Water Quality Report: 2019

Wachusett Reservoir Watershed

Crow Hill and Paradise Ponds - Princeton, MA (Dan Crocker, 2020)

August 2020

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

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Abstract

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management manages Wachusett Reservoir and lands within the watershed in order to assure the availability of safe drinking water to present and future generations. The Division's Environmental Quality Section implements a comprehensive water quality and hydrologic monitoring program to screen for potential pollutants, measure the effectiveness of watershed management programs, better understand the responses of the Reservoir to a variety of physical, chemical, and biological inputs, assess the ecological health of the Reservoir and the Watershed system, and demonstrate compliance with state and federal water quality standards. As part of this program, Environmental Quality Section staff perform field work, manage and interpret water quality data, and prepare reports of findings. This report is a summary and discussion of water quality monitoring methods and results from all water quality and hydrological monitoring activities carried out by the Division in the Wachusett Reservoir Watershed during 2019. This annual water quality report is intended to meet the needs of watershed managers, the interested public, and others whose decisions must reflect water quality considerations.

Monitoring of tributaries is a proactive measure aimed at identifying trends and potential problem areas that may require additional investigation or corrective action. In 2019, Wachusett Reservoir water quality satisfied the requirements of the Filtration Avoidance Criteria established under the United States Environmental Protection Agency Surface Water Treatment Rule. Compliance with state surface water quality standards among the tributaries varied, with minor exceedances attributed to higher solute loads measured during storm events, wildlife impacts, and/or natural attributes of the landscape. Excessive loading of dissolved salts to the tributaries and Reservoir has continued, as evidenced by specific conductance and chloride results for 2019. Other than dissolved salts and specific conductance, the results of the Wachusett Watershed monitoring programs were consistent with historical data and demonstrate continued adherence to high drinking water quality and aquatic life use standards.

The appendix to this report includes summary information on mean daily flows of gauged tributaries and a list of applicable water quality criteria/standards or thresholds of interest. Some of the ancillary data presented in this report have been compiled with the help of outside agencies (e.g., U.S. Geological Survey) and other workgroups within Division of Water Supply Protection whose efforts are acknowledged below.

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Abbreviations

The following abbreviations are used in this report:

AIS	Aquatic Invasive Species
Cl	Chloride
CWTP	Carroll Water Treatment Plant
DCR	Massachusetts Department of Conservation and Recreation
DWSP	Department of Conservation and Recreation, Division of Water Supply Protection
EPA	U.S. Environmental Protection Agency
EQ	Environmental Quality
E. coli	*Escherichia coli*
EWM	Eurasian Water-Milfoil (*Myriophyllum spicatum*)
LTF	Long-term Forestry [Monitoring]
MassDEP	Massachusetts Department of Environmental Protection
MassDOT	Massachusetts Department of Transportation
MassWildlife	Massachusetts Division of Fisheries and Wildlife
MCL	Maximum Contaminant Level
MWRA	Massachusetts Water Resources Authority
N/A	Not Applicable
OWM	Office of Watershed Management
NH_3-N	Ammonia-nitrogen
NH_4-N	Ammonium-nitrogen
NO_2-N	Nitrite-nitrogen
NO_3-N	Nitrate-nitrogen
NOAA	National Oceanographic and Atmospheric Administration
SMCL	Secondary Maximum Contaminant Level
SOP	Standard Operating Procedure
STF	Short-term Forestry [Monitoring]
SWE	Snow Water Equivalent
SWTR	Surface Water Treatment Rule
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
THM	Trihalomethane
TSS	Total Suspended Solids
UMass	University of Massachusetts
U.S.	United States
UV_{254}	Ultraviolet Absorbance at 254 Nanometers
USGS	U.S. Geological Survey
VWM	Variable Water-Milfoil (*Myriophyllum heterophyllum*)

Units of Measurement

Chemical concentrations of constituents in solution or suspension are reported in milligrams per liter (mg/L) or micrograms per liter (μg/L). These units express the concentration of chemical constituents in solution as mass (mg or μg) of solute per unit of volume of water (L). One mg/L is equivalent to 1,000 μg/L. Fecal coliform results are reported as the number of presumptive colony forming units per 100 milliliters of water (CFU/100 mL). Total coliform and *Escherichia coli (E. coli)* are reported as the most probable number (MPN/100 mL), which is equivalent to CFU/100 mL and acceptable for regulatory reporting. Mean UV_{254} results are reported as the amount of ultraviolet light at a 254 nm wavelength that is able to transmit through a water sample in absorbance units per centimeter of path length (ABU/cm).

The following units of measurement are used in this report:

ABU/cm	Absorbance units per centimeter of path length
ASU/mL	Areal standard units per milliliter
cfs	Cubic feet per second
CFU	Colony-forming unit
°C	Degrees Celsius
ft	Feet
in	Inches
μS/cm	Microsiemens per centimeter
MG	Million gallons
MGD	Million gallons per day
μg/L	Microgram per liter
mg/L	Milligram per liter
m	Meters
MPN	Most probable number (equivalent to CFU)
nm	Nanometers
NTU	Nephelometric turbidity units
S. U.	Standard Units (pH)

1 Introduction

The Department of Conservation and Recreation (DCR), Division of Water Supply Protection (DWSP), Office of Watershed Management (OWM[1]) 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 Massachusetts communities. The active watershed system includes Quabbin Reservoir, Ware River, and Wachusett Reservoir watersheds, interconnected by a series of aqueducts (Figure 1). Sudbury watershed, containing Sudbury and Foss Reservoirs, is also part of this system, however it was taken out of regular service in 1978 and is maintained as part of the MWRA emergency backup water supply[2].

The U.S. Environmental Protection Agency (EPA) introduced the Federal Surface Water Treatment Rule (SWTR) in 1989 to ensure that public water supply systems that use surface waters provide safeguards against the contamination of water by viruses and bacteria. These regulations require filtration by every surface water supplier unless strict source water quality criteria and watershed protection goals can be met, including the development and implementation of a detailed watershed protection plan. DWSP and MWRA have maintained a joint waiver for the filtration requirement of the SWTR since 1998 and work together to manage the water supply watersheds in fulfillment of the waiver[3].

DWSP monitors the quality and quantity of source water within the reservoirs and their tributaries, whereas MWRA is responsible for monitoring water quality upon withdrawal from the reservoirs and throughout the treatment and distribution process[4]. DWSP water quality sampling and field inspections help identify potential water quality issues, aid in the implementation of watershed protection plans, and ensure compliance with state and federal water quality criteria for public drinking water supply sources (e.g., the filtration avoidance requirements stipulated under the SWTR). Routine monitoring of bacteria and nutrients in the reservoirs and tributaries provides an indication of sanitary quality of water sources, promoting security of water resources and public health. Monitoring is also conducted by DWSP staff to better understand the responses of the reservoirs and tributaries to a variety of physical, chemical, and biological inputs, and to assess the ecological health of these water resources. A long-term record of water quality statistics provides information regarding potential controls on observed changes in water quality over time and represents a proactive effort to identify emerging threats to water quality.

This annual summary is intended to meet the needs of watershed managers, the interested public, and others whose decisions must reflect water quality considerations. The following pages summarize and discuss water quality monitoring methods, results and major findings from all water quality and hydrological monitoring activities carried out by DWSP in the Wachusett Reservoir watershed during 2019. Additionally, some background information is included for context and programmatic status updates are provided to document changes in monitoring programs. Data generated from water quality monitoring in 2019 and prior years are available upon request.

The remainder of Section 1 provides an overview of the water quality regulations applicable to the water resources of the Wachusett Reservoir watershed, summarizes DWSP goals and objectives with respect to its water quality monitoring programs and includes an overview of the MWRA water supply system and

[1] In most instances in this document DWSP is used to refer to DWSP-OWM-Wachusett/Sudbury Region
[2] Massachusetts Water Resources Authority [MWRA], 2014
[3] Massachusetts Department of Conservation and Recreation (DCR) & MWRA, 2004
[4] Ibid

Wachusett Reservoir watershed. Section 2 presents methods for water quality monitoring programs in 2019, including an overview of monitoring locations, the parameters monitored and their manner of analysis, and documentation of statistical methods and data management tools utilized. Section 3 presents results for all Wachusett watershed monitoring programs. Conclusions and recommendations are offered in Section 4, where significant findings are discussed and any proposed changes to Wachusett watershed water quality monitoring programs are presented. References are listed in Section 5 and additional information and data are provided in the Appendices.

1.1 Public Water Supply System Regulations

Water quality criteria in the SWTR rely on an indicator organism, fecal coliform bacteria, and a surrogate parameter, turbidity, to provide a measure of the sanitary quality of the water. The SWTR requires that fecal coliform concentrations at the intake of an unfiltered surface water supply shall not exceed 20 colony-forming units (CFU) per 100-mL in ninety percent of the samples in any six-month period. There are two standards for turbidity levels at source water intakes. The SWTR requires that turbidity levels at the intake are below five NTU at all times[5]. Massachusetts Department of Environmental Protection (MassDEP) regulations require that turbidity levels at the point of consumption for all public drinking water remains below 1 NTU at all times[6]. Authority to enforce the STWR has been delegated to MassDEP.

All waters within the Wachusett watershed are designated as Class A Public Water Supply[7] and thereby are considered Outstanding Resource Waters (ORW) for the purposes of water quality protection[8]. Massachusetts has developed numerical Class A water quality criteria for several parameters. These are presented in Appendix A along with the SWTR standards. Narrative criteria for Class A waters also exist for some parameters, including nutrients:

> *Unless naturally occurring, all surface waters shall be free from nutrients in concentrations that would cause or contribute to impairment of existing or designated uses and shall not exceed the site-specific criteria developed in a TMDL or as otherwise established by the Department pursuant to 314 CMR 4.00.*[9]

There are other standards that apply to various elements and compounds in public drinking water supplies, such as arsenic, polychlorinated biphenyls (PCBs), and haloacetic acids[10]. The required monitoring for these substances at different stages in the system (i.e. after treatment, after disinfection, and point of consumption) is conducted by MWRA. Separate reports are produced by MWRA that detail the monitoring results and compliance for those parameters, therefore they are not discussed as part of this report[11].

1.2 DWSP Monitoring Program Objectives

As an unfiltered public water supplier, MWRA is required to have a watershed protection program intended to promote and preserve high quality source water by utilizing a range of methods and strategies

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[5] Long Term 2 Enhanced Surface Water Treatment Rule, 68 Fed. Reg. 47640 (2003)
[6] 310 CMR 22.05(6) (2016)
[7] 314 CMR 4.06(1)(d)1 (2013)
[8] 314 CMR 4.06 (2013)
[9] 314 CMR 4.05(5) (2013)
[10] MWRA, 2012
[11] MWRA, n.d.

that ultimately control the release, transport and fate of pollutants in the watersheds. A primary function of DWSP is to design and implement this watershed protection program for the MWRA-DWSP water supply system. Since 1991, DWSP has written periodic watershed protection plans (WPP), which provide a systematic approach to evaluate potential water quality threats and develop programs that eliminate or minimize these threats. The current WPP was written in 2018 and covers fiscal years 2019 – 2023[12]. The broadly defined goal for water quality/quantity monitoring programs is:

> *Conduct tributary and reservoir sampling. Identify short-term water quality problems and maintain the historical record for long-term trend analyses. Use data analyses and assessments in management decisions.*

The data obtained from water quality and hydrologic monitoring programs are used to assess current water quality conditions, establish ranges of values for parameters considered normal or typical, screen for excursions from normal ranges, alert staff to potential contamination events, and assess watershed trends. Shorter term studies may be conducted to evaluate specific issues. These programs are re-evaluated with each iteration of the WPP in order to ensure that they are providing the breadth and depth of information necessary to evaluate the performance of DWSP water quality control programs. Specific water quality and hydrologic monitoring activities are also reviewed and updated by Division staff each year to incorporate new information or additional methods to evaluate DWSP watershed protection programs. Efforts that do not yield useful information are modified or discontinued. Any programmatic changes that are recommended for water quality and hydrologic monitoring will be discussed in this and any future annual water quality reports. These data and information provide a meaningful foundation to inform management decisions to minimize or eliminate water quality threats.

The specific objectives of the water quality and hydrologic monitoring programs in Wachusett watershed are directly related to the broader WPP goal listed above. These objectives are as follows:

1. Maintain long-term water quality data and statistics.
2. Document compliance with the EPA's SWTR requirements and criteria consistent with filtration avoidance.
3. Identify streams and water bodies that do not meet water quality standards and initiate specific control measures to mitigate or eliminate pollution sources.
4. Conduct proactive surveillance of water quality trends to identify emerging issues and support ongoing assessments of threats to water quality.

To meet these objectives, DWSP monitoring programs will continue to evolve as necessary by responding to emergent and high priority threats to water quality, making use of the best available scientific information and utilizing new tools and technologies. It is important to note that monitoring is just one element of a much larger watershed protection program carried out by DWSP. The achievement of water supply protection goals, including specific water quality targets, is due to the coordinated implementation of each of DWSP's many programs. The Watershed Protection Act of 1992 gives DWSP the authority to regulate certain land uses and activities that take place within critical areas of the watershed in order to protect drinking water quality[13].

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[12] Division of Water Supply Protection [DWSP], 2018a
[13] 313 CMR 11.00 (2017)

1.3 MWRA System and Wachusett Watershed Overview

The Quabbin Aqueduct connects three active water sources that ultimately serve as a source of drinking water to 51 communities in Massachusetts. The Quabbin Aqueduct connects, from west to east, Quabbin Reservoir, the Ware River watershed, and Wachusett Reservoir. Quabbin Reservoir is the largest of the sources, with a capacity of 412 billion gallons. In comparison, Wachusett Reservoir holds 65 billion gallons at full capacity (Table 1). The emergency backup Sudbury and Foss Reservoirs hold another 7.7 billion gallons combined[14].

Table 1: General Information on the Wachusett Watershed and Reservoir[15]

a) Wachusett Reservoir General Information		
Description	**Quantity**	**Units**
Capacity	65	Billion gallons
Surface Area at Full Capacity match below	4,147	Acres
Length of Shoreline	31	Miles
Maximum Depth	123	Feet
Mean Depth	49	Feet
Surface Elevation, at Full Capacity	395	Feet, relative to Boston City Base
Typical Operational Elevation	390.5	Feet, relative to Boston City Base

b) Wachusett Reservoir Watershed General Information[16]		
Description	**Quantity**	**Units**
Watershed Area	74,800	Acres
Land Area	70,678	Acres
	94	(% Total watershed area)
Forest Area	47,142	Acres
	67	(% Total land area)
Forested + Non-forested Wetland	5,442	Acres
	7.7	(% Total land area)
DWSP Controlled Area	20,743	Acres
	29.3	(% Total watershed area)

Water from Quabbin Reservoir is transferred to Wachusett Reservoir via the Quabbin Aqueduct Intake at Shaft 12, which outlets into the Quinapoxet River just upstream of the Quinapoxet Basin (Figure 1). Quabbin Reservoir water is also transferred directly to three western Massachusetts communities daily via the Chicopee Valley Aqueduct from the Winsor Dam Intake. Water from the Ware River may be used to supplement Quabbin Reservoir when water is diverted into the Quabbin Aqueduct at Shaft 8 in Barre, MA and delivered to Quabbin Reservoir via gravity flow. Ware River water enters the Reservoir at Shaft 11A, east of the baffle dams in Hardwick, MA. The diversion of water from the Ware River is limited to the period from October 15 to June 15 and is not permitted when mean daily flow at Shaft 8 is less than 85 MGD (131.5 cfs), per Chapter 375 of the Massachusetts Acts of 1926. DWSP and MWRA coordinate on diversions.

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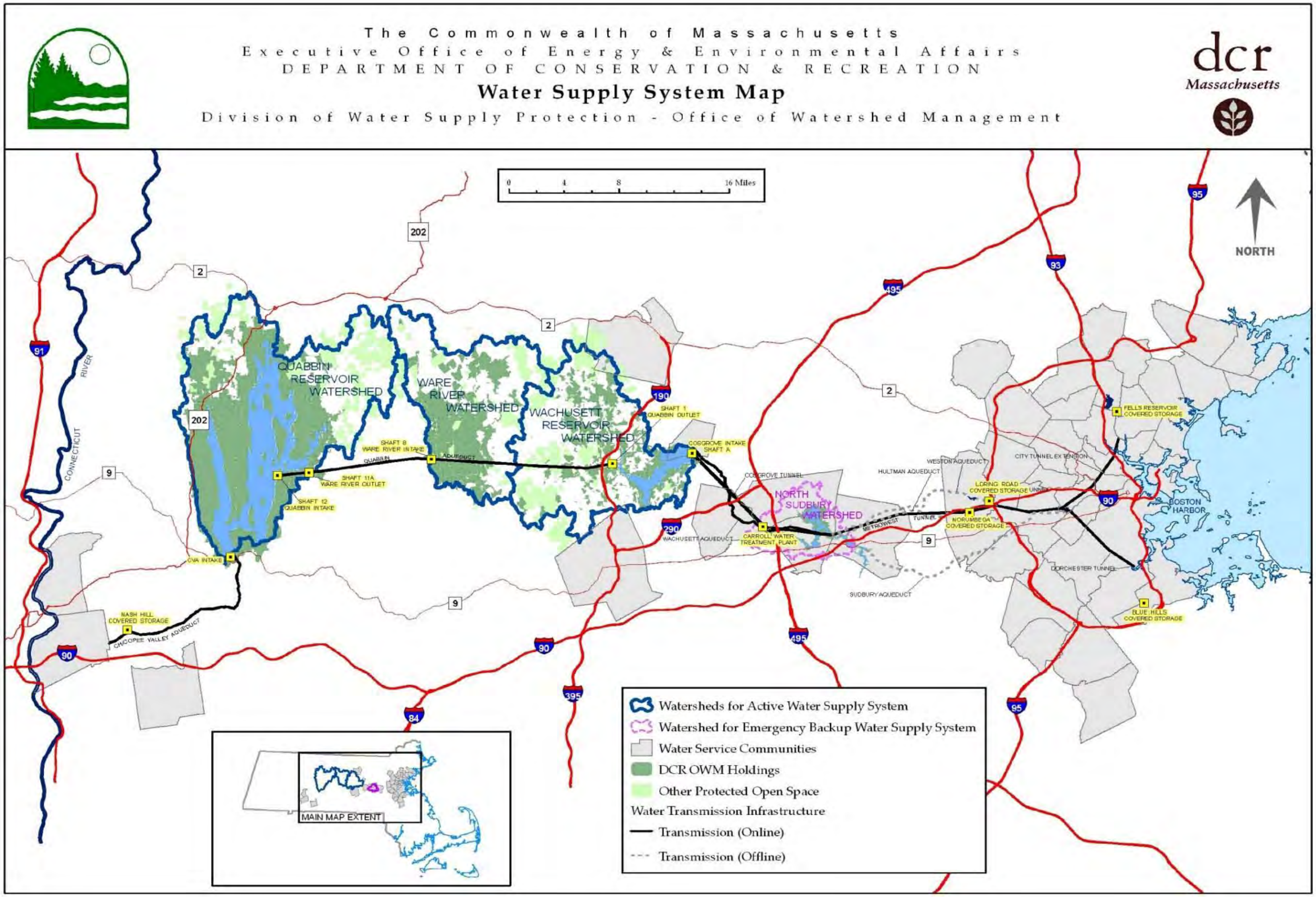
[14] MWRA, 2020a
[15] DWSP, 2018a
[16] DWSP – Wachusett EQ Land Cover 2016

Figure 1: Quabbin Reservoir, Ware River, and Wachusett Reservoir Watershed System

Interstate highways are represented by red lines. Inset map in lower left depicts location of the watershed system relative to MA.



Water from the Wachusett Reservoir is withdrawn at the Cosgrove Intake and transferred to the John J. Carroll Water Treatment Plant at Walnut Hill in Marlborough via the Cosgrove or Wachusett Aqueduct. The treated water leaves the plant through the MetroWest Water Supply Tunnel and the Hultman Aqueduct where it enters the storage and distribution system and is ultimately delivered to greater Boston and Metro-West communities and businesses.

The Wachusett Reservoir watershed is in central Massachusetts east of the Ware River and north of Worcester. With a surface area of approximately 6.5 square miles and a shoreline of 31 miles, Wachusett Reservoir drains 110 square miles (70,872 Acres) of land predominantly west of the reservoir. The headwaters of the watershed (Stillwater and Quinapoxet River basins) are situated within the Worcester/Monadnock Plateau portion of the Northeastern Highlands ecoregion. This ecoregion (58g) is described as a “rolling plateau, with hills and monadnocks, numerous ponds, lakes, and reservoirs; moderate gradient streams with bedrock, boulder, cobble, gravel, and sandy substrates”[17]. The eastern portion of the watershed, including the Reservoir, lies within the Gulf of Maine Coastal Plain portion of the Northeastern Coastal Zone ecoregion. This ecoregion (59h) is defined as having rolling plains and hills with glacial drumlins, ponds, small lakes and wetlands. Streams and large rivers have low to moderate gradients with sand, gravel, boulder and bedrock substrates[18].

The watershed landscape is spread across 12 towns, but lies predominantly in the towns of Boylston, Holden, Princeton, Rutland, Sterling, and West Boylston. The Stillwater and Quinapoxet Rivers are the largest tributaries to Wachusett Reservoir, collecting and delivering water draining from more than 80% of the watershed land area. Roughly two-thirds of watershed lands are forested, and DWSP owns or controls 20,743 acres (29.3%) of watershed area for water supply protection purposes. Including the Reservoir, DWSP owns or controls 35% or the entire watershed area, with an additional 21.1% protected by other government agencies and non-government organizations. Approximately 19% of watershed lands are developed (residential, commercial, industrial/other land cover) while 4.4% is in agriculture. Additional information regarding land use and ownership in the Wachusett Reservoir watershed is presented in the *Watershed Protection Plan FY19 – 23*[19] and the *2017 Land Management Plan*[20].

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[17] Griffith et al., 2009
[18] Ibid
[19] DWSP, 2018a
[20] DWSP, 2018b

2 Methods

This section provides an overview of how each element of DWSP water quality and hydrologic monitoring was carried out during 2019, including what parameters were sampled, why they were sampled, their frequency and locations. Additional details and information about equipment and techniques used during monitoring activities can be found in standard operating procedures (SOPs) that have been developed for each monitoring activity, which are available upon request.

2.1 Monitoring Programs

DWSP water quality and hydrologic monitoring programs are reviewed annually and updated as necessary to meet changing priorities and public health concerns, as well as to incorporate newly developed analytical methods and revised regulatory requirements. DWSP monitoring activities can be grouped into three broad categories:

1. Water quality sampling: Collecting water samples which are analyzed in a laboratory.
2. *In situ* field measurements: Sensors are placed in water bodies briefly or for extended periods of time and take direct measurements of physical/chemical characteristics of the water; direct observations or measurements are made by field personnel.
3. External monitoring: Monitoring activities that are conducted by other agencies and organizations related to water quality and hydrology within the Wachusett watershed.

2.1.1 Wachusett Watershed Monitoring Locations

DWSP staff collected routine water quality samples from 8 groundwater wells, 20 tributary monitoring stations and 27 stations on Wachusett Reservoir in 2019. These sampling locations (stations) are described in Table 2 (tributaries), Table 3 (reservoir) and Table 5 (groundwater). Figure 2 and Figure 3 are maps showing all routine monitoring locations within the Wachusett watershed.

Tributary sampling locations are established on all major streams and rivers that flow into Wachusett Reservoir. In order to capture water quality data representing as much of the watershed as possible, monitoring stations were positioned at the furthest downstream locations that were practical or convenient for sample collection. These stations are where flow is monitored and routine nutrient samples are collected and are listed as *Primary* sampling locations in Table 2. *Secondary* tributary stations are situated at upstream locations or on other tributaries to the major streams and rivers. Some sampling locations were established in areas where historical water quality problems were observed, on pristine streams to serve as reference sites, or to break up large drainage areas into smaller units. Although it is not a natural tributary, Shaft 1 (Quabbin Transfer) is sampled because it comprises a large percentage of total surface water inflows to the Reservoir. There are two monitoring locations that were established in 2013 for the long-term forestry study.

Wachusett Reservoir sample locations include primary stations at which phytoplankton and water quality profiles are routinely collected and stations at which nutrients are collected quarterly from three depths. Details on these locations and selection therefore can be found in the SOPs for each type of sampling. General characteristics of each are presented in the table below. Bacteria sampling is conducted at 23 surface stations situated along transect lines covering the Wachusett Reservoir basins east of Rt. 140 (Figure 3).

Figure 2: Hydrology, Subbasins, and Water Quality Monitoring Locations for Calendar Year 2019 in the Wachusett Reservoir Watershed

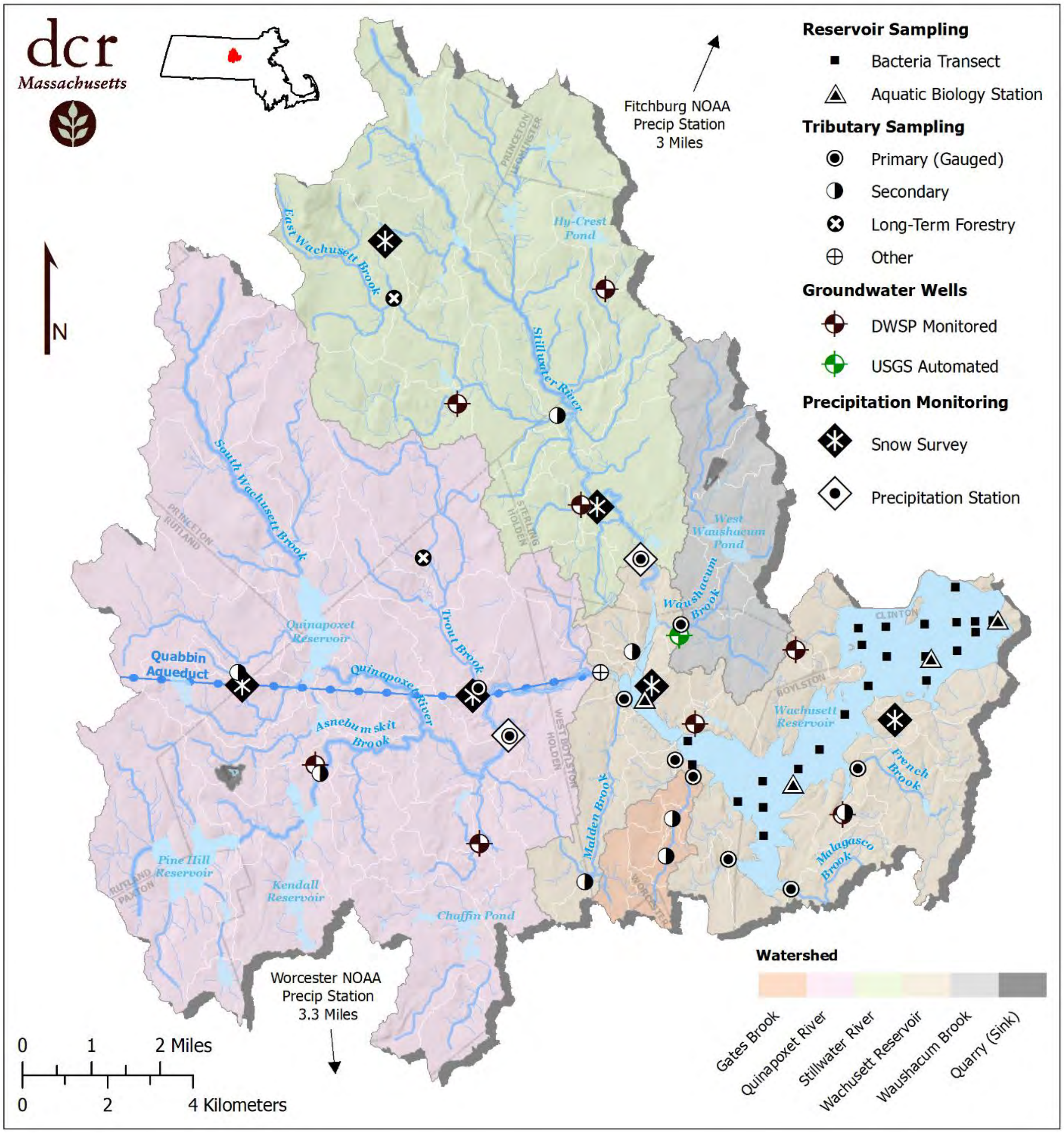


Table 2: Wachusett Tributary Sampling Locations (2019)

Map #	Location	Description	Sampling Category
1	Asnebumskit Brook (Princeton) - M102	Upstream of Princeton St. near post office, Holden	Secondary
2	Boylston Brook - MD70	Downstream of Rt. 70, Boylston	Secondary
3	Cook Brook - Wyoming - MD11	Wyoming Dr., Holden	Secondary
4	East Wachusett Brook (140) - MD89	Downstream of Rt. 140, Sterling	Secondary
5	French Brook - MD01	Downstream of Rt. 70, Boylston	Primary
6	Gates Brook 1 - MD04	Downstream of bridge inside Gate 25, West Boylston	Primary
7	Gates Brook 4 - MD73	Upstream of Pierce St., West Boylston	Secondary
8	Holden Forestry - FHLN	Off Mason Rd. inside Gate H-21, Holden	LTF
9	Jordan Farm Brook - MD12	Upstream of Rt. 68, Rutland	Secondary
10	Malagasco Brook - MD02	Upstream of W. Temple St. Extension, Boylston	Primary
11	Malden Brook - MD06	Upstream of Thomas St., West Boylston	Primary
12	Muddy Brook - MD03	Upstream of Rt. 140, West Boylston	Primary
13	Oakdale Brook - MD80	Downstream of Waushacum St. & East of Rt. 140, West Boylston	Secondary
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
16	Scarlett Brook (DS W.M.) - MD81	Behind Walmart above confluence with Gates Brook, West Boylston	Secondary
17	Shaft 1 (Quabbin Transfer) - MDS1	MWRA Shaft 1 outlet off River St., West Boylston	Other
18	Stillwater River - Muddy Pond Rd - MD07	Downstream of Muddy Pond Rd., Sterling	Primary
19	Trout Brook - M110	Downstream of Manning St., Holden	Primary
20	Waushacum Brook (Prescott) - MD83	Downstream of Prescott St., West Boylston	Primary
21	West Boylston Brook - MD05	Upstream of access road inside Gate 25, West Boylston	Primary

LTF = Long-term forestry

Figure 3: Wachusett Reservoir Sampling Locations

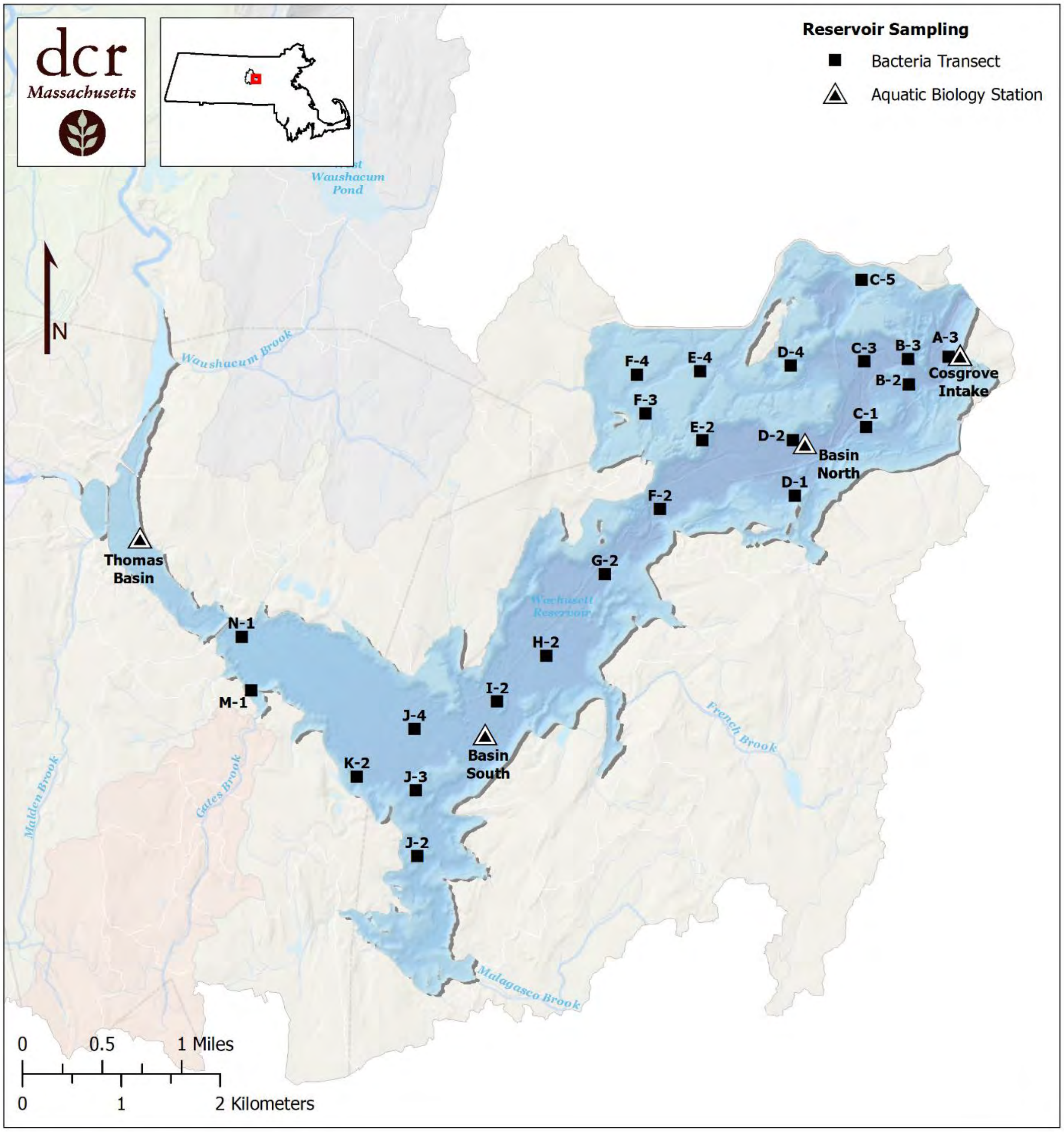


Table 3: Reservoir Sampling Locations

Station (Id)	Location Description	Approximate Maximum Depth (m)	Frequency	
			Plankton/profile	Nutrients
Cosgrove Intake (CI3409)	Adjacent to Cosgrove Intake, samples collected from the building catwalk	18	Weekly	N/A
Basin North (BN3417)	Mid reservoir near Cunningham Ledge	30	Weekly	Quarterly
Basin South (BS3412)	Mid reservoir near Scar Hill Bluffs	27	Occasionally	Quarterly
Thomas Basin (TB3727)	Thomas Basin at approximate intersection of Quabbin interflow/Quinapoxet River and Stillwater River	10	Occasionally	Quarterly

N/A = Not applicable

2.1.2 Meteorological and Hydrological Monitoring

2.1.2.1 *Precipitation and Air Temperature*

DWSP 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 are the dominant drivers of the water quality and hydrologic dynamics, thus it is important for DWSP to consider this hydrological context when evaluating water quality results, comparing interannual variability, or looking at trends.

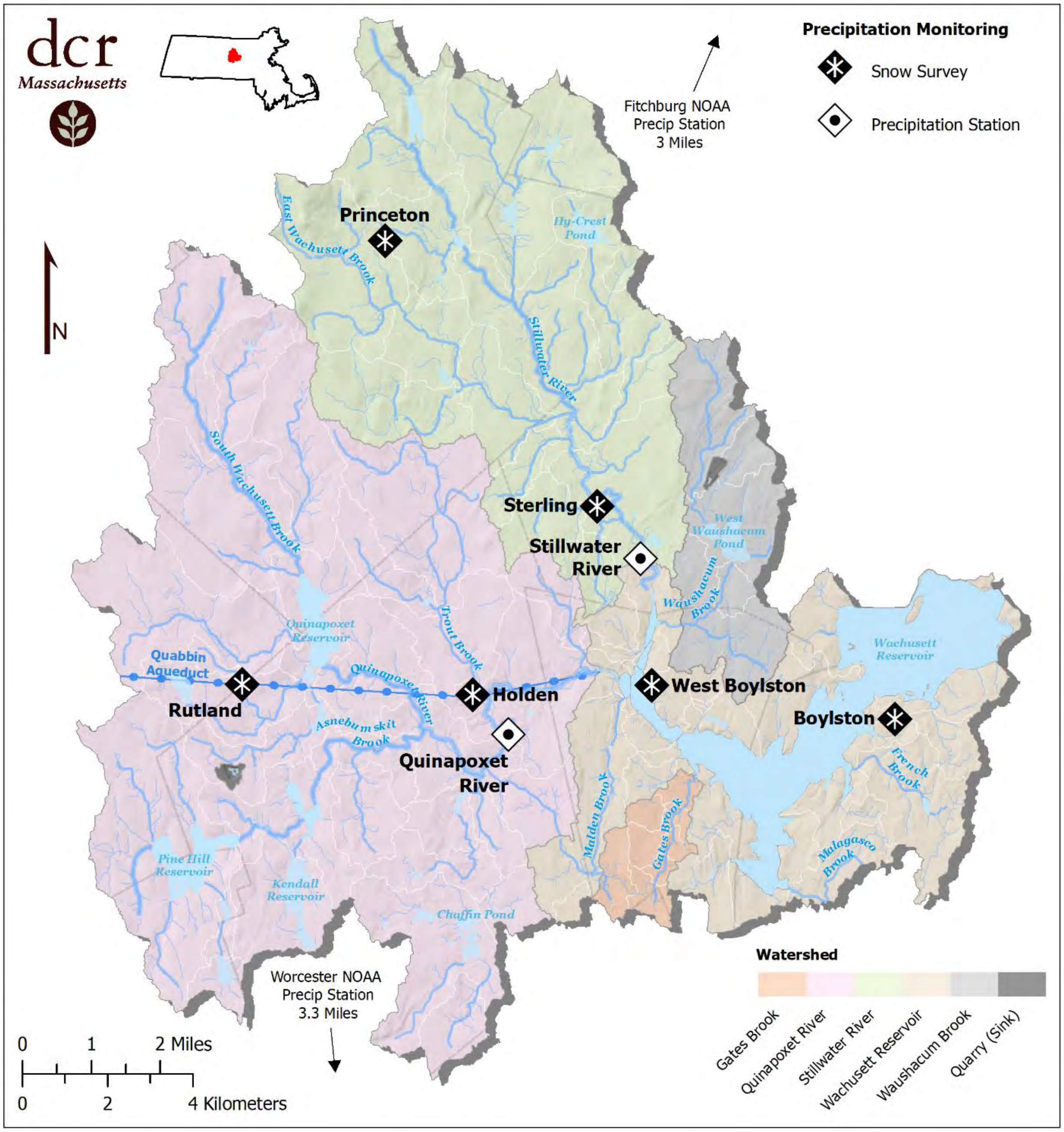
DWSP contracts with the U.S. Geological Survey (USGS) field station out of Northborough, MA for precipitation monitoring at two locations: the Stillwater River – MD07 (USGS 01095220) and the Quinapoxet River – MD69 (USGS 01095375) (Table 4). The National Oceanographic and Atmospheric Association (NOAA) monitors precipitation at two location situated a few miles outside of the Wachusett watershed to the south in Worcester (NOAA USW00094746) and to the north in Fitchburg (NOAA USW00004780) (Figure 2). There are several other entities monitoring meteorological parameters in the Wachusett watershed, however the USGS and NOAA have more rigorous quality controls for data products than any other source of local meteorological data, so these four stations are utilized for calculating average watershed precipitation.

Table 4: Wachusett Watershed Meteorological Stations

Gauge Name	Owner	Gauge Number	Start Date	Data Collected
Worcester	NOAA	USW00094746	1892	Precipitation, Air temperature
Fitchburg	NOAA	USW00004780	1998-04-01	Precipitation, Air temperature
Stillwater	USGS	01095220 (MD07)	2000-06-01	Precipitation
Quinapoxet	USGS	01095375 (MD69)	2012-10-01	Precipitation
Boylston Brook	DCR	MD02	2017-01-13*	Air temperature
Waushacum Brook	DCR	MD83	2017-08-03	Air temperature
Princeton Forestry	DCR	FPRN	2017-01-03	Air temperature

*This sensor was moved to Waushacum Brook on August 3, 2017

Figure 4: Active Precipitation Monitoring Stations in the Wachusett Reservoir Watershed



Since 1985, Wachusett watershed average annual precipitation is 46.7 inches, with a historical low of 35.36 inches (2001) and high of 61.20 (2018). Average monthly precipitation ranges from 2.96 inches (February) to 4.82 inches (October). Large precipitation events (> 2 inches) typically occur several times a year, usually related to localized summertime thunderstorms or larger tropical storms and hurricanes that come up the east coast from the South. These events often cause noteworthy responses in streamflows and solute loads and can lead to a series of cascading ecological responses in aqueous environments. Likewise, drought conditions can lead to adverse ecological consequences as some solutes can become concentrated and aquatic habitat can become diminished or degraded. DWSP acquires daily precipitation totals from both NOAA and USGS using automated scripts.

Effectively managing 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 is measured weekly throughout the winter unless there is not enough snow to obtain reliable measurements. DWSP measures snowpack at six locations (Figure 4) 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 these data along with other weather conditions and forecasts to predict near-term changes to river flows and provide flood threat information to the public.

Air temperature is a meteorological variable which has important implications for both water quality and the seasonal timing of water inputs to the Reservoir. Air temperatures determine if precipitation falls in liquid or frozen form. It is therefore a key factor in winter snowpack development and controls its subsequent melt. Heat exchange over time between the atmosphere and water at various stages of the water cycle (both gain and loss) drives seasonal water temperature fluctuations in both tributaries and the Wachusett Reservoir. Water temperature plays a significant role in aquatic ecology (see Section 2.2.8), and also determines seasonal ice formation on the Reservoir (see Section 3.4.1).

Daily air temperature statistics are recorded by NOAA at the precipitation stations discussed earlier in this section. Additionally, DWSP has two atmospheric sensors recording air pressure and temperature at 15-minute intervals. These stations and their periods of record are listed in Table 4.

2.1.3 Hydrologic Monitoring

2.1.3.1 *Streamflow*

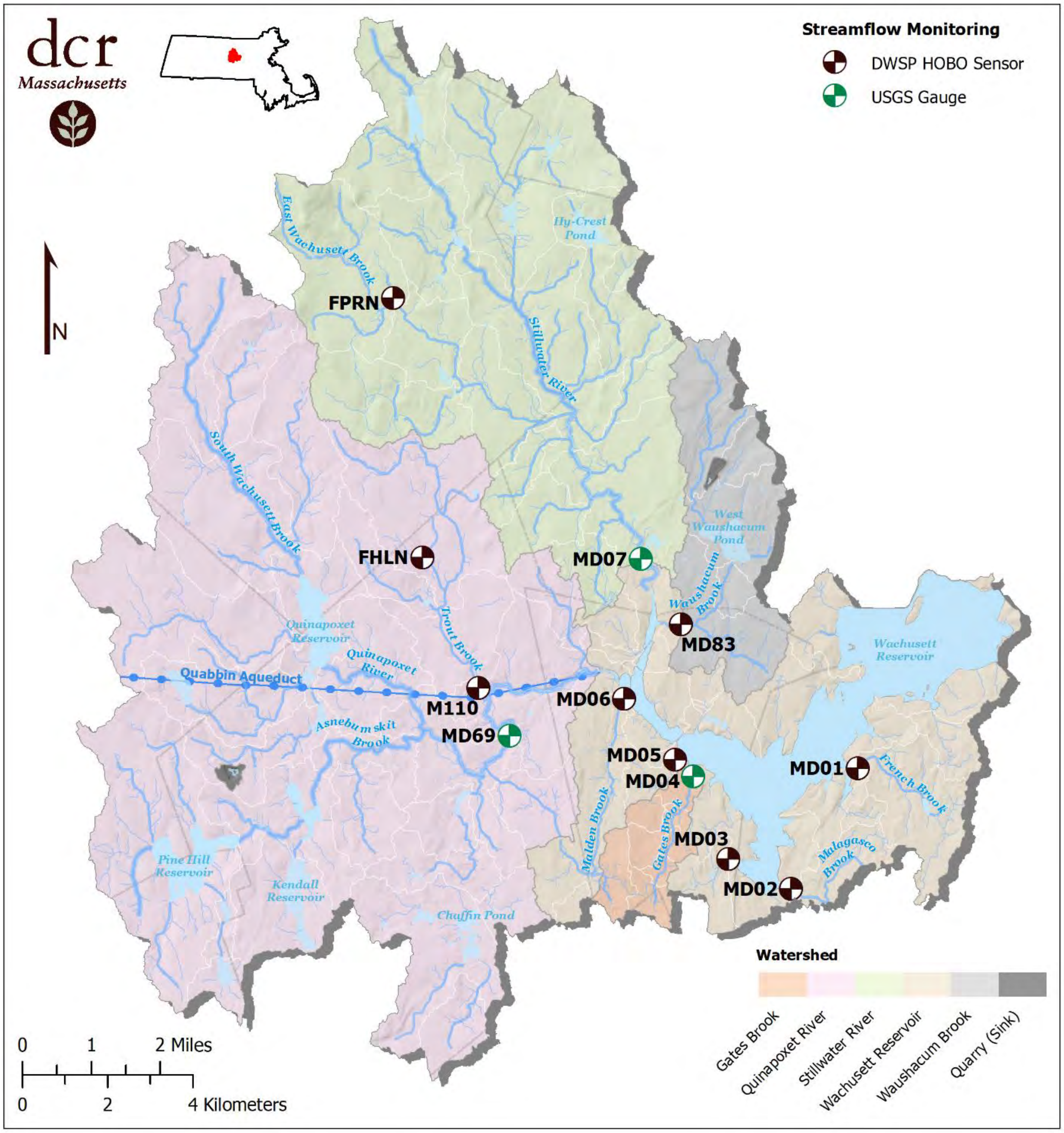
Streamflow monitoring of stage and discharge (flow) has been conducted at primary tributary sampling locations for more than two decades using both manual and automated methods. The USGS was responsible for the development and maintenance of stage-discharge relationships at these locations and continues to operate three stations (Quinapoxet River – 01095375, Stillwater River – 01095220, and Gates Brook – 01095434) using continuous monitoring technologies. Details about USGS monitoring methods and equipment for these stations can be found the National Water Information System (NWIS) website[21]. Responsibility for streamflow monitoring on the other primary tributaries was transferred to DWSP towards the end of 2011.

At seven DWSP flow monitoring stations (Figure 5) visual observations of stream depth (stage) are recorded from staff plates during all sampling visits (typically three times per month). Manual stage measurements were supplemented by continuous depth recordings using HOBO water level data loggers starting in 2013. Unfortunately, data management issues have prevented reliable use of HOBO data prior to 2017. Additionally, prior to 2017 HOBO devices were removed from streams in winter months due to concerns over freezing. This issue was resolved in late 2017 and HOBO devices are now in service year-

[21] https://waterdata.usgs.gov/ma/nwis/current/?type=MWRA&group_key=basin_cd

round. Additional details about continuous stream flow monitoring are provided in the *SOP for the Monitoring of Continuous Stream Flow*.

Figure 5: Streamflow Monitoring Locations in Wachusett Reservoir Watershed



Reliable stage-discharge relationships (ratings) allow the use of easily acquired stream depths to quickly estimate flow. Direct flow measurements (discharge measurements) at a range of depths is usually performed several times during the year using a FlowTracker handheld acoustic doppler velocimeter. A rating equation is calculated after a sufficient number of discharge measurements are obtained at a tributary, which is subsequently used to derive discharge as a function of stage. Additional details about stream discharge measurements are provided in the *SOP for the Monitoring of Stream Discharge*.

