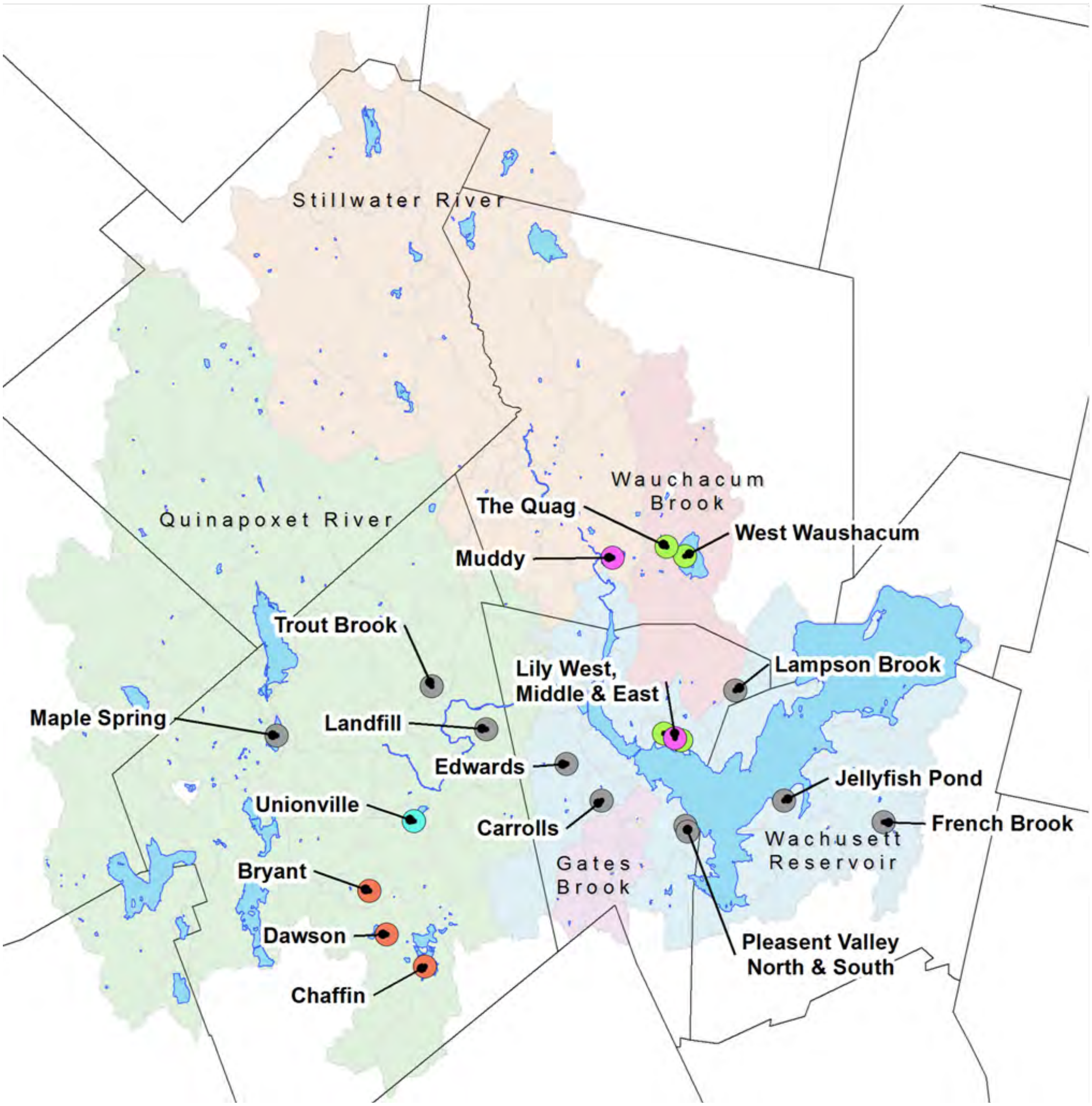
$^{\alpha}$ Management of the invasive species in these ponds was initiated in 2015 (see section 4.5.5.3)

Figure 23: Variable Milfoil at Chaffin Pond, Holden, MA

Figure 24: Native plants including Fern-leaf Pondweed and Bladderwort at The Quag, Sterling, MA

The following map (Figure 25) depicts the location of invasive aquatic plants observed in the watershed ponds surveyed during 2015 and listed in Table 19.

FIGURE 25: Locations of Wachusett watershed ponds surveyed in 2015 and presence/absence of select invasive aquatic vegetation (pond was omitted from most name labels for image clarity).



