Water Quality Report: 2020

Wachusett Reservoir Watershed

Wachusett Reservoir – Travis Drury (2020)

AUGUST 2021

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

Page Intentionally Left Blank

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 2020. 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 and the reservoir is a proactive measure aimed at identifying trends and potential problems that may require additional investigation or corrective action. In 2020, 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 and during low flow conditions, 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 2020. Elevated concentrations of some parameters (nutrients, turbidity, total suspended solids) occurred during 2020 due to drought conditions in the summer and early fall. This resulted in higher-than-normal mean annual concentrations at several tributaries, however these high concentrations did not result in higher loading since the high concentrations occurred during very low flows. Overall, the results of the Wachusett tributary monitoring programs were consistent with historical data and demonstrate continued adherence to high drinking water quality and aquatic life use standards, with the exception of impairments from dissolved salts in a few small subbasins and water temperatures rising above the MassDEP recommended threshold for coldwater fishery resources at several monitoring locations.

Results of reservoir monitoring align with those observed in the watershed. Reservoir monitoring focuses on two areas of water quality; physical and chemical parameters such as nutrients, temperature, and clarity, and biological conditions including phytoplankton density and composition, invasive aquatic plants, and fish populations. Apart from alkalinity and specific conductance, which remain elevated compared to historical results, 2020 results were within historical ranges across the reservoir. Patterns typical of oligotrophic water bodies were observed in the phytoplankton population which remains dominated by diatoms and/or chrysophytes for much of the year. Organisms that can produce undesirable tastes and odors were only briefly present above internally defined thresholds and cyanobacteria concentrations remained well below levels of concern. No new invasive species were detected in the reservoir in 2020 and management activities continue to reduce known populations.

The appendix to this report includes summary information on mean daily flows of tributaries where flow is monitored and a list of applicable water quality criteria/standards or thresholds of interest. Previously compiled background information and historical context for monitoring parameters is also included in the

appendix to assist in the interpretation of water quality results and serve as a reference for the reader. 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.

Plain Language Summary

Water used by people and businesses in metro-Boston comes from the Quabbin and Wachusett Reservoirs. Streams, rivers, and groundwater that flow into these water bodies, and the reservoirs themselves, are monitored for quality and quantity by the DCR Division of Water Supply Protection. Certain water quality standards set by federal and state regulations must be met annually. This report summarizes the monitoring methods and results for 2020 which satisfied these requirements and continue to ensure availability of safe drinking water to present and future generations.

CITATION
Division of Water Supply Protection. (2021). Water Quality Report: 2020 Wachusett Reservoir Watershed. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

Acknowledgements

This report was prepared by the Environmental Quality Section of the Office of Watershed Management, Wachusett/Sudbury Region. Daniel Crocker, Environmental Analyst IV, and Joy Trahan-Liptak, Aquatic Biologist III, were the primary authors. The authors acknowledge the following for their contributions to this report:

Juliana Berube, seasonal Aquatic Biologist I, for field work, collecting water quality data in the stormwater basins, analyzing zooplankton samples, and organizing references for this report.

Travis Drury, Environmental Analyst II, for watershed field work and sampling, and carrying out the hydrologic and groundwater monitoring programs; Writing, analysis, map production, and review of this report.

Dave Getman, Environmental Engineer II, for field work, sampling, and forestry project coordination.

Kristina Gutchess, Environmental Analyst III for the Quabbin/Ware Section, for collaboration, research, and assistance with Annual Report graphics and text.

Emily Lydell, 2020 summer intern, for completing a spatio-temporal analysis of on-lot waste disposal conversion from septic to sewer and its impacts on water quality in Wachusett Watershed tributaries, and for assisting with various field monitoring activities.

Max Nyquist, Aquatic Biologist II, for field work, monitoring for potential invasive species, leading the *Phragmites* management program, and collecting water quality data and phytoplankton collection, analysis, and reporting; Writing, analysis, and review for this report.

Larry Pistrang, Environmental Analyst V (retired), for leading the Environmental Quality Section, providing guidance, coordination, institutional knowledge, and support for all Wachusett Watershed monitoring programs.

Erica Tefft, DWSP GIS Director, for providing Geographical Information System data, maps, and support.

Joel Zimmerman, Regional Planner, for his assistance in final report production.

John Scannell, Director of the Division of Water Supply Protection, for providing program leadership and report review and comments.

Jamie Carr, Regional Director of the Wachusett/Sudbury Region, for providing program leadership and report review and comments.

Derek Liimatainen, Assistant Regional Director of the Wachusett/Sudbury Region.

Jason Stolarski, Aquatic Biologist at MassWidlife, for leading the Lake Trout monitoring program.

The Massachusetts Water Resources Authority (MWRA), whose laboratory staff conducted nutrient, pathogen, and bacteriological analyses and contributed to the management of laboratory data and sample bottle preparation.

Matt Walsh of MWRA, who provided water system data from MWRA facilities.

The U.S. Geological Survey, who, through a cooperative agreement established with DWSP, provided tributary flow and precipitation data included in this report.

The University of Massachusetts, Amherst – Department of Civil and Environmental Engineering faculty and graduate students, for collaboration and research leading to a better understanding and management of the DWSP-MWRA water supply system.

Table of Contents

Figures and Tables

Figures

Tables

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, followed by the introduction of the Interim Enhanced Surface Water Treatment Rule (IESWTR) in 2002 (US EPA, 1989; US EPA, 2002), to ensure that public water supply systems that use surface water, or groundwater under direct influence of surface water, 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 watershed aquifers, reservoirs, and 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, turbidity, 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 2020. 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 2020 and prior years are available upon request.

---

[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 [MassDCR] & MWRA, 2004
[4] Ibid

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 Wachusett Reservoir watershed. Section 2 presents methods for water quality monitoring programs in 2020, 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 5.0 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 1.0 NTU at all times[6]. Authority to enforce the SWTR 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].

---

[5] National Primary Drinking Water Regulations: Long Term 2 Enhanced Surface Water Treatment Rule, 2003
[6] Massachusetts Drinking Water Regulations, 2020A
[7] Massachusetts Surface Water Quality Standards, 2013a
[8] Ibid
[9] Massachusetts Surface Water Quality Standards, 2013b
[10] MWRA, 2012
[11] MWRA, n.d.

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 using a range of methods and strategies 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 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 used 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 implementing 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 dependent upon the coordinated implementation of each of DWSP's many watershed protection programs. The Watershed Protection Act

[12] Division of Water Supply Protection [DWSP], 2018a

of 1992 gives DWSP the authority to regulate certain land uses and activities that take place within critical areas of the watershed to protect drinking water quality[13].

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	32.6	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)
Other Protected Area	14,910	Acres
	21.1	(% 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 at Shaft 1 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,

[13] Watershed Protection, 2017
[14] MWRA, 2021a
[15] DWSP, 2018a
[16] DWSP, 2016

MA and delivered to Quabbin Reservoir via gravity flow. Ware River water enters the Quabbin 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.

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 MetroWest 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 32.6 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].

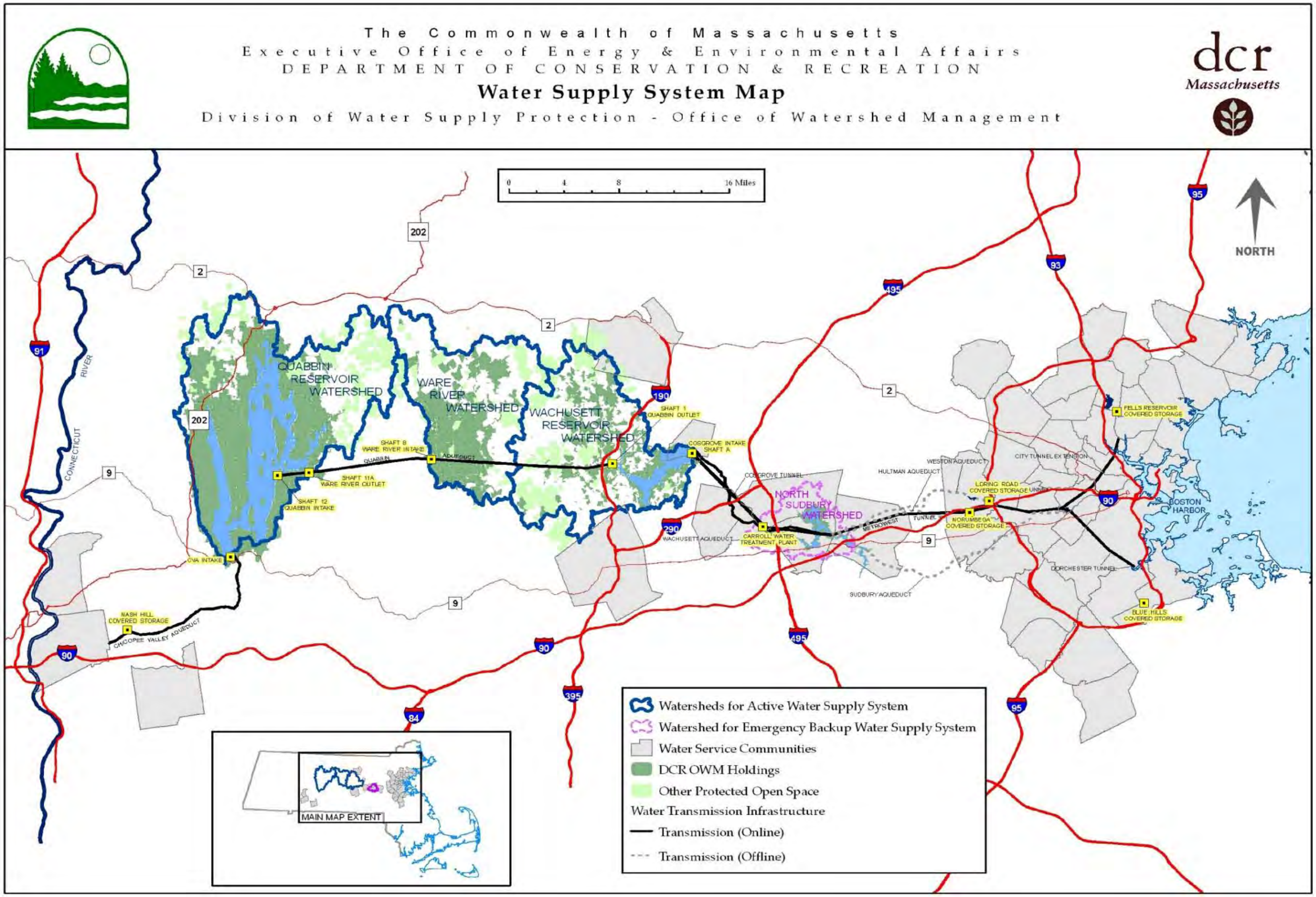
The watershed landscape is spread across 12 towns, but lies predominantly in the towns of Boylston, Holden, Princeton, Rutland, Sterling, and West Boylston. The Stillwater and Quinapoxet Rivers are the largest tributaries to Wachusett Reservoir, collecting and delivering water draining from more than 80% of the watershed land area. Approximately 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% of 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].

---

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

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.



2 Methods

This section provides an overview of how each element of DWSP water quality and hydrologic monitoring was carried out during 2020, including what parameters were sampled, their monitoring frequency and locations, and methods of analysis. 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: Water samples are collected and then 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 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 eight groundwater wells, 20 tributary monitoring stations, and 27 stations on Wachusett Reservoir in 2020. 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 and quantity 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 (Figure 7). These stations, listed as *Primary* sampling locations in Table 2, are where flow is monitored, and routine nutrient samples are collected. *Secondary* tributary stations are situated at upstream locations or on smaller 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 large drainage areas into smaller units. Although it is not a natural tributary, Shaft 1 (Quabbin Transfer) is routinely 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 thereof can be found in the SOPs for each type of sampling. General characteristics of each are presented in the table below (Table 3). 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 2020 in the Wachusett Reservoir Watershed

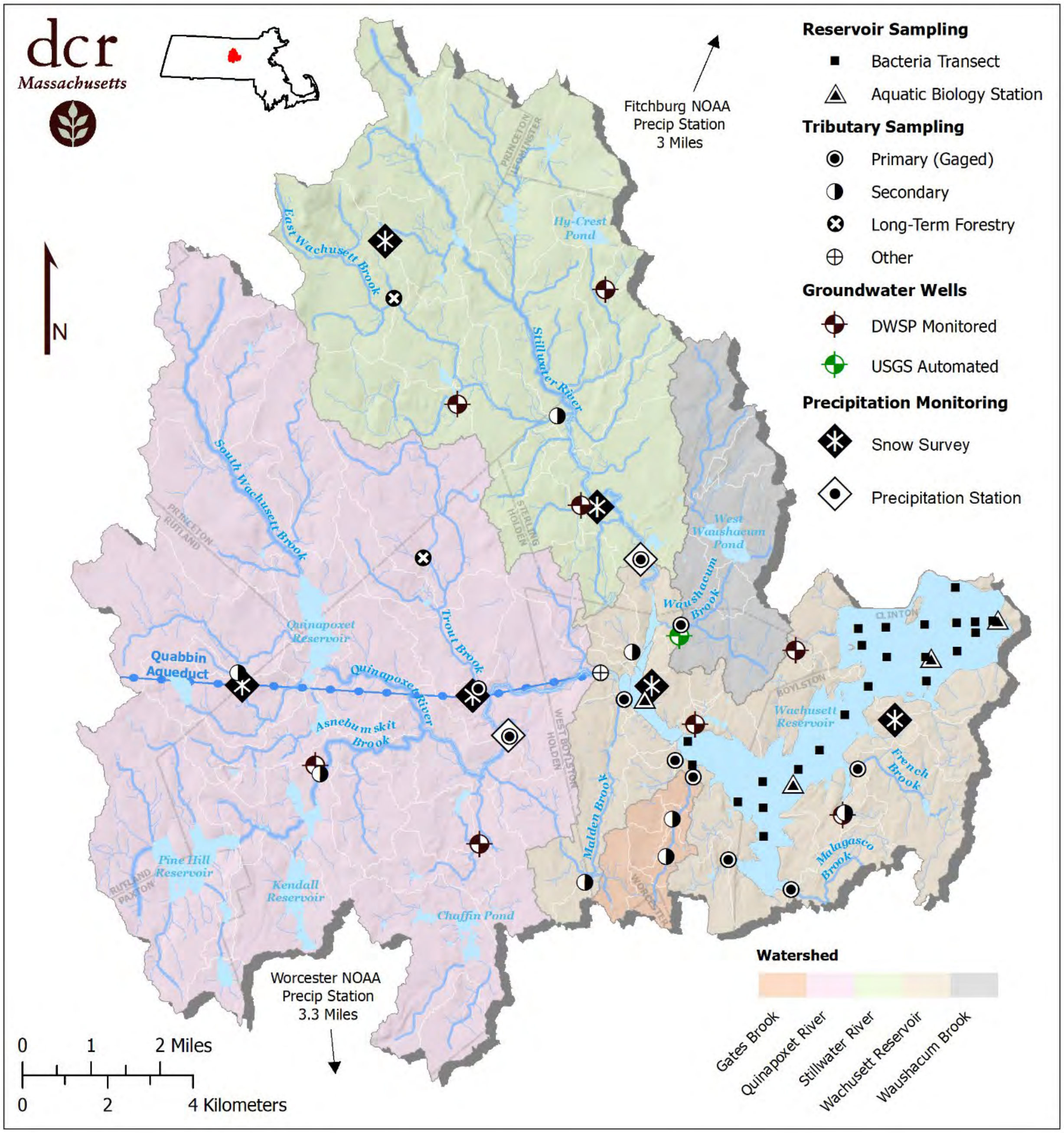


Table 2: Wachusett Tributary Sampling Locations (2020)

Location	Description	Sampling Category
Asnebumskit Brook (Princeton) - M102	Upstream of Princeton St. near post office, Holden	Secondary
Boylston Brook - MD70	Downstream of Rt. 70, Boylston	Secondary
Cook Brook - Wyoming - MD11	Wyoming Dr., Holden	Secondary
East Wachusett Brook (140) - MD89	Downstream of Rt. 140, Sterling	Secondary
French Brook - MD01	Downstream of Rt. 70, Boylston	Primary
Gates Brook 1 - MD04	Downstream of bridge inside Gate 25, West Boylston	Primary
Gates Brook 4 - MD73	Upstream of Pierce St., West Boylston	Secondary
Holden Forestry - FHLN	Off Mason Rd. inside Gate H-21, Holden	LTF
Jordan Farm Brook - MD12	Upstream of Rt. 68, Rutland	Secondary
Malagasco Brook - MD02	Upstream of W. Temple St. Extension, Boylston	Primary
Malden Brook - MD06	Upstream of Thomas St., West Boylston	Primary
Muddy Brook - MD03	Upstream of Rt. 140, West Boylston	Primary
Oakdale Brook - MD80	Downstream of Waushacum St. & East of Rt. 140, West Boylston	Secondary
Princeton Forestry - FPRN	Off Rt. 31 near Krashes Field, Princeton	LTF
Quinapoxet River (Canada Mills) - MD69	Upstream of River St. bridge (Canada Mills), Holden	Primary
Scarlett Brook (DS W.M.) - MD81	Behind Walmart above confluence with Gates Brook, West Boylston	Secondary
Shaft 1 (Quabbin Transfer) - MDS1	MWRA Shaft 1 outlet off River St., West Boylston	Other
Stillwater River - Muddy Pond Rd - MD07	Downstream of Muddy Pond Rd., Sterling	Primary
Trout Brook - M110	Downstream of Manning St., Holden	Primary
Waushacum Brook (Prescott) - MD83	Downstream of Prescott St., West Boylston	Primary
West Boylston Brook - MD05	Upstream of access road inside Gate 25, West Boylston	Primary

LTF = Long-term forestry

Figure 3: Wachusett Reservoir Sampling Locations

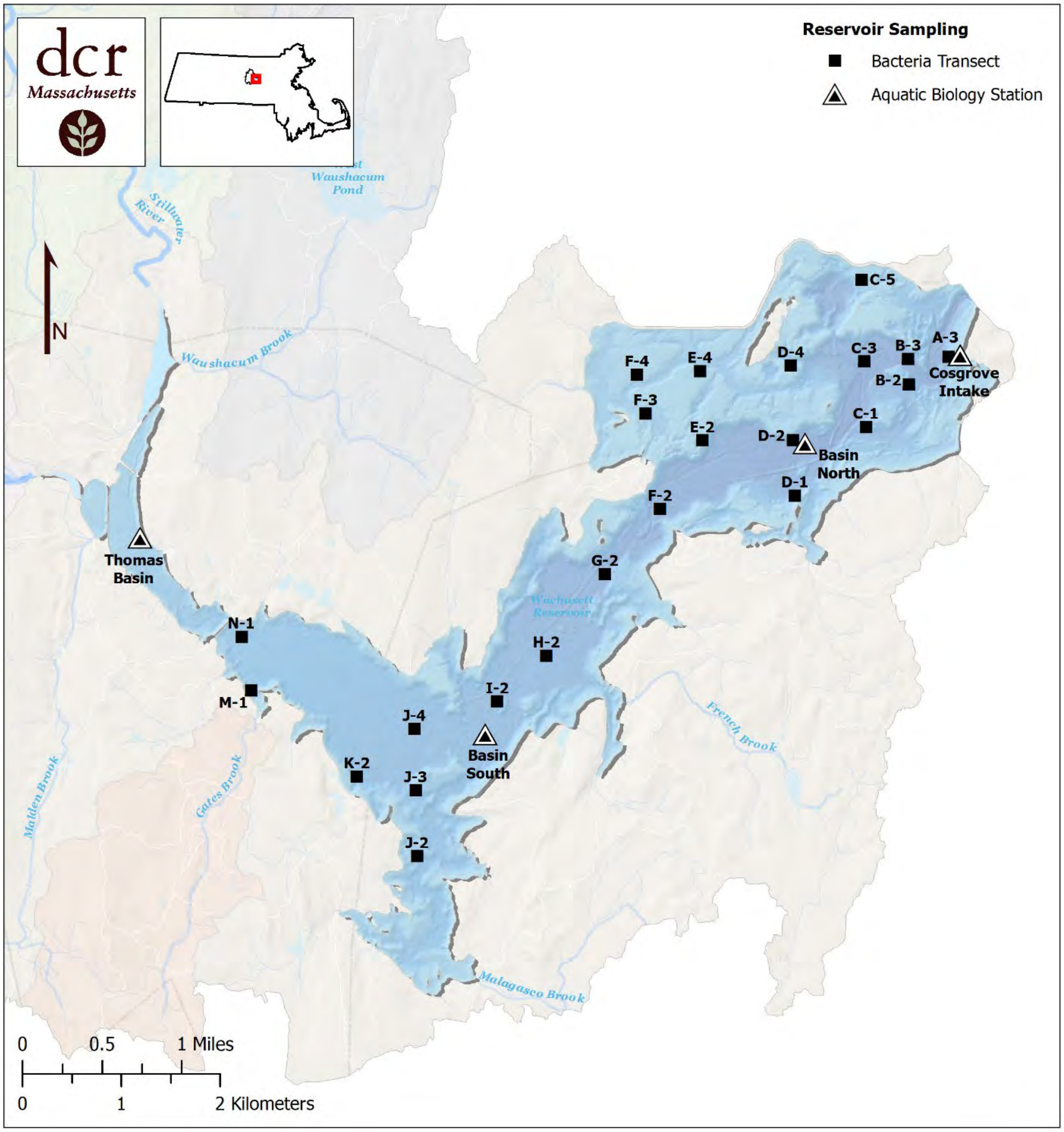


Table 3: Wachusett Reservoir Sampling Locations

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 locations 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). DWSP acquires daily precipitation totals from both NOAA and USGS servers using Application Programming Interfaces (APIs) and automated scripts. 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 used for calculating average watershed precipitation.

Table 4: Wachusett Watershed Meteorological Stations

Gage Name	Owner	Gage 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	DWSP	MD02	2017-01-13*	Air temperature
Waushacum Brook	DWSP	MD83	2017-08-03	Air temperature
Princeton Forestry	DWSP	FPRN	2017-01-03	Air temperature

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

Since 1985, the Wachusett Watershed average annual precipitation is 46.64 inches, with a historical low of 35.36 inches (2001) and high of 61.20 (2018). Average monthly precipitation ranges from 2.97 inches (February) to 4.84 inches (October). Large precipitation events (> 2 inches) typically occur several times per 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 stream flows 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.

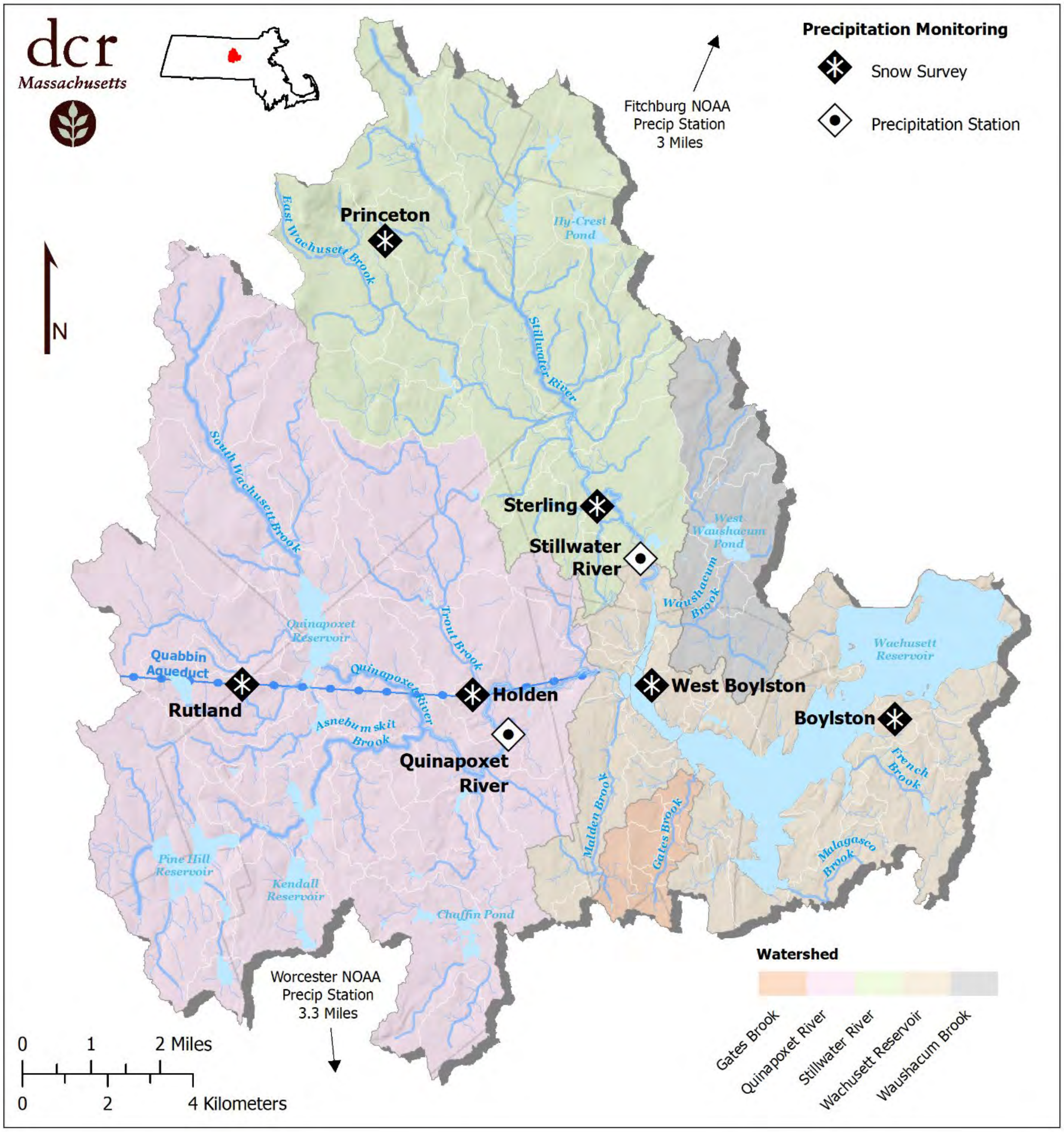
Effectively managing Wachusett Reservoir water storage volume requires an accurate prediction of water inputs to the reservoir which are derived from new precipitation and/or melting of past precipitation stored in the snowpack. Therefore, DWSP carries out a snowpack monitoring program to track the water 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. MWRA uses watershed snowpack measurements to predict future inputs to the reservoir from melt water.

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 A.8), and 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.

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



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

Reliable stage-discharge relationships (ratings) allow the use of easily acquired stream depths to quickly estimate discharge (flow). Direct flow measurements (discharge measurements) at a range of depths are usually performed several times during the year using a Sontek 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 to 15 minutes. Continuous data (15-minute increments) 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 to collect stage, temperature and conductivity data at 10-minute increments. All data and other information available for these locations are available from the USGS at the NWIS website for each station[22].