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 collects and transmits real-time data every ten minutes. All data and other information available for these locations are available from the USGS at the NWIS website for each station[22].

In 2019 new real-time monitoring instrumentation was added to the Waushacum Brook monitoring station to pilot a viable replacement for aging HOBO dataloggers. The equipment utilizes a Mayfly datalogger[23], which allows for the connection of several types of water quality probes, as well as cellular transmission of data to a cloud-based data storage server with built in visualization tools. Due to the increased interest in collecting additional specific conductance/Cl data this pilot station was outfitted with a Hydros21 CTD sensor, which measures specific conductance, temperature and depth.

If this pilot project is determined to be successful, then Mayfly units will be deployed at additional flow monitoring locations as HOBO units reach the end of life. Data for this station can be viewed publicly[24].

2.1.3.2 *Reservoir Elevation*

Wachusett Reservoir is controlled by MWRA, which manages aqueduct transfers and outflows to maintain a water surface elevation between 390 and 391.5 ft year-round. Water from Quabbin Reservoir is typically transferred to 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. Occasionally there are deviations in elevation due to large storm events or planned drawdowns. DWSP relies on reservoir elevation data collected by MWRA, which are available in real-time (15-minute increments), but typically presented as daily average elevation.

2.1.3.3 *Groundwater level*

Groundwater resources are important to the management of Wachusett Reservoir and tributaries due to base flow contributions to the tributaries and direct inflow to the Reservoir. Research by USGS hydrologists in the Housatonic River Basin in Berkshire County, Massachusetts found that base flow contributions represented 55 to 80 percent of total annual streamflow[25]. Base flow contributions in Wachusett watershed streams are likely to be of comparable proportions due to similar surficial geology. Long-term measurement of the depth to groundwater throughout various Wachusett watershed aquifers can yield useful information about seasonal and interannual fluctuations in groundwater storage.

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[22] https://waterdata.usgs.gov/ma/nwis/current/?type=MWRA&group_key=basin_cd
[23] https://stroudcenter.org/news/digital-mayfly-swarm-is-emerging/
[24] https://monitormywatershed.org/sites/WACHUSETT-01/
[25] Bent, 1999

In recent years, DWSP groundwater level monitoring was limited to a single USGS well (Sterling - Rt 140). In 2019, DWSP continued this partnership with USGS to measure monthly groundwater levels from Sterling - Rt 140 and report them to USGS for the National Water Information System and to DCR Office of Water Resources as part of the statewide hydrologic monitoring network.

In 2019, monthly groundwater monitoring was expanded, primarily due to the increased interest in collecting additional specific conductance/Cl data in Wachusett watershed (Figure 22). Water levels were measured as part of this expanded monitoring effort. Seven additional wells are now sampled by DWSP, which were previously monitored by USGS and have historical water level data. The periods of historical data and other summary information about the wells sampled by DWSP can be found in Table 5.

Table 5: Wachusett Groundwater Well Information

DWSP Code	Well Name	USGS Code	Type	Depth (ft)	Elevation (ft)	Historical Period
MDW1	Holden - Wachusett St	422102071501401	Dug	10.5	670	1995 - 2002
MDW2	Boylston - Rt 70	422125071440101	Augered	12.2	475	1995 - 2002
MDW3	West Boylston - Gate 27	N/A	Augered	15.1	403	N/A
MDW4	West Boylston - Rt 110	422334071444201	Augered	29.4	525	1995 - 2002
MDW5	Sterling - Justice Hill Rd	422805071480801	Dug	19.5	710	1947 - 2015
MDW6	Princeton - Rt 62	422636071503601	Augered	21.9	695	1995 - 2002
MDW7	Sterling - Rt 140	422520071483001	Augered	24.4	505	1995 - 2018
MDW8	Holden - Jefferson	422201071530201	Augered	20.3	815	1995 - 2002
WSW26	West Boylston - Prescott St	422341071464901	Augered	16.8	485	2012 - 2018

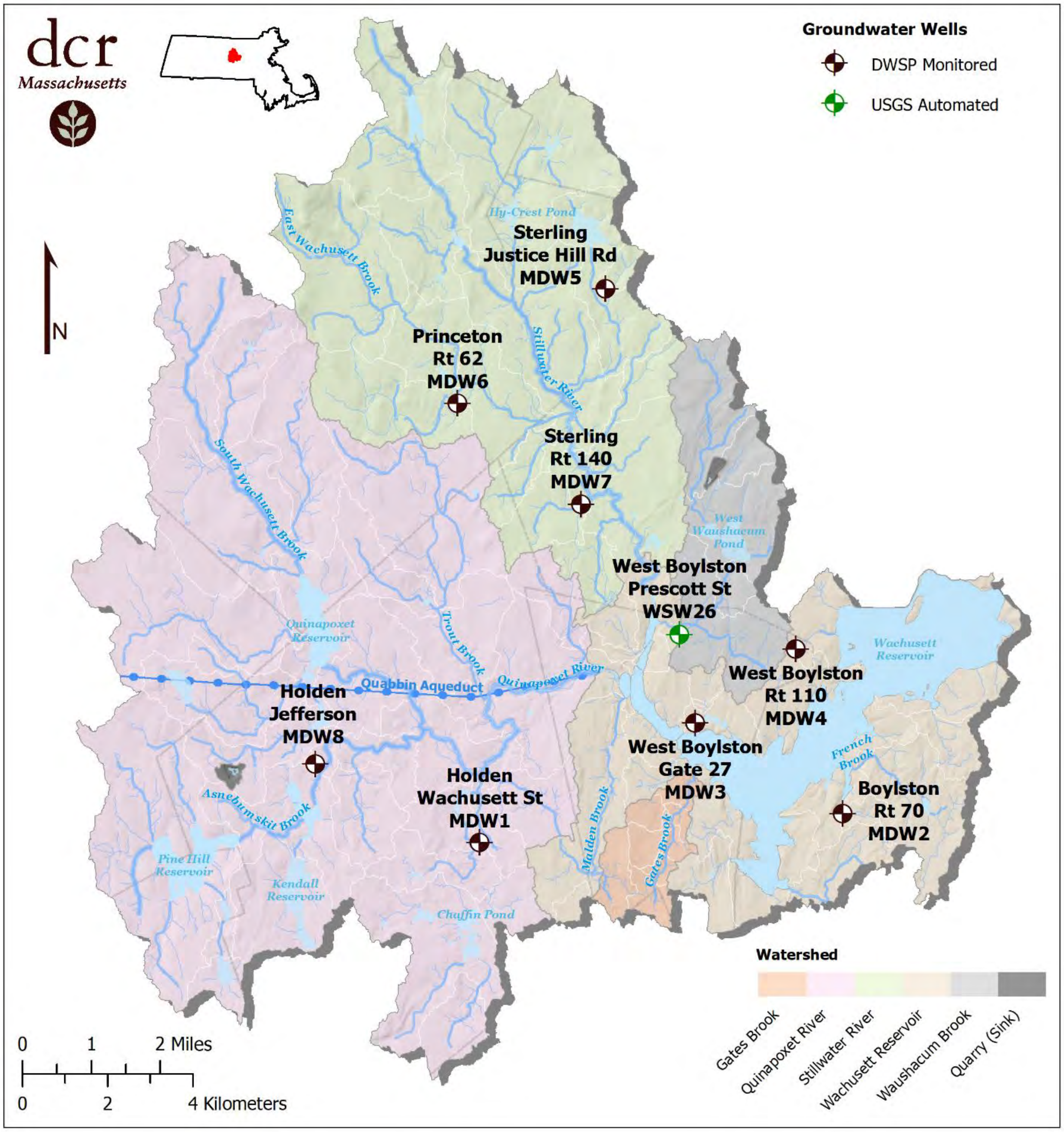
Manual measurements of depth to groundwater to the nearest one-hundredth inch are made with a Geoteck KECK water level meter, which is calibrated by USGS every two years. Additional water level measurements are collected by DWSP at Sterling - Rt 140 at four-hour intervals using a HOBO water level data logger. USGS also continues to maintain an automated groundwater observation well (West Boylston – Prescott St), which records groundwater levels hourly. Data and information about this USGS monitoring well can be found at the NWIS website[26]. Additional details about groundwater level monitoring are provided in the *SOP for the Monitoring of Groundwater (WATWEL)*.

2.1.4 Groundwater Quality Monitoring

Groundwater quality can differ drastically between and within groundwater aquifers. This water resource is a major component of the Wachusett watershed water budget, however there is very little data about the quality of groundwater in Wachusett watershed aquifers. As mentioned in the section above, DWSP groundwater monitoring was expanded to seven additional wells due to concern over concentrations of Cl and specific conductance observed in tributaries and the Wachusett Reservoir. Exploratory monitoring of the new wells began in April 2019 with regular monthly monitoring starting in July (Figure 6). Three additional parameters are now collected monthly in conjunction with well level measurements: specific conductance, Cl, and temperature. MWRA has assigned the project code “WATWEL” for groundwater Cl analysis.

[26] https://waterdata.usgs.gov/ma/nwis/current/?type=MWRA&group_key=basin_cd

Figure 6: DWSP Groundwater Monitoring Wells in Wachusett Reservoir Watershed



Samples were collected after purging two to three well volumes of water to ensure the samples were representative of the surrounding groundwater. Two wells (Holden – Wachusett St and Sterling – Justice Hill Rd) are dug wells and therefore unable to be purged due to the large volumes of water they contain. Additionally, the Holden – Jefferson well has a narrow diameter that prevents purging or sample collection with DWSP's pump. As a result, specific conductance and temperature readings are collected *in situ* without purging and Cl samples were unable to be collected in this well. Specific conductance and temperature are measured with a Yellow Springs Instrumentation (YSI) Professional Plus meter and Cl samples are collected in bottles and sent to the MWRA Deer Island Lab for analysis. Additional details about groundwater quality monitoring are provided in the *SOP for the Monitoring of Groundwater (WATWEL)*.

Beginning in August 2019, additional groundwater samples collected during routine well monitoring were sent to the University of Massachusetts (UMass) Amherst to be analyzed for stable isotopes, deuterium (^{2}H) and oxygen-18 (^{18}O), in the laboratory of Dr. David Boutt. These data add to Dr. Boutt's statewide database of stable isotopes in groundwater, surface water, and precipitation which is used to track the movement of water throughout the hydrologic cycle in Massachusetts. Additionally, these data allow DWSP to observe the influence of rain, which contains fewer heavy isotopes, in the samples collected from wells in the Wachusett watershed. Wells that are better mixed with deeper groundwater show less depletion of heavy isotopes, whereas wells containing a higher proportion of recently infiltrated precipitation show more depletion of heavy isotopes. This monitoring effort will hopefully lead to a better understanding of groundwater recharge and aquifer dynamics within the Wachusett watershed.

2.1.5 Tributary Monitoring

The principle tributary monitoring programs are divided into two groups: 1) Routine tributary monitoring for bacteria and turbidity (MWRA project code WATTRB) and 2) Nutrient and total suspended solids (TSS) monitoring (MWRA project code WATMDC, referred to as 'nutrient monitoring'). Other tributary monitoring occurs at the two long-term forestry (LTF) project study locations (MWRA project code WATBMP) and short-term forestry (STF) monitoring locations. *In situ* measurements for physiochemical parameters (field parameters) are also taken in conjunction with all tributary monitoring visits (except STF). Field parameters are measured with a YSI Professional Plus multi-sensor meter and include water temperature (°C) and specific conductance (μS/cm), dissolved oxygen (mg/L), and hydrogen ion activity (pH) (S.U.). Stage is recorded at the ten primary tributary monitoring locations (Table 2) so that parameter concentrations/values have corresponding flow data to aid in interpretation.

No records of routine maintenance and/or calibrations exist for field parameter measurements made prior to July 2019. Therefore, field parameter data collected prior to July 2019 may be subject to errors introduced by sensor drift over time, particularly for dissolved oxygen and pH. Thus, water temperature, dissolved oxygen and pH are not included in the following discussions. For specific conductance, sensor accuracy was verified by cross-referencing USGS specific conductance measurements recorded at the Stillwater River, Quinapoxet River and Gates Brook, and deemed acceptable for inclusion. Routine calibration and maintenance for tributary field sensors was implemented in July 2019 and any omitted parameters will be summarized in future water quality reports.

2.1.5.1 *Routine Tributary Monitoring*

In 2019, routine water quality samples for bacteria, turbidity, and field parameters were collected from nineteen stations on eighteen tributaries. Each tributary station was visited every other week throughout the entire year (Table 2 – Primary and Secondary), although samples were not collected at some stations, during low flow or no-flow conditions in the summer months. Discrete water samples were collected for analysis of *Escherichia coli* (*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. Samples were occasionally collected from additional locations to investigate water quality problems discovered during environmental assessment investigations. Follow-up samples were also collected when elevated bacteria levels were detected in order to verify if levels persisted. Additional details about routine tributary monitoring is provided in the *SOP for the Monitoring of Tributary Bacteria and Turbidity (WATTRB)*.

2.1.5.2 *Nutrient Monitoring*

In 2019, routine nutrient monitoring was conducted monthly at 10 tributary monitoring stations, typically during the second week of the month. The parameters for this project include: ammonia-nitrogen (NH_3-N), chloride (Cl), UV absorbance at 254 nm (UV_{254}), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), total Kjeldahl nitrogen (TKN), total organic carbon (TOC), total phosphorus (TP), and TSS. 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 and TP which is reported in µg/L. Since the Quabbin transfer comprises such a significant volume of water to Wachusett Reservoir, Shaft 1 is sampled for nutrients as well, usually monthly (when flowing). Most tributaries were sampled 12 times for nutrients in 2019. The Quabbin Transfer was sampled 10 times in 2019. Additional samples were collected to target specific flows that have been historically under sampled (Table 7). Results from all tributary sampling programs are discussed in Section 3.2. Additional details about how nutrient samples are collected are provided in the *SOP for the Monitoring of Tributary Nutrients (WATMDC)*.

Table 6: 2019 Tributary Monitoring Program Components

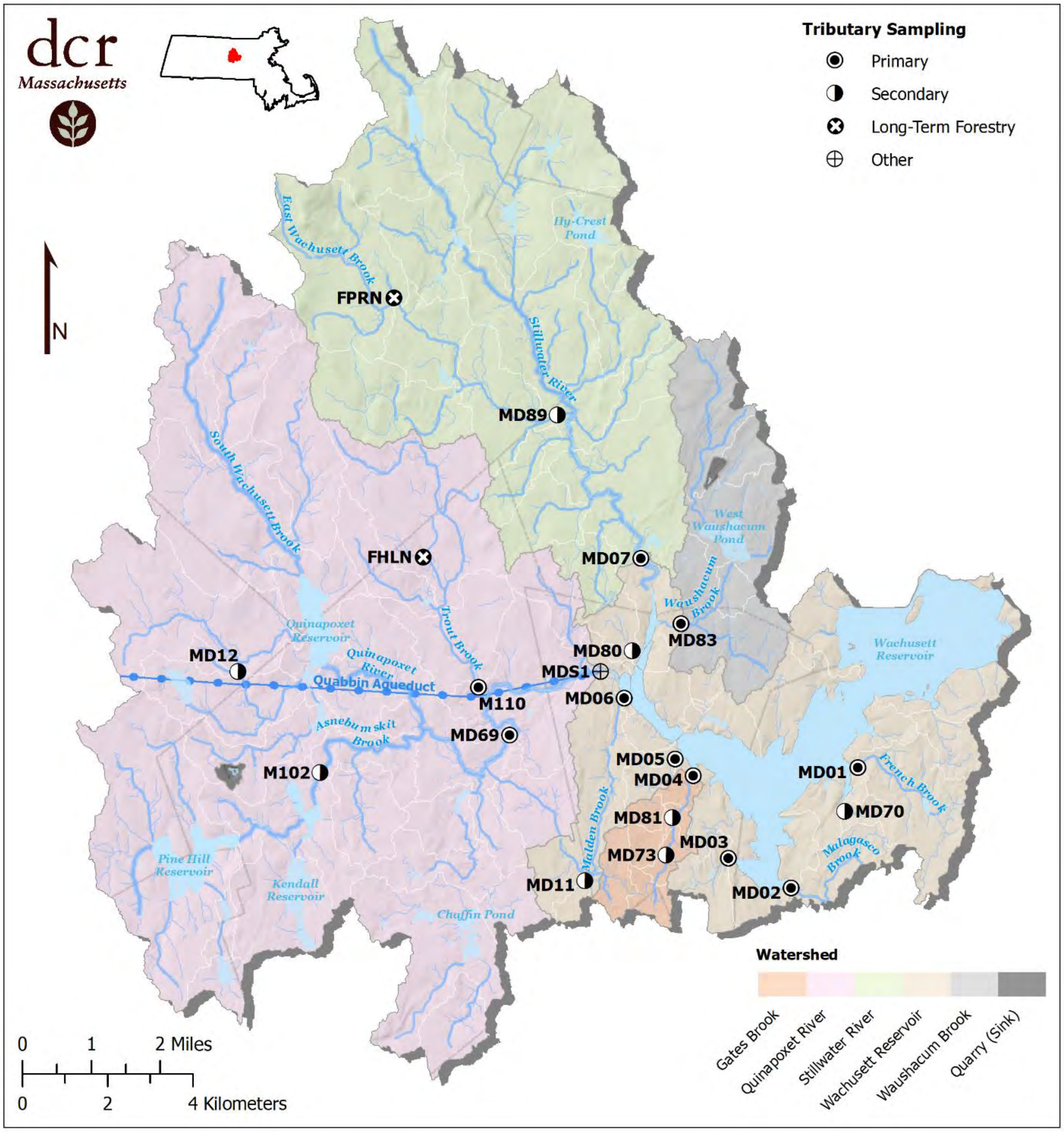
Samples with asterisk are analyzed for multiple parameters at the MWRA lab at Deer Island.

Program Name	MWRA Project Code	Parameters	Sampling Frequency	Sample Locations	# Samples/ Measurements Collected in 2019
Nutrients	WATMDC	NH_3-N, NO_2-N, NO_3-N, TKN, TP, TSS, TOC, UV_{254}, Cl	Monthly	Primary, Other	135*
Bacteria and Turbidity	WATTRB (Only for bacteria)	*E. coli*, turbidity	Twice per Month	Primary, Secondary	428 (*E. coli*) 425 (turbidity)
Field Parameters	N/A	Water temperature, dissolved oxygen, pH, specific conductance, stage (where applicable)	1 – 3 times per month in conjunction with WATMDC, WATTRB, WATBMP projects	Primary, Secondary, Other	560, 365 (stage)
Long-term Forestry	WATBMP	NH_3-N, NO_2-N, NO_3-N, TKN, TP, TSS, TOC, UV_{254}	Monthly/Quarterly Storms	LTF	16* (monthly) 14* (storm event)
Short-term Forestry	N/A	Turbidity	Varied	17 timber harvest lots (not mapped)	190

Table 7: Additional Flow Targeted Nutrient Samples in 2019

Sample Location	05/01/2019	05/02/2019
French Brook - MD01		X
Gates Brook 1 - MD04	X	
Malden Brook - MD06	X	
Stillwater River - Muddy Pond Rd - MD07	X	
Waushacum Brook (Prescott) - MD83	X	

Figure 7: Tributary Sampling Locations in the Wachusett Reservoir Watershed



2.1.6 Reservoir Monitoring

Monitoring of Wachusett Reservoir includes collection of *in situ* measurements, collection and analysis of water samples for plankton, nutrients, and bacteria, as well as collection or observation of other flora and fauna inhabiting the Reservoir (Table 8). Details of each program are provided below.

Table 8: 2019 Reservoir Monitoring Program Components

Samples with asterisk are analyzed for multiple parameters at the MWRA lab at Deer Island.

Program Name	MWRA Project Code	Parameter or Analysis	Typical Sampling Frequency	Sample Locations	# Samples Collected in 2019
Profiles	N/A	Water temperature, specific conductance, chlorophyll *a*, phycocyanin, dissolved oxygen, pH	Weekly (May – Sept), semi-weekly (Oct – April)	BN3417, BS3412, TB3427	47
Phytoplankton	N/A	Phytoplankton density	Weekly (May – Sept), semi-weekly (Oct – April)	Primary: BN3417, CI3409, Secondary: BS3412, TB3427, other	188
Nutrients	WATMDC	NH_3-N, NO_3-N TKN, Silica, TP, UV_{254}	Quarterly (4x)	BN3417, BS3412, TB3427	40*
Bacteria	WATTRN	*E. coli*	Monthly (minimum)	23 transect stations	322
Macrophytes	N/A	Species present, location, density	Throughout growing season	Entire reservoir	n/a
Zooplankton	N/A	Species screening	Quarterly (4x)	BN3417, BS3412, TB3427	23
Lake Trout	N/A	Species, length, weight	Multiple sample trips during fall spawn	Entire reservoir – spawning locations	See Section 3.4.8

2.1.6.1 *Water Quality Profiles*

DWSP staff routinely record water column profiles in Wachusett Reservoir using a YSI EXO2 multi-parameter sonde for the following hydrographic parameters: temperature, specific conductance, dissolved oxygen concentration, percent oxygen saturation, chlorophyll *a*, phycocyanin, turbidity, and pH. Data are recorded with a handheld display connected to the sonde with a 33-meter cable starting at the surface. Measurements are recorded at 0.5 to 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. Detailed procedures are contained in the *SOP for Collection of Reservoir Profiles*.

A total of 47 profiles were collected from four locations in 2019. These included 12 profiles collected in conjunction with reservoir nutrient monitoring.

Three remote sensing profiling buoys have been deployed annually by MWRA starting in 2016. Profiles are collected with YSI EXO2 sondes identical to those used by DWSP. The profilers automatically run every 6 hours (12am, 6am, 12pm, and 6pm) and collect data at 1-m increments. The data can be viewed remotely shortly after collection via the MWRA OMMS website. Results are frequently used by DWSP to augment the routine profile/plankton sampling program. For example, if elevated chlorophyll *a* values are observed in remote sensing data, DWSP may sample earlier than scheduled to capture associated phytoplankton data. The high frequency profile data also allows for identification and visualization of diurnal patterns and both short and long-term effects of environmental forces such as cooling temperatures during turnover and seiche effects due to wind events.

2.1.6.2 *Nutrient Monitoring*

Quarterly sampling for assessment of nutrient dynamics was conducted in May at the onset of stratification, July in the middle of the stratification, near the end of the stratification period in October, and following turnover in late November. The samples following turnover are typically collected in December, but in 2019 were collected in late November to better align with turnover which occurred earlier in the month. These samples were collected at three routine locations: Basin North (BN3417), Basin South (BS3412), and Thomas Basin (TB3427). Grab samples were collected from three depths representative of specific stratification layers during the stratified period and from the surface, middle, and bottom of the water column during periods of isothermy. These collections resulted in a total of 252 nutrient samples which were analyzed by MWRA staff at the Deer Island Central Laboratory for the following: NH_3-N, NO_3-N TKN, Silica, TP, and UV_{254}. Details of the sampling protocol are provided in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics[27] and in the *SOP for Collection of Reservoir Nutrients*.

2.1.6.3 *Bacteria Monitoring*

Bacterial transect samples (*E. coli*) are collected routinely (at least monthly) during ice-free conditions at 23 fixed surface locations on the Reservoir (Figure 3). These samples are collected to document the relationship between seasonal bacteria variability and visiting populations of gulls, ducks, geese, cormorants, and swans. Samples are collected at higher frequencies (up to weekly) during periods when waterfowl are present in higher numbers and the bird harassment program is active. All samples are brought to the MWRA lab in Southborough, MA for analysis. MWRA has designated project code "WATTRN" for Wachusett Reservoir bacteria sampling.

2.1.6.4 *Phytoplankton Monitoring*

Routine monitoring for phytoplankton follows a seasonal schedule with samples collected every other week from October through April and at least once per week from May through September. Sampling frequency may intensify in response to increases in density of specific phytoplankton genera (see Section 2.2.18, Table 10) or decrease when conditions such as ice cover physically prevent sampling. Monitoring by DWSP staff takes place at either Basin North (BN3417) or at the Cosgrove Intake Facility (CI3409) with additional locations sampled as necessary to characterize the phytoplankton community present throughout the Reservoir. Grab samples are typically collected from at least two depths including an epilimnion sample at 3 m and (during stratification) a metalimnion sample. The exact depth of the latter is typically selected based on results of a water column profile collected in conjunction with phytoplankton sample collection. Chlorophyll *a* data obtained during the reservoir profile are typically used to select the discrete metalimnion sample depths, typically corresponding to where chlorophyll *a* values are the highest. More information on sampling protocols and details of phytoplankton sample collection and enumeration may be found in the following SOPs: *SOP Collection of Reservoir Profiles*, *Phytoplankton Collection and Reporting* and *Microscopic Enumeration of Phytoplankton*.

In 2019 phytoplankton monitoring was carried out on 68 days, resulting in 188 individual samples. The entire phytoplankton community was assessed in 90% of these samples while the remainder were assessed for specific taxa of interest including *Synura*, *Chrysosphaerella*, and *Dolichospermum*. Three periods of elevated phytoplankton density were documented through routine monitoring necessitating an increase in monitoring frequency for a total of thirteen weeks in 2019. A special one-day investigation

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[27] Worden & Pistrang, 2003

into spatial distribution of the chrysophyte community and reservoir stratification was also conducted in 2019.

2.1.6.5 *Zooplankton Monitoring*

Quarterly collection of zooplankton samples was conducted in conjunction with nutrient sampling as described above. A total of 23 samples were field preserved in ~70% ethanol. Entire water column samples collected during each sample event from each site were scanned by DWSP aquatic biologists for invasive species, specifically *Bythotrephes longimanus* (spiny waterflea) and *Cercopagis pengoi* (fishhook waterflea). Details of zooplankton sample collection are documented in the *SOP: Collection of Reservoir Zooplankton*.

2.1.6.6 *Macrophyte Monitoring*

Frequent assessments of the aquatic vegetation community in and around Wachusett Reservoir are made as part of the invasive macrophyte control program. Monitoring takes place throughout the growing season, generally May through October and may include visual surveys conducted via boat, in-water assessments via snorkeling, and collection of vegetation biovolume data with boat-based sonar. Related activities undertaken by DWSP staff include maintenance of floating fragment barriers, inspection of boats and other vessels deployed to the Reservoir by contractors, emergency personnel, and others, management of *Phragmites australis* along the Reservoir shoreline, and oversight of aquatic invasive species (AIS) management programs in collaboration with MWRA.

All surveys conducted in 2019 by DWSP staff were in support of ongoing management programs including physical AIS management in the Reservoir and herbicide treatment projects in three local pond systems: Clamshell Pond in Clinton, the Lily Ponds in West Boylston, and South Meadow Pond Complex in Clinton and Lancaster.

2.1.6.7 *Fish Monitoring*

Study of fish populations within Wachusett Reservoir is necessary to develop an understanding of the Reservoir ecosystem and the impact of the ecosystem on drinking water quality. Historical fisheries work in the Reservoir includes angler creel surveys, conducted in 1979, 1980 and 1998, and sporadic and infrequent sampling. More recent angler creel surveys, conducted in 2011, 2012 and 2017, show that species most frequently caught by anglers have changed over the past 30 years, which likely reflects changes in the fish community composition over this time period. Angler creel surveys at Wachusett Reservoir are conducted every five years, starting in 2012. Results of the 2017 creel survey were published in a detailed report in 2019 and posted online[28]. In addition to the creel surveys, DWSP and Massachusetts Division of Fisheries and Wildlife (MassWildlife) have conducted an annual mark and recapture study of spawning Lake Trout (*Salvelinus namaycush*) since 2014 and conduct periodic investigations of other species including Rainbow Smelt (*Osmerus mordax*).

2.1.7 Additional Watershed Monitoring and Special Studies

In addition to routine monitoring of Wachusett Reservoir and its tributaries, DWSP staff conduct several special investigations. These studies vary in duration and depth of scope, but include storm sampling, monitoring of potential short-term and long-term water quality changes following forest management

[28] Carr & Nyquist, 2019

activities, and evaluation of spatial and temporal trends in specific conductance and Cl concentrations of waters impacted by roadway de-icing practices.

2.1.7.1 *Forestry Monitoring*

Forest Management operations, when conducted with proper best management practices, should not have significant short or long-term effects on water quality. Monitoring of harvest operations and water quality is conducted to ensure water quality standards are maintained on DWSP lands. Short-term monitoring focuses on direct water quality impacts that can occur during logging, while long-term monitoring involves evaluating water quality parameters as the forest regenerates following logging operations.

Long-term Forestry Monitoring: Two locations in the Wachusett Reservoir watershed have been established for long-term monitoring of the potential impacts of timber harvesting on water quality. This project involves collection of water quality and flow data downstream of a timber lot that will be sold and harvested and downstream of a second lot (control) that will not be harvested. Monitoring for this study will span a period of at least ten years, with at least five years of sampling occurring both pre and post-harvest. Six years of pre-harvest data have now been collected and data summary and comparison between the control and test lots will be presented in a preliminary report. The study includes monthly dry weather discrete grab sampling and quarterly storm event monitoring using automatic samplers. Parameters monitored in this study include flow, pH, water temperature, dissolved oxygen, TSS, TOC, NH_3-N, NO_3-N, NO_2-N, and TP. Methods for sample collection are the same as for these parameters on other tributaries. Additional details for this program are provided in the *SOP for Long-term Forestry Monitoring (WATBMP)*.

Short-term Forestry Monitoring: DWSP EQ staff monitor for potential impacts of forestry operations on soil and water by conducting periodic inspections of forestry lots and collecting water samples for turbidity analysis from all streams affected by logging, primarily those which are spanned by a temporary bridge used for transporting equipment and lumber. Elevated dry weather turbidity can be a signal that erosion is occurring above naturally fluctuating background levels and may help identify deficiencies in BMP implementation[29]. Turbidity sampling is conducted monthly below all proposed stream crossings prior to the start of logging. During harvest periods turbidity samples are collected weekly both upstream and downstream of all stream crossings. Post-harvest monitoring is conducted monthly for one year after the completion of all timber harvesting activities. Methods for turbidity collection and analysis are the same as for other tributaries. Additional details for this program are provided in the *SOP for Short-term Forestry Monitoring.*

2.1.7.2 *Storm Sampling*

Stormwater sampling on primary tributaries has been conducted in past years 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. Storm sampling is now only conducted for extreme precipitation events (2 or more inches of rain) in order to support UMass modelling efforts. No storms were sampled in 2019. A separate stormwater sampling report will be produced providing a detailed summary and analysis of the 46 storms that were

[29] DWSP, 2018b

sampled at routine water quality stations. Additional information about the storm sampling program is provided in the *SOP for Storm Sampling*.

2.1.7.3 *Stormwater Basins*

Monitoring of the stormwater basins located on either side of the Route 12/140 causeway was initiated in summer 2019. Baseline vegetation data were collected along shoreline transects of each forebay and within the wetlands. Water temperature, pH, dissolved oxygen, and specific conductance were recorded with a YSI Professional Plus multi-sensor meter at inlet and outlet locations of each forebay at least twice monthly from July through December. Photographic documentation of vegetation and water level was also recorded using a customized ESRI Collector application. These data will be used in the future to assess changes which may occur in water quality and vegetative composition as a result of inputs to the basins from road runoff and to estimate the effect these containment systems have on reducing inputs to the Reservoir. Frequent monitoring in these areas also serves to identify pioneer infestations of invasive species including *Phragmites australis* (common reed) and *Lythrum salicaria* (purple loosestrife) and the presence of other organisms which often inhabit standing water areas and may present a threat to the function of the basins, water quality, and/or public health, such as cyanobacteria, mosquitoes, and *Branta canadensis* (Canada geese).

2.2 2019 Watershed Monitoring Parameters and Historical Context

In 2019, 23 distinct physical, chemical, and biological parameters were monitored across all water quality and hydrologic monitoring programs throughout the Wachusett Reservoir watershed (Table 9). These parameters were selected because they either directly affect water quality or can indicate potential water quality issues. Criteria or regulatory standards exist for many of these parameters for aquatic life protection, drinking water supply, or both. Since wading and swimming are prohibited in tributaries and the Wachusett Reservoir, there are no applicable regulatory standards related to recreational contact. For some parameters which do not have specific regulatory standards, the EPA Ecoregional Nutrient Criteria for Rivers and Streams is referenced. All relevant regulatory and guidance thresholds for these parameters are listed in Table A-1 in Appendix A. In future water quality reports this section will be located in the Appendix, as it contains background information to help readers better understand the discussion of water quality and hydrologic monitoring results. Monitoring results for 2019 are presented and discussed in Section 3.

Table 9: 2019 Monitoring Parameters

The analysis location column indicates whether the parameter is measured directly in the field or if a water sample is collected and analyzed in a laboratory. Laboratory or field-based methods of analysis are listed under the method column. The water type where each parameter was measured is indicated in the last three columns, where R = reservoir, T = tributary, and G = groundwater. Precipitation and air temperature measurements are recorded from four specific land-based locations and are considered watershed-wide parameters.

Parameter Name	Units	Sampling Group	Analysis Location(s)	Analysis Method	R	T	G
Air Temperature	Deg-C	Meteorological	Field-Sensor				
Ammonia-nitrogen	mg/L	Nutrients	MWRA Lab	EPA 350.1, 353.2	X	X	
Alkalinity	mg/L $CaCO_3$	Nutrients	MWRA Lab	SM 2320 B	X		
Blue Green Algae	ug/L	Field parameter	Field-Sensor	*In situ* Fluorometry	X		
Blue Green Algae RFU	RFU	Field parameter	Field-Sensor	*In situ* Fluorometry	X		
Chloride	mg/L	Nutrients	MWRA Lab	EPA 300.0		X	X
Chlorophyll	ug/L	Field parameter	Field-Sensor	*In situ* Fluorometry	X		
Chlorophyll RFU	RFU	Field parameter	Field-Sensor	*In situ* Fluorometry	X		
Chlorophyll volts	volts	Field parameter	Field-Sensor	*In situ* Fluorometry	X		
Discharge	cfs	Field Parameter	Calculated using Staff Gauge Height	Calculated from stage-discharge rating curve		X	
Dissolved Oxygen	mg/L	Field Parameter	Field-Sensor	SM 4500-O G-2001	X	X	
E. coli	MPN/100 mL	Bacteria	MWRA Lab	9223B 20th Edition (Enzyme Substrate Procedure)		X	
UV_{254}	ABU/cm	Nutrients	MWRA Lab	SM 5910B 19th edition	X	X	
Nitrate-nitrogen	mg/L	Nutrients	MWRA Lab	EPA 350.1, 353.2	X	X	
Nitrite-nitrogen	mg/L	Nutrients	MWRA Lab	EPA 350.1, 353.2	X	X	
Oxygen Saturation	%	Field parameter	Field-Sensor	SM 4500-O G-2001	X		
pH	S.U.	Field parameter	Field-Sensor	SM4500-H+ B-2000	X	X	
Precipitation	in	Meteorological	Field-Sensor (USGS/NOAA)	N/A			
Secchi Depth	ft	Field parameter	Field-Sensor	SOP for Secchi Measurement	X		
Specific Conductance	µS/cm	Field parameter	Field-Sensor	SM 2510 B-1997	X	X	X
Staff Gauge Height	ft	Field parameter	Field-Sensor	Pressure Transducer/ Visual staff plate reading		X	
Total Kjeldahl Nitrogen	mg/L	Nutrients	MWRA Lab	EPA 351.2	X	X	
Total Nitrogen	mg/L	Nutrients	MWRA Lab	Calculated		X	
Total Organic Carbon	mg/L	Nutrients	MWRA Lab	SM 5310 B		X	
Total Phosphorus	µg/mL	Nutrients	MWRA Lab	EPA 365.1	X	X	
Total Suspended Solids	mg/L	Nutrients	MWRA Lab	SM2540		X	
Turbidity FNU	FNU	Field parameter	Field-Sensor	ISO7027	X		
Turbidity NTU	NTU	Bacteria	DWSP Lab, USGS	EPA 180.1		X	
Water Depth	m	Field Parameter	Field-Sensor	N/A	X		
Water Temperature	Deg-C	Field Parameter	Field-Sensor, USGS	SM 2550 B-2000	X	X	X

2.2.1 Ammonia-Nitrogen

Ammonia is an inorganic form of nitrogen that is usually present in surface water at low background concentrations (less than 0.1 mg/L)[30]. Ammonia is very soluble in water, highly reactive, and can be toxic to aquatic life under certain conditions. Ammonia is converted to nitrate naturally, which depletes water of dissolved oxygen, also negatively impacting aquatic life[31]. In 2013 the U.S. EPA updated its aquatic life ammonia criteria to incorporate findings from more recent studies which demonstrated that aquatic life toxicity is highly dependent on water temperature and pH. The updated criteria also accounted for more sensitive taxa (such as mussels) that were not protected under the previous criteria. The acute criteria of 17 mg/L (1-hour duration) and chronic criteria of 1.9 mg/L (a 4-day average within the 30-days, more than once in three years on average) for NH_3-N are applicable at pH = 7 and 20 °C[32]. Across the varying temperatures and pH values found in Wachusett Reservoir and the tributaries, the acute threshold ranges from 9.4 – 41 mg/L, while the chronic threshold ranges from 1.2 – 4.5 mg/L. Concentrations of NH_3-N have been below detection (0.005 mg/L) in 45% of all Wachusett tributary samples taken to date, with a maximum single result of 0.184 mg/L. Ammonia concentrations in the reservoir have been below detection (0.005 mg/L) is 35% of samples taken to date. The maximum Ammonia concentration recorded in the reservoir is 0.057 mg/L. There are no drinking water specific action levels or maximum contaminant levels (MCLs) designated by any U.S. statutes, however the World Health Organization guidelines on drinking water quality list odor and taste thresholds of 1.5 and 1.9 mg/L respectively[33]. Probable sources of NH_3-N in the Wachusett watershed include septic systems, landfill leachate, agriculture (from fertilizer and livestock), atmospheric deposition, and natural biological processes.

Although the concentrations of NH_3-N that have been observed historically in Wachusett Reservoir watershed tributaries are well below thresholds of concern, DWSP continues to monitor NH_3-N as a diagnostic tool for detection of contamination from high priority water quality threats (e.g., leaking septic/sewer, agricultural runoff). The current water quality goal for NH_3-N is to maintain local background concentrations.

2.2.2 Nitrate-Nitrogen

Nitrate-nitrogen (NO_3-N) is an important macro-nutrient for plants and the most abundant inorganic form of nitrogen found in water[34]. Sources of nitrate include runoff from agricultural sites and fertilized lawns, failing on-site septic systems, atmospheric deposition, and some industrial discharges. Background concentrations of NO_3-N + NO_2-N in rivers and streams of the Wachusett watershed ecoregions were found to range between 0.1 mg/L and 4.12 mg/L, with the 25th percentile value (all seasons) of 0.16 mg/L (ecoregion 58)[35] and 0.31 mg/L (ecoregion 59)[36], which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical NO_3-N + NO_2-N criteria for these ecoregions. NO_2-N is usually present in very low concentrations (see Section 2.2.3), therefore it can be assumed that these background concentrations are primarily composed of NO_3-N. At elevated concentrations, nitrates can cause significant water quality problems including increases in aquatic plant growth, reductions in

[30] USGS, 1999
[31] Mallin et al., 2006
[32] USEPA, 2013
[33] World Health Organization [WHO], 1996
[34] USGS, 1999
[35] USEPA, 2001a
[36] USEPA, 2000

dissolved oxygen concentrations, changes in plant and animal species composition, and loss of biodiversity[37].

In terms of drinking water quality, consumption of nitrates can become toxic to warm-blooded animals at very high concentrations (10 mg/L or higher), due to conversion to nitrite through reduction (see Section 2.2.3). The EPA MCL for NO_3-N is 10 mg/L[38]. Several other studies (mostly in Europe) have linked high levels of nitrate consumption, though in some cases below the EPA MCL, to various cancers[39]. However, more research is needed on this topic because high nitrate levels tend to be associated with other contaminants, which can confound the interpretation of study results. Fortunately, NO_3-N concentrations throughout the Wachusett watershed have remained well below the MCL. The current water quality goal for NO_3-N is to maintain existing local background concentrations.

2.2.3 Nitrite-Nitrogen

Nitrite-nitrogen (NO_2-N) is a short-lived nitrogen species that is produced during nitrification/denitrification processes. Sources of nitrite are the same as for nitrate, but it is typically present in surface waters in much lower concentrations. Elevated levels of nitrite have been shown to cause methemoglobinemia in humans, which is a reduction in the ability of blood to transport oxygen to tissues[40], and is particularly lethal to infants[41]. In order to protect human health, the EPA has established the MCL for NO_2-N in drinking water at 1.0 mg/L[42]. Although nitrite concentrations are rarely above the detection limit (0.005 mg/L) in Wachusett tributaries, this parameter continues to be monitored in order to demonstrate compliance with the MCL and to track nutrient inputs to the Reservoir. The current water quality goal for NO_2-N is to maintain existing local background concentrations, which are well below all thresholds of concern.

2.2.4 Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) is the sum of organic nitrogen plus NH_3-N and ammonium-nitrogen (NH_4-N). It often constitutes a significant proportion of the total nitrogen present in a natural water body (20 – 80% in Wachusett tributaries). Background concentrations of TKN in rivers and streams of the Wachusett watershed ecoregions were found to range between 0.05 mg/L and 1.45 mg/L, with the 25th percentile value (all seasons) of 0.10 mg/L (ecoregion 58)[43] and 0.30 mg/L (ecoregion 59)[44], which are the reference conditions for streams and rivers recommended by EPA for the development of numerical TKN criteria for these ecoregions. This fraction of nitrogen is important to account for because it can be converted to other forms of nitrogen through natural processes and can contribute to unwanted plant growth in the tributaries and Reservoir. There are no water quality standards for TKN, however this metric includes NH_3-N, which is toxic at low concentrations and has specific regulatory thresholds (see Section 2.21). Sampling for TKN in the Wachusett Reservoir watershed began in 2015 in order to account for organic sources of tributary nitrogen and allow for a better understanding of nutrient dynamics. The current water quality goal for TKN in streams, rivers, and the Reservoir is to maintain existing local background concentrations.

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[37] Camargo & Alonso, 2006
[38] Safe Drinking Water Act of 1974 (2019)
[39] Ward et al., 2018
[40] Ibid
[41] Walton, 1951
[42] Safe Drinking Water Act of 1974 (2019)
[43] USEPA, 2001a
[44] USEPA, 2000

2.2.5 Total Nitrogen

Total nitrogen (TN), as measured in water, is the sum of TKN, NO_3-N and NO_2-N. This calculated parameter is important to examine in conjunction with TP because the ratio of nitrogen to phosphorus in aqueous systems controls primary production and has important implications for the ecology and drinking water quality of a water body. The dominant forms of nitrogen in surface waters are NO_3-N and organic nitrogen, with much smaller fractions of inorganic NH_3-N and NH_4-N species (See Sections 2.2.1 – 2.2.4).

Massachusetts has only developed numeric water quality criteria for nitrogen for specific water bodies with significant impairments from nutrient over-enrichment. Nitrogen criteria are usually created in conjunction with phosphorous criteria, as they are the two primary causal agents for eutrophication. In absence of water body specific nitrogen criteria for Wachusett watershed water bodies, only the narrative criteria for nutrients applies – to not '*… cause or contribute to impairment of existing or designated uses'*. Thus, the internal numerical goal for TN in streams and rivers is to maintain naturally occurring local background concentrations. Background concentrations of TN in rivers and streams of the Wachusett watershed ecoregions were found to range between 0.34 mg/L and 5.57 mg/L, with the 25th percentile value (all seasons) of 0.42 mg/L (ecoregion 58)[45] and 0.59 mg/L (ecoregion 59)[46], which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TN criteria for these ecoregions. Long-term (seasonal or annual) TN concentrations above these recommended criteria likely indicate that excess nitrogen is entering waters. Any tributaries exhibiting long-term concentrations above these recommended nitrogen criteria should be examined more closely to determine if any response variables (chlorophyll, macrophytes, turbidity, macroinvertebrates) indicate that water quality impairments are occurring.

2.2.6 Total Phosphorus

Phosphorus is an important macronutrient, and the limiting factor controlling algal productivity in Wachusett Reservoir. Phosphorous is derived from the weathering of rocks and therefore it is naturally present in soils in varying concentrations as orthophosphate (PO_4^{3-}). Plants take up orthophosphate as they grow, which is then returned to the soil in organic compounds via animal waste and the decomposition of plant and animal tissue[47]. Through various human activities, additional phosphorous is released to both soil and water, often in highly concentrated quantities. Many agricultural operations intentionally add phosphorus to soils using chemical fertilizers and/or organic animal waste solids (manure). Concentrated animal feeding operations create large quantities of animal waste that can unintentionally release phosphorous to soils and groundwater when improperly managed. Sewage treatment discharges to streams and septic system effluent leaching to groundwater both usually contain elevated levels of phosphorous. Furthermore, human activities that accelerate erosion processes on the land surface and within streams can increase the release of phosphorous from soils and sediment into water bodies.

Lakes with TP concentrations exceeding 20-30 µg/L may experience nuisance algal growth[48]. Background concentrations of TP in rivers and streams of the Wachusett watershed ecoregions were found to range between 2.5 µg/L and 907.5 µg/L, with the 25th percentile value (all seasons) of 12 µg/L (ecoregion 58)[49]

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[45] USEPA, 2001a
[46] USEPA, 2000
[47] USGS, 2012
[48] Vollenweider, 1976
[49] USEPA, 2001a

and 23.75 µg/L (ecoregion 59)[50], which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TP criteria for these ecoregions. Similar to nitrogen, there are no Massachusetts numerical water quality standards for phosphorus for any Wachusett Reservoir watershed water bodies. However, the narrative water quality criteria do apply as previously described.

In Wachusett tributaries annual mean TP concentrations are historically below 30 µg/L, but occasionally are higher for some tributaries, though never above 50 µg/L. Reservoir concentrations are typically less than 10 µg/L. While elevated TP concentrations pose no direct threat to drinking water quality, they can promote algal blooms in the Reservoir, which can cause taste and odor issues when concentration thresholds for certain species are exceeded or become toxic in the case of specific cyanobacteria. With these concerns in mind, the DWSP goal for TP in streams, rivers, and Wachusett Reservoir are to maintain naturally occurring local background concentrations.

2.2.7 Silica

Silica is a necessary element for the cellular function of all living organisms. It is required for protein synthesis in all phytoplankton and is essential for the formation of siliceous skeletons and scales of diatoms and chrysophytes[51]. After oxygen, silica is the most abundant element, comprising approximately 30% of the Earth's crust. It enters aquatic systems through natural weathering processes although export can be accelerated by human activities such as mining, agriculture, and disturbances of terrestrial vegetation which serve as terrestrial silica sinks. Changes in silica abundance in freshwater reservoirs can be observed on a spatial and temporal gradient as water higher in silica enters from tributaries, disperses through the reservoir and is subsequently taken up by phytoplankton, particularly diatoms in the spring.

There are no water quality standards for silica, but the element's availability is an important driver of diatom and chrysophyte productivity; organisms which in abundance can cause filter clogging issues and undesirable tastes and odors in drinking water.

