Water Quality Report: 2018

Wachusett Reservoir Watershed

November 2019

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

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management (DWSP) manages and maintains a system of watersheds and reservoirs to provide raw water to the Massachusetts Water Resources Authority (MWRA), which in turn supplies drinking water to approximately 3.1 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 DWSP. 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 2018 water quality data from the Wachusett Reservoir tributaries and reservoir. A report summarizing 2018 water quality data from the Quabbin and Ware River watersheds is also available from the DWSP.

ACKNOWLEDGEMENTS

This report was prepared by the DWSP. Authors are Environmental Analysts Daniel Crocker, Lawrence Pistrang and Travis Drury and Aquatic Biologists Joy Trahan-Liptak and Max Nyquist. Internal review and comments were provided by Jamie Carr, Kristina Gutchess and Lawrence Pistrang. Jamie Carr, Joy Trahan-Liptak, Max Nyquist, David Getman, Daniel Crocker, and Steve Sulprizio collected the samples and were responsible for field measurements. Daniel Crocker was responsible for the development of stage-discharge relationships and flow monitoring, modeling efforts and database development. Turbidity analysis was performed by David Getman. Plankton samples were collected and analyzed by Jamie Carr, Joy Trahan-Liptak, and Max Nyquist. All remaining lab analyses (bacteria, nutrients, other parameters) were conducted off-site by MWRA staff.

The DWSP would like to once again thank the staff and management of the MWRA Deer Island lab for preparing and delivering sample bottles and performing all non-bacterial analyses during the year. They also thank the MWRA staff at the Southborough lab for completing all routine and non-routine *E. coli* analyses during the year and for arranging the transportation of all non-bacterial samples to Deer Island.

WATER QUALITY REPORT: 2018
WACHUSETT RESERVOIR AND TRIBUTARIES

1.0 INTRODUCTION

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management (DWSP) manages and maintains a system of watersheds and reservoirs to provide potable water to the Massachusetts Water Resources Authority (MWRA), which in turn supplies drinking water to approximately 3.1 million people and thousands of industrial users in 51 communities.

The Federal Surface Water Treatment Rule[1] requires filtration of all surface water supplies unless numerous criteria are met, including the development and implementation of a detailed watershed protection plan[2]. The DWSP and the MWRA have a joint waiver from the filtration requirement and continue to diligently manage the watershed in order to maintain this waiver. Water quality sampling and field inspections help identify tributaries with potential water quality issues, 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. DWSP staff also sample to better understand the responses of the reservoir and its tributaries to a variety of physical, chemical, and biological inputs, and to assess the ecological health of the reservoir and the watershed.

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

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

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

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[1] Surface Water Treatment Rule. Subpart H—Criteria for avoiding filtration (40 CFR141.71).

[2] MA DCR Division of Water Supply Protection. (2018). Watershed Protection Plan FY19-FY23.

All bacteria, nutrient, total suspended solids, specific conductance, turbidity, plankton, precipitation and flow data collected since 1989 are stored in a Microsoft Access database. A custom R[3]/Shiny[4] application called WAVE (WAtershed system data Visualization Environment), developed by a UMass Amherst graduate student and DWSP staff has been developed and serves as a portal to view and track data within the database. All data generated from tributary and reservoir water quality monitoring in 2018 are available upon request.

[3] R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/.

[4] Winston Chang, Joe Cheng, JJ Allaire, Yihui Xie and Jonathan McPherson. 2019. shiny: Web Application Framework for R. R package version 1.3.1. https://CRAN.R-project.org/package=shiny.

2.0 DESCRIPTION OF MONITORING PROGRAMS

DWSP staff collected water quality samples from tributary monitoring stations and from four stations on the Wachusett Reservoir in 2018. Stations are described in **Table 1** and **Table 2,** and sampling locations are shown on **Figure 1** - **Figure 3** on pages 4-7. Some samples were analyzed by DWSP staff including 427 turbidity samples from tributaries and 126 phytoplankton samples from the reservoir. A total of 876 physiochemical measurements (temperature and specific conductance) were taken in the field at tributary stations, with another 47 water column profiles (temperature, specific conductance, dissolved oxygen, percent oxygen saturation, chlorophyll *a*, turbidity, and pH) recorded from the reservoir. A total of 794 bacteria samples were collected and delivered to the MWRA Southborough laboratory for *E. coli* analysis, and 234 samples were collected and shipped to the MWRA Deer Island laboratory for a total of 2,145 analyses of nutrients and other parameters; this includes special studies (**Section 3.7**).

2.1 ROUTINE TRIBUTARY MONITORING

Each routine tributary station was visited every other week throughout the entire year (**Table 1** – "Primary"), 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 multi-sensor 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 DWSP West Boylston lab using a HACH 2100N meter.

Routine nutrient samples were collected monthly from 10 monitoring stations as well as the Quabbin Transfer (Shaft 1) (**Table 1** – (N)) and analyzed at the MWRA Deer Island lab for total phosphorus (TP), ammonia-nitrogen (NH_3-N), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), total Kjeldahl nitrogen (TKN), total organic carbon (TOC), total suspended solids (TSS), chloride (Cl) and mean UV_{254} (UV_{254}). The sample frequency of UV_{254} from the Stillwater and Quinapoxet Rivers was changed to monthly in 2018. All analyses were performed according to *Standard Methods for the Examination of Water and Wastewater 20th Edition*[5] or EPA methods[6]. 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 DWSP Environmental Quality staff. Daily flow in Gates Brook and the Stillwater and Quinapoxet Rivers was obtained from continuous recording devices installed by the United States Geological survey (USGS). Instantaneous flow for these sites is available from the USGS at the *NWIS website* for each station.

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

All water quality data, flow data, and precipitation data are routinely uploaded to Microsoft Access databases maintained by the DWSP Environmental Quality section.

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[5] Rice, E. W., & Bridgewater, L. Standard methods for the examination of water and wastewater. 20th Edition. Washington, D.C. American Public Health Association, 1998.

[6] EPA 600/4-79-020 Methods for Chemical Analysis of Water and Wastes. Revised March 1983 (NTIS / PB84-128677 or CD ROM or NEPIS / http://www.epa.gov/clariton/clhtml/pubtitleORD.html)

Figure 1. Wachusett Watershed Tributary Sampling Stations

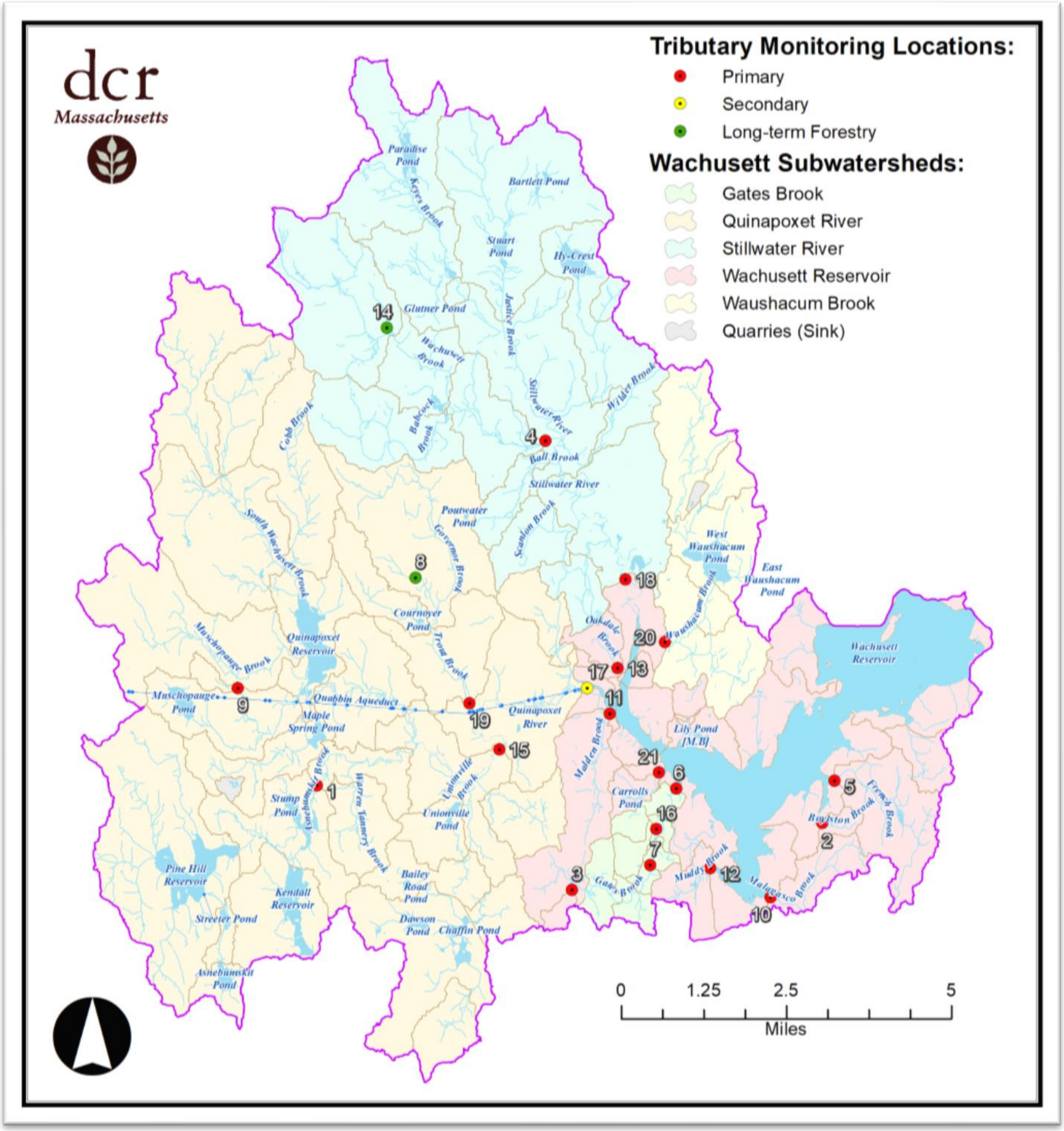
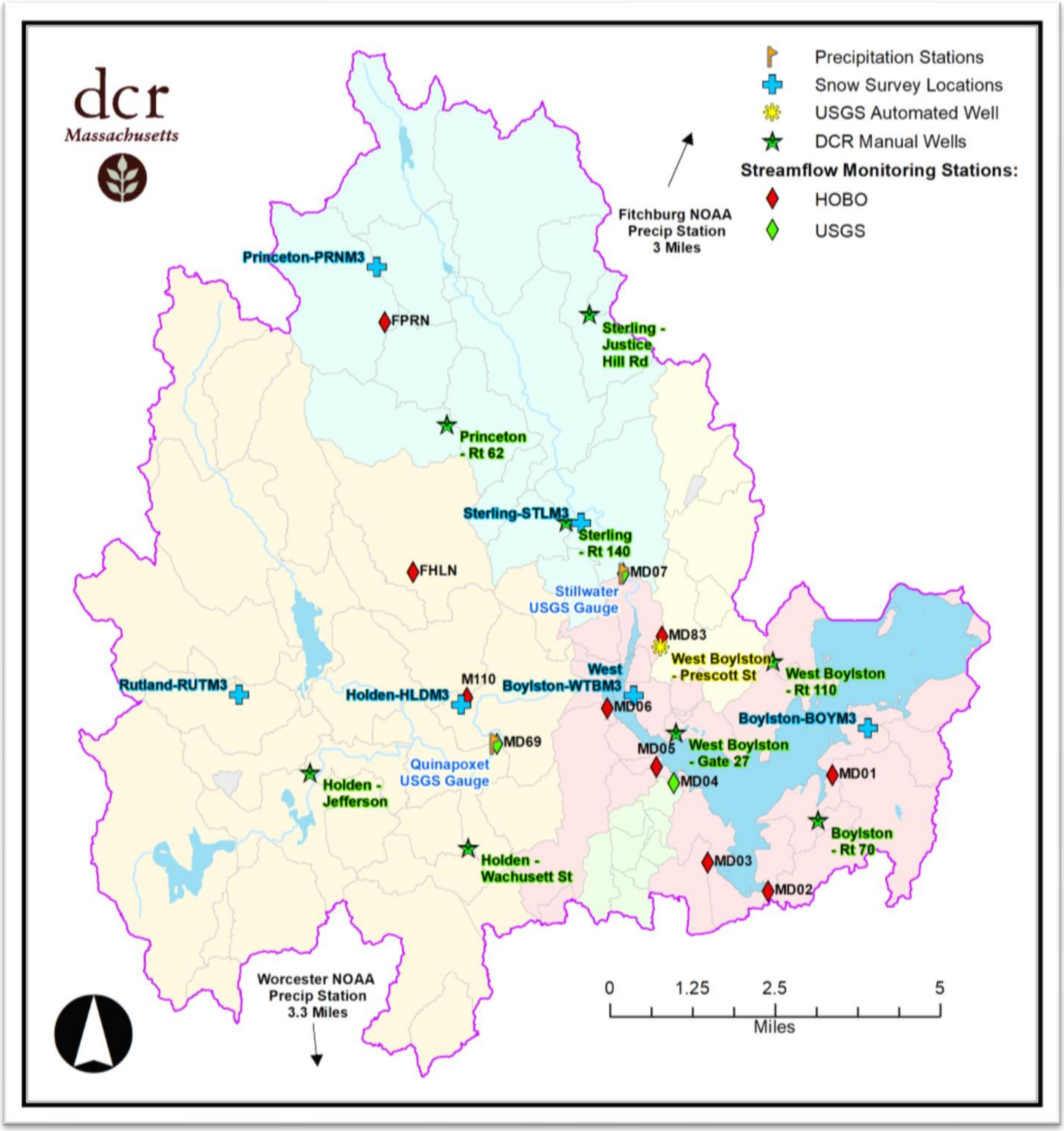


Table 1. Wachusett Tributary Sampling Stations (2018)

MAP #	LOCATION	DESCRIPTION	SAMPLING CATEGORY
1	Asnebumskit Brook (Princeton) - M102	Upstream of Princeton St Near Post Office, Holden	Primary
2	Boylston Brook - MD70	Downstream of Rt. 70, Boylston	Primary
3	Cook Brook - Wyoming - MD11	Wyoming Dr, Holden	Primary
4	East Wachusett Brook (140) - MD89	Downstream of Rt. 140, Sterling	Primary
5	French Brook - MD01	Downstream of Rt. 70, Boylston	Primary (N)
6	Gates Brook 1 - MD04	Downstream of Bridge Inside Gate 25, West Boylston	Primary (N)
7	Gates Brook 4 - MD73	Upstream of Pierce St, West Boylston	Primary
8	Holden Forestry - FHLN	Off Mason Rd Inside Gate H-21, Holden	LTF
9	Jordan Farm Brook - MD12	Upstream of Rt. 68, Rutland	Primary
10	Malagasco Brook - MD02	Upstream of W. Temple St. Extension Boylston	Primary (N)
11	Malden Brook - MD06	Upstream of Thomas St, West Boylston	Primary (N)
12	Muddy Brook - MD03	Upstream of Rt 140. West Boylston Ma	Primary (N)
13	Oakdale Brook - MD80	Downstream of Waushacum St, East of Rt 140, West Boylston	Primary
14	Princeton Forestry - FPRN	Off Rt 31 Near Krashes Field, Princeton	LTF
15	Quinapoxet River (Canada Mills) - MD69	Upstream of River St Bridge (Canada Mills), Holden	Primary (N)
16	Scarlett Brook (DS W.M.) - MD81	Behind Walmart above confluence with Gates Brook, West Boylston	Primary
17	Shaft 1 (Quabbin Transfer) - MDS1	MWRA Shaft 1 Outlet Off River St, West Boylston	Secondary (N)
18	Stillwater River - Muddy Pond Rd - MD07	Downstream of Muddy Pond Rd, Sterling	Primary (N)
19	Trout Brook - M110	Downstream of Manning St, Holden	Primary (N)
20	Waushacum Brook (Prescott) - MD83	Downstream of Prescott St, West Boylston	Primary (N)
21	West Boylston Brook - MD05	Upstream of Access Road Inside Gate 25, West Boylston	Primary (N)

(N) = Nutrient monitoring locations
LTF = Long-term forestry study

Figure 2. Wachusett Watershed Hydrologic Monitoring Stations



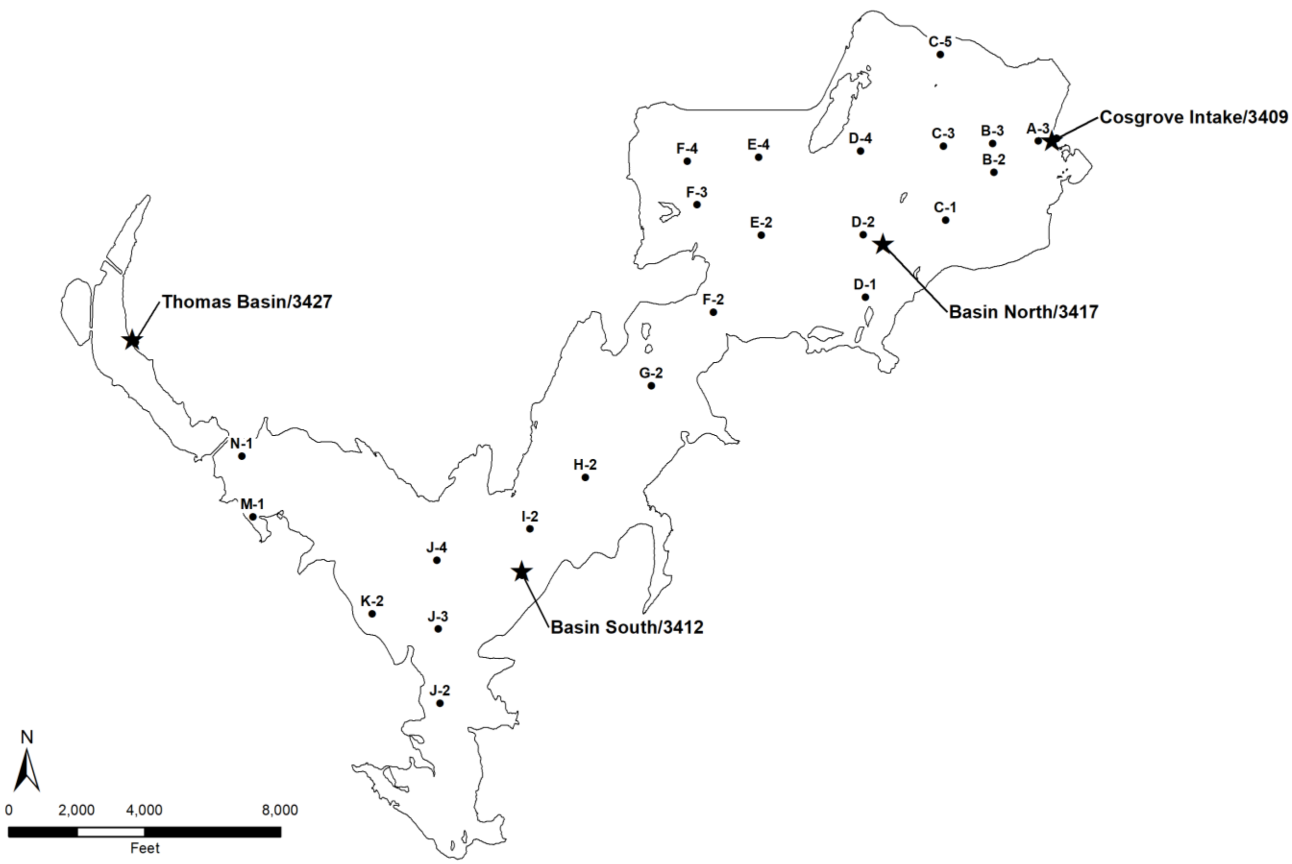
2.2 RESERVOIR MONITORING

Temperature, dissolved oxygen concentration and percent saturation, specific conductance, chlorophyll *a*, and pH water column profiles were recorded weekly during stratified conditions at Station 3417 (Basin North) in conjunction with routine plankton monitoring. A full panel of nutrient samples was collected quarterly (May, July, October, December) at Station 3417 (Basin North), Station 3412 (Basin South) and Thomas Basin (**Table 2** and **Figure 3**). At each nutrient station, samples were collected from the epilimnion, metalimnion, and hypolimnion and analyzed for nitrate-nitrogen, ammonia-nitrogen, total Kjeldahl nitrogen, total phosphorus, silica, UV_{254}, and alkalinity. All samples were analyzed at the MWRA Lab at Deer Island (see **Section 4.3** for complete discussion). Water column profiles were also recorded at each station during each nutrient sampling event.

Table 2. Wachusett Reservoir Sampling Stations (2018)

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

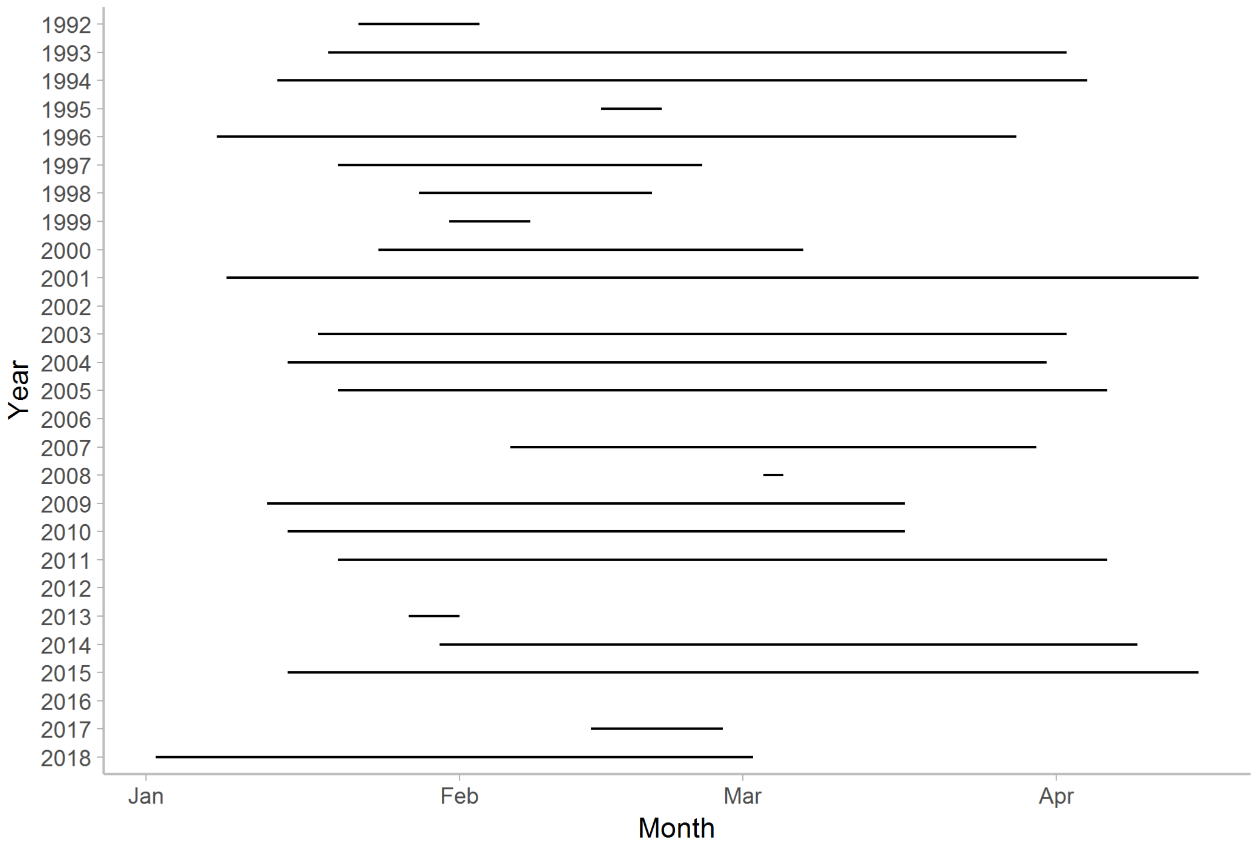
Figure 3. Reservoir Sampling Stations



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, MA. DWSP staff collected *E. coli* samples twice in April, once each in the months of May-August, three times in October, and twice in November and December from 23 reservoir surface stations shown above (**Figure 3** – points). Reservoir ice cover prevented transect sampling from January through March (**Section 3.2)**.

The reservoir was considered frozen as of December 31, 2017 and remained so until ice out on March 1, 2018. This 60-day period was the longest ice cover since 2015 when the reservoir was frozen for 90 days (**Figure 4**).

Figure 4. Historical Wachusett Reservoir Ice Cover Duration



3.0 RESULTS OF TRIBUTARY MONITORING PROGRAM FOR 2018

Statistics presented in this section may differ slightly from those reported in previous years due to changes in analytical methods. All numerical calculations and related graphics were generated using the R programming language[7] and preserved in scripts, which document the exact steps that were utilized to produce the results presented herein. This provides an additional level of transparency and will improve efficiency and consistency in the writing of future annual water quality reports. Graphics were produced with the ggplot2 package[8]. All seasonal statistics presented in this report use the following date cutoffs to determine season:

- December 21 (winter solstice)
- March 20 (spring equinox)
- June 21 (summer solstice)
- September 22 (autumn equinox)

All left-censored laboratory results (values that were below lower detection thresholds) were assigned values of one-half the detection limit. Any right-censored laboratory results (values above upper detection thresholds; none in 2018), were assigned a value equal to the detection limit. All censored results are flagged as such in the database. This method of handling censored data was chosen so that calculated statistics would not be biased high due to the filtering of predominantly left-censored results when performing statistical calculations.

3.1 WATERSHED HYDROLOGICAL MONITORING FOR 2018

3.1.1 PRECIPITATION

DWSP closely monitors precipitation and uses this information to provide context for the water quality and hydrological conditions observed in the tributaries, groundwater, and reservoir. The type, amount, intensity, frequency and spatial distribution of precipitation (or snowmelt) across the landscape is the dominant driver of the water quality and hydrologic dynamics, thus it is important to consider this hydrological context when evaluating water quality results, comparing interannual variability, or looking at trends.

DWSP contracts with the USGS field station out of Northborough, MA for precipitation monitoring at two locations: the Stillwater River – MD07 (USGS 01095220) and the Quinapoxet River - MD69 (USGS 01095375). Additionally, NOAA monitors precipitation at two location situated a few miles outside of the Wachusett watershed in Worcester (NOAA USW00094746) and Fitchburg (NOAA USW00004780) (**Figure 2**). These four stations are utilized for calculating average watershed precipitation. As illustrated by **Figure 5**, 2018 was the wettest year since at least 1985, with 61.21 inches of rainfall (14.55 inches more than average annual precipitation).

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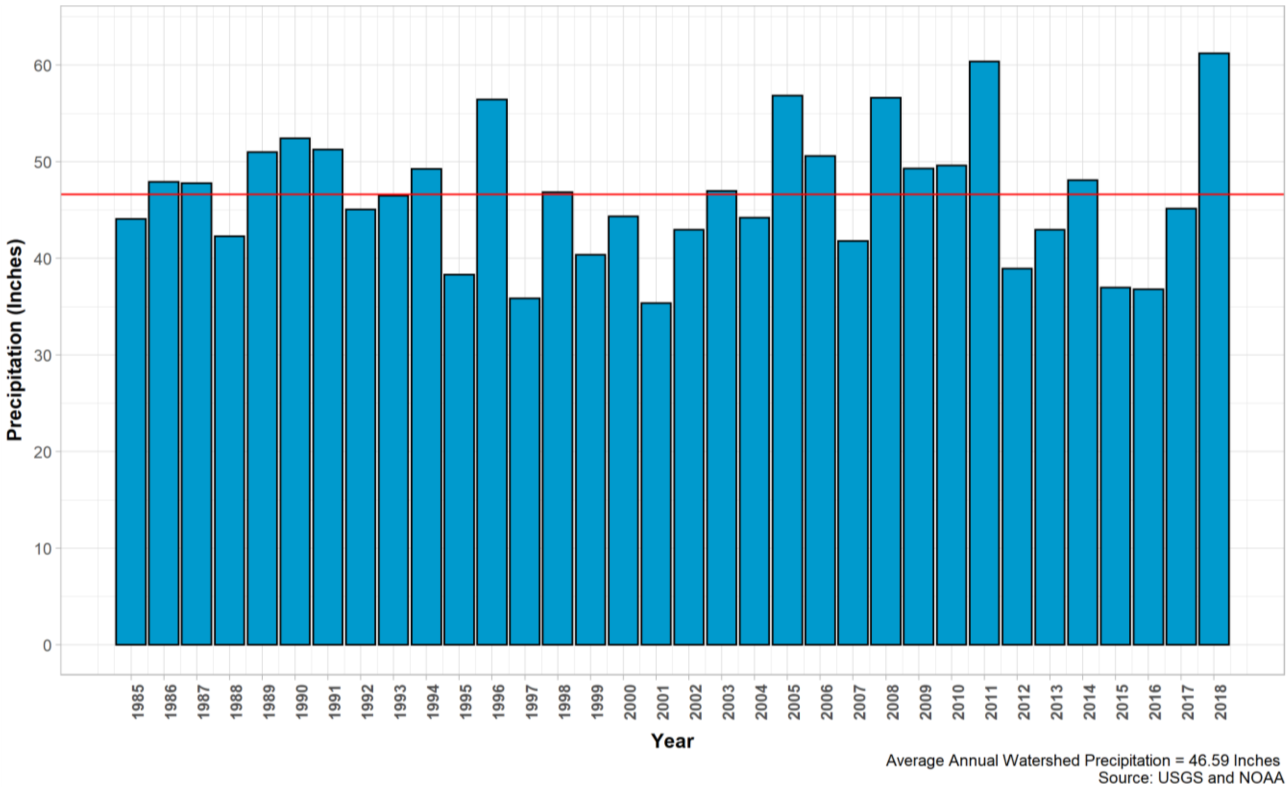
[7] ibid 2

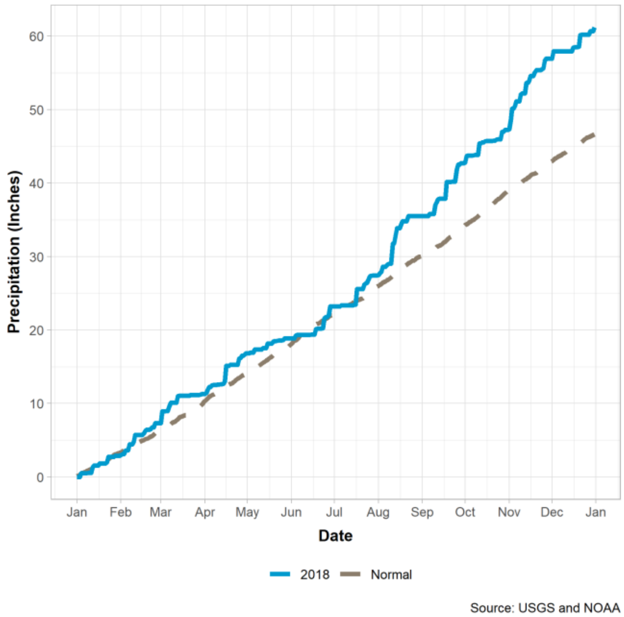
[8] H. Wickham. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2016.

Figure 5. Annual Precipitation in Wachusett Watershed (inches) (1985 - 2018)



As of mid-July, annual precipitation to calendar date was about normal , so the entire precipitation surplus was gained during the last half of the calendar year, almost entirely in the months of August, September, and November (**Figure 6**). This higher than normal volume of water entering the watershed was apparent in the streamflow observed during the fall. Noteworthy precipitation events (> 2 inches) occurred on April 16th, July 17th, August 11 - 14 (where nearly 5 inches of rain fell over 4 days), and September 18th.