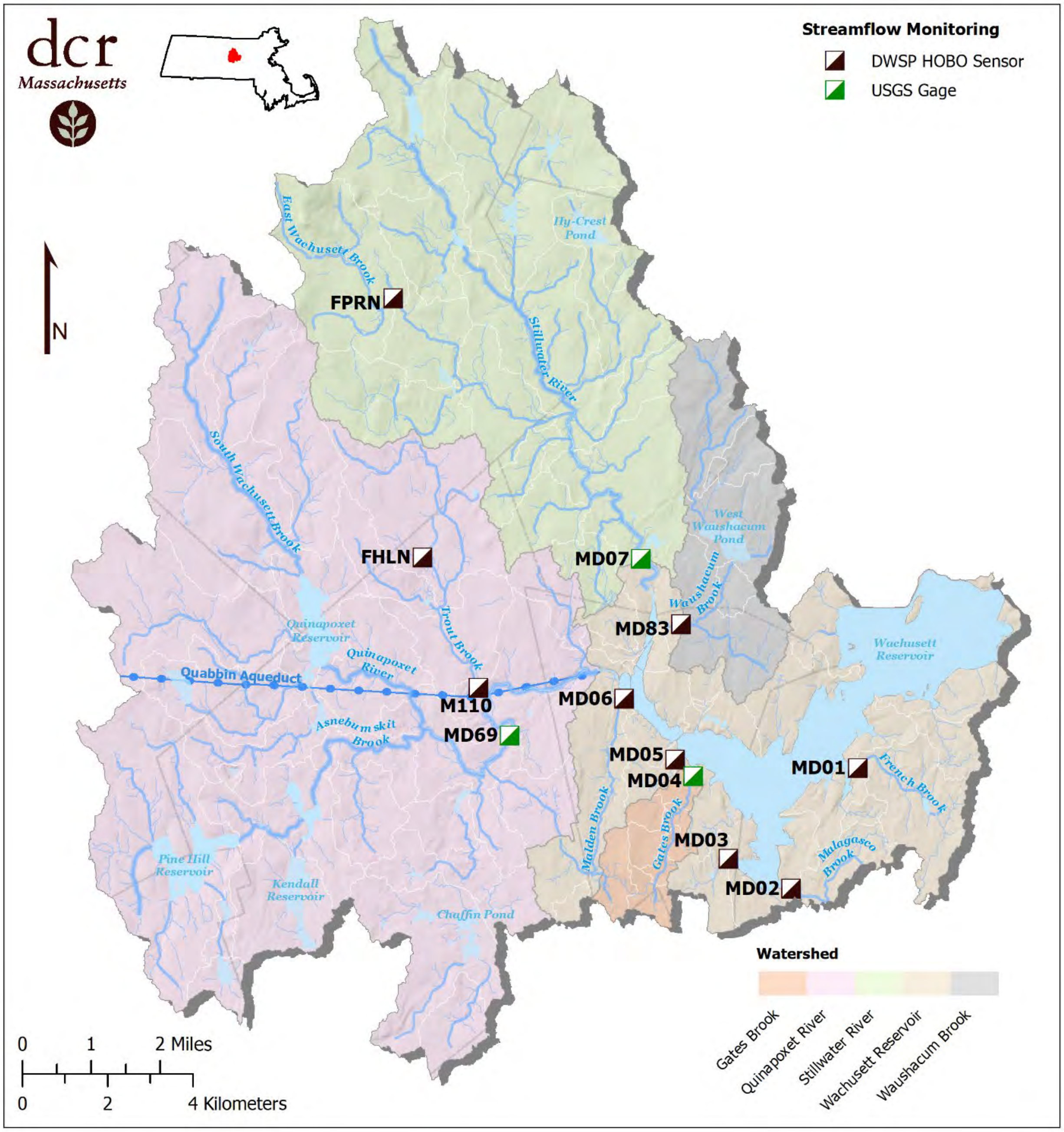
In 2019 new real-time monitoring instrumentation was added to the Waushacum Brook monitoring station to pilot a viable replacement for aging Onset HOBO dataloggers. The equipment utilizes a Mayfly datalogger[23], which allows for the connection of several types of water quality probes, as well as cellular transmission of data to a cloud-based data storage server with built in visualization tools. Data for this station can be viewed publicly[24]. Due to the increased interest in collecting additional specific conductance/Cl data this pilot station was outfitted with a Hydros21 CTD sensor manufactured by Meter Group, Inc., which measures specific conductance, temperature, and depth.

This pilot project was determined to be successful and additional Mayfly units will be deployed at monitoring locations as HOBO units reach the end of life.

---

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

Figure 5: Streamflow Monitoring Locations in Wachusett Reservoir Watershed



2.1.3.2 *Reservoir Elevation*

Wachusett Reservoir elevation is controlled by MWRA, which manages aqueduct transfers and outflows to maintain a water surface elevation within the normal operating band between 390 and 391.5 ft when the reservoir is not completely frozen over. During full ice over conditions the normal operating band lower elevation is reduced to 388 ft to accommodate large inputs from snow melt in the early spring. 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 normal 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.

In 2020, DWSP continued its 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.

An additional seven wells were sampled monthly in 2020, continuing the expanded groundwater monitoring that began in 2019, primarily due to the increased interest in collecting additional specific conductance/Cl data in the Wachusett Watershed (Figure 26). Water levels are measured as part of this expanded monitoring effort. A total of eight wells are now sampled by DWSP, seven of 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

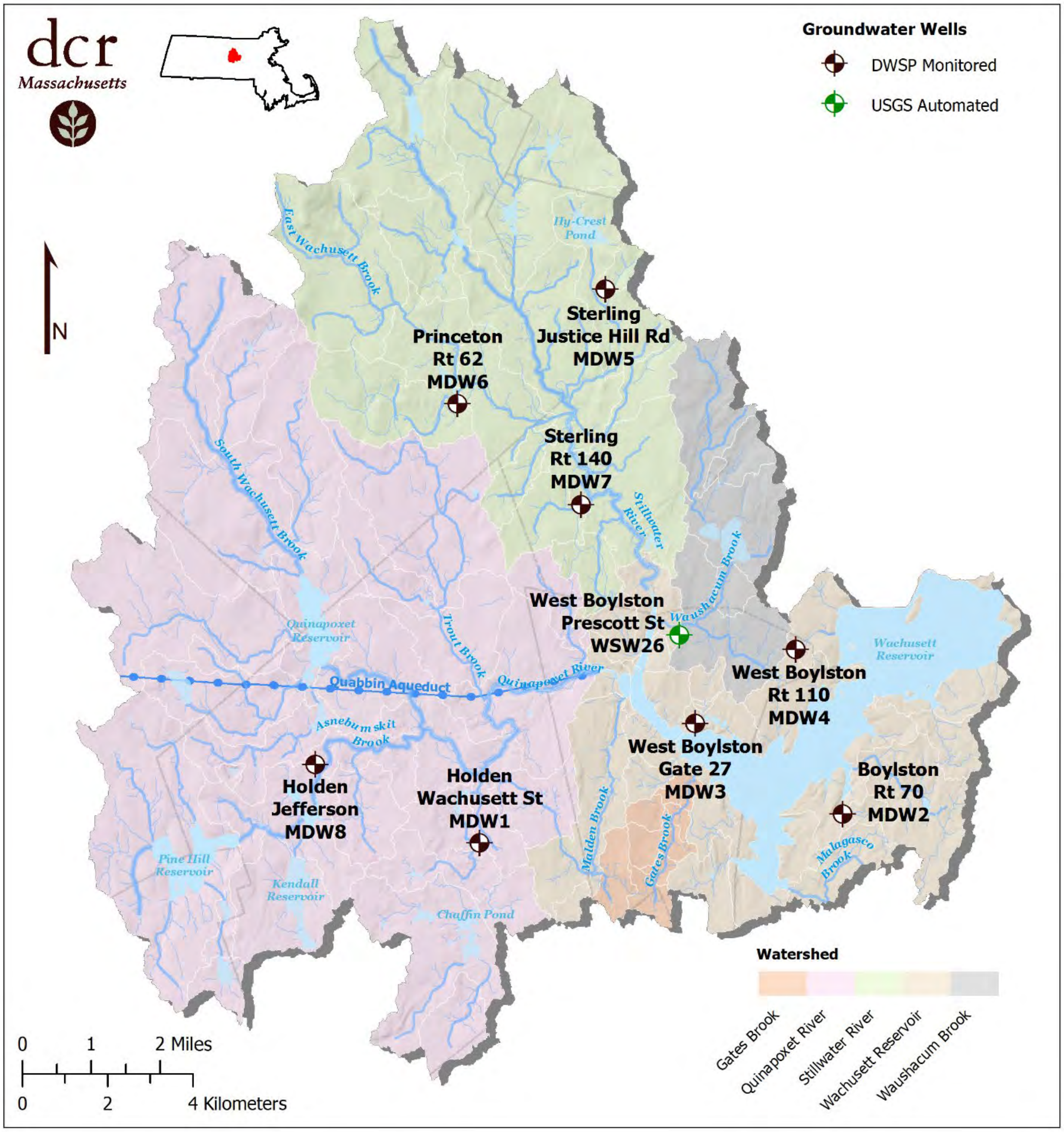
DWSP Code	Well Name	USGS Code	Type	Depth (ft)	Elevation (ft)	Historical Period
MDW1	Holden - Wachusett St	422102071501401	Dug	10.5	670	1995 - 2002
MDW2	Boylston - Rt 70	422125071440101	Augered	12.2	475	1995 - 2002
MDW3	West Boylston - Gate 27	N/A	Augered	15.1	403	N/A
MDW4	West Boylston - Rt 110	422334071444201	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 - 2019
MDW8	Holden - Jefferson	422201071530201	Augered	20.3	815	1995 - 2002
WSW26	West Boylston - Prescott St	422341071464901	Augered	16.8	485	2012 - 2019

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)*.

[25] Bent, 1999

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

Figure 6: DWSP Groundwater Monitoring Wells in Wachusett Reservoir Watershed



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 2019 and continuing through 2020 (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.

Prior to sample collection, groundwater wells were purged at a constant flow rate using a submersible pump until temperature and specific conductance readings stabilized over three consecutive five-minute intervals. This method[27] ensures 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 fully purged due to the large volumes of water they contain. Additionally, the Holden – Jefferson well has a narrow diameter that prevents purging with a submersible 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 (MDW8). Specific conductance and temperature are measured with a Yellow Springs Instrumentation (YSI) Professional Plus meter equipped with a flow cell 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)*.

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 is anticipated to 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.

2.1.5.1 *Routine Tributary Monitoring*

In 2020, routine water quality samples for bacteria, turbidity, and field parameters were collected from eighteen stations on seventeen 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 and four bacteria samples were not collected between March and May due to lab capacity restrictions during the beginning of the COVID-19 pandemic. DWSP only missed one scheduled collection of field parameters and turbidity due to

[27] United States Environmental Protection Agency [USEPA], 2017

pandemic related work closures. 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 within six hours of sample collection. 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 determine if levels persisted. Additional details about routine tributary monitoring are provided in the *SOP for the Monitoring of Tributary Bacteria and Turbidity (WATTRB)*.

2.1.5.2 *Nutrient Monitoring*

In 2020, 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: alkalinity[28], 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 total suspended solids (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). All primary tributaries were sampled 12 times for nutrients in 2020. The Quabbin Transfer was sampled eight times in 2020. 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)*.

[28] Alkalinity sampling was resumed at all primary tributary locations in September 2020

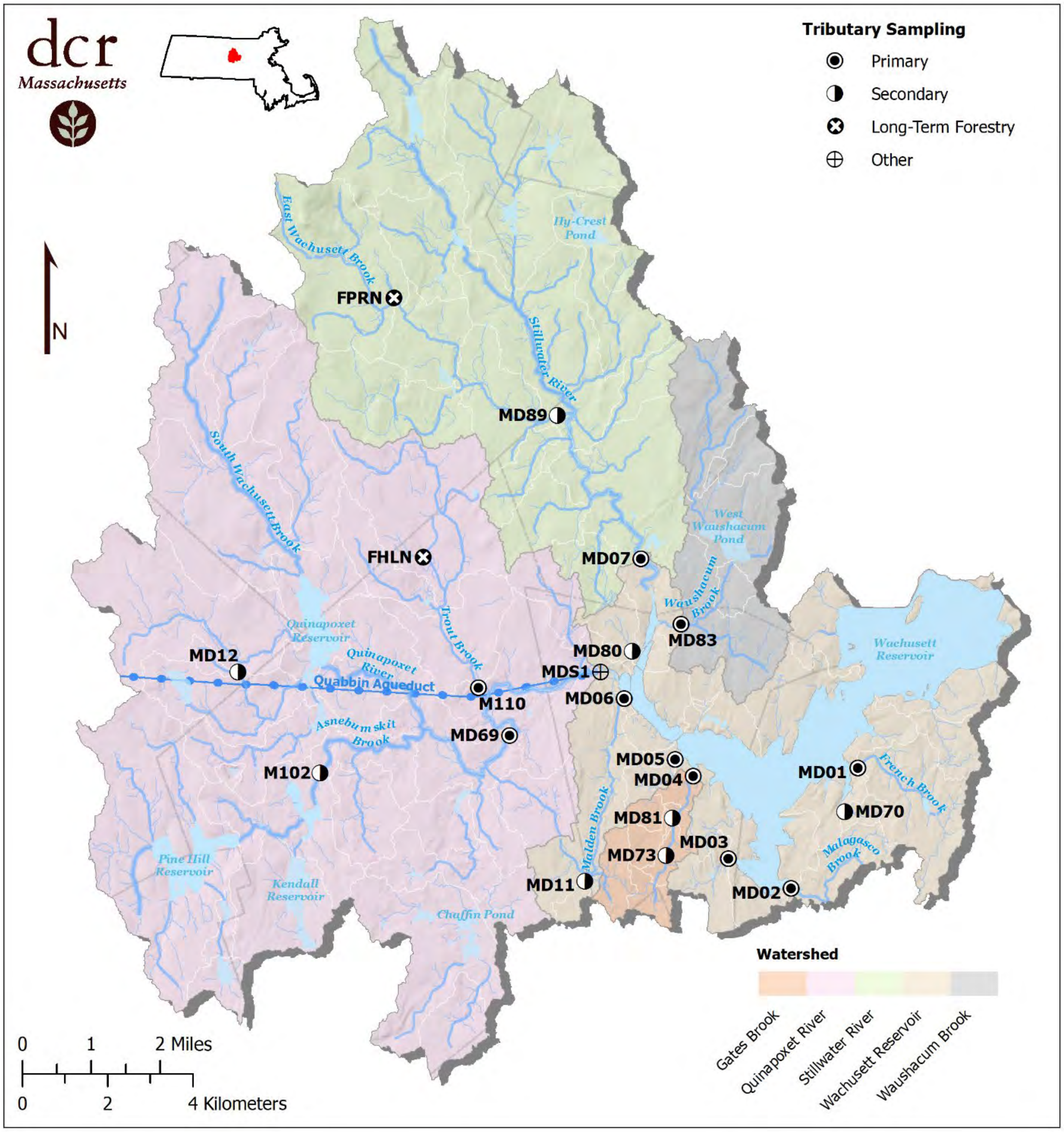
Table 6: 2020 Tributary Monitoring Program Components

Sample counts with a single 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 2020
Nutrients	WATMDC	NH_3-N, NO_2-N, NO_3-N, TKN, TP, TSS, TOC, UV_{254}, Cl, Alkalinity**	Monthly	Primary, Other	128*
Bacteria and Turbidity	WATTRB (Only for bacteria)	*E. coli*, turbidity	Twice per Month	Primary, Secondary	349 (*E. coli*) 403 (turbidity)
Field Parameters	N/A	Water temperature, dissolved oxygen, pH, specific conductance, stage (where applicable)	1 – 3 times per month in conjunction with WATMDC and WATTRB projects	Primary, Secondary, Other	567
		Stage		Primary	390
Long-term Forestry	WATBMP	NH_3-N, NO_2-N, NO_3-N, TKN, TP, TSS, TOC, UV_{254} + Field Parameters	Monthly/Quarterly Storms	LTF	16* (monthly) (No storms measured in 2020)
Short-term Forestry	N/A	Turbidity	Varied	17 timber harvest lots (not mapped)	114

** Alkalinity only sampled September - December

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 7). Details of each program are provided below.

Table 7: 2020 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 2020
Profiles	N/A	Water temperature, specific conductance, chlorophyll *a*, phycocyanin, dissolved oxygen, pH	Weekly (May – Sept), semi-weekly (Oct – April)	Primary: BN3417, CI3409, Secondary: BS3412, TB3427, other	45
Phytoplankton	N/A	Phytoplankton density	Weekly (May – Sept), semi-weekly (Oct – April)	Primary: BN3417, CI3409, Secondary: BS3412, TB3427, other	88
Nutrients	WATMDC	Alkalinity, NH3-N, NO3-N, Silica, TKN, TP, UV254	Quarterly (4x)	BN3417, BS3412, TB3427	40*
Bacteria	WATTRN	*E. coli*	Monthly (minimum)	23 transect stations	279
Macrophytes	N/A	Species present, location, density	Throughout growing season	Entire reservoir	n/a
Zooplankton	N/A	Population screening	Quarterly (4x)	BN3417, BS3412, TB3427	48
Lake Trout	N/A	Species, length, weight	Multiple sample trips during fall spawn	Entire reservoir – spawning locations	See Section 3.4.9

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 or more frequently, 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 45 profiles were collected from four locations in 2020. 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. In 2020 these buoys correspond to DWSP routine sampling sites at Basin South and Basin North. An additional profiling buoy was placed outside of Cosgrove Intake. 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 Operations Management Monitoring System (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 early December. 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 251 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[29] 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 A.18, Table A-2), 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 from the reservoir profile are typically used to select the discrete metalimnion sample depths, typically corresponding to depths where chlorophyll *a* values are 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 2020, phytoplankton monitoring was carried out on 37 days, resulting in 88 individual samples. The entire phytoplankton community was assessed in all samples except for one surface sample which was analyzed solely for *Dolichospermum*. Four periods of elevated phytoplankton density were documented through routine monitoring although an increase in monitoring frequency was only necessary for a total of three weeks in 2020 – one week in July and two weeks in August.

[29] Worden & Pistrang, 2003

2.1.6.5 *Zooplankton Monitoring*

Quarterly collection of zooplankton samples was conducted in conjunction with nutrient sampling as described above. A total of 48 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, typically 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.

DWSP staff conducted surveys of multiple ponds in the watershed as part of routine monitoring in 2020 (see Section 3.5.3.2). Additional surveys 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*

Surveys of two important Wachusett Reservoir fish populations, Rainbow Smelt and Lake Trout, were completed in 2020. Shoreline surveys for *Osmerus mordax* (Rainbow Smelt) spawning activity were carried out in early spring. *O. mordax* are considered an important prey species in the reservoir and consumption of Rainbow Smelt has been shown to improve *Salvelinus namaycush* (Lake Trout) condition. *S. namaycush* are the target of an annual mark and recapture study, which DWSP conducts each year in cooperation with MassWildlife.

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 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, beginning November 2013, 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[30]. Turbidity sampling is conducted monthly below all proposed stream crossings prior to the start of logging to establish baseline turbidity. 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 2020. A separate stormwater sampling report will be produced providing a detailed summary and analysis of the 46 storms that were sampled at routine water quality stations. 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 constructed 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 to assess

[30] DWSP, 2018b

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 *P. 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).

2.1.7.4 *Investigation of Reservoir Stratification*

An investigation of stratification and interflow depth across Wachusett Reservoir was carried out on September 25, 2019. A total of eleven profiles were collected at pre-selected locations to include sites with a range of maximum depths and distances from the main flow path through Wachusett Reservoir. Profiles were collected using the EXO2 sonde following the *SOP for Profile Collection*. Data was obtained from the MWRA profiling buoys for Basin North. Additional information and results are provided in Section 3.4.11.1.

2.2 2020 Watershed Monitoring Parameters

In 2020, 23 distinct physical, chemical, and biological parameters were monitored across all water quality and hydrologic monitoring programs throughout the Wachusett Reservoir watershed (Table 8). 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, results are compared to the EPA Ecoregional Nutrient Criteria for Rivers and Streams, when applicable. All relevant regulatory and guidance thresholds for these parameters are listed in Table A-1 in the Appendix. Scientific background information and historical context in relation to the Wachusett Watershed is also provided in the appendix to help readers better understand the discussion of water quality and hydrologic monitoring results. Monitoring results for 2020 are presented and discussed in Section 3.

Table 8: 2020 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 (as $CaCO_3$)	Nutrients	MWRA Lab	SM 2320 B	X	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 Gage 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 Gage 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

2.3 Statistical Methods and Data Management

All numerical calculations and related graphics were generated using the R programming language[31] 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[32]. All seasonal statistics presented in this report, apart from reservoir nutrients (see Section 3.4.6), 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 limit thresholds) were assigned values of one-half the lower detection limit. Any right-censored laboratory results (values above upper detection limit thresholds), 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 SQL Server database, maintained by DWSP-EQ. The WAtershed system data Visualization Environment (WAVE) is a custom R/Shiny[33] 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 database. Data generated from water quality monitoring in 2020 and prior years are available upon request.

[31] R Core Team, 2019
[32] Wickham, 2016
[33] Chang et al., 2019

3 Results

In 2020, DWSP staff analyzed 403 turbidity samples from 17 tributaries and 88 phytoplankton samples from the reservoir. A total of 2,258 physiochemical measurements (567 each of temperature, pH, dissolved oxygen and specific conductance) were taken in the field at tributary stations and Shaft 1, with another 45 water column profiles (temperature, specific conductance, dissolved oxygen, percent oxygen saturation, chlorophyll *a*, phycocyanin, and pH) recorded from the reservoir. A total of 628 bacteria samples were collected and delivered to the MWRA Southborough laboratory for *E. coli* analysis (349 from tributaries and 279 from the reservoir), and 1,437 samples (1,186 tributary, 251 reservoir) were collected and shipped to the MWRA Deer Island laboratory for a total of 2,065 analyses of nutrients and other parameters; this includes special studies. Daily climate statistics for the 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 two occasions during 2020.

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.

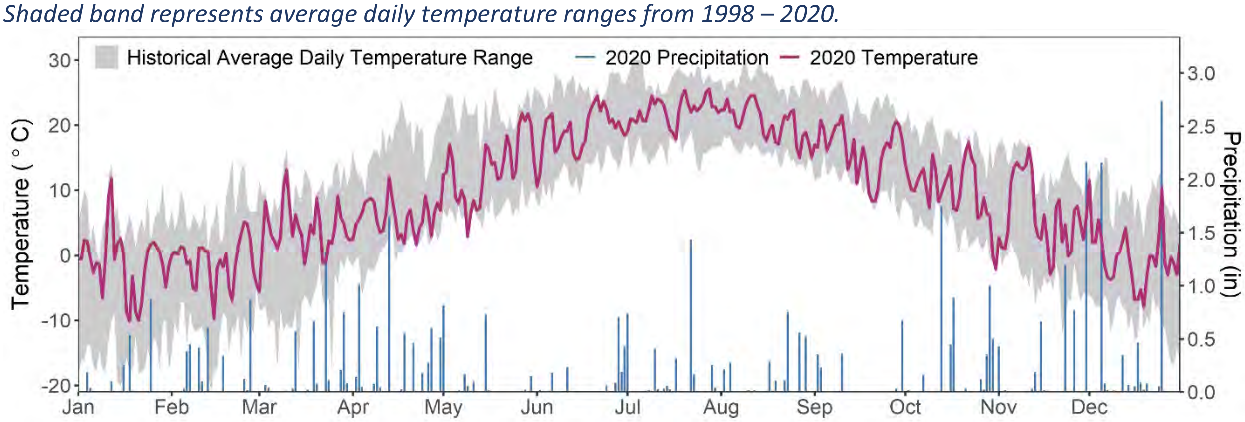
3.1.1 Climatic Conditions

3.1.1.1 *Air Temperature*

Average daily air temperatures in the Wachusett Reservoir watershed for 2020 ranged from -10.09 °C (January 18) to 25.55 °C (July 28) (Figure 8). The lowest daily minimum temperature (average of all stations) observed in 2020 was -16.43 °C on February 15, while the highest daily maximum temperature was 34.4 °C on July 19.

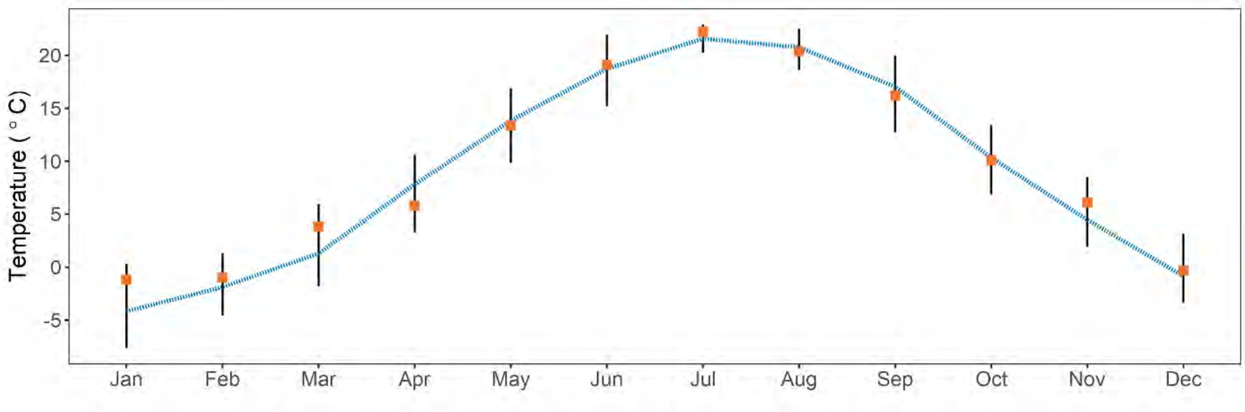
Figure 8: Climatograph of Daily Mean Temperatures and Daily Precipitation Totals for Wachusett Watershed from January 1 through December 31, 2020

Shaded band represents average daily temperature ranges from 1998 – 2020.



All monthly average temperatures were within historical ranges, with five months having below normal temperatures and seven above (Figure 9). The mean annual temperature for 2020 was 9.6 °C, which was 0.5 degrees above normal.

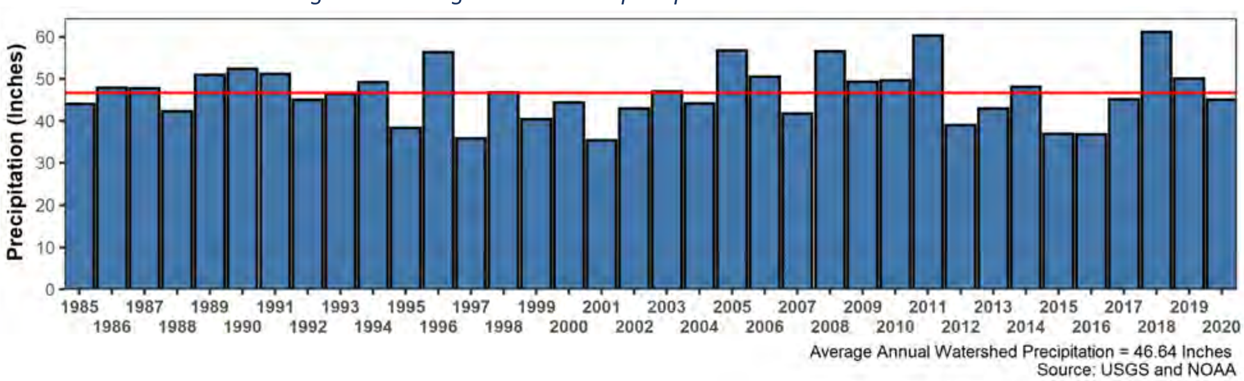
Figure 9: Wachusett Reservoir Watershed Monthly Mean Temperatures for 2020
Monthly mean temperatures for 2020 (orange squares) are shown in relation to the long-term average monthly temperatures (blue dashed line). The vertical black lines indicate the minimum and maximum monthly mean temperatures over the period of record, which began in 1998.



3.1.1.2 *Precipitation*

As illustrated by Figure 10**,** Wachusett Reservoir watershed received slightly less precipitation in 2020 than normal, with 45.04 inches of rainfall (1.60 inches less than average annual precipitation).

Figure 10: Annual Precipitation for Wachusett Watershed, 1985 to 2020
The red line indicates the long-term average annual total precipitation.