2.2.8 Water Temperature

Temperature is a critical parameter in controlling the amount of dissolved oxygen that is available in aquatic environments. As water temperatures increase, the amount of oxygen that can be dissolved in water decreases. Moreover, higher stream temperatures increase the solubility of nutrients and may correlate well with an increase in the growth of filamentous algae and may threaten sensitive aquatic habitats. Due to these aquatic life concerns, MassDEP has set regulatory thresholds for warm and coldwater fisheries. Unless naturally occurring, coldwater fisheries may not exceed 20 °C (68 °F) as a mean of 7-day maximum temperature. Warmwater fisheries may not exceed 28.3 °C (83 °F) as a mean of 7-day maximum temperature[52]. For tributaries, the water quality goal for water temperature is to remain under the threshold temperatures for cold and warmwater fisheries, depending on their respective fishery designations.

Water temperature regulatory thresholds within the reservoir are also based on MassDEP aquatic life use standards. Although there is no guidance describing how this standard applies to lakes and reservoirs, the presumed goal for coldwater fisheries is to maintain sufficient thermal habitat and refuge for naturally reproducing coldwater communities. Water temperature data collected from discrete water quality

[50] USEPA, 2000
[51] Reynolds, 2006
[52] 314 CMR 4.05(3)(a)2 (2013)

profiles are used to monitor thermal habitat at specific locations within the reservoir. Tracking changes in thermal structure is also an important component of reservoir monitoring as these dynamics affect both biological processes and hydrologic patterns including establishment of the Quabbin Interflow. 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.

2.2.9 Dissolved Oxygen

Dissolved oxygen dynamics in stream environments may be linked to fluctuations in temperature, rates of streamflow, channel depth, other physical characteristics of the stream channel (e.g., channel slope, morphology, tortuosity), and local hydrology. Depletion of dissolved oxygen in aquatic environments can result from the oxygen requirements of aquatic life, the decomposition of organic matter, and the introduction of oxygen-demanding substances (such as chemical reducing agents). The Massachusetts Class A standard is a minimum of 6.0 mg/L for waters designated as coldwater fisheries, and 5.0 mg/L for waters designated as warmwater fisheries. This standard is applied to both the tributaries and the Reservoir.

Dissolved oxygen values in the Reservoir remain near 100% saturation in the epilimnion most of the year due to atmospheric exposure and mixing due to wind-induced turbulence. In contrast, saturation values in the metalimnion and hypolimnion decline progressively due to microbial decomposition and the isolation of these strata from the atmosphere. The supply of oxygen at depth is not replenished until thermal structure dissipates and turnover occurs. Dissolved oxygen concentration in the hypolimnion of Wachusett Reservoir remains sufficient (typically > 6.0 mg/L) to provide suitable habitat for coldwater salmonids such as Lake Trout (*Salvelinus namaycush*) and Landlocked Salmon (*Salmo salar*).

2.2.10 Alkalinity and pH

The Hydrogen ion activity (pH) of a stream is largely a function of the groundwater hydrogeology of the basins and the effectiveness of the stream water in buffering the effects of acid precipitation. The Class A water quality standard is a range between 6.5 – 8.3 (or no change from background levels). The 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 = 5.5). 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 exhibiting only minor fluctuations in the Reservoir.

Buffering capacity, or the ability of a water body to resist changes in pH from acidic or basic inputs, is quantified by alkalinity as calcium carbonate ($CaCO_3$). Waters in the northeastern U.S. typically have low alkalinity due to the region's lack of carbonate-rich bedrock. Alkalinity may also be influenced by land use within the watershed including agriculture and landscaping which may involve application of lime, weathering of concrete, and use of road deicers. Within a water body, alkalinity can affect photosynthetic activity of algae and other plants. The minimum alkalinity for aquatic life published by EPA is 20 mg/L or if lower values are naturally occurring, results cannot be lower than 25% of the natural level[53]. Alkalinity in Wachusett Reservoir is much lower than this threshold. Increases observed over the past 30 years and accelerated in the last five years are likely linked to the observed increases in specific conductance caused by regional salinization[54] (see Section 2.2.12).

2.2.11 Bacteria

Water bodies naturally contain many microorganisms, most of which are benign. However, there are several harmful intestinal microorganisms (viruses, bacteria, and protozoa) that are sometimes present in water (e.g., *Cryptosporidium*, *Giardia, Salmonella*). Many of these are fecal microorganisms and are known to cause a host of illnesses such as intestinal and urinary tract infections, meningitis, and septicemia[55], dysentery, typhoid fever, and cholera[56]. *Escherichia coli* (*E. coli*) is a species in the fecal coliform group, which originates from fecal material of humans and other warm-blooded animals[57]. Some strains of *E. coli* can be deadly, especially for small children or people with weakened immune systems[58]. Studies have found that the presence of *E. coli* is often correlated with the presence of many other pathogenetic microorganisms[59], thus it has been selected as a useful indicator of pathogen contamination in waters. Human exposure to pathogens usually occurs through recreational contact or direct consumption of drinking water that was not adequately disinfected.

Sources of *E. coli* all stem from human or animal wastes: agricultural operations with livestock or that use manure to fertilize crops, treated wastewater, septic systems, urban runoff, land application of biosolids (sludge), pet waste, and wildlife[60]. The only two common *E. coli* sources not applicable to the Wachusett watershed are biosolids, which are prohibited, and treated wastewater discharges, of which there are none.

Massachusetts Class A surface water quality standards differentiate between bacteria standards for water supply intakes and other Class A waters, which rely on *E. coli* bacteria as the indicator of sanitary quality. The Massachusetts Class A standard for non-intake waters states that the geometric mean of all *E. coli* within the most recent six months must remain below 126 MPN/100 mL (based on a minimum of five samples) and that no single sample shall exceed 235 MPN/100 mL[61]. DWSP prohibits boating, wading and swimming in Wachusett Reservoir and its tributary waters, however fishing is allowed and that is probably the only (legal) avenue for public exposure to pathogens from the water supply prior to treatment. Despite there being low risk for pathogen exposure due to recreation, DWSP uses these regulatory thresholds to evaluate the sanitary quality of waters within the Wachusett watershed. As a major public water supply, regulatory requirements for pathogens at drinking water intakes are much more stringent.

MWRA is required to measure fecal coliform concentrations in raw water prior to treatment. State and federal regulations specify that fecal coliform concentrations shall not exceed 20 organisms per mL in 90%

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[53] USEPA, 2013
[54] Kaushal et al., 2005
[55] USGS, n.d.-a
[56] Myers et al., 2014
[57] USEPA, 1986
[58] USEPA & Tetra Tech Inc., 2013
[59] Myers et al., 2014
[60] Ibid
[61] 314 CMR 4.05(3)(a)4.c (2013)

of the samples taken in any six-month period[62]. Results for pathogen testing at the intake are discussed in separate reports published by MWRA[63].

2.2.12 Specific Conductance and Dissolved Salts

Specific conductance is a measure of the ability of water to conduct an electrical current at 25 °C, dependent on the concentrations of various ions in solution[64, 65]. Freshwater systems in Massachusetts naturally contain low levels of mineral salts in solution[66]. Elevated levels of specific conductance and associated dissolved solutes (e.g., Na, Cl) may stress sensitive biota, threaten ecosystems[67, 68], and degrade drinking water quality[69, 70, 71]. Contamination of drinking water supplies with excess Cl may increase the corrosivity of affected waters[72], posing a risk to communities with infrastructure containing lead fixtures.

Excess sodium in drinking water may compromise the health of individuals on sodium-restricted diets, such as those with hypertension, and increase the cation-exchange capacity of nearby soils[73], resulting in the mobilization of base cations (e.g., calcium, potassium, magnesium) to streams thereby altering natural biogeochemical cycles. The EPA established aquatic life criteria for Cl in 1988 at chronic (4-day average) and acute (1-hour average) concentrations of 230 and 830 mg/L, respectively[74]. Neither threshold is to be exceeded more than once every three years. MassDEP has established a linear regression model to derive Cl concentrations from specific conductance values: "Instantaneous exceedances of the acute and chronic Cl criteria are estimated to occur at [specific conductance] readings greater than 3,193 and 904 µS/cm, respectively"[75]. MassDEP also established an Office of Research and Standards Guideline (ORSG) of 20 mg/L sodium in drinking water, and a secondary maximum contaminant level (SMCL) for Cl of 250 mg/L[76]. MassDEP does not currently enforce regulatory standards for specific conductance in drinking water.

Elevated levels of specific conductance and associated ions in surface water and groundwater may indicate contamination from anthropogenically-derived sources of salts to natural water systems such as septic system effluent, stormwater discharges, agricultural runoff, or road salt runoff from deicing activities[77,78]. In the snowbelt region of the U.S., road salt is the dominant source of salinity to many natural water systems[79, 80, 81].

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62 314 CMR 4.05(3)(a)4.a (2013)
63 MWRA, 2020b
64 Granato et al., 2015
65 Rhodes et al., 2001
66 Granato et al., 2015
67 Jackson & Jobbágy, 2005
68 Corsi et al., 2010
69 Kaushal et al., 2005
70 Daley et al., 2009
71 Kelly et al., 2010
72 Stets et al., 2018
73 Kaushal et al., 2017
74 USEPA, 1988
75 Massachusetts Department of Environmental Protection - Division of Watershed Management [MassDEP-DWM], 2018
76 310 CMR 22.07D (2016)
77 Panno et al., 2006
78 Lautz et al., 2014
79 Kaushal et al., 2005
80 Kelly et al., 2008
81 Mullaney et al., 2009

Increases in specific conductance have been documented in the Wachusett watershed and within Wachusett Reservoir, where record high specific conductance values have been recorded over the past several years. Since many aquatic organisms are sensitive to increases in Cl, community composition is likely to shift in response[82]. For example, increases in Cl may negatively impact native *Potamogeton* species while facilitating growth of non-native species such as *Phragmites australis* and *Myriophyllum. spicatum*[83].

In 2018, Cl analysis was added to the Wachusett water quality tributary monitoring program with the objective of developing a strong correlation between specific conductance and Cl that will enable concentration and loading estimates using specific conductance as a surrogate. Ultimately, this information will help to inform management strategies aimed towards stabilizing and eventually reversing the upward trend of specific conductance/Cl that has been rising in recent years. Two years of Cl data have been collected and analyzed so far; however, except for the USGS monitored tributaries, corresponding specific conductance measurements have only been collected for the 2019 monitoring year.

Within the Reservoir, horizontal and vertical differences in specific conductance are reflective of interactions between native water contributed from the Wachusett watershed and water transferred from Quabbin Reservoir. Average specific conductance values from the largest tributaries to Wachusett Reservoir, the Stillwater and Quinapoxet Rivers, during 2019 were 174 µS/cm and 261 µS/cm, respectively, while the average for water entering via the Quabbin Aqueduct was 49 µS/cm. This difference in specific conductance can be used to track movement of native and Quabbin water through the Reservoir. During periods of isothermy, values typically range from 100 to 180 µS/cm depending on the volume of water received from Quabbin the previous year. During stratification, the Quabbin interflow is conspicuous in profile measurements as a metalimnetic stratum of low conductivity generally between 75 and 150 µS/cm.

2.2.13 Total Suspended Solids

Total suspended solids (TSS) are the dry weight of particles suspended in a water sample retained by a filter of 2-µm pore size. These particles, both organic and inorganic, may be naturally occurring, the result of human activities, or a combination of these sources. Typically, TSS concentrations are highest during and immediately after storms; overland flow erodes particles from the land surface and carries them into waterways and as stream velocity and turbulence increase with higher flow rates, sediment deposits on the stream bed and banks can be dislodged and resuspended into the flowing water. Common sources of elevated TSS concentrations are construction sites, agricultural operations, transportation infrastructure, and other areas with high proportions of impervious surfaces. In Massachusetts, and around the U.S., excessive TSS is one of the most prevalent causes of water quality impairment.

Depending on particle density, suspended solids may settle out of suspension at different rates and locations as a function of the changing hydraulic and geomorphological conditions between the headwaters and the Reservoir. The concentration and composition of TSS can vary widely across subbasins depending on soils, stream channel geomorphology, subbasin land cover type and conditions (e.g., disturbances). These solids provide benthic structure (bed material) and a stock of minerals and nutrients to support aquatic life. Local stream ecology evolved under a “normal” sediment regime, which underpins

[82] Van Meter & Swan, 2014
[83] June-Wells et al., 2013

much of the aquatic habitat and nutrient dynamics at the reach scale[84,85]. When the TSS concentration and composition deviates from “normal” over a sustained period it can be detrimental to aquatic life and cause other water problems. Chronically high TSS concentrations can block light passage in water and absorb solar radiation, which can reduce dissolved oxygen concentrations by inhibiting photosynthesis in plants and by reducing oxygen saturation concentrations due to higher water temperatures[86]. Furthermore, high TSS concentrations can harm fish by clogging gills, reducing visibility so that it is more difficult for fish to find food, and smothering eggs. Suspended solids that settle on the streambed can form thick deposits, reducing fish spawning areas and eliminating habitat for benthic macroinvertebrates. As suspended solids enter Wachusett Reservoir they begin to settle out in coves or along the shoreline and can negatively affect aquatic life in those places as well and promote invasive or nuisance plant growth by providing nutrient rich substrate.

Fortunately, Wachusett Reservoir is a large enough system that suspended solids rarely reach the intake except in rare instances of soil/debris washing off the shoreline immediately adjacent to the Cosgrove Intake. Nearly all runoff from roadways surrounding Wachusett Reservoir is treated to remove TSS prior to being discharged into the reservoir. Aggregations of phytoplankton which may contribute to elevated TSS are likewise rare in the area of the Cosgrove Intake. For water supplies it is desirable to have low TSS concentrations, as high TSS levels often lead to aesthetic issues (taste/odor), mostly due to organic suspended solids. Although TSS is often cited as the reason for water quality impairments, there are no state or federal standards for TSS in streams since other standards (turbidity, bacteria) are more useful predictors of drinking water quality. However, MassDEP does enforce specific stormwater management standards, which address both water volume and TSS loads from development projects exceeding certain size thresholds[87]. While these regulations have been helpful in mitigating stormwater runoff in recent years, there are many legacy stormwater issues that persist on properties that were developed before the standards were adopted.

Total suspended solids (TSS) in Wachusett tributaries are too low to be detected most of the time. Higher TSS concentrations were most often detected during targeted storm sampling, both during and after precipitation and high streamflows. Stormflow TSS in Wachusett tributaries can typically range from 5 – 50 mg/L, and occasionally can exceed 100 mg/L during large storm events. The water quality goal for TSS in Wachusett watershed tributaries is for mean concentrations during dry conditions to remain below detection (< 5 mg/L) and for concentrations during wet conditions to remain below 50 mg/L for any single sample.

2.2.14 Turbidity

Turbidity is another term for water clarity, which is determined by measuring the scatter of light in the water (USGS) and reported by DWSP in Nephelometric Turbidity Units (NTU). Any dissolved or suspended particle in water will cause light scatter and increase turbidity. In streams, high turbidity is often associated with storm events which increase suspended solid concentrations (see TSS), as well as concentrations of smaller particles like clay. Reservoir turbidity may be influenced by plankton production, pollen deposits, and shoreline disturbances of organic deposits. Clay particles can also remain suspended in the water column for extended periods as a result of eroding shorelines or clay laden tributary waters delivered by storm events. For drinking water supplies, the concern over turbidity relates to aesthetics, pathogens, and

[84] Southwood, 1977
[85] Wohl et al., 2015
[86] Murphey, 2007
[87] 310 CMR 10.05(6)(k) (2014); 314 CMR 9.06(6)(a) (2017)

treatment considerations. The particles that cause turbidity can make water cloudy or have displeasing taste or odor. These particles also promote regrowth of microbes by inhibiting disinfection and providing nutrients and minerals for their reproduction. For these reasons and its relative ease of measurement, turbidity is a good general water quality indicator.

There are two standards for turbidity levels at drinking water intakes. The SWTR mandates that raw water turbidity levels (at the intake) always remain below 5 NTU. MassDEP regulations specify that turbidity levels may exceed 1 NTU only if it does not interfere with effective disinfection[88]. Background concentrations of turbidity in rivers and streams of the Wachusett watershed ecoregions were found to range between 0.28 NTU and 4.33 NTU, with the 25th percentile value (all seasons) of 0.8 NTU (ecoregion 58)[89] and 1.68 NTU (ecoregion 59)[90], which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical turbidity criteria for these ecoregions. The current water quality goal for turbidity in streams and rivers is to maintain existing local background concentrations.

2.2.15 Total Organic Carbon

Total organic carbon (TOC) is the sum of all organic carbon in water, both dissolved and particulate (suspended). Organic carbon sources fall into three categories: 1) Terrestrial carbon such as decaying organic matter, proteins, organic acids, and animal waste, 2) Autochthonous sources produced in-stream/reservoir, such as algae, and 3) Anthropogenic sources such as industrial and wastewater discharges, petroleum related pollution, agricultural chemicals, and the accelerated release of natural organic carbon through landscape disturbance. Background TOC concentrations in rivers are typically 1 to 10 mg/L, though waters emanating from wetlands or bogs often have much higher natural concentrations of organic carbon[91].

While organic carbon is not a directly regulated drinking water quality parameter, carbon sources are precursors to disinfection byproducts (DBP) called trihalomethanes (THM's) and haloacetic acids, which are regulated at 60 µg/L and 80 µg/L, respectively. If TOC concentrations are above certain reactive thresholds which will cause DBP exceedances, then TOC removal is added to the water treatment process. To meet THM MCLs, water treatment guidelines typically suggest TOC removal when concentrations exceed 2 mg/L in the source water. The water quality goal for TOC in Wachusett watershed waters is to maintain background natural concentrations of TOC, preferably below 2 mg/L.

2.2.16 UV Absorbance

Ultraviolet light absorbance at 254 nm (UV_{254}) is used as a surrogate for the amount and reactivity of natural organic material in source water that is easier to measure than TOC. Measurements of UV_{254} are reported as the amount of ultraviolet light at a 254 nm wavelength that is able to transmit through a water sample in absorbance units per centimeter of path length (ABU/cm). Higher UV_{254} levels indicate higher organic carbon concentrations, which require increased ozone and chlorine demand for disinfection, which can subsequently increase disinfection byproduct formation. Tributary levels of UV_{254} are influenced by the same variables that are responsible for organic carbon discussed above (2.2.15).

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[88] 310 CMR 22.08(1) (2016)
[89] USEPA, 2001a
[90] USEPA, 2000
[91] Mulholland & Kuenzler, 1979

As with TOC, there are no regulatory limits for UV_{254}, however measurements are used to calculate the amount of carbon reduction required in the treatment process to meet the two DBP regulatory standards. After statistical relationships are developed to correlate TOC with UV_{254} for each tributary it is then possible to discontinue TOC sampling and use UV_{254} as a proxy for organic content. Water quality goals for UV_{254} would have to be specific to each tributary based on a statistically significant correlation to TOC concentration. The targeted UV_{254} values would be analogous to local their correlative background TOC concentrations, preferably below 2 mg/L. Although there are few management options to address organic carbon loading in streams, DWSP does proactively manage riparian vegetation along the Reservoir shoreline specifically to reduce carbon inputs from leaf litter[92].

2.2.17 Chlorophyll *a* and Phycocyanin

Plants, algae, and cyanobacteria use pigments to derive light energy for photosynthesis. Chlorophyll *a* is found in all photosynthetic organisms while small amounts of accessory pigments, which transfer energy to chlorophyll *a,* are associated with specific groups of organisms. One such pigment is phycocyanin, a blue light absorbing pigment that is only found in cyanobacteria. These pigments can be measured using *in situ* fluorometers which expose pigments in the water column to light at a specific wavelength and measure the response. This response can be used to estimate the density of algae and cyanobacteria populations. While chlorophyll *a* is used to estimate the overall biomass of the algal community, phycocyanin is used to estimate the proportion of that community comprised of cyanobacteria since this pigment is only produced by those organisms. These pigments measure the biological response to abiotic variables and are most often associated with the nutrients that fuel algal growth.

There are currently no MA statutory action levels for algal pigments in surface waters, including drinking water sources. The EPA Office of Water does include chlorophyll *a* in its Ambient Water Quality Criteria Recommendations which are specific to the fourteen U.S. nutrient Ecoregions. The reference condition ranges listed for Wachusett watershed's subecoregions 58 and 59 are 2.1 – 6 µg/L and 1.38 – 2.7 µg/L, respectively[93].

Chlorophyll *a* and phycocyanin data are only collected from reservoir locations at this time. Chlorophyll *a* has been measured in Wachusett Reservoir since 2011 when a fluorometer was added to the HydroLab multiprobe in use at that time. Upon upgrade to the YSI EXO2 probe in 2016, phycocyanin was also added as a routinely measured parameter. On average, measurements for these pigments are low (< 2.7 µg/L); however, periodic increases are observed in association with increases in algal growth. Like the algae increases, increased values are often limited to specific strata rather than spread through the entire water column.

2.2.18 Phytoplankton

Algae are a large, diverse group of organisms present in nearly every ecosystem from sandy deserts to artic permafrost to freshwater reservoirs[94]. In fresh water they can be planktonic (free-floating) or attached to structures including plants and rocks. Growth of freshwater algae is largely dependent on abiotic factors such as sunlight, temperature, and nutrients present in the water column. Changes in the algae community composition and density can therefore provide early indication of changes in water quality. In drinking water supplies, especially unfiltered systems, monitoring for these organisms can be

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[92] DWSP, 2018b
[93] USEPA, 2001b
[94] Reynolds, 2006

extremely important, as certain taxa can produce compounds causing undesirable tastes, odors, and in limited cases, toxins. Phytoplankton can proliferate rapidly when ideal conditions are available and routine monitoring is essential for detecting density increases early in the growth phase so that appropriate management actions can be taken. For Wachusett Reservoir, these management options include treatment of the algae present in the Reservoir with copper sulfate (the last treatment was in 2014) and adjustments within the treatment system such as increasing the ozone dose.

Phytoplankton undergo seasonal succession, with some genera becoming more or less prevalent throughout the year. In Wachusett Reservoir, phytoplankton follow the typical pattern of a freshwater temperate water body with diatoms most common in the spring followed by a period of decreased productivity where chlorophytes (green algae) typically become more diverse but remain at low density. An increase in chrysophytes (golden-brown algae) is often observed in mid-summer, especially when the Quabbin Interflow is well established. An increase in cyanophytes is occasionally observed as these organisms take advantage of warm summer temperatures and nutrient influxes in the fall. Following reservoir turnover, diatoms often undergo a slight increase and remain dominant in the phytoplankton community throughout the winter months.

While the entire phytoplankton community is assessed by DWSP biologists, MWRA and DWSP have established thresholds for five organisms (Table 10). These four chrysophyte genera and one cyanobacteria genus have previously attained problematic densities in Wachusett Reservoir and could cause undesirable tastes and odors in the water supply. Once these thresholds are exceeded, monitoring frequency is increased (typically to twice weekly) and action is considered.

Table 10: Early Monitoring and Treatment Consideration Thresholds for Select Phytoplankton Genera

Nuisance Organism Group	Nuisance Organism	Early Monitoring Trigger (ASU/mL)	Treatment Consideration Level (ASU/mL)
Cyanophyte	*Dolichospermum*	15	50
Chrysophyte	*Synura*	10	40
	Chrysosphaerella	100	500
	Uroglenopsis	200	1,000
	Dinobryon	200	800

2.2.19 Zooplankton

Zooplankton are small organisms found in nearly all surface waters and are the most abundant multicellular animal on earth. They maintain a vital role in the ecosystem as grazers, providing a pathway of energy from producers to consumers at higher trophic levels[95, 96]. They are also considered indicators of climate change as they are highly sensitive to changes in temperature and have a life span of less than one year, which means the zooplankton community can rapidly reflect environmental signals as populations change. The distribution of zooplankton, composed mostly of free-floating organisms, is largely affected by local factors of a water body, such as lake area, chemical composition, and predator abundance[97].

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95 Hintz et al., 2019
96 Richardson, 2008
97 Havel & Shurin, 2004

As of 2019, the potential invasive zooplankton of most concern are *Bythotrephes longimanus* (spiny waterflea) and *Cercopagis pengoi* (fishhook waterflea). Their native range is Europe and northeast Asia, and Southwest Asia, respectively.

The primary goal of current zooplankton monitoring at Wachusett Reservoir is to identify new occurrences of invasive species as soon as possible. No invasive zooplankton have been found in the Reservoir to date, but these species have colonized all the Great Lakes, the Finger Lakes of New York, and Lake Champlain of Vermont[98]. During these invasive species assessments, observations of native zooplankton are also made, establishing baseline data that may be used in the future to detect impacts from potential invaders and other environmental changes. Sample collection and scanning for presence of invasive species began in 2014. Samples from 2014 to present are maintained at DWSP offices and may also be assessed for community structure in the future.

2.2.20 Secchi Disk Depth/Transparency

A Secchi disk is a tool used to estimate water clarity and the amount of light penetration in a waterbody. The Secchi disk transparency is the water depth at which a Secchi disk, a round, alternately painted, black and white disk, is barely visible from the surface. This value can be used to estimate the depth of the euphotic zone; this area in which photosynthesis occurs is approximately three times the Secchi disk transparency[99]. In Wachusett Reservoir, Secchi disk transparency is most often affected by phytoplankton dynamics and contributions from the Wachusett watershed and Quabbin transfer. Weather patterns and percentage of native Wachusett watershed water also affect visibility. Secchi disk transparency is recorded in association with Basin North (BN3417) samples and at reservoir nutrient sample locations, following the *SOP for Secchi Measurement*. The reference condition ranges listed for Wachusett watershed's subecoregions 58 and 59 are 4.0 – 6.1 m and 1.2 – 4.9 m, respectively[100].

2.3 Statistical Methods and Data Management

Statistics presented in this section may differ slightly from those reported prior to the *2018 Annual Water Quality Report* due to changes in analytical methods. All numerical calculations and related graphics were generated using the R programming language[101] 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[102]. 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 lower detection limit. Any right-censored laboratory results (values above upper

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[98] USGS, n.d.-a
[99] Dodson, 2005
[100] USEPA, 2001b
[101] R Core Team, 2019
[102] Wickham, 2016

detection thresholds; none in 2019), were assigned a value equal to the upper 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.

Water quality, precipitation, and streamflow data generated since 1985 are stored in a Microsoft Access database, maintained by DWSP-EQ. The watershed system data Visualization Environment (WAVE) is a custom R/Shiny[103] application developed as a collaborative effort between individuals from the Department of Civil and Environmental Engineering at UMass Amherst and DWSP. WAVE serves as a portal to visualize and review data within the Access database.

[103] Chang et al., 2019

3 Results

DWSP staff analyzed 425 turbidity samples from 19 tributaries and 188 phytoplankton samples from the Reservoir. A total of 1,120 physiochemical measurements (560 each of 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*, phycocyanin, and pH) recorded from the Reservoir. A total of 787 bacteria samples were collected and delivered to the MWRA Southborough laboratory for *E. coli* analysis, and 1,707 samples were collected and shipped to the MWRA Deer Island laboratory for a total of 2,494 analyses of nutrients and other parameters; this includes special studies. Daily climate statistics for Wachusett watershed were calculated using records from NOAA, USGS, and DWSP monitoring stations. Daily streamflow statistics were calculated from DCR stream gauging stations or obtained from three USGS monitoring stations. Daily Quabbin transfer totals were provided by MWRA. DWSP staff measured watershed snowpack on nine occasions during 2019.

3.1 Hydrology and Climate

Climate is a primary driver of the hydrologic cycle and has major implications to water quality and water supply due to its role in water availability and temperature. There is often a response in both hydrologic conditions and water quality when local climatic conditions deviate from "normal" for a prolonged period or after short and intense extreme weather events. Thus, it is important to compare abnormal water quality results to hydrological and climate conditions at the time of observation in order to determine if there is a causal link, or if other factors may be responsible for the water quality response.

3.1.1 Climatic Conditions

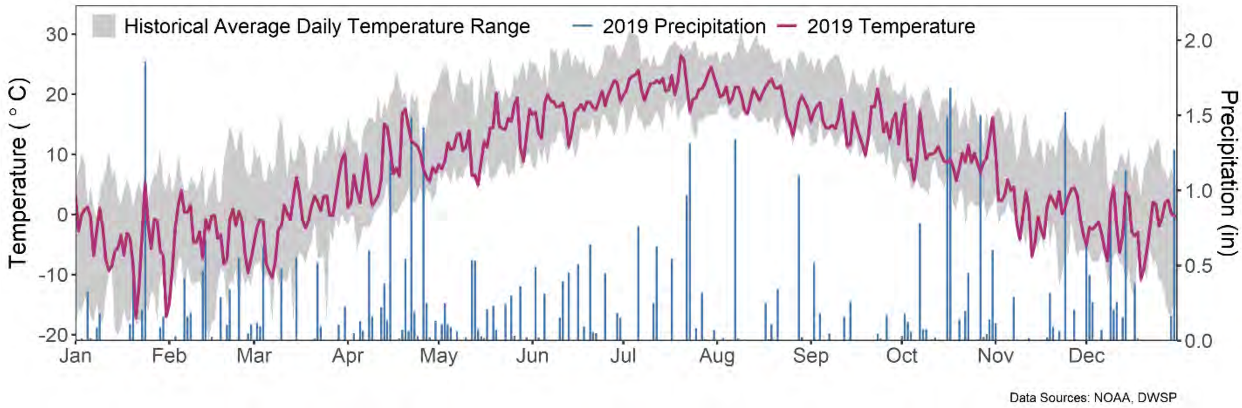
3.1.1.1 *Air Temperature*

Average daily air temperatures in the Wachusett Reservoir watershed for 2019 ranged from -17.2 °C (January 21) to 25.6 °C (July 20). With the exception of a period in early January, temperatures in 2019 were slightly below average for most months of the year. The mean temperature at Worcester for 2019 was 0.4 °F lower than normal (climate normal period 1981 – 2010). The mean temperature for November (all Wachusett watershed stations) was the coldest since 2003, with a record low daily temperature (tied with November 1971) of -9.44 °C (15 °F) occurring on November 9 (at NOAA Worcester station). November 13 also set a record for the lowest daily high temperature at -3.33 °C (26 °F) and the lowest daily low temperature at -10.56 °C (13 °F)[104]. Daily mean temperature for 2019 is shown in Figure 8.

[104] National Oceanic and Atmospheric Administration [NOAA], 2014

Figure 8. Climatograph of Daily Mean Temperatures and Daily Precipitation Totals for Wachusett Watershed from January 1 through December 31, 2019

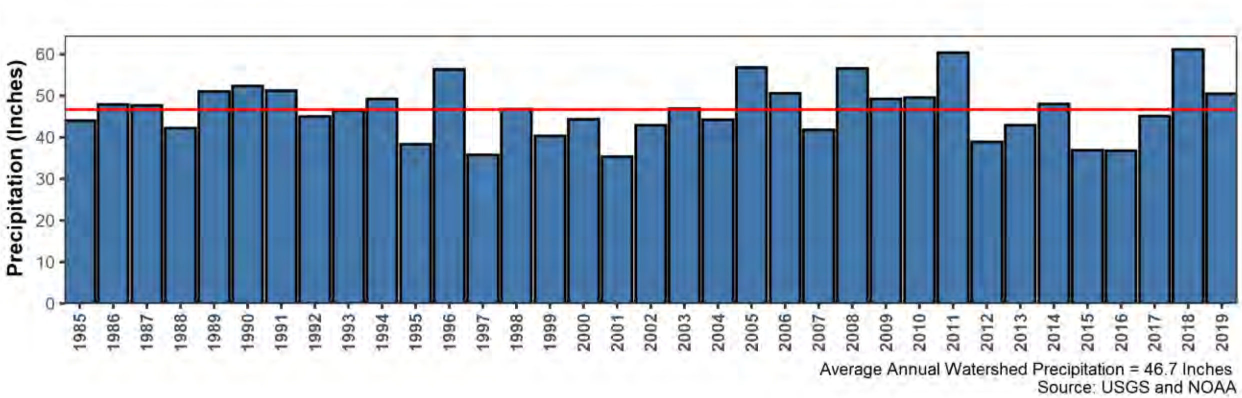
Shaded band represents average daily temperature ranges from 1998 – 2019.



3.1.1.2 *Precipitation*

As illustrated by Figure 9, Wachusett watershed received slightly more precipitation in 2019 than normal, with 50.54 inches of rainfall (3.88 inches more than average annual precipitation).

Figure 9: Annual Precipitation for Wachusett Watershed, 1985 – 2019



Precipitation to calendar date during 2019 was about average until April, which received 3.28 inches of precipitation above normal (Figure 10). September was the driest month of the year with only 1.42 inches of precipitation, which caused some smaller/intermittent tributaries to go dry. October was the wettest month of 2019 (7.65 inches), mostly due to a storm that delivered over three inches of rainfall over October 16 – 17, ending the prevailing dry conditions and bringing cumulative precipitation to calendar date back above normal. Other notable storms for the year occurred January 24 (1.86 in), July 22 – 23 (2.28 in), and October 27 (1.5 in).

Figure 10: Wachusett Watershed Monthly Total and Daily Cumulative Precipitation for 2019

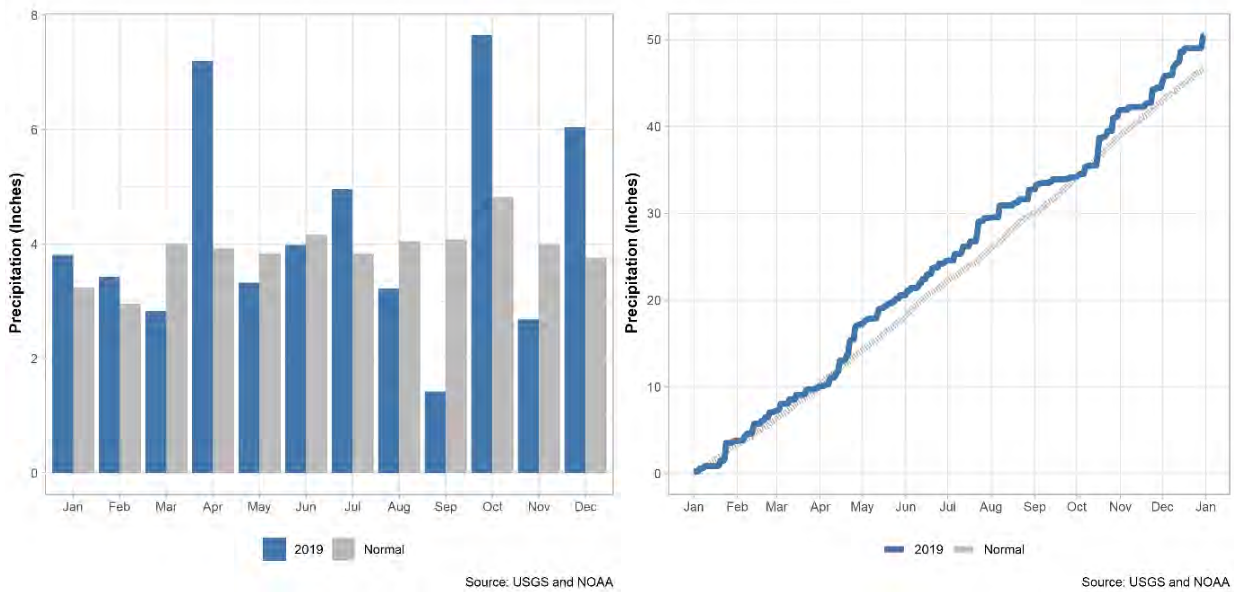


Table 11: Monthly Total Precipitation for 2019 and Statistics for the Period of Record 1985 – 2019

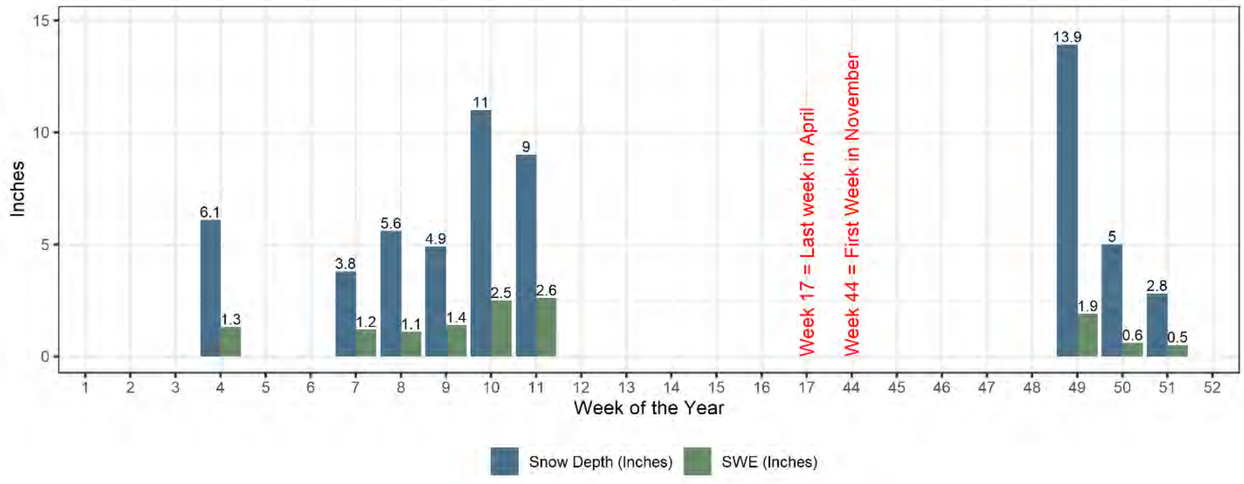
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Precipitation	3.81	3.43	2.83	7.20	3.32	3.98	4.96	3.22	1.42	7.65	2.68	6.04	50.54
Normal	3.23	2.96	4.00	3.92	3.84	4.16	3.84	4.05	4.08	4.82	4.00	3.76	46.66
Departure	0.58	0.47	-1.17	3.28	-0.52	-0.18	1.12	-0.83	-2.66	2.83	-1.32	2.28	3.88
Years	36	35	35	35	35	35	35	35	35	35	35	35	N/A

Snow

Figure 11 shows the snowpack measurement results for calendar year 2019. The weekly results presented 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.

The first accumulation of snowpack in 2019 occurred during the end of January (week 4) when 6.1 inches of snow (average) fell in the Wachusett watershed. By week 5 this snow had mostly melted, and the next significant accumulation was during week 7. Snowpack remained steady and below 6 inches until early March (week 10), when 8 – 12 inches of snow fell across the watershed. By week 12 average snow depth had decreased to 9 inches due to melt and compaction, however mixed precipitation brought SWE to its highest point of the year (2.6 inches). The 2019 – 2020 snow season began with the most significant event of the year, with almost 14 inches of snow falling across the watershed over December 2 – 3 (week 49). Warm temperatures and rainfall melted most of the snowpack within a week and additional snow fell during weeks 51 and 52, but warm temperatures led to complete melting of the snowpack by years end. More detailed information was recorded in snowpack reports that were produced each week that a measurement was taken.

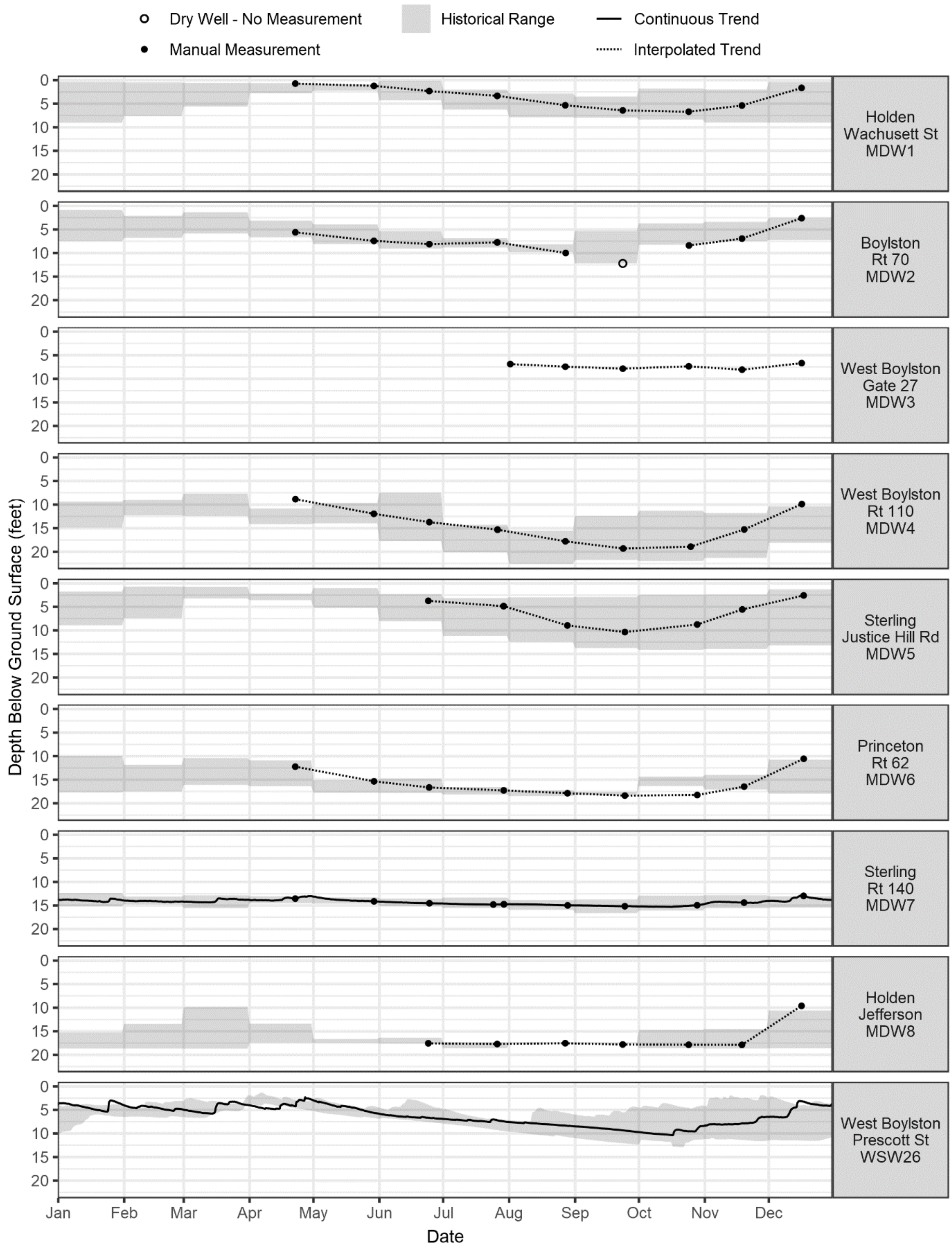
Figure 11: Snowpack Measurements in 2019



3.1.2 Groundwater Levels

Results of groundwater level monitoring are presented in Figure 12. During the 2019 sampling period, Boylston - Rt 62 was dry in late September, but all other wells had measurable water levels every month. Water levels are shown in comparison with monthly historical ranges for all wells except the West Boylston - Prescott St, which has daily historical ranges presented due to the availability of seven years of automated water level measurements by USGS. When compared with these historical ranges, groundwater levels can be indicative of drought or an unusual surplus of water in the watershed. For example, groundwater levels in the Wachusett watershed were near or above the highest historical value for most wells in April and December, which correlates with the above average precipitation in those months (Figure 10). The historical ranges of groundwater levels will become more robust as groundwater levels continue to be monitored.

Figure 12: Wachusett Groundwater Depth Measurements in 2019 With Historical Ranges for Comparison



3.1.3 Streamflow and Quabbin Transfer

The total surface water inflow to Wachusett Reservoir in 2019 was estimated to be 94,796 million gallons (MG); about 5% less than in 2018. This decline was likely due to reduced precipitation for 2019 compared to 2018. Water transfers from the Quabbin Reservoir comprised 47% of the total surface water inflow in 2019, which is a 11% greater contribution over 2018. Relative contributions from other tributaries remained consistent with the exception of Trout Brook and Waushacum Brook. Trout Brook discharges for 2018 were estimated for the first half of the year, and these estimates were likely a little low.

Figure 13 shows a breakdown of annual total flow (MG) among all the tributaries as well as ungauged areas and the Quabbin transfer. About 36% of surface water inputs came from the Quinapoxet and Stillwater Rivers, while about 17% was contributed by the smaller tributaries and ungauged areas (direct runoff to the Reservoir).

Figure 13: Wachusett Reservoir Surface Water Inflows for 2019

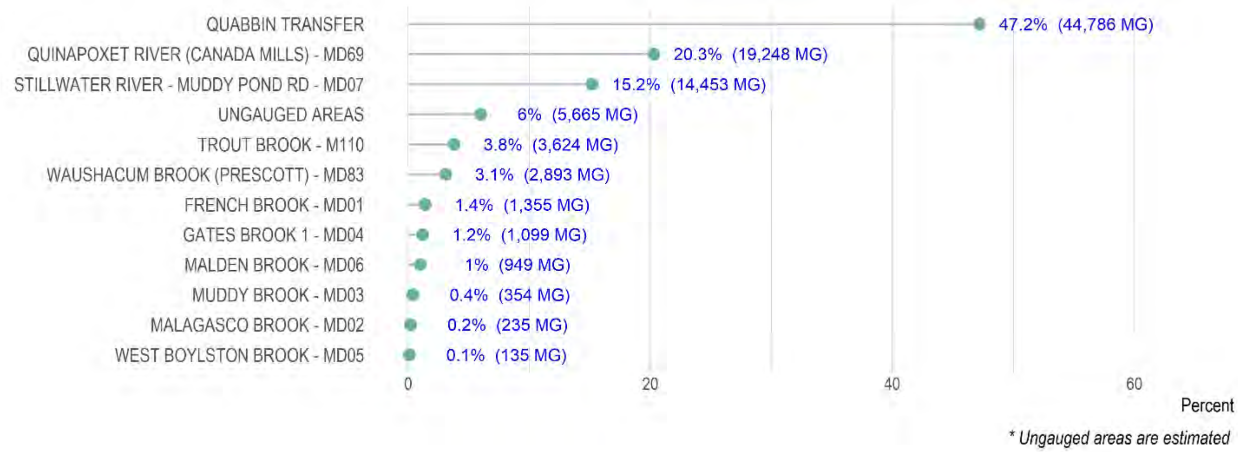


Table 12 provides summary statistics of surface water discharge for 2019. Daily flow rates in the smaller tributaries ranged from zero at West Boylston Brook to 156 cfs at Trout Brook. The maximum instantaneous flow at these tributaries ranged from 10 cfs at Malagasco Brook to 340 cfs at Trout Brook.

Total annual discharges for the Quinapoxet and Stillwater Rivers for 2019 were 19% and 4% above average, respectively (Figure 14).