Figure 6. Cumulative and Monthly Precipitation in Wachusett Watershed - 2018



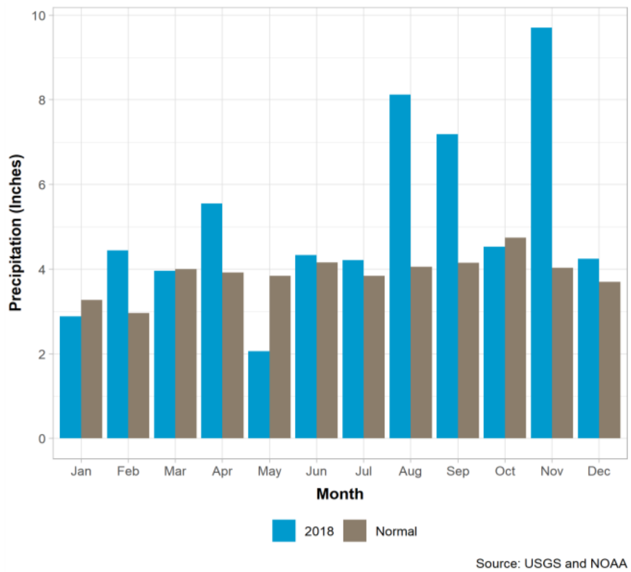


Table 3. Monthly Precipitation Totals for 2018

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Precipitation	2.88	4.44	3.96	5.55	2.06	4.33	4.21	8.12	7.19	4.53	9.70	4.24	**61.21**
Normal	3.27	2.96	4.00	3.92	3.84	4.16	3.84	4.05	4.15	4.74	4.03	3.70	**46.66**
Departure	-0.39	1.48	-0.04	1.63	-1.78	0.17	0.37	4.07	3.04	-0.21	5.67	0.54	**14.55**
Years	35	35	35	35	35	35	35	35	34	34	34	34	**NA**

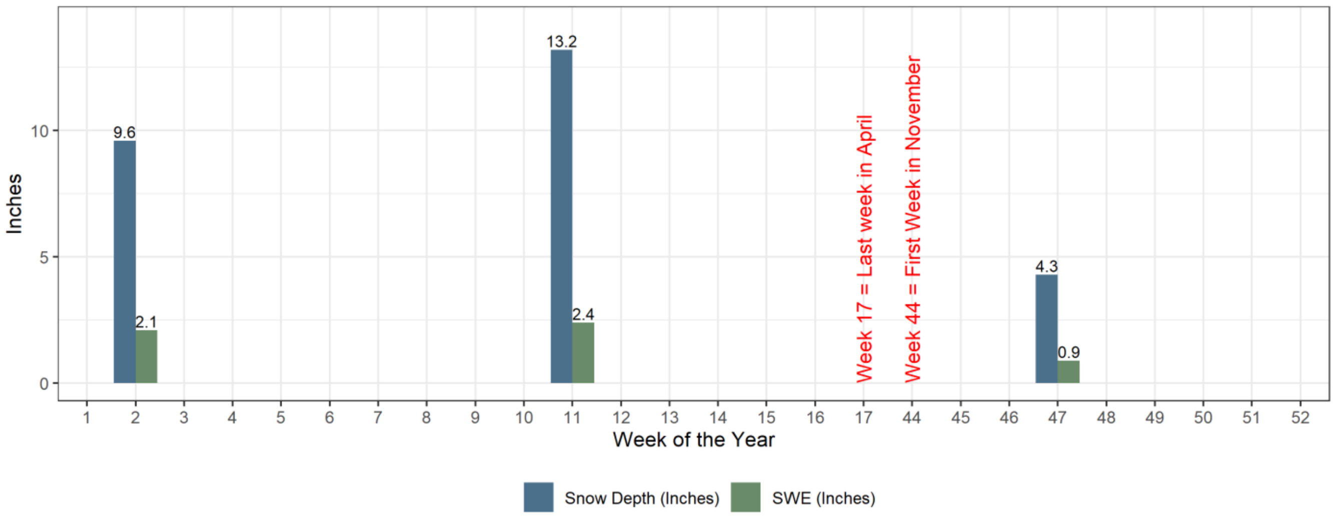
3.1.2 SNOWPACK

Effectively managing the Wachusett Reservoir water storage volume requires an accurate prediction of water inputs to the reservoir which are derived from new precipitation and/or melting of past precipitation stored in the snowpack. Therefore, DWSP carries out a snowpack monitoring program to track the water content of the snowpack and document any changes resulting from melt, evaporation and sublimation, so that future water inputs to the reservoir can be modeled and estimated.

Wachusett Reservoir watershed snowpack was measured weekly throughout the winter unless there was not enough snow to obtain reliable measurements. DWSP measures snowpack at six locations (**Figure 2**) with varied altitudes, aspects, and cover types in order to capture the variability of snowpack across the watershed. At each location five snow core samples are taken, the depth of the snow is recorded, and each core is weighed to determine its snow-water-equivalent (SWE). These measurements are averaged by location and then reported to the NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC). NOHRSC uses this data along with other weather conditions and forecasts to predict near-term changes to river flows and provide flood threat information to the public.

Figure 7 shows the snow depth and SWE measurements for 2018. The weekly amounts do not account for all snow accumulation that occurred during the season - it is just a weekly snapshot of the snow depth and SWE over time. Between measurements there can be losses due to sublimation/melt, gains due to additional frozen precipitation, or periods of both gain and loss.

Figure 7. Snowpack Measurements - 2018



At the outset of 2018 there was over 20 inches of snowpack in some parts of the watershed, however by week 2, melting had reduced this to 9.6 inches (watershed average) containing 2.1 inches of SWE. By the third week of the year snowpack had melted to a depth that precluded measurements, and snowpack remained below 3-4 inches until a storm in early March added more than 15 inches of snow across the watershed. By the week 11 measurement (March 15) only 13.2 inches of snow (2.4 inches SWE) remained of the rapidly melting snowpack. The snowpack had completely melted by April 1. The first measurable snowfall of the 2018-2019 snow season occurred in mid-November and was measured at 4.3 inches during week 47. The snowpack had melted to a depth insufficient to measure by week 48 and was completely gone by week 49 in early December. More detailed information was recorded in snowpack reports that were produced each week that a measurement was taken.

3.1.3 FLOW

Discharge (flow) monitoring has been conducted on primary tributaries throughout the Wachusett watershed for more than two decades using both manual and automated methods. The USGS was responsible for the development and maintenance of stage/discharge relationships at these sites and continues to operate three stations (Quinapoxet River – MD69, Stillwater River – MD07, and Gates Brook – MD04) using continuous monitoring technologies. Responsibility for flow monitoring on the other primary tributaries was transferred to the DWSP towards the end of 2011.

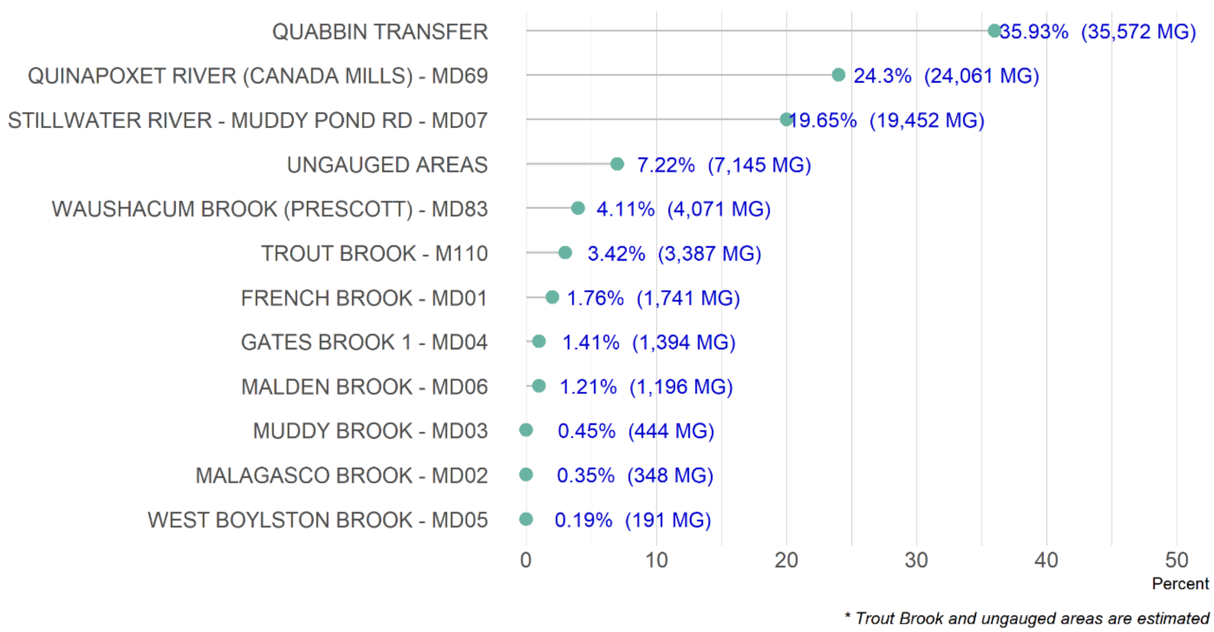
At seven DWSP flow monitoring stations (**Figure 2**) visual observations of stream depth (stage) are recorded from staff plates during all sampling visits (typically three times per month). Six stations have been monitored for many years; measurement of flow in Trout Brook began in 2014, however the staff gauge was repeatedly dislodged during high flows and the gauging location was moved each time, which prevented the finalization of a rating curve. The current gauging control point has been stable since it was established in the spring of 2018.

Manual stage measurements were supplemented during 2017 by continuous depth recordings using HOBO water level data loggers. Direct measurement of flow at a range of depths is usually obtained several times during the year using a FlowTracker handheld acoustic doppler velocimeter to develop and calibrate accurate stage-discharge relationships. Reliable stage-discharge relationships allow the use of easily acquired stream depths to quickly estimate flow. Stage-discharge relationships at Muddy Brook and Trout Brook were finalized in 2019 and discharges from 2018 were back calculated (Trout Brook rating development for the new gauging location did not begin until June 2018, and a HOBO was not deployed until mid-July).

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 and 1996, respectively. Stage data from Gates Brook were collected manually from 1994 until December 2011 when a flow monitoring sensor was installed. Continuous monitoring equipment at Gates Brook now collects and transmits real time data every ten minutes, although installation of a new bridge prevented measurements for four months in 2014 and a major storm in October 2016 altered the channel and buried the water quality probe. The downstream control structure was reconstructed, the data collection apparatus repaired, and a new stage-discharge relationship has been developed. The USGS generated estimated flow data for eight months when the relationship was unavailable.

The total surface water inflow to the Wachusett Reservoir was estimated to be 99,007 million gallons (MG) in 2018.
Figure 8 shows a breakdown of flow among all the tributaries as well as ungauged areas and the Quabbin transfer. The Quabbin transfer comprised over one-third of the total inflow to the reservoir. About 44% of surface water inputs came from the Quinapoxet and Stillwater Rivers, while about 20% was contributed by the smaller tributaries and ungauged areas (direct runoff to the reservoir).

Figure 8. Annual Surface Inflow to Wachusett Reservoir (MG) in 2018



The Wachusett Reservoir is operated to maintain a water surface elevation between 390 and 391.5 ft year-round. Water from the Quabbin Reservoir is typically transferred to the Wachusett Reservoir during the months of increased water demand, and/or as necessary to keep the reservoir within its target operational elevation in conjunction with drinking water withdrawals and other releases. In 2018, the reservoir elevation deviated from its operating range on four separate occasions (**Figure 9**). The April and August elevation peaks were directly related to the high precipitation events discussed in the prior section. The long period of high elevation from mid-November through the end of the year can be attributed to the surplus precipitation that occurred in November and December (> 6 inches), which resulted in tributary flows well in excess of normal ranges for those months (**Figure 13** and **Figure 14.**

Figure 9. 2018 Daily Wachusett Reservoir Water Elevation and Daily Quabbin Transfer Rate

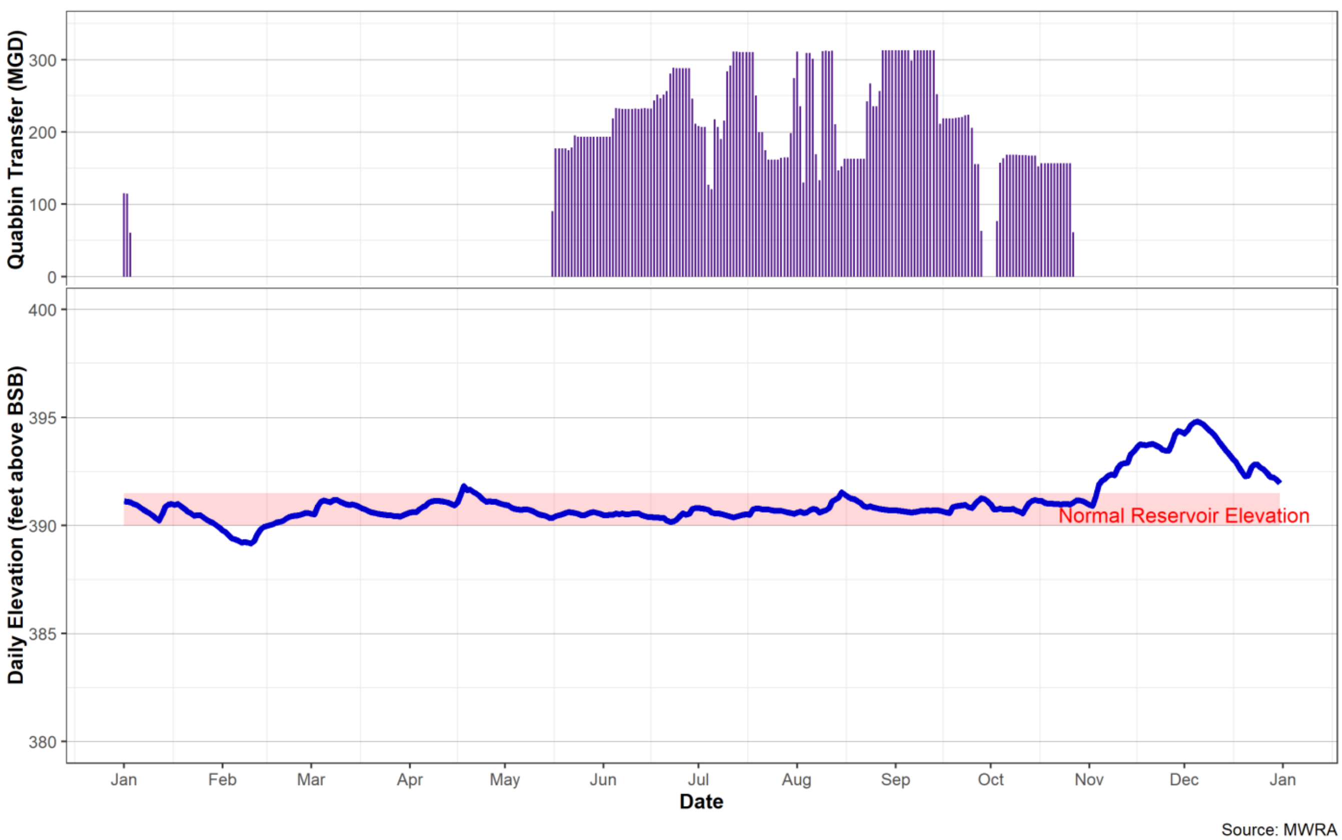


Table 4 provides summary statistics of surface water flows for 2018. The Stillwater River gauge experienced errors during the summer of 2018 from June 11 - July 19 and discharge during this time was estimated. The minimum flow presented in **Table 4** occurred during the estimated time range. Stillwater River flow likely did not drop this low considering there was no precipitation deficit in June and July and normal baseflows are typically higher than 2 cubic feet per second (cfs). DWSP stage observations indicate that flows were higher than 2 cfs during this low flow period. DWSP is working with USGS to amend the published data for 2018.

Daily flow rates in the smaller tributaries (not including Trout Brook) ranged from zero at Malagasco Brook to 66 cfs at French Brook. The maximum instantaneous flow at the gauges ranged from under 10 cfs at Malagasco Brook to nearly 123 cfs at French Brook.

Table 4. 2018 Annual and Monthly Discharge Statistics in Wachusett Tributaries

LOCATION	MIN DAILY FLOW (CFS)	AVE DAILY FLOW (CFS)	MAX DAILY FLOW (CFS)	MIN MONTH VOL (MG)	AVE MONTH VOL (MG)	MAX MONTH VOL (MG)	2018 TOTAL VOL (MG)	2018 PEAK INST. FLOW (CFS)
French Brook - MD01	0.11	7.43	66.09	12.82	145.12	426.54	1741	123.18
Gates Brook 1 - MD04	1.23	5.91	41.60	40.27	116.14	283.09	1395	93.00
Malagasco Brook - MD02	0.00	1.49	6.17	3.01	29.00	80.65	348	9.39
Malden Brook - MD06	0.84	5.09	21.93	24.04	99.74	274.92	1197	42.99
Muddy Brook - MD03	0.09	1.90	11.11	6.21	37.05	89.77	445	19.97
Quinapoxet River (Canada Mills) - MD69	5.99	101.99	670.00	272.49	2,005.05	5,398.04	24,061	995.00
Stillwater River - Muddy Pond Rd - MD07	1.28*	82.46	559.00	174.71	1,621.12	4,139.66	19,452	819.00
Waushacum Brook (Prescott) - MD83	0.58	17.33	63.20	31.45	339.30	862.77	4072	95.19
West Boylston Brook - MD05	0.06	0.82	16.75	3.61	15.96	58.75	192	61.83
Ungauged Areas	NA	NA	NA	NA	NA	NA	7,145**	NA
Quabbin Transfer – MDS1	NA	NA	NA	NA	NA	NA	35,572	NA
Trout Brook - M110	ND	ND	ND	ND	ND	ND	3,387**	NA

* Estimated flow (USGS) – likely erroneous

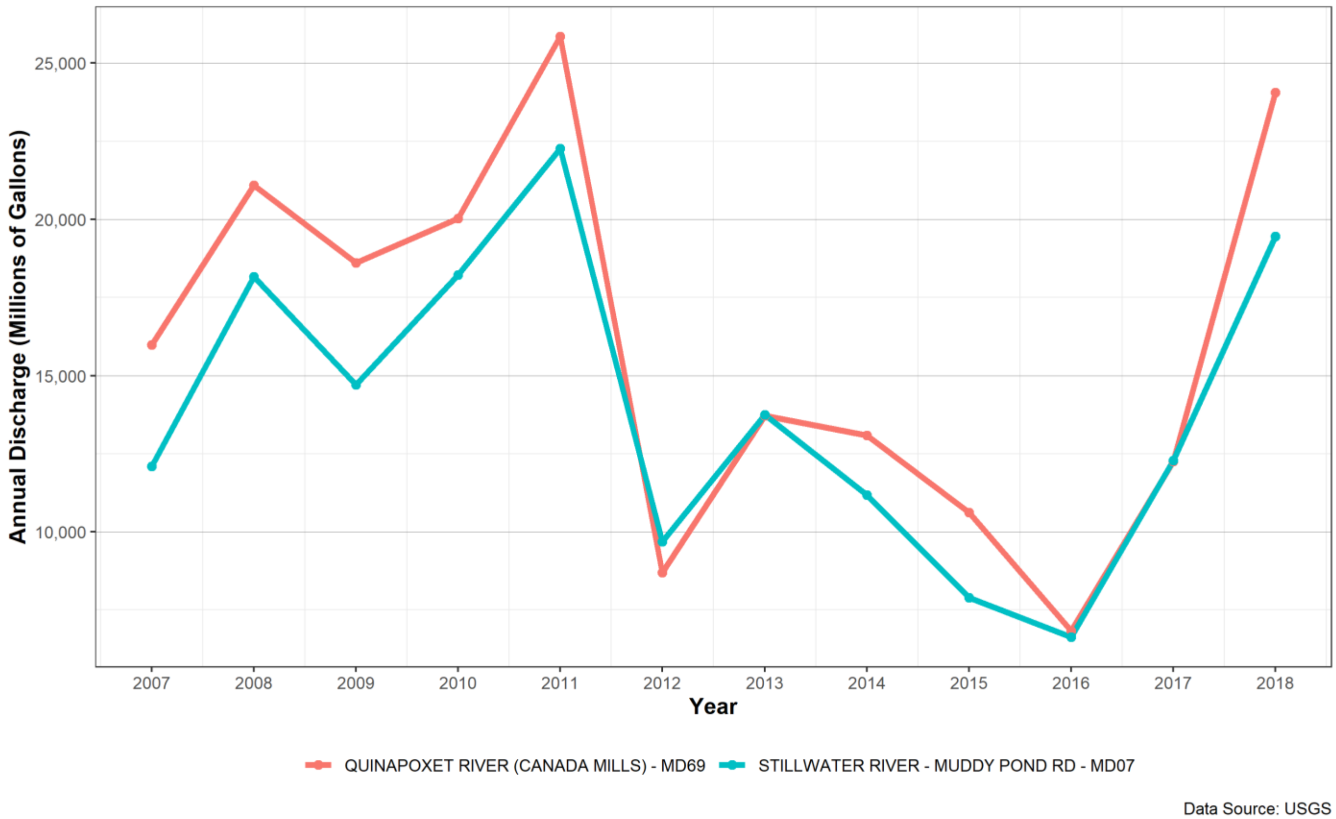
** Estimated (DWSP)

ND = No Data; NA = Not applicable

No annual statistics for Trout Brook were calculated because flow information only covers a portion of the year. The following figures for the two largest tributaries (Stillwater River and Quinapoxet River) provide historical context for the observed flows of 2018.

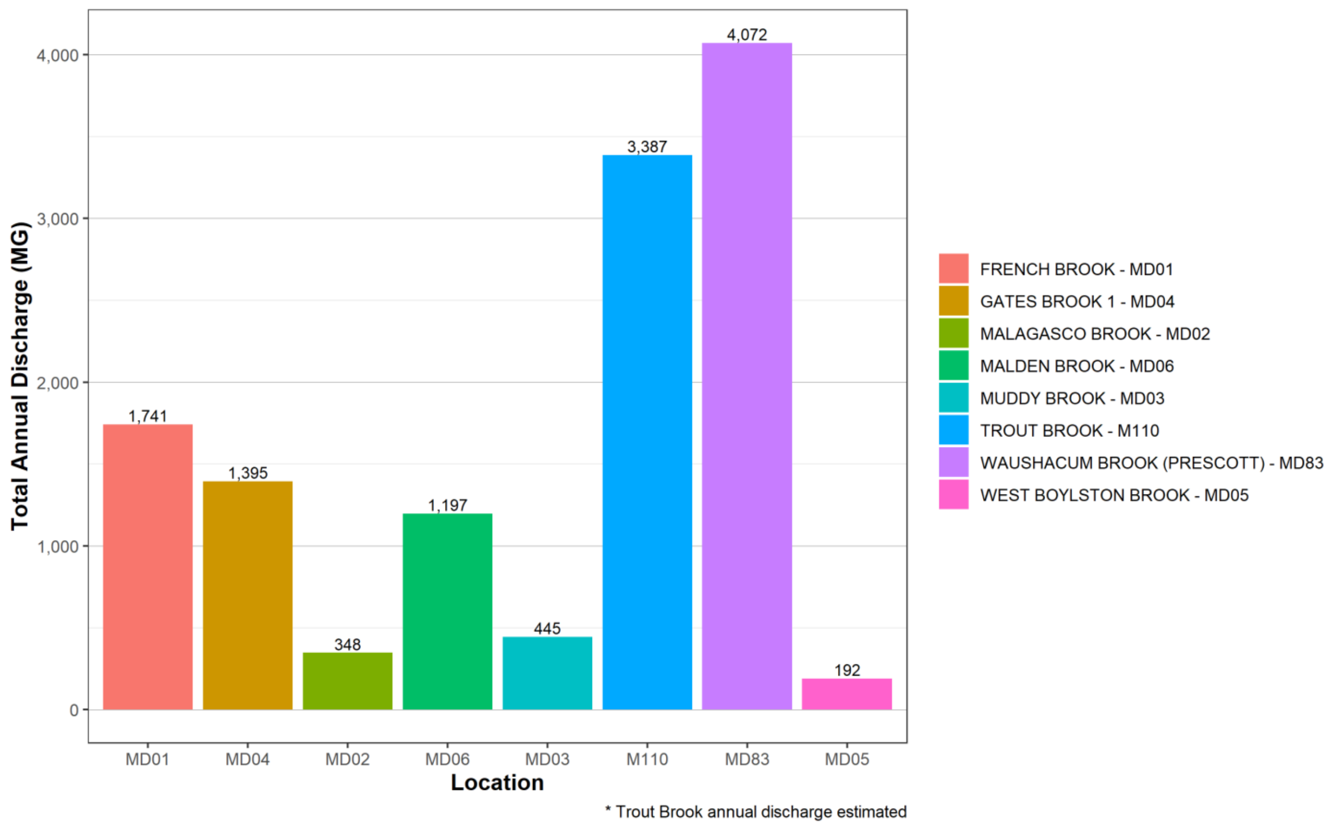
Total annual discharges for the Quinapoxet and Stillwater Rivers for 2018 were the second highest since 2007, only exceeded in 2011 when annual precipitation also topped 60 inches (**Figure 10**).

Figure 10. Annual Discharge in the Quinapoxet and Stillwater Rivers (MG) (2007 - 2018)



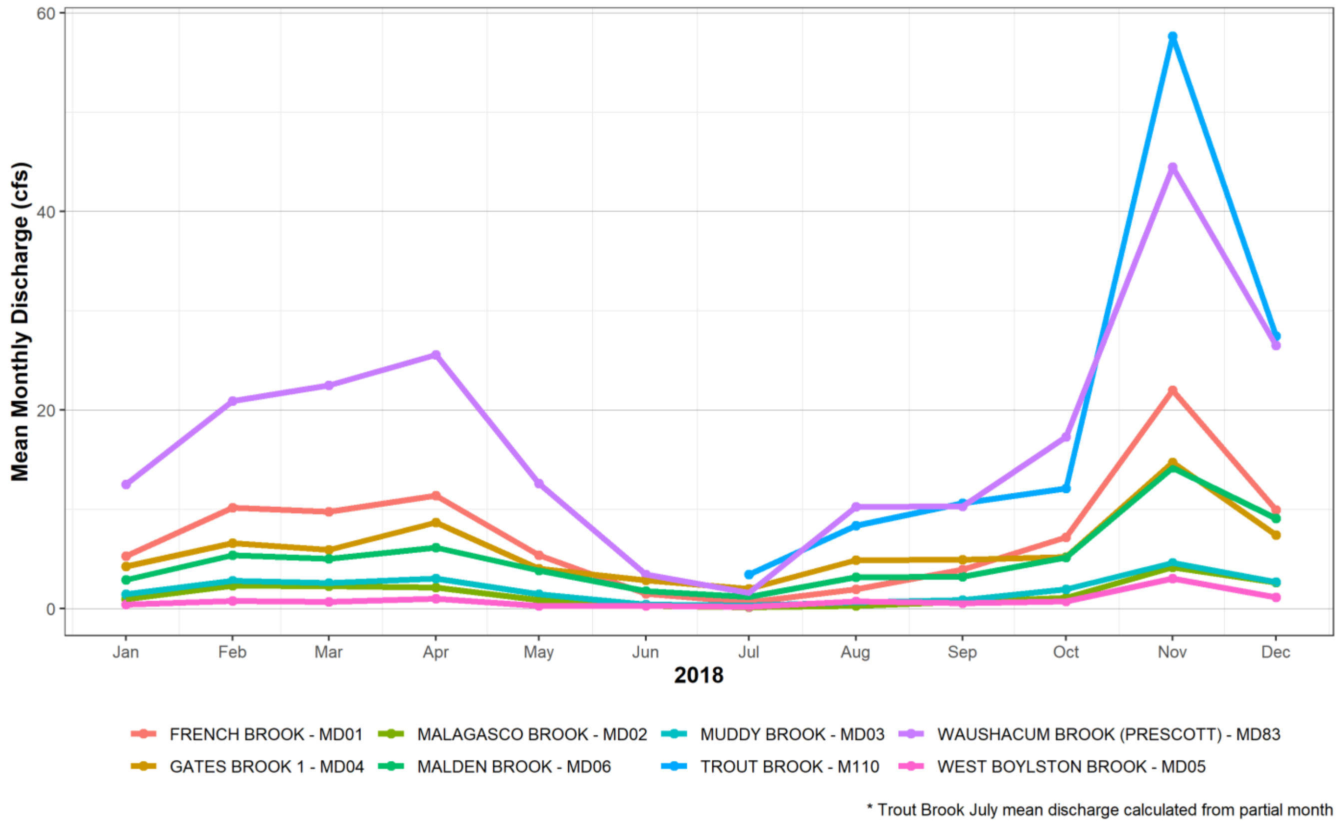
The annual discharge totals for the smaller tributaries are presented in **Figure 11**. 2018 was the first complete year for continuous discharge measurements at smaller tributaries, so no annual discharge comparisons can be made to prior years. Waushacum Brook contributed the largest water volume to the Wachusett Reservoir of the smaller tributaries (~ 4%). The Trout Brook discharge monitoring station was re-installed in July 2018, so the annual total was calculated using estimated flows for January - July.

Figure 11. Annual Discharge in Smaller Wachusett Tributaries for 2018



The mean monthly flows illustrate the fluctuations in flow throughout the year (**Figure 12)**. Typically, tributary flows are highest in spring with a receding snowpack and prior to the growing season. However, for 2018, flows were highest in November as Spring snowpack was minimal and late summer though fall precipitation was much higher than normal, with 14 inches of surplus precipitation falling between July and December.

Figure 12. Mean Monthly Discharge in Smaller Wachusett Tributaries (cfs) in 2018



2018 monthly flows in the Stillwater and Quinapoxet Rivers were seasonally normal until September, after which monthly flows were much higher than usual, with almost five times normal flow volumes observed for the month of November.