4.5.3.3 Invasive Species Management in the Lily Ponds

The 'Lily Ponds' consist of three small water bodies locally referred to as West, Middle, and East Lily Pond. The ponds are located in West Boylston approximately 500 feet to the north of Wachusett Reservoir, are fed via overland flow and groundwater seepage, and are not directly connected to the reservoir by surface flow. These water bodies are accessed via Wachusett Reservoir Gate 28 and are popular fishing and bait collection areas. The ponds are also frequented by ducks, geese, and wading birds.

FIGURE 26: Location of the Lily Ponds with respect to Wachusett Reservoir

Surveys of the ponds conducted by Division aquatic biologists as part of their assessment of ponds in the Wachusett Watershed in August 2015 revealed the presence of *Najas minor* (European/Brittle Naiad) in each of the three ponds as well as *Myriophyllum spicatum* (Eurasian Water-Milfoil) in Middle Lily Pond.

Both *M. spicatum* and *N. minor* spread via fragmentation of mature plants. These fragments can be spread via human and natural vectors such as transport on fishing gear and waterfowl movement (studies show that seeds of *N. minor* ingested by waterfowl remain viable even after passing through the birds' digestive tract). These characteristics make the presence of *M. spicatum* and *N. minor* in such close proximity to Wachusett Reservoir a severe threat. As established in previous sections of this document, these species have the potential to seriously impact water quality.

FIGURE 27: Invasive Species found in the Lily Ponds


Najas minor


Myriophyllum spicatum

As an immediate spread prevention measure, the Lily Ponds were closed to fishing upon discovery of the infestation due to public's use of the ponds for fishing and bait collection. Following review of several management techniques, the Division recommended a management plan for control of these invasive species begin as soon as possible in order to protect the reservoir. The implementation of an herbicide treatment plan was approved through a Negative Determination of Applicability by the West Boylston Conservation Commission at a meeting on September 22, 2015 as well as by a single adjoining landowner. A licensed herbicide application contractor (Aquatic Control Technology) was contracted with assistance from the MA DCR Lakes and Ponds Program in mid-September. The company applied for a DEP-OWM permit to apply U.S. EPA registered and state-approved herbicides to the ponds and the permit was issued on September 29, 2015.

FIGURE 28:

Middle Lily Pond prior to management – note Eurasian Milfoil plants reaching the surface of the water.

Middle Lily Pond following management – note degraded Eurasian Milfoil plants at right.

Due to the density of target species, especially in Middle Lily Pond, a split treatment of herbicide applied to only half of each pond at a time was conducted to insure against any negative effects on dissolved oxygen resulting from decay of target vegetation. Initial treatments of each of the three ponds were conducted on September 30th. Follow-up surveys conducted by Divison aquatic biologists on October 8th, showed that the initial treatment had sufficiently impacted growth in East Lily Pond.

Target plants in Middle and West Lily Pond displayed signs of treatment effects but some healthy plants remained. The second planned treatment of these two ponds was scheduled and carried out on October 16th (Aquatic Control Technology 2015).

Based on the extent of *M. spicatum* and *N. minor* present in 2015, it is expected that several years of management will be required. As growth is reduced, appropriate management strategies will continue to be selected based on results of the previous years' management and yearly vegetation surveys. It is anticipated that herbicide treatments will greatly reduce the distribution and density of *M. spicatum* and *N. minor* in the Lily Ponds and – following one to two years of pond-wide management – spot treatments, hand-harvesting, and other methods intended to target small infestations may be recommended.

<u>Reference Cited:</u>

Aquatic Control Technology. 2015. 2015 Year-End Report, Lily Ponds. Prepared for Massachusetts Department of Conservation and Recreation Lakes and Ponds Program.

4.5.4 PLANS FOR INVASIVE PLANT CONTROL EFFORTS IN 2016

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

Next year, during the 2016 growing season, plans call for a resumption of intensive DASH and hand-harvesting in Oakdale and Thomas Basins. The 3 year contract for this project has been updated to allow for finer scale mapping and tracking of where plants are being harvested, so that more information can be derived from year to year results. As usual, initial surveys will be conducted in May or June followed by harvesting in areas observed to support regrowth of invasive macrophytes. Dive crews will conduct additional hand-harvesting efforts during the summer as needed to suppress regrowth that occurs subsequent to initial harvesting efforts. The large scale Stillwater Basin DASH project is scheduled to resume again at the beginning of May 2016 for another full season of intensive harvesting.

Associated with hand-harvesting efforts, Division aquatic biologists will continue systematic scouting for invasive macrophytes throughout the reservoir system to identify and target any pioneering specimens found in new locations. An updated bathymetric map of the reservoir has been developed and divided into sections to ensure complete coverage and help focus scouting efforts on those areas most susceptible to colonization by hydrilla and other invasive aquatic plants. Areas with growth of recently discovered plants will be monitored to determine if spread is occurring and to evaluate if any potential management actions are prudent. The amount of growth of Eurasian Water-milfoil in Gates Brook Cove is a concern and this area will be a focus for plant removal again in 2016.