Figure 14: Annual Discharge in the Quinapoxet and Stillwater Rivers (MG) (2007 - 2019)

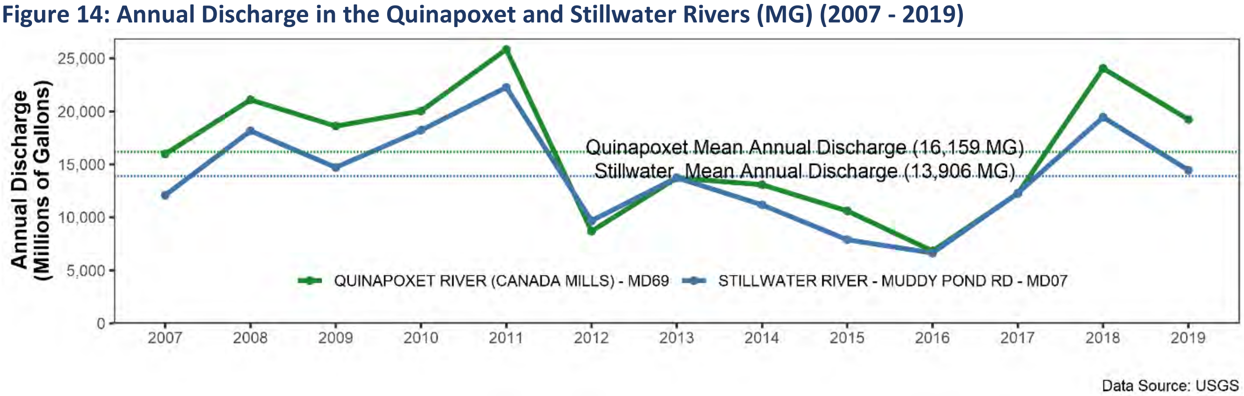


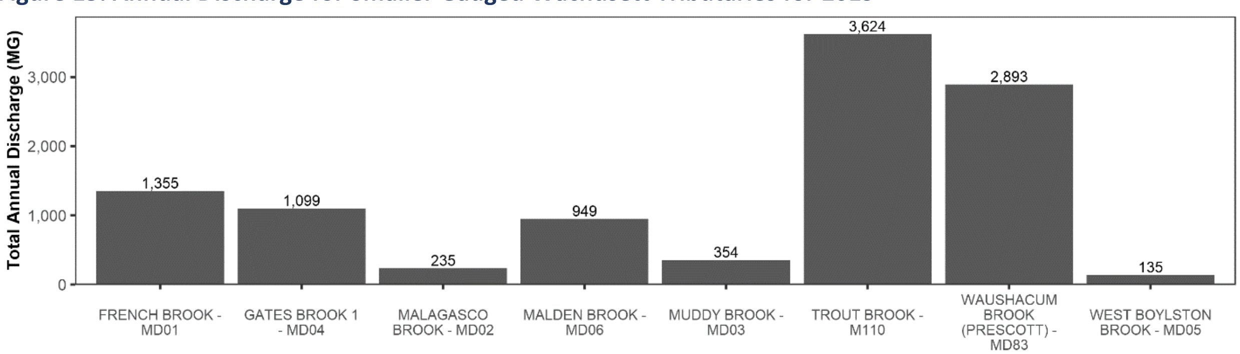
Table 12: 2019 Flow Statistics for Wachusett Reservoir Tributaries

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)	2019 Total Vol (Mg)	2019 Peak Inst. Flow (CFS)
French Brook - MD01	0.06	5.76	60.9	2.3	112.9	244.1	1,355	118
Gates Brook 1 - MD04	0.62	4.66	43.0	16.7	91.6	180.5	1,099	106
Malagasco Brook - MD02	0.05	1.00	6.7	1.7	19.6	44.5	235	10
Malden Brook - MD06	0.38	4.03	23.1	16.3	79.1	155.1	949	47
Muddy Brook - MD03	0.02	1.51	9.1	2.3	29.5	60.1	354	26
Quinapoxet River - MD69	3.92	81.59	880.0	141.7	1,604.0	4,643.8	19,248	1,280
Stillwater River - MD07	2.26	61.26	663.0	65.5	1,204.5	3,230.3	14,453	917
Trout Brook - M110	0.03	15.38	155.9	5.0	302.0	744.3	3,624	340
Waushacum Brook - MD83	0.16	12.29	69.5	7.4	241.1	561.9	2,893	90
West Boylston Brook - MD05	0.00	0.57	15.1	1.0	11.2	25.8	135	61
Ungauged Areas*	N/A	N/A	N/A	N/A	N/A	N/A	5,665	N/A
Quabbin Transfer	N/A	N/A	N/A	N/A	N/A	N/A	44,786	N/A

* Estimated

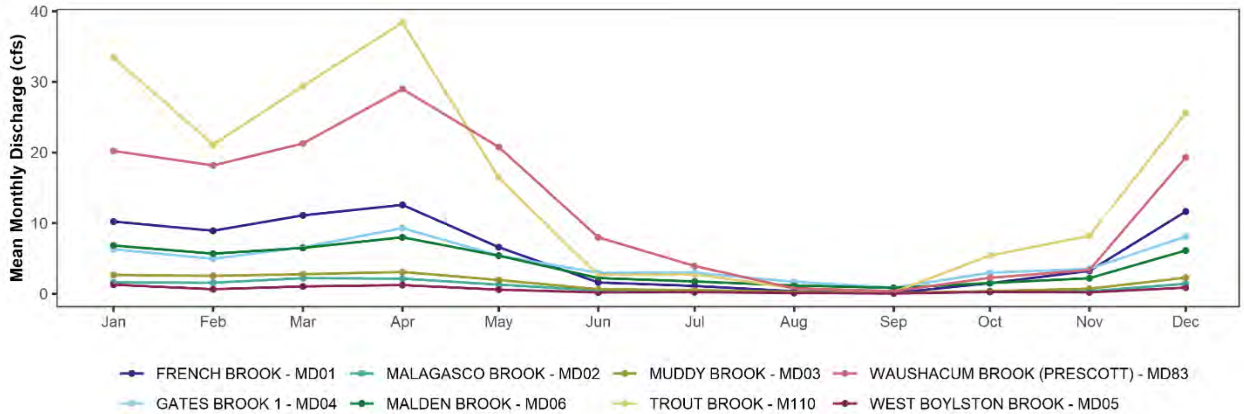
The annual discharge totals for the smaller tributaries are presented in Figure 15. Trout Brook contributed the largest water volume to Wachusett Reservoir of the smaller tributaries with 3,624 MG (~4%), while Waushacum Brook contributed 2,893 MG (~3%) of the surface water inflow to the Reservoir. The other gauged small tributaries combined to contribute less than 5% of the surface water inflows to Wachusett Reservoir. Ungauged areas contributed approximately 6% of the total inflows (estimated).

Figure 15: Annual Discharge for Smaller Gauged Wachusett Tributaries for 2019



Monthly tributary flows typically fluctuate substantially throughout the year (Figure 16). Flows are usually highest in spring with a receding snowpack and prior to the growing season, lowest though the summer months when evapotranspiration rates are highest and increase in the fall as evapotranspiration rates decline. Monthly flows for 2019 followed this seasonal pattern. Flows were higher than usual in April and December due to surplus precipitation. For smaller tributaries no summary statistics were calculated due to the limited period of record.

Figure 16: Mean Monthly Discharge in Smaller Wachusett Tributaries (CFS) in 2019



Monthly flows in the Stillwater and Quinapoxet Rivers for 2019 were seasonally high in January, April and December, but otherwise were close to normal for the other the months during the year.

Figure 17: Monthly Discharge in the Quinapoxet River (MG) 2019

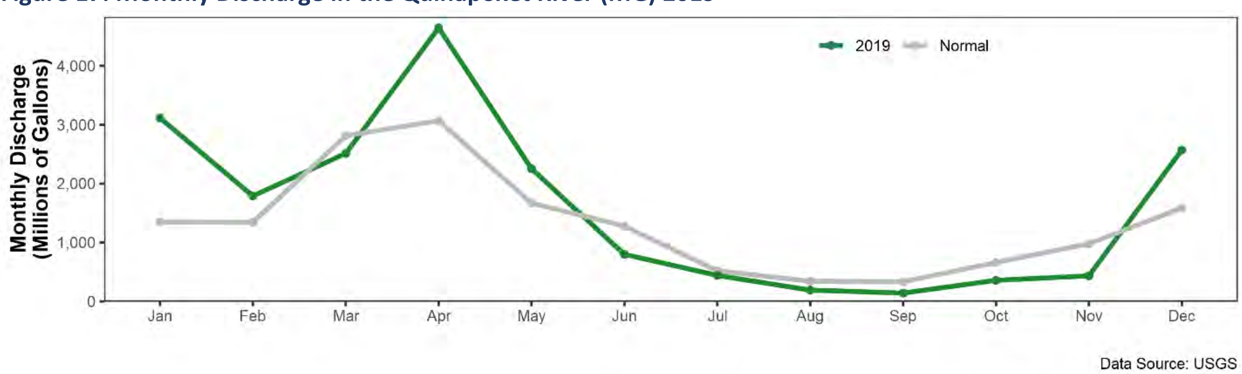
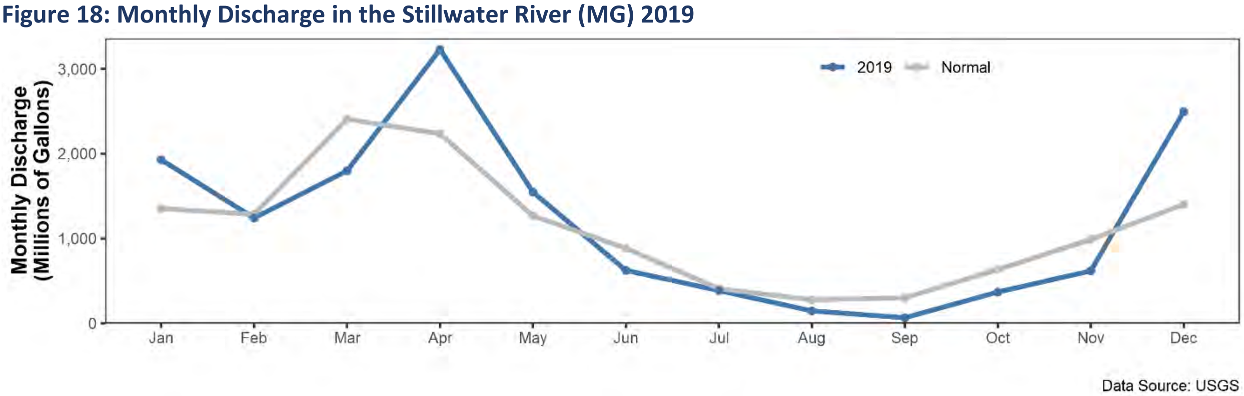


Figure 18: Monthly Discharge in the Stillwater River (MG) 2019



Complete hydrographs for the smaller tributaries are provided in Appendix A.

The Quabbin transfer was initiated on May 21 and water was transferred on a nearly continuous basis until December 3. Water was also transferred for shorter durations in January and March, resulting in a total of 225 transfer days, delivering a total volume of 44.8 billion gallons to Wachusett Reservoir with an average transfer rate of 199 MGD (Figure 19). This is equivalent to 68.9 % of Wachusett Reservoir capacity (65 billion gallons) and is close to the average transfer volume for the past 15 years (Figure 20).

Wachusett Reservoir elevation exceeded its operating range on five separate occasions (Figure 19). All of these elevation peaks were directly related to the high precipitation events discussed in Section 3.1.1. The extended duration of high reservoir elevation in April and May was probably due to saturated soil conditions combined with more than 3 inches of surplus precipitation in April.

Figure 19: 2019 Daily Wachusett Reservoir Water Elevation and Daily Quabbin Transfer Rate

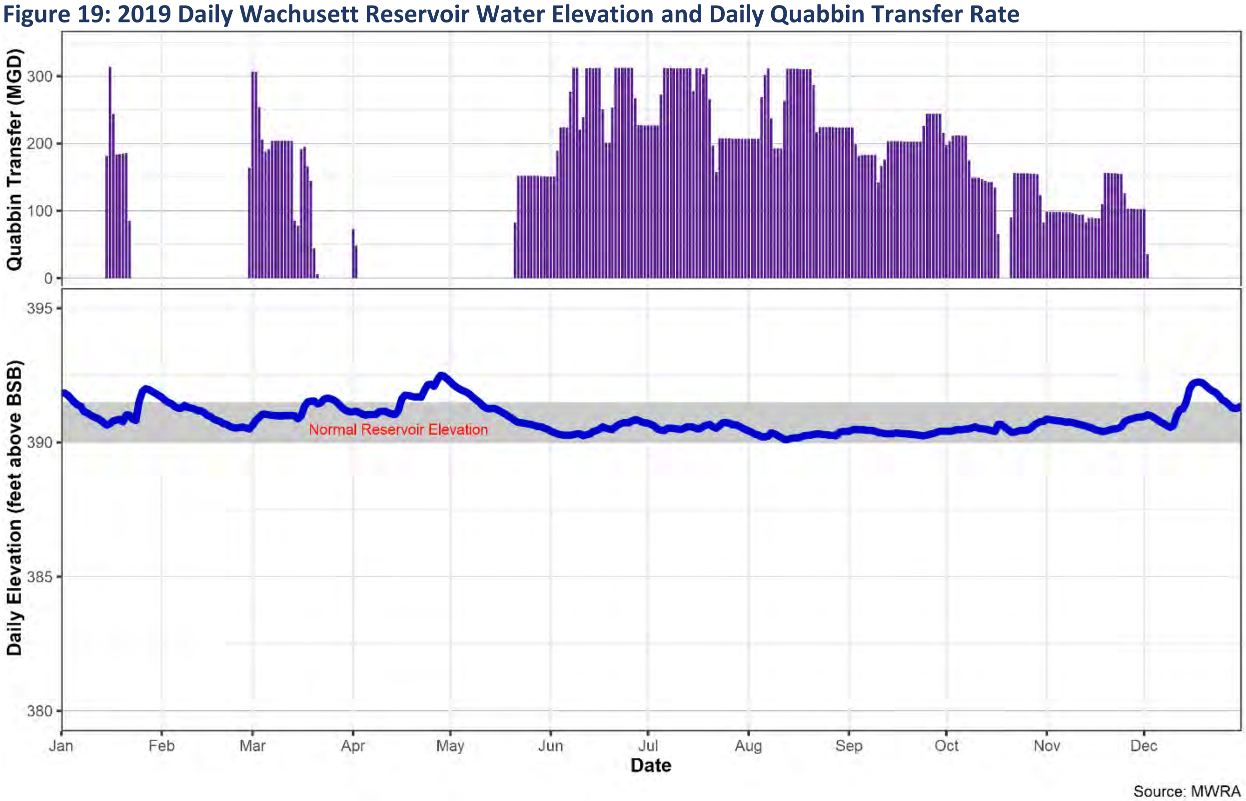
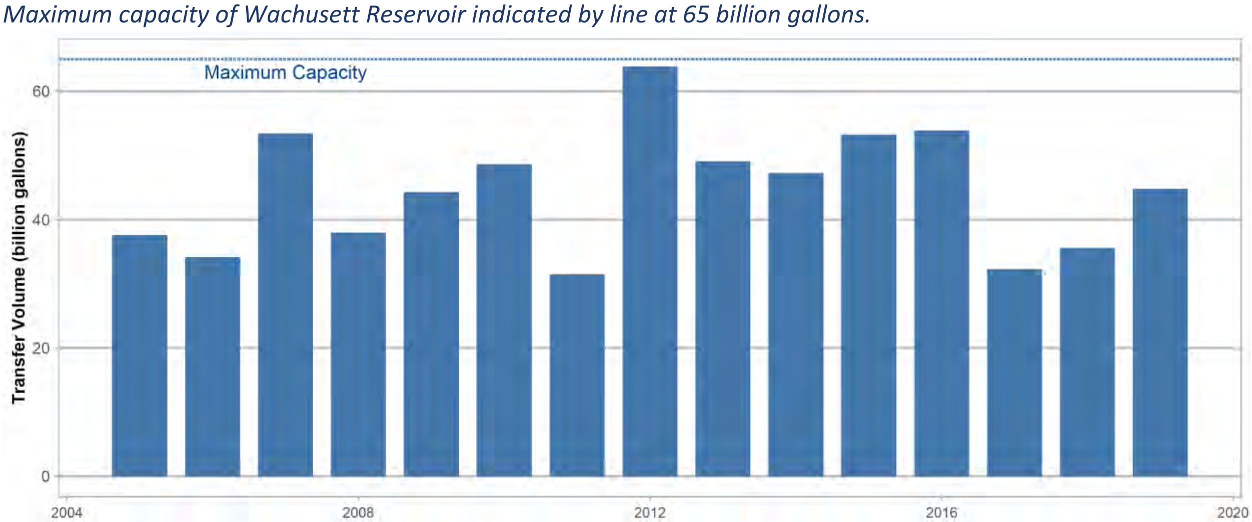


Figure 20: Annual Volume of Quabbin Transfer to Wachusett Reservoir

Maximum capacity of Wachusett Reservoir indicated by line at 65 billion gallons.



3.2 Tributary Monitoring

3.2.1 Water Temperature, pH, Dissolved oxygen

Measurements for water temperature, pH, and dissolved oxygen were collected during all tributary field visits in 2019 (WATTRB and WATMDC projects). However, as no records of routine maintenance and/or calibrations exist for field parameter measurements made prior to July 2019 these results will not be discussed in this report (see discussion in Section 2.1.5).

3.2.2 Specific Conductance and Dissolved Salts

In 2019, tributary specific conductance ranged from to 57 µS/cm at Trout Brook to 2,242 µS/cm at Scarlett Brook. Values of less than 100 µS/cm were recorded in 75% of all samples from Trout Brook (27 of 36) and only on one other occasion at East Wachusett Brook on January 3 (not including Shaft 1 (MDS1) samples). This represents less than about 5% of all specific conductance samples for the year from Wachusett tributaries. Measurements greater than 904 µS/cm, the proxy chronic Cl toxicity threshold, were recorded in 100% of samples from Gates Brook 4, 95% of samples from Gates Brook 1, 63% of samples from Oakdale Brook, 75% of samples from West Boylston Brook, and 21% of samples from Scarlet Brook. Extremely high specific conductance (>1,800 µS/cm) was observed on nine occasions during 2019. No specific conductance measurements in 2019 exceeded the MassDEP proxy acute Cl toxicity threshold of 3,193 µS/cm.

Table 13: Annual Mean Specific Conductance (µS/cm) in Wachusett Tributaries

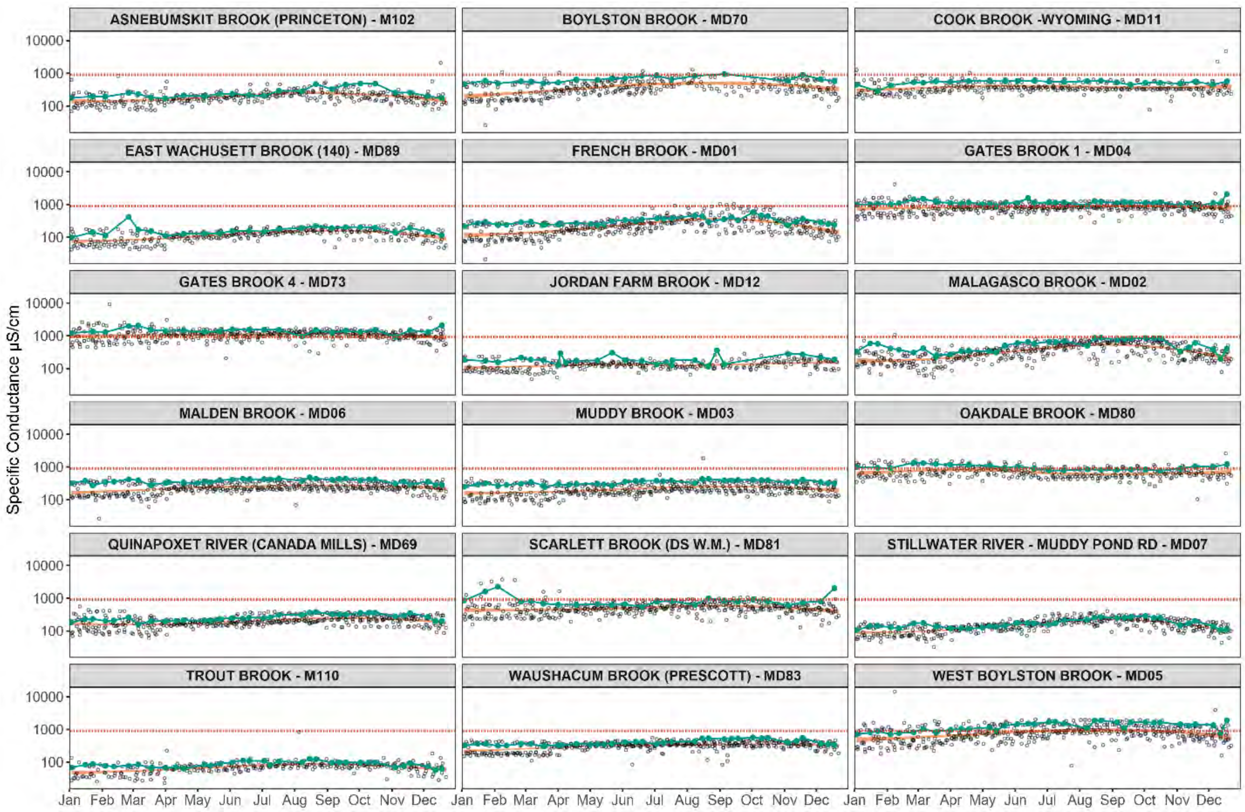
Sample Location	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Asnebumskit Brook (Princeton) - M102	175	150	197	183	215	254	336	279	249	267
Boylston Brook - MD70	268	261	271	278	373	579	542	594	686	661
Cook Brook -Wyoming - MD11	304	321	378	329	493	475	526	640	624	524
East Wachusett Brook (140) - MD89	108	89	108	123	133	166	174	171	151	169
French Brook - MD01	210	154	162	207	227	321	447	364	290	318
Gates Brook 1 - MD04	714	705	616	715	759	942	1,081	1,272	1,211	1,154
Gates Brook 4 - MD73	952	888	835	1,006	1,018	1,276	1,371	1,696	1,558	1,451
Jordan Farm Brook - MD12	116	129	129	122	128	124	181	175	183	193
Malagasco Brook - MD02	384	235	292	350	313	447	473	450	432	525
Malden Brook - MD06	175	192	192	199	220	288	334	364	365	371
Muddy Brook - MD03	186	160	154	174	203	273	320	344	333	340
Oakdale Brook - MD80	573	651	534	666	686	872	982	1,136	1,166	989
Quinapoxet River (Canada Mills) - MD69	170	151	167	172	195	255	304	296	250	261
Scarlett Brook (DS W.M.) - MD81	442	463	372	484	514	635	620	771	747	897
Stillwater River - Muddy Pond Rd - MD07	162	120	143	144	142	182	213	170	162	174
Trout Brook - M110	55	33	61	84	74	74	86	96	92	87
Waushacum Brook (Prescott) - MD83	292	275	280	315	284	339	396	420	395	408
West Boylston Brook - MD05	590	566	512	667	739	1,137	1,227	1,700	1,274	1,266

Note: Table cells are shaded to aid in visually consuming tabular data. Colors are based off the relative distance from the high and low values in the table and do not signify that values are below/above any particular threshold.

Overall, Wachusett tributary specific conductance levels for 2019 are consistent with average annual levels over the last few years, both for individual locations and among all locations, which still reflect the rising trend observed over the last several decades (Table 13). Five locations experienced their all-time highest mean annual specific conductance levels in 2019. Most locations exhibit a seasonal pattern of elevated levels in late summer through early fall when streamflows are predominantly baseflow driven. This pattern indicates that salts have accumulated in groundwater aquifers over time. Specific conductance levels at four tributaries are indicative of chronic elevated dissolved salt concentrations which are likely having deleterious effects on aquatic life: Gates Brook (two stations), Oakdale Brook, Scarlett Brook, and West Boylston Brook (Figure 21).

Figure 21: Specific Conductance Measurements at Wachusett Tributaries.

The green line shows specific conductance results for 2019, while the hollow points show results from years 2010 – 2018, with the orange band representing a LOESS smooth function 95% confidence interval for the same period. The red dashed line is the MassDEP proxy chronic Cl toxicity threshold of 904 µS/cm.



The cause of the elevated specific conductance is being studied in depth by DWSP and also by researchers at UMass. These investigations have confirmed what was suspected: that roadway deicing products (primarily rock salt) is the dominant source of dissolved ions detected in Wachusett tributaries. As expected, the more developed subbasins with more roads have a higher need for roadway deicing during the winter months, therefore they are experiencing the greatest increases in specific conductance. This topic will be discussed in a pending publication by UMass researchers[105] and in a separate DWSP report, which will provide much greater detail on this water quality problem and set out the initial phases of a mitigation strategy.

[105] Soper, 2020

3.2.2.1 *Chloride*

Chloride (Cl) concentrations in 2019 were similar to 2018 concentrations across most sampling locations (Table 14). Again, West Boylston Brook had the highest average Cl concentration (313 mg/L), followed by Gates Brook 1 (284 mg/L). Trout Brook and the Stillwater River had the lowest average Cl concentrations at 17 and 36 mg/L, respectively.

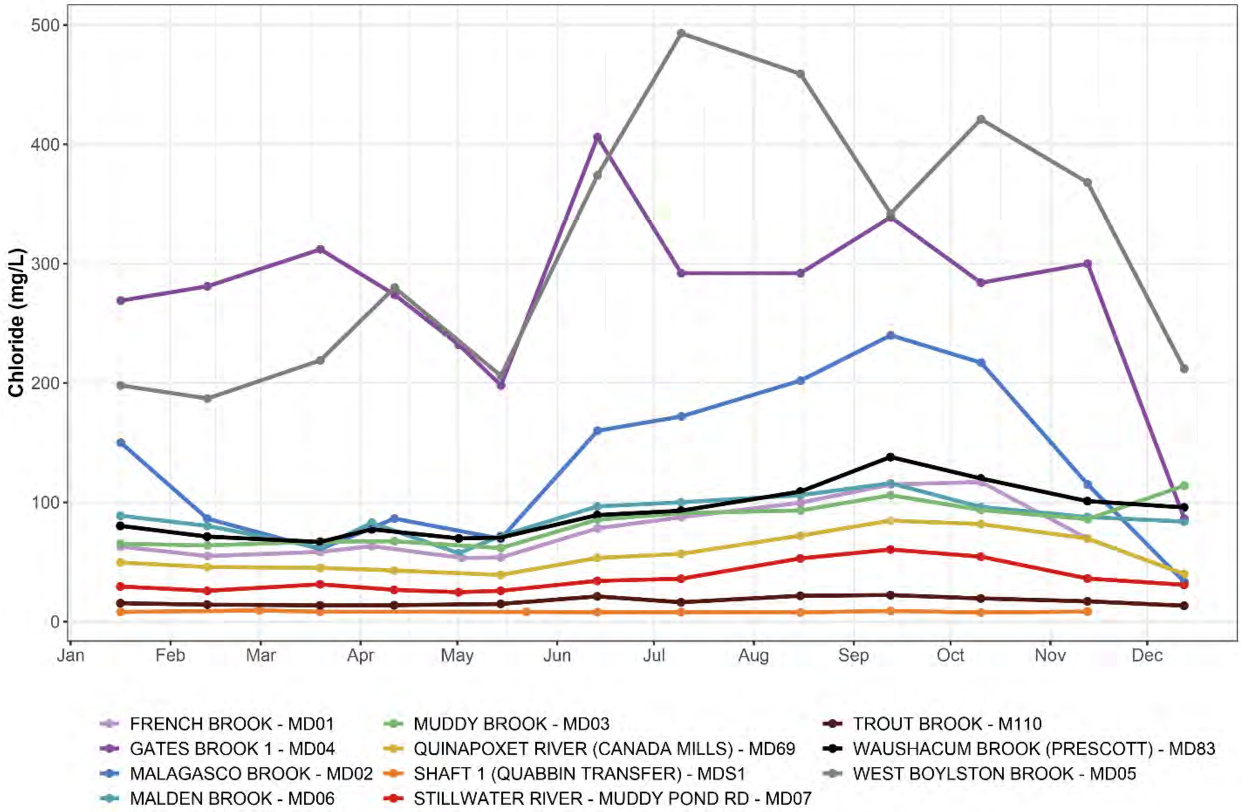
Although Cl is not monitored at a frequency high enough to detect exceedances of the EPA aquatic life criteria, it is probable that both Gates Brook 1 and West Boylston Brook exceed the chronic threshold (230 mg/L 4-day average) most of the year, and the acute threshold (860 mg/L 1-day average) several times a year after roadway deicing. The MassDEP SMCL for Cl (250 mg/L), which only applies to finished drinking water for public systems, would also be exceeded if Gates Brook 1 and West Boylston Brook were sole drinking water sources. Fortunately, these two tributaries are not directly used for drinking water and contribute less than 2% of the total inflow to Wachusett Reservoir, so the overall Wachusett Reservoir Cl concentration is well below this threshold. Still, Cl concentration at Gates Brook 1 and West Boylston Brook are detrimental to many species of aquatic plants and animals and contribute to the overall increase in dissolved salts in the Wachusett Reservoir, which has undesirable consequences for drinking water treatment processes.

Table 14: Chloride Concentration Summary for Wachusett Tributaries During 2019

Sample Location	Count	Minimum (mg/L)	Median mg/L)	Average (mg/L)	Maximum (mg/L)	Std. Dev (mg/L)
French Brook - MD01	13	40	63	73	117	25
Gates Brook 1 - MD04	13	86	284	274	406	75
Malagasco Brook - MD02	12	33	132	133	240	67
Malden Brook - MD06	13	57	88	87	116	17
Muddy Brook - MD03	12	62	86	83	114	18
Quinapoxet River (Canada Mills) - MD69	12	39	52	57	85	16
Shaft 1 (Quabbin Transfer) - MDS1	10	8	8	8	9	1
Stillwater River - Muddy Pond Rd - MD07	13	25	31	36	60	12
Trout Brook - M110	12	13	16	17	22	3
Waushacum Brook (Prescott) - MD83	13	67	89	91	138	22
West Boylston Brook - MD05	12	187	311	313	493	110

Consistent with 2018 and similar to seasonal patterns of specific conductance levels, seasonal Cl concentrations peak in the late summer and fall months when evapotranspiration rates are high and groundwater becomes the dominant source of streamflow (Figure 22). In 2019, Cl monitoring in groundwater was initiated in order to better understand the spatial variability of Cl contamination in Wachusett watershed aquifers (Section 3.3).

Figure 22: Chloride Concentrations in the Wachusett Tributaries During 2019

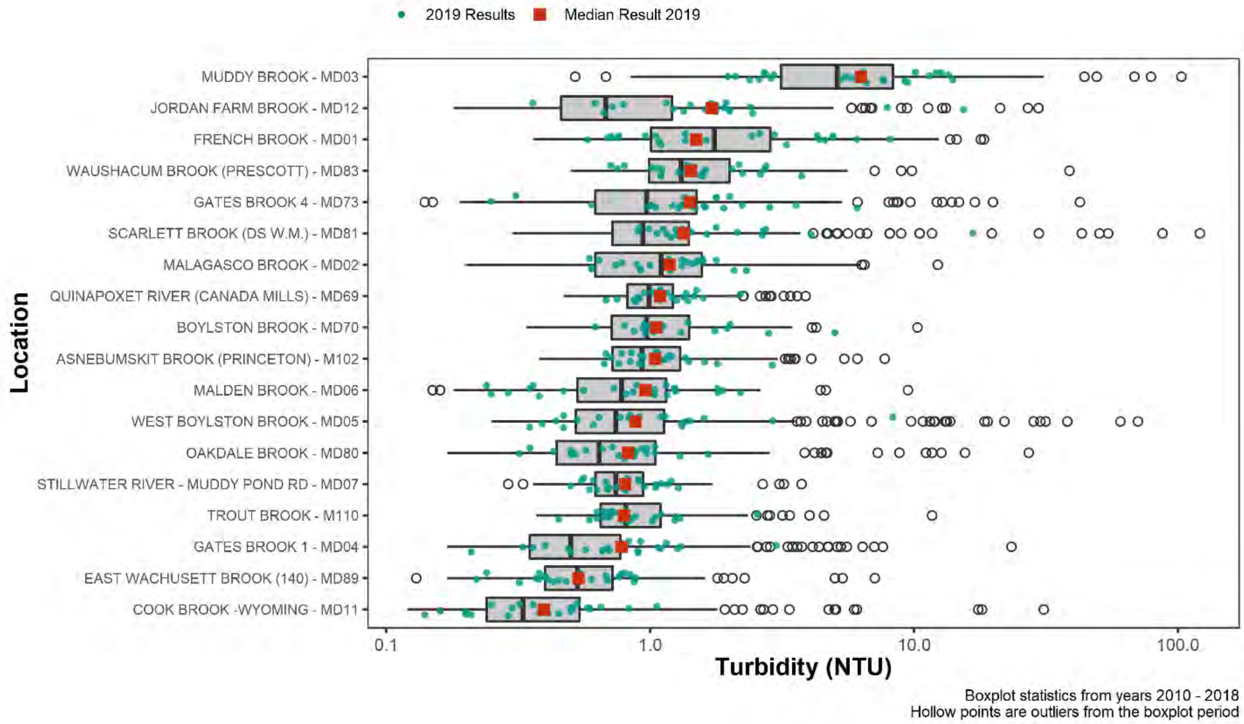


A discussion of other work completed in 2019 related to Cl and conductivity is summarized in Section 3.2.7.

3.2.3 Turbidity

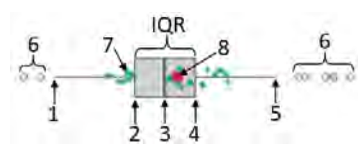
Turbidity results in Wachusett tributaries in 2019 ranged from 0.14 NTU at Cook Brook to 16.7 NTU at Scarlett Brook (Figure 23). There were 24 samples with turbidity levels of 5.0 NTU or higher, which were predominantly collected from Muddy Brook (16 samples), where elevated concentrations of fine particulate matter are historically persistent and naturally occurring. Not including Muddy Brook, there were eight turbidity results greater than or equal to 5.0 NTU in 2019; four associated with dry conditions and four with wet conditions. There were only two measurements above 10 NTU; one at Jordan Farm Brook (15.40 NTU), which is impacted by agricultural operations, and the other at Scarlett Brook (16.7 NTU), which is impacted by urban development. Other than Muddy Brook, the next two highest median annual turbidity values during 2019 were at Jordan Farm Brook (1.71 NTU) and French Brook (1.50 NTU) (Table 16).

Figure 23: Turbidity Levels in the Wachusett Tributaries During 2019 with 2010 – 2018 Statistics



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
7) Individual sample results from 2019 (green circle points)
8) Median result 2019 (red square point)



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

Annual mean turbidity in 2019 ranged from 0.42 NTU at Cook Brook to 6.83 NTU at Muddy Brook. For all sampling locations annual means in 2019 were consistent with annual means for years 2010 – 2018, with no discernable trends during that time range (Table 15).

Table 15: Annual Mean Turbidity at Wachusett Tributaries (NTU)

Sample Location	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Asnebumskit Brook (Princeton) - M102	1.02	1.14	1.14	0.94	—	1.47	1.14	1.63	1.07	1.12
Boylston Brook - MD70	1.21	1.44	1.35	1.48	0.90	0.97	0.92	1.06	1.13	1.44
Cook Brook -Wyoming - MD11	0.76	0.63	0.83	0.37	1.23	0.63	0.28	1.75	0.55	0.42
East Wachusett Brook (140) - MD89	0.68	0.79	0.56	0.55	0.56	0.60	0.47	0.86	0.65	0.57
French Brook - MD01	4.51	2.19	2.62	2.55	1.61	2.16	1.93	1.56	1.73	2.55
Gates Brook 1 - MD04	0.86	1.02	0.73	0.67	0.70	0.52	0.57	1.16	1.23	0.85
Gates Brook 4 - MD73	1.43	2.44	1.24	1.22	1.43	0.91	0.89	2.73	1.88	1.68
Jordan Farm Brook - MD12	1.62	1.01	1.67	1.39	1.21	1.61	0.51	1.68	2.22	2.44
Malagasco Brook - MD02	1.47	1.81	1.63	1.45	1.10	0.90	0.82	1.13	1.26	1.21
Malden Brook - MD06	1.08	1.12	1.09	0.99	0.79	0.84	0.52	0.75	0.95	0.96
Muddy Brook - MD03	5.41	10.28	7.07	6.90	5.87	5.45	5.48	9.12	6.86	6.83
Oakdale Brook - MD80	1.02	1.03	1.65	0.77	1.15	0.63	0.43	2.12	1.18	0.79
Quinapoxet River (Canada Mills) - MD69	1.31	1.10	1.14	0.94	0.97	1.09	1.00	1.01	1.11	1.17
Scarlett Brook (DS W.M.) - MD81	—	—	2.20	1.91	5.47	1.05	1.38	3.65	1.91	2.24
Stillwater River - Muddy Pond Rd - MD07	1.10	0.85	0.88	0.76	0.74	0.76	0.75	0.70	0.80	0.82
Trout Brook - M110	1.25	—	1.12	0.82	0.97	1.22	0.60	0.76	0.81	0.90
Waushacum Brook (Prescott) - MD83	1.67	2.34	1.63	1.31	1.64	1.29	2.04	1.74	1.66	1.63
West Boylston Brook - MD05	1.72	2.13	1.33	1.22	3.21	0.86	1.09	3.59	2.22	1.27

For most locations the 2019 median turbidity was higher than the 2010 – 2018 median. Annual median turbidity values (Table 16) ranged from 0.40 NTU in Cook Brook to 6.29 NTU in Muddy Brook. Turbidity levels were 0.32 NTU higher (on average) during or after wet weather conditions (> 0.2 inches of rainfall within 24 hours of sample) (Table 16).

Table 16: Turbidity Statistics in Wachusett Tributaries for 2019

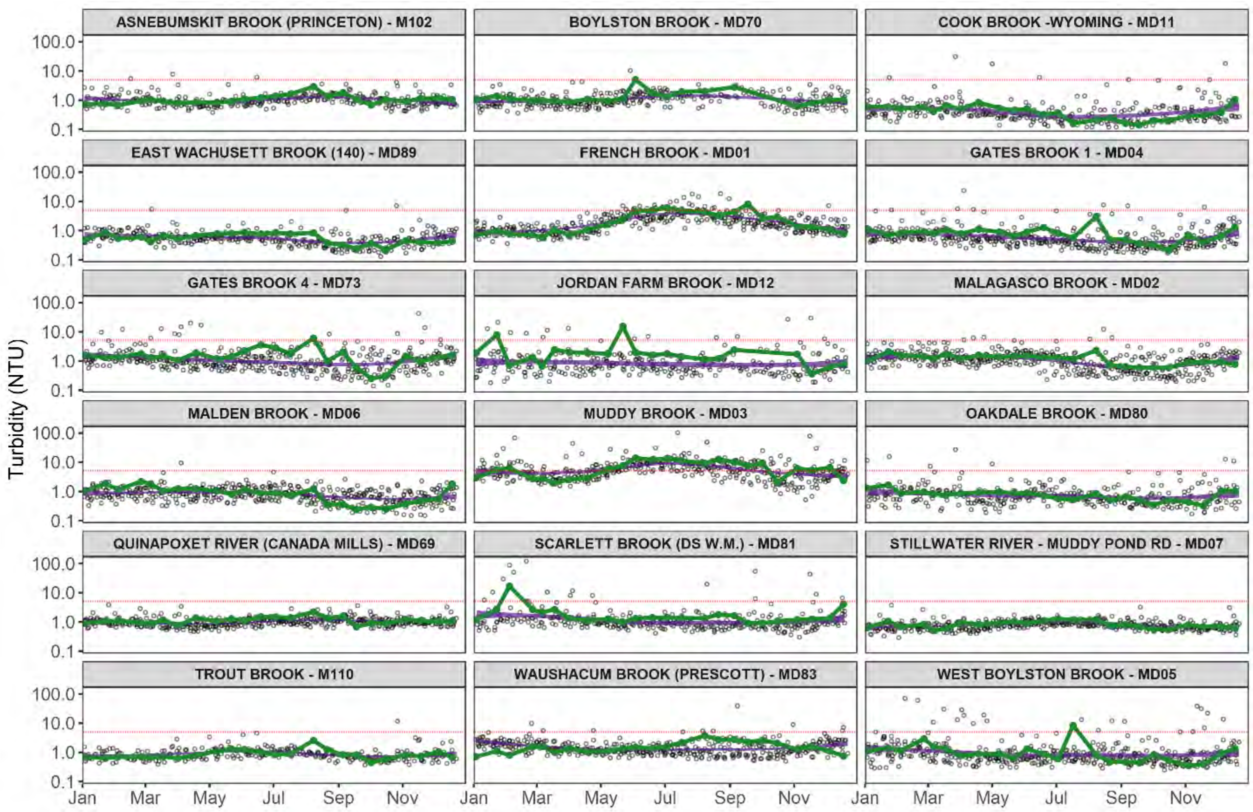
Wet weather samples were collected soon after or during precipitation events of 0.2 inches or more.

Sample Location	Minimum	Maximum	Annual Median	Dry Median	Wet Median
Asnebumskit Brook (Princeton) - M102	0.67	2.90	1.04	0.94	1.05
Boylston Brook - MD70	0.62	5.01	1.06	1.02	1.67
Cook Brook -Wyoming - MD11	0.14	1.06	0.40	0.41	0.25
East Wachusett Brook (140) - MD89	0.22	0.88	0.54	0.54	0.53
French Brook - MD01	0.58	8.10	1.50	1.36	2.96
Gates Brook 1 - MD04	0.21	3.01	0.78	0.80	0.70
Gates Brook 4 - MD73	0.25	6.08	1.42	1.44	1.31
Jordan Farm Brook - MD12	0.36	15.40	1.71	1.74	1.42
Malagasco Brook - MD02	0.59	2.32	1.19	1.32	1.16
Malden Brook - MD06	0.24	2.20	0.96	0.89	1.15
Muddy Brook - MD03	1.97	14.00	6.29	6.18	9.22
Oakdale Brook - MD80	0.32	1.66	0.82	0.80	0.85
Quinapoxet River (Canada Mills) - MD69	0.68	2.20	1.09	1.10	1.09
Scarlett Brook (DS W. M) - MD81	0.90	16.70	1.34	1.34	1.34
Stillwater River - Muddy Pond Rd - MD07	0.50	1.28	0.80	0.80	0.90
Trout Brook - M110	0.45	2.55	0.80	0.81	0.67
Waushacum Brook (Prescott) - MD83	0.71	3.75	1.42	1.37	2.04
West Boylston Brook - MD05	0.35	8.31	0.88	0.89	0.84
Wachusett Tributary Mean	**0.54**	**5.41**	**1.34**	**1.32**	**1.62**

Figure 24 shows the variability in turbidity by location for the last ten years compared to 2019 results. Several sampling locations show a seasonal pattern of elevated turbidity levels during the summer months (French Brook, Muddy Brook, Asnebumbskit Brook, Boylston Brook), while others are fairly consistent and low year-round (Stillwater River, Quinapoxet River). In 2019, summer season turbidity was consistently higher than normal at many tributaries (Gates Brook 1, Gates Brook 4, Waushacum Brook). Jordan Farm Brook turbidity was higher than usual for most of 2019. This could reflect changes in farming operations or ineffective soil stabilization or runoff control measures.

Figure 24: Turbidity Measurements at Wachusett Tributaries.

The green line shows turbidity samples for 2019, while the hollow points show measurements from years 2010 – 2018, with the purple band representing a LOESS smooth function 95% confidence interval for the same period. The red dashed line is the SWTR threshold of five NTU.



The standard for turbidity is five NTU at drinking water intakes under the SWTR and one NTU at the point of consumption under MassDEP regulations. While these standards are not directly applicable to tributary waters, they can be used as reference points in evaluating the turbidity results. Turbidity levels observed in 2019 were generally very low for moving surface waters and indicative of excellent water quality, predominantly below the 5 NTU intake standard. Differences observed between tributaries reflect variations in subbasin land cover, topography, native soils, land disturbances from development, agriculture and other factors. The overall mean turbidity for Wachusett tributaries was 1.60 NTU and the median was 1.34 NTU. Turbidity observed at Wachusett Reservoir raw water intake and points of consumption, where the standards apply, is monitored by MWRA and compliance reports are sent to MassDEP regularly.

3.2.4 Total Suspended Solids

Total suspended solids (TSS) in Wachusett tributaries ranged from less than 5.0 mg/L (detection limit) to 39 mg/L at French Brook. Only 12 of 135 samples contained more than the detection limit, and most were collected during or shortly after a rain event. While TSS is not typically considered a parameter of concern in Wachusett Reservoir tributaries, storm events can produce TSS measurements in excess of 100 mg/L. Mean TSS concentrations for 2019 were consistent with the previous nine years, with no significant trends over time (Table 17). It should be noted that TSS results below detection (typically 5 mg/L) were assigned values of one-half the detection limit (typically 2.5 mg/L), and since most samples were below detection, the values presented below are have a high degree of uncertainty relative to their magnitude.

Table 17: Total Suspended Solids Annual Mean Concentrations in Wachusett Tributaries (mg/L)

Sample Location	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
French Brook - MD01	7.00	2.52	9.08	5.80	4.66	3.02	3.84	3.00	4.71	7.65
Gates Brook 1 - MD04	3.47	2.93	3.13	2.23	4.20	2.48	3.25	2.21	2.56	3.08
Malagasco Brook - MD02	4.78	2.95	3.25	4.32	2.83	2.80	3.10	3.58	2.93	4.25
Malden Brook - MD06	3.25	—	3.42	2.45	3.60	4.27	3.13	2.50	2.77	2.82
Muddy Brook - MD03	3.25	4.43	4.90	4.11	2.82	2.50	6.74	11.99	6.12	5.21
Quinapoxet River (Canada Mills) - MD69	2.97	2.31	3.60	2.77	2.33	2.49	3.13	2.50	2.75	2.50
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	—	1.75	2.82	2.45
Stillwater River - Muddy Pond Rd - MD07	3.04	2.10	2.62	2.38	2.33	2.50	3.88	2.43	2.49	2.50
Trout Brook - M110	—	—	—	—	—	2.91	2.94	2.50	2.92	2.75
Waushacum Brook (Prescott) - MD83	—	—	2.65	3.83	2.44	2.50	2.89	2.43	5.06	3.00
West Boylston Brook - MD05	3.25	8.34	2.92	2.84	9.98	2.49	2.77	4.33	4.88	2.96

Dash (—) = No data

3.2.5 *E. coli* Bacteria in Tributaries

Bacteria samples collected from the tributary stations during 2019 contained a wide range of *E. coli* concentrations, from less than the lower detection limit (10 MPN/100 mL) in approximately 37 percent of all samples to a high of more than 24,200 MPN/100 mL (upper detection limit) at Jordan Farm Brook on August 29 (Figure 25). As in previous years, the highest concentrations were mostly recorded during or following precipitation events. Seven of the eight samples that exceeded 1,000 MPN/100 mL were collected immediately following more than one inch of rainfall, six of which were from August 8. The only dry weather sample that exceeded 1,000 MPN/100 mL was collected from Muddy Brook on June 19.