Figure 13. Monthly Discharge in the Quinapoxet River (MG) 2018

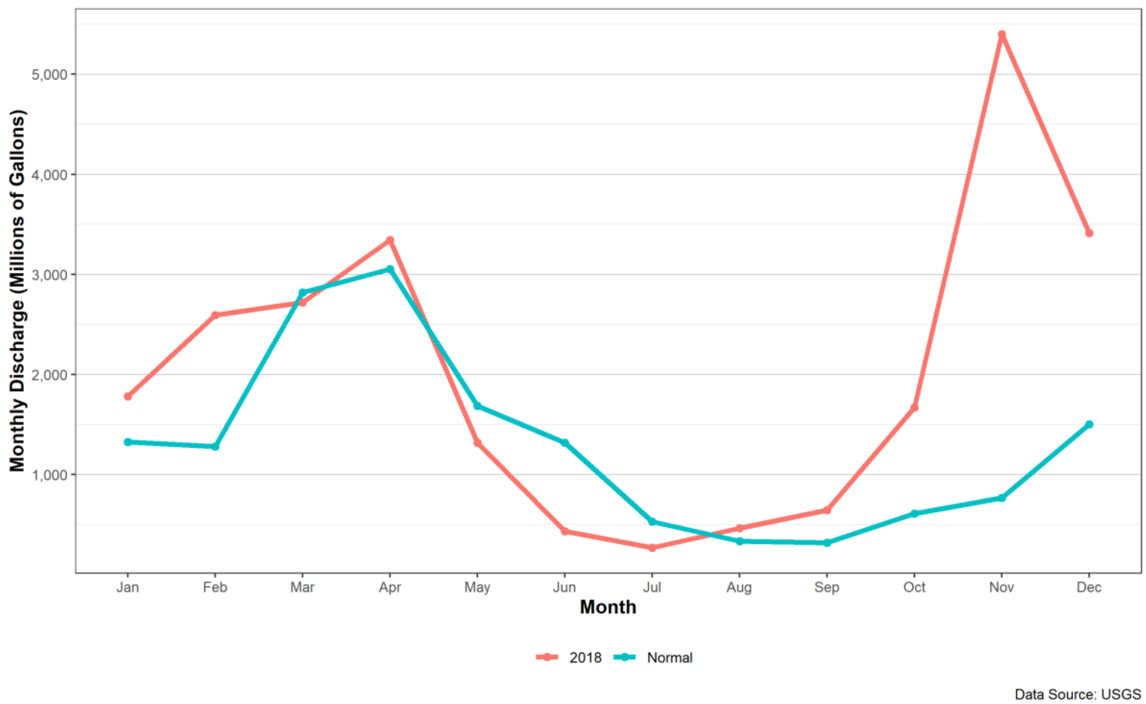
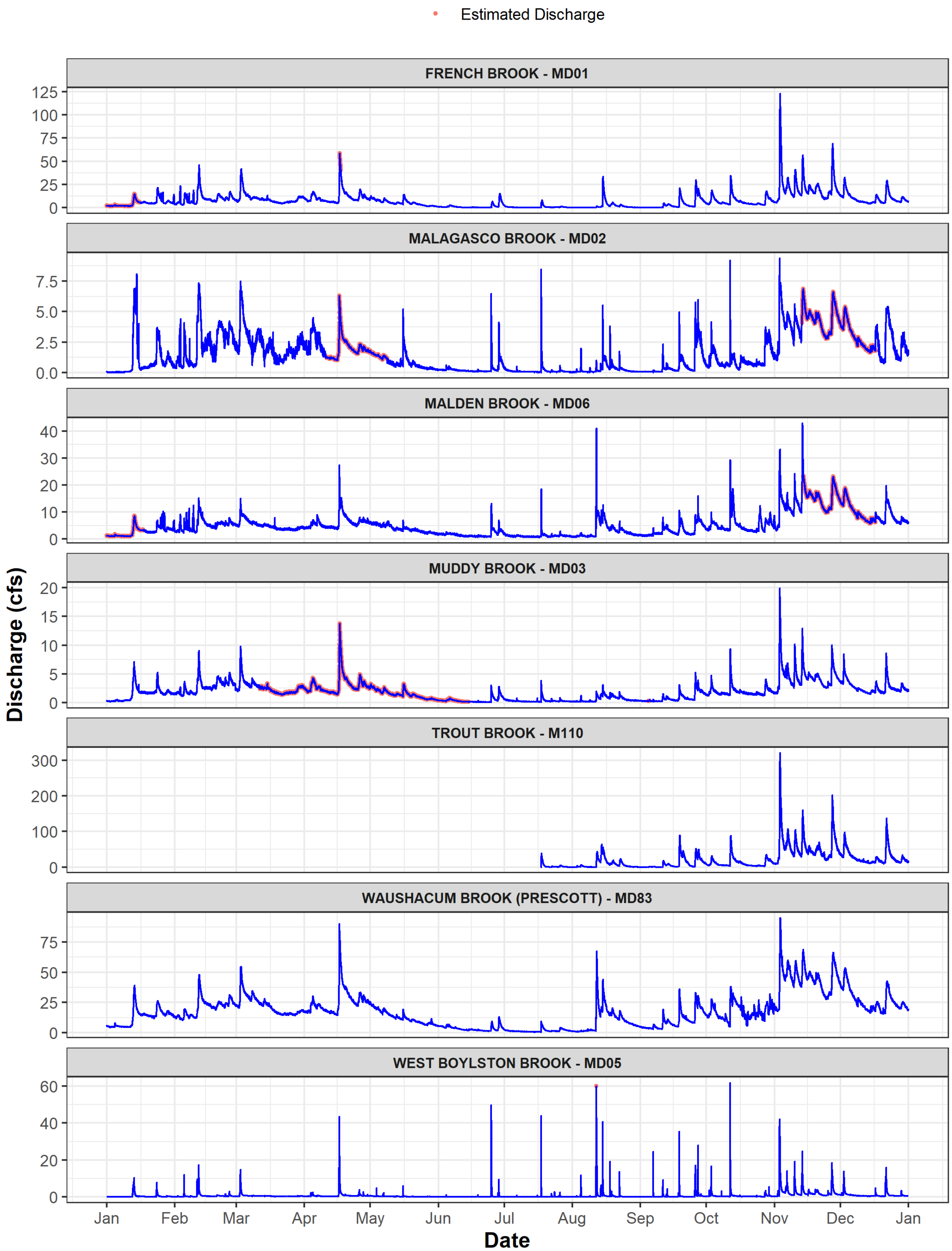


Figure 14. Monthly Discharge for the Stillwater River (MG) in 2018

Complete hydrographs for the smaller tributaries are provided in **Figure 15**.

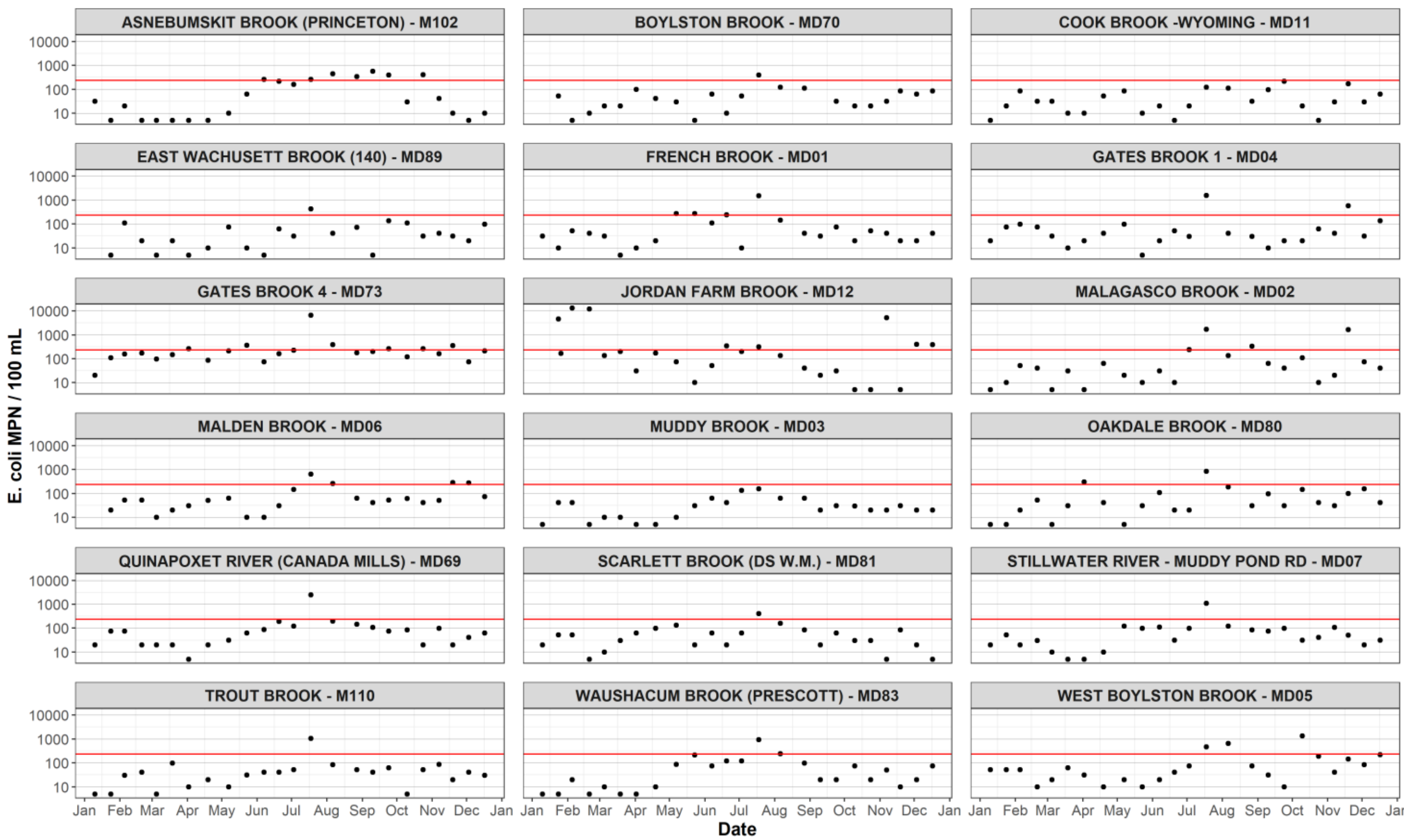
Figure 15. 2018 Hydrographs for DWSP Flow Monitored Tributaries



3.2 BACTERIA

The Massachusetts Class A surface water quality standards (314 CMR 4.05(3)(a)4.c) utilize *E. coli* as an indicator organism for sanitary quality of non-intake waters. The statutory limits are "a geometric mean not to exceed 126 *E. coli* colonies per 100 mL and with no single sample to exceed 235 colonies per 100 mL"[9]. The geometric mean standard was exceeded in 2018 at Gates Brook 4 and Jordan Farm Brook (**Table 5** and **Figure 17**). These stations have known sources of bacteria; avian wildlife and farming operations, respectively. There were only two stations that did not exceed the single sample limit of 235 MPN/100 mL[10] in 2018: Muddy Brook and Cook Brook (**Table 5** and **Figure 16**). It is very difficult for tributary water quality to meet the single sample standard, even in those with undeveloped watersheds. There can be dramatic fluctuations in bacteria concentrations due to precipitation events and variable flow conditions even without human-related sources of contamination.

Figure 16. 2018 Bacteria Concentrations for Wachusett Tributaries



*Red line is Class A surface water quality standard: 235 MPN/100 mL (Single sample)

[9] Mass. Gen. Laws ch. 21, § 27. Massachusetts Surface Water Quality Standards (314 CMR 4.05).

[10] MPN stands for "most probable number", which is a statistical probability of the number of organisms, not an actual count of coliform forming units, which are abbreviated "CFU".

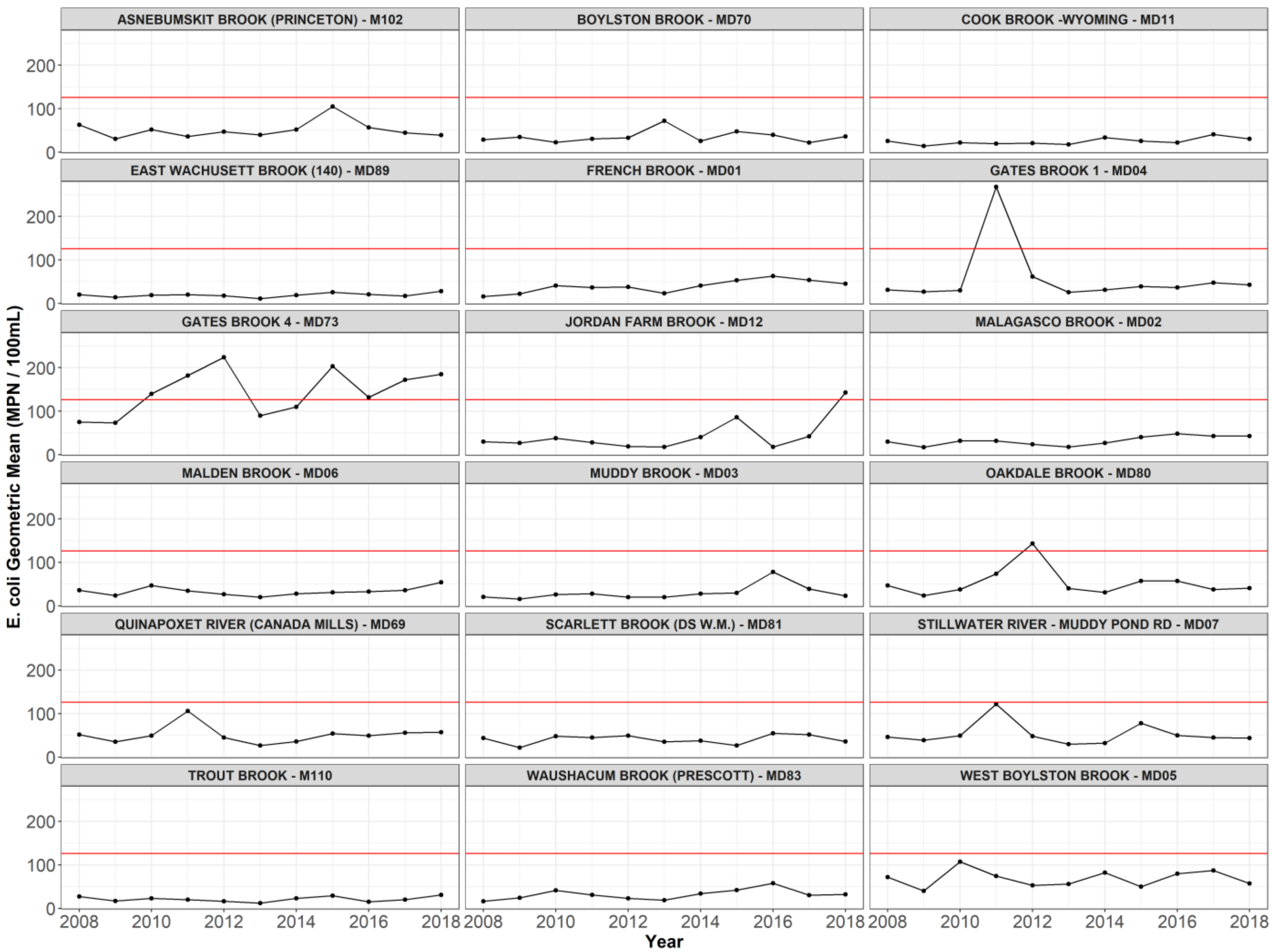
Table 5. Annual E. Coli geometric mean at Wachusett Tributaries

LOCATION	GMEAN 2015	GMEAN 2016	GMEAN 2017	GMEAN 2018	%>235 2015	%>235 2016	%>235 2017	%>235 2018
Asnebumskit Brook (Princeton) - M102	105	57	45	39	38	27	12	29
Boylston Brook - MD70	48	40	22	36	19	16	2	4
Cook Brook -Wyoming - MD11	26	22	41	31	16	0	12	0
East Wachusett Brook (140) - MD89	26	21	17	28	15	4	4	4
French Brook - MD01	53	63	54	45	15	21	14	17
Gates Brook 1 - MD04	39	37	48	43	15	10	10	8
Gates Brook 4 - MD73	203	132	172	185	40	24	45	29
Jordan Farm Brook - MD12	86	18	42	143	35	7	9	33
Malagasco Brook - MD02	40	48	43	43	14	10	14	17
Malden Brook- MD06	31	33	36	54	7	6	4	17
Muddy Brook- MD03	30	78	39	23	0	26	4	0
Oakdale Brook- MD80	57	57	38	41	10	20	16	8
Quinapoxet River (Canada Mills) - MD69	54	49	56	57	10	12	8	4
Scarlett Brook (DS W.M.) - MD81	27	55	52	36	14	16	14	4
Stillwater River - Muddy Pond Rd - MD07	78	50	45	44	21	12	12	4
Trout Brook- M110	29	15	20	31	19	0	2	4
Waushacum Brook (Prescott) - MD83	42	58	30	32	10	28	2	8
West Boylston Brook- MD05	50	80	87	57	17	24	22	12

Bacteria samples collected from the tributary stations during 2018 contained a wide range of *E. coli* concentrations, from less than 10 MPN/100 mL in approximately 20 percent of all samples to a high of 13,000 at Jordan Farm Brook. As in previous years, most of the highest concentrations were recorded during or following rain events of 0.20" or more. Eleven of the 13 samples that exceeded 1,000 MPN/100mL were collected during or immediately following wet weather (> 0.20 inches within 24 hours of sample). The only two dry weather samples that exceeded 1,000 MPN/100 mL were collected from Jordan Farm Brook in February and West Boylston Brook in October.

Annual geometric mean concentrations of *E. coli* over the past 10 years (**Figure 17**) do not show a clear and uniform trend although there are some indications that water quality may be declining in certain tributaries. Trout Brook, Malden Brook, Gates Brook 4, Jordan Farm Brook, and Malagasco Brook all had annual geometric means for 2018 that were at least 10 MPN/100 mL higher than the 10-year average. However, this could be true in any given year and then a subsequent year might be lower than the historical average. Several locations had geometric means more than 5 MPN/100mL higher than the five-year average (**Figure 17**, footnote 1) as well as more than 5 MPN/100mL below the five-year average (**Figure 17**, footnote 2). Four locations had the highest annual geometric mean ever recorded at their respective locations in 2018: East Wachusett Brook, Jordan Farm Brook, Malden Brook, and Trout Brook.

Figure 17. Annual Bacteria Geometric Mean in Wachusett Tributaries



*Red line is Class A surface water quality standard: 126 MPN/100 mL (Geometric Mean)

1. 2018 geometric mean > 5 MPN/100mL above 5-year average: East Wachusett Brook, Jordan Farm Brook, Gates 4, Malden Brook, Quinapoxet River, Trout Brook.
2. 2018 geometric mean > 5 MPN/100mL under 5-year average: Asnebumskit Brook, French Brook, Muddy Brook, Scarlet Brook, Stillwater River, Waushacum Brook, West Boylston Brook

In 2018, wet weather samples continued to contain much more bacteria than dry weather samples, with the exception of Asnebumskit Brook. **Table 6** compares 2018 wet weather and dry weather metrics in Wachusett Watershed tributaries.

Table 6. Wet vs. Dry Weather Bacteria Concentrations

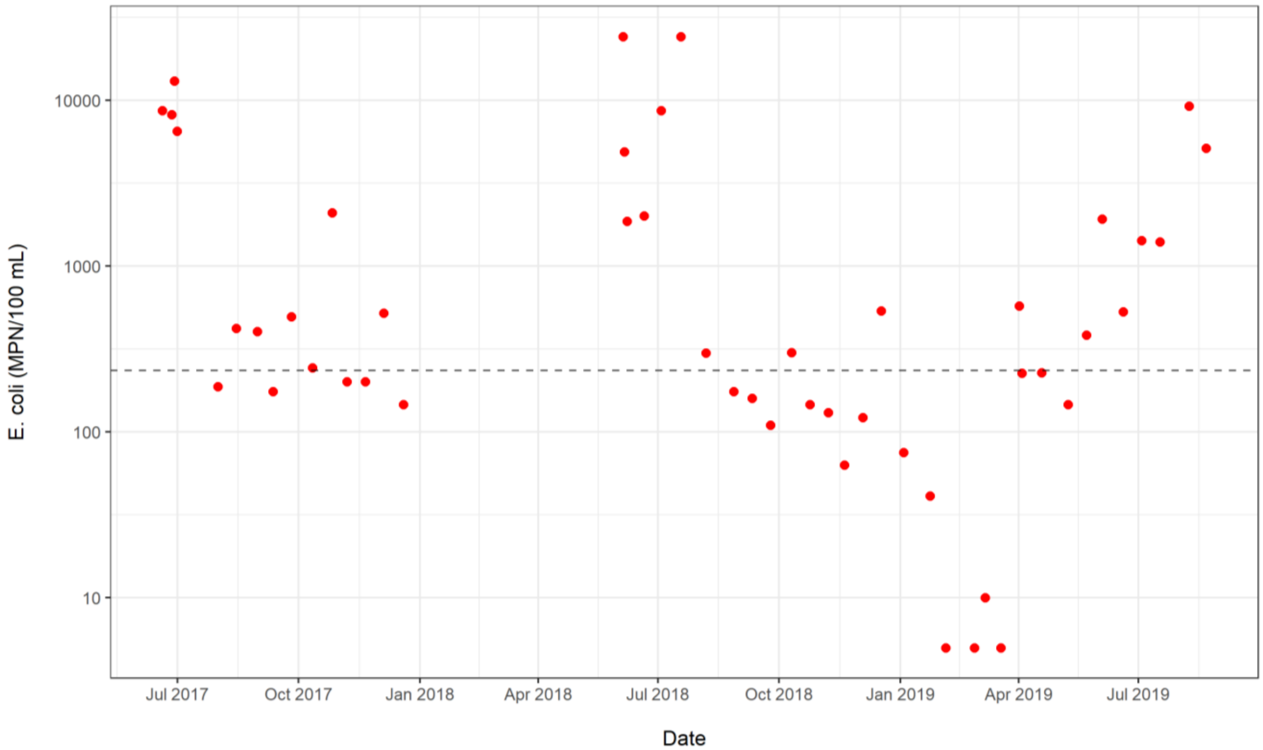
LOCATION	GMEAN DRY	GMEAN WET	% <10 DRY	% <10 WET	% >235 DRY	% >235 WET	COUNT DRY	COUNT WET
Asnebumskit Brook (Princeton) - M102	51	24	33.3	22.2	33.3	22.2	15	9
Boylston Brook - MD70	30	51	7.1	12.5	**0**	12.5	14	8
Cook Brook - Wyoming - MD11	20	63	20	**0**	**0**	**0**	15	9
East Wachusett Brook (140) - MD89	23	39	21.4	22.2	**0**	11.1	14	9
French Brook - MD01	41	55	6.7	**0**	13.3	22.2	15	9
Gates Brook 1- MD04	26	101	6.7	**0**	**0**	22.2	15	9
Gates Brook 4 - MD73	153	253	**0**	**0**	33.3	22.2	15	9
Jordan Farm Brook - MD12	81	364	13.3	11.1	13.3	66.7	15	9
Malagasco Brook - MD02	30	79	20	**0**	13.3	22.2	15	9
Malden Brook- MD06	39	93	**0**	**0**	7.1	33.3	14	9
Muddy Brook- MD03	21	29	26.7	**0**	**0**	**0**	15	9
Oakdale Brook- MD80	39	45	13.3	22.2	6.7	11.1	15	9
Quinapoxet River (Canada Mills) - MD69	45	85	6.7	**0**	**0**	11.1	15	9
Scarlett Brook (DS W.M.) - MD81	36	37	6.7	22.2	**0**	11.1	15	9
Stillwater River - Muddy Pond Rd - MD07	33	69	13.3	**0**	**0**	11.1	15	9
Trout Brook- M110	28	37	20	11.1	**0**	11.1	15	9
Waushacum Brook (Prescott) - MD83	29	37	26.7	11.1	6.7	11.1	15	9
West Boylston Brook- MD05	48	76	**0**	**0**	13.3	11.1	15	9

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

Seasonality is an important driver of trends in annual bacteria dynamics in river systems. Across all tributaries, the geometric mean for summer samples is the highest, followed by fall, then spring, then winter. If the seasonal samples are further split into wet versus dry weather samples, geometric means are highest for wet weather samples within each seasonal group. There are only three individual tributaries which defied this general correlation during 2018: Gates Brook 4, Asnebumskit Brook, and West Boylston Brook. Issues related to bacteria at Asnebumskit Brook were investigated many years ago and discussed in previous annual reports. The bacterial sources previously identified (roosting pigeons, domestic pets (dogs)) are assumed to still be the same in 2018.

Gates Brook 4 has consistently high bacteria measurements which prompted an upstream field investigation in 2017. The bacterial source was successfully traced to the outlet of a stormwater wetland complex adjacent to I-190 on Prospect St. in West Boylston. There were no obvious activities/conditions that were probable bacterial sources, so samples were sent to a lab for genetic analysis. The lab tested for fecal biomarkers of horse, dog, ruminants, human, bird, and beaver. Moderate levels of fecal biomarkers for birds were found. No other animal biomarkers were detected. Subsequent field observations confirmed the presence of birds roosting in large numbers within this wetland complex. Sampling at this location will continue as necessary so that bacteria spikes observed along Gates Brook can be compared to the Prospect St. *E. coli* levels in order to confirm that there is no other frequent bacteria source along this tributary. **Figure 18** presents all sample results at this location.

Figure 18. Bacteria results at Upstream Prospect #1



*Note - The dashed line represents the single sample bacteria standard (235 MPN/100mL)

Fortunately, these bacterial loads do not often survive the downstream journey to Gates Brook 1 and beyond to the Wachusett Reservoir. Therefore, management actions are not being considered since there is no water quality concern for the reservoir and the source is native wildlife.

Jordan Farm Brook drains a small headwaters area northwest of Muschopauge Pond in Rutland. The brook is named after the Jordan Farm Dairy, which has operations situated near an intermittent branch of Jordan Farm Brook. The high bacteria levels frequently measured in Jordan Farm Brook have been directly related to the dairy operations on the farm. The DWSP Environmental Quality section has been working with Jordan Farm as well as the Natural Resource Conservation Service (NRCS) to address the polluted farm runoff. 2018 had the highest median (151 MPN/100 mL) and geometric mean (143 MPN/100 mL) *E. coli* level since 2008. Additional samples will be collected in 2019 to help determine the exact sources and pathways of bacterial loads originating from the farm.

For most other locations, variability in annual geometric mean concentrations cannot be conclusively linked to specific pollution events or sources such as sewer releases, impacts from wildlife or domestic animals, or improper storage of manure because weekly concentrations of bacteria and annual statistics can vary greatly due to fluctuations in water temperature and in the amount, frequency, and timing of precipitation events. Annual variations in flow can also impact annual statistics. It is important to carefully compare yearly data and is usually best to look for longer term trends when assessing water quality rather than the results for a single year.

3.3 NUTRIENTS

In 2018 routine nutrient samples were collected monthly from 11 tributary stations (including Shaft 1), typically during the second week of the month. The parameters for this project include: ammonia-nitrogen (NH_3-N), chloride (Cl), mean UV_{254} (UV_{254}), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), total Kjeldahl nitrogen (TKN), total organic carbon (TOC), total phosphorus (TP), and total suspended solids (TSS). Additional samples were collected to target specific flows that have been historically under sampled (**Table 7**). All samples were analyzed at the MWRA lab on Deer Island. Nutrient measurement units are all mg/L with the exception of UV_{254}, which is reported in ABU/cm. Field parameters are also collected at the same time as nutrient samples in order to provide additional context for interpretation of laboratory results. Field parameters for 2018 included: Water Temperature (C) and Specific Conductance (μS/cm).

Table 7. Additional Flow Targeted Nutrient Samples in 2018

DATE	MD01	MD02	MD04	MD06	MD07	MD69	MD83
2018-01-24							X
2018-02-05							X
2018-08-07	X	X		X	X	X	X
2018-08-28	X	X			X	X	
2018-10-09		X	X		X		
2018-10-25			X				

3.3.1 NITRATE-NITROGEN

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 (particularly to human infants) at very high concentrations (10 mg/L or higher), but have never exceeded these levels 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 NO_3-N concentrations ranged from 0.053 mg/L at Shaft 1 to 1.069 mg/L at West Boylston Brook (**Table 8**), with individual measurements from below detection (< 0.005 mg/L) to 1.41 mg/L in West Boylston Brook. The average annual NO_3-N concentrations at individual tributaries have been stable over the last several years. Although the West Boylston Brook mean NO_3-N concentration for 2018 was the highest among all stations, it was in fact the lowest mean concentration for West Boylston Brook in the last ten years. In 2018, individual samples were predominantly within the historical 25th - 75th percentile ranges by respective tributary. Some notable exceptions include: Waushacum Brook, where seven NO_3-N samples were in excess of the historical 75th percentile concentration; French Brook, where about half of the results were above the historical 75th percentile and half were below the 25th percentile. No high-end outliers were observed for NO_3-N in 2018 (**Figure 19**).

Section 3 boxplots Explained:

1. lower whisker = smallest observation greater than or equal to lower hinge - 1.5 * IQR
2. 25% quantile (lower hinge)
3. median, 50% quantile
4. 75% quantile (upper hinge)
5. upper whisker = largest observation less than or equal to upper hinge + 1.5 * IQR
6. outliers = single observations above upper whisker or below lower whisker

Note: IQR = Interquartile Range (where 50% of observations fall; 25^{th} – 75^{th} percentile)

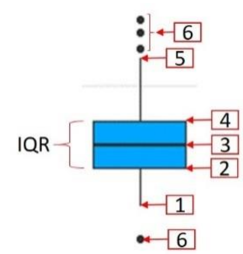
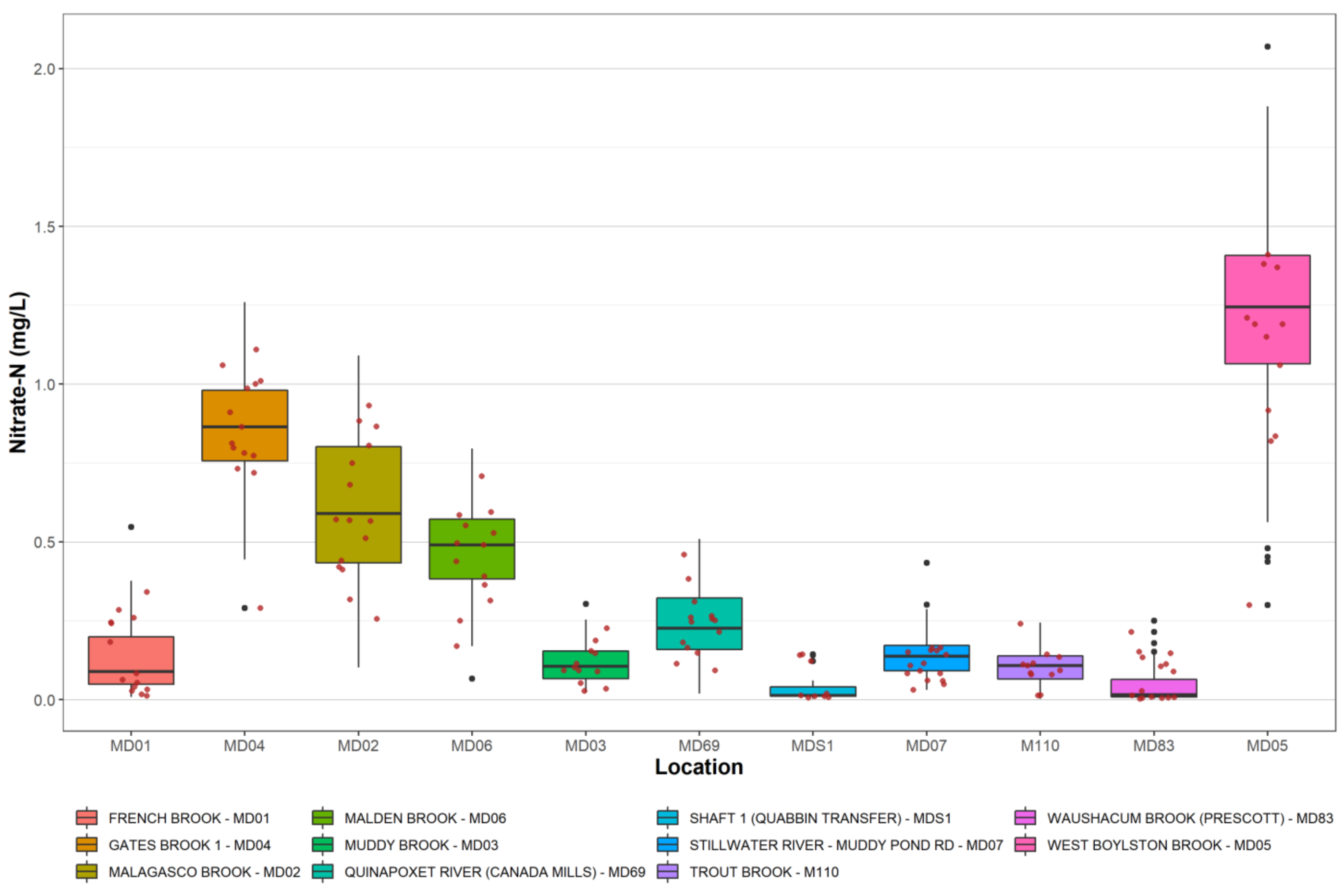


Table 8. Nitrate-Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

LOCATION | YEAR→	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
French Brook - MD01	0.10	0.14	0.15	0.13	0.16	0.17	0.09	0.15	0.11	0.13
Gates Brook 1 - MD04	1.03	1.01	0.93	0.80	0.92	0.86	0.79	0.76	0.92	0.85
Malagasco Brook - MD02	0.50	0.63	0.43	0.49	0.68	0.58	0.70	0.61	0.68	0.60
Malden Brook - MD06	0.40	0.47	ND	0.43	0.55	0.44	0.53	0.44	0.49	0.45
Muddy Brook - MD03	0.07	0.10	0.09	0.10	0.14	0.14	0.13	0.14	0.11	0.11
Quinapoxet River (Canada Mills) - MD69	0.20	0.26	0.18	0.22	0.25	0.25	0.29	0.21	0.32	0.24
Shaft 1 (Quabbin Transfer) - MDS1	ND	ND	ND	ND	ND	ND	ND	ND	0.02	0.05
Stillwater River - Muddy Pond Rd - MD07	0.12	0.16	0.16	0.14	0.16	0.14	0.15	0.12	0.13	0.11
Trout Brook - M110	ND	ND	ND	ND	ND	ND	0.11	0.10	0.10	0.10
Waushacum Brook (Prescott) - MD83	ND	ND	ND	0.04	0.04	0.04	0.05	0.02	0.03	0.07
West Boylston Brook - MD05	1.25	1.57	1.09	1.17	1.39	1.14	1.25	1.20	1.28	1.07

* ND = No Data

Figure 19. 2018 Nitrate-Nitrogen Concentrations vs. 2009 - 2018 Statistics



*Red points are results from 2018; Shaft 1 (MDS1) statistics derived from 2017-2018 samples

3.3.2 AMMONIA-NITROGEN

Ammonia is very soluble in water, highly reactive, and toxic to aquatic life (at chronic durations) at levels in excess of 1.9 mg/L[11]. There are no action levels or maximum contaminant levels (MCLs) for drinking water designated by any statutes, however World Health Organizations guidelines on drinking water quality list odor and taste thresholds of 1.5 and 1.9 mg/L respectively [12] . Probable sources of ammonia in the Wachusett watershed include septic systems, landfill leachate, agriculture (from fertilizer and livestock), atmospheric deposition, and natural biological processes.