Finally, Division staff will continue to maintain floating fragment barriers at their strategic bottleneck locations as done in previous years. Recent changes to the boom configuration at the Oakdale Basin Railroad Trestle appear to be effective and will be maintained; the configuration of the boom under the Beaman Street Bridge will be evaluated for the 2016 season.

The chevron boom below Beaman Street will once again be deployed for the entirety of the growing/harvesting season to trap fragments and measure the effectiveness of the upstream booms.

4.6 FISH

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

Actual sampling of fish in Wachusett Reservoir has been sporadic and infrequent due to a lack of available resources. In 2014, MA DFW and MA DCR partnered to begin 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.

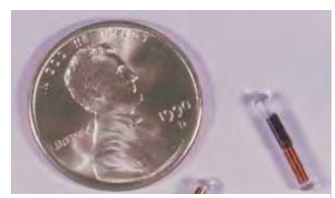


Figure 29: PIT tag tag used used for tagging lake trout

Despite a lack of information about lake trout spawning locations in the reservoir, crews managed to capture and tag 107 lake trout in 2014. 83% of lake trout captured on spawning grounds were male, while 17% were female. Male lake trout are typically caught more frequently because they spend more time on the spawning area making multiple passes searching for females. Females are believed to move onto the spawning area to spawn without lingering.

This effort was repeated in 2015 with one additional new spawning location being added to the known sites discovered in 2014. Crews captured and tagged 154 lake trout in 2015. 73% of lake trout captured on spawning grounds were male, while 27% were female. Four fish tagged in 2014 were recaptured in 2015. As more fish are tagged in subsequent years, more fish will be recaptured and more information will be gained. Comparisons between lake trout caught at Wachusett and Quabbin during 2014-2015 reveal that Wachusett fish are more robust and have a higher relative condition factor than Quabbin fish (Stolarski 2016). This holds true for both males and females. It remains to be seen if there will be differences in the growth rates of lake trout in Wachusett as compared to Quabbin reservoir, where the growth rate has been documented to be very slow.

Figure 30:A PIT tag being inserted into the abdomen of a lake trout by MA DFW and MA DCR staff

<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.

Stolarski, Jason. 2016. Personal communication January 2016. Massachusetts Division of Fisheries and Wildlife.

5.0 SAMPLING PLAN FOR 2016

The Wachusett watershed sampling program for 2016 follows protocols used during previous years. Temperature, specific conductance, *E. coli*, and turbidity will be measured weekly or biweekly at nineteen stations on eighteen tributaries during dry and wet weather. Additional sampling will be done as needed to help locate occasional sources of contamination. Samples will also be collected to support potential enforcement actions required by other Division staff. Nutrient samples will be collected monthly from ten tributary stations with available flow data and weekly UV-254 will continue to be collected from the Stillwater and Quinapoxet Rivers.

The routine sampling program provides data on the effects of storm events on tributary water quality using detailed precipitation data from several stations within or near the watershed. Sampling at Trout Brook to collect specific information on stormwater quality will be done approximately monthly as weather permits and once budgetary conditions improve. Additional stormwater sampling at several other locations will be done to obtain data on specific storm types (length, intensity, and season).

Samples during ‘extreme’ storm events will be collected when possible to support UMASS modeling efforts.

Understanding watershed hydrology is a necessary part of any water quality monitoring program. A continuation of the expanded hydrology monitoring program is planned for 2016. Precipitation data from NOAA weather stations in Worcester and Fitchburg, from the USGS stations on the Stillwater River in Sterling and the Quinapoxet River in Holden, and from a DCR rain gage in West Boylston will be collected daily. Snow pack measurements and calculation of snow-water equivalent amounts will be done regularly during the winter months throughout the watershed. All data will be regularly uploaded into the new Aquarius database.

Depth will be recorded at seven stations and flow calculated using rating curves developed by Division Environmental Quality staff and refined using Aquarius software tools. Additional locations may be added to increase our understanding of flow throughout the watershed. Flow measurements will be taken 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.

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.

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	05/15/15	07/22/15	10/06/15	12/01/15
MD25	Basin North (E)	0.015	0.006	<0.005	0.007
MD61	Basin North (M)	0.011	0.009	0.005	0.009
MD62	Basin North (H)	0.010	0.011	0.006	0.008
MD26	Basin South (E)	0.014	0.006	0.005	0.008
MD63	Basin South (M)	0.010	0.007	<0.005	0.008
MD64	Basin South (H)	0.010	0.010	0.007	0.007
MD27	Thomas Basin (E)	0.014	0.007	0.008	0.009
MD65	Thomas Basin (M)	0.010	0.009	0.005	0.009
MD66	Thomas Basin (H)	0.010	0.008	0.008	0.010