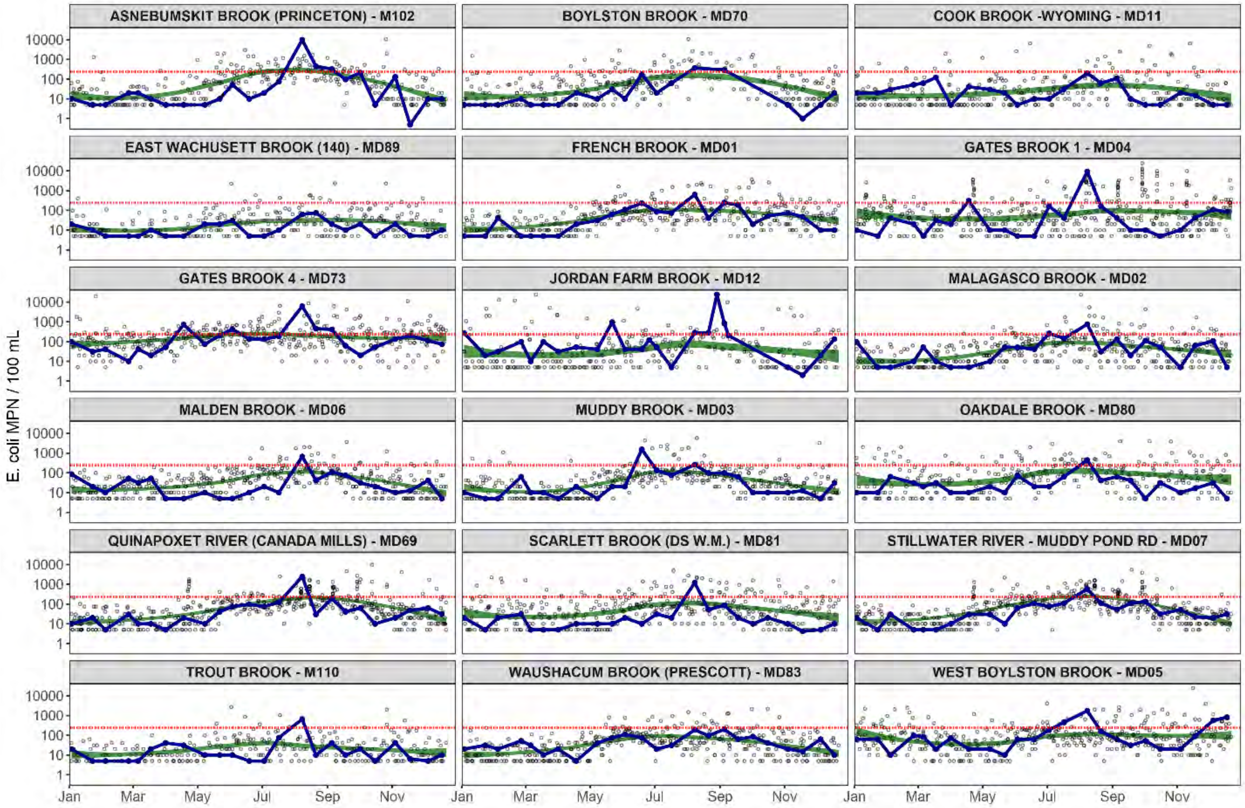
There were three stations that did not exceed the MA Class A surface water quality standard single sample limit of 235 MPN/100 mL in 2019: Cook Brook, Waushacum Brook, and East Wachusett Brook (Table 18 and Figure 25). All other tributaries exceeded the single sample limit on at least one occasion. Most tributaries exhibit a seasonal increase in bacteria levels during the summer months when there are more beneficial physical, chemical, and biological conditions for growth and survival, of which temperature is a dominant driver.

During the late summer and early fall of 2019, several routine bacteria samples were not collected at Boylston and Jordan Farm Brooks because the streams had no surface flow:

- Boylston Brook (MD70) dry on: 08/21/2019, 09/18/2019, 10/02/2019, 10/16/2019
- Jordan Farm (MD12) dry on: 09/18/2019, 10/02/2019, 10/16/2019

Figure 25: *E. coli* Concentrations in Wachusett Tributaries.

The blue line shows E. coli samples for 2019, while the hollow points show results from years 2010 – 2018, with the green band representing a LOESS smooth function 95% confidence interval for the same period. The red dashed line is the MA Class A surface water quality standard single sample limit (235 MPN/100 mL).

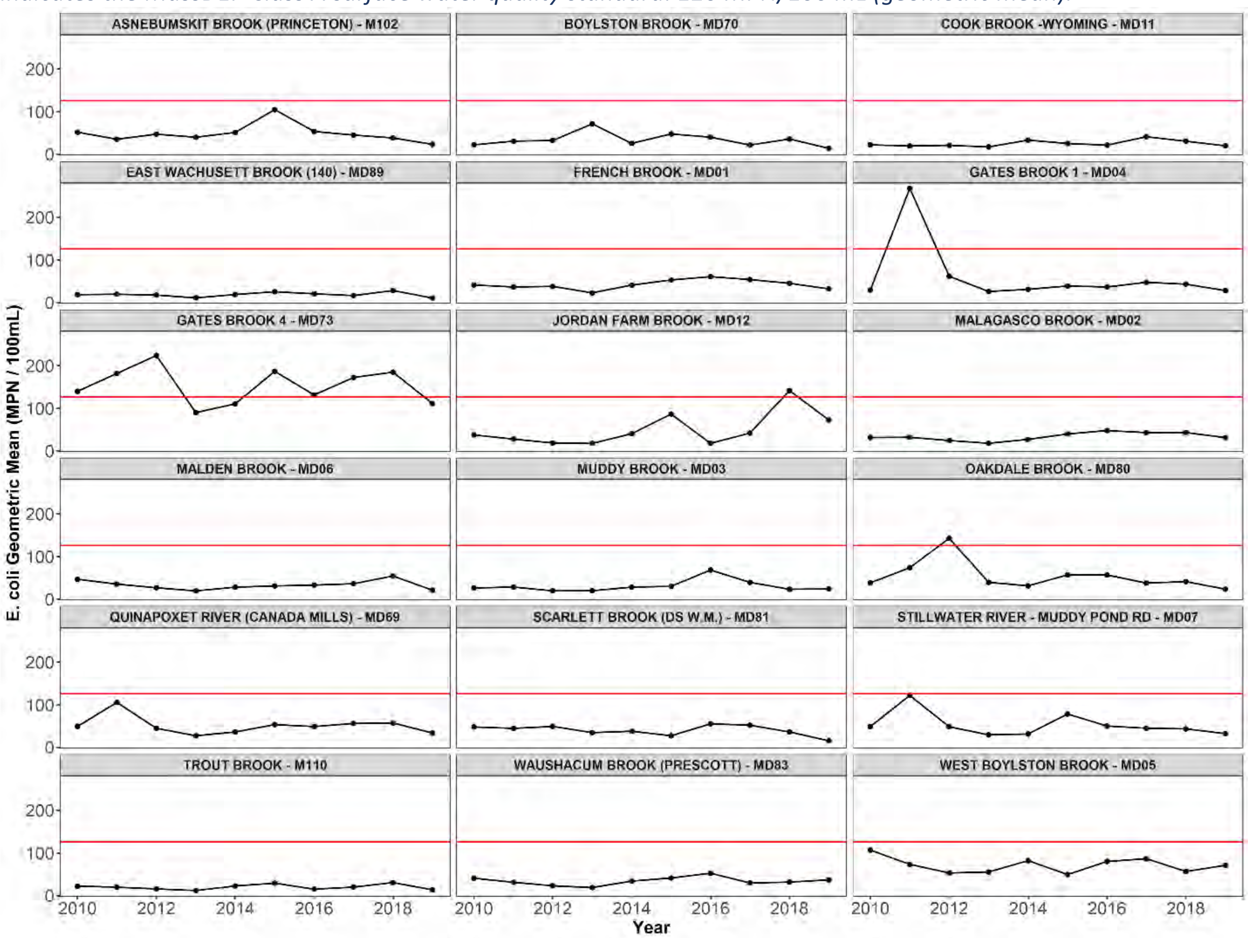


Additional bacteria samples were collected from Jordan Farm in 2019 in effort to identify specific bacteria sources on the farm. On September 9, 2019 seven samples were collected from various farm ditches and runoff pathways and one sample was collected on April 3, 2019 from an unnamed tributary South of Jordan Farm Brook. The results from the September 9 investigation identified several locations on the farm with extremely high bacteria concentrations (> 5,000,000 MPN/100 mL), which could potentially reach Jordan Farm Brook during storm events. Wet weather sampling at Jordan Farm Brook was conducted on seven extra occasions to monitor the effectiveness of manure management and stormwater control practices on the farm. The geometric mean of these seven results was 991 MPN/100 mL, which indicates that stormwater runoff from the farm was not being adequately treated prior to discharging into Jordan Farm Brook.

Jordan Farm Brook eventually flows into Muschopauge Brook, which flows to the Quinapoxet Reservoir and finally into the Quinapoxet River before reaching Wachusett Reservoir. A comparison of the downstream *E. coli* concentrations at the Quinapoxet River to the Jordan Farm concentration shows that both travel time and distance allow for significant degradation to the viability of *E. coli*, which continues as these waters flow to Wachusett Reservoir. Thus, while Jordan Farm Brook sanitary quality is often poor, these conditions tend not to persist to the point of becoming a water quality concern in Wachusett Reservoir. DWSP continues to work with the farm owners and MassDEP to ensure that farming operations are complying with all required management practices to control pollution sources.

Annual geometric mean concentrations of *E. coli* over the past 10 years do not show any discernible trend, however the 2019 annual geometric means were lower than usual (Figure 26).

Figure 26: Annual Geometric Mean *E. coli* for Wachusett Reservoir Tributaries.
Values below detection limits (<10 MPN/100 mL) were substituted with 1/2 the detection limit[106]. The red line indicates the MassDEP Class A surface water quality standard: 126 MPN/100 mL (geometric mean).



On an annual basis, all Wachusett tributaries met the MassDEP Class A surface water standard for *E. coli of* 126 MPN/100 mL in 2019 (Table 18). East Wachusett Brook had the lowest 2019 geometric mean (11 MPN/100 mL), while Gates Brook 4 had the highest (111 MPN/100 mL). The source of high bacteria concentrations at Gates Brook 4 (avian wildlife) were previously investigated and a discussion of this investigation was included in the 2018 Annual Water Quality Report[107].

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[106] MassDEP-DWM, 2018
[107] DWSP, 2019

Table 18: Annual *E. coli* Geometric Mean in Wachusett Tributaries

GMEAN = Geometric Mean

Sample Location	GMEAN 2016	GMEAN 2017	GMEAN 2018	GMEAN 2019	%>235 2016	%>235 2017	%>235 2018	%>235 2019
Asnebumskit Brook (Princeton) - M102	54	45	39	24	24	12	29	12
Boylston Brook - MD70	40	22	36	14	16	2	5	10
Cook Brook -Wyoming - MD11	22	41	31	20	0	12	0	0
East Wachusett Brook (140) - MD89	21	17	28	11	5	4	4	0
French Brook - MD01	61	54	45	32	19	14	17	8
Gates Brook 1 - MD04	37	48	43	28	10	10	8	8
Gates Brook 4 - MD73	131	172	185	111	24	45	29	21
Jordan Farm Brook - MD12	18	42	142	73	7	9	35	25
Malagasco Brook - MD02	48	43	43	31	10	14	17	8
Malden Brook - MD06	33	36	54	21	6	4	17	4
Muddy Brook - MD03	68	39	23	24	22	4	0	8
Oakdale Brook - MD80	57	38	41	24	20	16	8	4
Quinapoxet River (Canada Mills) - MD69	49	56	57	34	12	8	4	4
Scarlett Brook (DS W. M) - MD81	55	52	36	16	16	14	4	4
Stillwater River - Muddy Pond Rd - MD07	50	45	44	33	12	12	4	4
Trout Brook - M110	15	20	31	14	0	2	4	4
Waushacum Brook (Prescott) - MD83	53	30	32	37	25	2	8	0
West Boylston Brook - MD05	80	87	57	71	24	22	12	17

Except for Jordan Farm Brook, Waushacum Brook and West Boylston Brook, 2019 geometric means were lower than both the five-year average and ten-year average geometric means (Table 19).

Table 19: Trends in Geometric Mean *E. coli* Concentrations

Sample Location	2019 GMEAN	5 Year Mean	10 Year Mean
Asnebumskit Brook (Princeton) - M102	24	53	49
Boylston Brook - MD70	14	32	34
Cook Brook -Wyoming - MD11	20	28	26
East Wachusett Brook (140) - MD89	11	21	19
French Brook - MD01	32	49	42
Gates Brook 1 - MD04	28	39	61
Gates Brook 4 - MD73	111	157	153
Jordan Farm Brook - MD12	73	72	50
Malagasco Brook - MD02	31	41	34
Malden Brook - MD06	21	35	33
Muddy Brook - MD03	24	37	31
Oakdale Brook - MD80	24	43	54
Quinapoxet River (Canada Mills) - MD69	34	50	51
Scarlett Brook (DS W. M) - MD81	16	37	40
Stillwater River - Muddy Pond Rd - MD07	33	50	53
Trout Brook - M110	14	22	20
Waushacum Brook (Prescott) - MD83	37	39	34
West Boylston Brook - MD05	71	69	72

In 2019, wet weather samples continued to have higher bacteria concentrations than dry weather samples (Table 20), with the exception of Cook Brook, Malden Brook and Muddy Brook. For all sampling locations, exceedances of the MA Class A water quality single sample regulatory limit (235 MPN/100 mL) were more likely to occur during wet conditions.

Table 20: Wet and Dry Weather *E. coli* Metrics in Wachusett Watershed Tributaries During 2019
Wet weather samples were collected soon after or during precipitation events of 0.2 inches or more.

Sample Location	GMEAN DRY	GMEAN WET	% <10 DRY	% <10 WET	% >235 DRY	% >235 WET	COUNT DRY	COUNT WET
Asnebumskit Brook (Princeton) - M102	14	55	26.7	33.3	6.7	22.2	15	9
Boylston Brook - MD70	12	22	50.0	33.3	7.1	16.7	14	6
Cook Brook -Wyoming - MD11	25	14	6.7	55.6	0	0	15	9
East Wachusett Brook (140) - MD89	9	16	53.3	22.2	0	0	15	9
French Brook - MD01	32	34	26.7	22.2	6.7	11.1	15	9
Gates Brook 1 - MD04	24	37	13.3	33.3	6.7	11.1	15	9
Gates Brook 4 - MD73	95	144	0	0	13.3	33.3	15	9
Jordan Farm Brook - MD12	55	116	13.3	11.1	20.0	33.3	15	9
Malagasco Brook - MD02	28	37	20.0	33.3	6.7	11.1	15	9
Malden Brook - MD06	22	20	13.3	33.3	0	11.1	15	9
Muddy Brook - MD03	24	24	20.0	22.2	6.7	11.1	15	9
Oakdale Brook - MD80	22	27	0	22.2	0	11.1	15	9
Quinapoxet River (Canada Mills) - MD69	28	48	6.7	11.1	0	11.1	15	9
Scarlett Brook (DS W. M) - MD81	13	22	26.7	22.2	0	11.1	15	9
Stillwater River - Muddy Pond Rd - MD07	25	52	20.0	11.1	0	11.1	15	9
Trout Brook - M110	11	22	46.7	22.2	0	11.1	15	9
Waushacum Brook (Prescott) - MD83	32	48	6.7	0	0	0	15	9
West Boylston Brook - MD05	46	146	0	0	6.7	33.3	15	9

It is very difficult for tributary waters to meet the single sample standard (235 MPN/100 mL), even in streams 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. The longer term geometric mean standard has been met by most Wachusett tributaries in the last five years, and the tributaries which occasionally surpass this 126 MPN/100 mL threshold have known bacteria sources, which are either being actively monitored and managed (agricultural operations), or cannot be managed because of their location and origin (avian wildlife). Tributary *E coli* concentrations for 2019 continued to indicate good sanitary quality.

3.2.6 Nutrient Dynamics

Results for monthly tributary nutrient monitoring in Wachusett tributaries are presented below. Non-routine samples were collected at some locations to target specific flows that have been historically under sampled (Table 21). The extra samples at Shaft 1 (Quabbin transfer) were collected to capture first flush flows after the Quabbin transfer had been idle for extended periods of time. All extra samples are included in the results and statistics presented within this section. Sampling results for Quabbin transfer water are not discussed but are included in the tables and figures because transfer water is a large percentage of the annual inflow to Wachusett Reservoir and has a significant impact on reservoir nutrient dynamics and overall reservoir water quality.

Table 21: Additional Flow Targeted Nutrient Samples Collected in 2019

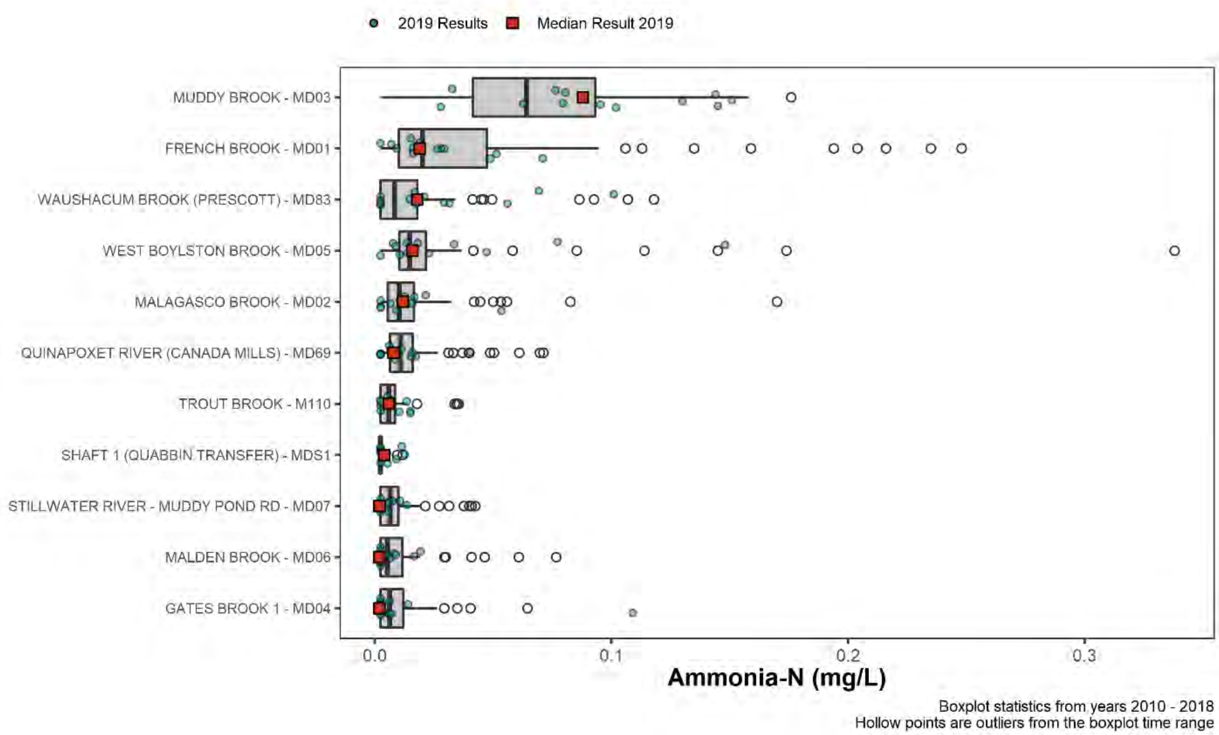
Sample Location	01/16/2019	02/28/2019	05/01/2019	05/02/2019	05/22/2019
Shaft 1 (Quabbin Transfer) - MDS1	X	X			X
French Brook - MD01				X	
Gates Brook 1 - MD04			X		
Malden Brook - MD06			X		
Stillwater River - Muddy Pond Rd - MD07			X		
Waushacum Brook (Prescott) - MD83			X		

3.2.6.1 *Nitrogen Species (Ammonia-Nitrogen, Nitrate-Nitrogen, Nitrite-Nitrogen, Total Kjeldahl Nitrogen, Total Nitrogen) in Wachusett Reservoir Watershed Tributaries*

Ammonia-Nitrogen

In 2019, NH_3-N was detected at very low concentrations at all tributaries with a high single sample result of 0.151 mg/L at Muddy Brook. Apart from French Brook in 2010, Muddy Brook continues to have the highest mean annual concentration of NH_3-N, with the highest in the previous ten years occurring in 2019 (0.094 mg/L) (Table 22 and Figure 27). Muddy Brook NH_3-N concentrations exhibit a rising trend over the last four years while other locations show no clear trend over the same period. The Muddy Brook sample location is immediately downgradient to a closed landfill in West Boylston, which is the likely source of increased NH_3-N.

Figure 27: 2019 Ammonia-Nitrogen Concentrations with 2010 - 2018 Statistics



Due to the high number of non-detection lab results (<0.005 mg/L) the values presented in Table 22 for NH_3-N have an inherent high level of uncertainty relative to their magnitude. Individual sample concentrations were mostly within historical 25th - 75th percentile ranges at each tributary, except for Muddy and Waushacum Brooks. These two tributaries had 2019 median NH_3-N concentrations close to their respective historical 75th percentiles. There were also eight high outlier samples occurring across a few locations. Trout Brook, Malden Brook, and the Stillwater River consistently have the lowest annual mean NH_3-N concentrations (typically below 0.01 mg/L).

Wachusett tributary NH_3-N concentrations are consistently below the MA acute and chronic aquatic life criteria (17mg/L and 1.9 mg/L) and below the WHO taste and odor thresholds for drinking water (1.5 mg/L and 1.9mg/L) by at least one order of magnitude. Thus, NH_3-N does not present a water quality concern for Wachusett tributaries.

Table 22: Ammonia-Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
French Brook - MD01	0.120	0.039	0.045	0.051	0.034	0.041	0.018	0.011	0.029	0.026
Gates Brook 1 - MD04	0.004	0.005	0.007	0.008	0.014	0.012	0.013	0.008	0.009	0.013
Malagasco Brook - MD02	0.010	0.016	0.014	0.013	0.015	0.029	0.012	0.014	0.011	0.014
Malden Brook - MD06	0.010	—	0.011	0.006	0.009	0.016	0.005	0.005	0.012	0.006
Muddy Brook - MD03	0.061	0.066	0.069	0.065	0.067	0.076	0.060	0.078	0.086	0.094
Quinapoxet River (Canada Mills) - MD69	0.014	0.015	0.012	0.012	0.017	0.021	0.010	0.015	0.011	0.011
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	—	0.004	0.003	0.006
Stillwater River - Muddy Pond Rd - MD07	0.010	0.010	0.008	0.008	0.012	0.011	0.006	0.006	0.005	0.005
Trout Brook - M110	—	—	—	—	—	0.012	0.006	0.008	0.005	0.007
Waushacum Brook (Prescott) - MD83	—	—	0.019	0.014	0.025	0.023	0.010	0.012	0.012	0.028
West Boylston Brook - MD05	0.012	0.022	0.013	0.014	0.049	0.021	0.016	0.037	0.027	0.034

Nitrite-Nitrogen

Nitrite-nitrogen (NO_2-N) is rarely detected in Wachusett Reservoir tributaries, therefore results are not displayed below. In 2019, the highest recorded (routine sample) NO_2-N concentration was 0.0094 mg/L at West Boylston Brook, with only five of the 135 samples collected in 2019 falling above the detection limit of 0.005 mg/L: three times at West Boylston Brook and twice at Gates Brook 1. These NO_2-N levels by themselves are not a concern for any designated use, however, nitrite's eventual conversion to nitrate in aqueous systems does contribute to the overall nutrient loading of the Wachusett tributaries and Reservoir. All NO_2-N results for 2019 were below the EPA MCL of 1.0 mg/L.

Nitrate-Nitrogen

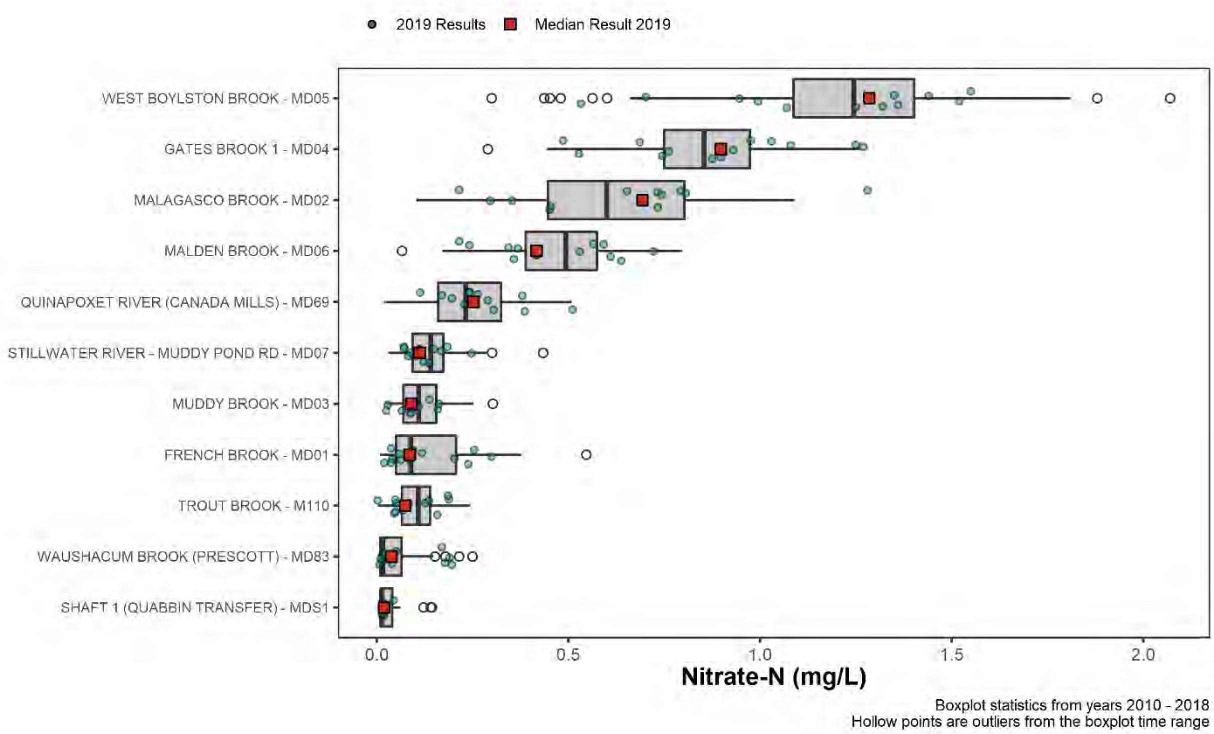
Annual mean NO_3-N concentrations for 2019 ranged from 0.073 mg/L at Waushacum Brook to 1.170 mg/L at West Boylston Brook (Table 23), with individual measurements from below detection (< 0.005 mg/L) to 1.55 mg/L in West Boylston Brook. The average annual NO_3-N concentrations at individual tributaries have been stable over the last several years. In 2019, individual samples were predominantly within the historical 25th - 75th percentile ranges by respective tributary. Median NO3-N concentrations in 2019 were close to historical medians from the 2010 – 2018 time period (Figure 28).

Table 23: Nitrate-Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
French Brook - MD01	0.135	0.154	0.127	0.159	0.167	0.093	0.153	0.110	0.134	0.119
Gates Brook 1 - MD04	1.006	0.930	0.801	0.920	0.856	0.786	0.762	0.925	0.846	0.886
Malagasco Brook - MD02	0.634	0.426	0.489	0.684	0.583	0.704	0.615	0.684	0.599	0.626
Malden Brook - MD06	0.472	—	0.432	0.550	0.443	0.534	0.443	0.488	0.452	0.463
Muddy Brook - MD03	0.105	0.089	0.098	0.144	0.135	0.134	0.139	0.108	0.110	0.095
Quinapoxet River (Canada Mills) - MD69	0.256	0.185	0.222	0.253	0.251	0.291	0.208	0.320	0.239	0.277
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	—	0.020	0.053	0.020
Stillwater River - Muddy Pond Rd -	0.156	0.157	0.140	0.163	0.136	0.155	0.122	0.134	0.108	0.127
Trout Brook - M110	—	—	—	—	—	0.107	0.097	0.099	0.101	0.095
Waushacum Brook (Prescott) - MD83	—	—	0.036	0.040	0.045	0.053	0.022	0.030	0.069	0.073
West Boylston Brook - MD05	1.575	1.087	1.168	1.392	1.142	1.250	1.198	1.284	1.069	1.170

Most Wachusett tributaries exhibit NO_3-N concentrations reflective of local ecoregional background levels (0.16 – 0.31 mg/L). However, several tributaries have mean NO_3-N concentrations that indicate excessive loading: West Boylston Brook and Gates Brook 1, which have well documented impacts from urban/suburban development, and Malagasco and Malden Brooks, which are less developed but could be impacted by a high percentage of agriculture (Malagasco) and septic system failures (Malden and Malagasco). While the NO_3-N concentrations at these four tributaries are somewhat elevated, they are still well below the EPA drinking water criteria of 10 mg/L and still low enough that impacts to aquatic life are likely negligible.

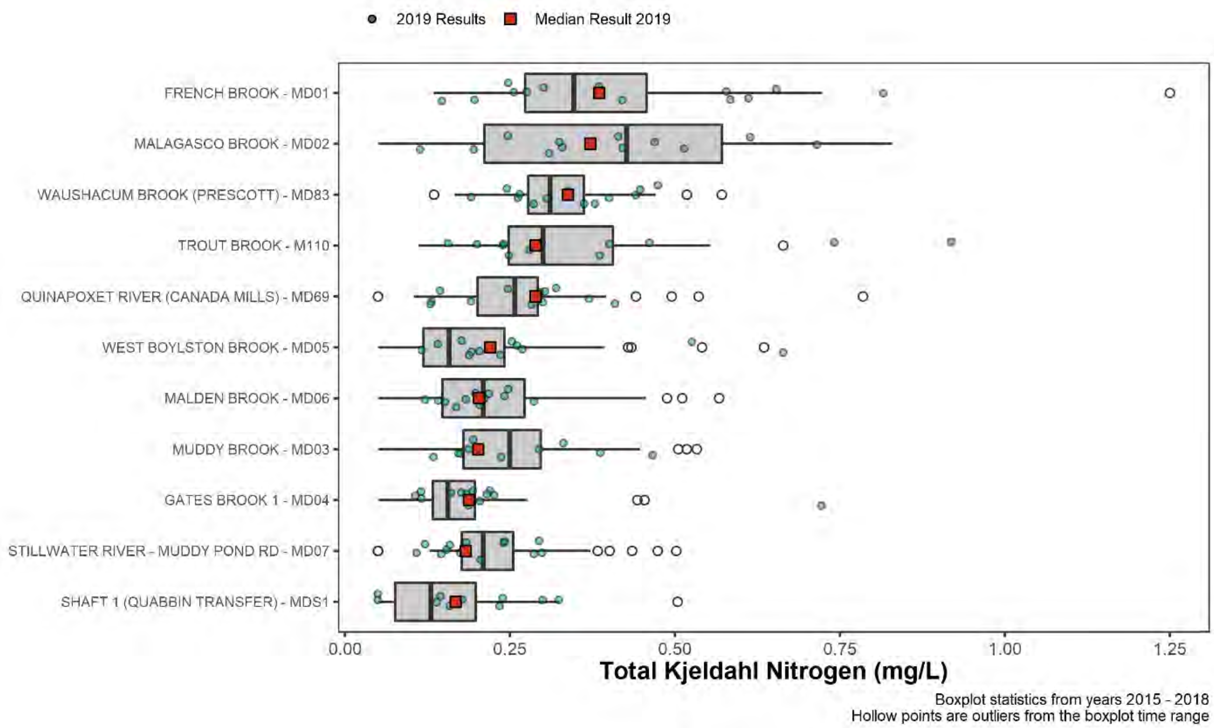
Figure 28: 2019 Nitrate-Nitrogen Concentrations with 2010 - 2018 Statistics



Total Kjeldahl Nitrogen

Annual mean TKN concentrations have been relatively consistent since 2015, when monitoring for this parameter in Wachusett tributaries began. Individual TKN sample concentrations in 2019 ranged from 0.106 mg/L at Gates Brook 1 to 0.919 mg/L at Trout Brook, which was the second highest TKN concentration ever observed in the Wachusett tributaries (Figure 29). French Brook had the highest mean TKN concentration for 2019 (0.421 mg/L), while Malden Brook had the lowest mean TKN concentration (0.198 mg/L).

Figure 29: 2019 Total Kjeldahl Nitrogen Concentrations with 2015 - 2018 Statistics



The mean and median annual TKN concentrations observed in 2019 are generally reflective of local ecoregional background concentrations (0.1 – 0.3 mg/L), however the four tributaries with the highest mean TKN concentrations (French, Malagasco, Trout, and Waushacum Brooks) frequently contain slightly higher concentrations, between 0.3 and 0.75 mg/L. These four tributaries all have significant proportions of wetlands and swamps within their subbasins, which are highly productive environments where organic compounds containing nitrogen and carbon are constantly breaking down and entering surface waters.

Table 24: Total Kjeldahl Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2015	2016	2017	2018	2019
French Brook - MD01	0.391	0.356	0.358	0.480	0.421
Gates Brook 1 - MD04	0.148	0.210	0.152	0.152	0.217
Malagasco Brook - MD02	0.351	0.342	0.465	0.472	0.389
Malden Brook - MD06	0.231	0.218	0.202	0.244	0.198
Muddy Brook - MD03	0.252	0.227	0.270	0.267	0.248
Quinapoxet River (Canada Mills) - MD69	0.290	0.288	0.246	0.260	0.260
Shaft 1 (Quabbin Transfer) - MDS1	—	—	0.102	0.208	0.182
Stillwater River - Muddy Pond Rd - MD07	0.206	0.266	0.224	0.212	0.201
Trout Brook - M110	0.257	0.310	0.351	0.345	0.381
Waushacum Brook (Prescott) - MD83	0.281	0.361	0.303	0.324	0.338
West Boylston Brook - MD05	0.174	0.188	0.174	0.244	0.269

There are no established water quality criteria for TKN to which Wachusett tributary concentrations can be evaluated against, therefore the only relevant water quality goal for this parameter is to maintain local background concentrations at each tributary. Since 2015, background concentrations have been relatively steady at each location, perhaps except for Trout Brook, which has been increasing slightly over the last five years. However, overall mean annual TKN concentrations, even at Trout Brook, are close to the ecoregional reference conditions and not indicative of any water quality problems.

Total Nitrogen

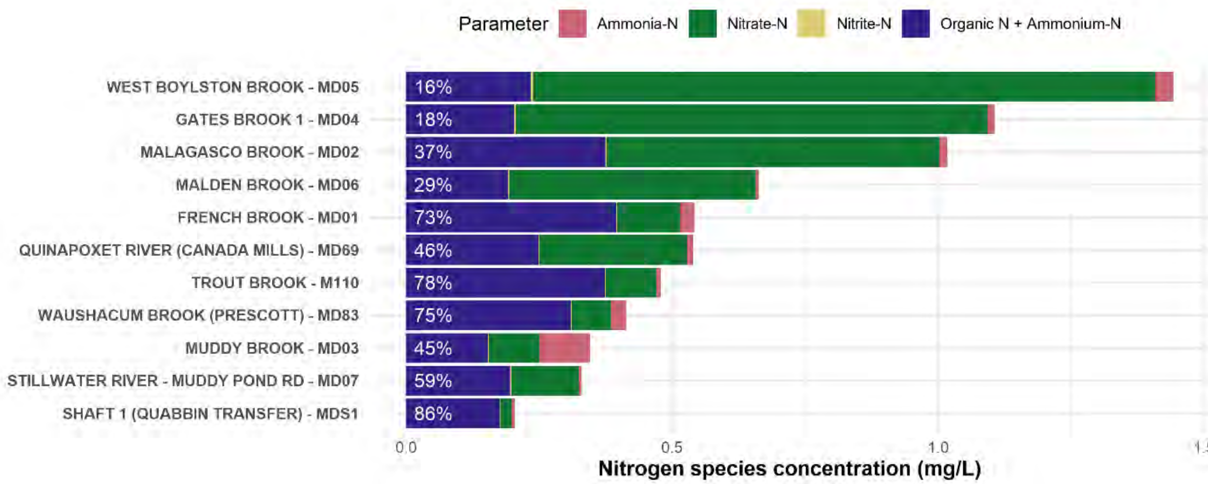
Total Nitrogen (TN) concentrations in 2019 ranged from 0.19 mg/L at the Stillwater River to 1.89 at West Boylston Brook, with mean annual concentrations for 2019 ranging from 0.33 mg/L to 1.44 mg/L at the same sample locations, respectively. Since 2015, when this parameter could first be calculated for Wachusett tributaries, TN has been very consistent at each tributary. Only three sampling locations had mean annual TN concentrations in excess of 1 mg/L: Gates Brook 1, Malagasco Brook, and West Boylston Brook (Table 25).

Table 25: Total Nitrogen Mean Annual Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2015	2016	2017	2018	2019
French Brook - MD01	0.486	0.511	0.470	0.617	0.542
Gates Brook 1 - MD04	0.936	0.975	1.069	1.001	1.106
Malagasco Brook - MD02	1.058	0.959	1.151	1.073	1.017
Malden Brook - MD06	0.768	0.664	0.693	0.699	0.663
Muddy Brook - MD03	0.389	0.370	0.381	0.379	0.346
Quinapoxet River (Canada Mills) - MD69	0.584	0.498	0.568	0.502	0.540
Shaft 1 (Quabbin Transfer) - MDS1	—	—	0.124	0.263	0.204
Stillwater River - Muddy Pond Rd - MD07	0.364	0.391	0.360	0.322	0.330
Trout Brook - M110	0.446	0.409	0.453	0.449	0.478
Waushacum Brook (Prescott) - MD83	0.337	0.385	0.336	0.395	0.413
West Boylston Brook - MD05	1.426	1.388	1.461	1.316	1.442

Figure 30 shows the relative proportion of all nitrogen species in the Wachusett tributaries, which differ considerably based on the landscape characteristics of each tributary subbasin. Less developed subbasins, such as Trout Brook, French Brook, and Waushacum Brook, usually have higher proportions of organic nitrogen (see discussion of TKN above), while more developed subbasins, such as West Boylston Brook and Gates Brook, have much lower proportions of organic nitrogen. This phenomenon is a function of the availability of organic nitrogen source material and inorganic nitrogen uptake by plants. On a per unit area basis, less developed subbasins have greater amounts of organic nitrogen within the landscape and more nutrient uptake by plants. The ratios of various nitrogen species play a significant role in aquatic ecology, both in the tributaries and Reservoir, in terms of algal production and bacteria growth and survival.

Figure 30: Mean 2019 Total Nitrogen Concentrations at Wachusett Tributaries.
Percentages indicate the organic nitrogen fraction of total nitrogen at each sample location.

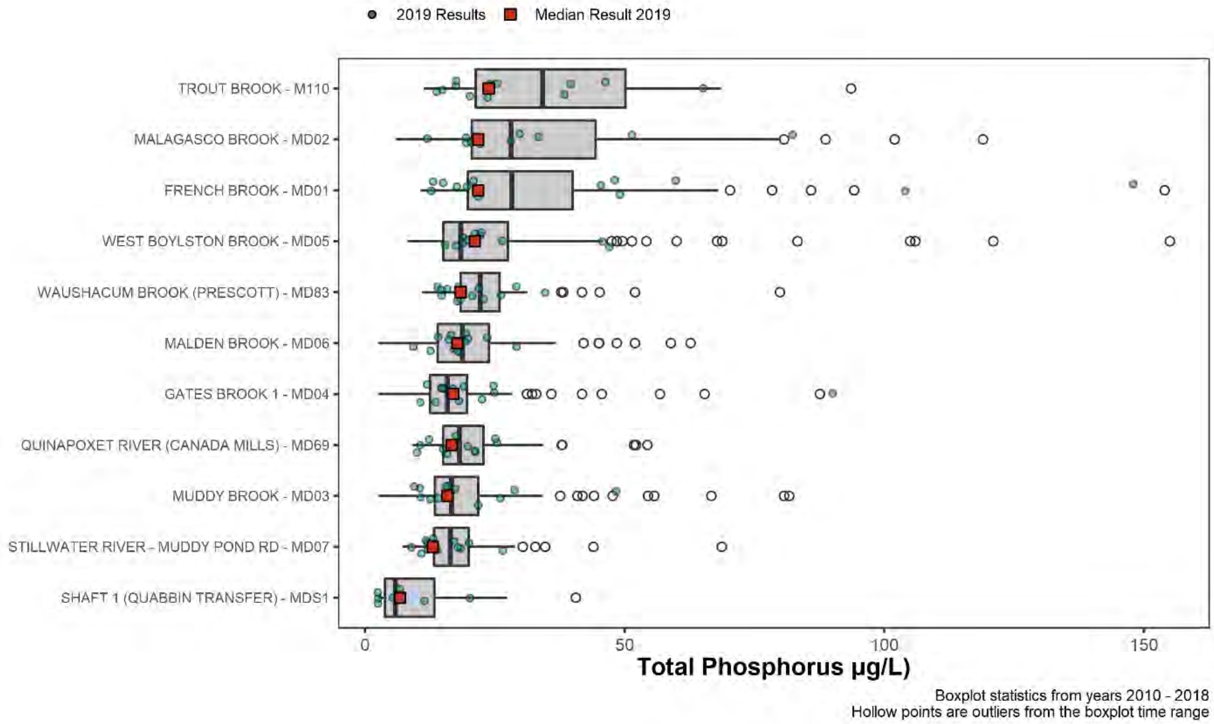


Concentrations of TN within Wachusett tributaries are mostly within the range of ecoregional background concentrations (0.42 – 0.69 mg/L), which are suggested reference conditions for numerical criteria development. West Boylston, Gates, Malagasco and Malden Brooks all exceed these concentrations, likely as a result of either urban/suburban development, septic systems, or agriculture. The Quinapoxet River and French Brook TN concentrations are also somewhat elevated above naturally occurring background conditions. The Quinapoxet River drainage area is large with many potential nitrogen sources, including significant urban/suburban landscapes and their associated uses. French Brook is a smaller subbasin, however there is a golf course which comprises a significant portion of this area and likely contributes nitrogen due to fertilizer use and irrigation. DWSP efforts to reduce nitrogen loads to Wachusett Reservoir should be targeted in the landscapes draining these six tributaries.

3.2.6.2 *Total Phosphorus in Wachusett Reservoir Watershed Tributaries*

Total phosphorus (TP) concentrations measured in Wachusett tributaries during 2019 ranged from less than 8.9 µg/L at the Stillwater River to 148 µg/L at French Brook, which was the second highest concentration observed at that tributary and the third highest among all tributaries since 2010 (Figure 31). Annual mean concentrations ranged from 15 µg/L at the Stillwater River to 44 µg/L at French Brook (Table 26). All annual mean TP concentrations were comparable to the 2010 – 2018 time period apart from French Brook, which was particularly influenced by a single high concentration. Except for West Boylston and Gates Brooks, annual median TP concentrations in 2019 were lower than the 2010 – 2018 time period (Figure 31). 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. However, the high concentration at French Brook occurred during moderate flows when the TSS concentration was below the detection limit.

Figure 31: 2019 Total Phosphorus Concentrations with 2010 - 2018 Statistics



Mean annual TP concentrations in 2019 for most Wachusett tributaries were commensurate to ecoregional background concentrations (12 -23.75 µg/L). Only French, Trout, and Malagasco Brooks have long-term median TP concentrations above 23 µg/L, which could be reflective of local background conditions, or possibly the result of anthropogenic sources. All three of these subbasins have on-lot waste disposal systems (septic) on developed parcels. Furthermore, French Brook subbasin contains a golf course which covers 10% of the drainage area and Malagasco Brook contains a nursery operation which covers 8% of its drainage area. The flow weighted mean TP concentration for all tributaries for 2019 was 17 µg/L. However, the Quabbin transfer contribution lowers the flow-weighted TP concentration to 12 µg/L for all surface water delivered to Wachusett Reservoir. The tributaries with long-term mean TP concentrations greater than 20 µg/L are not meeting DWSP water quality goals and are contributing towards unwanted nutrient enrichment within individual tributaries and the Reservoir. The drainage areas to these tributaries should be targeted for nutrient reduction opportunities, specifically looking at septic systems, golf courses, and agricultural operations.

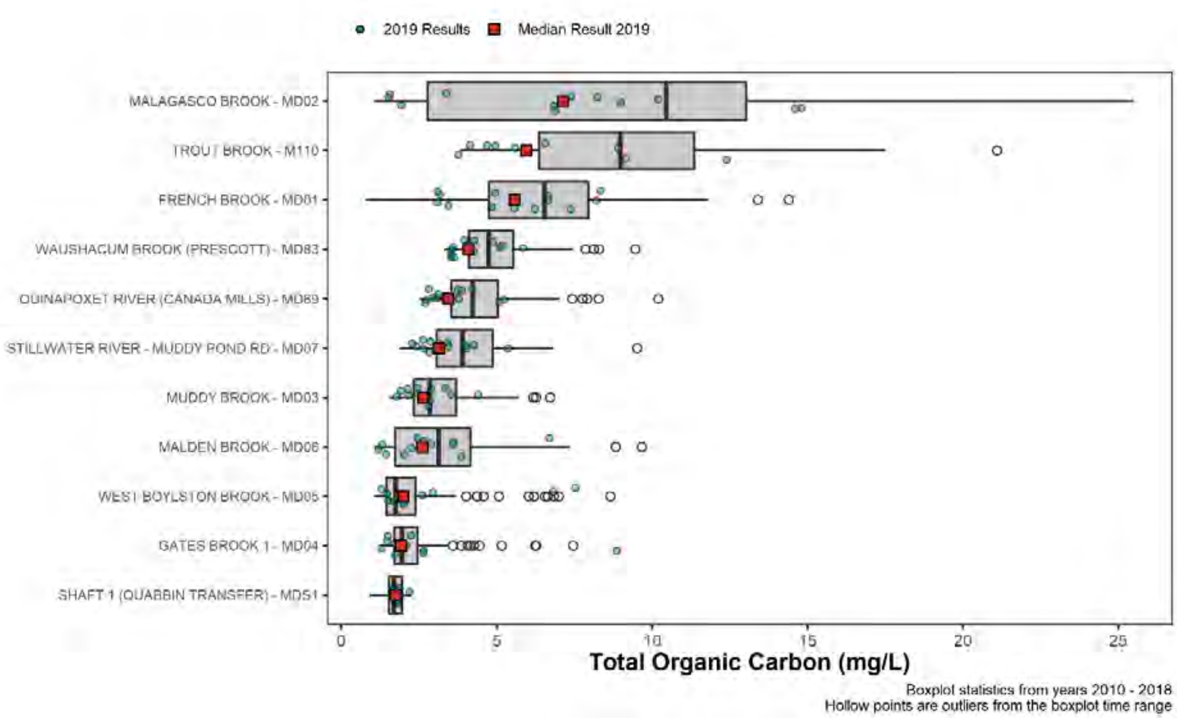
Table 26: Total Phosphorus Annual Mean Concentrations at Wachusett Tributaries (µg/L)

Sample Location	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
French Brook - MD01	55	36	49	32	31	32	29	23	26	44
Gates Brook 1 - MD04	13	17	25	17	25	15	17	15	19	23
Malagasco Brook - MD02	26	42	44	26	34	38	25	37	36	30
Malden Brook - MD06	19	—	28	18	25	24	19	16	20	18
Muddy Brook - MD03	15	24	27	21	19	18	20	21	21	19
Quinapoxet River (Canada Mills) - MD69	17	17	27	19	20	24	21	17	19	18
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	—	8	13	7
Stillwater River - Muddy Pond Rd - MD07	16	19	23	15	18	19	19	15	16	15
Trout Brook - M110	—	—	—	—	—	50	38	31	29	29
Waushacum Brook (Prescott) - MD83	—	—	29	23	25	22	26	20	19	21
West Boylston Brook - MD05	16	44	35	19	37	21	18	20	31	25

3.2.6.3 *Total Organic Carbon and UV_{254} in Wachusett Reservoir Watershed Tributaries*

In 2019, TOC sample concentrations in the Wachusett tributaries ranged from 1.2 mg/L at Malden Brook to 14.8 mg/L at Malagasco Brook (Figure 32), with an overall mean of 3.93 mg/L, which is the lowest mean concentration since 2013. The 2019 flow-weighted mean TOC concentration for all tributaries and Quabbin Transfer was 2.65 mg/L. Without the Quabbin transfer the flow-weighted mean concentration would have been 3.41 mg/L, or 29% higher. The highest mean annual concentrations were again recorded from Malagasco and Trout Brooks, with the lowest concentrations from Muddy, Gates and West Boylston Brooks (Figure 32). The source of elevated carbon loading at Trout Brook is thought to be the Poutwater Pond, a quaking bog located in Holden, yet this remains to be confirmed by TOC analysis on water collected from the bog outflow. The likely source of organic carbon in Malagasco Brook is a headwaters wetland that covers 17% subbasin drainage area. The large plant/tree nursery in Malagasco subbasin may be contributing to elevated carbon loads in that subbasin, however this also has not yet been investigated or confirmed.