In 2018, ammonia-nitrogen was detected at all tributaries at very low concentrations with a high of 0.153 at Muddy Brook. Apart from French Brook in 2010, Muddy Brook has consistently had the highest mean annual concentration of NH_3-N, with the highest in the previous ten years occurring in 2018 (0.086 mg/L). The Muddy Brook sample location is immediately downgradient to a closed landfill, which is the likely source of increased NH_3-N. Due to the high number of non-detection lab results (<0.005 mg/L) the statistics presented (**Table 9**) for ammonia-N have an inherent high level of uncertainty. Individual sample concentrations were mostly within historical 25th - 75th percentile ranges at each tributary, notwithstanding seven high outlier samples occurring across a few locations.

Although Wachusett NH_3-N levels are not a water quality concern for any designated use, the DWSP continues to monitor this parameter because it is useful for detecting contamination from high priority water quality threats such as septic systems, sewer leaks and agricultural operations.

Table 9. Ammonia-Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

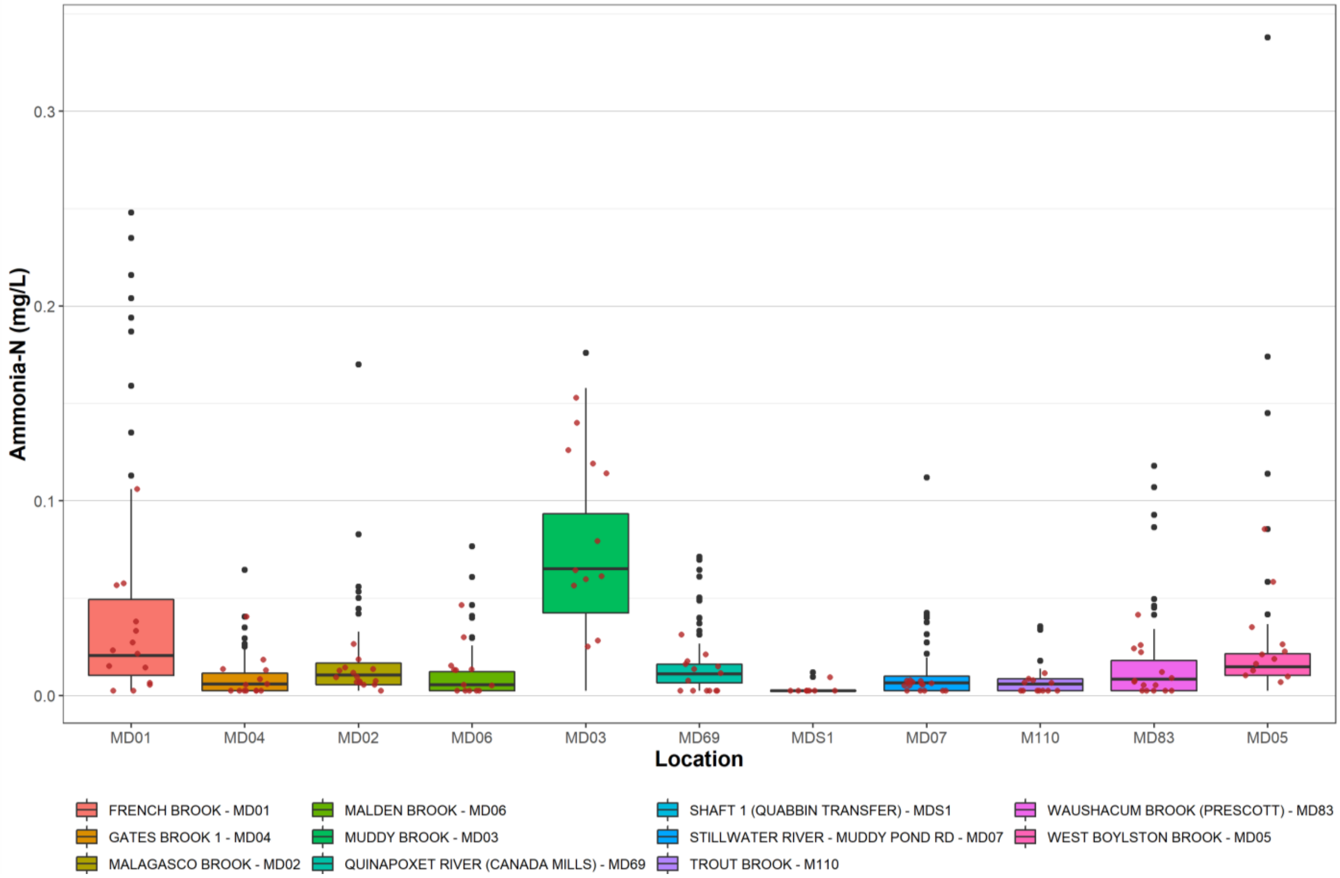
LOCATION | YEAR→	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
French Brook - MD01	0.068	0.120	0.039	0.045	0.051	0.034	0.041	0.018	0.011	0.029
Gates Brook 1 - MD04	0.005	0.004	0.005	0.007	0.008	0.014	0.012	0.013	0.008	0.009
Malagasco Brook - MD02	0.018	0.010	0.016	0.014	0.013	0.015	0.029	0.012	0.014	0.011
Malden Brook - MD06	0.017	0.010	ND	0.011	0.006	0.009	0.016	0.005	0.005	0.012
Muddy Brook - MD03	0.077	0.061	0.066	0.069	0.065	0.067	0.076	0.060	0.078	0.086
Quinapoxet River (Canada Mills) - MD69	0.015	0.014	0.015	0.012	0.012	0.017	0.021	0.010	0.015	0.011
Shaft 1 (Quabbin Transfer) - MDS1	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.003
Stillwater River - Muddy Pond Rd - MD07	0.015	0.010	0.010	0.008	0.008	0.012	0.011	0.006	0.006	0.005
Trout Brook - M110	ND	ND	ND	ND	ND	ND	ND	0.006	0.008	0.005
Waushacum Brook (Prescott) - MD83	ND	ND	ND	ND	0.014	0.025	0.023	0.010	0.012	0.012
West Boylston Brook - MD05	0.015	0.012	0.022	0.013	0.014	0.049	0.021	0.016	0.037	0.027

* ND = No Data

[11] US Environmental Protection Agency. "Aquatic Life Ambient Water Quality Criteria for Ammonia - Freshwater." Document ID: EPA-822-R-13-001. April 2013.

[12] Guidelines for drinking-water quality, 2nd ed. Vol. 2. Health criteria and other supporting information. World Health Organization, Geneva, 1996.

Figure 20. 2018 Ammonia-Nitrogen Concentrations vs. 2009 - 2018 Statistics



*Red points are results from 2018; Shaft 1 (MDS1) statistics derived from 2017-2018 samples

3.3.3 TOTAL KJELDAHL NITROGEN

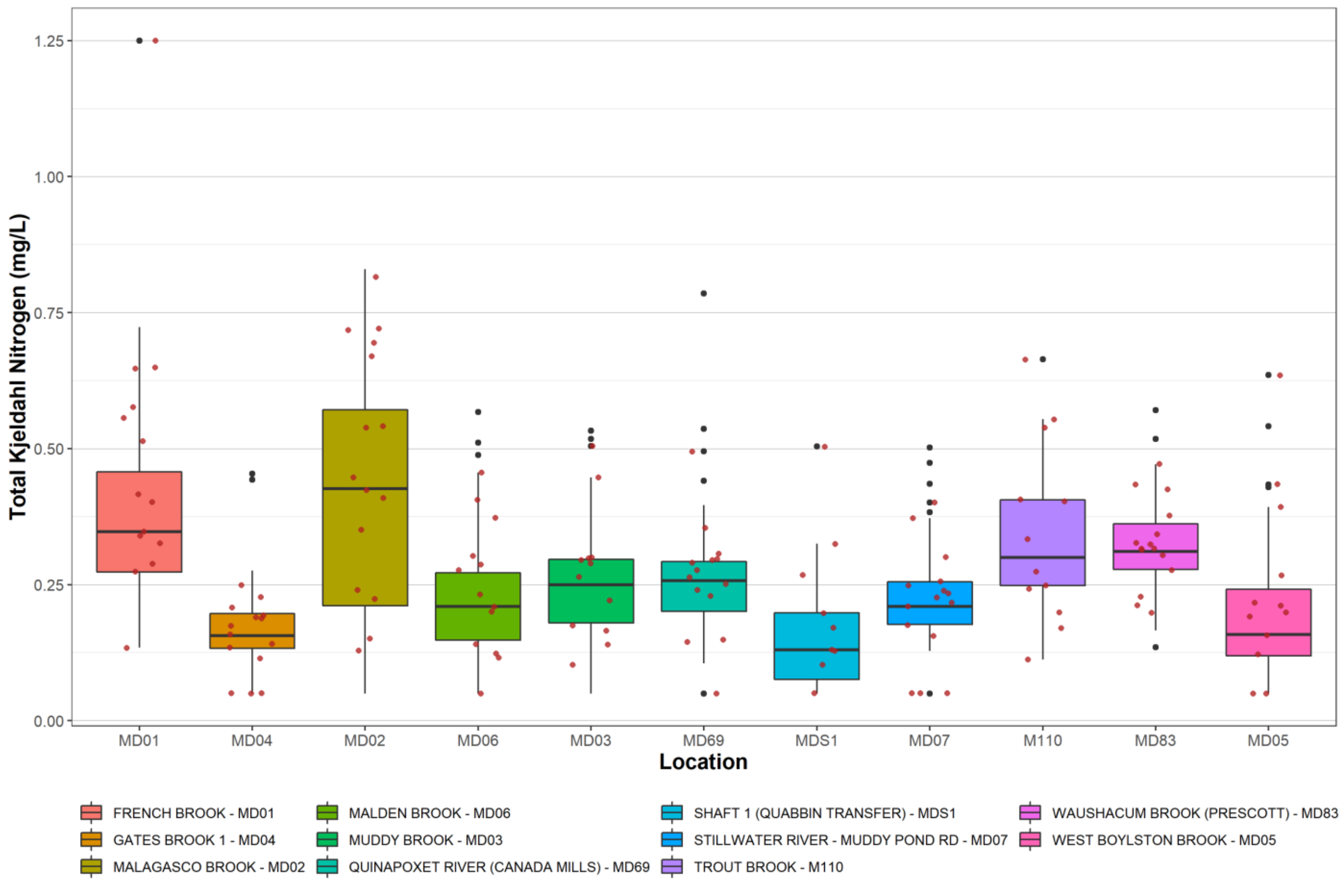
Total Kjeldahl nitrogen analysis began in 2015 in order to account for organic sources of tributary nitrogen. Annual mean concentrations have been relatively consistent for these years, ranging from 0.10 mg/L at Shaft 1 to 0.48 mg/L at French Brook in 2018. Individual TKN concentrations have been as high as 1.25 mg/L which occurred in 2018 at French Brook. This TKN sample occurred during dry weather and no other samples have exceeded 0.90 mg/L since this parameter has been evaluated.

Table 10. Total Kjeldahl Nitrogen Annual Mean Concentrations at Wachusett tributaries (mg/L)

LOCATION | YEAR→	2015	2016	2017	2018
French Brook - MD01	0.39	0.36	0.36	0.48
Gates Brook 1 - MD04	0.15	0.21	0.15	0.15
Malagasco Brook - MD02	0.35	0.34	0.46	0.47
Malden Brook - MD06	0.23	0.22	0.20	0.24
Muddy Brook - MD03	0.25	0.23	0.27	0.27
Quinapoxet River (Canada Mills) - MD69	0.29	0.29	0.25	0.26
Shaft 1 (Quabbin Transfer) - MDS1	ND	ND	0.10	0.21
Stillwater River - Muddy Pond Rd - MD07	0.21	0.27	0.22	0.21
Trout Brook - M110	0.26	0.31	0.35	0.34
Waushacum Brook (Prescott) - MD83	0.28	0.36	0.30	0.32
West Boylston Brook - MD05	0.17	0.19	0.17	0.24

* ND = No Data

Figure 21. 2018 Total Kjeldahl Nitrogen Concentrations vs. 2015 - 2018 Statistics



*Red points are results from 2018; Shaft 1 (MDS1) statistics derived from 2017-2018 samples

3.3.4 NITRITE-NITROGEN

Nitrite-nitrogen is rarely detected in Wachusett Reservoir tributaries. The highest recorded (routine sample) concentration was 0.0076 mg/L in 2018, with only four of the samples collected in 2018 falling above the detection limit of 0.005 mg/L.

3.3.5 TOTAL NITROGEN

Total nitrogen (TN), as measured in water, is the sum of TKN and nitrogen from nitrate and nitrite. This calculated parameter is important to examine in conjunction with total phosphorus because the ratio of nitrogen to phosphorus in aqueous systems has direct implications for the ecology and drinking water quality of a water body. Annual mean TN concentrations have been calculated each year since 2015, when routine TKN analysis began (**Table 11**). Since then annual mean concentrations have never exceeded 1.5 mg/L and only three tributaries have ever had mean annual TN concentrations in excess of 1 mg/L: Gates Brook 1, Malagasco Brook, and West Boylston Brook. Nitrogen levels of this magnitude are not a concern for any fresh water designated use.

Table 11. Total Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

LOCATION | YEAR→	2015	2016	2017	2018
French Brook - MD01	0.49	0.51	0.47	0.62
Gates Brook 1 - MD04	0.94	0.97	1.07	1.00
Malagasco Brook - MD02	1.06	0.96	1.15	1.07
Malden Brook - MD06	0.77	0.66	0.69	0.70
Muddy Brook - MD03	0.39	0.37	0.38	0.38
Quinapoxet River (Canada Mills) - MD69	0.58	0.50	0.57	0.50
Shaft 1 (Quabbin Transfer) - MDS1	ND	ND	0.12	0.26
Stillwater River - Muddy Pond Rd - MD07	0.36	0.39	0.36	0.32
Trout Brook - M110	0.45	0.41	0.45	0.45
Waushacum Brook (Prescott) - MD83	0.34	0.38	0.34	0.40
West Boylston Brook - MD05	1.43	1.39	1.46	1.32

* ND = No Data

3.3.6 TOTAL PHOSPHORUS

Phosphorus is an important nutrient, and the limiting factor controlling algal productivity in Wachusett Reservoir. Sources of phosphorus include fertilizers, manure, and organic wastes in sewage. Water Quality Criteria established by the EPA recommend a concentration of no more than 0.05 mg/L of TP in tributary streams in order to prevent accelerated eutrophication of receiving water bodies. Concentrations measured in ten Wachusett tributaries and at Shaft 1 during 2018 ranged from less than 0.005 mg/L (detection limit) to 0.106 mg/L, with annual mean concentrations from 0.013 mg/L to 0.036 mg/L (**Table 12**). All annual mean TP concentrations were comparable to the previous nine years. Only eight of the 145 samples collected in 2018 exceeded the recommended maximum concentration of 0.05 mg/L. Four of these samples were taken on August 14, after nearly four inches of rain in the 36 hours preceding the samples. Because phosphorus strongly adsorbs to soil particles, higher TP concentrations are typically observed during storm events when soil particles are eroded off the land and carried to tributaries with surface runoff.

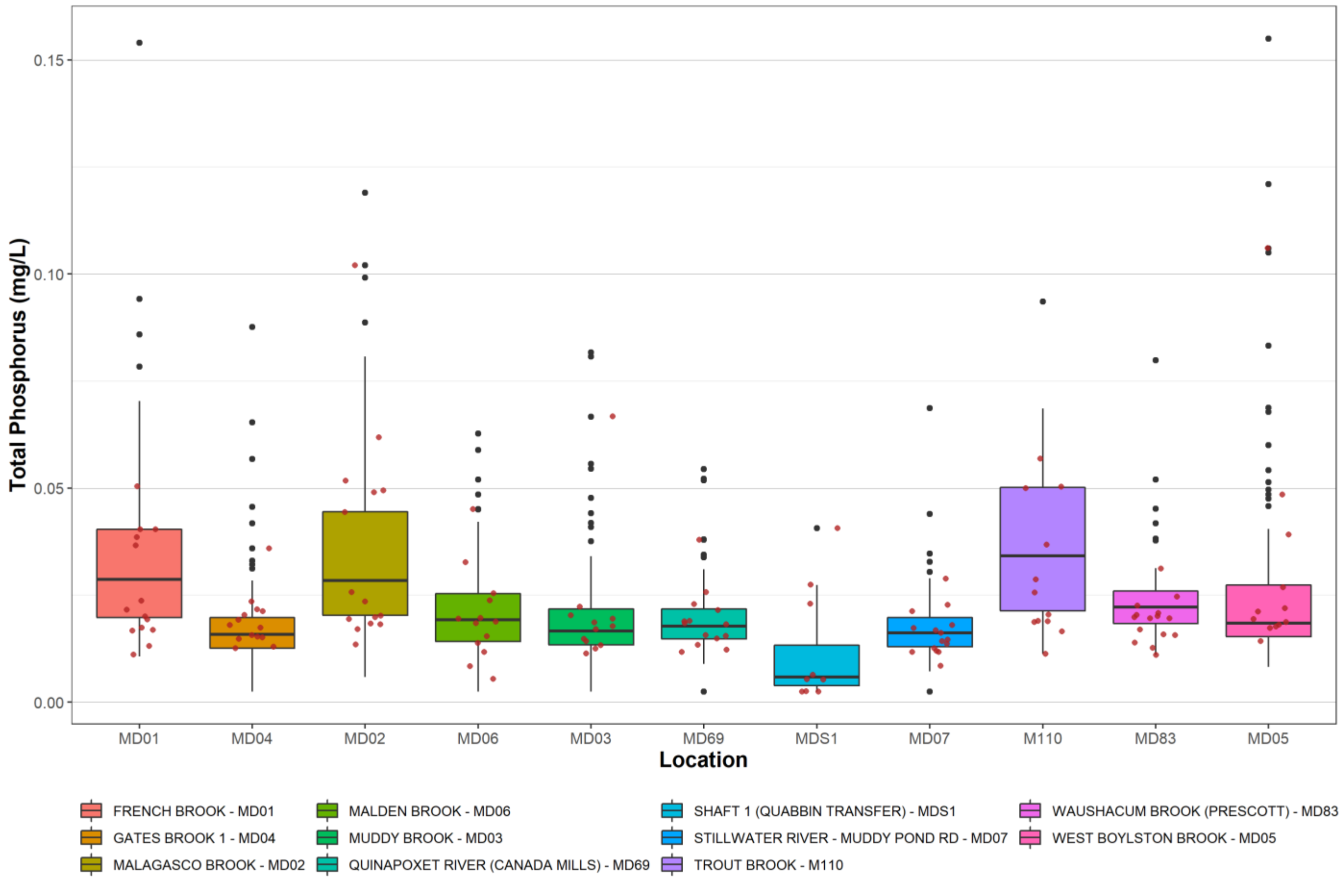
Table 12. Total Phosphorus Annual Mean Concentrations at Wachusett Tributaries (mg/L)

LOCATION | YEAR→	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
French Brook - MD01	0.03	0.06	0.04	0.05	0.03	0.03	0.03	0.03	0.02	0.03
Gates Brook 1 - MD04	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02
Malagasco Brook - MD02	0.04	0.03	0.04	0.04	0.03	0.03	0.04	0.02	0.04	0.04
Malden Brook - MD06	0.03	0.02	ND	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Muddy Brook - MD03	0.02	0.01	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Quinapoxet River (Canada Mills) - MD69	0.01	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Shaft 1 (Quabbin Transfer) - MDS1	ND	ND	ND	ND	ND	ND	ND	ND	0.01	0.01
Stillwater River - Muddy Pond Rd - MD07	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.02
Trout Brook - M110	ND	ND	ND	ND	ND	ND	0.05	0.04	0.03	0.03
Waushacum Brook (Prescott) - MD83	ND	ND	ND	0.03	0.02	0.02	0.02	0.03	0.02	0.02
West Boylston Brook - MD05	0.02	0.02	0.04	0.04	0.02	0.04	0.02	0.02	0.02	0.03

* ND = No Data

As illustrated in **Figure 22**, TP concentrations in 2018 (red points) were mostly within historical 25th – 75th percentile ranges. Historically, and in 2018, outlier concentrations (above upper whisker) were observed at many of the tributaries as a direct result of stormwater runoff events.

Figure 22. 2018 Total Phosphorus Concentrations vs. 2009 - 2018 Statistics



*Red points are results from 2018; Shaft 1 (MDS1) statistics derived from 2017-2018 samples

3.3.7 TOTAL SUSPENDED SOLIDS

Total suspended solids are those particles suspended in a water sample retained by a filter of 2-µm pore size. These particles may be naturally occurring, the result of human activities, or a combination of these sources. TSS in Wachusett tributaries ranged from less than 5.0 mg/L (detection limit) to 35 mg/L, but only ten of 145 samples contained more than the detection limit, and most were collected during or shortly after a rain event. TSS is not typically considered a parameter of concern in Wachusett Reservoir tributaries, except during storm events when measurements in excess of 100 mg/L can occur. TSS mean concentrations (**Table 13)** for 2018 were consistent with the previous nine years, with no significant trends over time.

Table 13. Total Suspended Solids Annual Mean Concentrations at Wachusett Tributaries (mg/L)

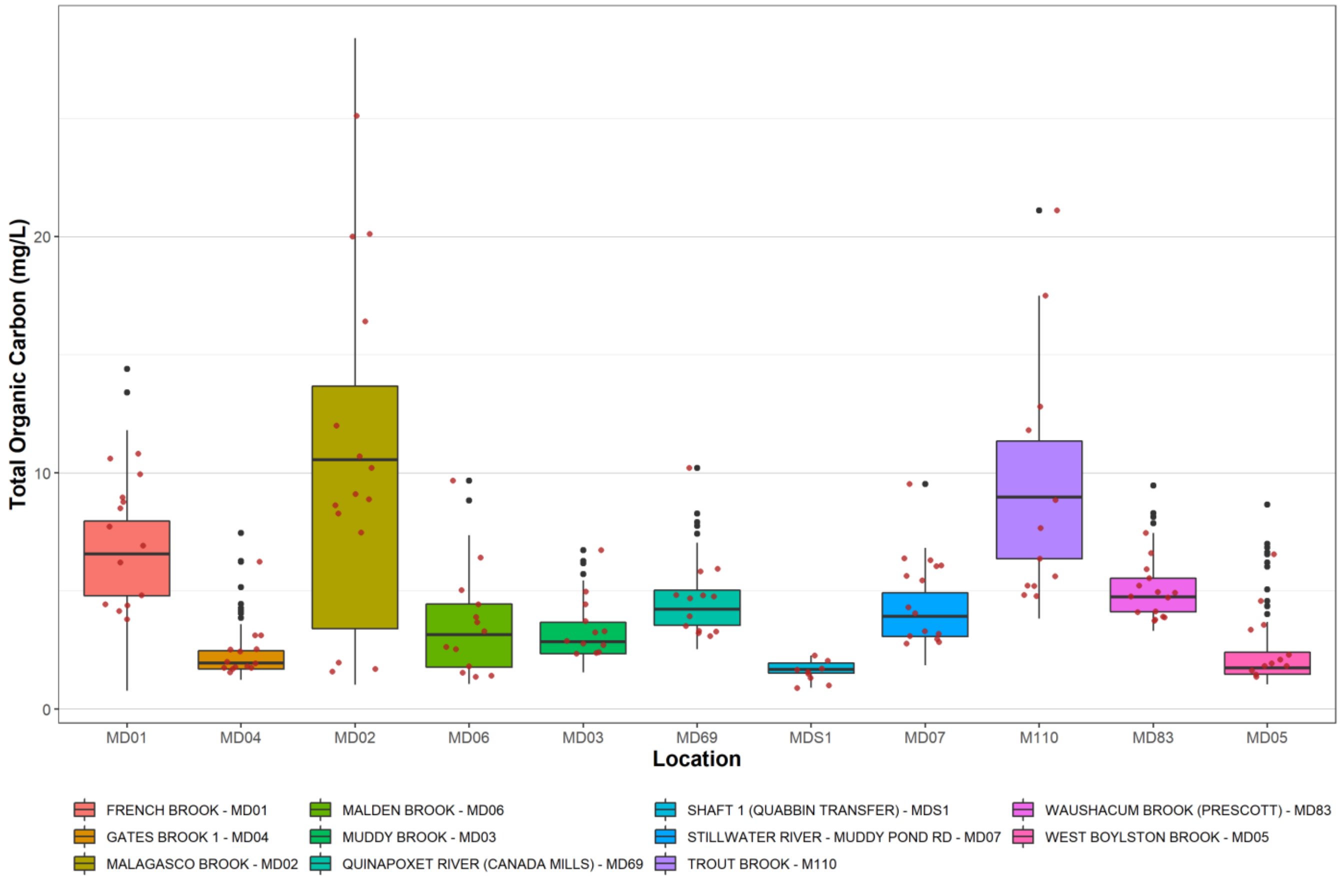
LOCATION | YEAR→	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
French Brook - MD01	4.67	7.00	2.52	9.08	5.80	4.66	3.02	3.84	3.00	4.71
Gates Brook 1 - MD04	2.50	3.47	2.93	3.12	2.23	4.20	2.48	3.25	2.21	2.56
Malagasco Brook - MD02	2.64	4.78	2.94	3.25	4.32	2.83	2.80	3.10	3.58	2.93
Malden Brook - MD06	3.33	3.25	ND	3.42	2.45	3.60	4.27	3.12	2.50	2.77
Muddy Brook - MD03	2.50	3.25	4.43	4.90	4.11	2.82	2.50	6.74	11.99	6.12
Quinapoxet River (Canada Mills) - MD69	2.50	2.97	2.31	3.60	2.77	2.33	2.49	3.12	2.50	2.75
Shaft 1 (Quabbin Transfer) - MDS1	ND	ND	ND	ND	ND	ND	ND	ND	1.75	2.82
Stillwater River - Muddy Pond Rd - MD07	2.50	3.04	2.10	2.62	2.38	2.33	2.50	3.88	2.43	2.49
Trout Brook - M110	ND	ND	ND	ND	ND	ND	2.91	2.94	2.50	2.92
Waushacum Brook (Prescott) - MD83	ND	ND	ND	2.65	3.83	2.44	2.50	2.89	2.43	5.06
West Boylston Brook - MD05	2.50	3.25	8.34	2.92	2.84	9.98	2.49	2.77	4.33	4.88

* ND = No Data

3.3.8 TOTAL ORGANIC CARBON AND MEAN UV_{254}

Total organic carbon and mean UV_{254} measure organic constituents in water and are a useful way to predict precursors of harmful disinfection byproducts. 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. TOC in the tributaries ranged from 0.90 to 25.1 mg/L, with an overall mean of 5.21 mg/L, which is comparable to 2017 levels. The highest concentrations were again recorded from Malagasco and Trout Brooks, with the lowest concentrations from Malden Brook, Gates Brook, and West Boylston Brook. The maximum TOC concentration at Trout Brook in 2018 was the highest ever observed at that location. The source of high carbon loading at Trout Brook is thought to be the Poutwater Pond peat bog, however the DWSP has yet to conduct any TOC analysis on water sampled from the tributary draining the bog. This may be considered in the future. The likely source of carbon in Malagasco Brook is a headwaters wetland that covers a large portion of the subbasin.

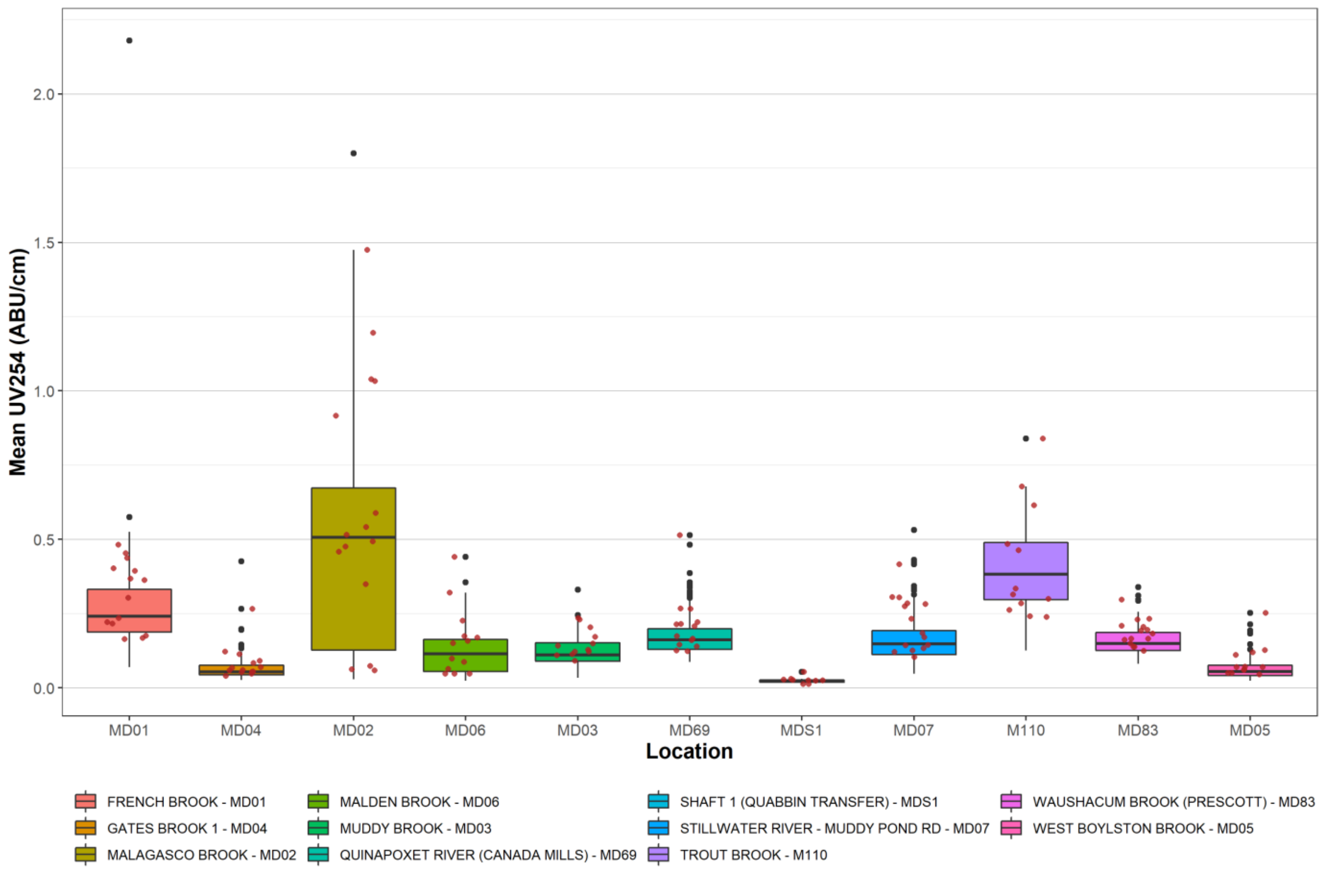
Figure 23. 2018 Total Organic Carbon Concentrations vs. 2009 - 2018 Statistics



*Red points are results from 2018; Shaft 1 (MDS1) statistics derived from 2017-2018 samples

Measurements of UV_{254} demonstrated variability comparable to TOC measurements in tributaries to the Wachusett Reservoir. Organic compounds such as tannins and humic substances absorb UV radiation, thus there is a strong correlation between UV absorption and organic carbon content in natural systems. The highest UV_{254} levels were from Malagasco Brook and Trout Brook, and the lowest were from Malden Brook, Gates Brook, and West Boylston Brook. The maximum UV_{254} at Trout Brook in 2018 was the highest ever observed at that location.