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

		Sampling Date			
ID	Sampling Station	05/15/15	07/22/15	10/06/15	12/01/15
MD25	Basin North (E)	<0.005	<0.005	<0.005	<0.005
MD61	Basin North (M)	0.007	0.007	<0.005	<0.005
MD62	Basin North (H)	0.011	0.025	<0.005	<0.005
MD26	Basin South (E)	<0.005	<0.005	<0.005	<0.005
MD63	Basin South (M)	0.006	<0.005	<0.005	<0.005
MD64	Basin South (H)	0.011	0.027	<0.005	<0.005
MD27	Thomas Basin (E)	<0.005	<0.005	<0.005	<0.005
MD65	Thomas Basin (M)	<0.005	<0.005	<0.005	<0.005
MD66	Thomas Basin (H)	<0.005	<0.005	<0.005	<0.005

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

ID	Sampling Station	Sampling Date			
		05/15/15	07/22/15	10/06/15	12/01/15
MD25	Basin North (E)	0.066	<0.005	<0.005	0.042
MD61	Basin North (M)	0.090	0.023	0.021	0.042
MD62	Basin North (H)	0.116	0.116	0.153	0.042
MD26	Basin South (E)	0.082	<0.005	<0.005	0.042
MD63	Basin South (M)	0.107	<0.005	0.017	0.041
MD64	Basin South (H)	0.096	0.111	0.142	0.042
MD27	Thomas Basin (E)	0.030	<0.005	0.007	0.031
MD65	Thomas Basin (M)	0.035	0.008	0.008	0.028
MD66	Thomas Basin (H)	0.036	0.014	0.015	0.031

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

ID	Sampling Station	Sampling Date			
		05/15/15	07/22/15	10/06/15	12/01/15
MD25	Basin North (E)	0.182	0.134	0.162	0.112
MD61	Basin North (M)	0.264	0.189	0.168	<0.100
MD62	Basin North (H)	0.199	<0.100	<0.100	<0.100
MD26	Basin South (E)	0.162	0.198	0.156	0.100
MD63	Basin South (M)	0.250	0.144	0.133	<0.100
MD64	Basin South (H)	0.227	0.170	0.217	0.193
MD27	Thomas Basin (E)	0.173	0.145	0.203	<0.100
MD65	Thomas Basin (M)	0.275	0.162	0.243	0.102
MD66	Thomas Basin (H)	0.225	0.140	0.212	<0.100

Results of Quarterly Nutrient Sampling:
UV254 (A/cm)

		Sampling Date			
ID	Sampling Station	05/15/15	07/22/15	10/06/15	12/01/15
MD25	Basin North (E)	0.064	0.050	0.036	0.037
MD61	Basin North (M)	0.069	0.063	0.038	0.037
MD62	Basin North (H)	0.065	0.061	0.056	0.037
MD26	Basin South (E)	0.066	0.051	0.037	0.036
MD63	Basin South (M)	0.072	0.057	0.038	0.035
MD64	Basin South (H)	0.071	0.061	0.055	0.036
MD27	Thomas Basin (E)	0.067	0.060	0.044	0.035
MD65	Thomas Basin (M)	0.053	0.065	0.043	0.038
MD66	Thomas Basin (H)	0.051	0.038	0.034	0.049

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

		Sampling Date			
ID	Sampling Station	05/15/15	07/22/15	10/06/15	12/01/15
MD25	Basin North (E)	2.70	1.43	1.73	2.66
MD61	Basin North (M)	3.08	2.26	2.27	2.48
MD62	Basin North (H)	3.06	4.05	4.06	2.41
MD26	Basin South (E)	2.81	1.47	1.73	2.62
MD63	Basin South (M)	3.17	1.69	2.12	2.36
MD64	Basin South (H)	3.15	3.90	3.98	2.32
MD27	Thomas Basin (E)	2.07	1.77	1.95	2.67
MD65	Thomas Basin (M)	1.83	2.08	1.94	2.86
MD66	Thomas Basin (H)	1.87	2.07	2.24	3.04

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

		Sampling Date			
ID	Sampling Station	05/15/15	07/22/15	10/06/15	12/01/15
MD25	Basin North (E)	6.20	6.54	6.10	5.86
MD61	Basin North (M)	6.32	6.16	5.42	6.18
MD62	Basin North (H)	6.24	6.44	6.26	5.84
MD26	Basin South (E)	6.40	6.62	6.24	5.70
MD63	Basin South (M)	5.78	6.44	5.76	5.64
MD64	Basin South (H)	6.34	6.56	6.48	5.66
MD27	Thomas Basin (E)	7.26	6.94	6.66	4.90
MD65	Thomas Basin (M)	5.56	6.96	6.62	4.70
MD66	Thomas Basin (H)	4.88	4.48	5.18	5.60