Figure 32: 2019 Total Organic Carbon Concentrations with 2010 - 2018 Statistics



Over the last ten years there are no discernable trends in TOC concentration for any of the Wachusett tributaries. In 2019 five tributaries had their lowest mean annual TOC concentration since 2010.

Table 27: Total Organic Carbon Annual Mean Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
French Brook - MD01	6.05	6.77	7.89	6.21	6.74	5.88	6.06	6.81	7.14	5.51
Gates Brook 1 - MD04	1.65	2.44	2.69	2.10	2.52	1.86	2.34	2.27	2.45	2.46
Malagasco Brook - MD02	9.15	11.08	11.70	6.40	10.80	7.79	8.83	10.82	10.81	7.20
Malden Brook - MD06	2.91	—	3.49	2.81	4.21	2.29	3.08	3.50	3.67	2.82
Muddy Brook - MD03	2.55	3.76	3.09	2.96	3.01	2.44	2.93	3.53	3.49	2.73
Quinapoxet River (Canada Mills) - MD69	3.91	4.42	4.56	4.28	4.76	4.11	4.92	4.53	4.73	3.61
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	—	1.89	1.55	1.79
Stillwater River - Muddy Pond Rd - MD07	3.34	4.12	3.79	3.55	4.58	3.89	3.84	4.54	4.79	3.34
Trout Brook - M110	—	—	—	—	—	9.54	8.50	9.43	9.31	6.51
Waushacum Brook (Prescott) - MD83	—	—	5.25	4.72	5.33	4.50	4.97	5.36	4.91	4.27
West Boylston Brook - MD05	1.59	2.59	2.50	2.11	3.20	1.76	1.88	2.26	2.71	2.80

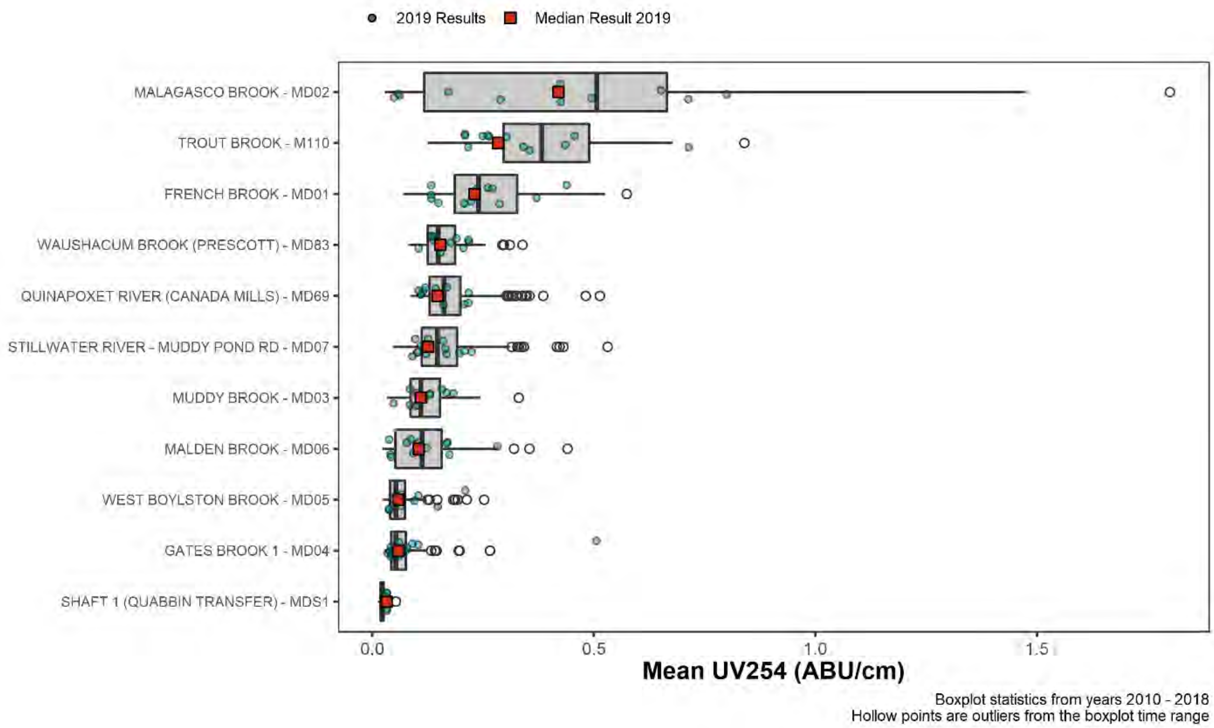
Total Organic Carbon (TOC) concentrations between 2 and 4 mg/L are considered low for surface waters, and the 2019 flow-weighted mean TOC concentration of 2.65 mg/L is not a concern for aquatic life. However, this concentration is higher than optimal from a drinking water treatment perspective. Although tributary TOC concentrations are within ranges that could be reflecting typical background concentrations, more research needs to be conducted to determine what portion of tributary organic carbon is of natural origin versus anthropogenic origin. Until those sources and relative quantities are better understood, recommendations for reduction cannot be made.

Measurements of UV_{254} absorbance for Wachusett tributaries in 2019 demonstrated variability comparable to TOC concentrations. The highest UV_{254} absorbance levels were from Malagasco Brook (0.80 ABU/cm) and Trout Brook, and the lowest were from were West Boylston Brook (0.081 ABU/cm), Gates Brook and Muddy Brook. At many sample locations, UV_{254} absorbance levels were lower in 2019 than during the previous year or two, but well within the 25^{th} – 75^{th} percentile ranges observed within the last 10 years.

Table 28: UV_{254} Mean Absorbance at Wachusett Tributaries (ABU/cm)

Sample Location	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
French Brook - MD01	0.300	0.331	0.315	0.229	0.251	0.226	0.199	0.248	0.313	0.237
Gates Brook 1 - MD04	0.048	0.083	0.077	0.057	0.068	0.051	0.065	0.057	0.084	0.095
Malagasco Brook - MD02	0.395	0.846	0.584	0.317	0.479	0.372	0.304	0.510	0.618	0.380
Malden Brook - MD06	0.125	—	0.132	0.102	0.153	0.078	0.100	0.126	0.156	0.116
Muddy Brook - MD03	0.116	0.167	0.117	0.108	0.108	0.101	0.103	0.133	0.151	0.117
Quinapoxet River (Canada Mills) - MD69	0.164	0.191	0.164	0.156	0.167	0.162	0.162	0.197	0.210	0.152
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	—	0.020	0.026	0.032
Stillwater River - Muddy Pond Rd - MD07	0.139	0.185	0.140	0.140	0.152	0.167	0.125	0.193	0.215	0.144
Trout Brook - M110	—	—	—	—	—	0.432	0.316	0.437	0.421	0.335
Waushacum Brook (Prescott) - MD83	—	—	0.175	0.138	0.158	0.146	0.153	0.169	0.186	0.163
West Boylston Brook - MD05	0.051	0.087	0.078	0.052	0.075	0.050	0.057	0.053	0.091	0.081

Figure 33: 2019 UV_{254} Absorbance with 2010 - 2018 Statistics



3.2.7 Special Studies and Investigations - Tributaries

3.2.7.1 *Forestry Water Quality Monitoring*

Long-term forestry monitoring

In 2019, monthly monitoring at the LTF monitoring locations—Holden (FHLN) and Princeton (FPRN)—continued as part of the pre-harvest phase, except for July – October when the streams at both study locations were dry. Storm event sampling efforts were reduced in 2019 because sufficient data for storm events in the pre-harvest phase has been acquired (21 events prior to 2019). One additional storm event was sampled in 2019 on October 17. Additional project work included installation of a weir at the Holden LTF location, which was completed in September. The previously used gauging station is located below a culvert which becomes clogged occasionally, diverting water around the gauging pool. The weir was installed upstream of this culvert and will allow for the accurate measurement of all flows, as it is not impacted by the culvert.

The addition of a weir at the Princeton LTF location is planned for 2020 in order to obtain more accurate baseline flow data. At least six months of flow monitoring with the weir will be necessary to confirm the accuracy of the prior rating and adjust historical discharges if necessary. Once flow data accuracy at the Princeton location has been confirmed all pre-harvest monitoring data required for analysis will have been collected and the harvest phase can proceed.

Short-term forestry monitoring

In 2019, 126 lot visits were made lots across 17 distinct forestry lots in various stages of harvest. Pre-harvest monitoring began at proposed stream crossings on three lots: WA-20-113, WA-20-215, WA-20-

124. Post-harvest monitoring was completed at one lot: WA-18-284. A total of 190 turbidity samples were collected from stream crossing sampling locations. Dry conditions prevented sample collection at more than one in every three sample attempts (Table 29).

Table 29: Short-term Forestry Monitoring in 2019

Metric	Pre-harvest	Harvest - Active	Harvest - Suspended	Post-harvest	Total
Lot Visits	126	32	0	20	178
Crossing Observations	193	48	0	28	269
Sample Locations Checked	193	79	0	34	306
Turbidity Samples Collected	107	54	0	29	190

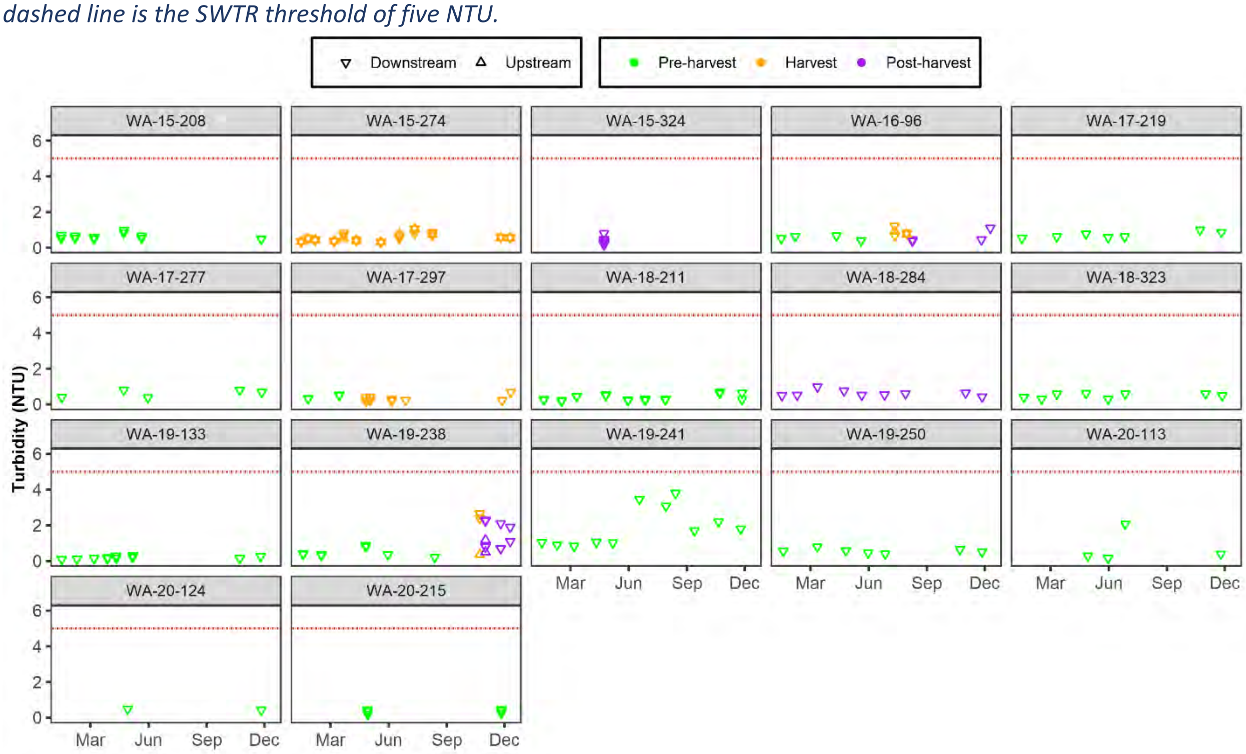
Turbidity results ranged from 0.10 NTU to 3.80 NTU (Figure 34). The highest three results (above 2.66 NTU) were recorded during pre-harvest, before any logging activity had begun. Turbidity results were less than 1 NTU in 88% of all samples collected. Mean turbidity values did not differ substantially between upstream and downstream sample locations or between harvest periods (Table 30). The turbidity results for 2019 indicate that erosion control practices at Wachusett forestry operations were sufficient to protect water quality.

Table 30: Mean Turbidity (NTU) at Short-term Forestry Monitoring Locations

Sample Location	Pre-harvest	Harvest (Active and Suspended)	Post-Harvest
Upstream	N/A	0.57	0.84
Downstream	0.62	0.63	0.82

Figure 34: Turbidity Results at Short-term Forestry Monitoring Locations in 2019

Upstream and downstream designations are only applicable during harvest periods when stream crossings were installed. Only the downstream location was sampled during pre and post-harvest monitoring periods. The red dashed line is the SWTR threshold of five NTU.



3.2.7.2 *Conductivity and Chloride*

In 2018, a working group was formed to evaluate increasing specific conductance observed in the Quabbin and Wachusett Reservoirs and many of their tributaries. This is expected to be a long-term collaborative effort between DWSP, MWRA, UMass researchers and local stakeholders such as the watershed town public works departments and drinking water providers. Members of the conductivity/Cl working group proceeded independently with research and information gathering efforts in 2019.

UMass graduate student Josh Soper completed a master's thesis in support of conductivity/Cl research tasks assigned to UMass as part of the FY2019 – FY2020 ISA. This research involved modeling tributary Cl loads and calculating a mass balance for years 2000 – 2019. An important finding from this work was that Wachusett watershed export of Cl has not approached equilibrium with inputs until recently[108]. It is expected that efforts to reduce Cl inputs will also have a decadal export response time. Continued monitoring for specific conductance/Cl and in the tributaries and the Reservoir will detect any shifting trends in these loads. The most optimistic scenario is that current loading rates will plateau for many years and then slowly begin to decline. Future work for UMass researchers will be included in the next ISA, covering FY2021 – FY2022.

Salt use amounts were obtained from all Wachusett watershed communities and from the Massachusetts Department of Transportation (MassDOT). A consultant for MassDOT also provided information on impervious surfaces in the watershed that are likely treated regularly with salt. The estimates on salt use and impervious surfaces were similar to those derived independently by DWSP staff. Town water departments were added to the information exchange and provided useful information on local groundwater quality. There was continued research by DWSP staff on specific costs, documentation of effectiveness of new technologies, current practices, possible legislative actions, and scientific studies. A number of documents were shared with the group using Dropbox.

Training for 36 local DPW employees and DWSP and MWRA staff was arranged through UMass Baystate Roads and paid for by MWRA. DWSP watershed maintenance staff used knowledge obtained at the training to change practices and sharply reduce salt application amounts during December snowstorms.

A PowerPoint presentation on road salt and the problems associated with over-application was shown to DWSP and MWRA staff at the fall Reservoir Operations meeting, to MassDEP inspectors at the annual watershed inspection, and at the Watershed Trust meeting. The presentation was also shared with the Water Supply Citizen's Advisory Committee for further distribution in other communities.

Staff discussed grant opportunities for watershed communities to obtain new technologies that would help reduce salt applications, and $100,000 was included in the proposed FY2021 Division budget for this purpose.

3.3 Groundwater Quality Monitoring

2019 marked the beginning of expanded groundwater monitoring (see Figure 6), and what little data have been collected so far have provided preliminary insights on the groundwater levels, specific conductance, and Cl in Wachusett watershed aquifers. Results of well monitoring in 2019 revealed a wide range in specific conductance and Cl concentrations in Wachusett watershed groundwater (Figure 35). The means of both parameters in West Boylston - 110 were two orders of magnitude higher than the means in

[108] Soper, 2020

Sterling – Justice Hill Rd with values from the other wells between those two extremes (Table 32). In total, three wells — Holden - Wachusett St, Boylston - Rt 70, West Boylston - Rt 110 — have Cl levels higher than the EPA SMCL of 250 mg/L for taste and odor in drinking water. The ranges and medians of specific conductance and Cl results are shown in the box plots in Figure 35 and Figure 36 with logarithmic Y-axes due to the high and low skews in values. Elevated Cl levels in the Wachusett watershed are assumed to be primarily attributable to the chronic application of deicing road salt, but due to the particularly elevated specific conductance and Cl levels in West Boylston – Rt 110, DWSP has launched a supplementary investigation to determine additional sources impacting the groundwater at that location.

Table 31: Dates During 2019 When Groundwater Monitoring Wells Had Insufficient Water to Sample

Well	July	August	September	October	November	December
Holden - Wachusett St	X					
Boylston - Rt 70		X	X			
West Boylston - Gate 27						
West Boylston - Rt 110						
Sterling - Justice Hill Rd						
Princeton - Rt 62	X	X	X	X		
Sterling - Rt 140						
Holden - Jefferson*		X	X	X	X	X

* Holden - Jefferson cannot be purged with present field equipment – only depth to water, temperature and specific conductance are relevant.

Figure 35: Chloride Results in Wachusett Watershed Wells in 2019

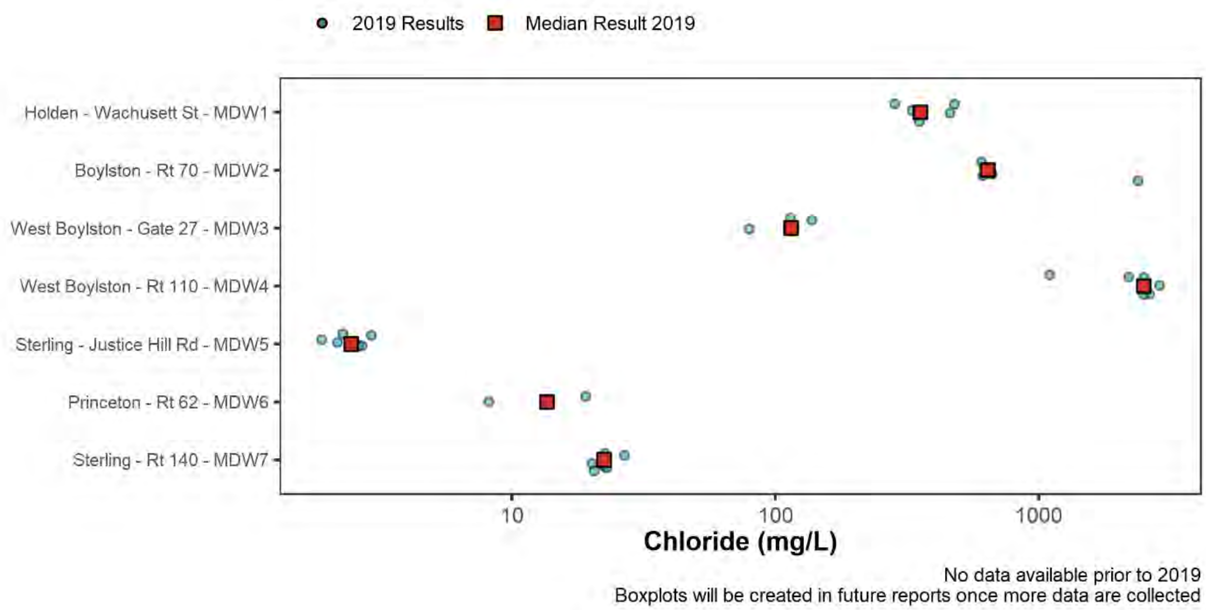


Figure 36: Specific Conductance Results in Wachusett Watershed Wells in 2019

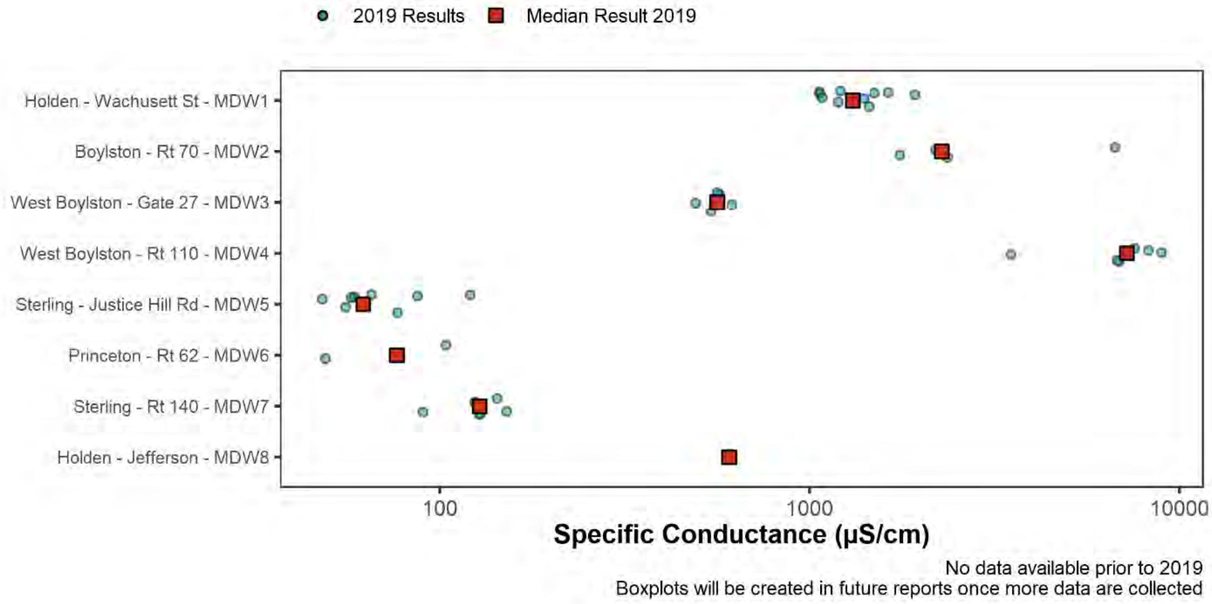


Table 32: Groundwater Monitoring Summary for 2019

Well	Mean Water Depth Below Ground Surface (ft)	Mean Specific Conductance (µS/cm)	Mean Chloride (mg/L)
Holden - Wachusett St	3.6	1,353	377
Boylston - Rt 70	6.4	3,253	1,069
West Boylston - Gate 27	7.5	557	113
West Boylston - Rt 110	16.1	6,985	2,302
Sterling - Justice Hill Rd	6.2	71	2
Princeton - Rt 62	13.5	77	14
Sterling - Rt 140	14.4	128	23
Holden - Jefferson	17.5	606	—

Well monitoring will continue in 2020 to determine if seasonal or long-term trends are present in groundwater specific conductance and Cl concentrations. Additional data will also assist in establishing a relationship between specific conductance and Cl in each well, at which time DWSP staff may consider ending Cl sample collection as it will be possible to estimate Cl concentrations from specific conductance measurements. Groundwater contributions of Cl in Wachusett tributaries are being further explored by researchers at UMass Amherst and a publication on this topic is expected sometime in 2020[109].

Specific conductance and Cl concentrations observed in Holden - Wachusett St, Boylston - Rt 70, and West Boylston - Rt 110 are indicative of widespread water quality impairment in groundwater aquifers. Cl concentrations in West Boylston - Rt 110 are almost an order of magnitude higher than the highest tributary concentrations. The wide ranges of Cl concentrations in groundwater also demonstrate how certain hotspot areas can go undetected when only monitoring surface waters because of the blending of various ground/surface waters from an entire drainage area that occur within tributaries. Unfortunately, there is limited capacity to expand the spatial extent of the groundwater sampling program due to the lack of additional monitoring wells. However, there are other methods that may be able to provide better

[109] Soper, 2020

spatial resolution of groundwater impairment, such as monitoring baseflow at first order tributaries that are not routinely monitored.

3.4 Reservoir Monitoring

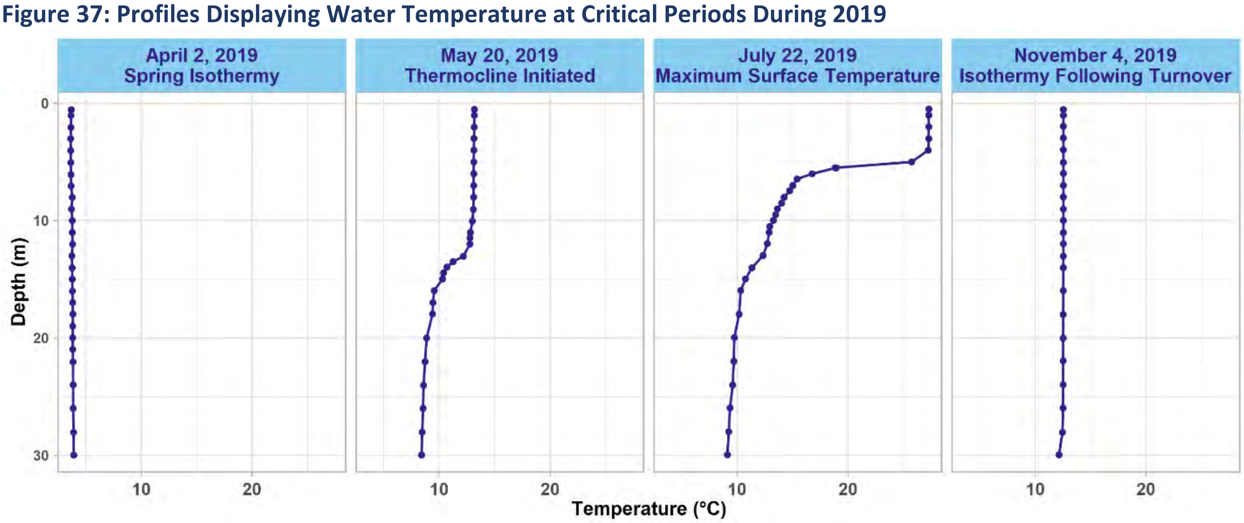
In general, results of reservoir monitoring programs followed expected trends and fell within or close to historical values. Notable deviations are likely related to the low volume of water transferred from Quabbin to Wachusett, resulting in native Wachusett watershed water having a larger influence on water quality parameters related to organic inputs such as specific conductance, silica, and UV_{254}. Two periods during which chrysophytes were elevated above early monitoring thresholds were also experienced in 2019. These events reduced Secchi disk transparency, resulting in the lowest average measurements since 2011. Details on these and all other water quality and aquatic life monitoring programs are presented below.

Unless otherwise noted, results reported in this section were obtained by DWSP aquatic biologists via hand-held instruments *in situ*, microscopy, or via samples processed by an MWRA lab (see Section 2.1).

3.4.1 Water Temperature

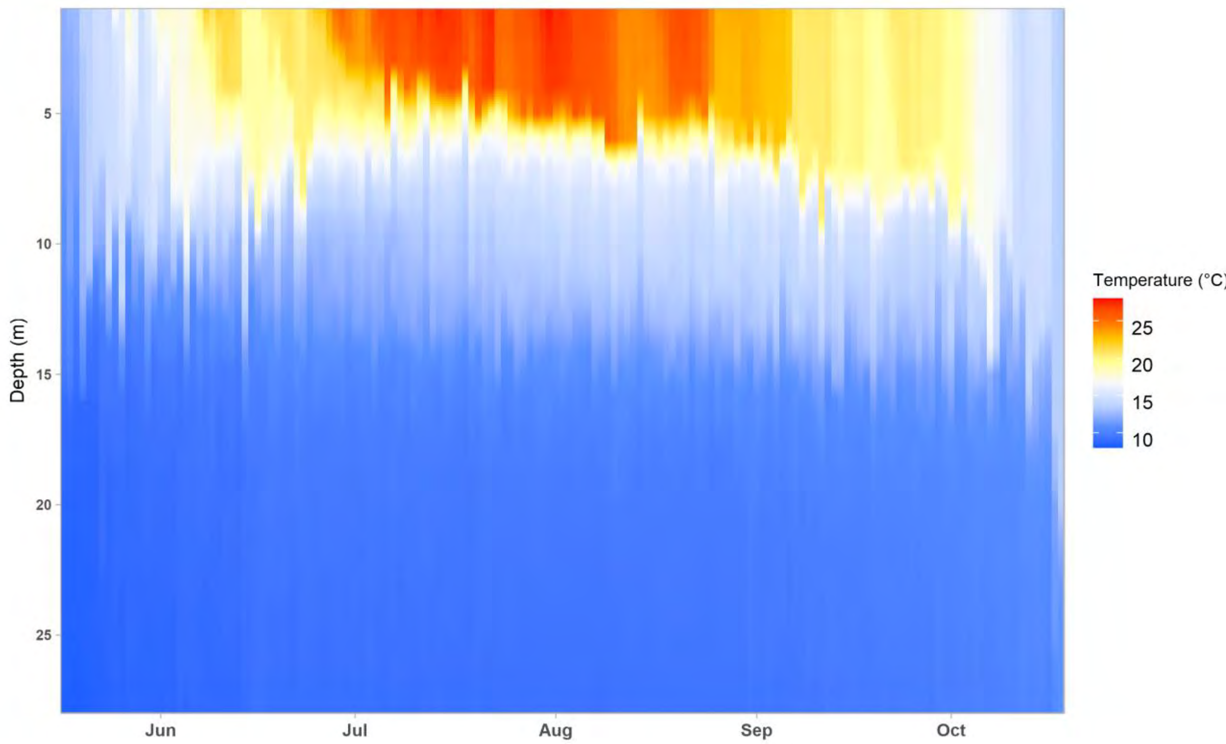
2019 reservoir temperatures supported MassDEP aquatic life use standards for coldwater and warmwater fisheries. The aquatic life use temperature threshold as a mean of 7-day maximum temperature for coldwater fisheries and warmwater fisheries may not exceed 20 °C (68 °F) and 28.3 °C (83 °F) respectively. Reservoir temperatures ranged from 1.5 °C to 27.3 °C during 2019. This range does not include periods when ice prevented sampling and temperatures were likely colder. Full ice cover was not achieved in the 2018/2019 season, although ice did prevent sampling by boat and off the Cosgrove Intake between January 30 and March 25. Substantial warming started in May and the presence of a thermocline, as indicated by a 1 °C temperature decrease over one meter in depth, was first recorded on May 20. Surface temperatures continued to warm, attaining a maximum temperature of 27.3 °C on July 22. Cooling of the epilimnion started in late August when the combination of cooling air temperatures and wind energy pushed the thermocline deeper. Turnover occurred by November 4 and the water column continued to cool for the remainder of the season.

Figure 37: Profiles Displaying Water Temperature at Critical Periods During 2019



The high temporal resolution data obtained from MWRA remote sensing buoys provide an opportunity to visualize reservoir temperature changes over the entire season (Figure 38).

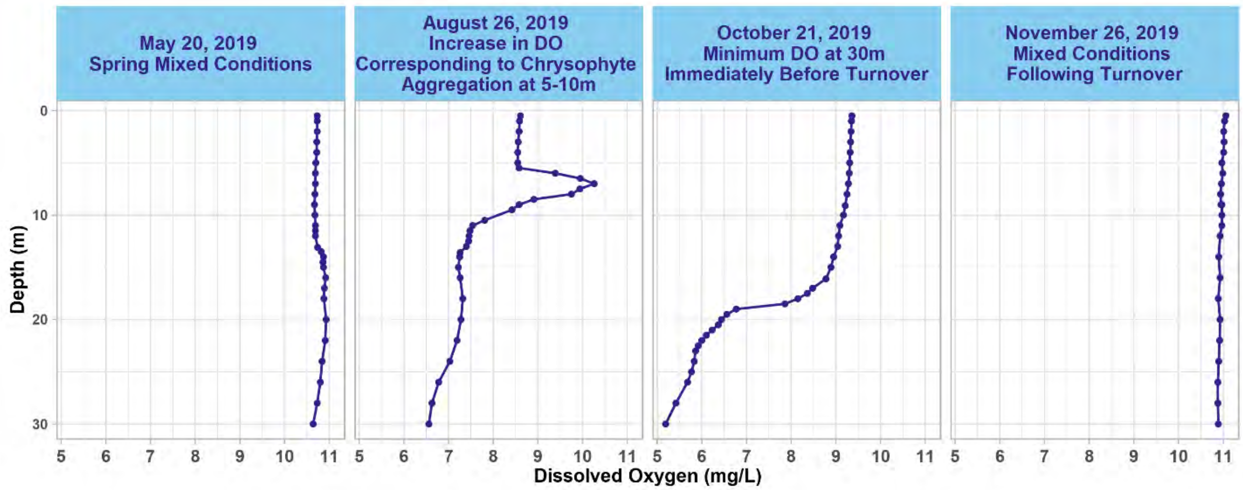
Figure 38: Water Temperature Recorded by Basin North Profiling Buoy May – November 2019
Plot based on data recorded daily at 12 pm.



3.4.2 Dissolved Oxygen

Expected patterns in dissolved oxygen were observed throughout the 2019 season, meeting MassDEP aquatic life use criteria of 6.0 mg/L for coldwater communities and 5.0 mg/L warmwater communities. Cool temperatures, which allow water to hold more oxygen, and isothermic conditions present through the spring season allowed dissolved oxygen to remain above 10 mg/L in the entire water column until late May. Stratification then strengthened, isolating water below the thermocline from atmospheric diffusion of oxygen. Dissolved oxygen therefore gradually declined within the hypolimnion, reaching a minimum concentration of 5.19 mg/L at 30 m on October 21, the last profile collected before turnover occurred. Despite oxygen depletion at depth, the mean dissolved oxygen concentration in the hypolimnion remained above 6.0 mg/L, maintaining concentrations required to support coldwater species. Once turnover occurred in late October, oxygen was again able to disperse through the water column and was approximately 11 mg/L from the surface to bottom on November 26. Elevated dissolved oxygen below the thermocline associated with increased phytoplankton activity, specifically chrysophytes, occurred several times in late August.

Figure 39: Profiles Displaying Dissolved Oxygen at Critical Periods During 2019

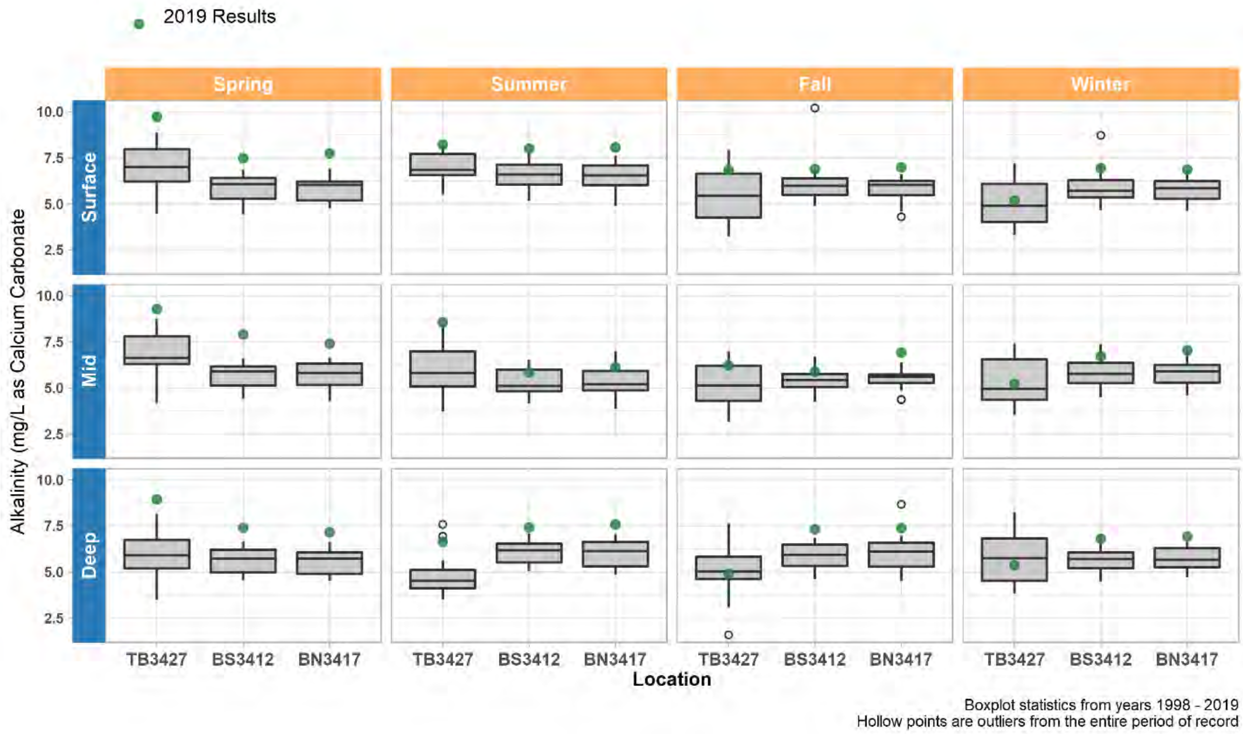


3.4.1 Alkalinity and pH

The average pH across all reservoir sample sites and depths was 6.59 in 2019, within the MassDEP regulatory acceptable range of 6.5 and 8.3. Individual site averages were similar, ranging from 6.57 at Basin North to 6.80 at Thomas Basin. Minimum pH around 5.5 was recorded in the mid to late summer at depths below 18 m as CO_2 released during decomposition was isolated in the hypolimnion during stratification.

Alkalinity in Wachusett Reservoir has gradually increased over the period of record, with a steady increase each year since 2015. Average alkalinity across all sites and depths in 2019 was 7.11 mg/L as $CaCO_3$ and results for individual sites were generally higher than annual means, with several record high values recorded. The maximum alkalinity of 9.72 mg/L as $CaCO_3$ was recorded in the spring at Thomas Basin while the minimum of 4.90 mg/L as $CaCO_3$ was recorded at Thomas Basin in the fall during a period when water at this location was heavily influenced by the Quabbin transfer.

Figure 40: 2019 Alkalinity in Wachusett Reservoir

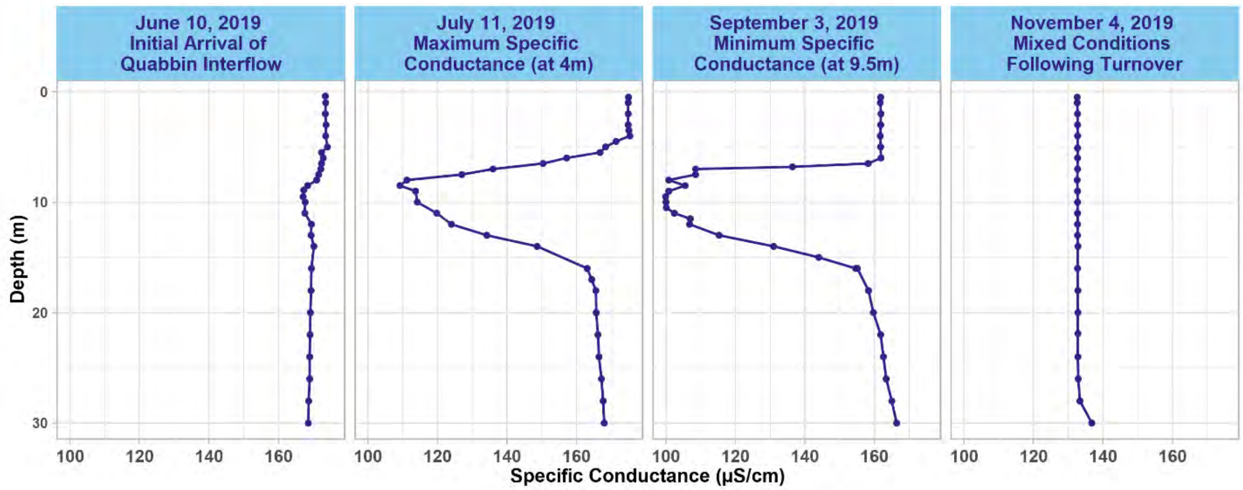


3.4.2 Specific Conductance

Following two years of record specific conductance values in 2017 and 2018, the maximum value decreased in 2019, attaining a maximum of 175.4 µS/cm at a depth of 4 m at Basin North on July 11. However, specific conductance values greater than 170 µS/cm continued at the surface (0 to 5 m) of Basin North through August.

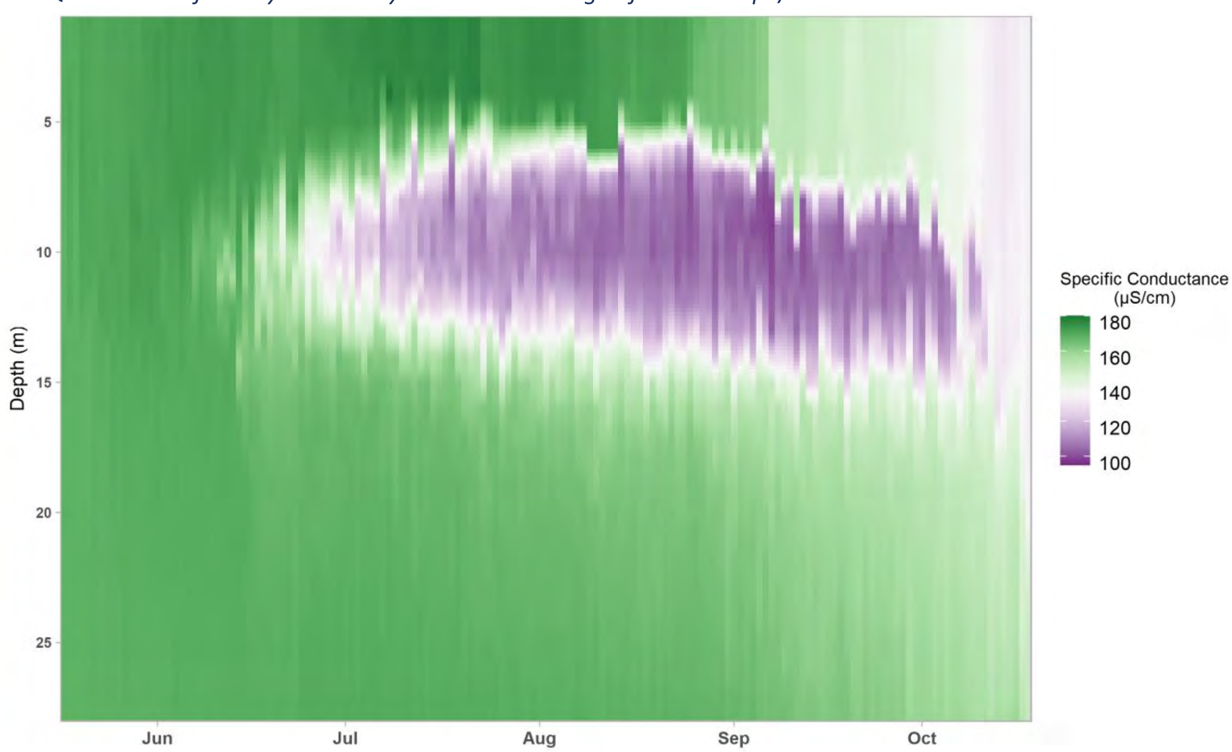
Arrival of the Quabbin interflow at Basin North (BN3417) was first observed on June 10 with a slight decrease in specific conductance observed around 8 m. By June 17, a definitive decrease in specific conductance between 8.5 and 9 m indicated infiltration of the Wachusett metalimnion by the Quabbin interflow. Following this date, the specific conductance within the metalimnion continued to decrease, reaching a minimum of 99.9 µS/cm at 9.5 m on September 3. At this point, the interflow had grown to encompass 9.5 m of water between the depth of 6.5 and 16 m. As the Reservoir epilimnion temperature decreased in late September, higher conductivity water found in the Wachusett epilimnion began mixing with the lower conductivity hypolimnion and Quabbin interflow, reducing the difference in specific conductance between the epilimnion and hypolimnion. By the beginning of November, the Reservoir was again fully mixed, with a nearly uniform specific conductance of approximately 133 µS/cm (Figure 41).

Figure 41: Profiles Displaying Specific Conductance at Critical Periods During 2019



Formation of the Quabbin interflow and the stark differences between interflow specific conductance and that of native Wachusett water throughout the year is shown below using the high resolution data obtained from the MWRA profiling buoy in Basin North (Figure 42).

Figure 42: Specific Conductance Recorded by Basin North Profiling Buoy May – November 2019
The Quabbin interflow layer is clearly visible in the range of 99 to 130 µS/cm between mid-June and October.



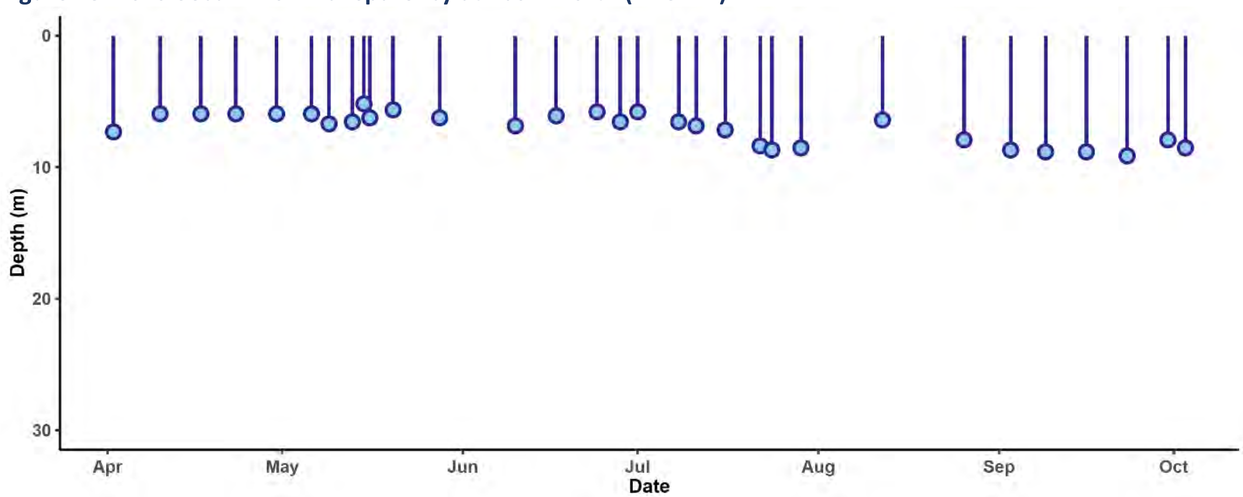
3.4.3 Turbidity

Turbidity in the Reservoir was measured with sensors installed on the YSI EXO sondes used by DWSP and on the remote profiling buoys. The precision of these sensors is 0.3 FNU, which is the typical result observed in the Reservoir. Therefore, turbidity values observed *in situ* are used for observational purposes only. Data for regulatory compliance are collected by MWRA at various points throughout the distribution system once water leaves the Reservoir.

3.4.4 Secchi Disk Depth/Transparency

Water transparency as measured by Secchi disk depth was slightly lower in spring 2019 than previous years, likely due to an influx of native Wachusett water following greater than normal precipitation in April. Secchi disk depth remained less than 7 m through June, influenced by elevated concentrations of the chrysophyte algae *Synura* (Figure 43). By mid-July, *Synura* density decreased and Secchi disk depth increased to a seasonal maximum of 8.69 m on July 24. Transparency was again reduced by increased chrysophyte density in the late summer. The annual maximum Secchi disk depth of 9.41 m was recorded on September 23 when a narrow aggregation of chrysophytes was present at 11 m. Secchi disk depth typically increases following turnover. However, chrysophyte densities continued to negatively impact water transparency for the remainder of the year, resulting in the lowest mean annual Secchi disk depth since 2011. Although low compared to historic Wachusett Reservoir data, this annual mean Secchi disk depth of 7.0 m remained greater than the reference range for the Reservoir ecoregion.