Figure 24. 2018 Mean UV_{254} absorbance vs. 2009 - 2018 Statistics



*Red points are results from 2018; Shaft 1 (MDS1) statistics derived from 2017-2018 samples

3.3.9 NUTRIENT AND SEDIMENT LOADING

Nutrient and sediment load estimates were not calculated for 2018. Alternative models are being explored that will simplify the modeling process and provide a better means to document the model inputs and outputs so that results are transparent and reproducible. It is anticipated that a new modeling framework will be in place in 2020 and loading estimates will again be calculated for the 2019 Annual Water Quality Report.

3.4 SPECIFIC CONDUCTANCE AND DISSOLVED SALTS

Fresh water systems in Massachusetts naturally contain low levels 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 may indicate contamination from stormwater or failing septic systems or can be the result of watershed soil types, which may contribute to degradation of water quality. Specific conductance was measured at least twice per month at all routine tributary sampling stations. Values of less than 100 µS/cm were recorded in 80% of all samples from Trout Brook (20 of 25) and four separate occasions, twice each at Stillwater River and East Wachusett Brook. This represents less than 6% of all specific conductance samples for the year. Measurements greater than 1,000 µS/cm were recorded in 92% of samples from Gates Brook 4, 84% of samples from Gates Brook 1, 79% of samples from Oakdale Brook and 68% of samples from West Boylston Brook. Only five other specific conductance results exceeded 1,000 µS/cm in 2018. Extremely high specific conductance (>1,800 µS/cm) was observed on eight occasions during 2018. As noted in prior reports, median specific conductance values in the more developed subbasins have increased substantially over the last two decades.

Table 14. Specific Conductance Annual Mean Concentrations in Wachusett Tributaries (µS/cm)

LOCATION | YEAR→	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Asnebumskit Brook (Princeton) - M102	243	229	164	195	191	162	175	150	197	183	215	254	336	279	249
Boylston Brook - MD70	417	437	350	339	303	262	268	261	271	278	373	579	542	594	686
Cook Brook - Wyoming - MD11	440	383	341	355	407	337	304	321	378	329	493	475	526	640	624
East Wachusett Brook (140) - MD89	126	117	101	148	111	95	108	89	108	123	133	166	174	171	151
French Brook - MD01	193	254	169	184	155	146	210	154	162	207	227	321	447	364	290
Gates Brook 1- MD04	771	801	635	788	676	682	714	705	616	715	759	942	1081	1272	1211
Gates Brook 4 - MD73	923	893	823	948	891	901	952	888	835	1006	1018	1276	1371	1696	1558
Jordan Farm Brook - MD12	133	123	121	132	139	116	116	129	129	122	128	124	181	175	183
Malagasco Brook - MD02	331	421	341	481	269	237	384	235	292	350	313	447	473	450	432
Malden Brook- MD06	201	187	172	199	223	184	175	192	192	199	220	288	334	364	365
Muddy Brook- MD03	144	149	140	158	191	157	186	160	154	174	203	273	320	344	333
Oakdale Brook- MD80	742	747	608	654	820	675	573	651	534	666	686	872	982	1136	1166
Quinapoxet River (Canada Mills) - MD69	215	199	172	191	181	173	170	151	167	172	195	255	304	296	250
Scarlett Brook (DS W.M.) - MD81	411	630	636	517	423	391	442	463	372	484	514	635	620	771	747
Stillwater River - Muddy Pond Rd - MD07	165	199	146	188	162	127	162	120	143	144	142	182	213	170	162
Trout Brook- M110	70	80	63	83	59	62	55	33	61	84	74	74	86	96	92
Waushacum Brook (Prescott) - MD83	392	393	341	366	321	302	292	275	280	315	284	339	396	420	395
West Boylston Brook- MD05	624	662	601	644	561	507	590	566	512	667	739	1137	1227	1700	1274

In 2018, chloride analysis was added to the Wachusett water quality monitoring program with the goal of developing a strong correlation between conductivity and chloride that will enable concentration and loading estimates using specific conductance as a surrogate. Ultimately, it is intended that this information will help to inform management strategies aimed towards stabilizing and eventually reversing the upward trend of specific conductance/chloride that has been worsening in recent years. Only one year (2018) of chloride data has been collected so far, with corresponding specific conductance measurements available at the USGS tributaries. Concentrations of chloride measured after 2018 have a paired specific conductance measurement.

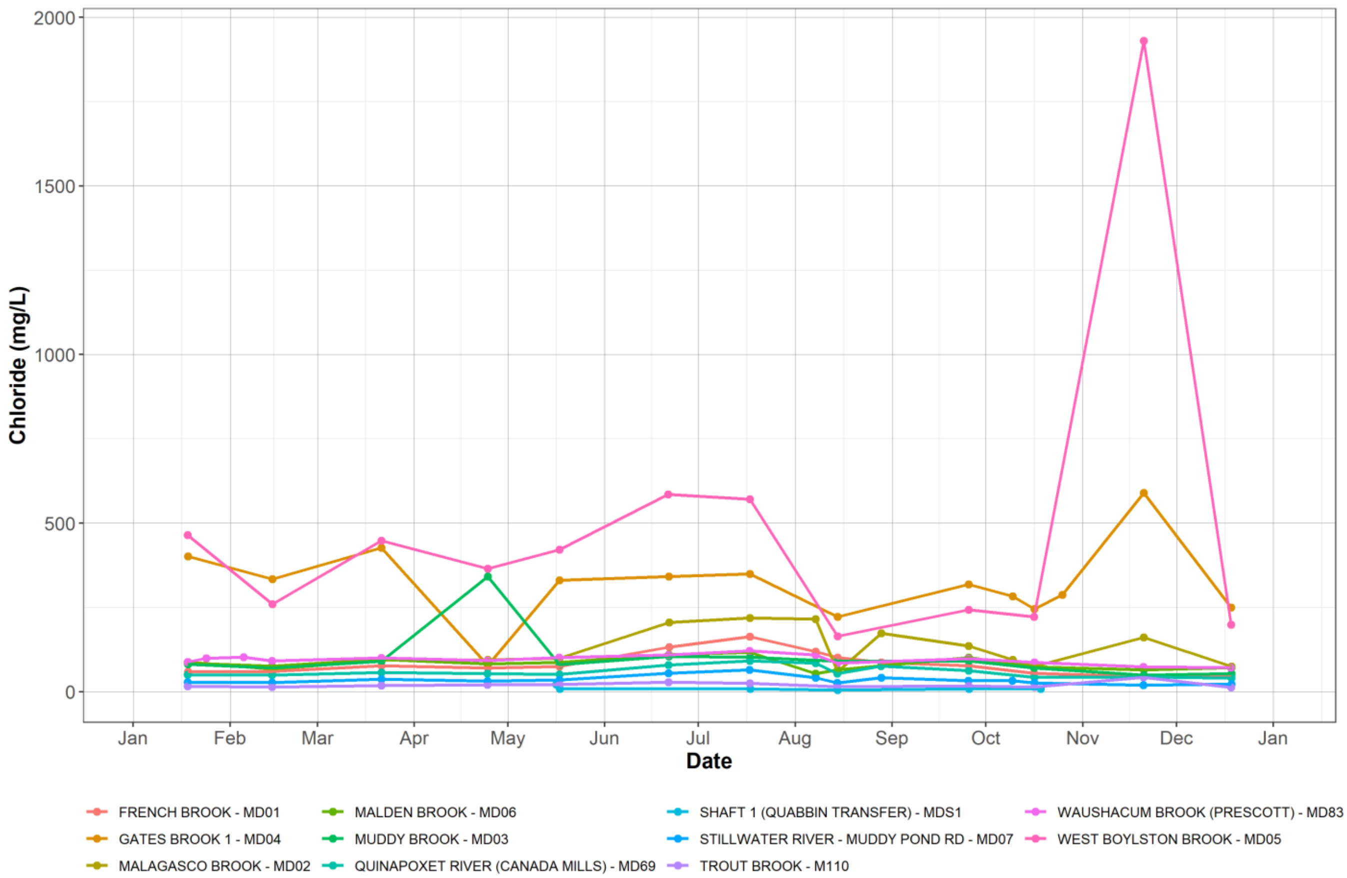
Table 15 is a summary of the 2018 chloride data for the Wachusett tributaries.

Table 15. 2018 Chloride Concentration Summary for Wachusett Tributaries (mg/L)

LOCATION	Count	Minimum	Median	Average	Maximum	Std. Dev
French Brook - MD01	14	45	76	84	163	34
Gates Brook 1 - MD04	14	78	325	319	590	116
Malagasco Brook - MD02	15	60	95	124	219	57
Malden Brook - MD06	13	54	82	83	117	19
Muddy Brook - MD03	12	49	86	102	342	77
Quinapoxet River (Canada Mills) - MD69	14	41	54	60	92	16
Shaft 1 (Quabbin Transfer) - MDS1	7	5	8	11	22	7
Stillwater River - Muddy Pond Rd - MD07	15	20	33	35	65	12
Trout Brook - M110	12	13	18	21	42	8
Waushacum Brook (Prescott) - MD83	15	72	98	95	121	13
West Boylston Brook - MD05	12	165	394	490	1930	476

Tributary chloride (not including Shaft 1) ranged from 13 mg/L at Trout Brook to 1,930 mg/L at West Boylston Brook. West Boylston Brook also had the highest standard deviation among the tributaries with a range spanning more than entire order of magnitude. The maximum chloride concentration at West Boylston Brook (**Figure 25**) occurred in November after freezing rain earlier in the day, which likely prompted the application of de-icing of roads using salt products, and subsequent runoff of road salt containing waters to nearby tributaries. For most tributaries, chloride concentrations were usually higher during the summer months during low flows. This observation raised the question about surface water and groundwater contributions of chloride. In 2019, monitoring of chloride concentrations and specific conductance in groundwater in the Wachusett Reservoir watershed began to explore seasonal dynamics and annual chloride inputs to Wachusett Reservoir tributaries further. The 2019 Wachusett Reservoir water quality report will include groundwater sample results and a preliminary discussion on chloride concentrations in the Wachusett Watershed.

Figure 25. 2018 Chloride Concentrations in Wachusett Tributaries



3.5 TURBIDITY

Routine samples were collected from all tributary stations twice per month throughout the year, with individual measurements from 0.15 NTU to 28.40 NTU (**Figure 26**). The 23 samples with turbidity of 5.0 NTU or higher were predominantly collected from Muddy Brook (12 samples) which historically has contained elevated concentrations of fine particulate matter. In a departure from prior years, a majority of the 23 recorded measurements > 5.0 NTU occurred during dry weather conditions (17 samples).

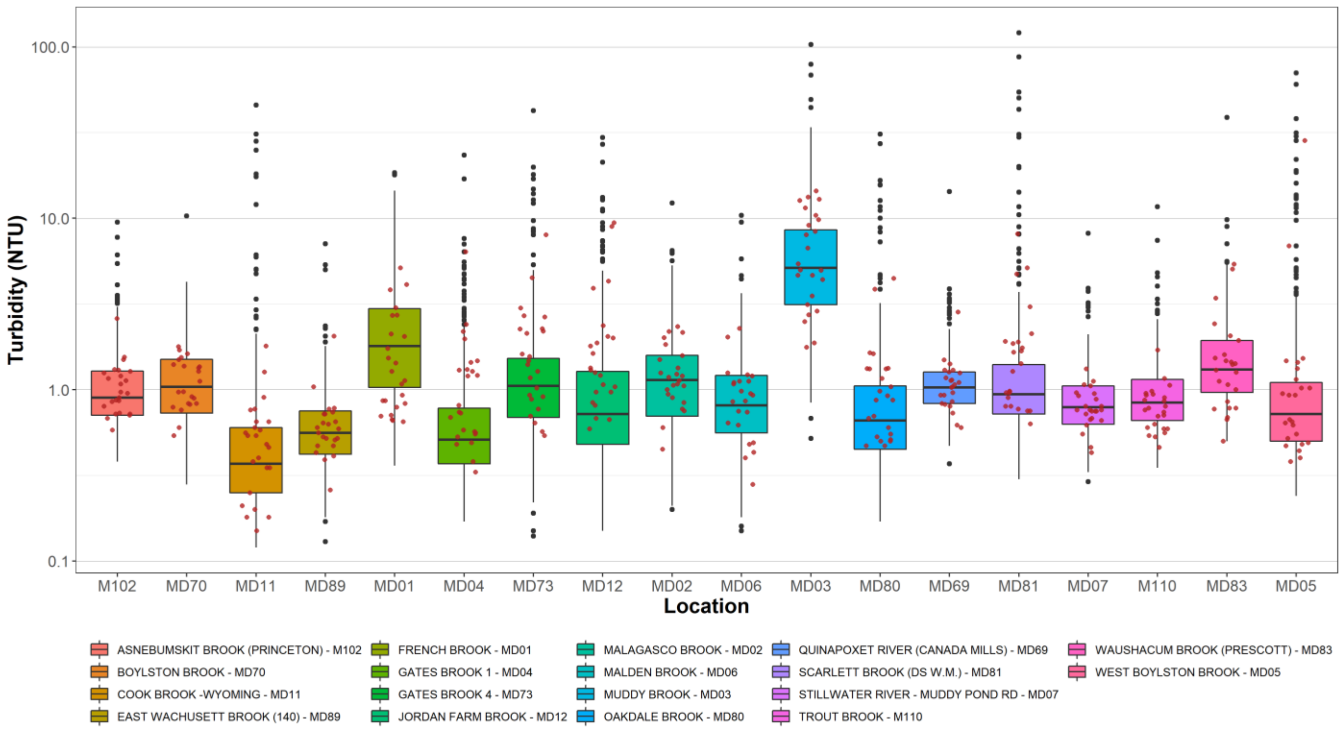
Annual median turbidity values (**Table 16**) ranged from 0.51 NTU in Cook Brook to 5.20 NTU in Muddy Brook. The overall watershed median turbidity of 1.23 NTU was higher than the previous year, which is likely the result of above normal precipitation during the latter half of 2018. Turbidity levels were higher during or after wet weather conditions (> 0.2 inches of rainfall within 24 hours of sample) for fifteen out of eighteen locations. However, the dry weather median for Muddy Brook was so much higher than any other location that the overall Wachusett tributary wet versus dry weather median turbidity did not differ substantially.

Table 16. Wet vs. Dry Weather Turbidity Statistics in Wachusett Tributaries

LOCATION	ANNUAL MEDIAN	DRY MEDIAN	WET MEDIAN
Asnebumskit Brook (Princeton) - M102	0.96	0.97	0.86
Boylston Brook - MD70	1.04	0.93	1.44
Cook Brook - Wyoming - MD11	0.51	0.40	0.58
East Wachusett Brook (140) - MD89	0.59	0.55	0.64
French Brook - MD01	1.21	1.43	0.93
Gates Brook 1- MD04	0.78	0.58	1.30
Gates Brook 4 - MD73	1.44	1.02	2.26
Jordan Farm Brook - MD12	1.30	1.06	2.04
Malagasco Brook - MD02	1.15	1.08	1.50
Malden Brook- MD06	0.93	0.80	1.12
Muddy Brook- MD03	5.20	8.00	4.64
Oakdale Brook- MD80	0.90	0.70	1.32
Quinapoxet River (Canada Mills) - MD69	1.06	1.03	1.14
Scarlett Brook (DS W.M.) - MD81	1.35	0.98	1.65
Stillwater River - Muddy Pond Rd - MD07	0.76	0.75	0.76
Trout Brook- M110	0.77	0.76	0.78
Waushacum Brook (Prescott) - MD83	1.35	1.42	1.07
West Boylston Brook- MD05	0.80	0.64	0.93
MEAN TRIBUTARY MEDIAN	**1.23**	**1.28**	**1.39**

*Wet weather samples taken within 24 hours of 0.2 inches of rainfall or more

Figure 26. 2018 Turbidity vs. 2009 - 2018 Statistics



*Red points are results from 2018

3.6 STORM WATER SAMPLING

Stormwater sampling is conducted to supplement routine monthly nutrient sampling and provide detailed information about the variability of solute concentrations during storm events. Since 2000, over 67 storm events have been sampled, usually at 2-4 locations per storm. Twenty-one of these storms were sampled specifically for the long-term forestry study (**Section 3.7**). Storm sampling is now only conducted for extreme precipitation events (2 or more inches of rain) in order to support UMass modelling efforts. In 2018 only two storms were sampled, not including the long-term forestry sampling events. A separate stormwater sampling report will be produced providing a detailed summary and analysis of the 46 storms that were sampled at routine water quality stations. The storms sampled for the long-term forestry study will be discussed within the report for that project.

3.7 SPECIAL STUDIES

DWSP staff continue to monitor potential short-term and long-term water quality impacts from forest management activities. Investigation of short-term impacts consists of monthly turbidity monitoring above and below stream crossings prior to and following completion of all activity at logging sites, with more frequent sampling during active forestry or during storm events. The purpose of this monitoring is to establish baseline turbidity conditions and track water quality during active logging and installation/removal of stream crossings so that any logging activities that may degrade water quality can be mitigated quickly. In 2018, a total of 113 visits were made at 27 stream crossing on 14 different lots. Conditions were dry during many of these visits which prevented sample collection, however a total of 127 samples were analyzed for turbidity. Only one sample (June 25th) exceeded 1.0 NTU during active harvest (Lot Number 5273 off Legg Rd. in West Boylston). Turbidity upstream of the crossing was 1.10 NTU; immediately downstream of this crossing the turbidity was 1.34 NTU; further downstream the turbidity had decreased to 0.93 NTU. No additional problems with elevated turbidity at forestry monitoring sites were noted during the year.

Long-term forestry monitoring involves collection of data at a control site and an active site for a span of at least ten years before, during, and following completion of forestry operations. Five years of data have now been collected and a preliminary report summarizing results to date will be completed in FY 2020. 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-nitrogen, nitrate-nitrogen, nitrite-nitrogen, and total phosphorus.

Macroinvertebrate samples were collected at more than twenty historical reservoir tributary stations during the spring of 2012, 2014, 2016, and 2018. All 2012 samples have been sorted, identified, and counted, samples from other years await processing. Information obtained from these recent samples will be compared with historical long-term macroinvertebrate data from the same locations and will be presented in a future water quality report.

In 2018, a working group was formed to evaluate increasing conductivity observed in the Quabbin and Wachusett Reservoirs and many of their tributaries. This is expected to be a long-term collaborative effort between the DWSP, MWRA, UMass researchers and local stakeholders such as the watershed town public works departments and drinking water providers. At present, this group is reviewing literature, compiling existing data, collecting additional data (chloride in tributaries and groundwater), and meeting regularly to review progress and plan the future initiatives and steps to take by participating members. It is anticipated that a special report and will be prepared after certain milestones are reached.

4.0 RESULTS OF RESERVOIR MONITORING PROGRAM

4.1 BACTERIA

Bacterial transect samples (*E. coli*) are collected routinely during ice-free conditions at 23 fixed surface locations on the reservoir (**Figure 3**). Data from 2018 are presented in **Table 17**. These samples are collected to document the relationship between seasonal bacteria variations and visiting populations of gulls, ducks, geese, cormorants, and swans.

Table 17. 2018 Wachusett Reservoir Bacteria Transect Data (MPN/100 mL)

Date	A3 *	B2	B3	C1	C3	C5	D1	D2	D4	E2	E4	F2	F3	F4	G2	H2	I2	J2	J3	J4	K2	M1	N1
Apr 12	0	0	0	1	3	1	0	3	10	14	0	0	21	1	1	0	0	0	0	0	0	0	0
Apr 23	0	ND	1	0	1	0	1	4	3	1	0	0	0	1	0	0	0	0	0	1	0	1	1
May 14	0	0	0	0	0	0	0	0	1	0	1	0	2	0	0	0	0	0	0	0	ND	1	3
Jun 11	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Jul 12	0	0	0	1	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug 15	4	10	4	2	3	4	5	6	3	0	18	4	11	8	3	4	3	8	3	2	6	6	3
Sep 05	3	0	5	0	0	2	3	2	5	31	4	0	2	0	0	3	0	0	1	3	0	0	1
Sep 13	5	0	0	1	5	4	1	2	6	3	3	0	0	9	4	1	5	4	2	9	4	5	3
Sep 17	0	4	2	0	1	11	1	3	3	0	1	6	70	1	8	1	2	3	2	4	0	1	1
Oct 04	1	0	2	3	3	0	2	4	0	1	3	1	5	1	2	2	4	0	2	1	1	9	2
Oct 17	1	5	3	2	2	1	3	5	3	5	6	2	0	5	1	2	3	3	4	6	5	8	4
Oct 31	1	5	3	1	2	0	1	3	3	4	1	1	5	5	2	5	0	1	1	0	1	3	1
Nov 15	0	0	0	1	2	0	1	1	1	2	0	1	4	4	3	3	4	1	14	6	5	11	6
Nov 28	1	0	2	2	2	1	3	1	1	3	4	3	6	1	6	10	9	3	8	16	12	18	50
Dec 12	0	0	0	1	1	1	1	1	1	0	0	3	2	1	0	5	8	5	29	36	32	10	22
Dec 27	2	4	5	2	5	5	5	6	1	2	1	8	3	3	6	9	8	15	27	21	34	18	16

*Cosgrove Intake
ND = No Data

In 2018, there was full ice cover on Wachusett Reservoir from January 1 until the beginning of March. High bacteria results were observed on April 12 at the typical loafing areas near Crescent Island (F3). By the end of April most water bodies in the area were completely ice free and transect bacteria levels had declined as birds spread out across the region. On two other occasions during September high bacteria levels were recorded at single transect points by the shallows near Greenhaldge Point (E2) and Crescent Island (F3), where gulls often loaf during the day. High concentrations of bacteria were again recorded in November and December at the southern end of the reservoir (where birds typically roost at night).

Bacteria samples were collected seven days per week by MWRA staff from the John J. Carroll Water Treatment Plant at Walnut Hill in Marlborough. EPA's criteria for drinking water require that a minimum of ninety percent of all source water samples contain less than 20 MPN/100mL fecal coliform[13] . All of the 365 samples collected at Walnut Hill contained less than the standard, with a maximum concentration of 6 MPN/100mL. Most samples (69%) did not contain any detectable bacteria. The DWSP has put considerable time and effort into implementing a rigorous bird harassment program, and the results in 2018 continued to prove that the efforts are effective at maintaining low numbers of both birds and bacteria.

[13] Surface Water Treatment Rule. Subpart H—Filtration and Disinfection (40 CFR141.71(a)(1).

4.2 WATER COLUMN CHARACTERISTICS

4.2.1 FIELD PROCEDURES

DWSP staff routinely record water column profiles in Wachusett Reservoir using a Yellow Springs Instrumentation (YSI) EXO2 multi-parameter sonde for the following hydrographic parameters: temperature, specific conductance, dissolved oxygen concentration, percent oxygen saturation, chlorophyll *a*, phycocyanin, turbidity, and hydrogen ion activity (pH). Data are recorded with a handheld display connected to the sonde with a 30-meter cable starting at the surface. Repeated measurements are recorded as the instrument is gradually lowered to the bottom. Measurements are recorded at 1-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.

4.2.2 THERMAL STRATIFICATION

As is 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 (**Section 4.4**), (2) to track the progress of the Quabbin interflow through Wachusett Reservoir 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 stratified period but are still typically collected twice per month when the reservoir is not frozen. Samples are usually collected at 1-meter intervals, with an additional half-meter surface sample also recorded. In situations where layers of water are well mixed, samples may be collected every two meters. Half-meter intervals are often measured at certain depths when aggregations of algae are suspected, or to determine the precise depth of the Quabbin interflow layer.

Water column profile data has been collected from various locations in Wachusett Reservoir using a multi-parameter sonde since 1988. All historical profile data from 1988-present is compiled into a single format, housed in a single database and accessible via Access and WAVE.

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 to 100% of the volume of the Wachusett

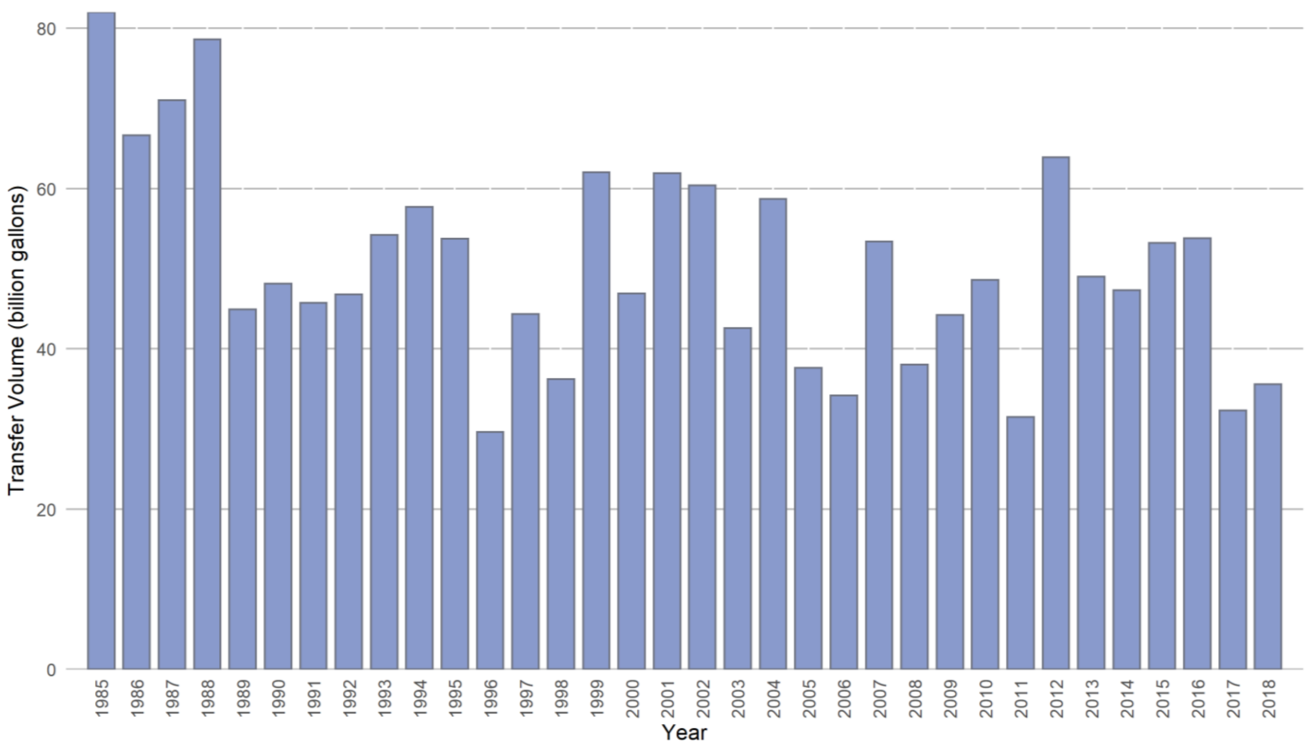
Reservoir. The period of peak transfer rates generally occurs from June through November. However, at any time of the year, approximately half of the water in Wachusett Reservoir is derived from Quabbin Reservoir.

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 10 to 14° C from June through October. In 2018, the average water temperature at Shaft 12 was 9° C. 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 transferred water is not as cold and dense as the Wachusett hypolimnion. Therefore, Quabbin water transferred during the period of thermal stratification flows conformably into the metalimnion of Wachusett where water temperatures and densities coincide.

The term 'interflow' describes this metalimnetic flow path for the Quabbin transfer that, once fully developed, generally occupies the Wachusett water column from approximately six to sixteen meters in depth. Interflow water quality is distinctive from ambient Wachusett water in having the low specific conductivity characteristic of Quabbin Reservoir. Profile measurements of conductivity readily distinguish this layer 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 three to five weeks depending on the timing and rate of transfer from Quabbin. The interflow essentially connects Quabbin inflow to Cosgrove Intake in a "short circuit" resulting in limited mixing with ambient Wachusett Reservoir water.

In 2018 the Quabbin transfer was initiated on May 16 and water was transferred on a nearly continuous basis until October 27. Water was transferred for a total of 164 days, delivering a total volume of 35.6 billion gallons (134,654,983 m^3) to Wachusett Reservoir. This is equivalent to 59.5% of Wachusett Reservoir volume and is the fourth lowest volume transferred in the past 20 years (**Figure 27**). This low transfer volume was, in part, a result of refilling Quabbin to capacity following drought conditions and subsequent water loss in 2017. Quabbin refilled to 100% capacity by November 2018.

Figure 27. Historical Volume of Quabbin Transfer to Wachusett Reservoir (billion gallons)



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 in July, August, October, and November (

Figure 28 - **Figure 31**) 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 7.5° and 10.5° 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), to provide suitable habitat for cold water salmonids such as Lake Trout and Landlocked Salmon which 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). 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 **Figure** 28 through **Figure 31** since this parameter typically exhibits only minor fluctuations in the reservoir.

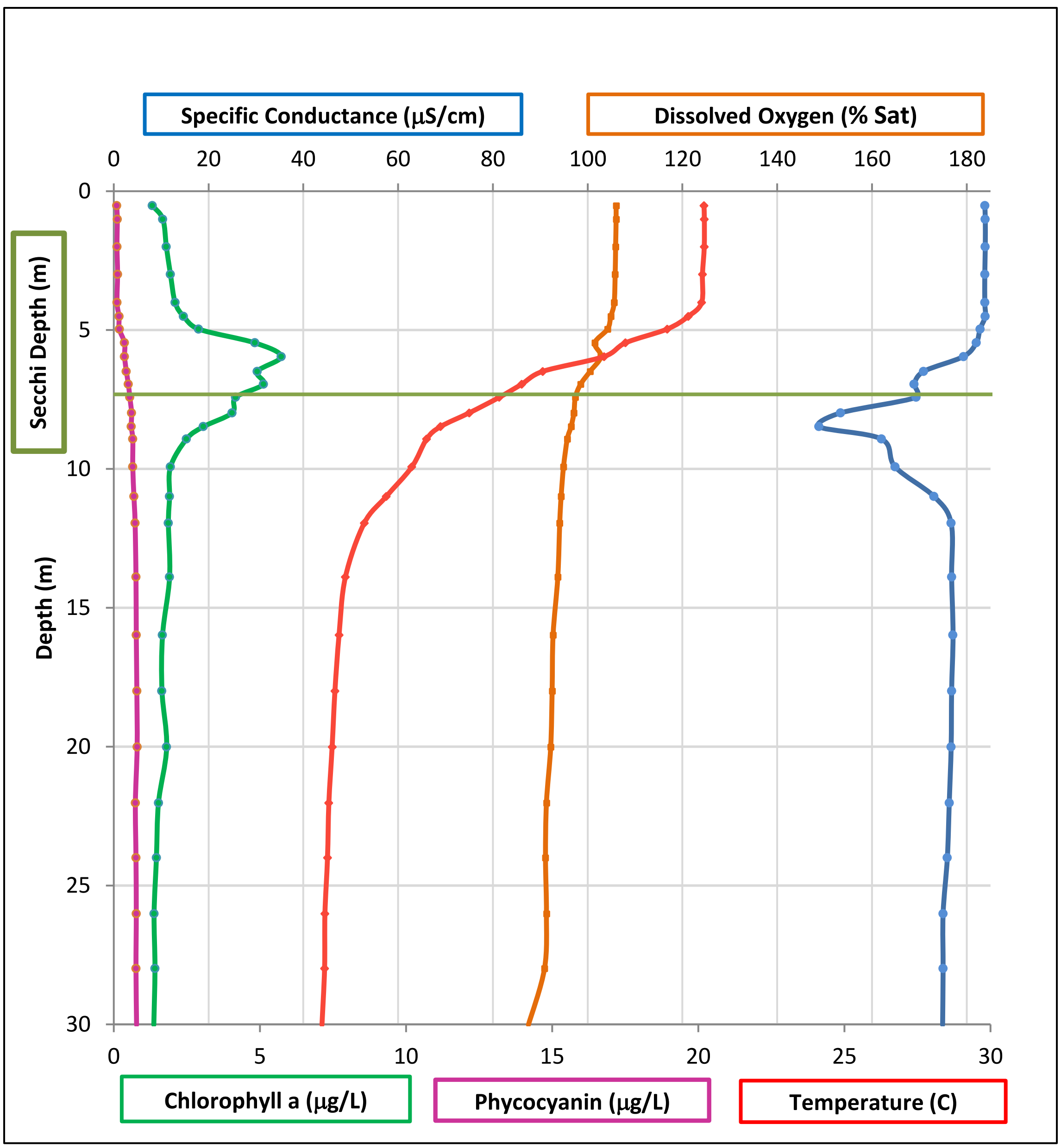
Specific conductance (conductivity) profiles in Wachusett Reservoir reflect the interplay between native water contributed from the Wachusett watershed and water transferred from Quabbin Reservoir. The Quinapoxet and Stillwater Rivers are the two main tributaries to Wachusett Reservoir and are estimated to account for approximately 75% of annual inflow from the reservoir watershed. Measurements of conductivity in these rivers generally range between 150 and 300 µS/cm in the Quinapoxet River and 100 to 250 µS/cm in the Stillwater River. The 2018 average conductivity of these two rivers was 250 and 162 µS/cm, respectively. In contrast, water entering the Quabbin aqueduct at Shaft 12 in the Quabbin Reservoir had an average conductivity of 70 µS/cm in 2018. The increasing trend in conductivity documented in the region[14] has also been observed in the source watersheds and reservoirs. The investigation into this trend and its potential effects on water quality are ongoing.