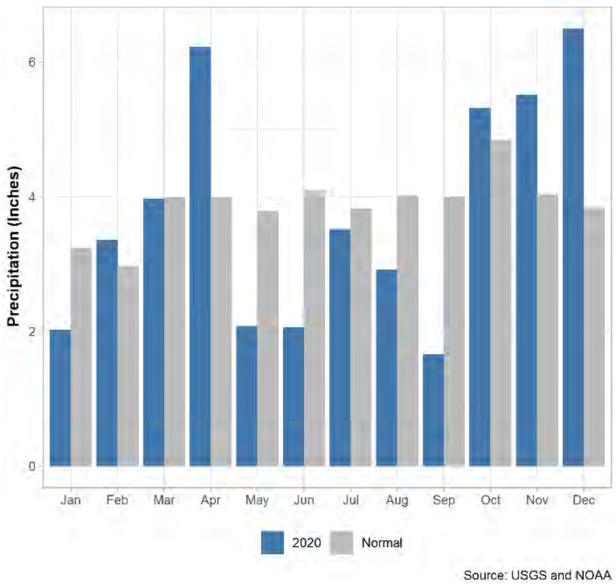


In late May, the calendar year cumulative precipitation dropped below normal and a significant (level 2) drought was declared and persisted until November[34]. The drought declaration was lowered to level 1 (mild drought) on November 1 after above average precipitation in October (Figure 11) combined with seasonal decline in evapotranspiration eased water stress in the watershed. By December 1 the drought status declaration had been updated to level 0 (Normal). September was the driest month of the year with only 1.66 inches of precipitation. Many small and intermittent streams were dry though the summer and early fall. December was the wettest month of 2020 (6.5 inches), mostly due to a storm that delivered

[34] MA Drought Management Taskforce, 2020

over three inches of rainfall just before Christmas. Other notable storms for the year occurred April 13 (1.65 in), October 13 (1.75 in), November 30 (2.17 in.) and December 5 (2.16 in).

Figure 11: Wachusett Watershed Monthly Total (left) and Daily Cumulative Precipitation (right) for 2020



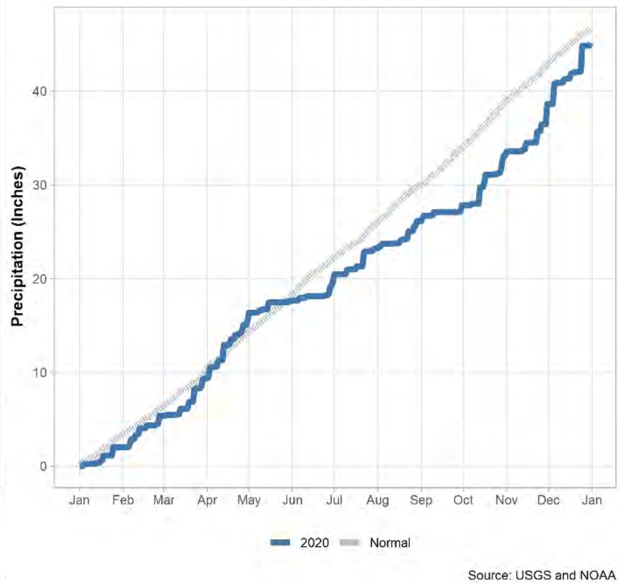


Table 9: Monthly Total Precipitation for 2020 and Statistics for the Period of Record 1985 to 2020

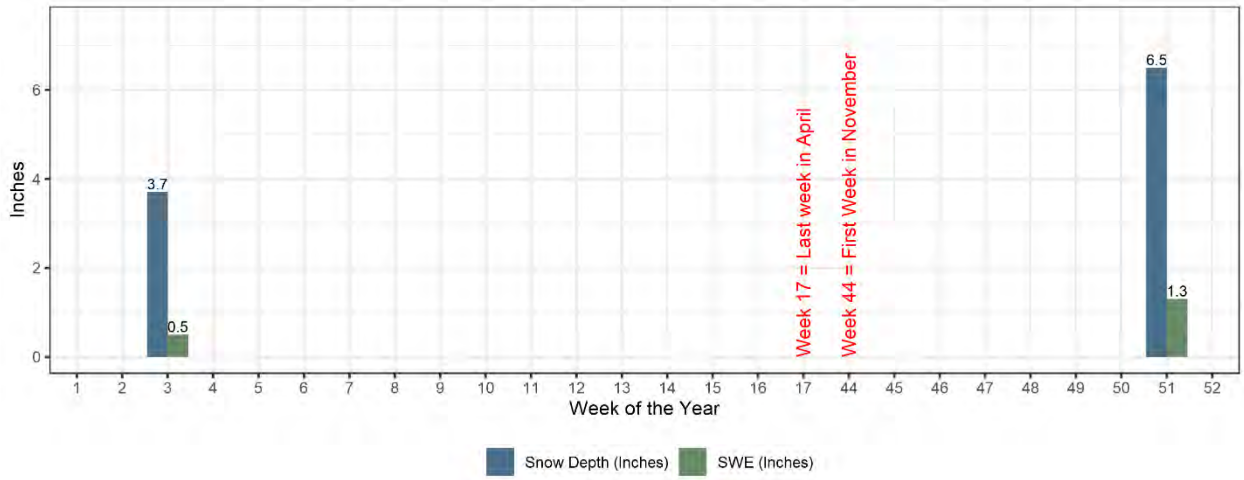
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Precipitation (in)	2.02	3.36	3.97	6.22	2.08	1.93	3.55	2.92	1.66	5.32	5.51	6.50	45.04
Normal (in)	3.22	2.97	3.95	3.99	3.85	4.10	3.83	4.02	4.01	4.84	4.03	3.84	46.64
Departure (in)	-1.20	0.39	0.02	2.23	-1.77	-2.17	-0.28	-1.10	-2.35	0.48	1.48	2.66	-1.60
Years	37	37	37	37	37	37	36	36	36	36	36	36	NA

Snow

Figure 12 shows the snowpack measurement results for calendar year 2020. 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 snow-water-equivalent (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 2020 occurred during the end of January (week three) when 3.7 inches of snow (average) fell in the Wachusett Watershed. By week four, this snow had mostly melted, and the next significant accumulation was during week 51 with an average accumulation of 6.5 inches across the watershed. Total snowfall for the winter months of 2020 was below normal and the lack of any substantial winter snowpack contributed to the early drought conditions that arose in the late spring and early summer. More detailed information was recorded in snowpack reports that were produced for the two weeks that a measurement was taken.

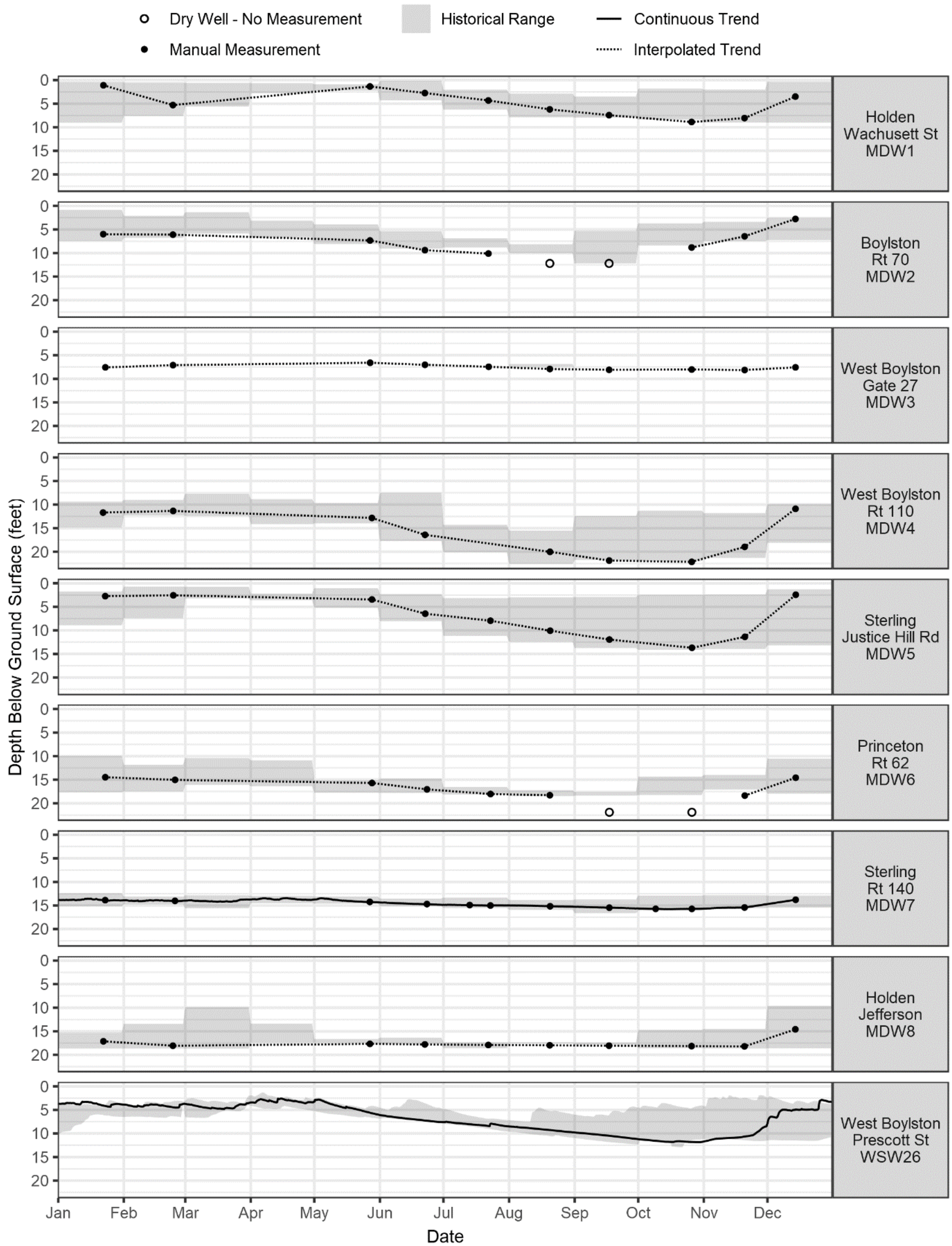
Figure 12: Snowpack Measurements in 2020
SWE = Snow-water-equivalent.



3.1.2 Groundwater Levels

Results of groundwater level monitoring are presented in Figure 13. During the 2020 sampling period, Boylston - Rt 70 was dry in August and September, Princeton - Rt 62 was dry in September and October, but all other wells had measurable water levels every month. Water levels are shown in comparison with monthly historical ranges for all wells except West Boylston - Prescott St, which has daily historical ranges presented due to the availability of eight years of automated water level measurements by USGS. When compared with these historical ranges, groundwater levels can be indicative of drought or excess saturation water in the watershed. The historical ranges of groundwater levels will become more robust as groundwater levels continue to be monitored.

Figure 13: Wachusett Groundwater Depth Measurements in 2020 With Historical Ranges for Comparison

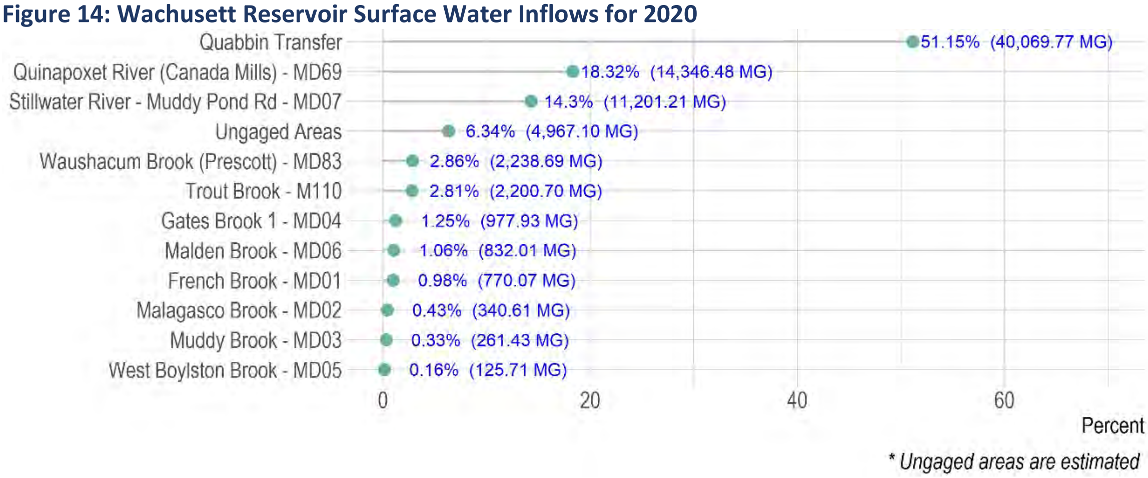


3.1.3 Streamflow and Quabbin Transfer

The total surface water inflow to Wachusett Reservoir in 2020 was estimated to be 78,332 million gallons (MG); about 17% less than in 2019. This decline over the prior two years is in line with the reduction in precipitation, which was just below normal for 2020. Water transfers from the Quabbin Reservoir comprised 51% of the total surface water inflow in 2020, which is a 4% greater contribution over 2019. Contributions from other tributaries remained consistent relative to historical contributions.

Figure 14 shows a breakdown of annual total flow (MG) among all the tributaries as well as ungaged areas and the Quabbin Transfer. About 33% of surface water inputs came from the Quinapoxet and Stillwater Rivers, while about 16% was contributed by the smaller tributaries and ungaged areas.

Figure 14: Wachusett Reservoir Surface Water Inflows for 2020



Total annual discharges for the Quinapoxet and Stillwater Rivers for 2020 were 10.5% and 18.3% below average, respectively (Figure 15).

Figure 15: Annual Discharge in the Quinapoxet and Stillwater Rivers (MG) (2007 to 2020)

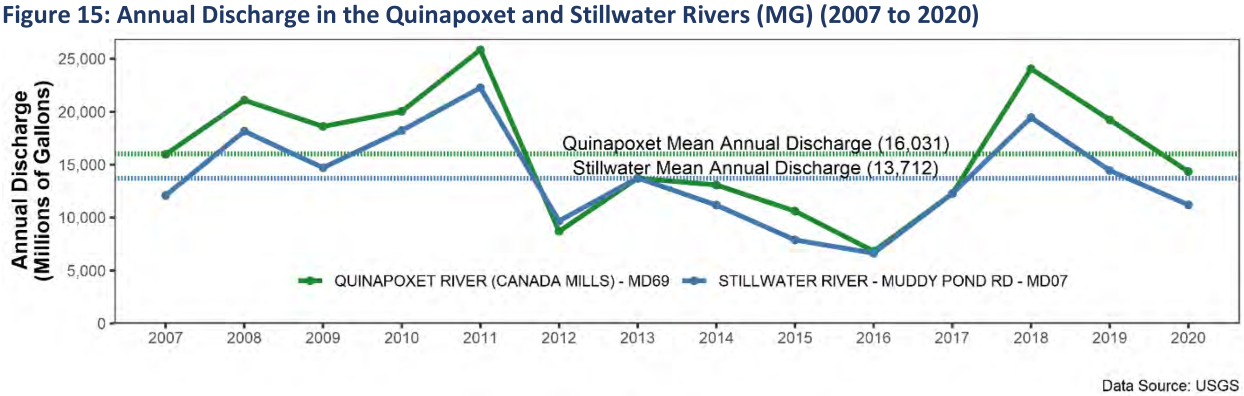


Table 10 provides summary statistics of surface water discharge for 2020. Daily flow rates in the smaller tributaries ranged from less than 0.01 cfs at French and Trout Brooks to 122 cfs at Trout Brook. The maximum instantaneous flows at these tributaries ranged from 10 cfs at Malagasco Brook to 240 cfs at Trout Brook.

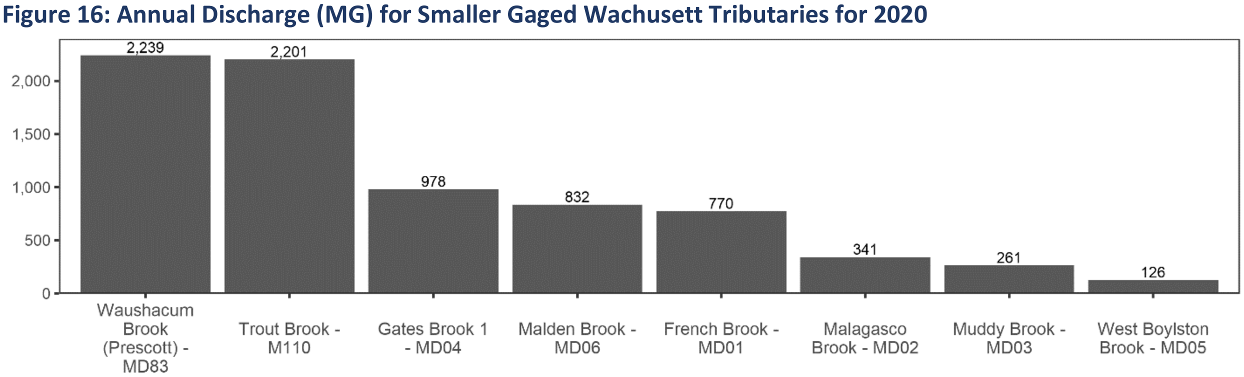
Table 10: 2020 Flow Statistics for Wachusett Reservoir Tributaries

Location	Min Daily Flow (CFS)	Ave Daily Flow (CFS)	Max Daily Flow (CFS)	2020 Peak Inst. Flow (CFS)	Min Month Vol (MG)	Ave Month Vol (MG)	Max Month Vol (MG)	2020 Total Vol (MG)
French Brook - MD01	<0.01	3.26	49.01	81	0.0	64.2	186.5	770
Gates Brook 1 - MD04	0.49	4.13	42.90	73	14.1	81.6	199.7	978
Malagasco Brook - MD02	0.10	1.44	7.76	10	3.1	28.4	75.2	341
Malden Brook - MD06	0.24	3.52	22.28	31	10.7	69.3	167.7	832
Muddy Brook - MD03	0.01	1.11	10.46	16	0.6	21.8	53.5	261
Quinapoxet River - MD69	1.43	60.65	644.00	1,090	56.6	1,195.6	3,492.1	14,346
Stillwater River - MD07	0.43	47.35	649.00	982	19.6	933.5	2,350.0	11,201
Trout Brook - M110	<0.01	9.31	121.97	240	1.4	183.4	482.8	2,201
Waushacum Brook - MD83	0.05	9.47	52.66	61	2.3	186.6	578.2	2,239
West Boylston Brook - MD05	0.01	0.53	15.38	34	1.6	10.5	25.8	126
Ungaged Areas*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4,967
Quabbin Transfer	N/A	N/A	N/A	N/A	N/A	N/A	N/A	40,070

* Estimated

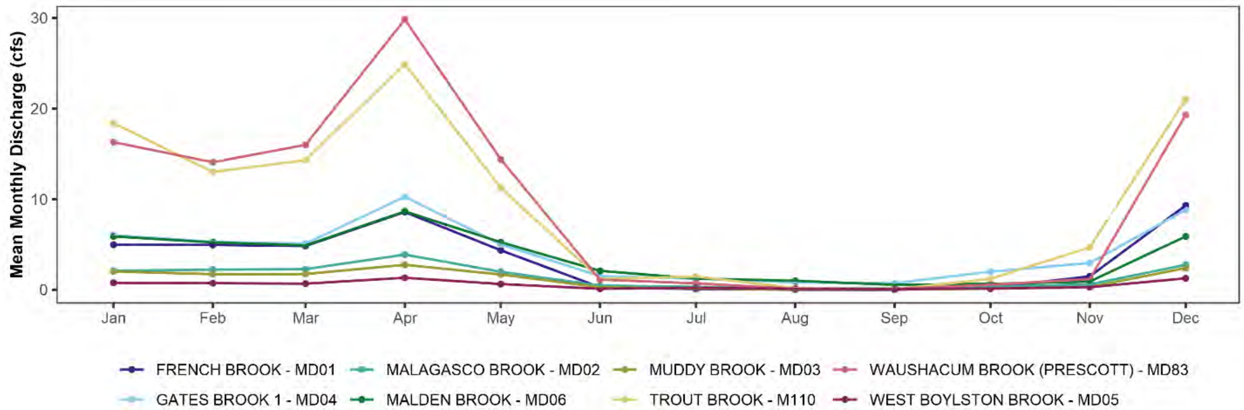
The annual discharge totals for the smaller tributaries are presented in Figure 16. Waushacum Brook contributed the largest water volume to Wachusett Reservoir of the smaller tributaries with 2,239 MG (~2.9%), while Trout Brook contributed 2,201 MG (~2.8%) of the surface water inflow to the reservoir. The other gaged small tributaries combined to contribute less than 5% of the surface water inflows to Wachusett Reservoir. Ungaged areas contributed approximately 6% of the total inflows (estimated).

Figure 16: Annual Discharge (MG) for Smaller Gaged Wachusett Tributaries for 2020



Monthly tributary flows followed their typical seasonal patterns during 2020 (Figure 17). Flows were highest in spring with a receding snowpack and prior to the growing season, lowest though the summer months when evapotranspiration rates are highest, and higher in the fall as evapotranspiration rates declined. Flows were higher than usual in April and December due to surplus precipitation. Summertime low flows reached extremely low levels due to the prolonged drought period. All tributaries except for the Quinapoxet River fell below 0.5 cfs (daily average) during late August and early September, which influenced the chemical and biological conditions in these waters due to lack of dilution and higher water temperatures. For smaller tributaries, no summary statistics were calculated due to the limited period of record.

Figure 17: Mean Monthly Discharge in Smaller Wachusett Tributaries (CFS) in 2020



Monthly flows in the Quinapoxet River for 2020 were above normal in January, February, and December. Stillwater River flows were above normal for January and December. Both Stillwater and Quinapoxet River flows were below normal for March and the seven-month stretch from June through November with late summer low flows dropping to extremely low levels.

Figure 18: Monthly Discharge in the Quinapoxet River (MG) 2020

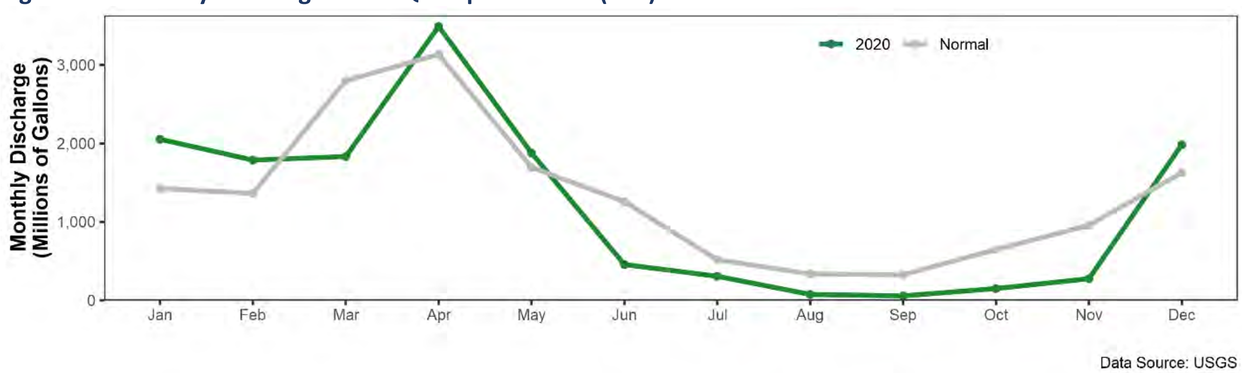
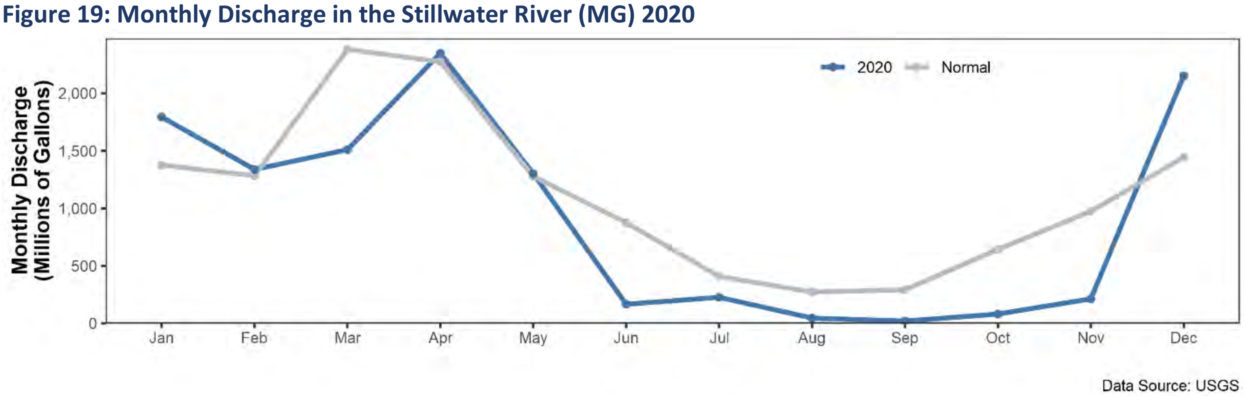


Figure 19: Monthly Discharge in the Stillwater River (MG) 2020



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

The Quabbin Transfer was initiated on May 19 and water was transferred on a nearly continuous basis until December 3. Water was also transferred for two days in January, once in February and about one week in March, resulting in a total of 210 transfer days, delivering a total volume of 40.1 billion gallons to

Wachusett Reservoir with an average transfer rate of 191 MGD (Figure 20). This is equivalent to 61.6% of Wachusett Reservoir capacity (65 billion gallons) and is about 4,133 MG less than the average transfer volume since 2005 (44,203.55 MG) (Figure 21).

Wachusett Reservoir elevation exceeded its operating range on two separate occasions (Figure 20), but these exceedances were slight and for short durations. The rise in elevation through the end of March and April was due to higher-than-normal precipitation during that period. The rain – snowmelt event on Christmas Day caused more than 1.5 feet of elevation gain observed during the final week of 2020.

Figure 20: 2020 Daily Wachusett Reservoir Water Elevation and Daily Quabbin Transfer Rate

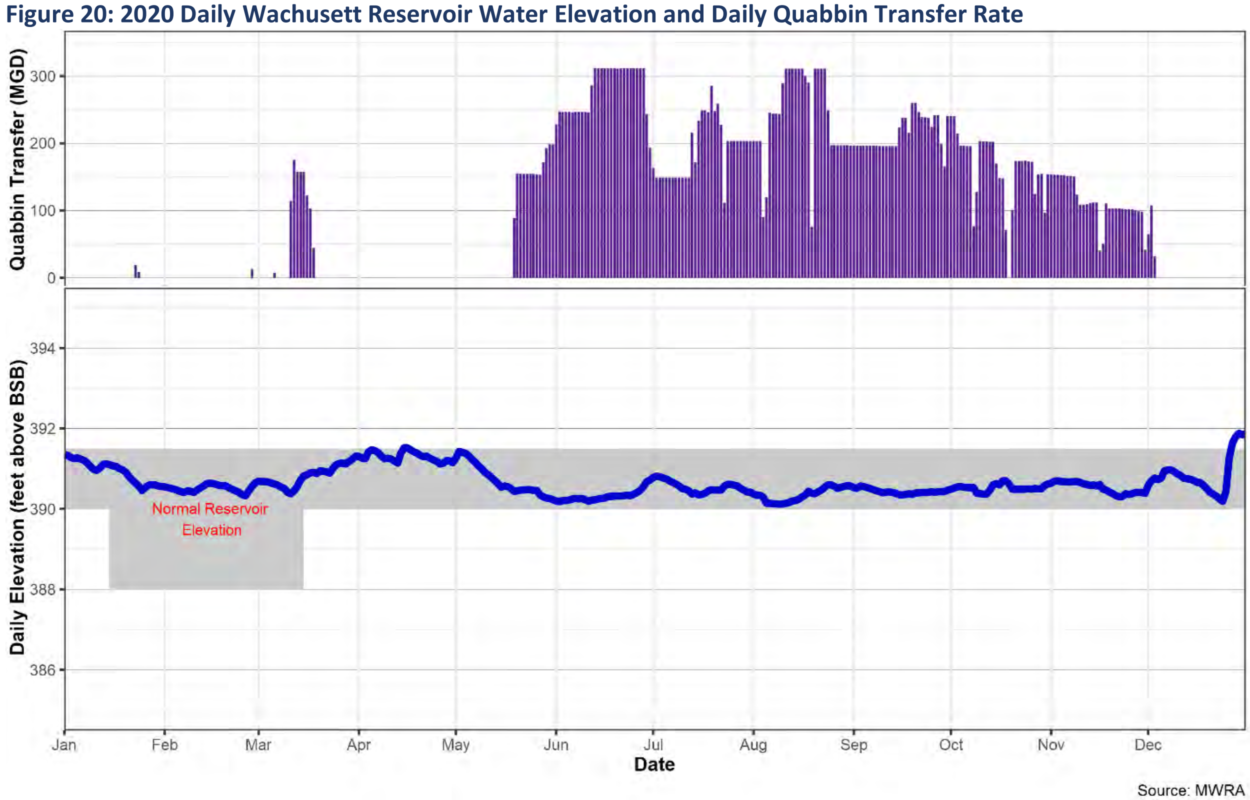
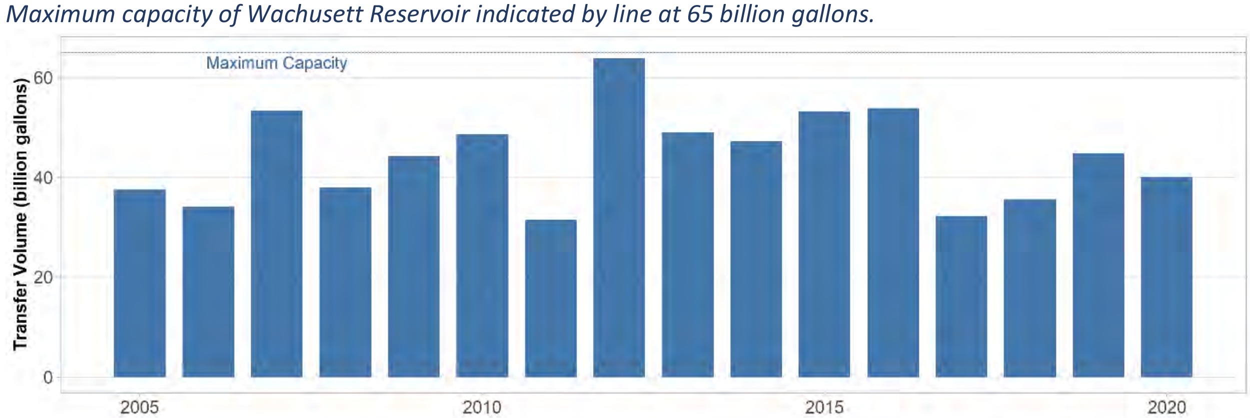


Figure 21: Annual Volume of Quabbin Transfer to Wachusett Reservoir
Maximum capacity of Wachusett Reservoir indicated by line at 65 billion gallons.