Figure 43: 2019 Secchi Disk Transparency at Basin North (BN3417)



3.4.5 Nutrient Dynamics

The patterns of nutrient distribution in 2019 quarterly samples generally followed those documented in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics[110]. 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 organic matter in sediment, (2) interannual fluctuations in nutrient concentrations occurring throughout the system as a result of the opposing influences of the Quabbin transfer and the Wachusett watershed with temporary lateral and

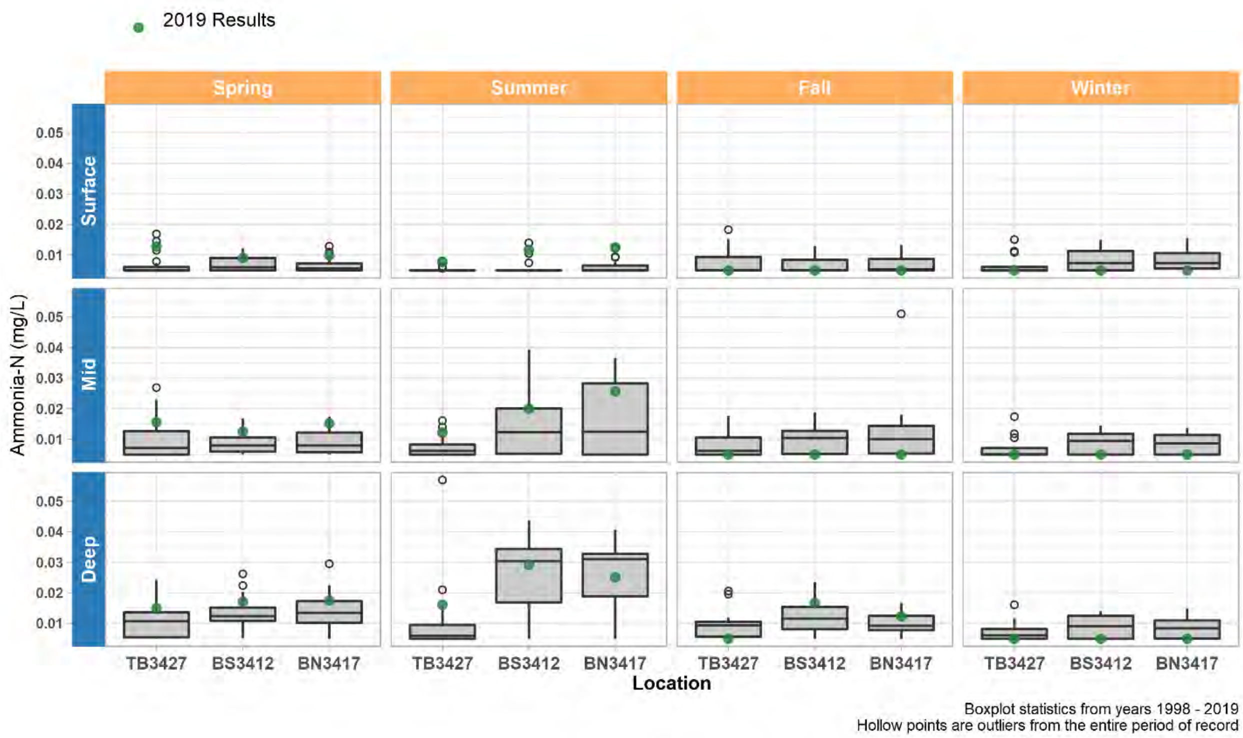
[110] Worden & Pistrang, 2003

vertical gradients becoming pronounced for nitrate, silica, UV_{254}, and specific conductance downgradient of Thomas Basin and within the interflow if present. As in 2018, the low volume of water transferred from Quabbin in 2019 resulted in Wachusett watershed water quality more heavily influencing reservoir water quality than in a typical year. This influence is exemplified by increases in UV_{254} observed at Basin South and Basin North where results met or slightly exceeded the maximum historical value for UV_{254} at these locations.

3.4.5.1 *Nitrogen Species (Ammonia-Nitrogen, Nitrate-Nitrogen, and Total Kjeldahl Nitrogen)*

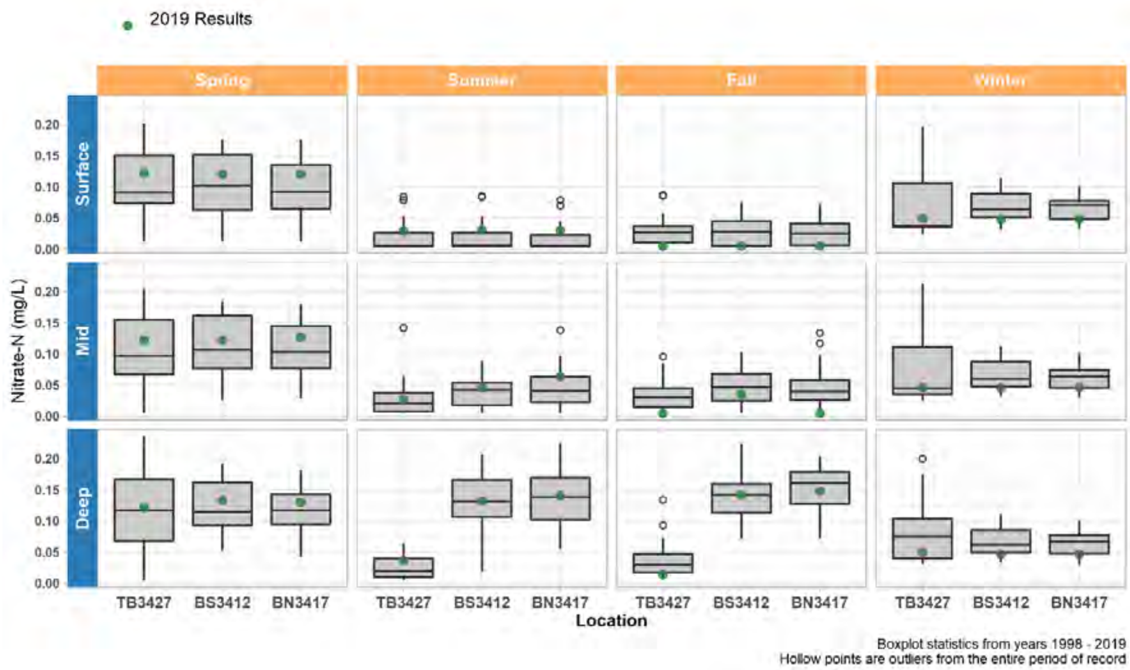
Ammonia-nitrogen (NH_3-N) levels within the Reservoir remain low, with concentrations ranging from below the detection limit (0.005 mg/L) to a maximum observed value of 0.029 mg/L in 2019 (Figure 44). These values are within the historical range for all sites and well below regulatory thresholds.

Figure 44: 2019 Ammonia-Nitrogen in Wachusett Reservoir



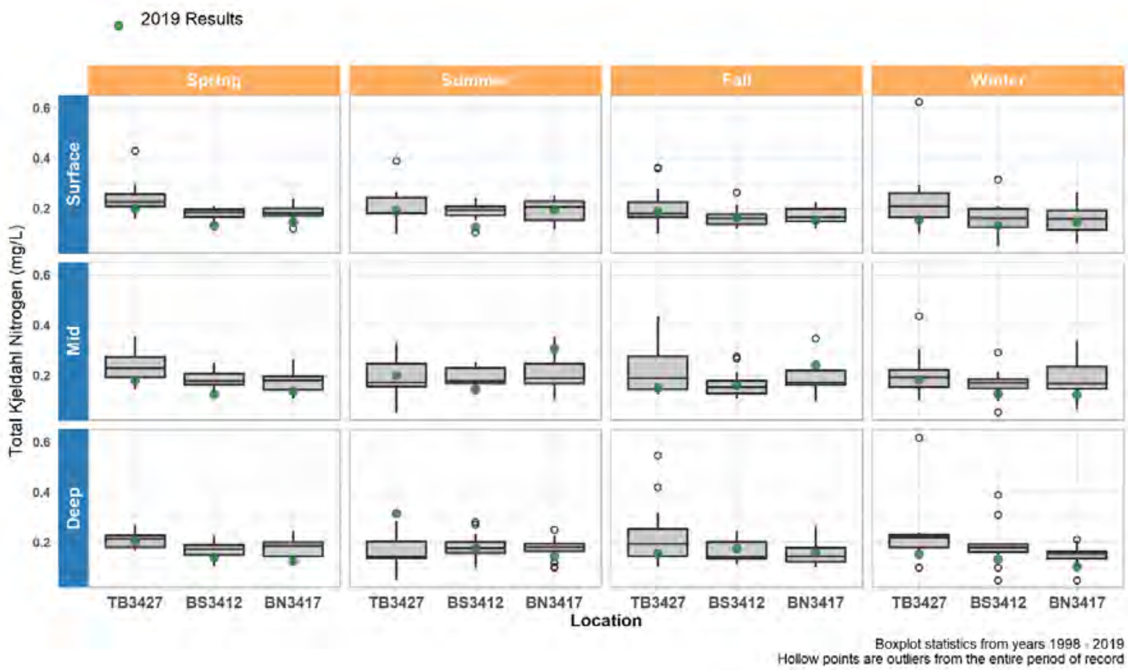
Nitrate-nitrogen (NO_3-N) concentrations also remain low with all 2019 results falling within historical ranges (Figure 45). The highest concentrations are most often observed in the spring and in the main basin locations at depth during periods of stratification. This pattern continued in 2019, with spring values at all sites falling between 0.120 and 0.133 mg/L which is slightly greater than historical means. Summer and fall concentrations in the hypolimnion at BS3412 and BN3417 were similar, ranging between 0.132 and 0.148 mg/L, close to historical means and well below the SDWA threshold of 10 mg/L.

Figure 45: 2019 Nitrate-Nitrogen in Wachusett Reservoir



Concentrations for TKN fell between 0.104 and 0.316 mg/L, within the historical range (Figure 46). Annual concentrations at each site were generally lower than or close to historical means with a notable exception in the summer hypolimnion sample at Thomas Basin (TB3427) where a seasonal high of 0.316 mg/L was recorded. This value is slightly above the ecoregional threshold of 0.3 mg/L, likely due to the higher percentage of native Wachusett watershed water present at that sample station and its proximity to two tributaries (Trout and Waushacum Brooks) which often have high mean TKN values (see Section 3.2.6).

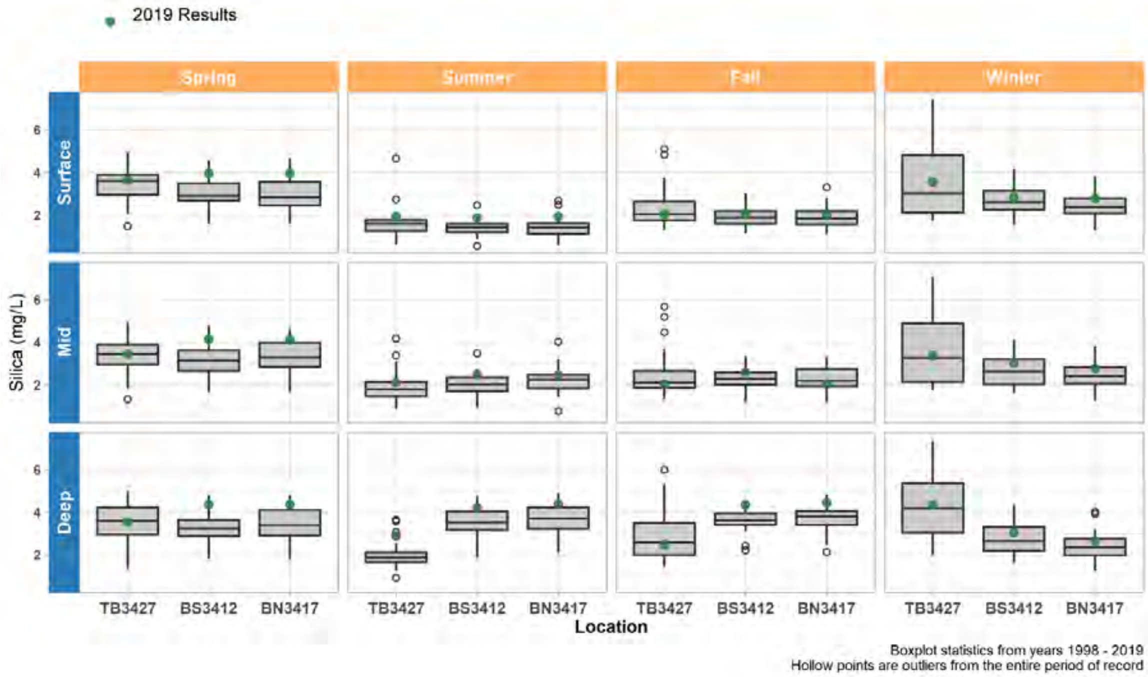
Figure 46: 2019 Total Kjeldahl Nitrogen in Wachusett Reservoir



3.4.5.2 *Silica*

Silica concentrations were between 1.87 and 4.45 mg/L in 2019. While these values are within historical ranges, 86% were greater than historical means and almost half (47%) were above the 75th percentile. Silica was elevated compared to historical data at main basin locations in the spring and summer with values between 1.87 and 4.39 mg/L: an average of 0.56 mg/L higher than historical means. Concentrations reduced slightly in these locations during the fall and winter, but the majority remained above annual means.

Figure 47: 2019 Silica in Wachusett Reservoir

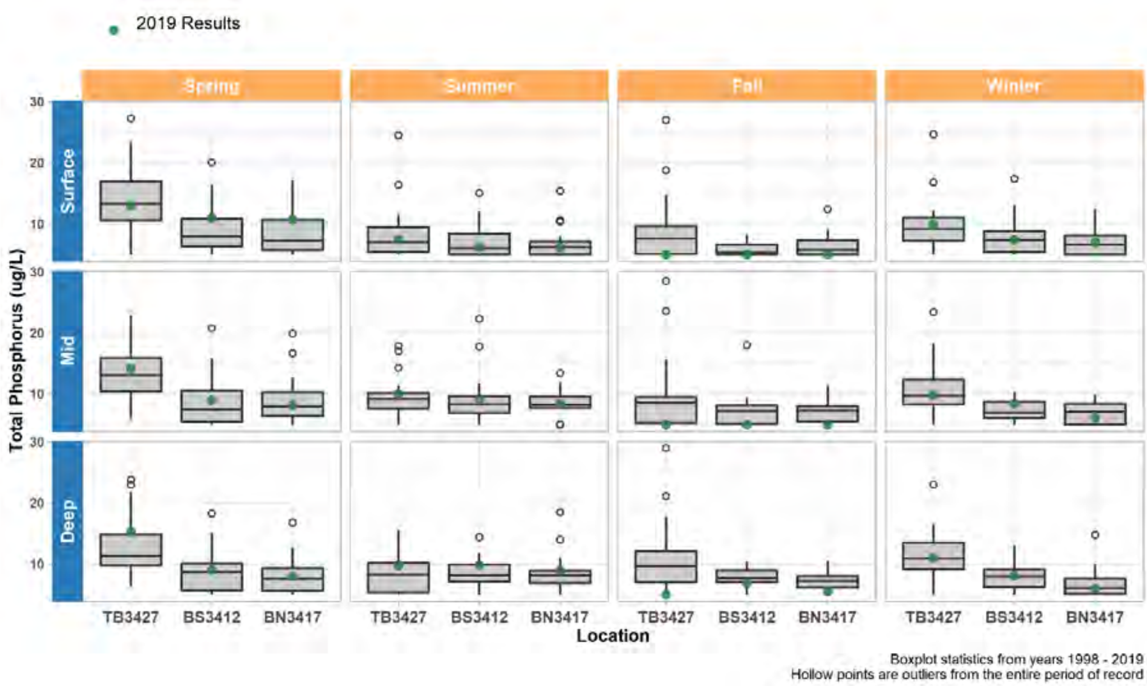


3.4.5.3 *Total Phosphorus*

Total phosphorus (TP) results for 2019 were below the 75th percentile of the historical range (1998 – 2018) with the exception of three sites in the spring: Thomas Basin (TB3427) hypolimnion, and epilimnion samples at both Basin South (BS3412) and Basin North (BN3417), which had slightly higher concentrations. The majority of 2019 results were lower than the 10 µg/L threshold for classification as an oligotrophic water body.

These results reflected expected seasonal patterns with phosphorus transport to the Reservoir during the spring season. Exceptionally high precipitation events in April (see Section 2.1.1) likely contributed to elevated TP observed in spring (May) samples. Phosphorus concentrations were reduced by the summer season and were notably low (78% of results were below the 5 µg/L detection limit) at all sites in the fall. Phosphorus increased again following turnover but remained close to historical means.

Figure 48: 2019 Total Phosphorus in Wachusett Reservoir

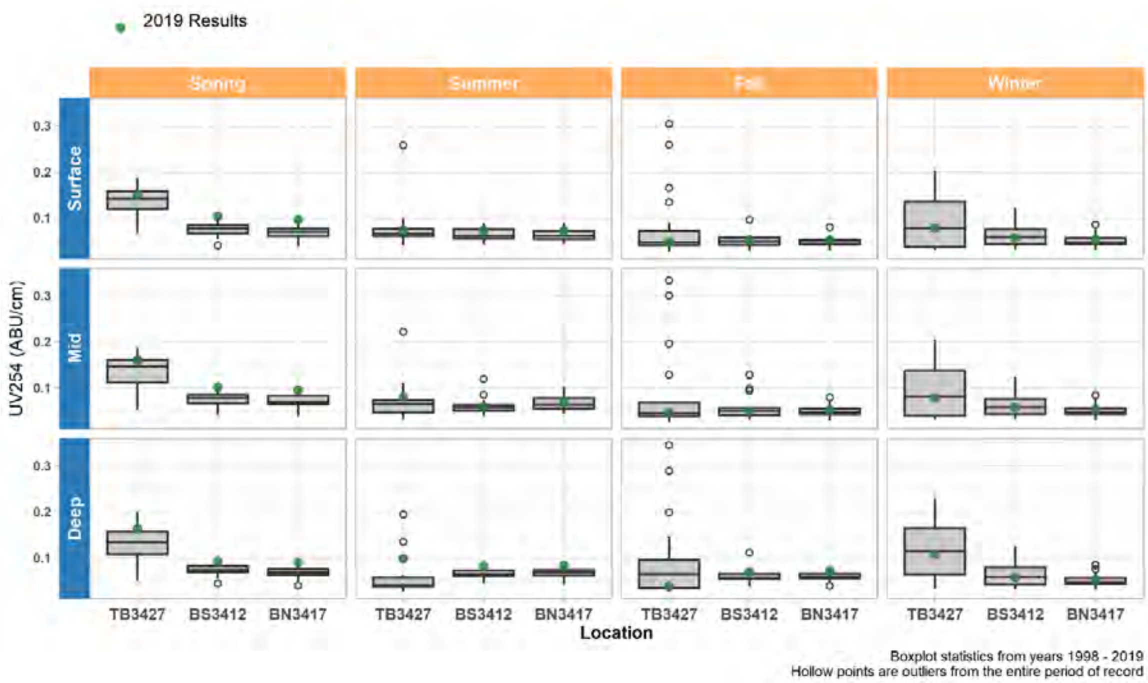


3.4.5.4 *UV Absorbance*

Ultraviolet absorption at 254 nm (UV_{254}) levels in Wachusett Reservoir are highly dependent on the proportion of water received annually from Quabbin transfers, stratification, and intensity and duration of the Quabbin interflow. The spatial and seasonal gradient in UV_{254} can be readily observed across the Reservoir. At Thomas Basin, values are typically higher in the spring and winter, corresponding to lower transfer rates and therefore increased influence of native water contributed from the Stillwater and Quinapoxet Rivers.

Measurements of UV_{254} fell between 0.038 and 0.163 ABU/cm in 2019 which is within the historical range. Values were slightly higher than those previously observed at all depths in Basin South (BS3412) and at Basin North (BN3417) in the spring at all depths and in the summer within the hypolimnion. Levels did not exceed historical ranges but remained elevated at most sites through the summer and reduced to align with historical ranges in the fall and winter.

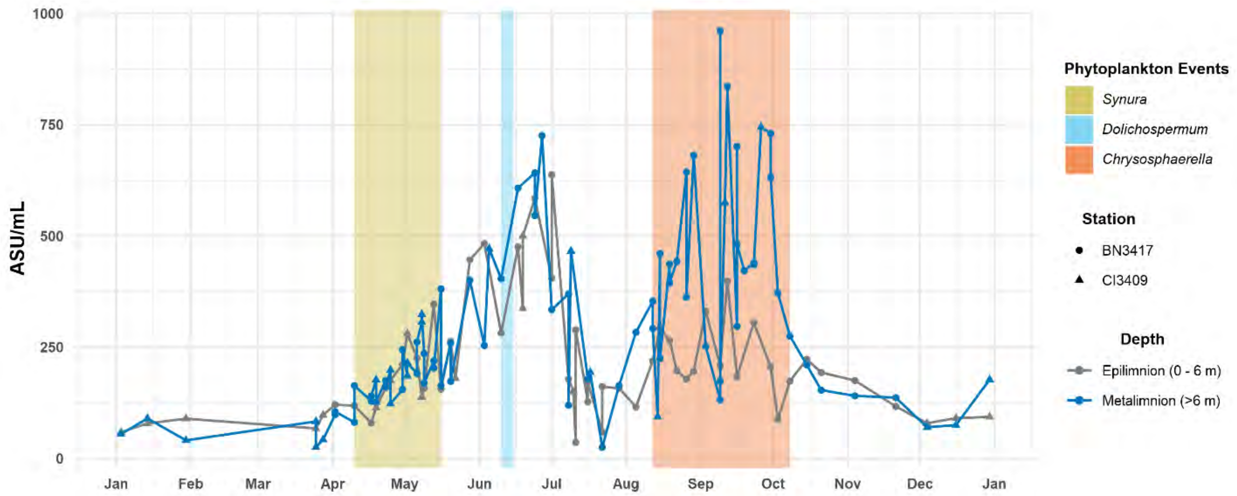
Figure 49: 2019 Wachusett Reservoir UV_{254}



3.4.6 Phytoplankton

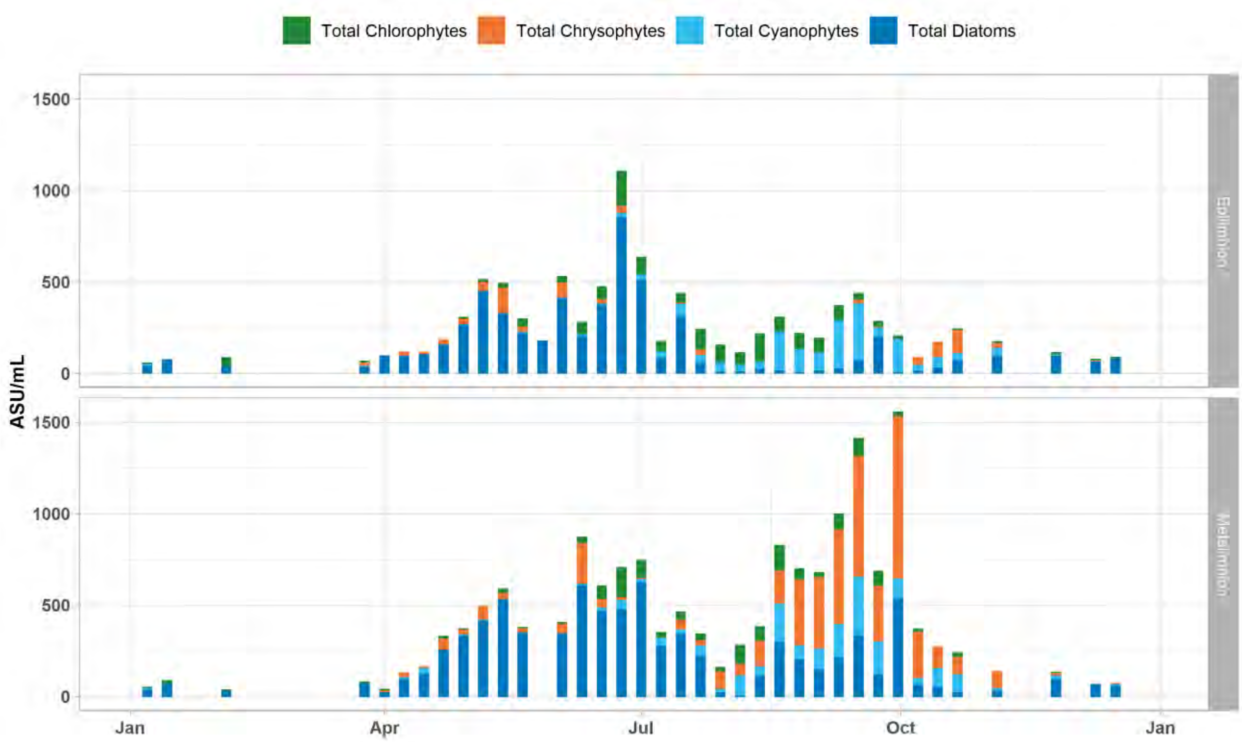
A total of 188 algae samples were collected and analyzed on 68 days during the 2019 season. Sampling from Cosgrove Intake was conducted during the month of January and then suspended due to ice conditions until March 25. Reservoir sampling was initiated April 2 and sampling continued through the end of the year with the last sample collected on December 30. Three notable increases in nuisance phytoplankton genera occurred over this time: a period of elevated *Synura* occurred between April 10 and May 16, an aggregation of *Dolichospermum* was observed in mid-June, and chrysophytes, especially *Chrysosphaerella* were elevated above DCR early monitoring thresholds for an extended period of time between August 12 and October 8 (Figure 50).

Figure 50: 2019 Wachusett Reservoir Phytoplankton Totals
Epilimnion range is 1 – 6 m, metalimnion range is 6 – 15 m



The pattern of succession observed in 2019 followed the seasonal changes in phytoplankton community composition and density typically observed in the Wachusett Reservoir. Community composition by group is displayed in Figure 51.

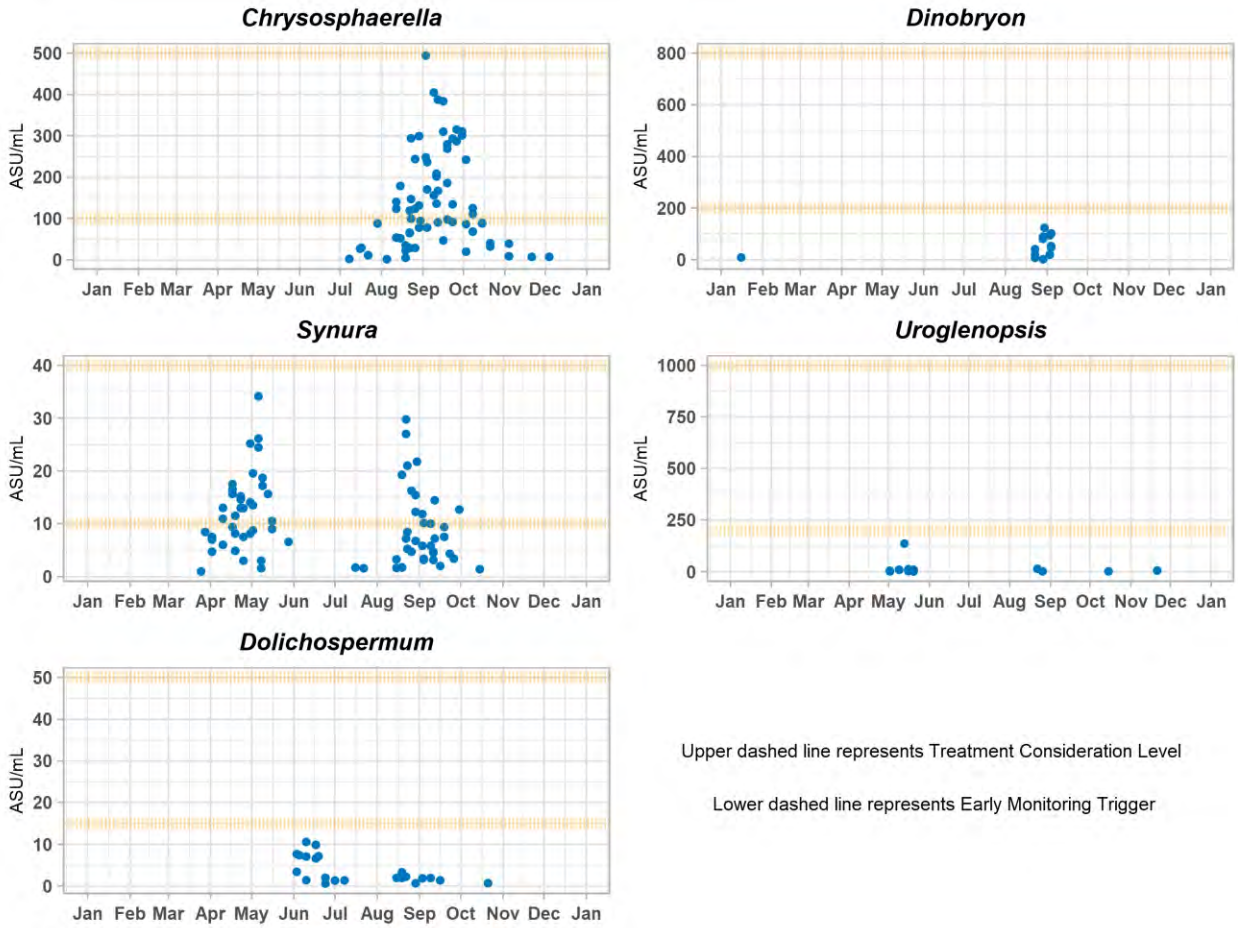
Figure 51: 2019 Phytoplankton Community Composition
Reported as weekly maximums for BN3417 and CI3409



Reservoir phytoplankton densities were low early in the season, with grand totals less than 250 ASU/mL, between January and May. Diatoms were the most prevalent group during these months but did not attain the higher densities typically observed in the spring until late June. The maximum 2019 diatom density of 624.6 ASU/mL was observed June 27 at Basin North at a depth of 7.5 m. The dominant taxa during this period were *Asterionella* and *Cyclotella* which accounted for 55% and 31% of the total phytoplankton community, respectively.

An increase in the chrysophyte *Synura* started in late March and densities above the early monitoring trigger of 10 ASU/mL occurred over a period of six weeks from April 10 through May 16 (Figure 52). After reaching a maximum density of 34.1 ASU/mL on May 6, *Synura* density declined as water temperature increased through the spring. Twice weekly sampling was conducted throughout this period.

Figure 52: 2019 Occurrence of Nuisance Phytoplankton Taxa in Wachusett Reservoir



Elevated *Dolichospermum* was observed within the epilimnion in early to mid-June, but all recorded densities remained below the early monitoring trigger of 15 ASU/mL. A localized aggregation of *Dolichospermum* was also observed during this period in Hastings Cove when surface scum was first observed on a calm June afternoon along approximately 1,000 ft of downwind shoreline. Within 18 hours of the initial observation, the scum had disappeared. Additional coves and shoreline areas around the Reservoir, including all shoreline areas in the North Basin, were surveyed and no masses or scums were observed. All *Dolichospermum* values for collected from Basin North (BN3417) and Cosgrove Intake (CI3409) during this period and the remainder of the year were below early monitoring triggers (Figure 52).

A brief period of low overall phytoplankton density was experienced from July through mid-August. During this time, chlorophytes were the most diverse group. Total densities remained below 250 ASU/mL through mid-August until an increase in chrysophytes, most notably *Chrysosphaerella*.

Chrysosphaerella, which has historically caused problems in the MWRA system by producing undesirable, metallic tastes and odors, first appeared at a depth of 6 m at Basin North (BN3417) on June 24 below countable density. As the Quabbin Interflow was established over the following weeks, the *Chrysosphaerella* population increased and moved down in the water column to the widening interflow layer where low specific conductance and temperatures provide optimal habitat (Figure 52). By August 12, the *Chrysosphaerella* density rose above the early monitoring threshold of 100 ASU/mL and remained above this level, but below the treatment threshold for eight weeks, until October 8.

Unlike historical *Chrysosphaerella* events in Wachusett Reservoir, which typically end abruptly with or before turnover as the Quabbin Interflow breaks down, *Chrysosphaerella* remained present for the remainder of the year. As turnover approached and surface temperatures cooled in early October, *Chrysosphaerella,* which had been mostly isolated in the metalimnion, appeared to become entrained and well distributed in surface waters. For example, on September 30 *Chrysosphaerella* densities at 10 and 12 m were approximately 300 ASU/mL while *Chrysosphaerella* was present below countable density at 3 m. A week later, following a 2 °C decrease in temperature at the surface, the *Chrysosphaerella* density at 3 m was 68 ASU/mL. *Chrysosphaerella* and other chrysophytes which were simultaneously present at lower densities remained present for the remainder of the season and into 2020.

A second period of elevated *Synura* density occurred simultaneous to the fall *Chrysosphaerella* event. *Synura* was present starting in late July and peaked at a density of 29.8 ASU/mL on August 22 (Figure 52). Densities remained above the early monitoring threshold for several more weeks until September 30. Like *Chrysosphaerella*, *Synura* remained present at low density for the remainder of the season.

Overall cyanobacteria levels were lower throughout 2019 than those recorded in recent years. The maximum total cyanobacteria density of 308.9 ASU/mL was recorded on September 12 and the dominant cyanobacteria taxa on that day was *Anathece*. Maximum cyanobacteria totals over the past five years were all greater than this 2019 maximum, with an average of approximately 550 ASU/mL.

3.4.7 Zooplankton

A total of 23 zooplankton samples were collected in conjunction with the 2019 quarterly nutrient sampling program. A subset of these samples – at least one sample from the full water column tows for each station and date – were scanned for invasive species. No invasive species were detected during these analyses. Frequently observed zooplankton in these samples include Cladocerans in the Bosminidae, Daphniidae, Holopedidae (including *Holopedium gibberum*), and Leptodoridae (including *Leptodora kindti*) families as well as an abundance of copepods of the orders Calanoida and Cyclopoida.

3.4.8 Fish

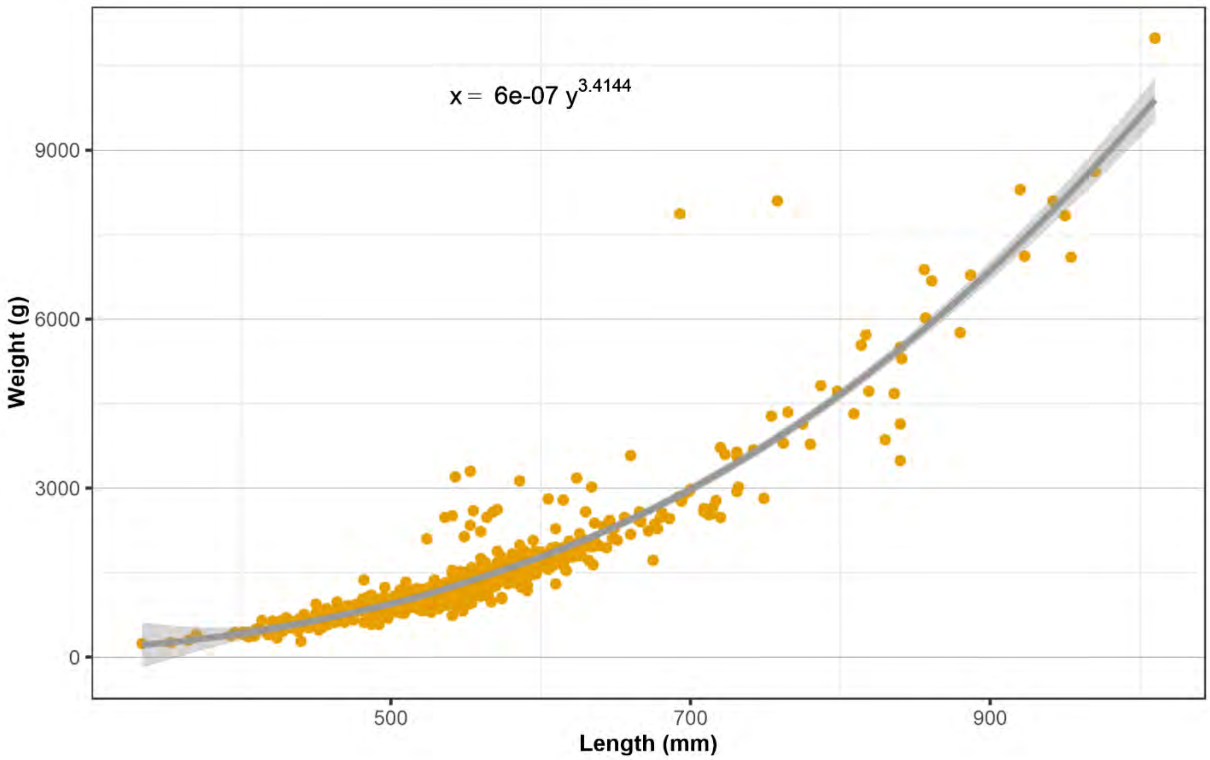
Monitoring programs conducted in 2019 include continuation of the Lake Trout mark-recapture study and investigations for evidence of spawning Rainbow Smelt, an important forage species for Lake Trout.

3.4.8.1 Lake Trout (*Salvelinus namaycush*)

The creel survey reports recommend further study of Lake Trout in Wachusett Reservoir to learn more about the status, life history, and sustainable yield of the Wachusett population. Lake Trout are considered the primary coldwater predator in the Reservoir food web and have become the most popular game fish; however, there is a lack of information about the current population that must be augmented to evaluate the effects of both angling pressure and the population's susceptibility to climate change[111].

As a result, in 2014, MassWildlife and DWSP partnered to initiate a tagging study of Lake Trout in Wachusett Reservoir similar to the ongoing effort at Quabbin Reservoir. This project involves setting gill nets to capture Lake Trout moving onto 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. The length and weight data collected during this study are used to develop a length-weight relationship for the Wachusett Lake Trout population (Figure 53). When a tagged Lake Trout is recaptured, the PIT tag identifies the individual fish, which is then measured, weighed, and released. The changes in weight and length collected from recaptured fish helps develop growth rates for the Wachusett population.

Figure 53: Wachusett Lake Trout Length-Weight Relationship, 2014 – 2019



To date, 654 Lake Trout have been captured during fall sampling efforts between 2014 and 2019, and 600 of these individuals have been tagged and released (Table 33). Thirty-three fish that had been tagged have been recaptured (five fish have been recaptured at least twice). Fifty-four fish have been released without being tagged, harvested for collection of otoliths to aid in age analysis, or considered mortalities.

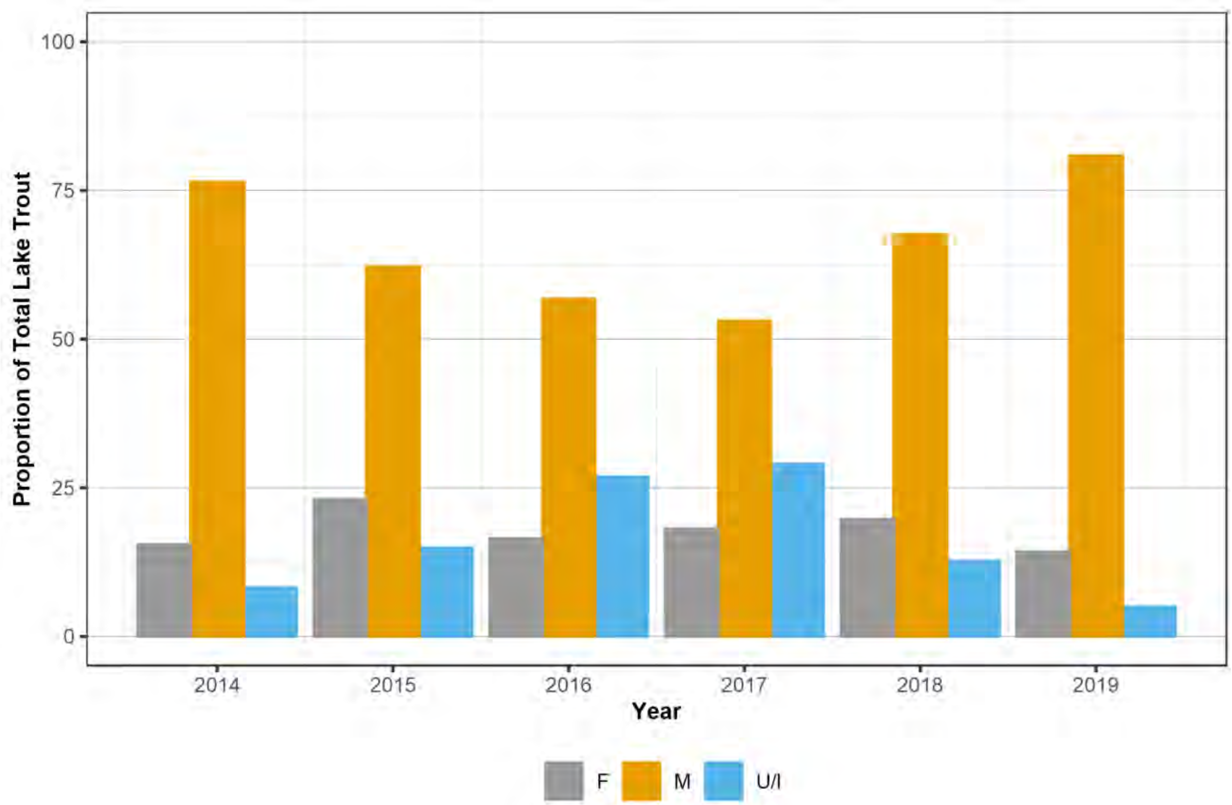
111 Thill, 2014

Table 33: Lake Trout Annual Caught and Tagged Results

Year	Caught	Tagged	Caught Mean Weight (g)	Caught Mean Length (mm)	Not Tagged
2014	110	102	2,067	582	8
2015	161	147	1,427	547	14
2016	67	60	1,312	553	7
2017	83	76	1,016	515	7
2018	71	65	1,402	541	6
2019	162	150	1,422	538	12
Total	**654**	**600**	**1,441**	**546**	**54**

To date, 68% of Lake Trout captured in Wachusett Reservoir were males, 18% were females, and the remainder were immature or of unknown sex. Annually, a higher proportion of the Lake Trout total catch is male (Figure 54). Male Lake Trout may be caught more frequently in gill nets when spawning because they spend more time making multiple passes of the spawning area searching for females[112]. Studies have shown that females likely spend less time on the spawning grounds to find a mate, and thus are less likely to be captured in gill nets[113].

Figure 54: Proportion of Total Lake Trout Catch by Sex



3.4.8.2 *Other Fish Species*

Rainbow smelt (*Osmerus mordax*) are a coldwater fish species with preferences for deep, oligotrophic lakes, and are considered a valuable prey item for salmonids. This coldwater species is another important

[112] Binder et al., 2016
[113] Binder et al., 2014

component of the Wachusett Reservoir food web. In spring of 2019, DWSP and MassWildlife biologists scouted several tributaries and portions of the reservoir shoreline for Rainbow Smelt schools, eggs, and specimens as evidence of spawning activity. Approximately 100 deceased Rainbow Smelt and several unfertilized eggs were found washed ashore between Gate 14 and Dover Point on April 16. On the same day, more deceased smelt were found washed ashore between Gates Brook Cove and Goose Harbor, and west of Clarendon Cove. No fertilized eggs were found, but congregations of Rainbow Smelt may serve as an important indicator of spring spawning. These locations and the nearby tributaries may serve as important spawning locations for Rainbow Smelt and evidence of spawning activity will be sought out at these locations and documented in the coming years.

3.4.9 Bacteria

In 2019, partial ice cover on Wachusett Reservoir prevented sampling for bacteria until early April. Elevated *E. coli* concentrations were observed between the end of April and July near the typical roosting areas in the Southern end of the Reservoir (M1, N1). Bacteria levels remained low for the summer and early fall, with no concentrations above 10 MPN/100 mL. Elevated concentrations of bacteria were again recorded in November and December at the southern end of the Reservoir. The highest result in 2019 at location A3 (closest to the Cosgrove Intake) was 3 MPN/100 mL on September 25. All reservoir transect bacteria results are provided in Table 34.

Table 34: Reservoir Bacteria Transect Results for 2019 – *E. coli* (MPN/100/mL); Sampled at 0.1 – 0.3 m

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 02	1	0	2	2	1	0	2	3	1	12	0	1	1	0	3	3	1	5	3	10	8	4	3
Apr 25	2	0	1	1	3	1	2	1	1	3	0	3	0	0	3	1	0	1	2	2	3	9	18
May 15	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	4	0
Jun 17	1	0	0	0	0	2	0	0	0	0	0	1	0	0	1	1	0	0	2	0	0	22	0
Jul 24	2	3	1	1	1	0	2	1	1	3	0	1	4	1	1	0	1	0	3	2	1	16	18
Aug 28	1	0	0	1	4	10	2	0	3	4	10	0	6	0	0	0	1	0	2	0	0	0	0
Sep 11	1	5	1	0	1	0	1	0	1	9	1	4	6	0	1	5	2	0	0	3	1	0	0
Sep 25	3	3	9	2	2	2	1	0	0	1	1	1	9	2	2	0	1	1	3	3	2	0	0
Oct 08	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	3	8	4	8	0	2
Oct 24	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	1	4	0	0	1
Nov 06	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	5	0	5	16	2	0	3
Nov 19	0	0	1	1	0	0	0	0	0	1	1	1	0	1	0	4	1	4	24	27	15	2	1
Dec 06	0	0	1	1	0	1	1	1	0	1	2	0	0	0	5	1	2	4	11	32	6	12	22
Dec 16	0	1	1	0	1	0	1	0	1	3	2	3	0	0	5	4	5	8	34	34	23	50	26

* Cosgrove Intake

Bacteria samples were collected seven days per week by MWRA staff from Carroll Water Treatment Plant (CWTP) at Walnut Hill in Marlborough to demonstrate regulatory compliance. The SDWA regulations for drinking water require that a minimum of ninety percent of all source water samples contain less than 20 MPN/100 mL fecal coliform. All 365 samples collected at CWTP in 2019 contained less than the standard, with a maximum concentration of 9 MPN/100 mL. Most samples (71%) did not contain any detectable bacteria. DWSP has put considerable time and effort into implementing a rigorous bird harassment program, and the results in 2019 continued to prove that the efforts are effective at maintaining low numbers of both birds and bacteria.

3.5 Macrophyte Monitoring and Management

Non-native aquatic invasive species (also referred to as AIS) such as macrophytes have serious water quality implications including increases in water color, turbidity, phytoplankton growth, and 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.[114] It is updated periodically to reflect changes in AIS composition within and in proximity to the Reservoir.

Table 35. 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. *Myriophyllum spicatum* (Eurasian water-milfoil, subsequently referred to as EWM) and *Cabomba caroliniana* (fanwort) are present in several basins of Wachusett Reservoir and are the primary species managed in this system. Variable water-milfoil (*Myriophyllum heterophyllum*, subsequently referred to as VWM) is also present in several areas of the Reservoir and is managed on a limited basis. Several minute and cryptic AIS including *Glossostigma cleistanthum* (mudmat) and *Elatine ambigua* (Asian waterwort) have also been documented in the Reservoir and are monitored on a routine basis as part of an overall AIS detection and management program.