During periods of isothermy (November through March), conductivity values throughout the main basin of Wachusett Reservoir typically range from 75 to 147 µS/cm depending on the amount of water received from Quabbin the previous year. During the summer stratification period the Quabbin interflow is conspicuous in profile measurements as a metalimnetic stratum of low conductivity. Following a year with record specific conductance values in 2017, levels increased well above the previous record of 169.8 µS/cm to a new record value of 184.4 µS/cm recorded near the surface at Basin North on July 12. Specific conductance values greater than 170 µS/cm were recorded at the surface at Basin North throughout the year. The highest specific conductance readings on record at the Basin South and Thomas Basin monitoring stations also occurred in 2018.

[14] Kaushal, Sujay S. et al. "Freshwater Salinization Syndrome on a Continental Scale." Proceedings of the National Academy of Sciences 115.4 (2018). Web. doi:10.1073/pnas.1711234115.

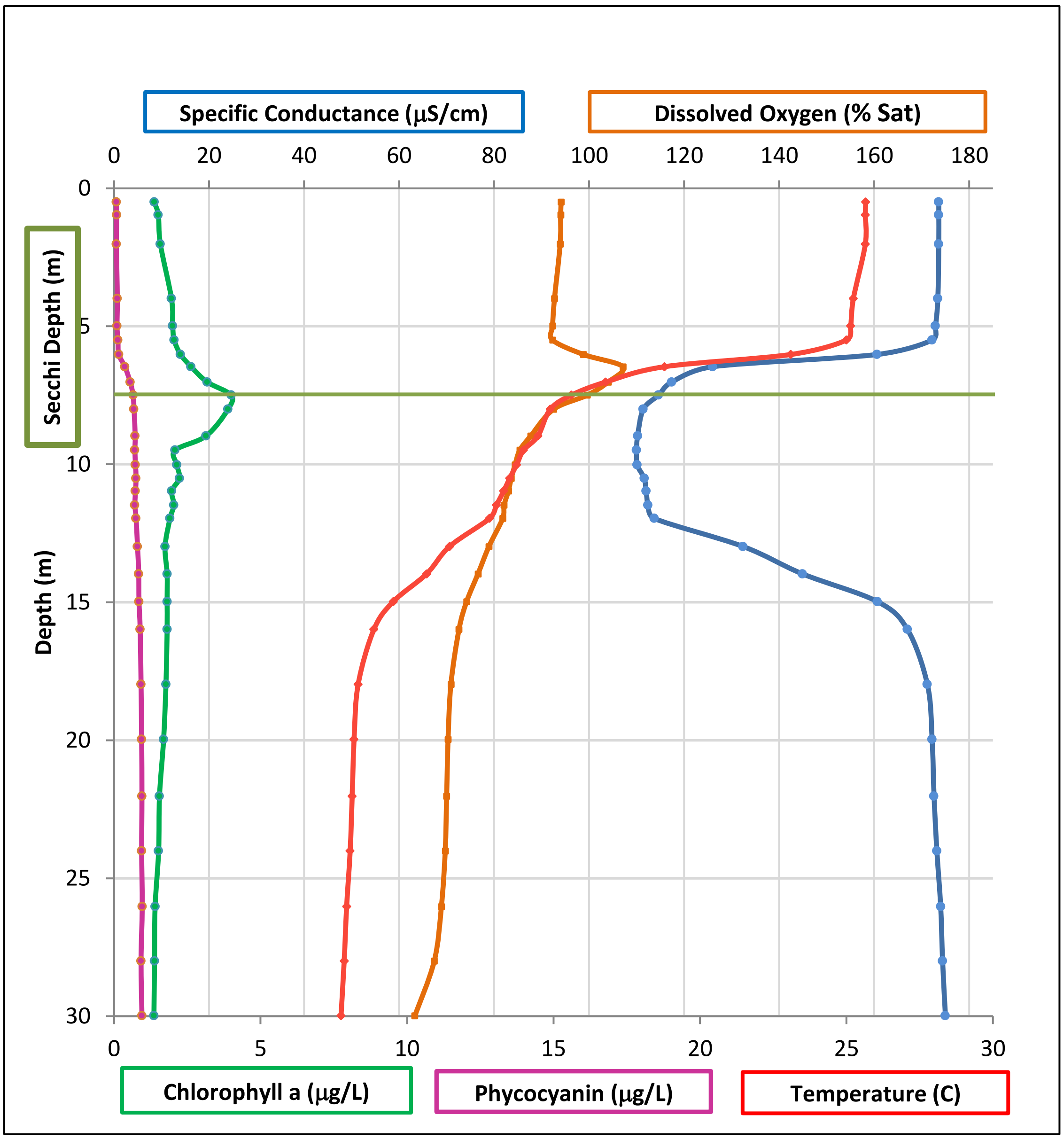
Interflow penetration at Basin North/3417 was first observed on June 4 and by June 11 had fully penetrated the Wachusett metalimnion at Basin North by June 11 (
Figure 28). This indentation in the conductivity profile intensifies (extends to lower conductivity values) over the period of transfer as water in the interior of the interflow undergoes less mixing with ambient reservoir water at the boundaries of the interflow stratum. It is noteworthy that specific conductance values at all depths are higher than typically observed. The epilimnion occupied the top six meters of the water column on this date and had reached a temperature of 20.2° C. Epilimnetic dissolved oxygen measured 102.8% saturation on this date due to photosynthetic activity by phytoplankton. Chlorophyll *a* was elevated on this day between five and nine meters with a peak at six meters. This increase corresponded with the end stages of a bloom of the chrysophyte *Uroglenopsis* which was present in the reservoir from early May to June (see for more details).

Figure 28. Profile at Basin North/Station 3417 on June 11, 2018



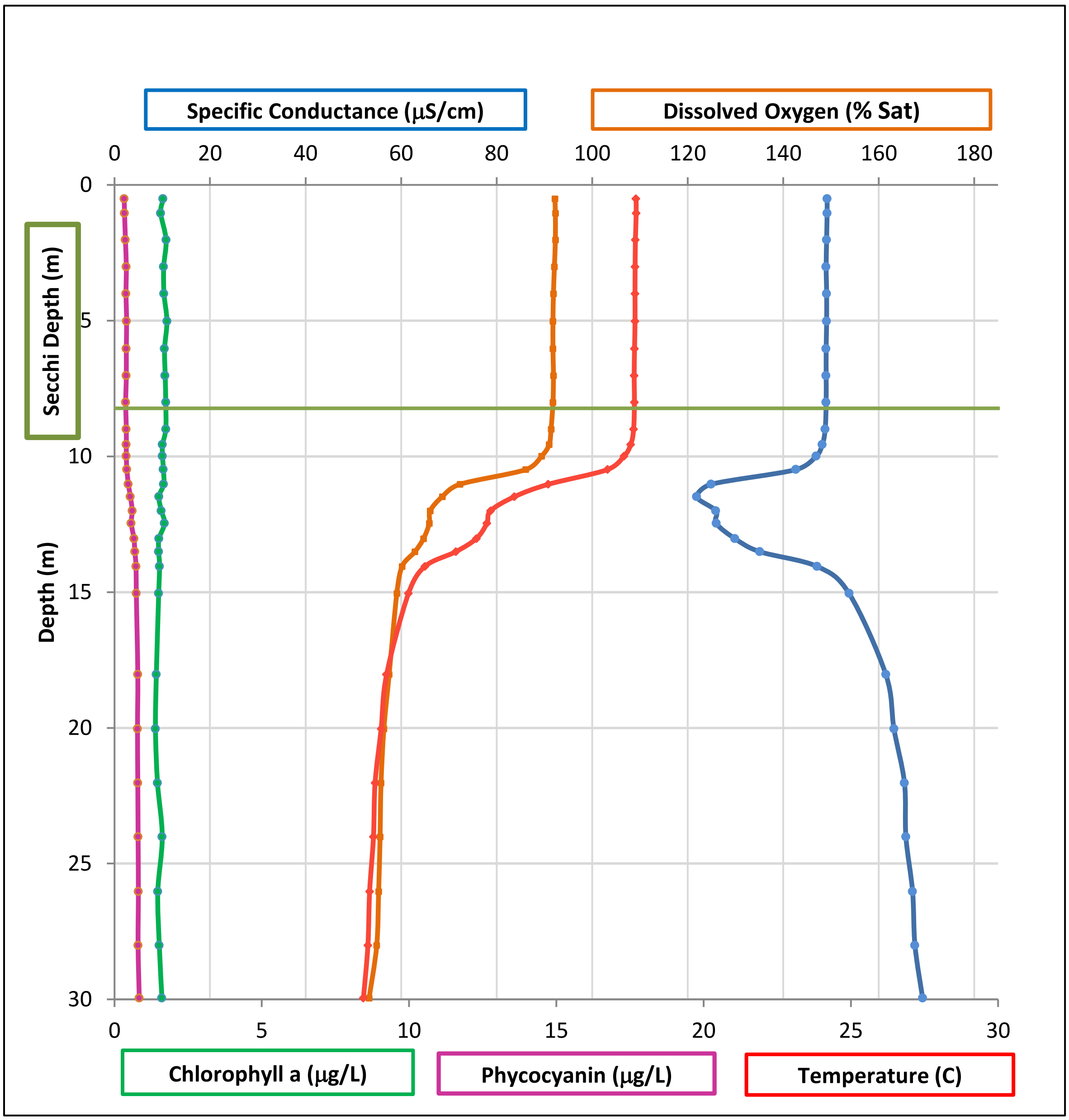
The interflow continued to become more fully established, remaining as a discrete layer through the summer months. On August 16, the negative excursion in the conductivity profile (**Figure 29**) shows the typical mid-summer configuration of the fully established interflow with a thickness of eight meters present between depths of 6 and 14 meters. Conductivity reached minimum values of around 110 µS/cm at a depth of 9.5 meters. The epilimnion still occupied the top six meters of the water column with temperatures of around 25° C. The steep gradient in temperature and density between the epilimnion and interflow can be seen in this profile where the temperature decreases 10° C between depths of 5 and 8 meters. Chlorophyll *a* concentrations were slightly elevated as was overall phytoplankton density at this time. The cyanophyte *Rhabdoderma* was the dominant taxa on this sample date and moderate densities of Chrysophytes; *Chrysosphaerella* and *Dinobryon*, were present.

Figure 29. Profile at Basin North/Station 3417 on August 16, 2018



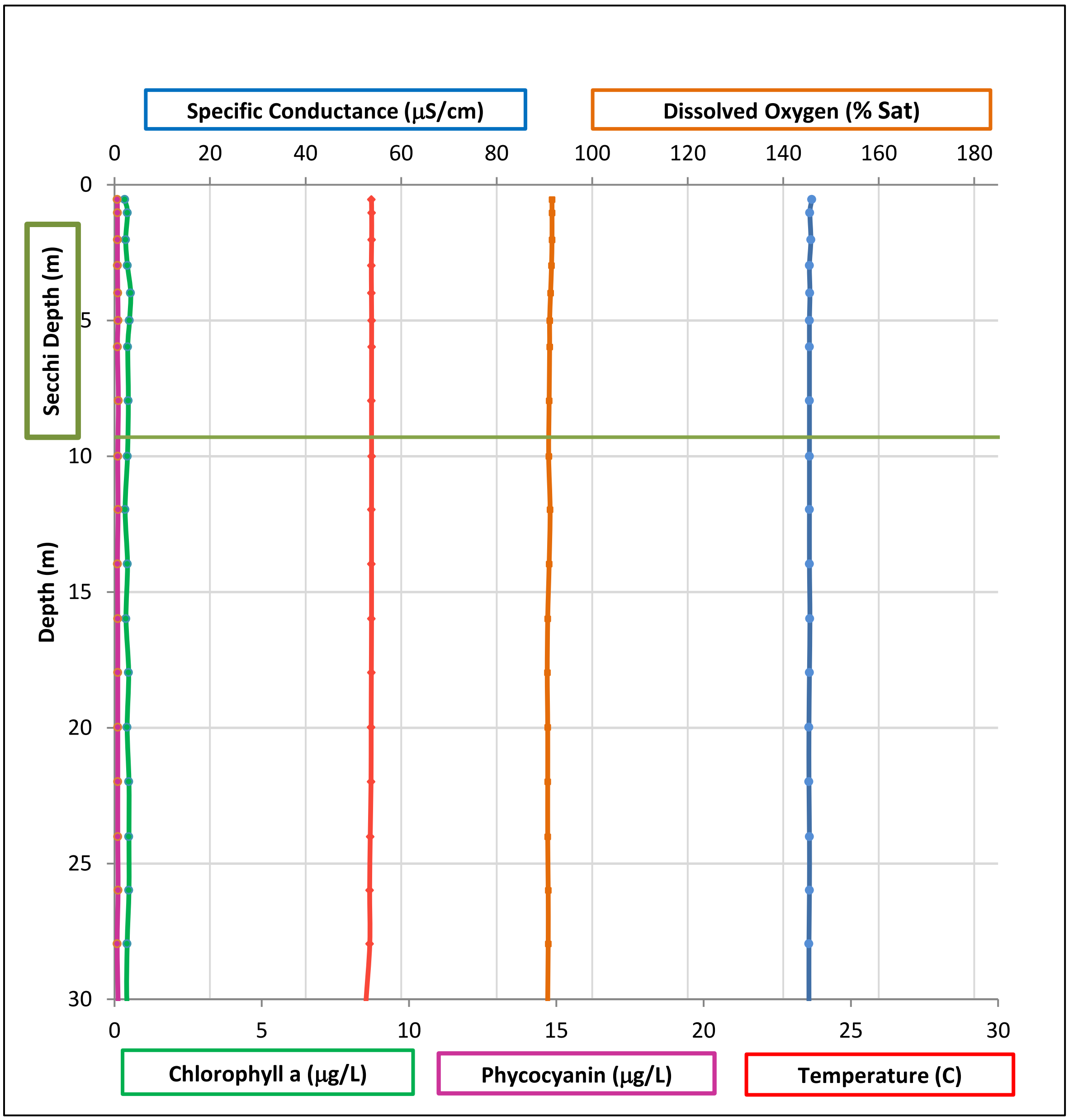
Epilimnetic temperatures typically begin to steadily decrease throughout September. However, as in 2017, temperatures in the epilimnion did not begin to decrease until mid-October in 2018. By October 10 (**Figure 30**), heat losses and wind energy had pushed the thermocline downward. The interflow is still clearly visible as a distinct layer, although at this point in the season it is shrinking in size as the top portion is eroded. At this point, the change to lower specific conductivity values takes place between 10 and 11.5 meters with the interflow just four meters thick. Dissolved oxygen remained near saturation in the epilimnion but had declined to a low of 55% 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 30. Profile at Basin North/Station 3417 on October 10, 2018



A profile recorded on November 15 (**Figure 31**) documents the complete breakdown of the stratification structure and reveals that turnover is complete. This profile shows the water column was isothermal, with a difference of less than 0.2° C from the surface to the bottom (8.7° C – 8.5° C). Fall turnover mixes the oxygen-rich epilimnion with the slightly oxygen-depleted hypolimnion, replenishing dissolved oxygen concentrations through the water column. Conductivity values were constant at 146 µS/cm from the surface to bottom, continuing the trend of higher than normal values.

Figure 31. Profile at Basin North/Station 3417 on November 15, 2018



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/Station 3427 (**Figure 3**).

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

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

Modifications to the historical sampling program have consisted only of a lower minimum detection limit for TKN (reduced to 0.1 mg/L from previous limits of 0.2 and 0.6 mg/L) and the addition of mean UV_{254} absorbance (in 2000) to the suite of parameters being measured.

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 2017 is used as a basis for interpreting data generated in 2018. Results from quarterly nutrient sampling in 2018 were within historical ranges apart from increased UV_{254} at three sites. Overall, nutrient concentrations for 2018 are comparable to measurements recorded in recent years (see **Table 18** and the complete 2018 reservoir nutrient results in **Appendix A**).

The patterns of nutrient distribution in 2018 quarterly samples generally followed those documented in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics.[15] 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, UV_{254}, and conductivity, either increasing or decreasing downgradient of Thomas Basin depending on the dominant influence. As in 2017, the low volume of water transferred from Quabbin again in 2018 resulted in the Wachusett watershed water quality more heavily influencing reservoir water quality than in a typical year. This

[15] 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.

influence is exemplified by increases in mean UV_{254} observed at Basin South and Basin North where results met or slightly exceeded the maximum historical value for mean UV_{254} at these locations.

Table 18. Wachusett Reservoir Nutrient Concentrations:
Comparison of Ranges from 1998-2017 Database[1] to Results from 2018 Quarterly Sampling [2]

Sampling Station[3]	Ammonia-N (NH_3-N; µg/L)		Nitrate-N (NO_3-N; µg/L)		Silica (SiO_2; mg/L)		Total Phosphorus(µg/L)		UV_{254} (Absorbance/cm)	
	1998-2017	2018	1998-2017	2018	1998-2017	2018	1998-2017	2018	2000-2017	2018
Basin North (E)	<5 - 16	<5 - 7	<5 - 176	<5 - 86	0.59 - 4.66	1.53 - 3.05	<5 - 17	<5 - 6	0.029 - 0.090	0.059 - 0.085
Basin North (M)	<5 - 51	<5 - 17	<5 - 180	16 - 103	0.77 - 4.67	1.81 - 3.05	<5 - 20	<5 - 12	0.029 - 0.102	0.058 - 0.084
Basin North (H)	<5 - 41	<5 - 31	30 - 225	69 - 148	1.27 - 4.91	2.96 - 3.47	<5 - 19	<5 - 9	0.030 - 0.084	0.067 - 0.085
Basin South (E)	<5 - 15	<5 - 7	<5 - 176	<5 - 97	0.56 - 4.58	1.49 - 3.95	<5 - 20	<5 - 7	0.028 - 0.102	0.061 - 0.123
Basin South (M)	<5 - 39	<5 - 16	<5 - 184	9 - 98	0.95 - 4.8	1.71 - 3.95	<5 - 32	<5 - 8	0.031 - 0.128	0.053 - 0.125
Basin South (H)	<5 - 44	<5 - 28	19 - 224	94 - 130	1.64 - 4.78	3.33 - 4.03	<5 - 37	<5 - 10	0.032 - 0.111	0.065 - 0.125
Thomas Basin (E)	<5 - 18	<5 - 8	<5 - 201	<5 - 182	0.62 - 7.44	1.64 - 6.11	<5 - 27	7 - 10	0.026 - 0.305	0.064 - 0.175
Thomas Basin (M)	<5 - 27	<5 - 23	<5 - 213	11 - 180	0.88 - 7.07	1.8 - 6	<5 - 29	9 - 12	0.026 - 0.334	0.057 - 0.177
Thomas Basin (H)	<5 - 57	<5 - 20	<5 - 236	13 - 174	0.92 - 7.39	1.82 - 6.03	<5 - 29	7 - 10	0.026 - 0.345	0.050 - 0.174

Notes: (1) 1998-2017 database composed of 1998-99 year of monthly sampling and subsequent quarterly sampling through December 2017, except for measurement of UV_{254} initiated in 2000 quarterly sampling
(2) 2018 quarterly sampling conducted May, July, October, and December
(3) Water column locations are as follows: E = epilimnion/near surface, M = metalimnion/middle, H = hypolimnion/bottom

4.4 PLANKTON

4.4.1 FIELD PROCEDURES

Plankton monitoring consists of three tasks typically conducted from a boat: measurement of water column profiles (see **Section 4.2.4**), measurement of Secchi disk transparency, and collection of grab samples. 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 reservoir 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 (Cosgrove Intake/Station 3409) is an additional location suitable for plankton grab sampling. Seiche effects or turbulence from water withdrawals can destabilize stratification boundaries and obscure associated phytoplankton distribution patterns at Cosgrove Intake during summer. However, samples collected from the catwalk during the late-November through early-April period of mixis are adequately representative of the main basin. Samples collected at Cosgrove Intake under stratified conditions may not be representative of any other location but are informative as to plankton densities in proximity to the intake.

Monitoring was conducted weekly (usually Mondays) from May through September, when episodes of rapid population growth of taste and odor organisms have occurred in the past, and typically every other week (ice permitting) outside of that period. During the annual stratification period, samples are typically collected at two discrete depths: near the middle of the epilimnion at a depth of three meters and 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 occasionally collected in summer months to monitor for increased densities of the Cyanophyte *Anabaena,* which may accumulate at the surface. During the period of mixis, collection of samples at two depths (3 and 6 meters) generally suffices, but other samples are collected as needed. Samples are collected using a Van Dorn bottle and kept in a cooler until they are returned to the laboratory for concentration and microscopic analysis. Secchi disk transparency is recorded in association with Basin North samples as an approximate measure of the amount of particulates, mostly plankton, suspended in the water column.

During the stratification period, sampling is focused where profile measurements show a spike in dissolved oxygen concentration, chlorophyll *a* concentration, or phycocyanin, as appropriate. Peaks in these parameters are indicative of photosynthetic activity associated with a phytoplankton bloom or aggregation within a specific stratum of the water column. Additional grab samples are collected at the precise depth where spikes are indicated. Motile colonial Chrysophytes such as *Chrysosphaerella*, *Dinobryon* and Synurophytes such as *Synura* are known to produce subsurface blooms in Wachusett Reservoir and are generally the most potent taste and odor taxa encountered. The aggregation stratum that these organisms have historically preferred is often between 6 and 8 meters, coincident with the steep temperature gradient at the interface between the epilimnion and the metalimnetic interflow (see **Section 4.3.2**). However, in recent years, chlorophyll *a* maxima have been documented at depth, with targeted sampling revealing aggregations of these organisms present in the middle or even lower portion of the interflow layer.

MWRA and DWSP 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 (typically to twice weekly) 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 DWSP 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) and further documented in in the Microscopic Enumeration of Phytoplankton Standard Operating Procedure for DWSP-Wachusett. The method entails gravity filtration of sample water through a layer of fine sand. The concentrated sample and sand is gently washed with waste filtrate water in a beaker to detach organisms from the sand grains and promptly decanted after the sand has been allowed to settle. A known quantity of the concentrated sample is then analyzed microscopically using quantitative techniques.

Phytoplankton taxa in concentrated samples are enumerated using a Sedgewick-Rafter (S-R) Cell which enables phytoplankton densities to be quantified. Each concentrated sample is mixed to homogenize the sample and then 1 mL of the sample is withdrawn with a pipette and placed into the S-R Cell. Initial inspection of phytoplankton within the S-R Cell is accomplished with a stereozoom microscope capable of magnification from 6X to 50X. Use of this instrument to scan the entire S-R Cell is important to detect colonies of certain motile taxa present at low densities such as *Synura*, colonies floating against the underside of the cover such as *Dolichospermum,* or to view large colonies such as *Uroglenopsis*. Analysis of surface samples collected in summer is typically limited to scanning unless *Dolichospermum* is detected at densities sufficient to warrant enumeration using a compound microscope (see below).

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

After the scanning procedure described above, microscopic analysis of phytoplankton samples is next performed with a Zeiss Axio Imager A2 compound microscope at a magnification of 200X using either bright field or phase-contrast illumination. Approximately 15 minutes are allowed for the phytoplankton to settle to the bottom of the S-R Cell before enumeration. The perimeter of the S-R Cell is scanned to confirm that phytoplankton are still alive, record presence/absence of taxa, and allow the taxonomist to familiarize themselves with taxa present in the sample before counting. Phytoplankton is then enumerated in a total of ten fields described by an ocular micrometer. The area of the ocular field is determined by calibration with a stage micrometer and the fields are selected for viewing at approximately 0.5-cm intervals across the length of the S-R Cell. If the initial count of ten fields reveals that known taste and odor organisms are present in densities approaching treatment consideration thresholds, up to forty additional fields are recorded for the density of that 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 DWSP biologists using sand filtration and microscopic analysis.

4.4.3 PHYTOPLANKTON MONITORING RESULTS

A total of 129 total algae samples were collected and analyzed during the 2018 season. Sampling for the year commenced when ice conditions at Cosgrove Intake first allowed on February 21 and continued through the end of the year with the last sample collected on December 20. Three notable phytoplankton events occurred over this time period: an extensive bloom of *Uroglenopsis* occurred in late May, Chrysophytes and Cyanobacteria were elevated in late July and August, and a remarkable decrease in overall phytoplankton was observed starting in October.

Overall phytoplankton densities were low between February and May. As is common, diatoms were the most prevalent group during these months, but did not attain the high densities typically observed in the spring. The maximum diatom density for 2018 was 365 ASU/mL observed on April 4 at 6m which is 74% lower than observed in 2017.

Densities remained low until late May when a significant bloom of the Chrysophyte *Uroglenopsis* occurred. *Uroglenopsis* was present in reservoir samples starting April 12 but did not reach countable densities until May 7 when a density of 70 ASU/mL was recorded in the 3m sample at Basin North. Densities then increased steadily, reaching a maximum of 4,717 AUS/mL on May 24. *Uroglenopsis* densities persisted above the early monitoring trigger of 200 ASU/mL through June 14 and remained present in samples at low densities until June 18. The maximum density recorded during this bloom event was approximately three times higher than the next most significant bloom of this taxa which occurred in 1996. Despite the high concentrations, water quality issues were not experienced and a treatment was therefore not warranted.

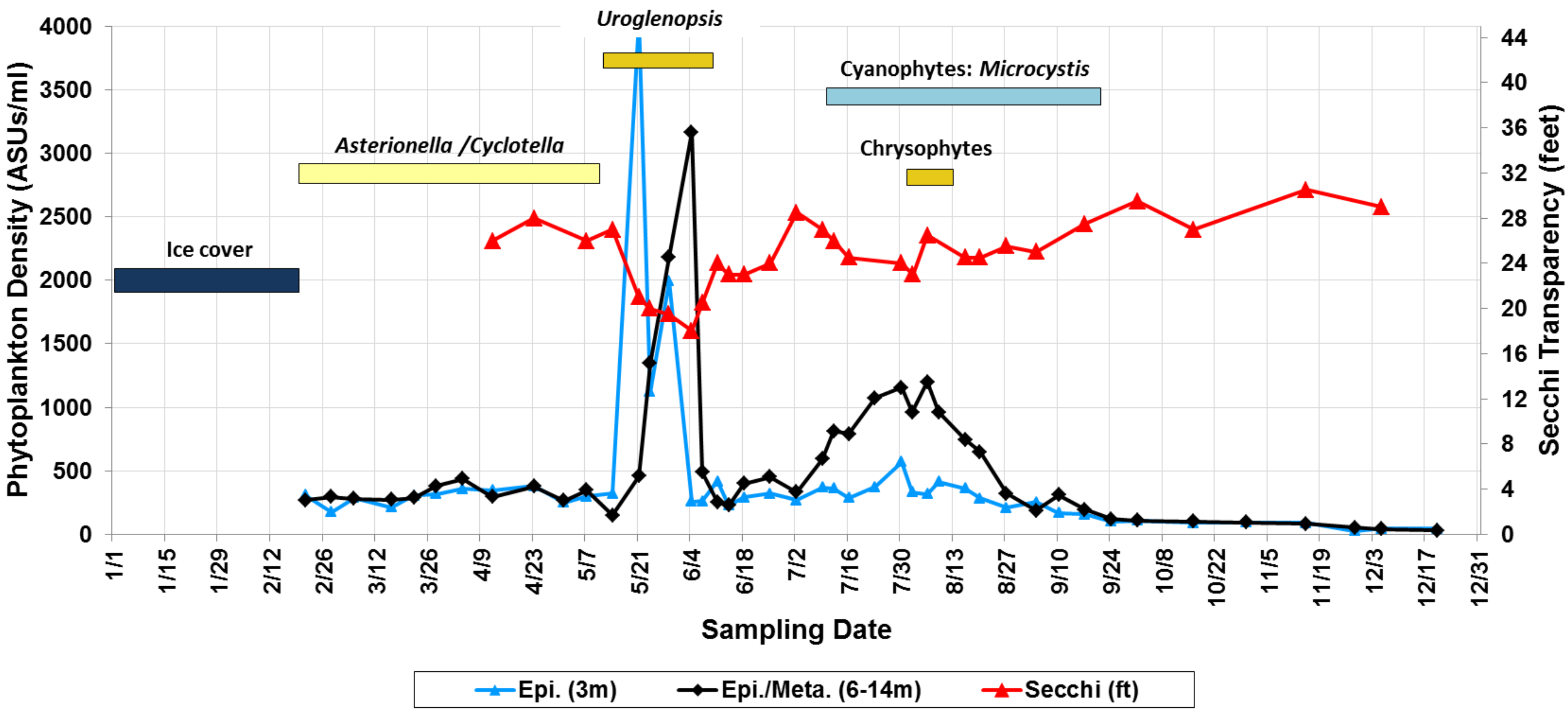
Following the *Uroglenopsis* bloom, overall densities returned to pre-bloom levels and remained moderate within the epilimnion. A brief period of increased phytoplankton density occurred in the interflow layer between July and late August. The composition between 6 and 9m was initially dominated by Chrysophytes, particularly *Dinobryon*, but these taxa subsided in late July when the community became cyanobacteria dominated. A variety of cyanobacteria taxa were present during this period. Most notable in their abundance were *Rhabdoderma, Chroococcus,* and *Microcystis*. The peak 2018 cyanobacteria density of 733 ASU/mL was observed at Basin North on August 6 at a depth of 8m. A total of eight cyanobacteria taxa were present in this sample with *Cyanodictyon*, *Microcystis*, and *Rhabdoderma* each comprising approximately 25% of the community. Despite this being the greatest total cyanobacteria value for the period of record, no water quality issues were experienced. Overall phytoplankton densities rapidly decreased at the end of August and decreased to historical lows during the fall months.

Chrysophytes and Synurophytes have recently been the most frequently occurring nuisance algae in Wachusett Reservoir. As mentioned, *Uroglenopsis* was present starting in mid-April and reached bloom conditions between May and July. *Dinobryon* was typically present at low levels from March through August, but never proliferated and remained well below levels of concern. *Synura* was observed above the early monitoring trigger of 10 ASU/mL three times – once in May (17 ASU/mL) and twice in late July (16 and 11 ASU/mL). Most notable for the second year in a row was the lack in abundance of *Chrysosphaerella*. This motile Chrysophyte typically begins to aggregate within the interflow beginning in mid-June. However, this increase in density and duration did not occur again in 2018. *Chrysosphaerella* was observed at concentrations greater than the early monitoring threshold just three times; August 2, 6, and 9, and did not exceed 167 ASU/mL.

Secchi disk transparency is affected by the phytoplankton dynamics outlined above, as well as the water contributions from the Wachusett watershed and Quabbin transfer. As has been mentioned in nutrient and phytoplankton discussions, weather patterns and percentage of native Wachusett watershed water also affects visibility. In 2018, Secchi disk transparency started in the typical spring range of 23 to 27 m (**Figure 32**). During the *Uroglenopsis* bloom that occurred between May and July, Secchi disk depths decreased to a low of 18 feet due to the abundance of algal colonies present in the epilimnion. Secchi disk depths increased as the bloom dissipated, but remained moderate for the remainder of the season, reaching greater than 30 ft on just one day – November 15 – with a value of 30.5 ft.

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, although data was recorded in several different electronic formats. All phytoplankton data has been compiled and imported into a single database, in order to facilitate future analysis of nearly 5,800 samples collected over this 29-year time period.