3.2 Tributary Monitoring

3.2.1 Water Temperature and Dissolved Oxygen

Tributary water temperature and dissolved oxygen results for 2020 are presented below; however, they are not compared to results from prior years because there are no records of routine maintenance and/or calibrations for field sensors prior to July 2019, and therefore those data do not meet current quality control standards for approval.

In 2020, water temperature in Wachusett Watershed tributaries ranged from -0.1 °C at the Quinapoxet River and Trout, Malden, and East Wachusett Brooks to 27.8 °C, at French Brook. At the 10 monitoring locations where temperature sensors were installed, the 7-day mean maximum temperature (purple line) is shown in Figure 22 and Figure 23 for comparison to the of 20 °C MassDEP coldwater fish resources (CFR) and the 28.3 °C warmwater fish resource (WFR) limit. For the CFR tributaries with temperature sensors, all monitoring locations except for Malden Brook and West Boylston Brook exceeded the 20 °C limit on multiple days over the summer (Table 11). It is likely that the other three CFR tributaries without temperature sensors also exceeded the 20 °C threshold over multiple days in 2020. Based on manual point measurements and continuous sensor data (where available) no tributaries exceeded the WFR threshold during 2020 (Figure 23). While there is no regulatory limit or guidance for drinking water supply temperatures, colder waters are preferred because many solutes (e.g., trace metals) are less soluble and biological productivity (algae, *E. coli*) is slower, which generally helps reduce the likelihood of taste, odor, and other sanitary issues.

Table 11: Coldwater Fish Resource Tributaries that Exceeded the MassDEP Water Temperature Recommended Limit of 20 °C (mean 7-day maximum temperature) in 2020

Monitoring Location	Days Exceeded
Gates Brook 1 - MD04	19
Quinapoxet River (Canada Mills) - MD69	96
Stillwater River - Muddy Pond Rd - MD07	89
Trout Brook - M110	55

Figure 22: Water Temperature and Dissolved Oxygen for Wachusett Tributaries Designated as Coldwater Fish Resources (CFR)

The red horizontal line represents the upper temperature limit for CFR waters (20 °C), while the teal horizontal line represents the lower recommended dissolved oxygen concentration for CFR waters (5.0 mg/L).

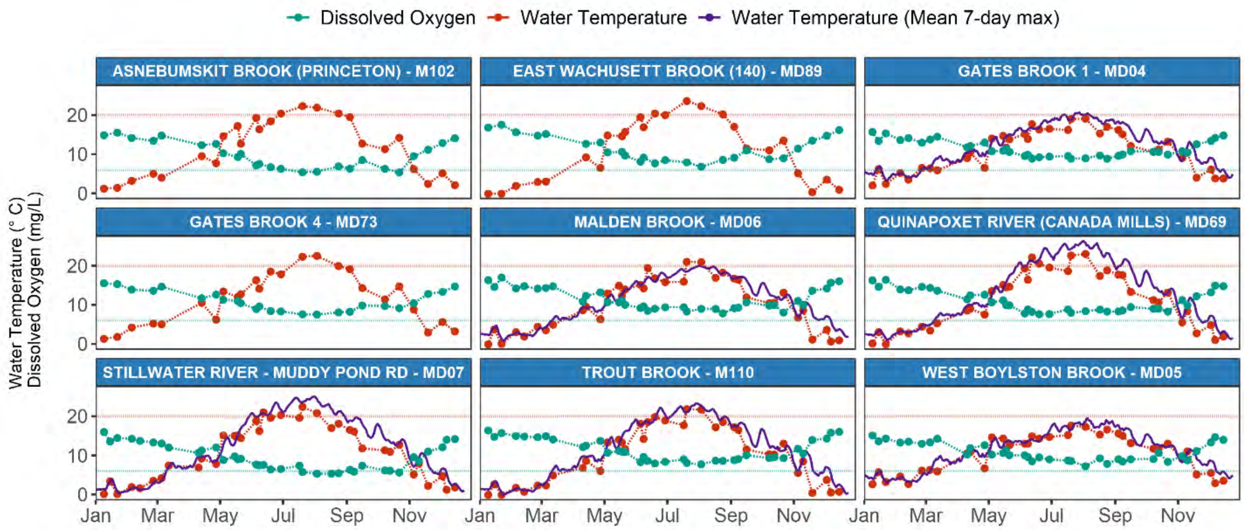
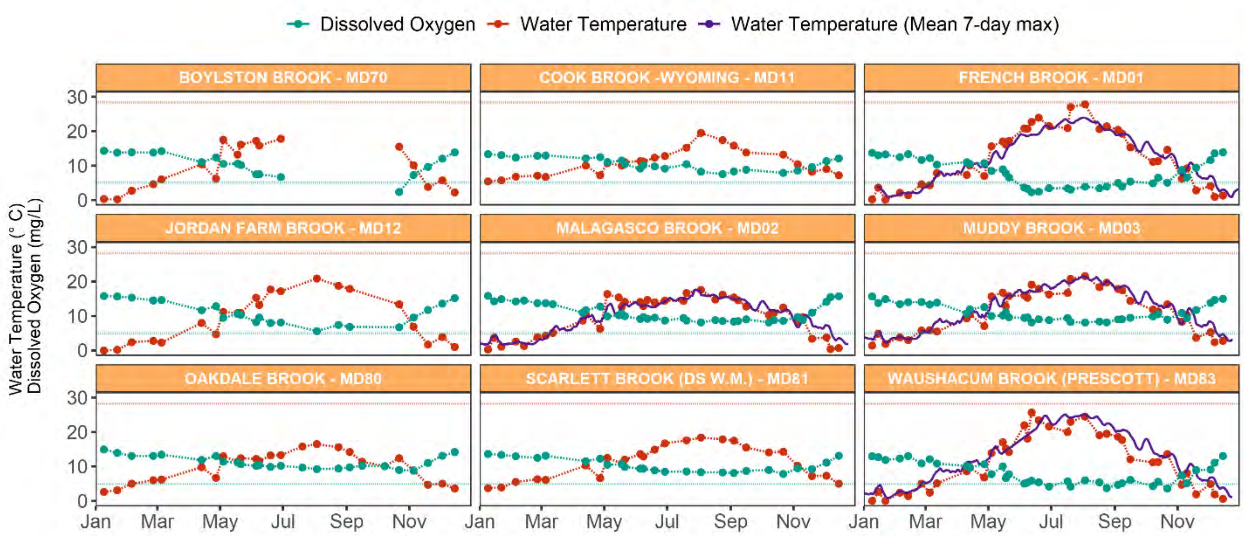


Figure 23: Water Temperature and Dissolved Oxygen for Wachusett Tributaries designated as Warmwater Fish Resources (WFR)

The red horizontal line represents the upper temperature limit for WFR waters (28.3 C), while the teal horizontal line represents the lower recommended dissolved oxygen concentration for WFR waters (5.0 mg/L).



Dissolved oxygen (D.O.) concentrations in 2020 were generally inversely correlated with water temperatures, with the highest concentrations observed during the winter months when water was cold and lowest concentrations observed during the summer months when water was warm. D.O. ranged from a low of 2.29 mg/L to a high of 17.54 mg/L – both at French Brook. For CFR monitoring locations D.O. fell below the MassDEP aquatic life threshold (6 mg/L) at the Stillwater River (six samples) and Asnebumskit Brook (three samples) (Figure 22). For WFR monitoring locations D.O. fell below the MassDEP aquatic life threshold (5 mg/L) at French Brook (13 samples), Waushacum Brook (six samples), and Boylston Brook (one sample) (Figure 23). All of the low D.O. concentrations occurred when water temperatures were high and flows were extremely low and/or stagnant in some reaches.

There are no drinking water standards for D.O., however this parameter is important for regulating many biogeochemical processes that do have ecological importance, which ultimately affect the suitability of water as a drinking water source. Waters with higher D.O. are preferred because they are typically colder and less stagnant, which helps to reduce problematic concentrations of bacteria and algal growth. Low dissolved oxygen is also an indication of eutrophication, which is undesirable for source waters.

3.2.2 Alkalinity and pH

Alkalinity monitoring in Wachusett tributaries was conducted between 2000 and 2012, however the results were not discussed in prior water quality reports. Routine sampling for alkalinity was resumed at all primary tributary monitoring locations in September of 2020 to gain insight into the observed increase in Wachusett Reservoir alkalinity in recent years.

In 2020, and in the earlier monitoring period, alkalinity (as $CaCO_3$) concentrations in the tributaries correspond well with the underlying bedrock carbonate content. A band of calcpelite, which is composed of 15 – 45% carbonate minerals[35], stretches across the Wachusett Watershed through Gates Brook, West Boylston Brook, and Waushacum Brook subbasins. These three tributaries have the highest mean and median alkalinity concentrations in the Wachusett Watershed. Another narrow finger of calcpelite runs under the eastern half of Wachusett Reservoir and the shoreline in Boylston, however this is situated mostly downgradient from monitoring locations on Malagasco, French and Boylston Brooks. Granite and metamorphic rocks, which have little to no carbonic content, comprise most of the bedrock throughout the rest of the watershed. Accordingly, streams draining those areas have lower alkalinity since the groundwater is largely free of carbonic minerals originating from the bedrock.

While there are four or less samples from 2020 to compare with historical results, it appears that several tributaries have experienced a significant increase in alkalinity over the last decade. Median alkalinity in French Brook and the Stillwater and Quinapoxet Rivers may have doubled over the last decade while the other tributaries with data from both time periods have remained relatively static (Table 12). The single 2020 sample from the Quabbin Transfer (3.88 mg/L) is consistent with Quabbin Reservoir alkalinity results from recent years. Quabbin Reservoir experienced a steady rise in alkalinity between 2005 and 2015 - from concentrations just below 3 mg/L to concentrations around 4 mg/L. Thus, the rise in alkalinity in Wachusett Reservoir over the last decade can be explained by the contributions of the Quabbin Transfer and Stillwater and Quinapoxet Rivers. The cause of increasing alkalinity in these tributaries is an area of active DWSP research and any findings will be presented in future water quality reports.

There are no drinking water criteria for alkalinity, however the EPA recommends a minimum concentration of 20 mg/L for the protection of aquatic life. From the limited data collected in 2020 it seems that most Wachusett tributaries satisfied this minimum alkalinity requirement to protect aquatic life. Malagasco and Trout Brooks and the Quinapoxet River were the only Wachusett tributaries more than 2 mg/L below the recommended 20 mg/L alkalinity concentration. As more data is collected it will become possible to make stronger conclusions about how alkalinity has changed over the years and whether the tributaries show any inter-seasonal variation.

---

[35] Grady & Mullaney, 1998

Table 12: Wachusett Tributary Alkalinity (mg/L) 2000 – 2012 Compared to 2020 Results

Sample Location	# Samples 2000-2012	Mean 2000-2012	Median 2000-2012	# Samples 2020	Mean 2020	Median 2020
Cook Brook -Wyoming - MD11	61	30.85	30.80	—	—	—
French Brook - MD01	71	13.32	10.80	4	21.35	19.28
Gates Brook 1 - MD04	77	43.64	44.90	4	42.67	42.55
Jordan Farm Brook - MD12	48	16.88	15.50	—	—	—
Malagasco Brook - MD02	78	11.63	11.10	4	9.65	11.10
Malden Brook - MD06	65	20.37	22.00	4	22.92	26.65
Muddy Brook - MD03	78	21.66	22.55	4	17.92	18.80
Quinapoxet River (Canada Mills) - MD69	138	8.36	7.96	4	12.87	14.00
Rocky Brook (E Branch) - MD13	48	1.47	0.56	—	—	—
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	1	3.88	3.88
Stillwater River - Muddy Pond Rd - MD07	138	7.94	6.85	4	17.12	20.10
Trout Brook - M110	—	—	—	1	8.44	8.44
Waushacum Brook (Prescott) - MD83	—	—	—	4	39.92	41.80
West Boylston Brook - MD05	78	31.63	32.80	4	27.38	32.75

The pH of Wachusett Watershed tributaries has not been discussed in more than two decades. Previous summaries about tributary pH noted that more than a decade of data had been reviewed (pre-2000) and there had been "very little variation either seasonally or over time"[36]. Unfortunately, this historical data is not in digital format and paper records are not available.

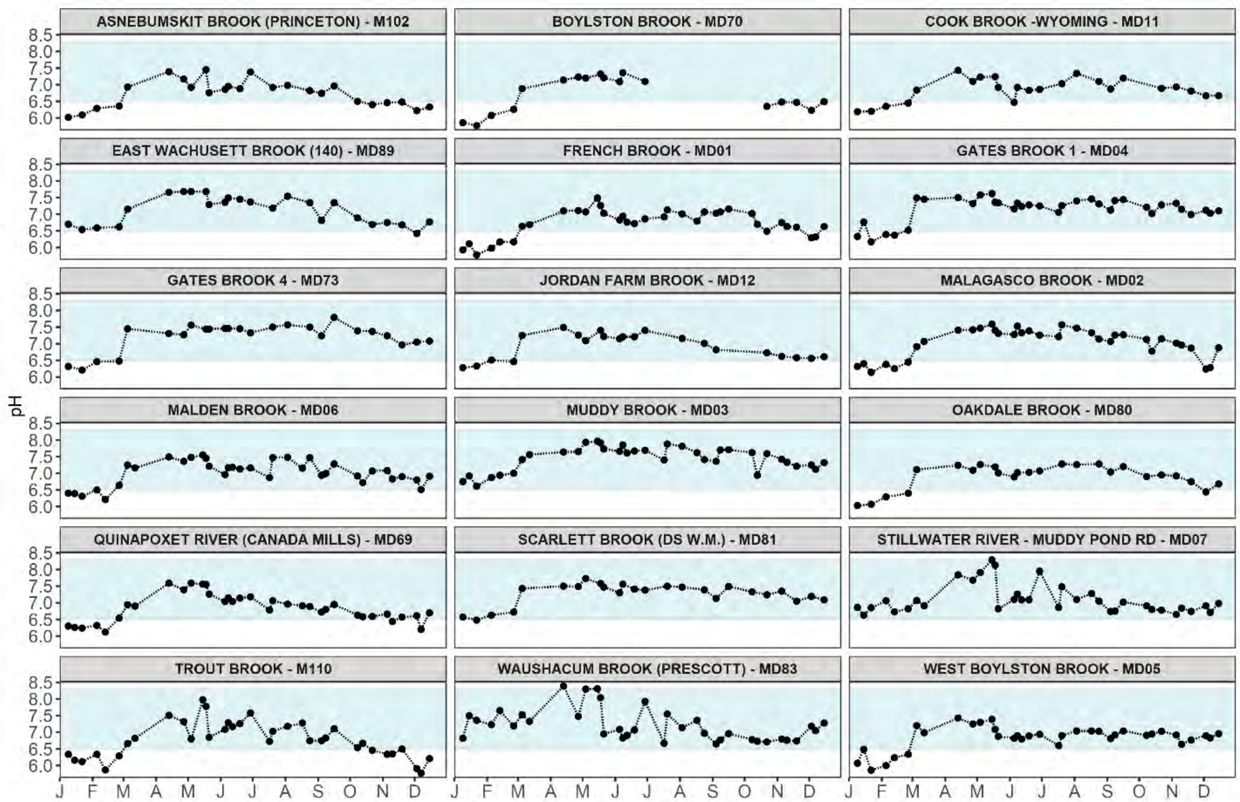
Across all tributary monitoring locations pH values in 2020 ranged from 5.77 at Boylston and Trout Brooks to 8.39 at Waushacum Brook. Waushacum Brook exceeded the MassDEP recommended range for the protection of aquatic life (6.5 – 8.3)[37] on two occasions. pH values below the recommended range are more common in Wachusett tributaries and occurred in every single tributary at least once except for Waushacum Brook, Muddy Brook, and the Stillwater River. Most tributaries experienced a drop in pH during the winter months and an increase in pH during the summer months. Low pH in the colder months was most common in Boylston, Asnebumskit, Trout, and French Brooks.

[36] DWSP, 2008

[37] Massachusetts Surface Water Quality Standards, 2013b

Figure 24: 2020 Results for pH in Wachusett Tributaries

The blue band represents the MassDEP Class A Surface Water standard range for pH, 6.5 – 8.3.



This seasonal pH pattern in Wachusett tributaries mimic findings by the Massachusetts Acid Rain Monitoring Project, which showed average pH values increase in the summer and decrease in the winter in their 1,610 statewide samplings sites[38]. This pattern is most prominent in subbasins with granite and metamorphic bedrock because there is low carbonate mineral content to enhance the buffering capacity of streams, which causes stream pH to be more influenced by precipitation and biological processes. Waushacum Brook does not experience this seasonal decline in pH due to its high alkalinity derived from its calcpelite bedrock.

The pH of natural precipitation, unaffected by anthropogenic acidification, ranges between 4.5 and 5.6[39]. During the last five years, the pH of precipitation in central Massachusetts has been approximately 5.1, which is still somewhat influenced by anthropogenic emissions despite significant increases over the last 30 years[40]. During the growing season, forest vegetation helps buffer the acidity of rainwater and high evapotranspiration rates slow transit times and prevents some of the precipitation from ever reaching the streams[41]. However, during the winter, forest vegetation is primarily dormant and unable to provide acid buffering ecosystem services. Additionally, frozen soils reduce infiltration and precipitation more quickly enters the streams without being buffered by any environmental processes. These seasonal patterns—in addition to some minor land use impacts such as the addition of lime to lawns to improve the growth of

---

[38] Godfrey et al., 1996

[39] Turk, 1983

[40] National Atmospheric Deposition Program, 2021

[41] Hornbeck et al., 1977

grasses—drive the seasonal pattern in pH observed in most of the watershed's streams. While the pH values of Wachusett tributaries are mostly within desired ranges for aquatic life, there is likely some degree of human influenced change to aquatic chemistry due to the weathering of urban landscapes and application of road salt for deicing[42], which may present other threats to aquatic life and degrade overall water quality. The extent and magnitude of these anthropogenic influences on Wachusett tributary chemistry is not certain, however, DWSP will be investigating them as part of its goal to better understand the sources and ramifications of freshwater salinization observed in the watershed.

3.2.3 Specific Conductance and Dissolved Salts

In 2020, tributary specific conductance ranged from to 62 µS/cm at Trout Brook to 3,604 µS/cm at West Boylston Brook. Values of less than 100 µS/cm were recorded in 84% of all samples from Trout Brook (31 of 37) and not at any other location (not including Shaft 1 (MDS1) samples). This represents less than approximately 6% of all specific conductance samples for the year from Wachusett tributaries. Measurements greater than 904 µS/cm, the proxy chronic Cl toxicity threshold[43], were recorded in 17% of all samples from 2020. For individual tributaries, this threshold was exceeded in 92% of samples from Gates Brook 4, 81% of samples from Gates Brook 1, 40% of samples from Oakdale Brook, and 78% of samples from West Boylston Brook. Extremely high specific conductance (>1,800 µS/cm) was observed on one occasion at two tributaries during 2020. On February 13 Gates Brook 1 and West Boylston Brook specific conductance levels were 3,454 and 3,604 µS/cm, respectively – both above the MassDEP proxy acute Cl toxicity threshold of 3,193 µS/cm[44]. The Gates Brook USGS monitoring station recorded a maximum specific conductance on this day of 4,920 µS/cm. Overall, Wachusett tributary specific conductance levels for 2020 are consistent with average annual levels since roughly 2015, both for individual locations and among all locations (Table 13).

[42] Kaushal et al., 2020
[43] MassDEP, 2018
[44] Ibid.

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

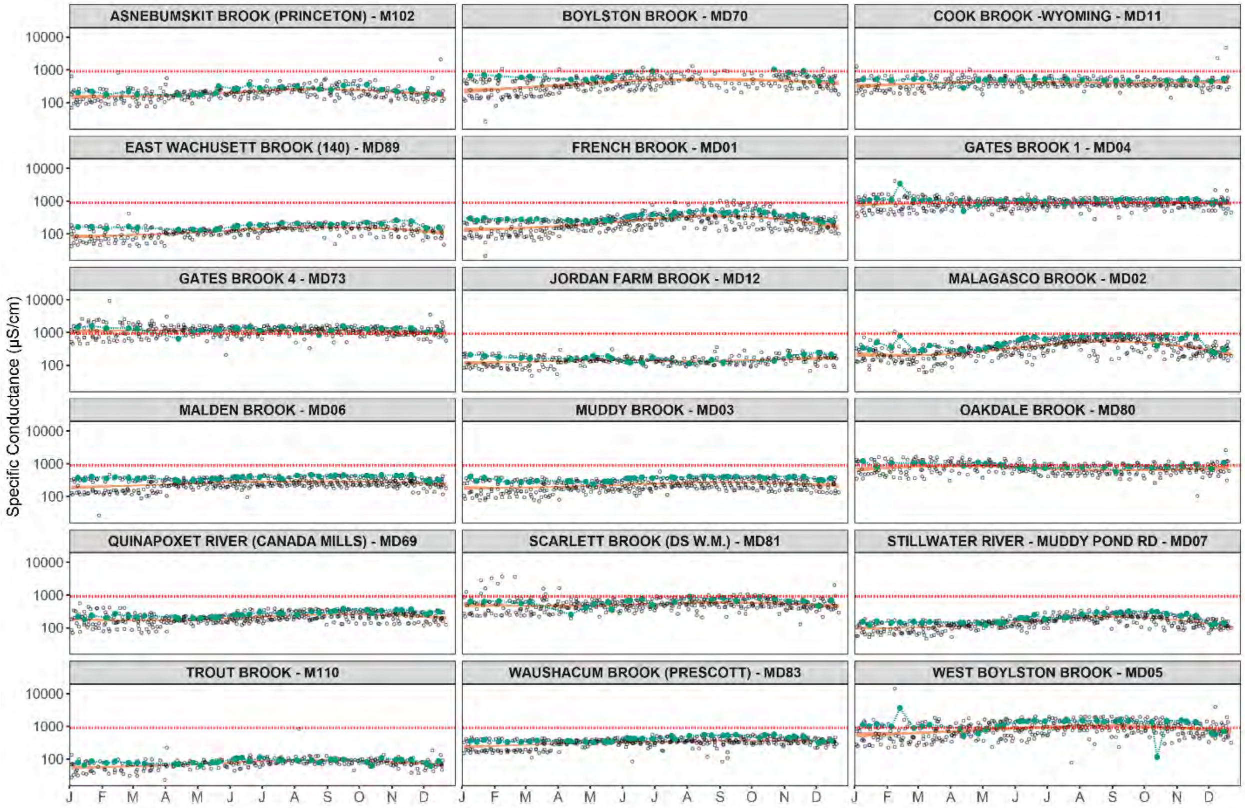
Sample Location	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Asnebumskit Brook (Princeton) - M102	150	197	183	215	254	336	279	249	267	243
Boylston Brook - MD70	261	271	278	373	579	542	594	686	661	679
Cook Brook -Wyoming - MD11	321	378	329	493	475	526	640	624	524	489
East Wachusett Brook (140) - MD89	89	108	123	133	166	174	171	151	169	180
French Brook - MD01	154	162	207	227	321	447	364	290	318	347
Gates Brook 1 - MD04	705	616	715	759	942	1,081	1,272	1,211	1,154	1,075
Gates Brook 4 - MD73	888	835	1,006	1,018	1,276	1,371	1,696	1,558	1,451	1,253
Jordan Farm Brook - MD12	129	129	122	128	124	181	175	183	193	169
Malagasco Brook - MD02	235	292	350	313	447	473	450	432	525	558
Malden Brook - MD06	192	192	199	220	288	334	364	365	371	382
Muddy Brook - MD03	160	154	174	203	273	320	344	333	340	351
Oakdale Brook - MD80	651	534	666	686	872	982	1,136	1,166	989	878
Quinapoxet River (Canada Mills) - MD69	151	167	172	195	255	304	296	250	261	268
Scarlett Brook (DS W.M.) - MD81	463	372	484	514	635	620	771	747	897	632
Stillwater River - Muddy Pond Rd - MD07	120	143	144	142	182	213	170	162	174	200
Trout Brook - M110	33	61	84	74	74	86	96	92	87	86
Waushacum Brook (Prescott) - MD83	275	280	315	284	339	396	420	395	408	421
West Boylston Brook - MD05	566	512	667	739	1,137	1,227	1,700	1,274	1,266	1,221

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 those values are below/above any particular threshold.

Five locations experienced their all-time highest mean annual specific conductance levels in 2020 (East Wachusett Brook, Malagasco Brook, Malden Brook, Muddy Brook, and Waushacum Brook). These locations could have exhibited higher than normal specific conductance due to the prolonged drought. The locations that have historically had the highest mean specific conductance levels showed a slight decline in 2020 and the rising trend seems to have leveled off in recent years. Most locations exhibit a seasonal pattern of elevated levels in late summer through early fall when streamflows are predominantly baseflow driven. In 2020, this was likely amplified by the prolonged drought from June to November, which could explain the all-time high annual mean specific conductance observed at several monitoring locations. This pattern indicates that salts have accumulated in groundwater aquifers over time. The unusually low result at West Boylston Brook on October 13 (116 µS/cm) was recorded during a rainstorm when most of the flow was from overland runoff. Since 2015 or 2016, specific conductance levels at three tributaries remain indicative of chronic elevated dissolved salt concentrations (above 904 µS/cm) which are likely having negative effects on aquatic life: Gates Brook (two stations), Oakdale Brook, and West Boylston Brook. Oakdale Brook fell below the chronic threshold in 2020 but remains very high (Figure 25).

Figure 25: Specific Conductance Measurements at Wachusett Tributaries

The green points show specific conductance results for 2020, while the hollow points show results from years 2011 – 2019, 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.



Roadway deicing products (primarily rock salt) are 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 is discussed in greater detail in a publication by UMass researchers[45].