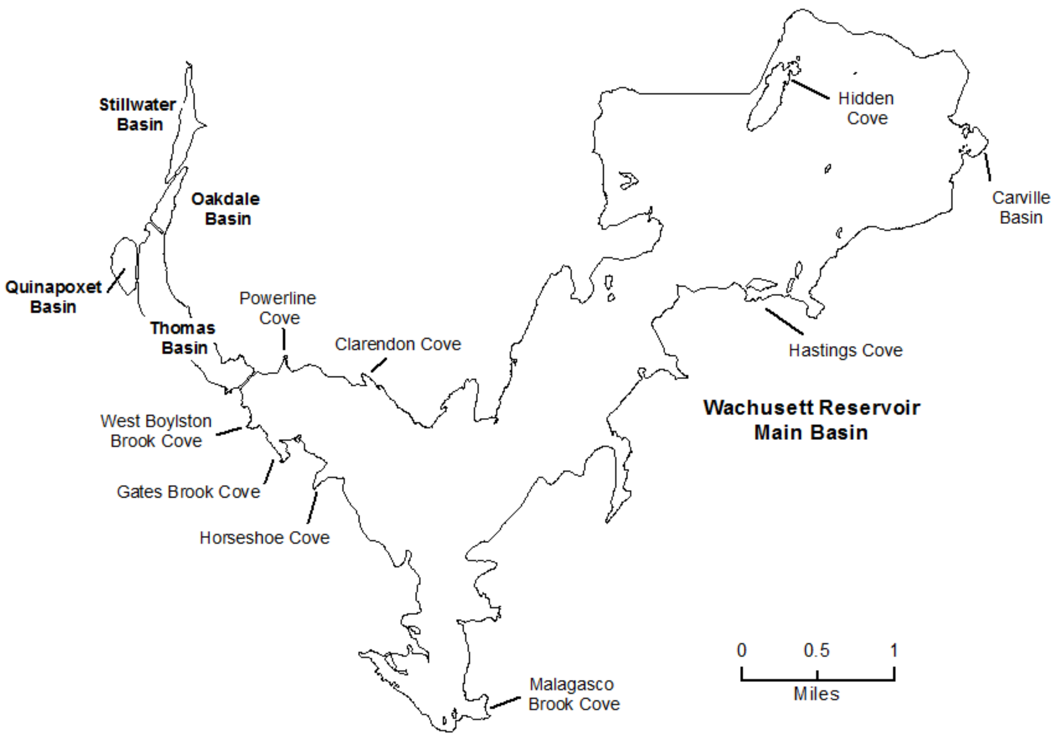
The following sections of this report provide details of AIS management activities undertaken in the Reservoir, elsewhere in the watershed, and near the Reservoir during 2019 and those planned for 2020.

[114] Trahan-Liptak & Carr, 2016

3.5.1 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 DWSP and MWRA to design and implement an invasive macrophyte control program. This program was initiated in 2002 and continues to the present.

Figure 55: Locations of 2019 AIS Management in the Wachusett Reservoir System



Removal of EWM and fanwort via hand-harvesting was initiated in Oakdale Basin in 2002. Despite these efforts, EWM and fanwort have gradually spread throughout Thomas Basin and into several coves of the main basin (Figure 55). 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:

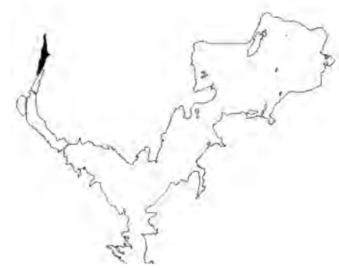
- Deployment and maintenance of floating fragment barriers.
- Hand-harvesting and Diver Assisted Suction Harvesting (DASH).
- Routine scouting within the Reservoir and watershed by the DWSP aquatic biologists to ensure early detection of pioneering infestations.

- 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 Wachusett Reservoir and in surrounding water bodies in 2019.

3.5.1.1 *Stillwater Basin*

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



Location of Stillwater Basin

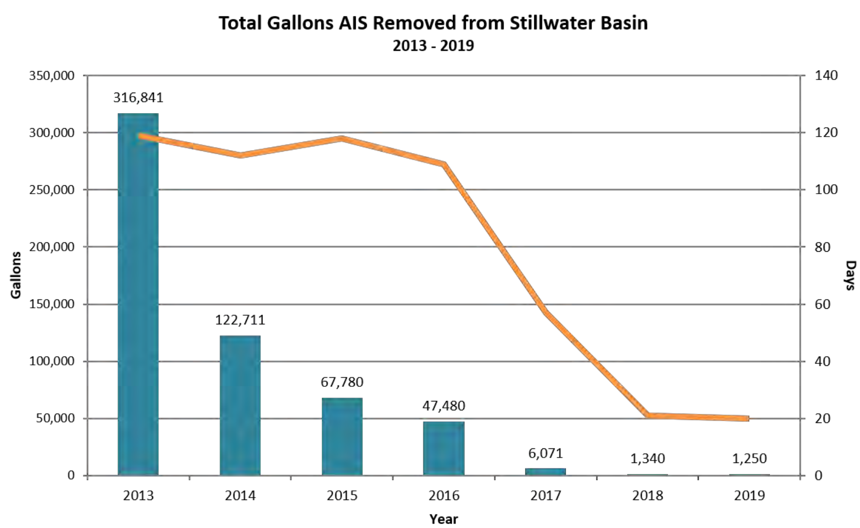
Program Highlights

- 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.

General Management Method

- DASH is conducted between April and November.
- The basin is broken into 3 work zones.
- Each zone is covered by DASH efforts twice per year.
- Fragment barriers are installed 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.

2019 Activities



- 1,250 gallons of invasive biomass were 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 areas.
- An online dashboard linked directly to a custom reporting 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.

3.5.1.2 *Oakdale & Thomas Basin*

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

Program Highlights

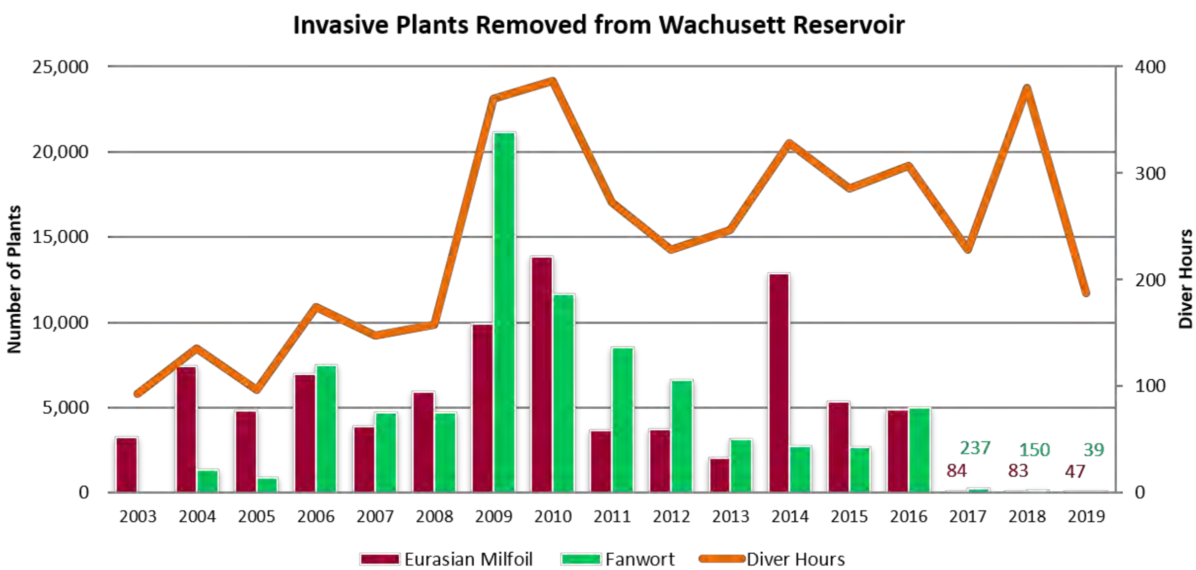
- Substantial decrease in EWM and fanwort realized in 2002, the first year of the project.
- Year-to-year fluctuations in both EWM and fanwort are common.
- In general, plants growing in these two basins exist as single stems or isolated plant beds.

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 and to help quality assurance divers track and ensure success of removal efforts.

2019 Activities



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

- Two complete passes of each basin were conducted; late July/ August and October.
- There was an approximately 64% reduction in total plants removed, with just 39 EWM and 47 FW plants found and removed in 2019. Overall, one AIS plant per littoral acre was harvested.

Future Plans

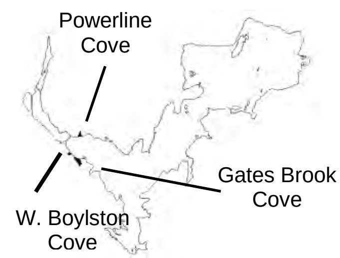
- Management is expected to continue in a similar manner in 2020.

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

Invasive Species	Documented	Management Technique(s)
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

- 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.
- VLM has proliferated in this cove in recent years and has been added as a target species.



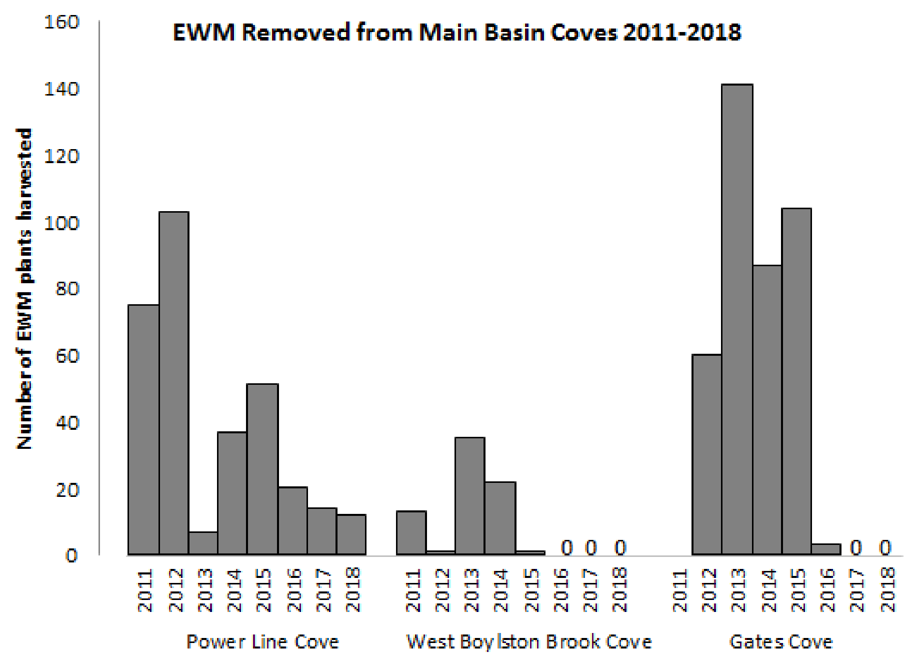
Location of managed main basin coves

General Management Method

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

2019 Activities

- 2019 is the third consecutive year where no EWM plants were discovered in West Boylston Brook Cove or Gates Cove.
- 4 total EWM plants were removed from Powerline Cove.
- 2 days of DASH were used to partially remove a bed of VWM that has increased in Powerline Cove in recent years. 520 gallons of VWM were removed.



Future Plans

- Management is anticipated to continue in a similar manner in 2020.

3.5.1.4 *Quinapoxet Basin*

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

Location of Quinapoxet Basin

Program Highlights

- Management of EWM and fanwort was initiated immediately following discovery in 2016.
- VWM has been present throughout the basin at great densities since the 1980s.

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 railroad bridge between Quinapoxet and Thomas Basins to reduce movement of plant fragments to downstream locations.

2019 Activities

- A similar number of EWM plants were removed in both 2018 and 2019 (105 total).
- Divers found a larger bed of fanwort in 2019 and removed a total of 36 plants.
- DASH removal of VWM was initiated in 2017 and continued in 2019 with removal efforts focused on the inflow channel to reduce the fragmentation and movement of VWM downstream to the main reservoir.
- A total of 26,040 gallons of VWM were harvested over approximately 20 days.

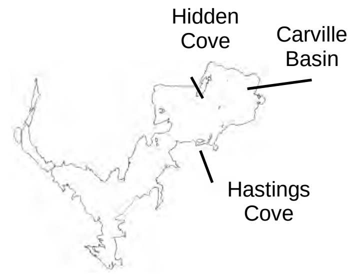
Future Plans

- A substantial increase in effort is anticipated for this basin in 2020. Methods similar to those used in the early years of Stillwater Basin management will be implemented.

3.5.1.5 *Hastings Cove, Carville Basin, and Hidden Cove*

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

Program Highlights



Location of Carville Basin and Hastings and Hidden Cove

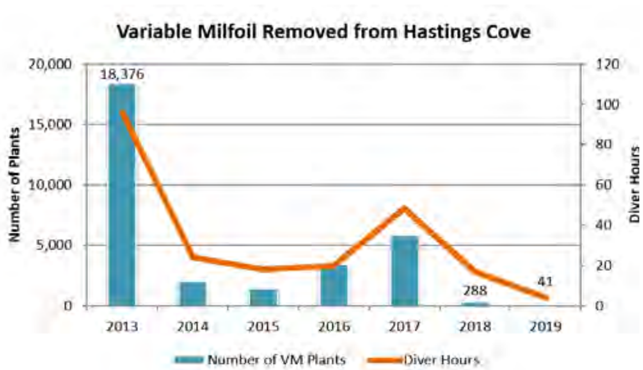
- These areas are the closest to the Cosgrove Intake known to contain VWM. Harvesting was initiated to prevent the spread of these plant beds, reduce the potential for fragments to migrate downstream and impact the intake works, and reduce the spread to other areas of the north basin.
- The VWM bed in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

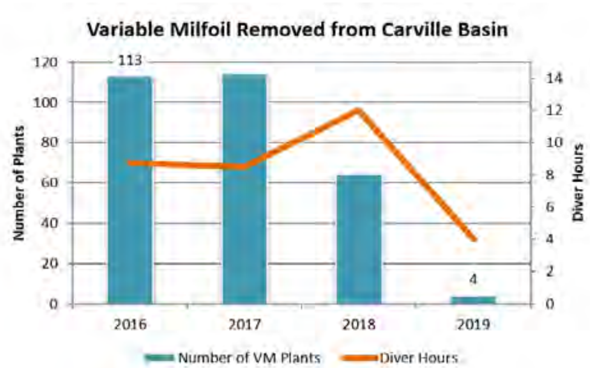
General Management Method

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

2019 Activities

- A total of 39 gallons of VLM were removed from Hidden Cove compared to 460 gallons in 2018.
- Reductions in VLM for both Hastings Cove and Carville Basin continue with just 41 and 4 plants removed from each area, respectively.





Future Plans

- Management is anticipated to continue in a similar manner in 2020.

3.5.1.6 *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 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. 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. No EWM plants were discovered during these surveys in 2019.

Table 36. Locations of EWM in Outlying Reservoir Areas
2013 and 2015 are not included as no AIS were observed in these areas during that period

	Number of EWM Plants Removed						
Location	**2011**	**2012**	**2014**	**2016**	**2017**	**2018**	**2019**
Andrews Harbor	–	–	–	1	–	3	–
Clarendon Cove	–	–	–	1	–	–	–
Flagg Cove	–	–	–	1	–	–	–
Horseshoe Cove	4	6	–	1	–	–	–
Malagasco Brook Cove	–	–	1	–	–	–	–

3.5.2 Wachusett Reservoir – Additional Management Activities

3.5.2.1 *Contracted Aquatic Macrophyte Surveys*

2019 is the seventh year in a row that MWRA has contracted with ESS Group, Inc. to carry out point-intercept surveys of DWSP/MWRA source and emergency reservoirs. No new AIS were discovered in Wachusett Reservoir during the 2019 survey and increases in distribution and density were not observed, with the following exception. *Glossostigma cleistanthum* (mudmat) was observed at seven additional sites in 2019, the third year of increases. Increased or new growth was observed at 36 of the 57 identified locations.

3.5.2.2 *Phragmites Management*

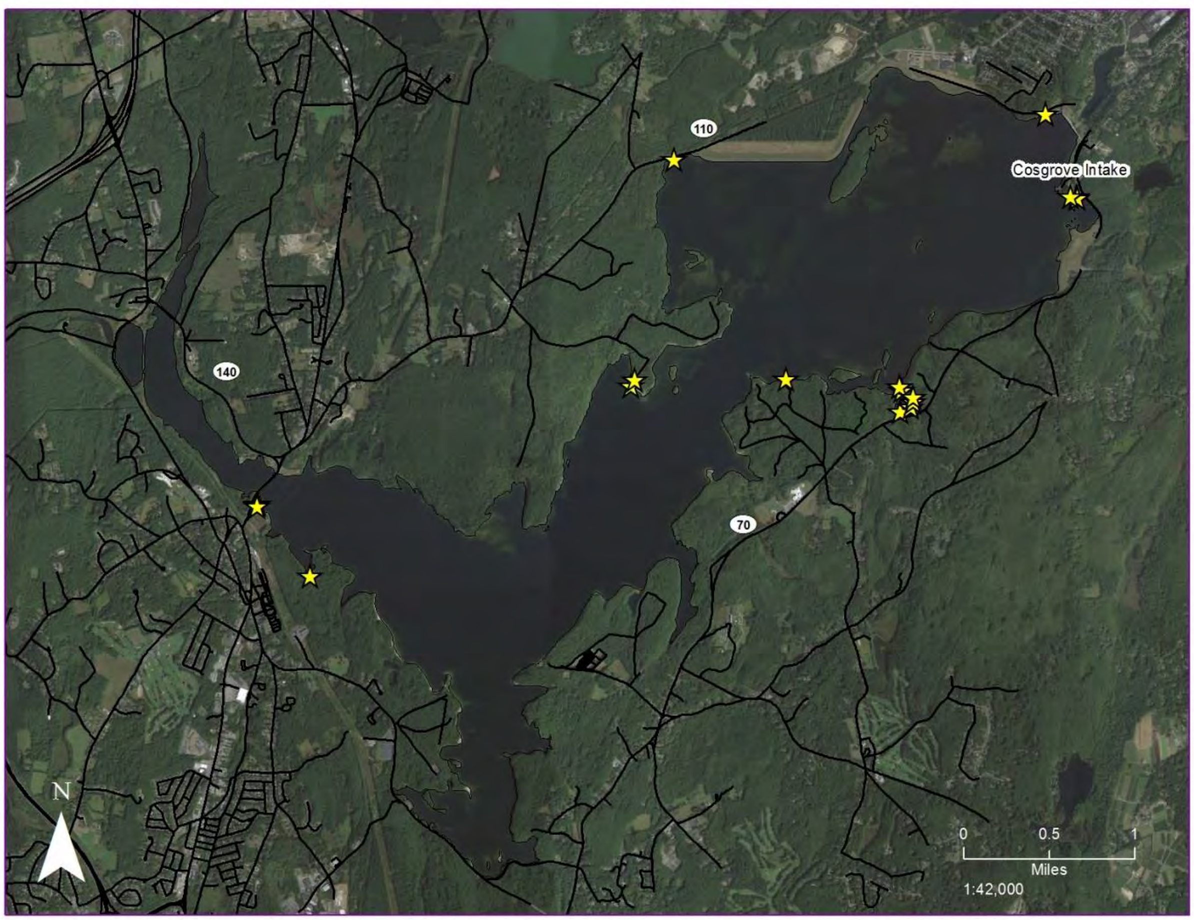
DWSP staff manages 17 stands of *Phragmites australis* (common reed) around the Wachusett Reservoir shoreline (Table 37, Figure 56). *P. australis* stands are primarily managed by cutting stems and hand-pulling root and rhizome systems. The primary method for tracking progress of *P. australis* removal is photographic documentation. A full directory of *P. australis* photographs is stored on the DCR DWSP shared network drive. In general, the stands are managed monthly from June to October. Management actions are timed to prevent the mature stands from producing seeds, reduce the above ground biomass of each stand, and reduce underground energy stores of mature stands. In 2019, *P. australis* was managed and photographed on June 17, July 16, August 20, September 18, and October 16.

Additional background on *Phragmites* management at Wachusett Reservoir can be found in *Phragmites in Wachusett Reservoir 2017*. A detailed report of *Phragmites* management during 2019 can be found in the internal document *2019* Phragmites *Shoreline Management*.

Table 37: *Phragmites australis* Stands Around Wachusett Reservoir

Stand ID	Initial Area (ft^2)	First Documented	Management Method
Boat Cove A	1071	2013	Cutting
Boat Cove B	1640	2013	Cutting
Boat Cove C	316	2013	Cutting
Gates Brook	1314	2014	Cutting
Hastings Cove A	422	2009	Cutting
Hastings Cove B	6034	2009	Cutting
Hastings Cove C	1635	2009	Cutting
Hastings Cove D	504	2009	Cutting
Hastings Cove E	190	2009	Cutting
Hastings Cove F	146	2009	Cutting, Hand pull
Rainbow Cove	896	2009	Cutting
Tahanto Point A	860	2016	Cutting
Tahanto Point B	511	2016	Cutting, Hand pull
Storm Water Basin	19	2017	Cutting
Gate 3	200	2013	Cutting
Rock Piles	112	2018	Cutting, Hand pull
Dam	6	2018	Cutting, Hand pull

Figure 56: *Phragmites australis* Stands Around Wachusett Reservoir



General management method

- Watershed Maintenance Staff, Aquatic Biologists, and DCR NR perform all management.
- Management takes place during the growing season, generally June through October.
- Each stand has a unique ID for tracking throughout the management season and over subsequent seasons.
- Stands are cut to the surface of the water or below using line trimmers and loppers.
- Root and rhizome systems of small stands are pulled by hand.
- Pre and post management photographs are taken before and after each cut.

Program highlights

- Middle and end of growing season stand height is consistently reduced compared to non-management years.
- New *P. australis* location found between Tahanto Point A and Tahanto Point B.
- After hand pulling, no regrowth found at Tahanto Point B.
- Possible that two stands have been completely removed since management began in 2017, but continued monitoring is necessary.
- Cuts completed in 2019 for established stands: Hastings Cove, Boat Cove, Tahanto Point, Rainbow Cove.
- Hand pulling effort at small expansion locations and edge of stands: Dam, Rock Piles, Boat Cove, Hastings Cove, Gates Cove.

Future plans

- Management is anticipated to continue in a similar manner in 2020.
- Physical barrier methods may be employed at smaller stands.

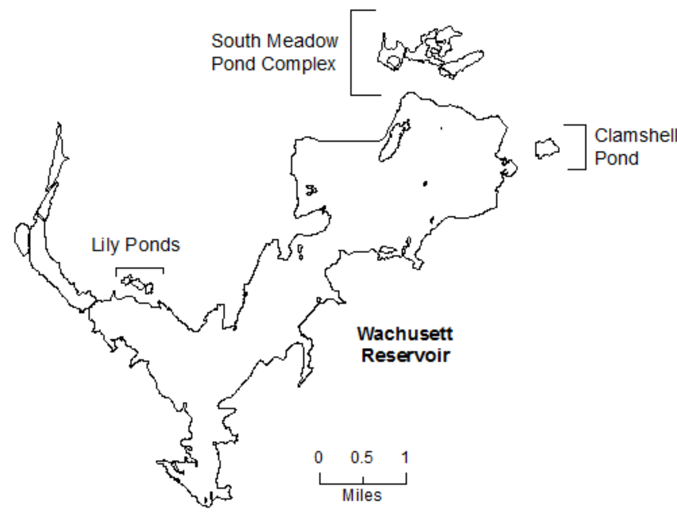
3.5.3 Supplemental Invasive Macrophyte Control Activities

Additional activities were conducted in 2019 outside of Wachusett Reservoir in conjunction with the main components of the in-reservoir invasive control program. Details of these activities are presented below.

3.5.3.1 *Management of AIS Outside of Wachusett Reservoir*

In recent years AIS have been discovered in several local ponds (Figure 57). 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.

Figure 57. Locations of local ponds managed for AIS



South Meadow Pond Complex

In August 2010, the invasive macrophyte *Hydrilla verticillata* (Hydrilla) was discovered in South Meadow Pond in the Towns of Clinton and Lancaster. 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 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 2019 and now includes management of *Potamogeton crispus* (curly-leaf pondweed) which was discovered in 2015.

Management of *Hydrilla* focused on whole-pond treatments using fluridone, a systemic herbicide, for several years. Biomass was greatly reduced and a transition to spot-treatment and contact herbicide use was made for 2012 through 2017. Tuber densities decreased until no tubers were found during surveys in 2015. In 2016 tuber densities rebounded and growth of *Hydrilla* was observed to expand in several areas. As a result, DCR transitioned back to whole-pond treatment using fluridone starting in 2018.

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.

The entire littoral area of the South Meadow Pond Complex was treated with fluridone three times; initial treatment took place on June 28 followed by booster treatments on August 14 and October 7. Results of fluridone concentration analysis in each basin showed a range of concentrations of less than one to 3.0 ppb, with an average of 1.5 ppb to 1.8 ppb for the three sampling rounds performed. The contractor claims that the concentration is likely higher at the sediment interface where herbicide interaction with plants is greater. Tuber density rose slightly from 0.14 tubers/m^2 in 2018 to 0.18 tubers/m^2 in 2019 but *Hydrilla* biomass observed by DCR biologists appeared to be reduced.

Management of *P. crispus* in 2019 was not possible due to contract timing.

Clamshell Pond

Clamshell Pond is located approximately 1,300 ft (400 m) from the Wachusett Reservoir shoreline, east of Cosgrove Intake. 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 in abundance.

Egeria densa was treated with the contact herbicide diquat in June 2018. DWSP biologists continued to monitor the pond through 2018 and 2019. Despite numerous surveys including a snorkel survey in July 2019, growth of *Egeria densa* has not been detected since the initial treatment. Therefore, a treatment was not conducted in 2019. *Trapa natans* have also been greatly reduced with DWSP biologists finding and removing only two plants during 2019. Volunteers from the Raucher Farm Management Subcommittee also surveyed the pond in August and did not find any *Trapa natans*. Monitoring of this pond will continue in 2020 and management will be conducted as needed.

Lily Ponds

Two invasive species, *Najas minor* (European/Brittle Naiad) and *M. 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), as well as treatment utilizing state-approved and 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.

In 2019, *N. minor* was observed in each of the three ponds. Isolated areas of moderate/dense growth were observed in the west and east pond while *N. minor* was observed along the majority of the middle pond's shoreline. A total of 4.4 acres across all three ponds were therefore treated using diquat on September 10. Follow-up surveys showed that the treatment was effective, as no signs of living *N. minor* were observed. Notably, 2019 is the fourth year that *M. spicatum* has not been observed.

4 Conclusions and Recommendations

4.1 Wachusett Tributary Water Quality

Routine tributary monitoring results for bacteria and turbidity in 2019 were consistent with historical data and demonstrate continued adherence to drinking water quality standards, with the exception of occasional individual bacteria concentrations above single sample regulatory limits. The occasions when bacteria levels at individual tributaries were elevated above Class A surface water standards were either due to storm water runoff events or from known bacterial sources, for which management actions have been ongoing (agricultural operations) or are otherwise not feasible (avian wildlife). There were no new sources of bacteria or turbidity identified in 2019 which warrant additional investigation or management action.

Routine tributary and groundwater monitoring results for dissolved salts and specific conductance in 2019 continue to be elevated across several Wachusett watershed subbasins. Gates Brook and West Boylston Brook are likely suffering from aquatic life water quality impairments due to chronic elevated concentrations of Cl. Preliminary findings by DWSP as well as UMass researchers have confirmed that roadway deicing materials (principally rock salt) are the primary cause of elevated specific conductance and Cl in the tributaries and Reservoir.

Elevated Cl/conductivity in the Wachusett Reservoir and tributaries is a high priority concern for DWSP and is the focus of additional research and planning efforts at DWSP and UMass. Mitigation strategies are still being developed; however, some measures have already been implemented where feasible. For example: a training by Baystate Roads was provided (funded by MWRA) to watershed town DPW employees and DWSP and MWRA staff in order to educate road maintenance crews about salt application reduction practices; $100,000 was included in the proposed FY2021 DWSP budget to fund grants for watershed communities to obtain new technologies that would help reduce salt applications. This problem is not expected to be resolved quickly, as dissolved salts do not readily break down in the environment and they have accumulated in soils and aquifers. Expanded monitoring for Cl and specific conductance throughout the Wachusett watershed may be necessary to better target mitigation measures and track progress. Any changes to the current sampling strategy for specific conductance and Cl will be informed by the pending recommendations of the UMass and DWSP investigations and in consultation with MWRA.

Routine tributary nutrient monitoring results for 2019 were consistent with historical data and demonstrate continued adherence to drinking water quality standards. Elevated nitrogen loading is occurring in West Boylston Brook and Gates Brook due to urban/suburban development and stormwater runoff. Although they have less developed watersheds, Malagasco and Malden Brooks also have somewhat elevated concentrations of nitrogen, likely due to septic systems, agriculture, or perhaps local ecological characteristics that have yet to be fully understood. While nitrogen concentrations for these four tributaries are elevated above ecoregional background levels, they are well below regulatory standards and are not sufficiently elevated to be a water quality concern.

Phosphorous concentrations in Wachusett tributaries are generally low, however a few of the smaller tributaries had mean concentrations in 2019 that were slightly elevated compared to ecoregional background concentrations; French Brook was most notable, with a mean annual TP concentration of 44 µg/L. There are no obvious multi-year trends in TP for any of the tributaries, and with only 12 samples taken per tributary each year, the annual means can be heavily influenced by one or two elevated results. If time and resources allow, additional investigations could be conducted to confirm sources of excess nitrogen in Malagasco and Malden Brooks and sources of excess phosphorous in French, Malagasco, and Trout Brooks.

Total organic carbon (TOC) and UV_{254} levels in Wachusett Tributaries for 2019 were the lowest since 2013. The low levels observed in 2019 were not reflective of any downward trend, but rather interannual variation. Although the organic carbon levels observed in Wachusett tributaries are considered normal for streams and rivers, any organic carbon in raw drinking water sources is considered undesirable because it can be a precursor to several disinfection byproducts that are harmful to human health and have regulatory limits. If time and resources allow, it may be worthwhile to investigate the organic carbon sources within the tributaries with the highest organic carbon concentrations (Malagasco, Trout, French, and Waushacum Brooks). Possible management actions to reduce organic carbon delivery to tributaries can be explored once specific tributary organic carbon sources and types are better understood. There are few opportunities for DWSP to implement management programs that address nutrient pollution from developed areas. Without numerical nutrient criteria for nutrients in Wachusett watershed tributaries the most effective regulatory drivers to control nutrient pollution lie in the MA Wetlands Protection Act, MS4 requirements of the federal NPDES program, and the Watershed Protection Act.

4.2 Wachusett Reservoir Water Quality

Overall, results of the Wachusett Reservoir monitoring program were consistent with historical data and demonstrate continued adherence to high drinking water quality and aquatic life use standards. The limited number of results which were characterized as elevated or fell above historical ranges were only slightly elevated beyond the 75th percentile, were isolated events, or can be tied to specific biologic factors such as diatom production and silica availability.

Specific conductance was lower in 2019 than the prior two years; however, it remains elevated compared to historical values. This trend continues to be a concern, as it is in the watershed as a whole. Enhanced monitoring and mitigation programs (see Section 4.1) are being implemented to address this trend and monitoring of specific conductance within the Reservoir will continue to provide a reference for detection of downstream changes resulting from these modifications within the watershed.

In the past 100 years 90% of United States drainage basins have exhibited changes in alkalinity, a trend which is most prevalent in the more developed eastern and midwestern portions of the country[115]. Alkalinity in the Reservoir has displayed an increasing trend over the past 30 years, with a steady increase since 2015. Increases in alkalinity are often attributed to recovery from acid rain; however, may also be linked to salinization. Considering the increases in Cl and specific conductance in the watershed and Reservoir, it is likely that the trend in alkalinity is also due to salinization and other anthropogenic processes.

Silica is commonly removed from the water column in the spring and fall by proliferation of diatoms in the reservoir. Limited production of diatoms in the spring and fall during 2019 (Section 3.4.8) may have allowed for increased silica availability in 2019. A similar pattern was observed in 2018 when diatom production was also limited while silica was lower in 2017 following a spring diatom proliferation.

Results of routine water quality profiles were similar to historical trends and continued to provide guidance for phytoplankton sampling, detection of the Quabbin interflow, and stratification. Monitoring

[115] Kaushal et al., 2005

results of these conditions were also similar to previous years with the exception of extended periods of elevated chrysophytes as detailed in Section 3.4.6.

4.3 Proposed Wachusett Watershed Monitoring Programs for 2020

4.3.1 Hydrological and Climate Monitoring

There are no proposed changes to the hydrological and climate monitoring programs. The pilot Mayfly station at Waushacum Brook will continue to operate in tandem with the HOBO device. Plans are in place to purchase and deploy additional Mayfly units as existing HOBO units near the point of battery depletion failure.

Monitoring Element	Current Program	Proposed Changes
Real-time flow monitoring	10 tributaries (3 by USGS)	No change
Precipitation	2 USGS Stations, 2 NOAA Stations	No change
Snowpack (seasonally)	Weekly, 6 locations	No change
Groundwater Levels	Monthly manual + Automated (4-hr intervals @ Rt 140 Well	No change

4.3.2 Groundwater Quality Monitoring

The expansion of groundwater monitoring was largely successful during 2019 and will continue without modification. If additional monitoring wells are discovered, they may be investigated for possible inclusion in the routine groundwater monitoring program.

Monitoring Element	Current Program	Proposed Changes
Groundwater Quality (WATWEL)	Monthly – 8 wells for specific conductance and temperature; 7 wells for Cl	No change

4.3.3 Tributary Monitoring

Routine tributary monitoring (WATMDC and WATTRB) will continue at the same frequency as in prior years. No changes are proposed for turbidity monitoring. DWSP biologists have recommended adding alkalinity to the suite of parameters monitored in project WATMDC due to the recent rising alkalinity trend observed in Wachusett Reservoir. Bacteria monitoring at the temporary sample location MD75.4 has been discontinued, as the source of elevated bacteria in Gates Brook was confirmed and additional monitoring is no longer justified on a routine basis. This location may be monitored occasionally in order to confirm that no other bacteria source is the cause of elevated *E. coli* in Gates Brook.

Monitoring Element	Current Program	Proposed Changes
Nutrients, Cl, UV absorbance, TSS (WATMDC)	Monthly, 10 primary tributaries + Quabbin Transfer (MDS1)	Add alkalinity analysis
Bacteria and Turbidity (WATTRB)	2x per month, 18 Locations	Drop location MD75.4
Field parameters (water temperature, pH, specific conductance, pH, stage)	3x per month in conjunction with other projects	No change
Real-time conductivity monitoring (USGS or DWSP – using Mayfly)	3 USGS, Waushacum Brook	Possibly substitute Mayfly for HOBO at West Boylston Brook or Trout Brook

4.3.4 Special Projects and Other Sampling

4.3.4.1 *Short-term Forestry Monitoring*

Monitoring of forestry operations for short-term water quality impacts will continue at the same frequency as in prior years, dependent on harvest stage. All new data are now being input into the EQ Water Quality database, which will continue until upgrades are completed in the Forestry database which will facilitate water quality data entry. Final summary and assessment reports will only be written for lots with mean turbidity levels in excess of 5.0 NTU during any harvest phase.

4.3.4.2 *Long-term Forestry Study*

Monitoring for long-term effects of water quality at forestry locations will continue with routine monthly samples during dry weather and targeted storm sampling for large events, if feasible. New project work for 2020 will include the installation of a weir at the Princeton location in order to obtain more accurate flow data. The completion of a preliminary summary report for the first six years of monitoring was anticipated for 2020, however this may be delayed in order to allow for sufficient time to collect additional flow data at the Princeton weir and recalculate historical flows. The sale of timber at the Princeton site and subsequent harvest will proceed as soon as feasible once sufficient flow data have been collected at the new weir.

4.3.4.3 *Quabbin Transfer (Shaft-1) Monitoring*

Nutrient and field parameter monitoring of Quabbin transfer water (Shaft 1 - MDS1) will continue in conjunction with routine tributary nutrient monitoring (when flowing). First flush samples will be collected when possible to capture water quality impacts that may arise due to prolonged residence times within the aqueduct. This information is extremely useful in understanding the influence of Quabbin water on Wachusett Reservoir water quality.

4.3.4.4 *Follow-up Bacteria Monitoring and DNA Fingerprinting*

Follow-up samples for bacteria (*E. coli*) at routine sampling locations will be conducted 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. Additional locations may be sampled if elevated bacteria levels persist for extended periods of time for unknown reasons. If upstream tracking cannot determine the cause of elevated bacteria levels samples may be sent in for DNA analysis.

4.3.4.5 *Flow Targeted Nutrient Samples*

Supplementary nutrient samples may also be collected from routine nutrient monitoring stations when specific flow conditions are present that have been under-sampled in the past.

4.3.4.6 *Groundwater Isotope Sampling*

Stable isotope sample collection will continue at the seven routine groundwater monitoring wells that allow for pumping. These samples are delivered to Dr. David Boutt (UMass) for analysis.

4.3.4.7 *Tributary Storm Sampling*

Storm sampling will remain on hold except for extreme events (>2 inches of predicted rainfall). Once the accumulated storm sampling data has been analyzed a determination will be made about how best to continue this program.

4.4 Proposed Reservoir Monitoring for 2020

Reservoir monitoring programs will continue as carried out in 2019. The majority of these programs have a well-established framework which provide for flexibility in response to current environmental conditions. These programs are detailed elsewhere in this report and briefly described below, but overall no changes are proposed.

Temperature, specific conductance, dissolved oxygen concentration, percent oxygen saturation, chlorophyll *a*, phycocyanin, turbidity, and pH profiles as well as Secchi disk transparency will be measured at Basin North (BN3417) in conjunction with weekly or twice weekly plankton monitoring. More frequent profiles will be collected when necessary to document changing conditions in the Reservoir. Nutrient samples will be collected quarterly at Basin North (BN3417), Basin South (BS3412), and Thomas Basin (TB3427) using standard methodologies described in Section 2 of this report. Quarterly collection of zooplankton for invasive species screening and identification of common zooplankton present in the Reservoir will also continue.

Monitoring and management of AIS within Wachusett Reservoir and in ponds near the Reservoir will continue on an as-needed basis in 2020. Surveys for AIS in ponds within the Wachusett watershed will also be undertaken during 2020.

The Lake Trout mark-recapture study is anticipated to continue for a sixth year in conjunction with MassWidlife during the fall spawning season.

Movement of water and contaminants through the Reservoir remains 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.

Monitoring Element	Current Program	Proposed Changes
Reservoir Profiles	Weekly May – Sept. at BN3417 or CI3409 Biweekly Oct – April at BN3417 or CI3409 Increased frequency and/or locations as needed in response to thresholds for specific genera.	No change
Secchi Disk Depth		No change
Phytoplankton		No change
Nutrients	Quarterly	No change
Zooplankton	Quarterly	No change
Fish	Fall Lake Trout spawn and other seasonal observations as appropriate	No change
Macrophytes	Surveys and contractor monitoring throughout the growing season	No change
Bacteria	At least monthly at 23 locations	No change
Stormwater Basins	Monthly	No change

Alkalinity has not been measured in watershed tributaries since 2012. Considering the increasing trend in Reservoir alkalinity and potential links to Cl increases, further investigation to identify any similar trends and/or sources is warranted. It is recommended that sampling for this parameter be reinstated as part of routine tributary monitoring.

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Appendix

Figure A-1: Hydrographs for Small Tributaries in Wachusett Watershed During 2019

Discharge data are interpolated from measurements collected at 15-minute intervals.

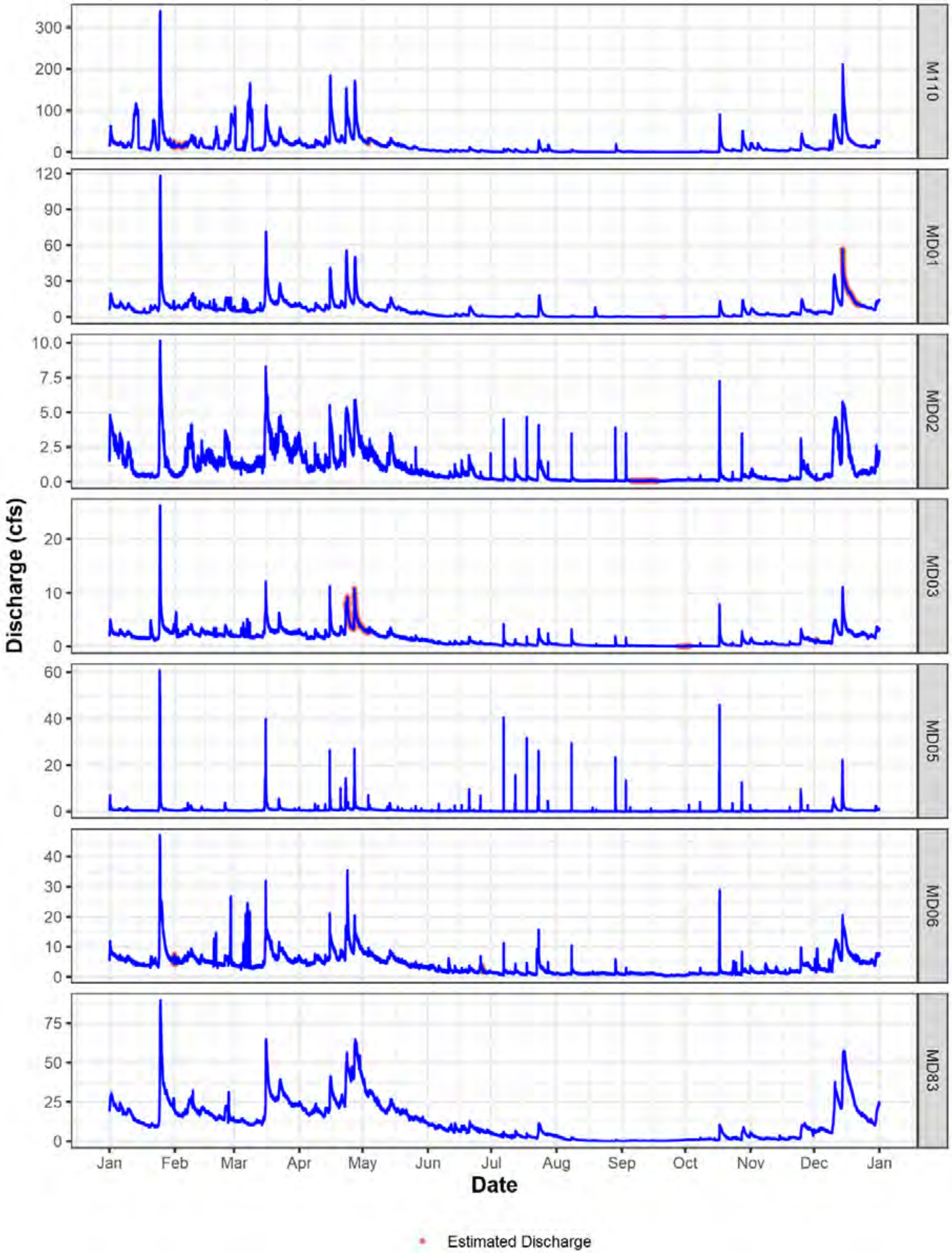

Table A-1: Water Quality Standards/Criteria Applicable to Wachusett Watershed Surface Waters

Parameter	Standard/Criteria	Regulatory reference	Threshold Value	Notes
Alkalinity	Aquatic Life – Freshwater (Chronic)	EPA	Minimum 20 mg/L	Except where is naturally lower; then the criterion cannot be lower than 25% of the natural level
Ammonia-nitrogen	Aquatic Life – Freshwater (Chronic)	EPA	Maximum 1.9 mg/L (pH 7.0, T = 20 C)	Not to exceed 2.5 times Criteria Continuous Concentrations (CCC) or 4.8 mg TAN/L (at pH 7, 20°C) as a 4-day average within the 30-days, more than once in three years on average
	Aquatic Life – Freshwater (Acute)	EPA	Maximum 17 mg/L (pH 7.0, T = 20 C)	1-hr Average; Not to be exceeded more than once in three years on average.
Chloride	Drinking Water SMCL	MassDEP 310 CMR 22.07D	Maximum 250 mg/L	Drinking water point of consumption
	Aquatic Life (Acute)	EPA	Maximum 860 mg/L	1-hour average once every 3 years (when associated with sodium)
	Aquatic Life (Chronic)	EPA	Maximum 230 mg/L	4-day average once every 3 years (when associated with sodium)
Dissolved Oxygen	Coldwater Fisheries (Aquatic Life)	MassDEP 314 CMR 314 4.05(3)(a)1	Minimum of 6 mg/L	Instantaneous value, background conditions considered
	Warmwater Fisheries (Aquatic Life)	MassDEP 314 CMR 314 4.05(3)(a)1	Minimum of 5 mg/L	Instantaneous value, background conditions considered
Escherichia coli (*E. coli*)	Non-bathing waters	MassDEP 314 CMR 314 4.05(3)(a)4	Maximum 126 CFU/100/mL; No single sample > 235 CFU/100mL	Geometric mean over 6-month period
Fecal coliform	Unfiltered Water Supply Intakes	MassDEP 314 CMR 314 4.06(1)(d)1.)	20 organisms /100 mL OR 90% samples over any 6 months must be < 100 CFU/100mL	
Nitrate-nitrogen	Drinking Water	EPA SDWA MCL	Maximum of 10 mg/L	Drinking water point of consumption
Nitrite-nitrogen	Drinking Water	EPA SDWA MCL	Maximum of 1 mg/L	Drinking water point of consumption
Nitrate-nitrogen + Nitrite-nitrogen	Ecoregional reference – (Streams/Rivers)	EPA Recommended criteria	0.16 – 0.31 mg/L	25^{th} Percentile subecoregion 58 – 25^{th} Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA Recommended criteria	0.014 – 0.05 mg/L	25^{th} Percentile subecoregion 58 – 25^{th} Percentile subecoregion 59
pH	Class A Inland Waters	MassDEP 314 CMR 314 4.05(3)(a)3	6.5 – 8.3 S.U.	Acceptable Range; No change from background level
Specific Conductance	Aquatic Life Chronic Recommendation	MassDEP	Maximum 904 µS/cm	At 25 °C; Proxy for chloride
	Aquatic Life Acute Recommendation	MassDEP	Maximum 3,193 µS/cm	At 25 °C; Proxy for chloride
Temperature (Freshwater)	Coldwater Fisheries	MassDEP 314 CMR 314 4.05(3)(a)2	Maximum of 68 °F (20 °C)	7-day mean-maximum daily temperature unless naturally occurring
	Warmwater Fisheries	MassDEP 314 CMR 314 4.05(3)(a)2	Maximum of 83 °F (28.3 °C)	7-day mean-maximum daily temperature unless naturally occurring

Parameter	Standard/Criteria	Regulatory reference	Threshold Value	Notes
Total Phosphorus	Ecoregional reference – (Streams/Rivers)	EPA recommended criteria	12.00 – 23.75 µg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA recommended criteria	7.0 – 8.0 µg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
Total Kjeldahl Nitrogen	Ecoregional reference – (Streams/Rivers)	EPA recommended criteria	0.10 – 0.30 mg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA recommended criteria	0.33 – 0.43 mg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
Total Nitrogen	Ecoregional reference – (Streams/Rivers)	EPA recommended criteria	0.42 – 0.59 mg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA recommended criteria	0.27 – 0.40 mg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
Turbidity	Unfiltered Surface Water Supplies	EPA SWTR MCL	Maximum 5.0 NTU	May not exceed at any time
	Unfiltered Surface Water Supplies	MassDEP	Maximum of 1.0 NTU	Determined by a monthly average rounded to the nearest significant whole number. May only exceed if does not interfere with effective disinfection