Figure 32. 2018 Phytoplankton Monitoring at Wachusett Reservoir



4.4.4 WACHUSETT RESERVOIR PHYTOPLANKTON IMAGES

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

Figure 33. Bacillarophycaea (diatoms): *Navicula*, August 28, 2018, Thomas Basin

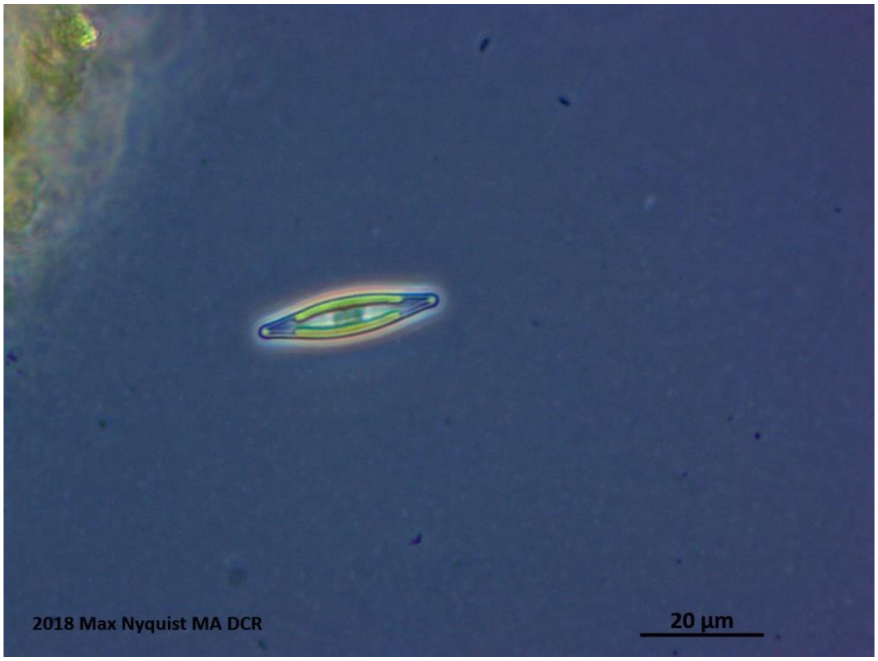


Figure 34. Chlorophyta (green algae): *Pediastrum*, July 9, 2018, Basin North

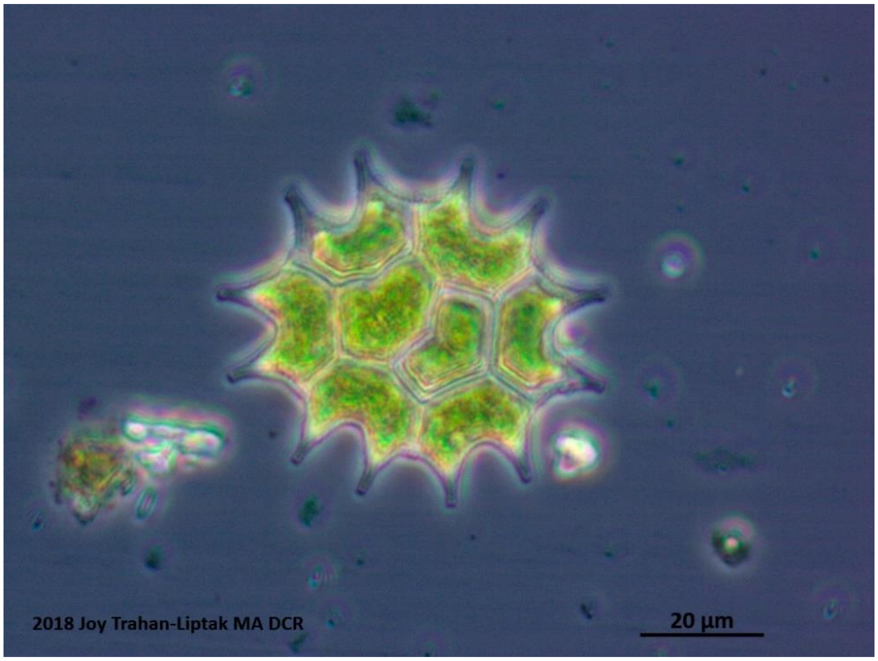


Figure 35. Chlorophyta (green algae): *Sphaerocystis*, September 17, 2018, Basin North

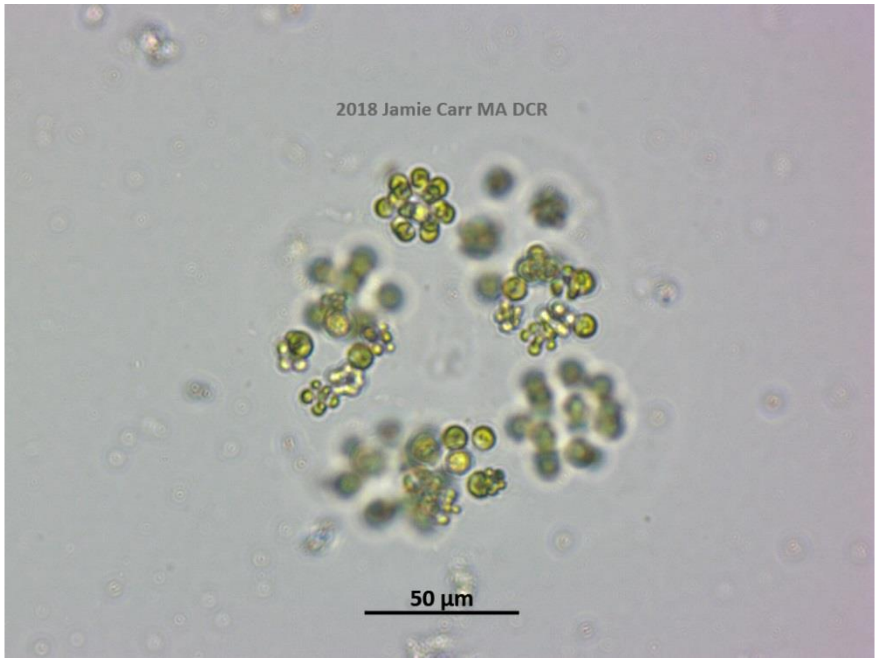


Figure 36. Chrysophyta (golden/golden-brown algae): *Uroglenopsis*, July 9, 2018, Basin North

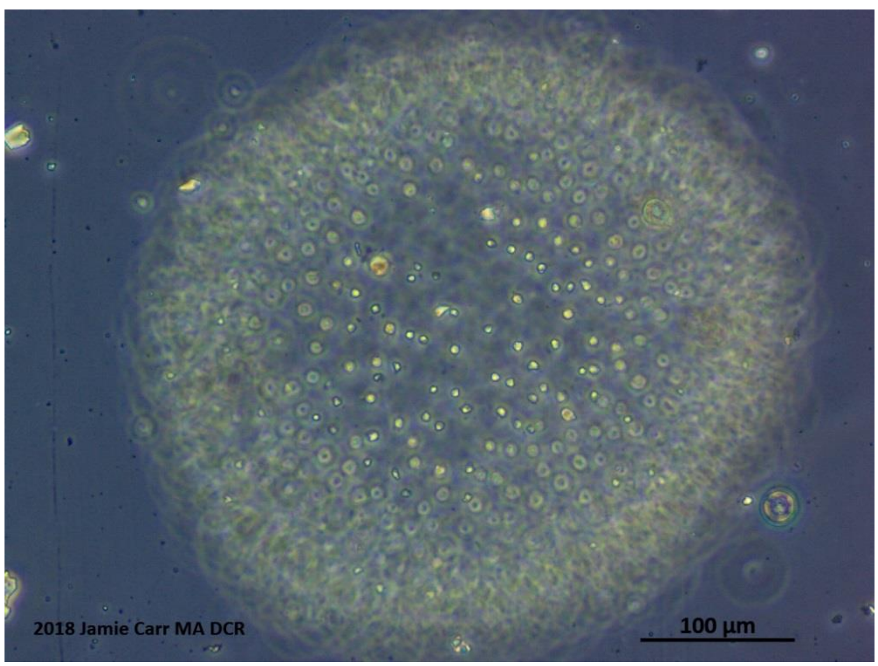


Figure 37. Cyanophyta: *Planktothrix*, May 14, 2018, Basin North

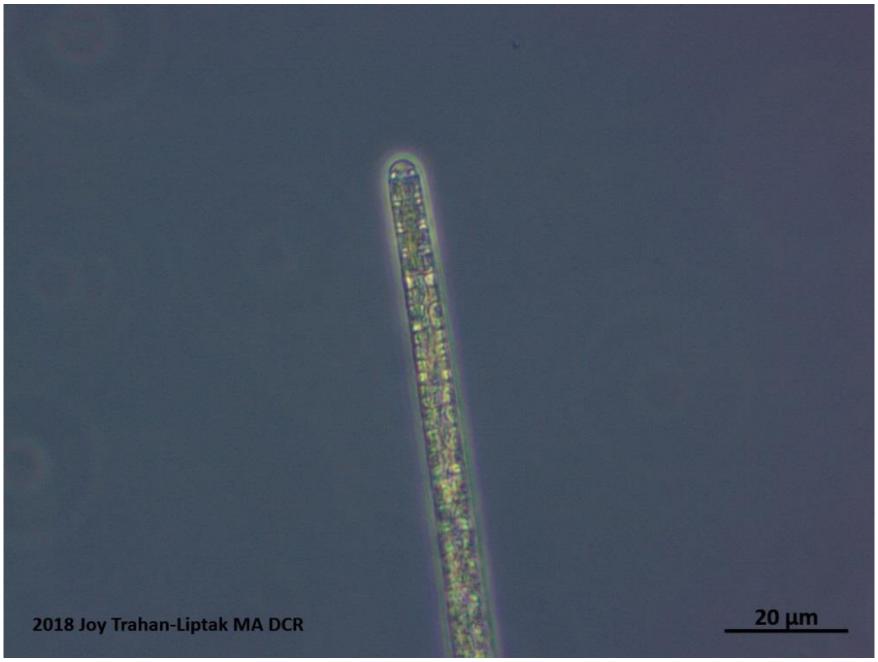
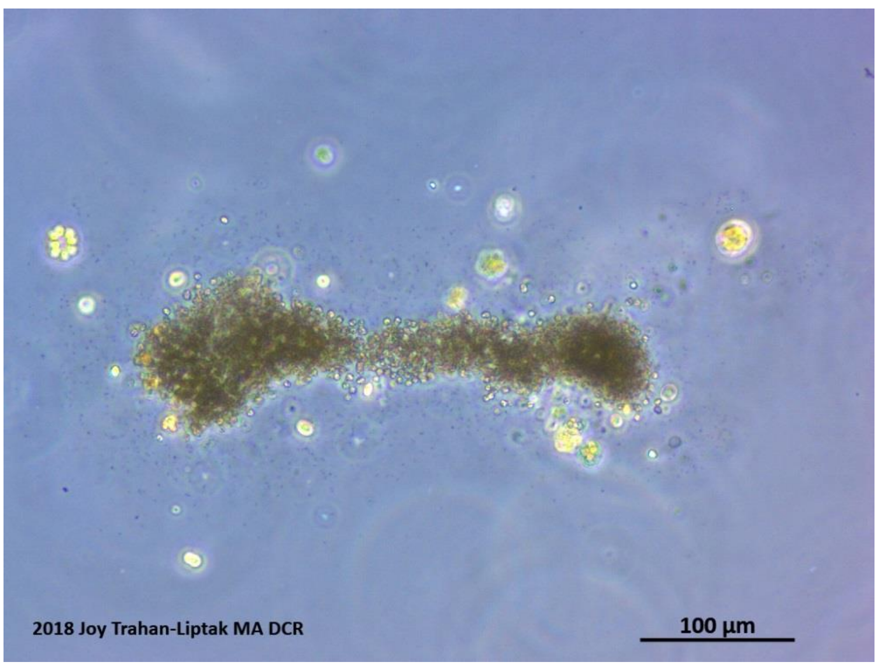


Figure 38. Cyanophyta: *Microcystis*, September 17, 2018, Basin North



4.5 MACROPHYTES

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

An update to the 2010 "Aquatic Invasive Species Assessment and Management Plan" was completed in spring of 2016. This document, titled "Wachusett Reservoir Aquatic Invasive Species Summary; Historical Update and Ongoing Actions" summarizes the history and threat of AIS in and around Wachusett Reservoir and addresses future actions.[16] It is updated periodically to reflect changes in AIS composition within and in proximity to the reservoir.

Table 19. Aquatic Invasive Species in or Around Wachusett Reservoir

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

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

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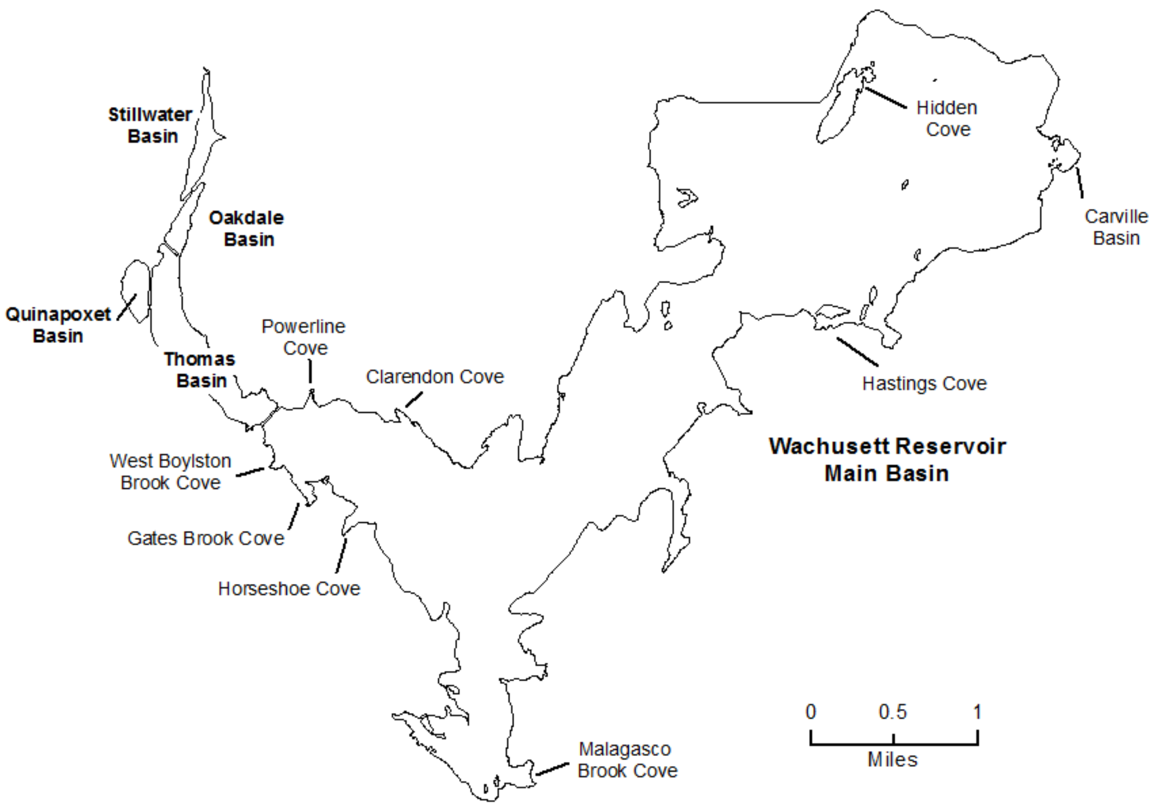
[16] Trahan-Liptak, J., & Carr, J. (2016). *Wachusett Reservoir Aquatic Invasive Species Summary; Historical Update and Ongoing Actions*. MA DCR Division of Water Supply Protection.

The following sections of this report provide details of AIS management activities undertaken during 2018 and those planned for 2019.

4.5.1 WACHUSETT RESERVOIR INVASIVE MACROPHYTE CONTROL PROGRAM

EWM was first identified in the Wachusett Reservoir system on August 31, 1999. The plants were initially isolated to Stillwater Basin; however, over the next several years, distribution extended southerly, in the direction of water flow, progressing through Oakdale Basin, into Thomas Basin and the upper coves of the Main Basin west of the Route 12/140 causeway in West Boylston. Fanwort followed a similar trend, with the initial discovery of the plant in Stillwater Basin in August 2000. The 2001 expansion of EWM into Oakdale Basin prompted the DWSP and the MWRA to design and implement an invasive macrophyte control program. This program was initiated in 2002 and continues to the present.

Figure 39. Locations of 2018 AIS Management in the Wachusett Reservoir System



Removal of EWM and fanwort via hand-harvesting was initiated in Oakdale Basin in 2002. Despite these efforts, EWM and fanwort have gradually spread throughout Thomas Basin and into several coves of the main basin (Error! Reference source not found.). As new infestations are identified, these areas are also targeted in annual removal efforts. DASH (Diver Assisted Suction Harvesting) was first utilized in 2012 and has been continued as an additional control strategy for dense patches of plant growth as a complement to the typical hand-harvesting efforts. An extensive DASH project in Stillwater Basin was initiated in 2013 to reduce the potential for re-infestation from dense growth in this uppermost basin of the reservoir. These physical control efforts are carried out by MWRA contractors and are supervised and at times supplemented by DWSP aquatic biologists. Details of control efforts in past years are provided in previous annual reports. The main components of this program are as follows:

- deployment and maintenance of floating fragment barriers
- hand-harvesting and Diver Assisted Suction Harvesting (DASH)
- routine scouting within the reservoir and watershed by the DWSP aquatic biologists to ensure early detection of pioneering infestations
- immediate removal of pioneer infestations upon detection
- point-intercept vegetation surveys by independent contractors (ESS Group, Inc.)
- scouting the entire littoral zone of Wachusett Reservoir every 5 years (completed in 2012 and 2016)

The following sections provide information on specific management activities that took place throughout the Wachusett Reservoir and in surrounding water bodies in 2018.

Stillwater Basin

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

Program Highlights

- 322,880 gallons of plants removed in the first season of DASH
- Steady decrease in invasive plant biovolume in each year
- Native plants recolonizing previously infested areas
- Stem counts initiated in 2017, phase 2

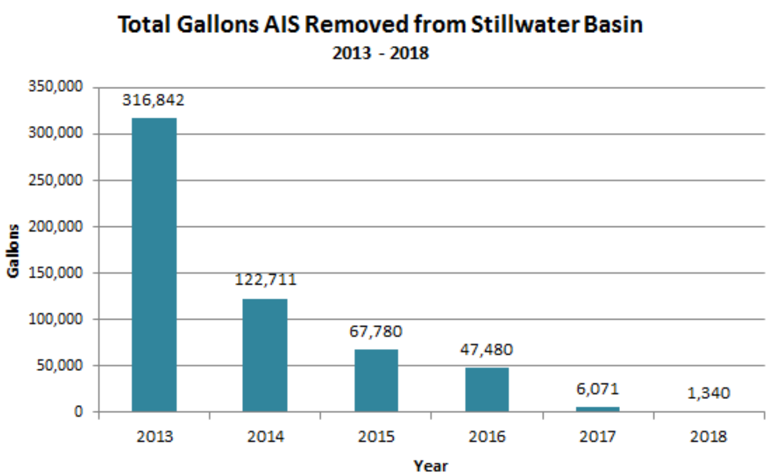
Location of Stillwater Basin

General Management Method

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

2018 Activities

- 1,340 gallons of invasive biomass removed
- 'Hot spots' where yearly re-growth is typically most dense were targeted first in phase 1.
- Two full passes of zones 1 and 2 were conducted. Low densities observed in zone 3 allowed for just one full pass.
- Native plants continue to recolonize previously infested area.
- A new data collection method using a customized app built with ESRI's Survey123 platform allowed for immediate, daily reporting of plant removal activities by the contractor. An online dashboard linked directly to this app allows for real-time monitoring of progress by DWSP and MWRA.



Future Plans

- Management is anticipated to continue in a similar manner. Level of effort will continue to decrease as biomass is reduced; however contingency hours are built into this program should unexpected increases occur or new AIS be discovered within the management areas.

Oakdale & Thomas Basins

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

Program Highlights

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

Location of Thomas and Oakdale Basins

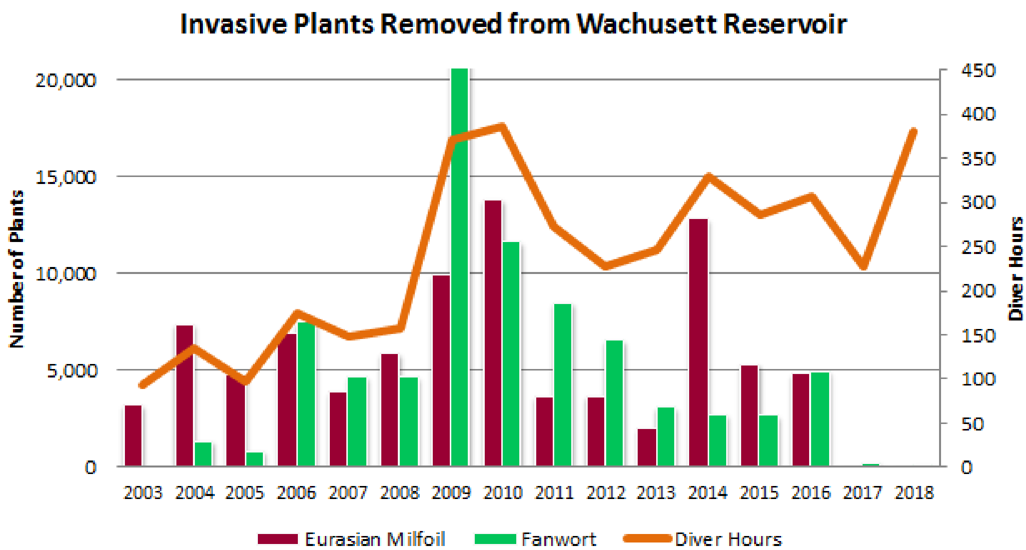
General Management Method

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

2018 Activities

- Two complete passes of each basin were conducted; late July/ August and October
- The number of plants removed in 2018 was consistent with that removed in 2017. Overall, three AIS plants per littoral acres were harvested. In total, 83 Eurasian milfoil and 150 fanwort plants were removed in 2018.

Notes: In 2002, 496.5 diver-hours were expended in removing an estimated 75,000 to 100,000 EWM plants; 2012 – 2015 totals include hand-harvesting by divers as well as DASH; The diver-hour numbers reported here for 2015-2017 are adjusted to reflect raw data reported to DWSP



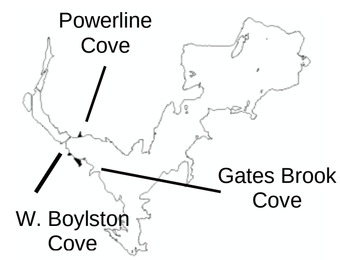
Future Plans

- Management is anticipated to continue in a similar manner in 2019.

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

Powerline	EWM: 2002 – present FW: 2007, 2009-2012, 2014	• Hand-harvesting • Hand-harvesting / DASH combination since 2012
Gates Brook	EWM: 2012 – 2017	
W. Boylston Brook	2012 – 2016	

Program Highlights



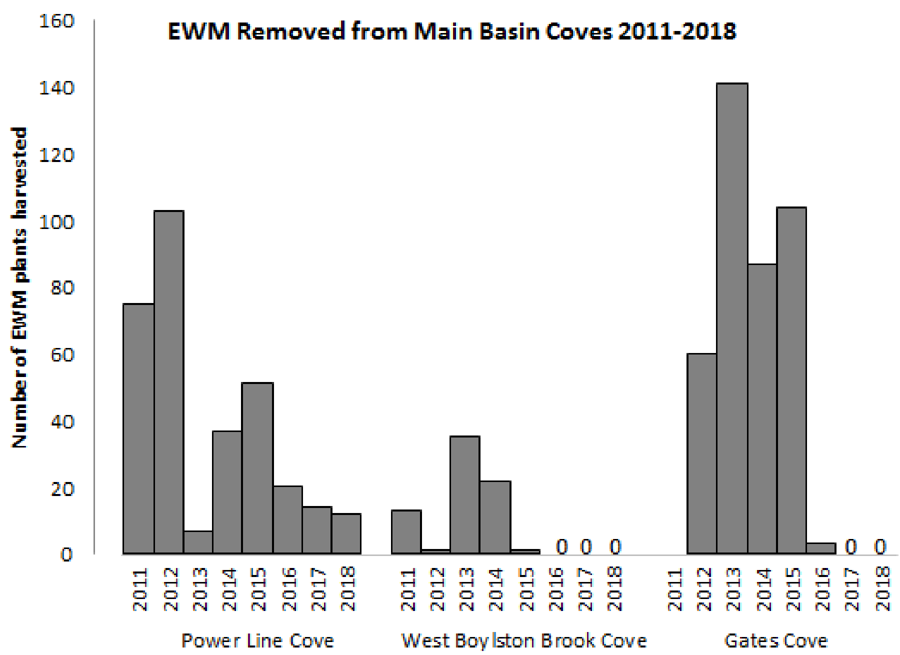
Location of managed main basin coves

- Overall density of invasive plants in these coves is low; however, soft substrates, especially those found in Gates Brook Cove, provide ideal growing conditions for aquatic plants.
- Year-to-year fluctuations in EWM are common
- Fanwort has not been found outside of Powerline Cove and has not occurred since 2014.

General Management Method

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

2018 Activities



- 2018 is the second consecutive year where no EWM plants were discovered in West Boylston Brook Cove or Gates Cove.
- Beaver activity in Powerline Cove continued in 2018 and divers noted that many of the 12 EWM plants removed were located within the cache. DWSP Natural Resources is addressing this issue when possible within the beaver management program.
- 2 days of DASH were used to partially remove a bed of VWM that has increased in Powerline Cove in recent years. 460 gallons of VWM were removed.

Future Plans

- Management is anticipated to continue in a similar manner in 2019.

Quinapoxet Basin

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

Program Highlights

Location of Quinapoxet Basin

- Management of EWM and fanwort was initiated immediately following discovery in 2016; total numbers of plants decreased between 2016 and 2018
- VWM is present throughout the basin at great densities
- Following a pilot program in 2017, it was determined that VWM removal via DASH is feasible in this basin.

General Management Method

- Surveys of the basin are conducted by DWSP biologists to identify the location and extent of AIS to guide removal operations
- Two rounds of DASH targeting EWM and fanwort are conducted; generally August and late September
- A fragment barrier is installed on the upstream side of the rail road bridge between Quinapoxet and Thomas Basins to reduce movement of plant fragments to downstream locations
- DASH removal of VWM was initiated in 2017 and is anticipated to continue with several weeks at the end of each season allocated to removing VWM in and around the inflow channel to reduce the fragmentation and movement of VWM downstream to the main reservoir.

2018 Activities

- EWM density increased slightly since 2017 with 102 plants removed.
- A decrease in fanwort was observed with 6 fanwort plants removed in 2018 compared with 96 in 2017.
- A total of 10,820 gallons of VWM were harvested from approximately 5 acres within and adjacent to the inflow channel. 14 days were expended in this endeavor until ice precluded further work.

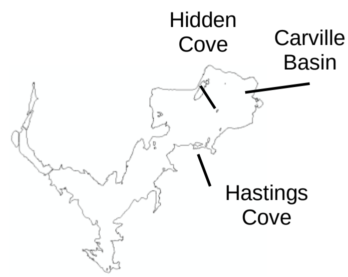
Future Plans

- Management is anticipated to continue in a similar manner in 2019

Hastings Cove, Carville Basin, and Hidden Cove

Invasive Species	VWM First Documented	Management Technique(s)
Hastings Cove	2013	• DASH
Carville Basin	2016	
Hidden Cove	2018	

Program Highlights



Location of Carville Basin and Hastings and Hidden Cove

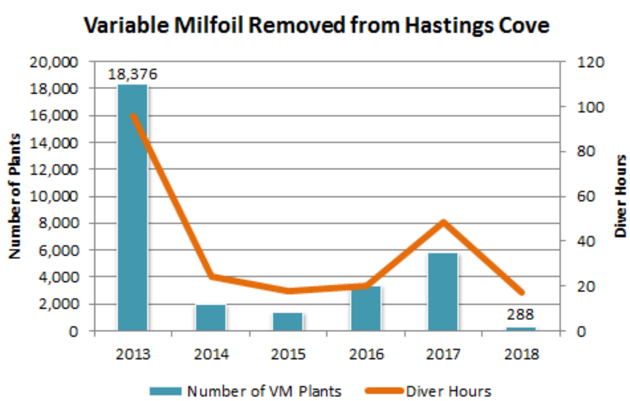
- These areas are the closest to the Cosgrove Intake known to contain VWM. Harvesting was initiated in an effort to prevent the spread of these plant beds and to reduce the potential for fragments to migrate downstream and impact the intake works and for spread to the north basin and the shallows.
- The VWM bed in Hidden Cove was discovered during a snorkel survey in August 2018. DASH was initiated and a fragment barrier has been installed to isolate fragments in this area.

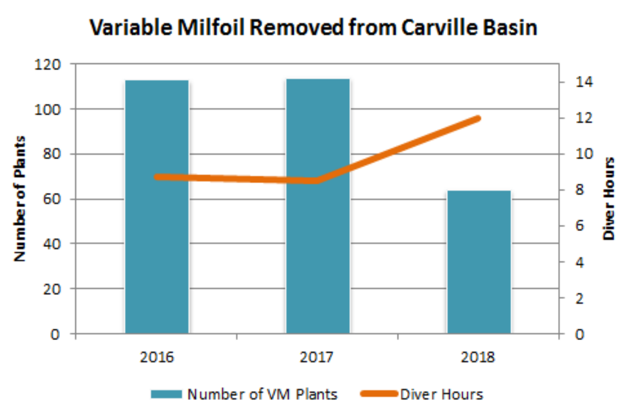
General Management Method

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

2018 Activities

- VLM was discovered in Hidden Cove during a survey in August and DASH was initiated through contract contingency hours in October. 460 gallons of VLM was removed from this 0.12-acre area.
- A substancial reduction in plant numbers was realized in Hastings Cove with just 288 plants removed over two phases.
- There was an approximately 60% reduction in VLM plants present and removed from Carville Basin.





Future Plans

- Management is anticipated to continue in a similar manner in 2019.

Outlying Occurrences of Eurasian water-milfoil

DWSP biologists conduct regular surveys of reservoir areas where EWM has been observed and removed in previous years, as well as areas which have been identified as likely to support invasive species. These include areas which are in proximity to other occurrences of invasive species (both within and nearby the reservoir), areas near roadways or popular fishing areas, and areas where nutrient-rich substrates may provide ideal habitat for new infestations. In 2018, three EWM plants were discovered and removed from Andrews Harbor where plants have been observed previously. Early identification and removal of pioneer plants such as these reduce the risk that these plants will proliferate and become a larger management and budget concern in the future.

Table 20. Locations of EWM in Outlying Reservoir Areas

	Number of EWM Plants Removed					
Location	**2011**	**2012**	**2014**	**2016**	**2017**	**2018**
Andrews Harbor	–	–	–	1	–	3
Clarendon Cove	–	–	–	1	–	–
Flagg Cove	–	–	–	1	–	–
Horseshoe Cove	4	6	–	1	–	–
Malagasco Brook Cove	–	–	1	–	–	–

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

Additional Management Activities:

Contractor Aquatic Macrophyte Surveys

MWRA contracted with ESS Group, Inc. in 2018 to carry out point-intercept surveys of DWSP/MWRA source and emergency reservoirs. These surveys have been conducted on an annual basis since 2013 with a previous survey conducted in 2010. No new AIS were identified in Wachusett Reservoir during the 2018 survey. ESS noted that, a decrease in mudmat bed density observed in 2017 did not continue into 2018, with locations of increased density exceeding the number of locations with decreased density. Mudmat was also identified in 24 new locations, bringing the total to 50 of the 284 ESS routine monitoring sites. ESS further reports that "…the minute size of this plant, the impact of this species on reservoir water quality and ecology is unlikely to be significant."

Management of Phragmites

Common reed (*Phragmites australis*, subsequently referred to as *Phragmites*) has been present along the Wachusett Reservoir shoreline since at least 2009, when it was found in Hastings Cove. *Phragmites* has since spread north and west of this original location and can be found in monotypic stands in at least 18 locations (**Table 21**). Management of *Phragmites* began in 2016. The history of *Phragmites* at Wachusett Reservoir can be found in the document "Spread of *Phragmites* at Wachusett Reservoir"[17] A detailed report of *Phragmites* management during 2018 can be found in "2018 *Phragmites* Shoreline Management."[18]

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[17] MA DCR Division of Water Supply Protection. (2017). Spread of *Phragmites* at Wachusett Reservoir.