3.2.3.1 *Chloride*

Chloride (Cl) concentrations in 2020 were similar to 2019 concentrations across most sampling locations (Table 14). Again, West Boylston Brook had the highest average Cl concentration (360 mg/L), followed by Gates Brook 1 (326 mg/L). Trout Brook and the Stillwater River had the lowest average Cl concentrations at 16 and 45 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

[45] Soper, 2020

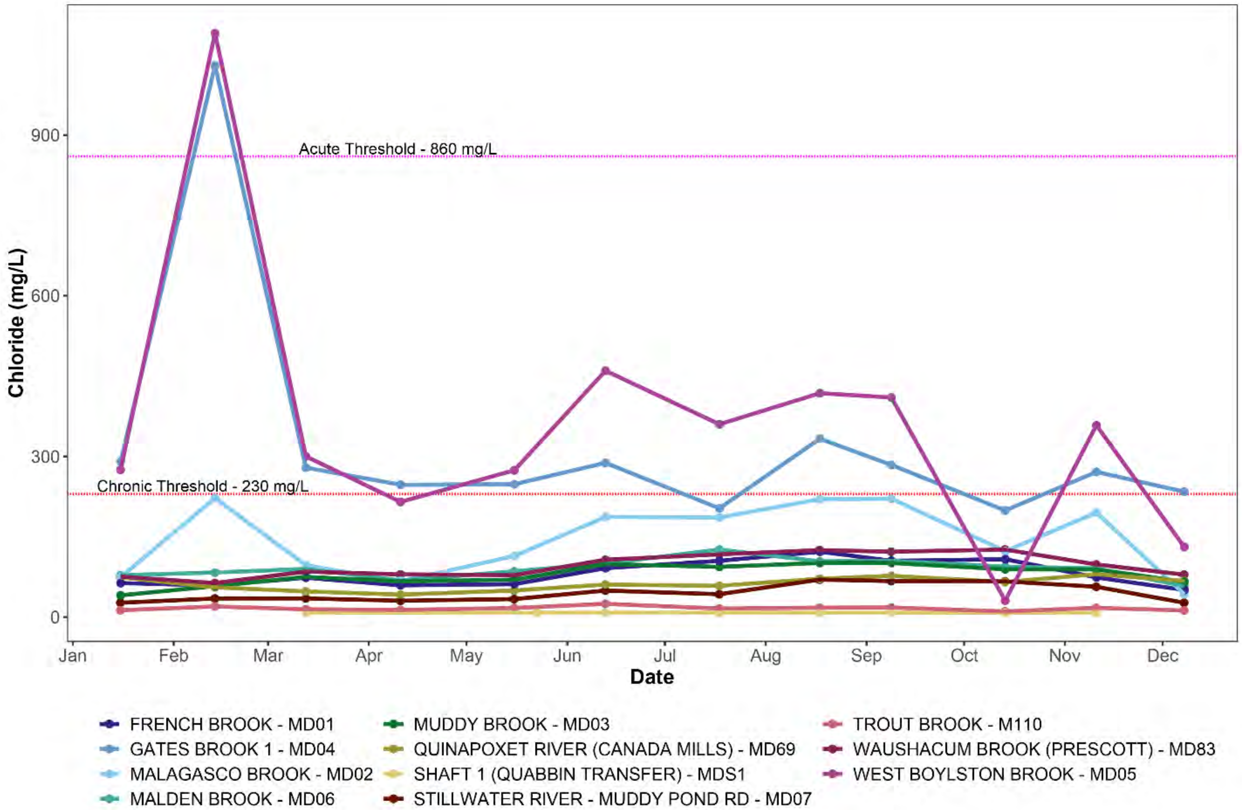
contribute less than 2% of the total inflow to Wachusett Reservoir, so the overall Wachusett Reservoir Cl concentration is well below this threshold. Still, Cl concentration at Gates Brook 1 and West Boylston Brook are detrimental to many species of aquatic plants and animals and contribute to the overall 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 2020

Sample Location	Count	Minimum (mg/L)	Median mg/L)	Average (mg/L)	Maximum (mg/L)	Std. Dev (mg/L)
French Brook - MD01	12	51	74	81	122	24
Gates Brook 1 - MD04	12	199	275	326	1,030	225
Malagasco Brook - MD02	12	42	154	146	222	66
Malden Brook - MD06	12	58	90	90	126	18
Muddy Brook - MD03	12	41	82	79	101	19
Quinapoxet River (Canada Mills) - MD69	12	42	63	62	80	12
Shaft 1 (Quabbin Transfer) - MDS1	8	8	8	8	9	0
Stillwater River - Muddy Pond Rd - MD07	12	27	39	45	70	16
Trout Brook - M110	12	10	16	16	25	4
Waushacum Brook (Prescott) - MD83	12	64	92	96	126	22
West Boylston Brook - MD05	12	31	329	360	1,090	261

Seasonal chloride concentrations in Wachusett tributaries mostly followed the seasonal patterns of specific conductance levels, where concentrations peak in the late summer and early fall months when evapotranspiration rates are high, and groundwater becomes the dominant source of streamflow (Figure 26). The February 13 sampling event coincided with salt-laden melt runoff following a winter storm event where deicing products were applied to the roadways. Chloride monitoring in groundwater is discussed in Section 3.3.

Figure 26: Chloride Concentrations in the Wachusett Tributaries During 2020

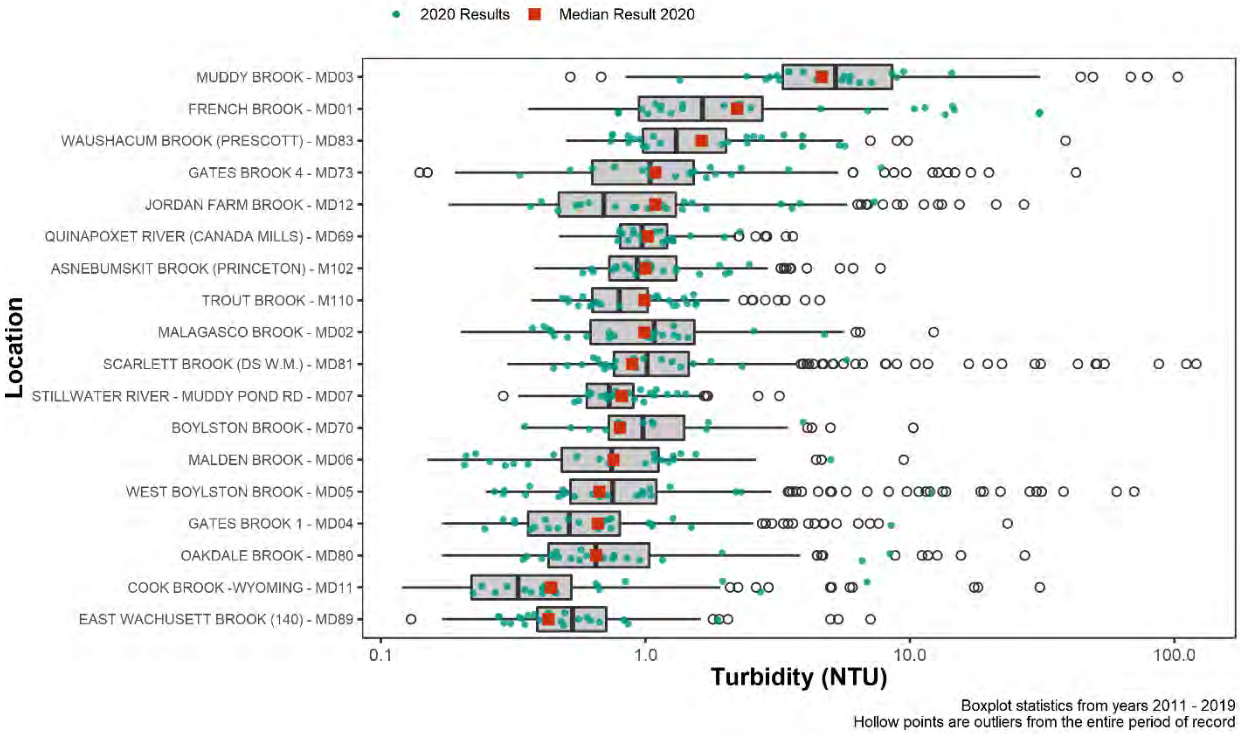


A discussion of other work completed in 2020 related to Cl and conductivity is provided in Section 3.2.9.2.

3.2.4 Turbidity

Turbidity results in Wachusett tributaries in 2020 ranged from 0.21 NTU at Malden Brook to 31 NTU at French Brook. There were 29 samples with turbidity levels of 5.0 NTU or higher, which were predominantly collected from Muddy Brook (10 samples), where elevated concentrations of fine particulate matter are historically persistent and naturally occurring, and at French Brook (8), due to extremely low flows between June and October. Other tributaries accounted for the remaining 11 turbidity results above 5.0 NTU, which were predominantly associated with storm events documented in Section 3.1.1. Dry weather turbidity results above 5.0 NTU were recorded at Waushacum Brook on September 16 and October 8, coinciding with extremely low flows (< 0.5 cfs), and probably due to autochthonous sources (algae) or inadvertent collection of streambed sediment during sample collection.

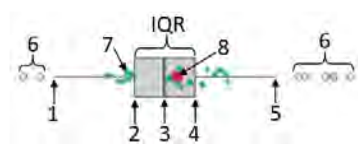
Figure 27: Turbidity Levels in the Wachusett Tributaries During 2020 with 2011 – 2019 Statistics



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 2020 (green circle points)
8) Median result 2020 (red square point)

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



Annual mean turbidity in 2020 ranged from 0.54 NTU at East Wachusett Brook to 6.86 NTU at French Brook. For all sampling locations, aside from French Brook, annual means in 2020 were consistent with annual means for years 2011 – 2019, with no discernable trends during that time range (Table 15).

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

Sample Location	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Asnebumskit Brook (Princeton) - M102	1.14	1.14	0.94	--	1.47	1.14	1.63	1.07	1.12	1.16
Boylston Brook - MD70	1.44	1.35	1.48	0.90	0.98	0.92	1.06	1.13	1.44	1.09
Cook Brook -Wyoming - MD11	0.63	0.83	0.37	1.23	0.63	0.28	1.75	0.55	0.42	0.91
East Wachusett Brook (140) - MD89	0.79	0.56	0.55	0.56	0.60	0.47	0.86	0.65	0.57	0.54
French Brook - MD01	2.19	2.62	2.55	1.61	2.16	1.93	1.56	1.73	2.55	6.86
Gates Brook 1 - MD04	1.02	0.73	0.67	0.70	0.53	0.57	1.16	1.23	0.85	1.00
Gates Brook 4 - MD73	2.44	1.24	1.22	1.43	0.91	0.89	2.73	1.88	1.68	1.63
Jordan Farm Brook - MD12	1.01	1.67	1.39	1.21	1.61	0.51	1.68	2.22	2.44	1.65
Malagasco Brook - MD02	1.81	1.63	1.45	1.10	0.90	0.82	1.13	1.27	1.21	1.08
Malden Brook - MD06	1.12	1.09	0.99	0.79	0.84	0.52	0.75	0.95	0.96	0.96
Muddy Brook - MD03	10.28	7.07	6.90	5.87	5.46	5.48	9.12	6.86	6.83	5.36
Oakdale Brook - MD80	1.03	1.65	0.77	1.15	0.63	0.43	2.12	1.18	0.79	1.28
Quinapoxet River (Canada Mills) - MD69	1.10	1.14	0.94	0.97	1.09	1.00	1.01	1.11	1.17	1.14
Scarlett Brook (DS W.M.) - MD81	5.81	2.20	1.91	5.47	1.05	1.38	3.65	1.91	2.24	1.17
Stillwater River - Muddy Pond Rd - MD07	0.85	0.88	0.76	0.74	0.76	0.75	0.70	0.80	0.83	0.86
Trout Brook - M110	--	1.13	0.82	0.97	1.22	0.60	0.76	0.81	0.90	0.97
Waushacum Brook (Prescott) - MD83	2.34	1.64	1.31	1.64	1.29	2.04	1.74	1.67	1.63	2.09
West Boylston Brook - MD05	2.13	1.33	1.22	3.21	0.86	1.09	3.59	2.22	1.27	1.29

For most locations, the 2020 median turbidity was higher than the 2011 – 2019 median. Annual median turbidity values ranged from 0.43 NTU at East Wachusett Brook to 4.65 NTU in Muddy Brook (Table 16). Turbidity levels were 1.09 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 2020 (NTU)

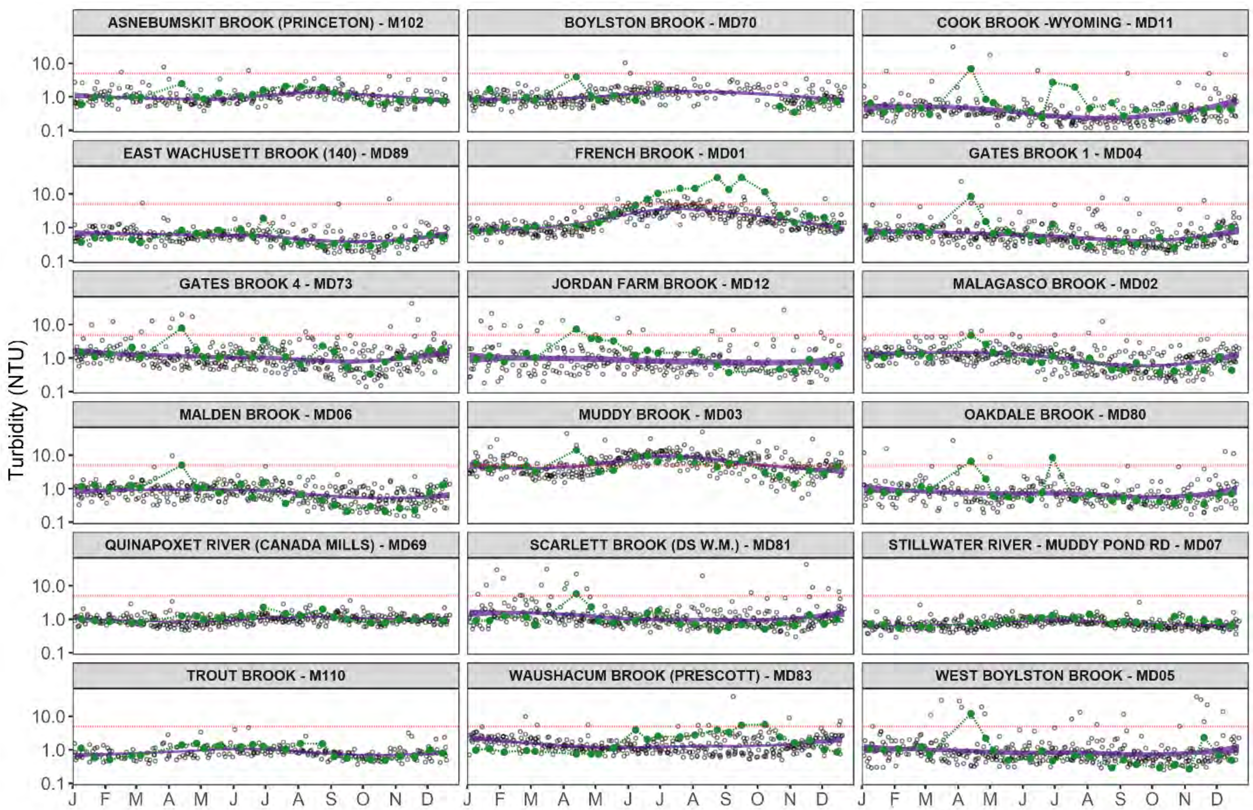
Wet weather samples were collected soon after or during precipitation events of 0.2 inches or more.

Sample Location	Minimum	Maximum	Annual Median	Dry Median	Wet Median
Asnebumskit Brook (Princeton) - M102	0.58	2.5	1.00	0.92	1.75
Boylston Brook - MD70	0.35	4.0	0.80	0.79	1.73
Cook Brook -Wyoming - MD11	0.22	6.9	0.44	0.41	0.75
East Wachusett Brook (140) - MD89	0.28	1.9	0.43	0.43	0.50
French Brook - MD01	0.79	31.0	2.22	1.98	12.00
Gates Brook 1 - MD04	0.25	8.5	0.66	0.66	0.82
Gates Brook 4 - MD73	0.34	7.8	1.09	1.05	2.03
Jordan Farm Brook - MD12	0.37	7.3	1.09	0.97	1.45
Malagasco Brook - MD02	0.37	4.8	0.99	0.76	1.07
Malden Brook - MD06	0.21	5.0	0.76	0.76	0.88
Muddy Brook - MD03	1.35	14.4	4.65	3.95	5.94
Oakdale Brook - MD80	0.34	8.4	0.65	0.60	1.30
Quinapoxet River (Canada Mills) - MD69	0.79	2.3	1.02	0.97	1.26
Scarlett Brook (DS W. M) - MD81	0.45	5.8	0.89	0.89	1.25
Stillwater River - Muddy Pond Rd - MD07	0.54	1.4	0.81	0.81	0.82
Trout Brook - M110	0.48	1.6	0.99	0.68	1.46
Waushacum Brook (Prescott) - MD83	0.74	5.7	1.63	1.14	2.66
West Boylston Brook - MD05	0.27	12.1	0.67	0.69	0.57
All Wachusett Tributaries	**0.21**	**31.0**	**1.16**	**1.03**	**2.12**

Figure 28 shows the variability in turbidity by location for 2020 compared to the prior ten years. Several sampling locations show a historical seasonal pattern of elevated turbidity levels during the summer months (French Brook, Muddy Brook, Asnebumbskit Brook, Boylston Brook), while others exhibit less seasonality, remaining low year-round (Stillwater River, Quinapoxet River). In 2020, summer season turbidity was consistently higher than normal at many tributaries, likely because of extremely low flows. French Brook experienced extremely elevated turbidity levels from June through October and the elevated turbidity was likely attributed to autochthonous particles in the water column, rather than turbid runoff from the land surface. Other instances of elevated turbidity were observed at several locations on April 13 and again on June 29; both were related to stormwater runoff.

Figure 28: Turbidity Results at Wachusett Tributaries

The green points show turbidity results for 2020, while the hollow points show results from years 2011 – 2019, 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 5.0 NTU.



The standard for turbidity is 5.0 NTU at drinking water intakes under the SWTR and 1.0 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 2020 were generally very low for moving surface waters and indicative of excellent water quality, predominantly below the 5.0 NTU intake standard. Differences observed between tributaries reflect variations in subbasin land cover, topography, surficial geology, land disturbances from development, agriculture, and other factors. The overall mean turbidity for Wachusett tributaries was 1.72 NTU and the median was 1.16 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.

3.2.5 Total Suspended Solids

Total suspended solids (TSS) in Wachusett tributaries ranged from less than 5.0 mg/L (detection limit) to 148 mg/L at West Boylston Brook. Only 14 of 128 samples contained more than the detection limit, and most of these samples 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 2020 were consistent with the previous nine years, with no significant trends over time (Table 17). The three locations that reflected higher mean TSS than in prior years were West Boylston Brook, French Brook, and Muddy Brook. Elevated TSS in French Brook in 2020 was directly related to the extreme low flows between June and October (water depths less than one inch). The elevated mean TSS concentrations at Muddy Brook and West Boylston Brook were mostly due to single high concentrations on October 13 after nearly two inches of rainfall. It should be noted that TSS results below detection limits (typically 5 mg/L) were assigned values of one-half the detection limit (typically 2.5 mg/L), and since most samples (89%) were below detection limits, the values presented below 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	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
French Brook - MD01	2.52	9.08	5.80	4.66	3.02	3.84	3.00	4.71	7.65	10.96
Gates Brook 1 - MD04	2.93	3.13	2.23	4.20	2.48	3.25	2.21	2.56	3.08	3.33
Malagasco Brook - MD02	2.95	3.25	4.32	2.83	2.80	3.10	3.58	2.93	4.25	4.50
Malden Brook - MD06	—	3.42	2.45	3.60	4.27	3.13	2.50	2.77	2.82	2.83
Muddy Brook - MD03	4.43	4.90	4.11	2.82	2.50	6.74	11.99	6.12	5.21	8.58
Quinapoxet River (Canada Mills) - MD69	2.31	3.60	2.77	2.33	2.49	3.13	2.50	2.75	2.50	2.50
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	1.75	2.82	2.45	2.50
Stillwater River - Muddy Pond Rd - MD07	2.10	2.62	2.38	2.33	2.50	3.88	2.43	2.49	2.50	2.71
Trout Brook - M110	—	—	—	—	2.91	2.94	2.50	2.92	2.75	2.50
Waushacum Brook (Prescott) - MD83	—	2.65	3.83	2.44	2.50	2.89	2.43	5.06	3.00	2.79
West Boylston Brook - MD05	8.34	2.92	2.84	9.98	2.49	2.77	4.33	4.88	2.96	15.96

Dash (—) = No data

3.2.6 *E. coli* Bacteria in Tributaries

Bacteria samples collected from the tributary stations during 2020 contained a wide range of *E. coli* concentrations, from less than the lower detection limit (10 MPN/100 mL) in approximately 26% of all samples to a high of more than 24,200 MPN/100 mL (upper quantification limit) at Gates Brook 4 on June 29 (Figure 29). As in previous years, the highest concentrations were mostly recorded during or following precipitation. Nine of the eleven samples that exceeded 1,000 MPN/100 mL were collected during or immediately following rain events, six of which were from June 29. The only dry weather samples that exceeded 1,000 MPN/100 mL were collected from Muddy Brook on November 5 and from West Boylston Brook on February 5 after a winter thaw (air temperatures in 40s (°F)). A follow up sample was taken on November 9 at Muddy Brook following the high result on November 5 (9,800 MPN/100 mL). This sample result (399 MPN/100 mL) and the subsequent routine sample result on November 19 (10 MPN/100 mL) confirmed that the bacteria source was not persistent. Field reconnaissance on November 10 located a beaver dam that had been constructed on Muddy Brook less than 1,000 feet upgradient of the sample location. It is possible that beaver were the source of elevated bacteria, however this was never confirmed. DWSP Natural Resources staff worked with the property owner at the beaver dam site to address the beaver activity at this location.

In 2020, all Wachusett Reservoir tributaries exceeded the MA Class A surface water quality standard single sample limit of 235 MPN/100 mL on at least one monitoring occasion (Table 18 and Figure 29). Most tributaries exhibit a seasonal increase in bacteria levels during the summer months when there are more favorable physical, chemical, and biological conditions for growth and survival, of which temperature is a dominant driver.

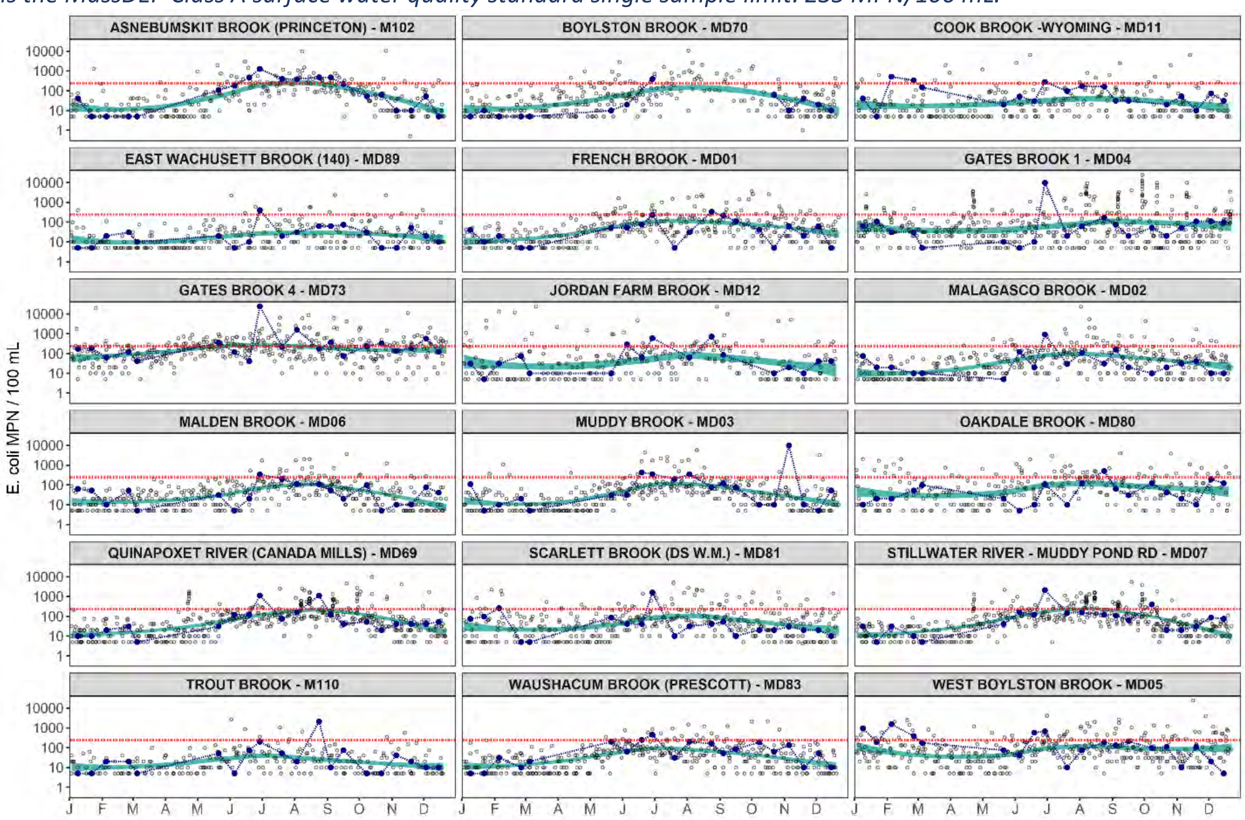
During the late summer and early fall of 2020, several routine bacteria samples were not collected because the streams had no surface flow:

- Boylston Brook (MD70) dry on: 06/19/2020, 07/20/2020 to 10/08/2020
- Jordan Farm (MD12) dry on: 07/20/2020, 09/16/2020, 10/08/2020
- Cook Brook (MD11) dry on: 10/08/2020

Three scheduled sample events during April and early May 2020 were also missed due to MWRA lab closure for the COVID-19 pandemic.

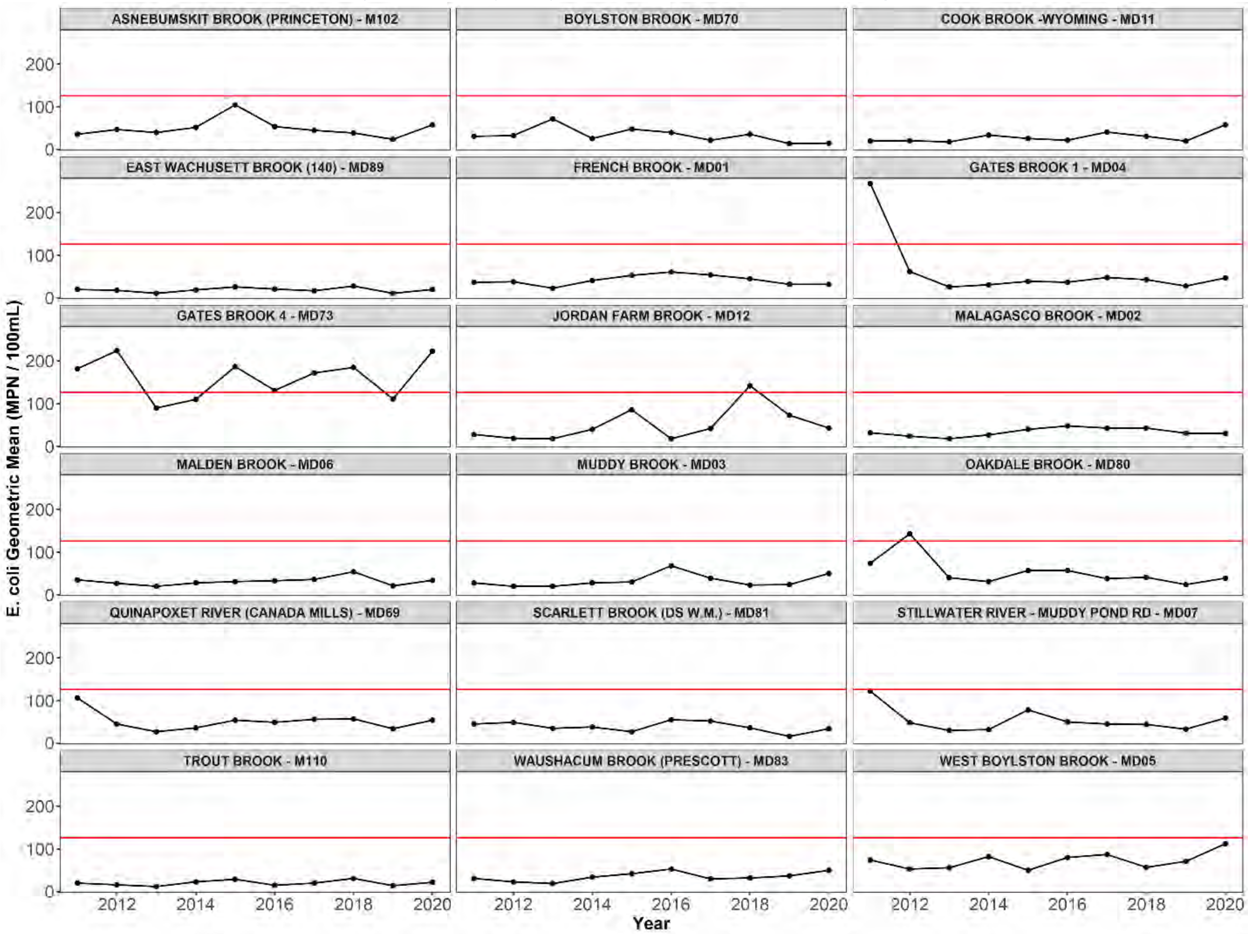
Figure 29: *E. coli* Concentrations in Wachusett Tributaries

The blue points show E. coli results for 2020, while the hollow points show results from years 2011 – 2019, with the green band representing a LOESS smooth function 95% confidence interval for the same period. The red dashed line is the MassDEP Class A surface water quality standard single sample limit: 235 MPN/100 mL.