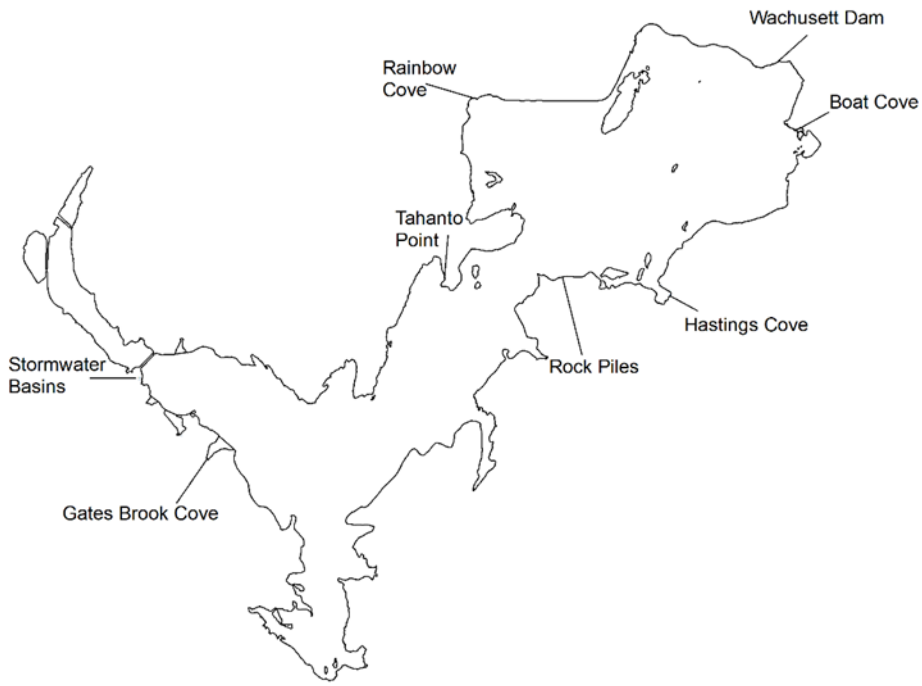
[18] MA DCR Division of Water Supply Protection. (2018). 2018 *Phragmites* Shoreline Management.

Table 21. Known Locations of *Phragmites* around the Reservoir

Stand Location	Area (sq. ft.)	First Documented	Management Methods
Boat Cove A	1,071.48	2013, possibly earlier	Cutting, Acetic acid
Boat Cove B	1,640.00	2013, possibly earlier	Cutting, Acetic acid
Boat Cove C	316.25	2013, possibly earlier	Cutting, Acetic acid
Gates Brook	1,314.14	2014	Cutting
Hastings Cove A	421.57	2009	Cutting, Acetic acid
Hastings Cove B	6,033.95	2009	Cutting
Hastings Cove C	1,634.72	2009	Cutting
Hastings Cove D	190.41	2009	Cutting
Hastings Cove E	503.81	2009	Cutting
Hastings Cove F	145.71	2009	Cutting, Hand pull
Rainbow Cove	896.10	2009	Cutting
Tahanto Point A	511.46	2016, possibly earlier	Cutting
Tahanto Point B	859.85	2016, possibly earlier	Cutting, Hand pull
Stormwater Basin @ Gate 25 A	19.38	2017	Cutting, Glyphosate*
Stormwater Basin @ Gate 25 B	19.88	2017	Cutting, Glyphosate*
Stormwater Basin @ Gate 25 C	16.40	2017	Cutting, Glyphosate*
Rock Piles (NE of narrows)	111.85	2018	Cutting, Hand pull
Dam	5.50	2018	Cutting, Hand pull

*Glyphosate treatment performed as part of DOT ROW contract

Figure 40. Locations of *Phragmites* at Wachusett Reservoir



Program highlights

- Based on photo documentation, middle and end of the year stand height and density was greatly reduced compared to non-management years.
- Two stands have been completely removed, but continued monitoring is necessary.

General management method

- Watershed Maintenance Staff and Aquatic Biologists will perform all management.
- 2018 management took place between June and October.
- Stands are given unique ID values for tracking throughout the management season.
- Stands are cut to the surface of the water or below using line trimmers and loppers.
- Pre and post cut photos are taken before and after each cut at each stand.
- 5 cuts were completed in 2018 for established stands at Hastings Cove, Boat Cove, Tahanto Point, and Rainbow Cove.
- Hand pulling is used at small expansion locations and at the edge of stands at the Dam, Rock Piles, Boat Cove, and Hastings Cove.
- Isolated herbicide treatment in select storm water basins occurred in 2018 in association with a DOT contract.

Table 22. 2018 *Phragmites* Management Activities

June 5	Photo 1
June 8	Cut 1
June 20	Cut 1 completed in the boat cove
June 21	Document Cut 1 in the boat cove
June 22	Pre and post-cut photos of BoatCvC
July 12	Photo 2
July 13	Cut 2
August 13	Photo 3, except Hastings Cove
August 15	Photo 3 at Hastings and Cut 3 at all locations
September 12	Photo 4
September 20	Cut 4
October 17	Photo 5
October 23	Cut 5

Figure 41. DWSP Staff performed five manual cutting treatments of *Phragmites* in 2018. The photos shown below are of the *Phragmites* stand in the reservoir Boat Cove prior to each cutting treatment. The final photo demonstrates the potential height of the *Phragmites* in this location had there been no treatment.

Future plans

- Management is anticipated to continue in a similar manner in 2019

Additional AIS Observations

DWSP Aquatic biologists continue to monitor for known AIS in new locations and potential new introductions. The three non-native aquatic plants most recently detected in Wachusett Reservoir: Mudmat (*Glossostigma cleistanthum*), Asian waterwort (*Elatine ambigua*), and Onerow yellowcress (*Rorippa microphyla*) were discussed in the 2014 Annual Report[19]. Field observations of these species continue 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.

4.5.2 SUPPLEMENTAL INVASIVE MACROPHYTE CONTROL ACTIVITIES

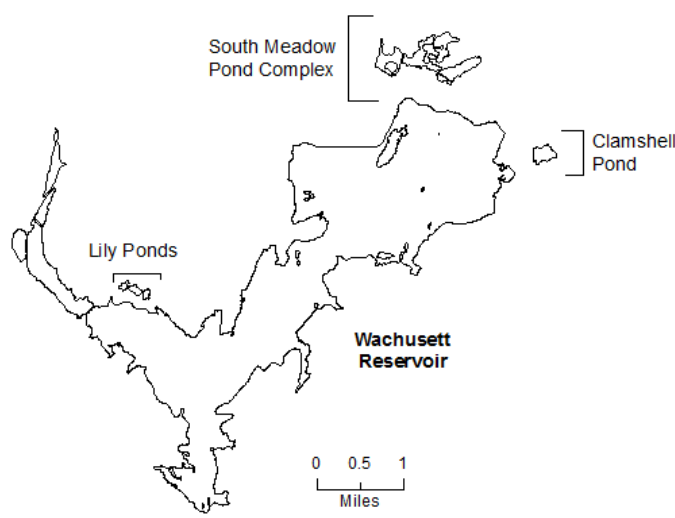
Additional activities were conducted in 2018 outside of the Wachusett Reservoir in conjunction with the main components of the in-reservoir invasive control program. Details of these activities are presented below.

Management of AIS Outside of Wachusett Reservoir

In recent years AIS have been discovered in several local ponds (**Figure 42**). Although technically outside of the Wachusett Reservoir watershed, two of these ponds/complexes have been identified as potential sources of invasive species due to their proximity to the reservoir. The potential for transfer of invasive species present in these water bodies to the reservoir by waterfowl or bait buckets necessitates special management and monitoring efforts. Management of the following ponds is on-going.

South Meadow Pond Complex

Figure 42. Locations of Local Ponds Managed for AIS



In August of 2010, the invasive macrophyte hydrilla (*Hydrilla verticillata*) was discovered in South Meadow Pond in the Town of Clinton. The South Meadow Pond complex (which includes South Meadow Pond West and East as well as Coachlace and Mossy Ponds) is located only about 1,970 feet (600 m) north of Wachusett Reservoir. Within a month of the discovery of hydrilla in the South Meadow Pond complex, DWSP and the MWRA collaborated on response efforts and implemented a program to suppress hydrilla biomass, hiring a contractor to implement a control plan and apply herbicides. The treatment and monitoring program has continued through 2018.

Sediment tuber density is measured in several areas of the ponds complex to monitor the effectiveness of treatments along with surveys conducted by the contractor and DWSP aquatic biologists to monitoring growth thought the year. Following an initial year of whole-pond systemic herbicide

[19] MA DCR Division of Water Supply Protection. (2015). *Water Quality Report: 2014*. Available from https://www.mass.gov /service-details/dcr-watershed-water-quality-reports

treatment, the management plan focused on spot treatment of hydrilla beds with contact herbicides between 2012 and 2017. This method requires careful surveys to find all target plant beds so that the herbicide can be placed directly on or within the bed. Tuber densities were greatly reduced from pre-management levels between 2012 and 2015, with no tubers discovered in 2015.

In 2016, tuber density increased with an average per-site density of 3.16 tubers/m^2 in South Meadow Pond West and 1.8 tubers/m^2 in South Meadow Pond East (although plants were observed in additional areas, no tubers were reported from Coachlace Pond in 2016 and there were no sampling sites in Mossy Pond).

Based on these results, the contractor recommended a change in treatment methods to include use of endothall, an herbicide that has provided control of hydrilla in New York water bodies. Despite use of this product in 2017, a follow-up survey conducted by DWSP biologists showed significant re-growth of hydrilla, necessitating a second treatment. It should be noted that the DWSP survey was conducted while the pond complex was undergoing an algae bloom which caused reduced water clarity, obscuring the view of hydrilla in many areas. Therefore, the extent of hydrilla re-growth was likely underestimated. Following these two treatments, tuber densities were higher than those observed in any year since management started. DWSP decided to return to systemic herbicide treatments for the entire pond complex. This method is better suited to current conditions at South Meadow Pond where many beds of Hydrilla are present and poor clarity makes finding additional areas difficult.

Surveys of the South Meadow Pond complex conducted by DWSP and the contractor during the 2018 treatment showed a reduction in hydrilla biomass with actively growing plants observed at two locations in South Meadow Pond East. Tuber density was also decreased since previous years with an estimated complex-wide tuber density of 0.14 tubers/m^2.

Two additional submerged invasive aquatic species are present in the South Meadow Ponds complex; Curly-leaf pondweed and VWM. Following a survey conducted by DWSP biologists, approximately 25 acres of Curly-leaf Pondweed were treated over all four basins of the pond complex during an early season treatment performed on May 15, 2018. VWM is not a direct target of this management program but is treated concurrently with Curl-leaf pondweed and hydrilla where the species coexist.

Lily Ponds

Two invasive species, *Najas minor* (European/Brittle Naiad) and *Myriophyllum spicatum* (Eurasian water-milfoil) were identified in the Lily Ponds during 2015. Due to the highly invasive nature of these non-native species, DWSP implemented a rapid response and initiated management of these species in the fall of 2015. Management includes closure of the ponds to recreation (i.e., fishing and bait collection, (**Figure 43**) as well as treatment utilizing state-approved and US EPA registered herbicides. The initial treatment of *N. minor* and *M. spicatum* in 2015 was successful in reducing the biomass of both species within each treated pond (see previous management reports for details). The continuing management plan for these ponds includes annual monitoring for *N. minor*, *M. spicatum,* and any other non-native species that may present a threat to the ponds and in turn Wachusett Reservoir.

Figure 43. Signage posted at Gate 28 by the Rangers notifying the public of the Lily Ponds closure

Several surveys were conducted by DWSP Aquatic biologists during the summer of 2018 to assess the effects of the 2017 treatment and determine if additional treatment would be necessary in 2018. During the initial survey on June 13, neither *N. minor* nor *M. spicatum* was observed in any of the three ponds.

A second survey conducted on July 18 showed growth of one invasive species, *N. minor* in each of the three ponds. Moderate to dense growth was observed along the shoreline of Middle Lily Pond while small, sparse patches were observed in the other two ponds with a total area of 3.5 acres. A treatment of these areas was conducted by DWSP contractor SOLitude Lake Management on August 17[20]. Follow-up surveys conducted in September and October by DWSP aquatic biologists showed that the treatment was effective in removing *N. minor* and no additional invasive plants were observed. Notably, 2018 is the third year where *M. spicatum* has not been observed.

Clamshell Pond

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

Brazilian elodea was found in more than 70% of the pond with dense growth most common during the initial survey in 2016 and again 2017. This invasive species is uncommon in Massachusetts (reported in less than 20 locations state-wide) and may be the result of an aquarium release. Although the historical record and extent of

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[20] SOLitude Lake Management. (2018). 2018 Year-End Report, Lily Ponds. Prepared for Massachusetts Department of Conservation and Recreation Lakes and Ponds Program.

growth indicate that this species has likely been present within the pond for some time, and may have expanded to its maximum extent, it remains a water quality threat to Wachusett Reservoir.

DWSP worked with the Town of Clinton Conservation Commission through the DWSP Partnership Program to develop a management plan to reduce the potential for spread of this species to the reservoir and other area water bodies. A DWSP partnership grant was awarded to the Town of Clinton in late 2017 for herbicide treatment of the pond in fiscal year 2018.

DWSP biologists prepared and submitted a Notice of Intent and an Order of Conditions, DEP File #135-0267 was subsequently granted for management of invasive species in Clamshell Pond issued on May 16, 2018 with an expiration date of May 16, 2021. The following is an excerpt of the 2018 Management Summary[21] provided to the Conservation Commission in accordance with the OoC.

> *A spring survey of Clamshell Pond was conducted on May 30th in preparation for herbicide treatment. As observed in previous years, aquatic vegetation was dense throughout the pond's littoral zone and was dominated by E. densa which occurred in sparse to dense patches in approximately 15 acres. Associated native vegetation included Brasenia schreberi (watershield), Potamogeton amplifolius (large-leaf pondweed), Nymphaea odorata (white water lily), Nuphar variegata (yellow water lily), Potamogeton robbinsii (fern-leaf pondweed), and Schoenoplectus subterminalis (water bulrush). Large clouds of filamentous algae were also observed in several areas.*
>
> *Based on the results of this survey, treatment for approximately 13 acres of the littoral zone was scheduled with DCR contractor SOLitude Lake Management. The Clinton Conservation Commission was notified via email ahead of each treatment and treatment notices were posted at public access areas around the pond along with a DEP File number poster. The treatment was conducted over two days separated by several weeks, a standard practice for water bodies with high density of vegetation, which allows for a gradual reduction in plant biomass, limiting oxygen depletion and resulting impacts on fish and wildlife. The initial treatment was conducted on June 6th and the second on June 25th. Treatment areas were developed by DCR based on results of pre and interim surveys. The first treatment targeted the densest areas of E. densa while the second treatment focused on areas of lighter density with some overlap of the initial treatment areas to increase herbicide contact time in these dense beds of E. densa.*
>
> *An interim assessment was conducted by DCR between treatments on June 14th and post-treatment surveys were conducted a month following treatment on July 27th and in the fall on September 19th. Results of these surveys showed that E. densa biomass was greatly reduced during this first treatment year, with just one deteriorated stem of the plant collected during the fall survey. Native vegetation persisted throughout the treatment with growth patterns similar to those observed in 2016 and 2017. Dense floating-leaf species were present along the majority of the pond's shoreline especially within coves and the north, east, and south shorelines. Vegetation observed from the surface was dominated by N. odorata with floating mats of lily rhizomes common along with Utricularia (bladderwort) and clouds of filamentous algae. P. robbinsii was dominant along the pond's bottom, blanketing much of the substrate (see image below).*
>
> *A total of 64 T. natans rosettes were removed from seven locations, primarily along the southern shoreline of the pond during DCR's May survey. An additional 23 plants were removed by volunteers on June 22nd.*

[21] MA DCR Division of Water Supply Protection. (2018). *Invasive Species Management in Clamshell Pond Clinton, MA: 2018*.

No additional T. natans were identified during DCR's follow-up surveys bringing the total water chestnut harvest to just 87 plants, a substantial reduction compared to the 904 plants removed in 2016.

Figure 44. Clamshell Pond Images

Clockwise from top left: E. densa plant sampled on May 30, filamentous algae mass on May 30, the only E. densa fragment found during the September survey, a T. natans rosette removed by DWSP on May 30.

Results of spring/early summer surveys of Clamshell Pond conducted by DWSP will continue to determine management actions on an annual basis. We anticipate that a littoral zone treatment similar to that conducted in 2018 will be necessary in 2019. Following several years of decreased biomass, treatment areas will be reduced to target any remaining patches of *E. densa*. *T. natans* removal will continue via hand-harvesting with a combination of DWSP biologists and volunteers.

4.5.3 Watershed Pond Assessments

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

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

Table 23. Wachusett Reservoir Area Ponds Surveyed in 2018 for Non-native Aquatic Vegetation

Name	Town	Proximity to Wachusett Reservoir (miles)*	Acres	Number of Invasive Vegetation Species Observed	Year management initiated
Clamshell Pond	Clinton	0.25	24.3	2	2016
Lily Pond East	West Boylston	0.21	4.7	1	2015
Lily Pond Middle	West Boylston	0.21	7.5	2	2015
Lily Pond West	West Boylston	0.26	4.3	1	2015
South Meadow Pond Complex	Clinton/Lancaster	0.3	130	3	2010
Paradise Pond	Princeton	7.5	61	2	n/a$^{\alpha}$

* number of miles to closest reservoir shoreline location

$^{\alpha}$ shoreline survey conducted 6/13/2018 for informational purposes confirms large areas of *Utricularia inflata* and *M. heterophyllum*. DWSP is investigating the possibility of treatment here in coordination with the DWSP Lakes and Ponds Program.

4.5.4 PLANS FOR INVASIVE PLANT CONTROL EFFORTS IN 2019

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

Plans for the 2019 season call for continuation of DASH in all upper basins of the reservoir (Oakdale, Quinapoxet, and Thomas Basins), as well as coves of the main basin. DWSP aquatic biologists will continue to conduct surveys and guide contractor harvest efforts as well as manage data collection throughout the project. The large-scale Stillwater Basin DASH project is scheduled to resume in June 2019 for another full season of intensive harvesting.

Associated with harvesting efforts, DWSP aquatic biologists will continue systematic scouting for invasive macrophytes throughout the reservoir system to identify and target any pioneering specimens found in new locations.

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

- Coordinate with AIS contractors for access, progress monitoring, direct work
- Monitor efficacy of herbicide treatments in area ponds
- Install, maintain, and monitor floating fragment barriers

- Conduct surveys of areas of interest (Stillwater, Oakdale, Thomas, main basin coves)
- Document and lead management of *Phragmites* around the reservoir shoreline
- Conduct surveys of local water bodies
- Respond to any new AIS discoveries as appropriate
- Inspect all boats, divers, and other in-water equipment or individuals accessing the reservoir and collect decontamination forms
- Keep the Wachusett Watershed Rangers up to date on AIS topics to guide their interactions with recreational users

4.6 FISH

Fish are an important component of the reservoir ecosystem and knowledge of fish population dynamics in the reservoir is important to understanding the Wachusett Reservoir food web and its impacts upon drinking water quality. Historical fisheries work in the reservoir consisted of angler creel surveys, conducted in 1979, 1980 and 1998, along with sporadic and infrequent sampling in the reservoir. More recent angler creel surveys conducted in 2011 and 2012 show that the species most frequently caught by anglers have changed over the past 30 years, and that this likely reflects changes in the fish community composition over this time period. An angler creel survey was conducted at Wachusett Reservoir during the 2017 angling season, following the recommendation to complete one every 5 years [22]. Results of the 2017 creel survey will be published in a separate report in 2019.

Lake Trout

The creel survey report recommended further study to learn more about the current population status, life history, and sustainable yield of Lake Trout (*Salvelinus namaycush*) in the Wachusett Reservoir due to their presence as the top cold water predator in the reservoir food chain, the absence of information about their population, and their susceptibility to climate change[23].

As a result, in 2014, MA DFW and MA DWSP partnered to initiate a tagging study of lake trout in Wachusett Reservoir similar to an ongoing effort for Quabbin Reservoir. This project involves setting gill nets to capture lake trout moving onto their shallow spawning areas after dark in the fall, weighing and measuring each fish caught, inserting a passive integrated transponder (PIT) tag, and releasing the fish. If a lake trout is recaptured, the PIT tag will identify that specific fish and changes in weight and length can be recorded. As more fish are tagged in subsequent years, more fish will be recaptured, and more information will be gained.

To date, 492 lake trout have been captured during fall sampling efforts between 2014 and 2018, and 359 of these individuals have been tagged and released. 27 fish that had been tagged and released previously have been recaptured (five fish have been recaptured twice). 42 fish were either released without being tagged, harvested for collection of otoliths to aid in future age analysis, or considered mortalities.

To date, 64% of lake trout captured in Wachusett Reservoir were males, while 19% were females (the remainder were immature of unknown sex). It is believed that male lake trout are caught more frequently in gill nets when spawning

[22] Carr, J. 2015. Wachusett Reservoir Creel Survey Report; Survey Years 2011-2012. MA DCR Division of Water Supply Protection. Retrieved Available from https://www.mass.gov/files/documents/2017/09/29/wachusettcreelsurveyreport2011-2012.pdf

[23] ibid

because they spend more time making multiple passes of the spawning are searching for females. Females are believed to move onto the spawning area to spawn without lingering and thus are less likely to be captured.

Figure 45. A DWSP Biologist Measures a Lake Trout Captured in a Gill Net

Figure 46. PIT Tag

Other Fish Species

MA DWSP and MA DFW biologists collaborated over two days in late June to conduct the first known electroshocking event in Wachusett Reservoir. Results of this and future electroshocking efforts will provide information about the smaller warm water fish species in the Reservoir.

5.0 SAMPLING PLAN FOR 2019

The Wachusett watershed tributary sampling program for 2019 is very similar to 2018 and is outlined below. Field parameters (temperature, specific conductance, pH, dissolved oxygen, and stage (where available)) will be measured along with all other routine water quality samples. For years leading up to 2018, issues with field measurements of dissolved oxygen and pH resulted in the exclusion of these parameters from routine monitoring. SOPs for water quality and hydrologic monitoring were developed in 2019 and include regular equipment calibration and maintenance, and have resolved prior concerns with the integrity of field measures of these variables. pH and dissolved oxygen were incorporated into the suite of routinely measured field parameters in 2019.

E. coli and turbidity will be measured twice per month at 18 stations on 17 tributaries without regard to weather conditions (no change from 2018). Bacteria sampling at Upstream Prospect #1 will only be conducted to confirm the source of high bacteria observed at Gates Brook 1 and Gates Brook 4, and only if bacteria levels are not uniformly elevated across all sample locations as a result of a precipitation event or extreme low flows. At other tributaries additional sampling for *E. coli* will be performed within 48-72 hours when a result is higher than a predetermined metric based on historical observations and overall watershed conditions at the time of the sample. Supplementary samples may also be collected from these stations when specific flow conditions are present that have been under-sampled in the past, or when/where necessary to help identify sources of contamination (Jordan Farm).

Nutrients, total suspended solids, and chloride will be sampled monthly from ten tributary stations with available flow data, and hopefully a second time each month during previously under-sampled conditions, such as low flow during extended drought or periods of high flow caused by snow melt or large precipitation events. Shaft #1 (Quabbin transfer) will continued to be sampled monthly (when flowing) for nutrients, TSS, and chloride.

Groundwater sampling for chloride will be conducted monthly at eight wells in order to characterize groundwater chloride concentrations in various aquifers in the watershed (new for 2019). Additionally, specific conductance, temperature, and water depth will be collected at the time of each chloride sample. Groundwater chloride sample collection will continue until enough data are collected to derive a correlation between chloride and specific conductance, at which point chloride concentrations will be estimated from specific conductance measurements. This new sampling project has been assigned the project name “WATWEL” by MWRA.

Routine sampling provides some data on the effects of storm events on tributary water quality when samples are collected during or following precipitation. More detailed stormwater sampling may be done to obtain data on specific storm types (length, intensity, and season) following an evaluation and assessment of existing information. Samples for a variety of parameters will be collected during extreme precipitation events (>2" of rainfall/runoff) when possible to support UMass/DWSP modeling efforts.

Understanding watershed hydrology is a necessary part of any water quality monitoring program. A continuation of the hydrology monitoring program is planned for 2019. Precipitation data from NOAA weather stations in Worcester and Fitchburg and from the USGS stations on the Stillwater River in Sterling and the Quinapoxet River in Holden will be downloaded daily. Snowpack measurements and calculation of snow-water equivalent amounts will be done regularly during the winter months throughout the watershed.

Water depth will be recorded at seven stations and flow calculated using rating curves developed by DWSP staff. Depth measurements will be collected continuously using HOBO water level data loggers. Additional locations may be added to increase our understanding of flow throughout the watershed. Discharge measurements will be taken at several times throughout the year to correct or improve existing rating curves. Daily flow in Gates Brook and the Stillwater and Quinapoxet Rivers will be obtained from continuous recording devices installed by the USGS. A pilot hydrologic monitoring station will be installed at Waushacum Brook in 2019. This station will be outfitted with a HYDROS 21 sensor (Meter Group, Inc.) that will record specific conductance, water depth, and temperature measurements every 15 minutes and store the data on a Mayfly datalogger. Additionally, the data will be available to view and download in real-time on the web. Pending the results of this pilot station all tributaries monitored using HOBO dataloggers will be phased over to Mayfly dataloggers, allowing for real-time flow and water quality information at all major Wachusett Tributaries.

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 50 feet of a stream or steep slopes are present. Summary reports will be produced for each location once active operations are complete and post-cutting monitoring has ended.

Monitoring to assess impacts of active forest management will continue. The monitoring effort utilizes paired subbasin sampling at and near a single forestry site in the Wachusett watershed. Sampling includes monthly dry weather grab sampling for turbidity, TSS, TOC, NH_3-N, UV_{254}, NO_3-N, NO_2-N, TKN, and TP and quarterly storm event monitoring using automatic samplers. Documentation of tributary flow, 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 DWSP forestry management methods prevent measurable impacts upon stream water quality. A summary report that covers the first five years of the study will be completed in FY2020.

Temperature, dissolved oxygen, chlorophyll *a*, pH, turbidity, 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 NH_3-N, NO_3-N, TKN, TP 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 Reservoir Nutrient Sampling

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

		Sampling Date			
ID	Sampling Station	5/9/2018	7/20/2018	10/10/2018	12/5/2018
MD25	Basin North (S)	<0.005	0.0062	<0.005	<0.005
MD61	Basin North (M)	<0.005	0.0119	<0.0056	<0.005
MD62	Basin North (D)	<0.005	0.0094	0.0062	<0.005
MD26	Basin South (S)	<0.005	0.0067	<0.0054	0.0063
MD63	Basin South (M)	<0.005	0.0083	0.0072	0.0061
MD64	Basin South (D)	<0.005	0.0104	0.0074	0.0062
MD27	Thomas Basin (S)	0.0096	0.007	0.0096	0.0089
MD65	Thomas Basin (M)	0.0121	0.0086	0.0100	0.0091
MD66	Thomas Basin (D)	0.007	0.0086	0.0098	0.0093

Ammonia-Nitrogen (NH_3-N) (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	5/9/2018	7/20/2018	10/10/2018	12/5/2018
MD25	Basin North (S)	0.0068	0.0069	<0.005	<0.005
MD61	Basin North (M)	0.0080	<0.005	0.0165	<0.005
MD62	Basin North (D)	0.0095	0.0309	<0.005	<0.005
MD26	Basin South (S)	0.0070	<0.005	<0.005	<0.005
MD63	Basin South (M)	<0.0053	<0.005	0.0159	<0.005
MD64	Basin South (D)	0.0122	0.0284	<0.005	<0.005
MD27	Thomas Basin (S)	<0.005	0.0080	<0.005	<0.005
MD65	Thomas Basin (M)	0.0229	<0.0055	0.0095	<0.005
MD66	Thomas Basin (D)	0.0110	<0.005	0.0196	<0.005

Nitrate-Nitrogen (NO_3-N) (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	5/9/2018	7/20/2018	10/10/2018	12/5/2018
MD25	Basin North (S)	0.0861	<0.005	0.0130	0.0735
MD61	Basin North (M)	0.1030	0.0162	0.0592	0.0746
MD62	Basin North (D)	0.0960	0.1150	0.1480	0.0686
MD26	Basin South (S)	0.0961	<0.005	0.0120	0.0966
MD63	Basin South (M)	0.0975	0.0088	0.0492	0.0929
MD64	Basin South (D)	0.1050	0.1120	0.1300	0.0942
MD27	Thomas Basin (S)	0.0996	<0.005	0.0228	0.1820
MD65	Thomas Basin (M)	0.1360	0.0105	0.0449	0.1800
MD66	Thomas Basin (D)	0.1630	0.0128	0.0435	0.1740

Total Kjeldahl Nitrogen (TKN) (mg/L; MDL = 0.1 mg/L)

		Sampling Date			
ID	Sampling Station	5/9/2018	7/20/2018	10/10/2018	12/5/2018
MD25	Basin North (S)	0.239	0.228	0.146	0.133
MD61	Basin North (M)	0.180	0.247	<0.1	0.171
MD62	Basin North (D)	0.177	0.195	<0.1	0.206
MD26	Basin South (S)	0.178	0.190	0.119	0.314
MD63	Basin South (M)	0.139	0.233	0.128	0.185
MD64	Basin South (D)	0.176	0.174	0.119	0.167
MD27	Thomas Basin (S)	0.281	0.204	0.161	0.188
MD65	Thomas Basin (M)	0.356	0.174	0.145	0.182
MD66	Thomas Basin (D)	0.169	0.158	0.122	0.201

Mean UV_{254} (mg/L)

		Sampling Date			
ID	Sampling Station	5/9/2018	7/20/2018	10/10/2018	12/5/2018
MD25	Basin North (S)	0.0757	0.0606	0.0594	0.0852
MD61	Basin North (M)	0.0825	0.0581	0.0682	0.0843
MD62	Basin North (D)	0.0744	0.0749	0.0661	0.0846
MD26	Basin South (S)	0.0839	0.0613	0.0643	0.1227
MD63	Basin South (M)	0.0874	0.0525	0.0986	0.1250
MD64	Basin South (D)	0.0821	0.0744	0.0648	0.1248
MD27	Thomas Basin (S)	0.1577	0.0637	0.1341	0.1752
MD65	Thomas Basin (M)	0.1774	0.0569	0.1285	0.1754
MD66	Thomas Basin (D)	0.1258	0.0503	0.0981	0.1744

Silica (mg/L)

		Sampling Date			
ID	Sampling Station	5/9/2018	7/20/2018	10/10/2018	12/5/2018
MD25	Basin North (S)	2,680	1,530	1,850	3,050
MD61	Basin North (M)	3,050	1,810	2,450	3,010
MD62	Basin North (D)	2,960	3,470	3,350	3,010
MD26	Basin South (S)	2,930	1,490	1,960	3,950
MD63	Basin South (M)	3,150	1,710	3,020	3,950
MD64	Basin South (D)	3,330	3,470	3,510	4,030
MD27	Thomas Basin (S)	2,960	1,640	3,400	6,110
MD65	Thomas Basin (M)	3,320	1,800	3,710	6,000
MD66	Thomas Basin (D)	3,600	1,820	3,020	6,030

Alkalinity (mg/L)

		Sampling Date			
ID	Station	5/9/2018	7/20/2018	10/10/2018	12/5/2018
MD25	Basin North (S)	6.28	7.08	6.62	6.84
MD61	Basin North (M)	6.32	5.84	6.20	7.04
MD62	Basin North (D)	6.18	6.50	6.70	6.62
MD26	Basin South (S)	6.42	7.14	6.86	7.08
MD63	Basin South (M)	6.42	6.00	6.36	7.36
MD64	Basin South (D)	6.28	6.42	6.86	7.06
MD27	Thomas Basin (S)	8.88	7.50	7.88	7.20
MD65	Thomas Basin (M)	8.24	5.66	6.54	7.10
MD66	Thomas Basin (D)	6.22	4.90	5.82	7.22