Annual geometric mean concentrations of *E. coli* over the past 10 years do not show any discernible trend and 2020 annual geometric means were similar to previous years across all sample locations (Figure 30).

Figure 30: Annual Geometric Mean *E. coli* for Wachusett Reservoir Tributaries (MPN/100 mL)
Values below detection limits (<10 MPN/100 mL) were substituted with 1/2 the detection limit[46]. 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, except for Gates Brook 4, met the MassDEP Class A surface water standard for *E. coli of* 126 MPN/100 mL in 2020 (Table 18). Boylston Brook had the lowest 2020 geometric mean (15 MPN/100 mL); however, it was dry during the typical months of elevated bacteria. As in 2019, Gates Brook 4 had the highest geometric mean (223 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[47].

[46] MassDEP, 2018
[47] DWSP, 2019

Table 18: Annual *E. coli* Geometric Mean in Wachusett Tributaries (MPN/100 mL)
GMEAN = Geometric Mean.

Sample Location	GMEAN 2017	GMEAN 2018	GMEAN 2019	GMEAN 2020	%>235 2017	%>235 2018	%>235 2019	%>235 2020
Asnebumskit Brook (Princeton) - M102	45	39	24	58	12	29	12	30
Boylston Brook - MD70	22	36	14	15	2	5	10	8
Cook Brook -Wyoming - MD11	41	31	20	58	12	0	0	16
East Wachusett Brook (140) - MD89	17	28	11	20	4	4	0	5
French Brook - MD01	54	45	32	32	14	17	8	5
Gates Brook 1 - MD04	48	43	28	47	10	8	8	5
Gates Brook 4 - MD73	172	185	111	223	45	29	21	30
Jordan Farm Brook - MD12	42	142	73	43	9	35	25	18
Malagasco Brook - MD02	43	43	31	30	14	17	8	5
Malden Brook - MD06	36	54	21	34	4	17	4	5
Muddy Brook - MD03	39	23	24	50	4	0	8	20
Oakdale Brook - MD80	38	41	24	39	16	8	4	5
Quinapoxet River (Canada Mills) - MD69	56	57	34	54	8	4	4	10
Scarlett Brook (DS W. M) - MD81	52	36	16	34	14	4	4	10
Stillwater River - Muddy Pond Rd - MD07	45	44	33	59	12	4	4	10
Trout Brook - M110	20	31	14	22	2	4	4	5
Waushacum Brook (Prescott) - MD83	30	32	37	50	2	8	0	10
West Boylston Brook - MD05	87	57	71	112	22	12	17	25

2020 geometric means were higher than both the five-year average and ten-year average geometric means for 10 of 18 tributaries (Table 19). Gates Brook 4, Cook Brook and West Boylston Brook were the only tributaries to have a 2020 geometric mean substantially higher than normal, whereas other tributaries had 2020 geometric means close to their historical averages.

Table 19: Trends in Geometric Mean *E. coli* Concentrations (MPN/100 mL)

Sample Location	2020 GEOMETRIC MEAN	5 YEAR MEAN	10 YEAR MEAN
Asnebumskit Brook (Princeton) - M102	58	44	50
Boylston Brook - MD70	15	25	34
Cook Brook -Wyoming - MD11	58	34	29
East Wachusett Brook (140) - MD89	20	19	19
French Brook - MD01	32	45	42
Gates Brook 1 - MD04	47	41	63
Gates Brook 4 - MD73	223	164	162
Jordan Farm Brook - MD12	43	64	51
Malagasco Brook - MD02	30	39	34
Malden Brook - MD06	34	36	32
Muddy Brook - MD03	50	41	33
Oakdale Brook - MD80	39	40	54
Quinapoxet River (Canada Mills) - MD69	54	50	52
Scarlett Brook (DS W. M) - MD81	34	39	39
Stillwater River - Muddy Pond Rd - MD07	59	46	54
Trout Brook - M110	22	20	20
Waushacum Brook (Prescott) - MD83	50	40	35
West Boylston Brook - MD05	112	81	72

In 2020, wet weather samples continued to have higher bacteria concentrations than dry weather samples (Table 20). For all sampling locations, exceedances of the MassDEP 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 2020 (MPN/100 mL)

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	33	577	31.2	0	12.5	100	16	4
Boylston Brook - MD70	12	393	33.3	0	0	100	12	1
Cook Brook -Wyoming - MD11	47	125	6.7	0	13.3	25	15	4
East Wachusett Brook (140) - MD89	14	84	31.2	0	0	25	16	4
French Brook - MD01	21	151	31.2	0	0	25	16	4
Gates Brook 1 - MD04	30	297	12.5	0	0	25	16	4
Gates Brook 4 - MD73	145	1249	0	0	18.8	75	16	4
Jordan Farm Brook - MD12	26	220	7.7	0	7.7	50	13	4
Malagasco Brook - MD02	20	149	6.2	0	0	25	16	4
Malden Brook - MD06	24	120	18.8	0	0	25	16	4
Muddy Brook - MD03	36	183	18.8	0	12.5	50	16	4
Oakdale Brook - MD80	28	143	6.2	0	0	25	16	4
Quinapoxet River (Canada Mills) - MD69	33	394	6.2	0	0	50	16	4
Scarlett Brook (DS W. M) - MD81	26	102	12.5	0	6.2	25	16	4
Stillwater River - Muddy Pond Rd - MD07	41	257	12.5	0	6.2	25	16	4
Trout Brook - M110	15	96	37.5	0	0	25	16	4
Waushacum Brook (Prescott) - MD83	37	166	12.5	0	6.2	25	16	4
West Boylston Brook - MD05	99	188	6.2	0	25	25	16	4

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 2020 continued to indicate good sanitary quality.

3.2.7 Nutrient Dynamics

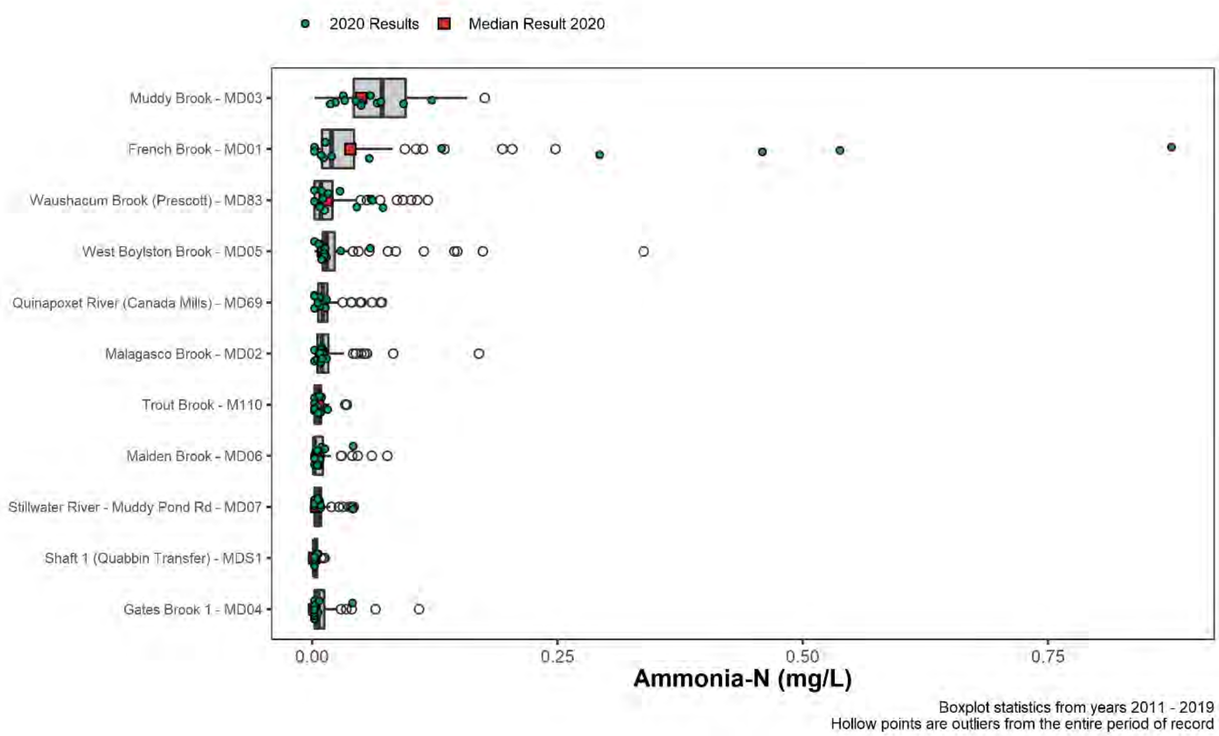
Results for monthly tributary nutrient monitoring in Wachusett tributaries are presented below. Sampling results for Quabbin Transfer water are not discussed but are included in the tables and figures because transfer water is a large percentage of the annual inflow to Wachusett Reservoir and has a significant impact on reservoir nutrient dynamics and overall reservoir water quality.

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

Ammonia-Nitrogen

In 2020 Ammonia-nitrogen (NH_3-N) was detected above historical 75th percentile concentrations at several tributaries due to the summer drought conditions. Concentrations at French Brook exceeded 0.25 mg/L on four occasions, three of which are the highest tributary NH_3-N concentrations ever observed in the Wachusett Watershed except for a single instance at Jordan Farm Brook. Despite the high concentrations at French Brook during the summer, Muddy Brook continues to have the highest median annual concentration of NH_3-N (Figure 31). After four years of successively higher NH_3-N concentrations at Muddy Brook the 2020 mean concentration was at its lowest level since 2011. The Muddy Brook sample location is immediately downgradient to a closed landfill in West Boylston, which is a potential source of elevated NH_3-N, although this has yet to be verified.

Figure 31: 2020 Ammonia-Nitrogen Concentrations with 2011 - 2019 Statistics



Due to the high number of non-detection lab results (<0.005 mg/L) the values presented in Table 21 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 French and Waushacum Brooks. These two tributaries had 2020 median NH_3-N concentrations close to their respective historical 75th percentiles. There were also several high outlier samples occurring across a few locations during the late summer/fall low flow period – most notably at French Brook. Trout and Gates Brooks had the lowest annual mean NH_3-N concentrations in 2020 (0.006 mg/L).

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

Table 21: Ammonia-Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
French Brook - MD01	0.039	0.045	0.051	0.034	0.041	0.018	0.011	0.029	0.026	0.201
Gates Brook 1 - MD04	0.005	0.007	0.008	0.014	0.012	0.013	0.008	0.009	0.013	0.006
Malagasco Brook - MD02	0.016	0.014	0.013	0.015	0.029	0.012	0.014	0.011	0.014	0.008
Malden Brook - MD06	—	0.011	0.006	0.009	0.016	0.005	0.005	0.012	0.006	0.009
Muddy Brook - MD03	0.066	0.069	0.065	0.067	0.076	0.060	0.078	0.086	0.094	0.055
Quinapoxet River (Canada Mills) - MD69	0.015	0.012	0.012	0.017	0.021	0.010	0.015	0.011	0.011	0.008
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	0.004	0.003	0.006	0.003
Stillwater River - Muddy Pond Rd - MD07	0.010	0.008	0.008	0.012	0.011	0.006	0.006	0.005	0.005	0.008
Trout Brook - M110	—	—	—	—	0.012	0.006	0.008	0.005	0.007	0.006
Waushacum Brook (Prescott) - MD83	—	0.019	0.014	0.025	0.023	0.010	0.012	0.012	0.028	0.028
West Boylston Brook - MD05	0.022	0.013	0.014	0.049	0.021	0.016	0.037	0.027	0.034	0.016

Nitrite-Nitrogen

Nitrite-nitrogen (NO_2-N) is rarely detected in Wachusett Reservoir tributaries, therefore results are not displayed below. In 2020, the highest recorded (routine sample) NO_2-N concentration was 0.0076 mg/L at Muddy Brook, with only four of the 128 samples collected in 2020 falling above the detection limit of 0.005 mg/L: at West Boylston Brook, Muddy Brook, and the Quinapoxet River on June 12 and at French Brook on October 13. 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 2020 were below the EPA MCL of 1.0 mg/L.

Nitrate-Nitrogen

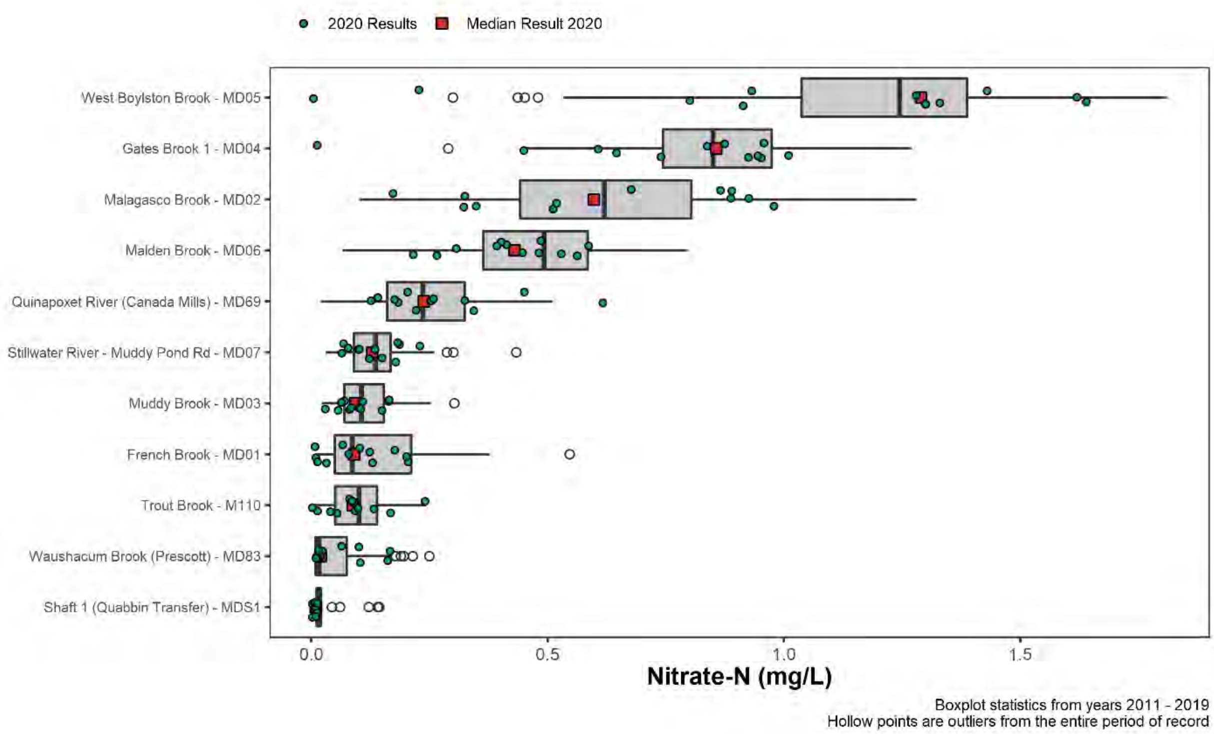
Annual mean NO_3-N concentrations for 2020 ranged from less than 0.059 mg/L at Waushacum Brook to 1.065 mg/L at West Boylston Brook (Table 22), with individual measurements from below detection (< 0.005 mg/L) to 1.64 mg/L in West Boylston Brook. The average annual NO_3-N concentrations at individual tributaries have been stable over the last several years, with 2020 concentrations slightly lower than in 2019 for most tributaries. In 2020, individual samples were predominantly within the historical 25th - 75th percentile ranges by respective tributary. Median NO_3-N concentrations in 2020 were close to historical medians from the 2011 – 2019 period (Figure 28).

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

Sample Location	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
French Brook - MD01	0.154	0.127	0.159	0.167	0.093	0.153	0.110	0.134	0.119	0.096
Gates Brook 1 - MD04	0.930	0.801	0.920	0.856	0.786	0.762	0.925	0.846	0.886	0.747
Malagasco Brook - MD02	0.426	0.489	0.684	0.583	0.704	0.615	0.684	0.599	0.626	0.619
Malden Brook - MD06	—	0.432	0.550	0.443	0.534	0.443	0.488	0.452	0.463	0.424
Muddy Brook - MD03	0.089	0.098	0.144	0.135	0.134	0.139	0.108	0.110	0.095	0.098
Quinapoxet River (Canada Mills) -	0.185	0.222	0.253	0.251	0.291	0.208	0.320	0.239	0.277	0.275
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	0.020	0.053	0.020	0.009
Stillwater River - Muddy Pond Rd -	0.157	0.140	0.163	0.136	0.155	0.122	0.134	0.108	0.127	0.133
Trout Brook - M110	—	—	—	—	0.107	0.097	0.099	0.101	0.095	0.092
Waushacum Brook (Prescott) - MD83	—	0.036	0.040	0.045	0.053	0.022	0.030	0.069	0.073	0.059
West Boylston Brook - MD05	1.087	1.168	1.392	1.142	1.250	1.198	1.284	1.069	1.170	1.065

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 higher proportion of agricultural runoff (Malagasco) and potential septic system failures (Malden and Malagasco). The impact of septic systems on nitrate loading in Wachusett subbasins is discussed further in Section 3.2.9.4. 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.

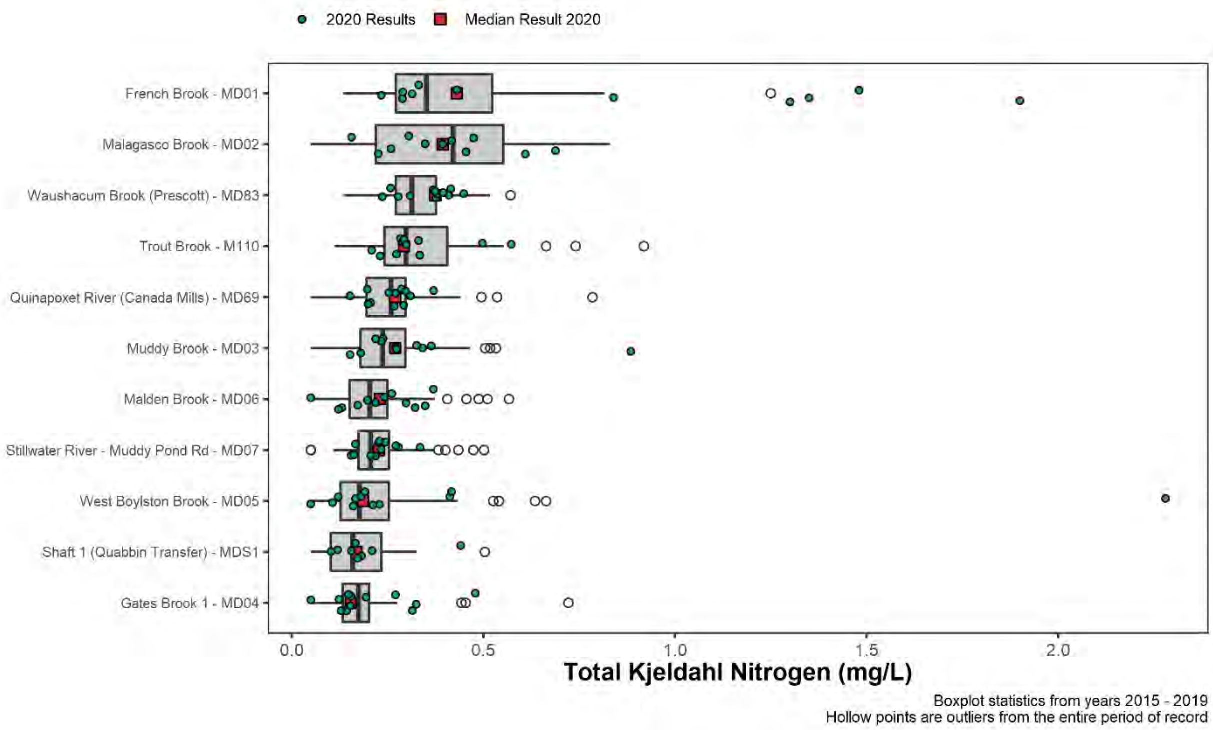
Figure 32: 2020 Nitrate-Nitrogen Concentrations with 2011 - 2019 Statistics



Total Kjeldahl Nitrogen

Annual mean Total Kjeldahl Nitrogen (TKN) concentrations have been relatively consistent since 2015, when monitoring for this parameter in Wachusett tributaries began. Individual TKN sample concentrations in 2020 ranged from 0.05 mg/L at Gates Brook 1 to 2.28 mg/L at West Boylston Brook, which was the highest TKN concentration ever observed in the Wachusett tributaries (Figure 33). French Brook had the highest mean TKN concentration for 2020 (0.796 mg/L), and elevated concentrations (1.3 mg/L and above) persisted through the low flow period of the summer/fall and were the next highest TKN results on record after the 2.28 mg/L result at West Boylston Brook. The Stillwater River had the lowest mean TKN concentration (0.227 mg/L).

Figure 33: 2020 Total Kjeldahl Nitrogen Concentrations with 2015 - 2019 Statistics



The mean and median annual TKN concentrations observed in 2020 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 23: Total Kjeldahl Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2015	2016	2017	2018	2019	2020
French Brook - MD01	0.3910	0.3560	0.3580	0.4800	0.4210	0.7960
Gates Brook 1 - MD04	0.1480	0.2100	0.1520	0.1520	0.2170	0.2070
Malagasco Brook - MD02	0.3510	0.3420	0.4650	0.4720	0.3890	0.3940
Malden Brook - MD06	0.2310	0.2180	0.2020	0.2440	0.1980	0.2280
Muddy Brook - MD03	0.2520	0.2270	0.2700	0.2670	0.2480	0.3170
Quinapoxet River (Canada Mills) - MD69	0.2900	0.2880	0.2460	0.2600	0.2600	0.2580
Shaft 1 (Quabbin Transfer) - MDS1	—	—	0.1020	0.2080	0.1820	0.1940
Stillwater River - Muddy Pond Rd - MD07	0.2060	0.2660	0.2240	0.2120	0.2010	0.2270
Trout Brook - M110	0.2570	0.3100	0.3510	0.3450	0.3810	0.3290
Waushacum Brook (Prescott) - MD83	0.2810	0.3610	0.3030	0.3240	0.3380	0.3540
West Boylston Brook - MD05	0.1740	0.1880	0.1740	0.2440	0.2690	0.3770

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, except for French Brook which had a mean annual TKN concentration in 2020 nearly double what it has been in prior years. Fortunately, the flow contribution of French Brook to Wachusett Reservoir during the months of elevated TKN was a relatively insignificant and it did not influence the reservoir TKN concentrations. Overall, mean annual TKN concentrations are close to the ecoregional reference conditions and not indicative of any water quality problems.

Total Nitrogen

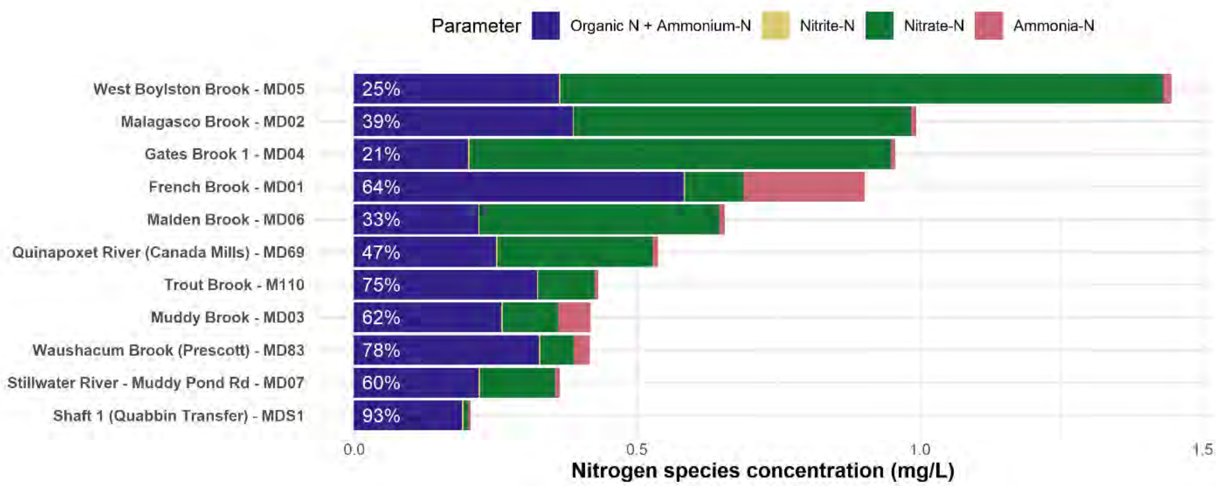
Total Nitrogen (TN) concentrations in 2020 ranged from 0.18 mg/L at Muddy Brook to 2.51 at West Boylston Brook, with mean annual concentrations for 2020 ranging from 0.36 mg/L at Stillwater River to 1.45 mg/L at West Boylston Brook. TN has been very consistent at each tributary since 2015, until 2020 when the French Brook mean TN concentration was nearly double the concentration of prior years. Once again, this mean is not flow weighted, and was heavily skewed by the concentrated nutrient levels that occurred during low flow conditions in the summer and fall months. In 2020 West Boylston Brook was the only tributary with a mean annual TN concentration in excess of 1 mg/L (Table 24).

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

Sample Location	2015	2016	2017	2018	2019	2020
French Brook - MD01	0.486	0.511	0.470	0.617	0.542	0.903
Gates Brook 1 - MD04	0.936	0.975	1.069	1.001	1.106	0.956
Malagasco Brook - MD02	1.058	0.959	1.151	1.073	1.017	0.993
Malden Brook - MD06	0.768	0.664	0.693	0.699	0.663	0.654
Muddy Brook - MD03	0.389	0.370	0.381	0.379	0.346	0.418
Quinapoxet River (Canada Mills) - MD69	0.584	0.498	0.568	0.502	0.540	0.537
Shaft 1 (Quabbin Transfer) - MDS1	—	—	0.124	0.263	0.204	0.205
Stillwater River - Muddy Pond Rd - MD07	0.364	0.391	0.360	0.322	0.330	0.363
Trout Brook - M110	0.446	0.409	0.453	0.449	0.478	0.431
Waushacum Brook (Prescott) - MD83	0.337	0.385	0.336	0.395	0.413	0.416
West Boylston Brook - MD05	1.426	1.388	1.461	1.316	1.442	1.445

Figure 34 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 in the Appendix, Section A.4) 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 34: 2020 Mean Total Nitrogen Concentrations at Wachusett Tributaries.
Percentages indicate the organic nitrogen fraction of total nitrogen at each sample location.



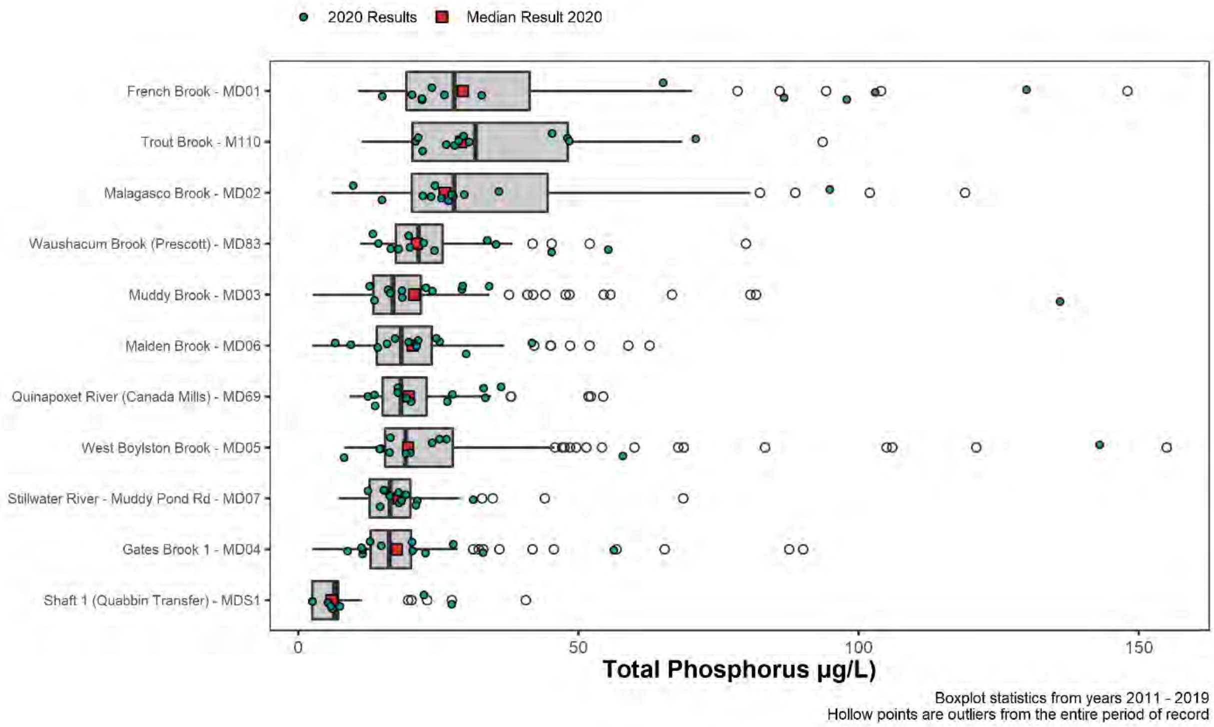
Concentrations of TN within Wachusett tributaries are mostly within the range of ecoregional background concentrations (0.42 – 0.69 mg/L), which are suggested reference conditions for numerical criteria development. West Boylston, Gates, Malagasco and French Brooks all exceed these concentrations, likely because of either urban/suburban development, golf courses, or agriculture. The Quinapoxet River and Malden 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. DWSP efforts to reduce nitrogen loads to Wachusett Reservoir should be targeted in the landscapes draining these six tributaries, especially the Quinapoxet River drainage area due to its higher relative loading contribution.

3.2.7.2 *Total Phosphorus in Wachusett Reservoir Watershed Tributaries*

Total phosphorus (TP) concentrations measured in Wachusett tributaries during 2020 ranged from 6.6 µg/L at Malden Brook to 143 µg/L at West Boylston Brook, which was the second highest concentration observed at that tributary and the third highest among all tributaries since 2011 (Figure 35). Annual mean concentrations ranged from 18 µg/L at the Stillwater River to 54 µg/L at French Brook (Table 25). All annual mean TP concentrations were comparable to the 2011 – 2019 period, apart from French Brook. Most of the high concentrations observed at French Brook occurred during very low flows in the summer and fall when water depth at the sample site was only about one inch. These samples likely contained a high concentration of sediment due to the high ratio of wetted stream bed perimeter versus total flow.

Annual median TP concentrations in 2020 were slightly higher than the 2011 – 2019 period (Figure 35). Because phosphorus strongly adsorbs to soil particles, higher TP concentrations were typically observed during storm events when soil particles are eroded off the land and carried to tributaries with surface runoff; this was the case on October 13.

Figure 35: 2020 Total Phosphorus Concentrations with 2011 - 2019 Statistics



Mean annual TP concentrations in 2020 for most Wachusett tributaries were within typical 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 2020 was 20 µg/L. However, the Quabbin Transfer contribution lowers the flow-weighted TP concentration to 15 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.

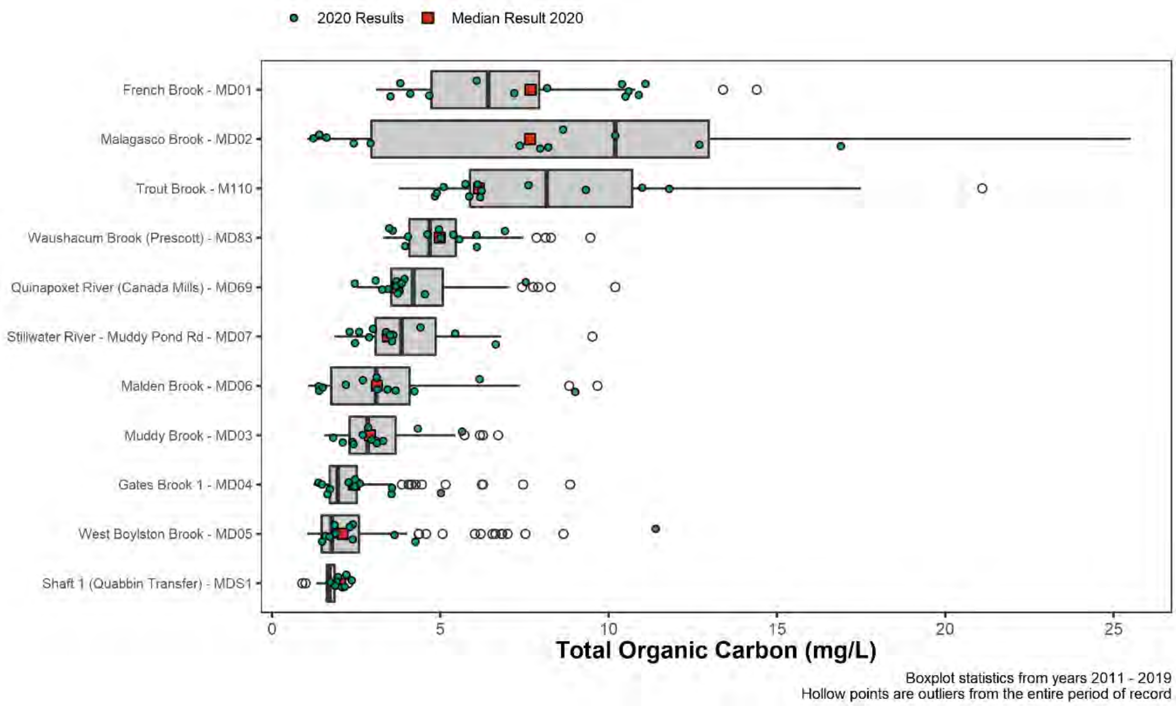
Table 25: Total Phosphorus Annual Mean Concentrations at Wachusett Tributaries (µg/L)

Sample Location	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
French Brook - MD01	36	49	32	31	32	29	23	26	44	54
Gates Brook 1 - MD04	17	25	17	25	15	17	15	19	23	21
Malagasco Brook - MD02	42	44	26	34	38	25	37	36	30	30
Malden Brook - MD06	—	28	18	25	24	19	16	20	18	21
Muddy Brook - MD03	24	27	21	19	18	20	21	21	19	31
Quinapoxet River (Canada Mills) - MD69	17	27	19	20	24	21	17	19	18	23
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	8	13	7	10
Stillwater River - Muddy Pond Rd - MD07	19	23	15	18	19	19	15	16	15	18
Trout Brook - M110	—	—	—	—	50	38	31	29	29	35
Waushacum Brook (Prescott) - MD83	—	29	23	25	22	26	20	19	21	26
West Boylston Brook - MD05	44	35	19	37	21	18	20	31	25	32

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

In 2020, Total Organic Carbon (TOC) sample concentrations in the Wachusett tributaries ranged from 1.23 mg/L to 16.9 mg/L, with both the high and low results from Malagasco Brook (Figure 36; Table 26). The overall mean concentration for 2020 was 4.38 mg/L, which is slightly lower than the long-term mean concentration since 2011. The 2020 flow-weighted mean TOC concentration for all tributaries and Quabbin Transfer was 2.81 mg/L. Without the Quabbin Transfer the flow-weighted mean concentration would have been 3.61 mg/L, or 29% higher. The highest mean annual concentrations were again recorded from French and Trout Brooks, with the lowest concentrations from Muddy, Gates, and West Boylston Brooks (Figure 36). The source of elevated carbon loading at Trout Brook is thought to be 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% of the 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. Carbon export in Malagasco Brook subbasin is typically elevated in the winter when carbon uptake through plant growth is lower or when storm events flush the upstream wetland systems.

Figure 36: 2020 Total Organic Carbon Concentrations with 2011 - 2019 Statistics



Over the last ten years TOC concentrations have been relatively stable for most of the Wachusett tributaries with neither increasing nor decreasing trends evident.

Table 26: Total Organic Carbon Annual Mean Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
French Brook - MD01	6.77	7.89	6.21	6.74	5.88	6.06	6.81	7.14	5.51	7.59
Gates Brook 1 - MD04	2.44	2.69	2.10	2.52	1.86	2.34	2.27	2.45	2.46	2.55
Malagasco Brook - MD02	11.08	11.70	6.40	10.80	7.79	8.83	10.82	10.81	7.20	6.80
Malden Brook - MD06	—	3.49	2.81	4.21	2.29	3.08	3.50	3.67	2.82	3.50
Muddy Brook - MD03	3.76	3.09	2.96	3.01	2.44	2.93	3.53	3.49	2.73	3.06
Quinapoxet River (Canada Mills) - MD69	4.42	4.56	4.28	4.76	4.11	4.92	4.53	4.73	3.61	3.92
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	1.89	1.55	1.79	2.04
Stillwater River - Muddy Pond Rd - MD07	4.12	3.79	3.55	4.58	3.89	3.84	4.54	4.79	3.34	3.65
Trout Brook - M110	—	—	—	—	9.54	8.50	9.43	9.31	6.51	7.06
Waushacum Brook (Prescott) - MD83	—	5.25	4.72	5.33	4.50	4.97	5.36	4.91	4.27	4.98
West Boylston Brook - MD05	2.59	2.50	2.11	3.20	1.76	1.88	2.26	2.71	2.80	3.07

TOC concentrations between 2 and 4 mg/L are considered low for surface waters, and the 2020 flow-weighted mean TOC concentration of 2.81 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.

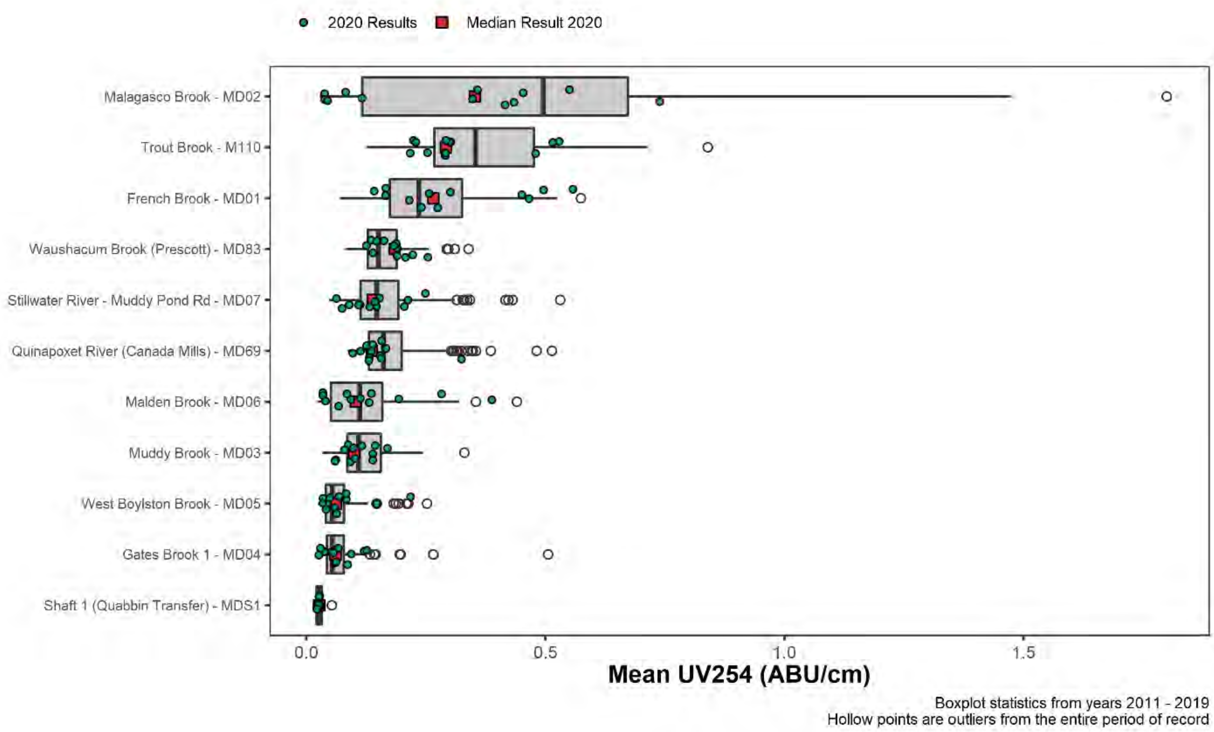
Measurements of UV_{254} absorbance for Wachusett tributaries in 2020 demonstrated variability comparable to TOC concentrations (Figure 37, Table 27). The highest UV_{254} absorbance levels were from Malagasco Brook (0.74 ABU/cm) and Trout Brook, and the lowest were from Gates Brook 1 (0.026

ABU/cm) and Malden Brook. Overall, UV_{254} absorbance levels were similar in 2020 compared with the prior nine years, with the higher levels typically coinciding with precipitation events.

Table 27: UV_{254} Mean Absorbance at Wachusett Tributaries (ABU/cm)

Sample Location	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
French Brook - MD01	0.332	0.315	0.229	0.251	0.226	0.199	0.248	0.313	0.237	0.311
Gates Brook 1 - MD04	0.083	0.077	0.057	0.068	0.051	0.065	0.057	0.084	0.095	0.068
Malagasco Brook - MD02	0.846	0.584	0.317	0.479	0.372	0.304	0.510	0.618	0.380	0.302
Malden Brook - MD06	—	0.132	0.102	0.153	0.078	0.100	0.126	0.156	0.116	0.133
Muddy Brook - MD03	0.167	0.117	0.108	0.108	0.101	0.103	0.133	0.151	0.117	0.107
Quinapoxet River (Canada Mills) - MD69	0.191	0.164	0.156	0.167	0.162	0.162	0.197	0.210	0.152	0.153
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	—	0.020	0.026	0.032	0.027
Stillwater River - Muddy Pond Rd - MD07	0.185	0.140	0.140	0.152	0.167	0.125	0.193	0.215	0.144	0.141
Trout Brook - M110	—	—	—	—	0.432	0.316	0.437	0.421	0.335	0.327
Waushacum Brook (Prescott) - MD83	—	0.175	0.138	0.158	0.146	0.153	0.169	0.186	0.163	0.179
West Boylston Brook - MD05	0.087	0.078	0.052	0.075	0.050	0.057	0.053	0.091	0.081	0.077

Figure 37: 2020 UV_{254} Absorbance with 2011 - 2019 Statistics



3.2.9 Special Studies and Investigations – Tributaries

3.2.9.1 *Forestry Water Quality Monitoring*

Long-term forestry monitoring

In 2020, monthly monitoring at the LTF monitoring locations—Holden (FHLN) and Princeton (FPRN)—continued as part of the pre-harvest phase, except for June, August, and September when the streams at both study locations were dry and in March when most field work was suspended because of the COVID-

19 pandemic. The suspension of storm event sampling continued through 2020 because sufficient data for storm events in the pre-harvest phase has been acquired (21 events prior to 2019). Additional project work included installation of a weir at the Princeton LTF location, which was completed in September.

All necessary pre-harvest data has been collected at both study locations and the experimental lot (Princeton) was put out to bid and sold in 2021. It is expected that timber harvesting will commence at the Princeton site in 2021 and storm sampling will resume. Regular monthly sampling will continue in the harvest phase as it was conducted during the pre-harvest phase.

Short-term forestry monitoring

In 2020, 66 lot visits were made across 17 distinct forestry lots in various stages of harvest. Pre-harvest monitoring began at proposed stream crossings on two lots: WA-21-148, WA-21-232. Post-harvest monitoring was completed at two lots: WA-16-96 and WA-19-238. A total of 114 turbidity samples were collected from stream crossing sampling locations. Dry conditions prevented sample collection at almost one in every three sample attempts (Table 28).

Table 28: Short-term Forestry Monitoring in 2020

Metric	Pre-harvest	Harvest - Active	Harvest - Suspended	Post-harvest	Total
Lot Visits	33	16	0	17	66
Crossing Observations	47	43	0	23	113
Sample Locations Checked	47	109	0	25	181
Turbidity Samples Collected	31	66	0	17	114

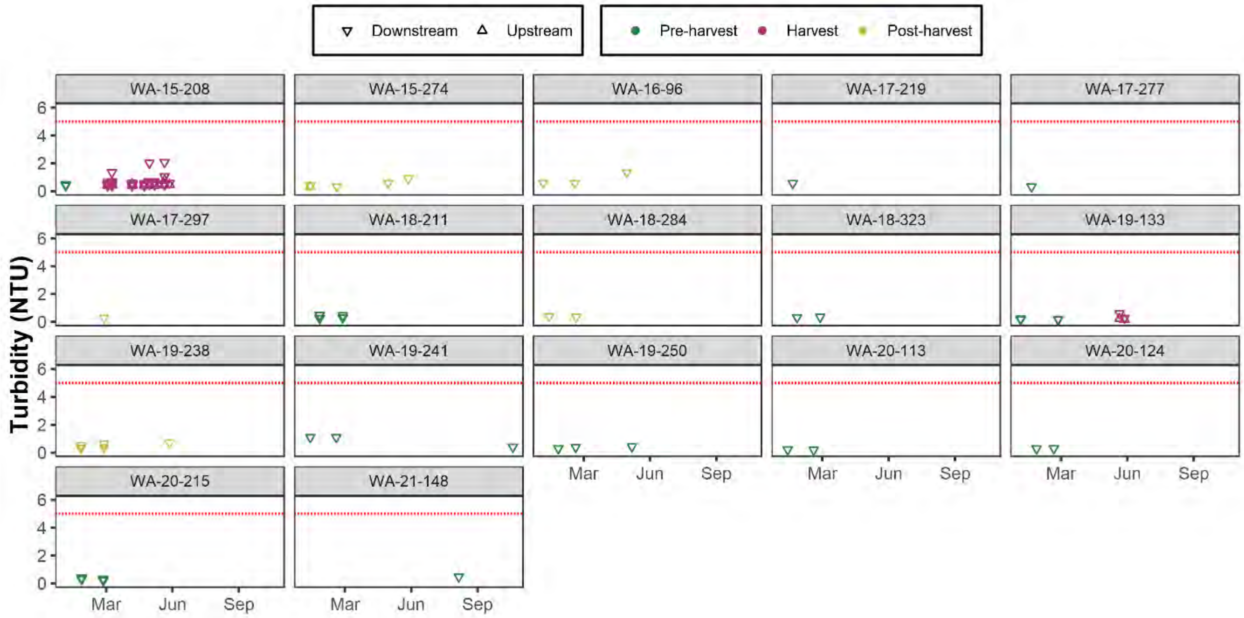
Turbidity results ranged from 0.16 NTU at WA-19-133 to 2.07 NTU at WA-15-208 (Figure 38). Turbidity results were less than 1.0 NTU for 95% of samples in 2020. Mean turbidity values during harvest and non-harvest phases differed slightly, however all mean turbidity values for 2020 were low and representative of background water quality conditions (Table 29). The turbidity results for 2020 indicate that sediment erosion control practices at Wachusett forestry operations continue to adequately protect water quality.

Table 29: Mean Turbidity (NTU) at Short-term Forestry Monitoring Locations

Sample Location	Pre-harvest	Harvest (Active and Suspended)	Post-Harvest
Upstream	NA	0.44	0.32
Downstream	0.38	0.61	0.55

Figure 38: Turbidity Results at Short-term Forestry Monitoring Locations in 2020

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 5.0 NTU.



3.2.9.2 *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 Chloride/Conductivity working group proceeded independently with research and information gathering efforts in 2020.

For FY 2021, which began on July 1, 2020, DWSP offered targeted matching reimbursement grants of up to $20,000 for the towns of Boylston, West Boylston, Sterling, Holden, Princeton, Paxton, and Rutland for specific salt use reduction expenses. Reimbursable expenses included purchases for items such as brine production equipment, more efficient plowing and salt application technologies, temperature sensors for pavement, and improved containment of salt piles. Grants were awarded on a competitive basis and in addition to evaluation of the merits of the planned use of grant funding, applications which provided additional data on town salt use, snow removal or deicing operations, were given higher preference. Three grants were awarded, totaling $58,592 (Table 30). The towns of Holden and West Boylston successfully purchased the proposed equipment to integrated into their snow removal program. The town of Princeton was unable to spend the requisite funds in FY2021, so the grant was rolled over to FY2022.

Table 30: Salt Use Reduction Grants Awarded for FY 2021

Town	Amount	Grant Purchase
Holden	$20,000	Flexible, segmented plow blades
Princeton	$20,000	Salt shed
West Boylston	$18,592	Flexible plow blades; small salt spreader; temperature sensors for all plows

A requirement of all grant awards is that total salt application amounts will be provided to DWSP for the 2020 – 2021 winter season and the following three winter seasons. This data has been requested from the three towns but has not yet been received as of the writing of this report. These usage totals will be included in subsequent water quality reports.

The grant program is expected to be offered again for FY2022. The working group did not move ahead with any additional programs or initiatives in 2020.

3.2.9.3 *Stormwater Basins*

Since July 2019, the stormwater basins located on either side of the Rt 12/140 causeway have been monitored on 23 individual occasions in all weather conditions. In 2020, the basins were monitored a total of 11 individual occasions.

Basins holding water were also monitored for developing mosquito larvae; visually and through collected water samples. No larvae were found through either method. The stormwater basins were entirely or mostly dry on the following monitoring dates in 2020: 6/23, 7/9, 7/20, 8/31, 9/28.

Figure 39: Water Chemistry per Forebay from 2019-2021

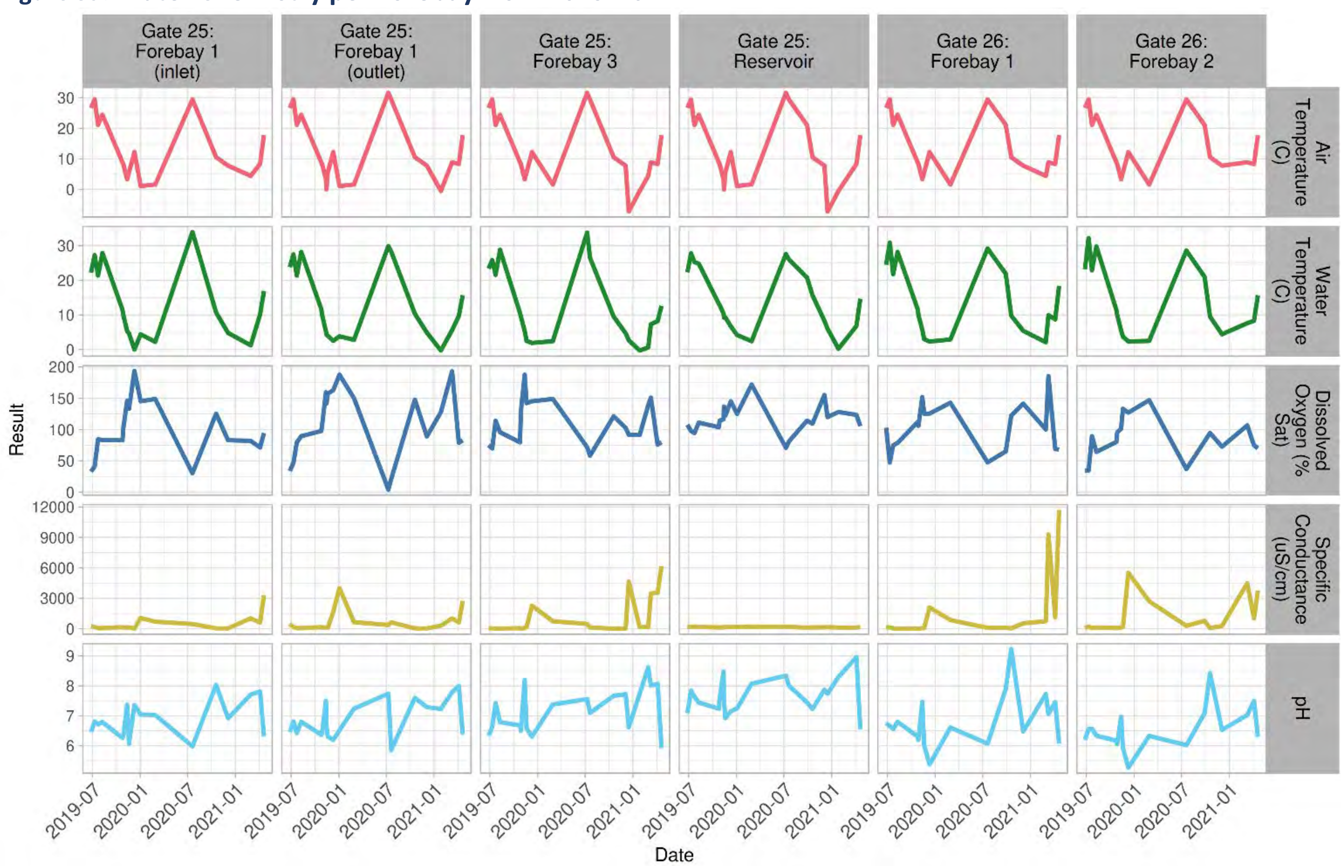
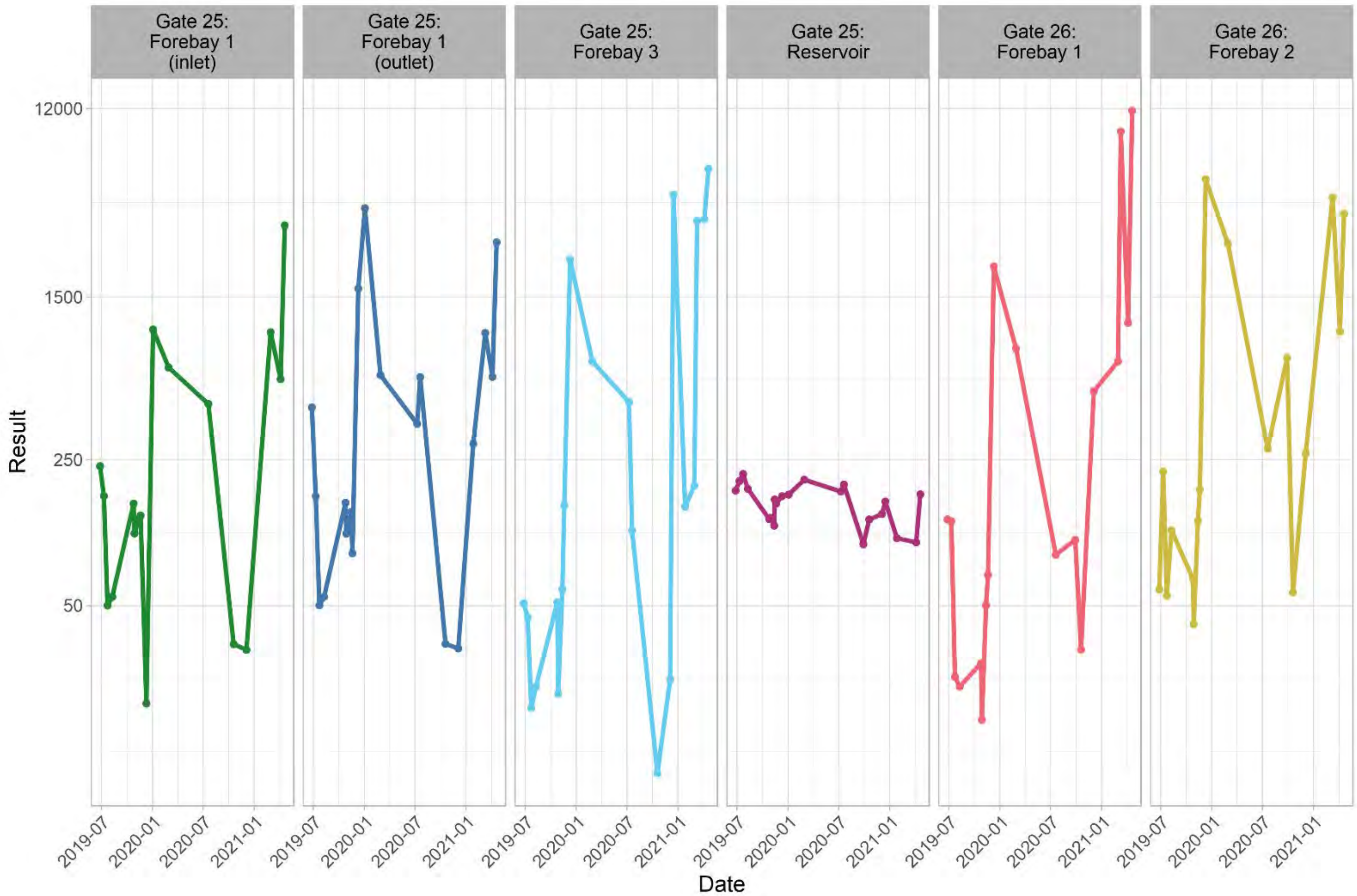


Figure 40: Stormwater Basin Specific Conductance (μS/cm) 2019 - 2021



3.2.9.4 *Historical Analysis of Septic to Sewer Conversion*

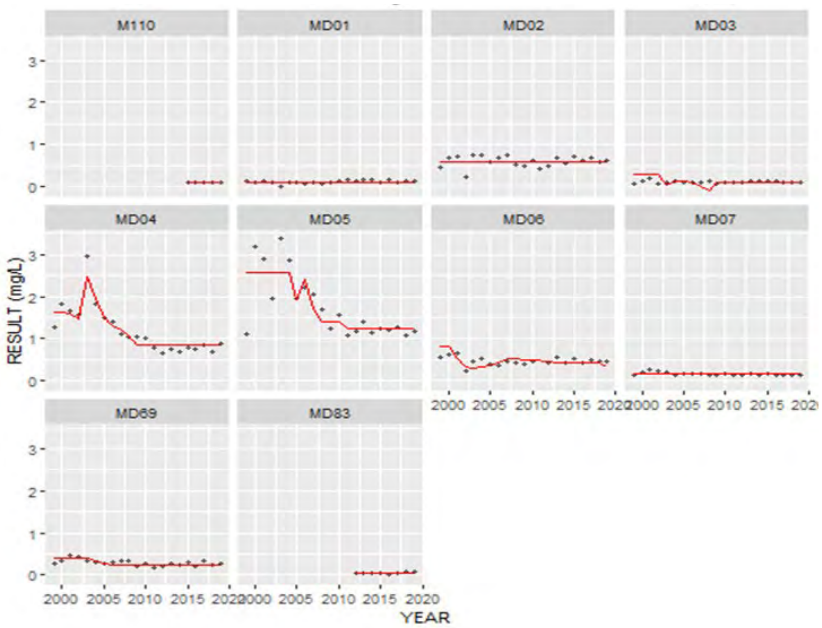
2020 summer intern Emily Lydell[48] conducted a spatio-temporal analysis of the water quality effects of the on-lot waste disposal conversions from septic to sewer that occurred in Wachusett Watershed between 1999 and 2019. This analysis involved mapping the spatial distribution (by year) of on-lot waste systems from the pre-sewer era (1999) through the years of sewer conversion (~2001 – 2010) until 2019 and building a model to test for correlation with concentrations of different water quality parameters (ammonia, nitrate, phosphorus, *E. coli*). A generalized additive model (GAM) was constructed to predict mean annual water quality concentrations based on septic system density (CNX_DENS), the proximity of those septic systems to streams (NEAR_STREAM), and the proximity of those septic systems to the closest downstream monitoring station with available water quality data (NEAR_STA). The predictor variables were significant for nitrate, total phosphorus, and ammonia ($p < 0.05$), however the only parameter that showed a significant trend in concentration during this time was nitrate.

[48] Boston University School of Public Health graduate student

Since the other parameter concentrations did not vary significantly over this period, despite dramatic decreases in septic density in certain subbasins, no conclusions can be made concerning the influence of septic to sewer conversion for those parameters. The GAM performed the best at predicting mean annual nitrate concentrations and the overall GAM coefficient of determination (R^2) was excellent (0.91), indicating that septic system density and locations were strong predictors of nitrate concentrations over these years (Figure 41). This association was most obvious at Gates Brook 1 – MD04 and West Boylston Brook – MD05, where septic densities decreased by 99% and 87% over these years, respectively. Analysis of rates of change of nitrate concentrations compared with septic conversion rates showed that there was a 0.29 mg/L reduction in nitrate concentration per 100 septic system per square mile reduction in septic density in Gates Brook – MD04 and a 0.37 mg/L reduction in West Boylston Brook – MD05. This analysis has helped confirm the assumption that the sewering project in West Boylston and Holden could be credited for the subsequent decline of nitrate levels observed in certain subbasins in the mid and late 2000s.

Figure 41: Generalized Additive Model Results for Nitrate by Year (1999 – 2019)

Nitrate (mg/L) ~ NEAR_STA + NEAR_STREAM + CNX_DENS. The red line represents the GAM model prediction for annual mean nitrate at each subbasin.



3.3 Groundwater Quality Monitoring

Expanded groundwater monitoring was continued in 2020 after launching in 2019 (see Figure 6), and the data collected so far have provided preliminary insights on the groundwater levels, specific conductance, and Cl in Wachusett Watershed aquifers. Results of well monitoring in 2020 continued to indicate a wide range in specific conductance and Cl concentrations in Wachusett Watershed groundwater (Figure 42). The means of both parameters in West Boylston - 110 were two orders of magnitude higher than the means in 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, and 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 42 and Figure 43 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 launched a supplementary investigation in 2019 to determine additional sources impacting the groundwater at that location. To date, this investigation has not created any additional insights.

Table 31: Months During 2020 When Groundwater Monitoring Wells Had Insufficient Water to Sample

Well	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Holden - Wachusett St												
Boylston - Rt 70								X	X			
West Boylston - Gate 27												
West Boylston - Rt 110												
Sterling - Justice Hill Rd												
Princeton - Rt 62									X	X	X	
Sterling - Rt 140												
Holden - Jefferson*												

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

Figure 42: Chloride Results in Wachusett Watershed Wells in 2020

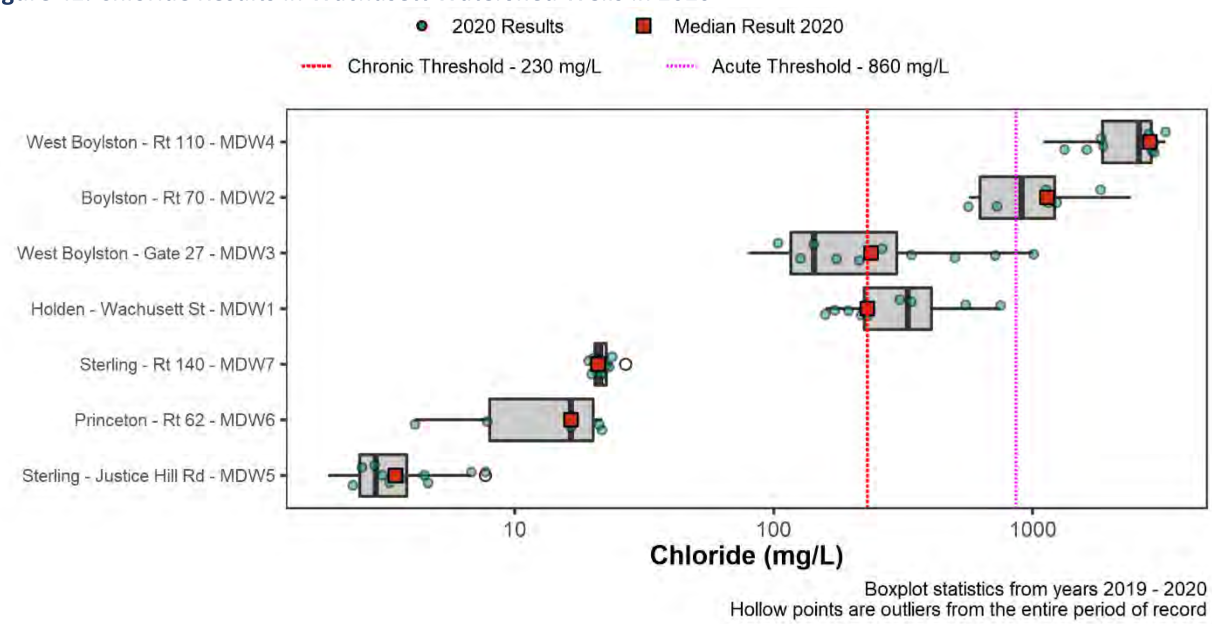


Figure 43: Specific Conductance Results in Wachusett Watershed Wells in 2020

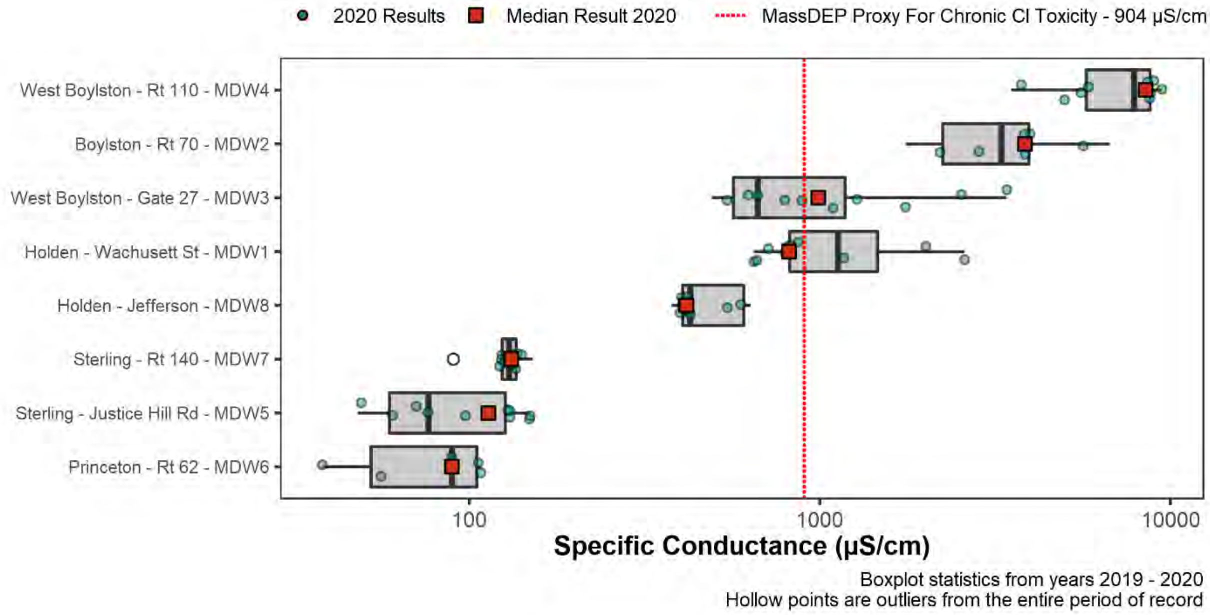


Table 32: Groundwater Monitoring Summary for 2020

Well	Mean Water Depth Below Ground Surface (ft)	Mean Specific Conductance (µS/cm)	Mean Chloride (mg/L)
Holden - Wachusett St	4.9	1109.2	324.8
Boylston - Rt 70	6.2	3727.3	1107.3
West Boylston - Gate 27	7.5	1359.4	359.4
West Boylston - Rt 110	16.2	7307.9	2437
Sterling - Justice Hill Rd	7.3	104.2	4.1
Princeton - Rt 62	15.4	79.5	14.3
Sterling - Rt 140	14.8	130.7	21.3
Holden - Jefferson	17.6	443.3	-

Well monitoring will continue in 2021 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 the final publication on this topic is expected sometime in 2021[49].

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 provide increased spatial

[49] Soper, 2020

resolution of groundwater impairment, such as monitoring baseflow at first order tributaries that are not currently 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 Reservoir to Wachusett Reservoir, resulting in native Wachusett Watershed water having a larger influence on water quality parameters such specific conductance, silica, and UV_{254}. Three brief periods during which chrysophyte algae exceeded early monitoring thresholds were also documented in 2020. 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

2020 reservoir temperatures supported MassDEP aquatic life use standards for coldwater and warmwater fisheries. Reservoir temperatures ranged from 1.82 °C to 27.4 °C during 2020. Full ice cover was not achieved in the 2019/2020 season (Figure 44). 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 26 (Figure 45). Surface temperatures continued to warm, attaining a maximum temperature of 27.4 °C on August 3. Cooling of the epilimnion started in mid-August when the combination of cooling air temperatures and wind energy pushed the thermocline deeper. Turnover occurred on November 2 and the water column continued to cool for the remainder of the season.

Figure 44: Ice Cover Duration for Wachusett Reservoir for the Period of Record (1992 – 2020)

Ice cover is considered complete when a majority of the north basin in frozen over. Ice may have been present during 'No Ice' years, but complete cover was not achieved.

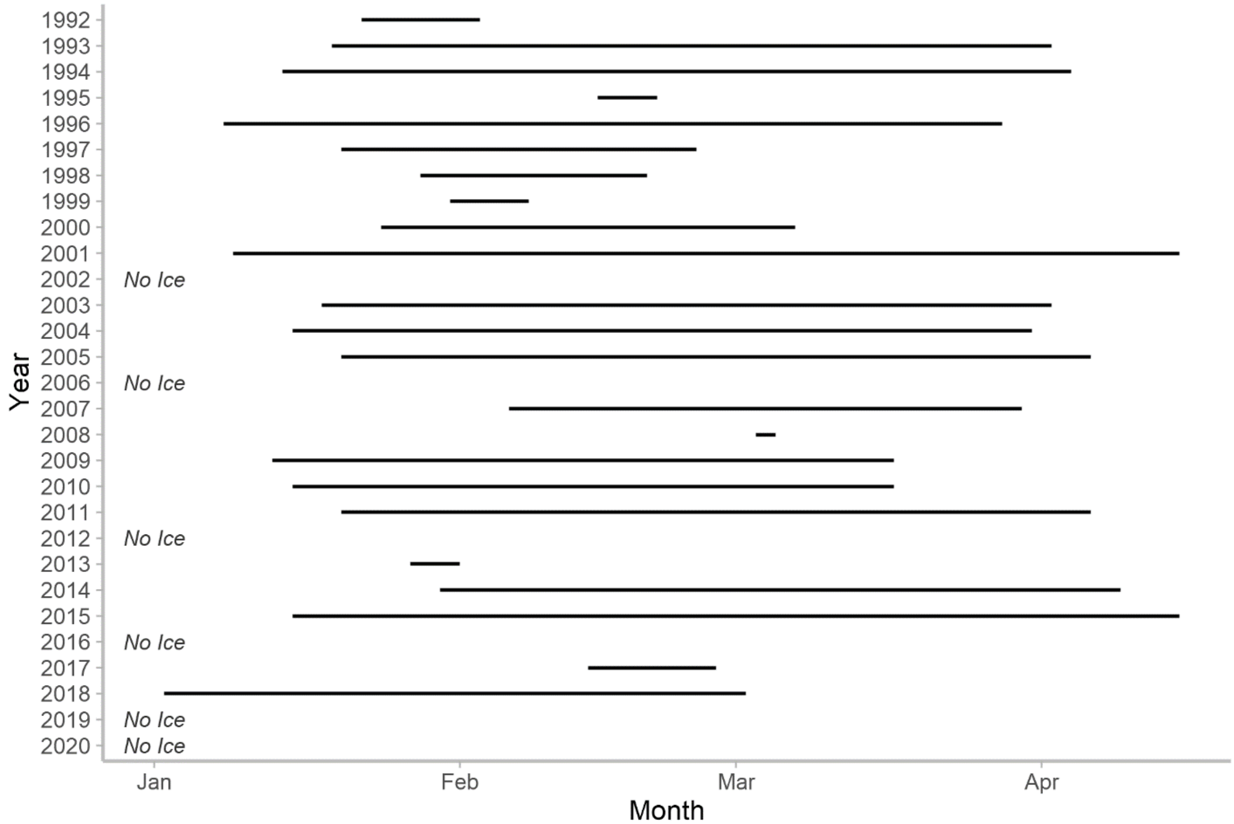
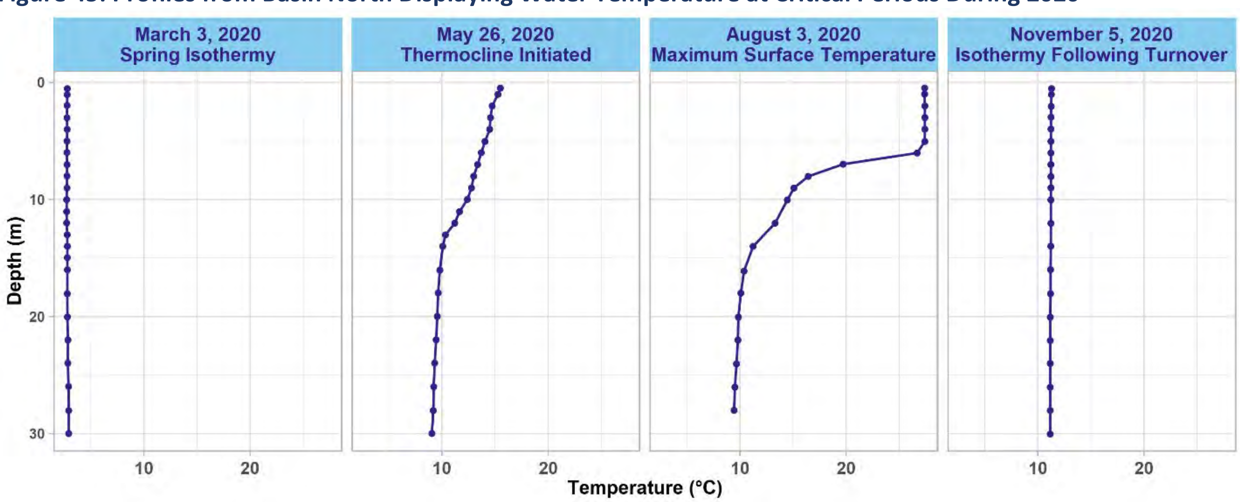
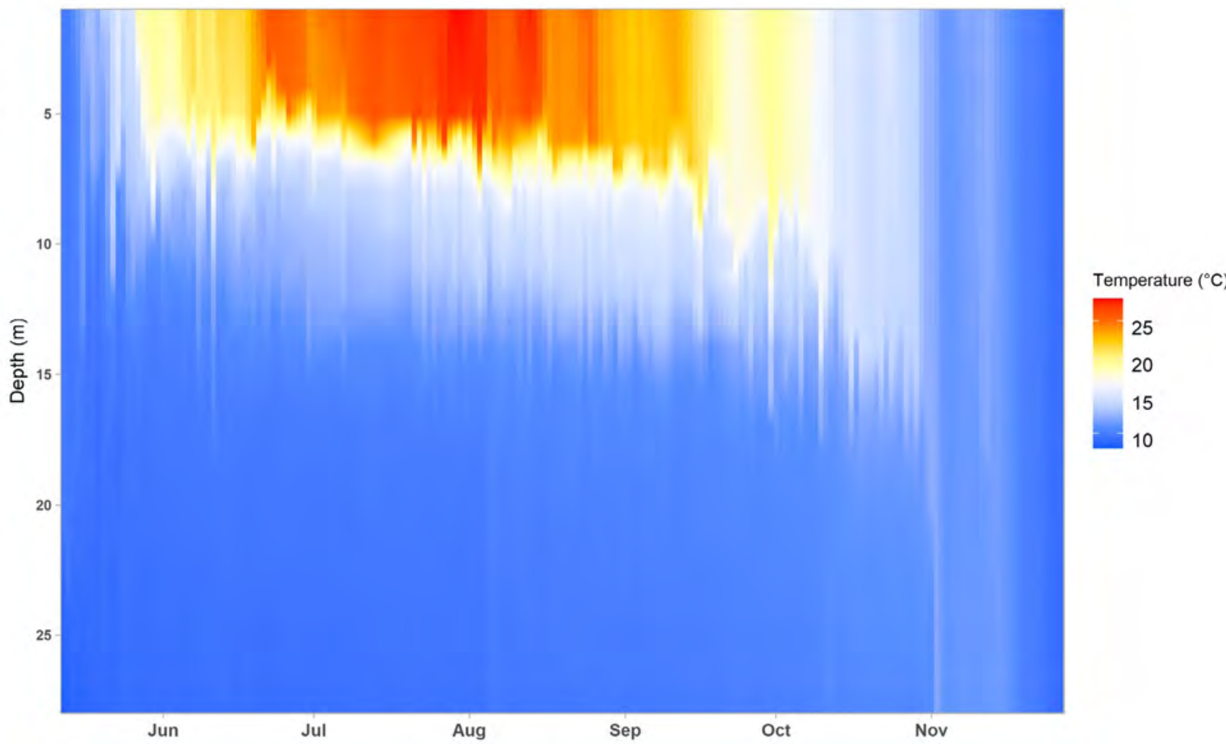


Figure 45: Profiles from Basin North Displaying Water Temperature at Critical Periods During 2020



The high temporal resolution data obtained from MWRA remote sensing buoys provide an opportunity to visualize reservoir temperature changes over the entire season (Figure 46).

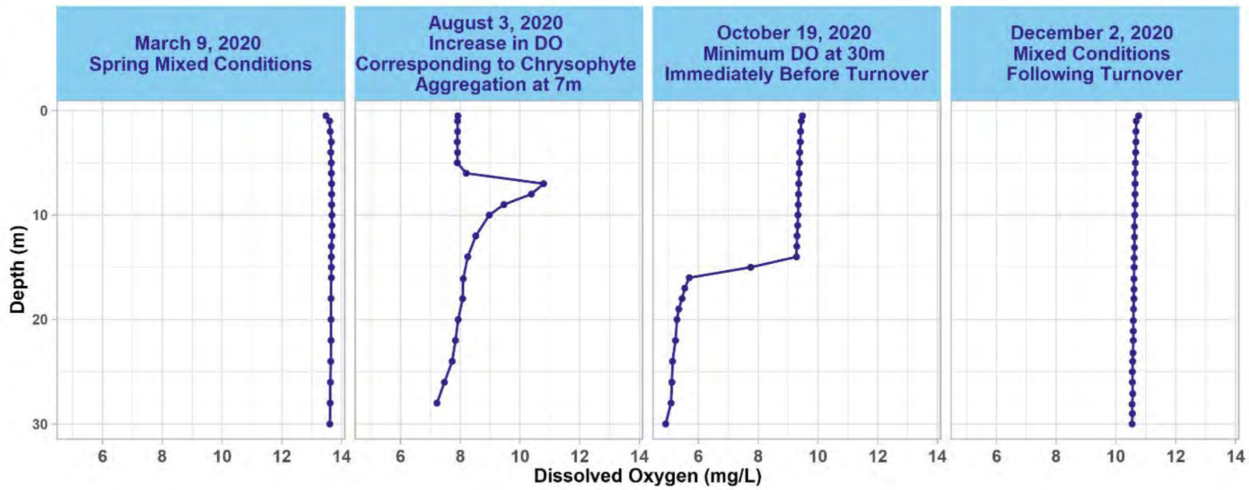
Figure 46: Water Temperature Recorded by Basin North Profiling Buoy May – November 2020
Plot based on data recorded daily at 12 pm.



3.4.2 Dissolved Oxygen

Expected patterns in dissolved oxygen were observed throughout the 2020 season. MassDEP aquatic life use criteria of 6.0 mg/L for coldwater communities and 5.0 mg/L for warmwater communities were met with one exception (4.90 mg/L) at 30 m immediately before fall turnover (Figure 47). 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 early June. Stratification then strengthened, isolating water below the thermocline from atmospheric diffusion of oxygen. Dissolved oxygen gradually declined within the hypolimnion, reaching a minimum concentration of 4.90 mg/L at 30 m on October 19, 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 on November 2 (as recorded by MWRA profile buoys), oxygen was again able to disperse through the water column and was approximately 10.5 mg/L from the surface to bottom on December 2. Elevated dissolved oxygen below the thermocline associated with increased phytoplankton activity occurred several times throughout the summer.

Figure 47: Profiles from Basin North Displaying Dissolved Oxygen at Critical Periods During 2020

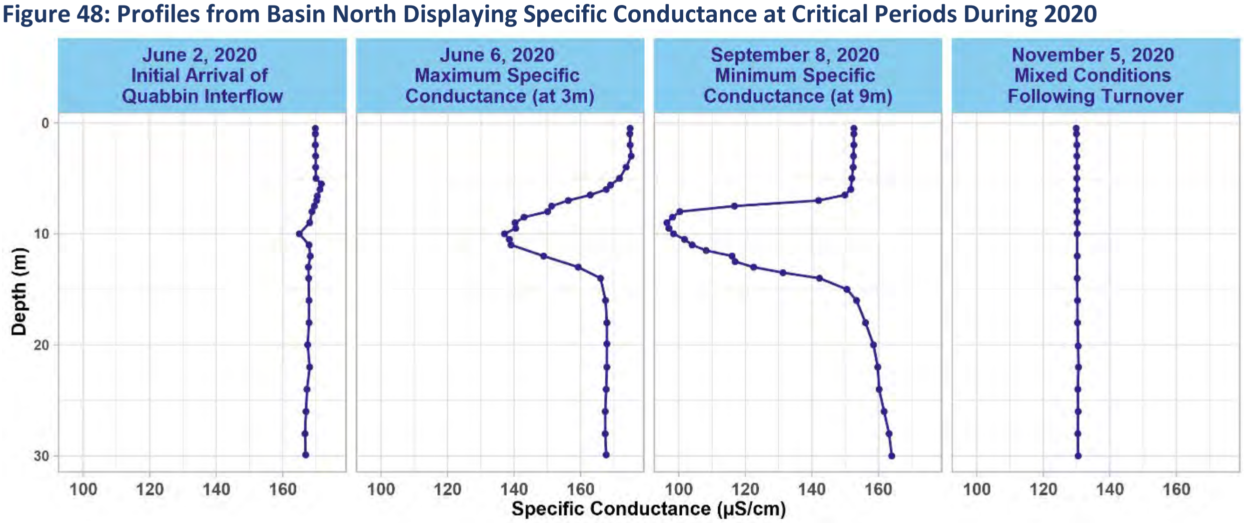


3.4.3 Specific Conductance

Specific conductance values in the reservoir remained elevated for the fourth consecutive year. The maximum value of 175.2 µS/cm was recorded at a depth of 3 m at Basin North on June 6.

Arrival of the Quabbin interflow at Basin North was first observed on June 2 with a slight decrease in specific conductance observed around 10 m. By June 23, a definitive decrease in specific conductance between 7.5 and 11 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 96.4 µS/cm at 9 m on September 8. At this point, the interflow had grown to encompass 9.5 m of water between the depth of 6.5 and 15 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 130 µS/cm (Figure 48).

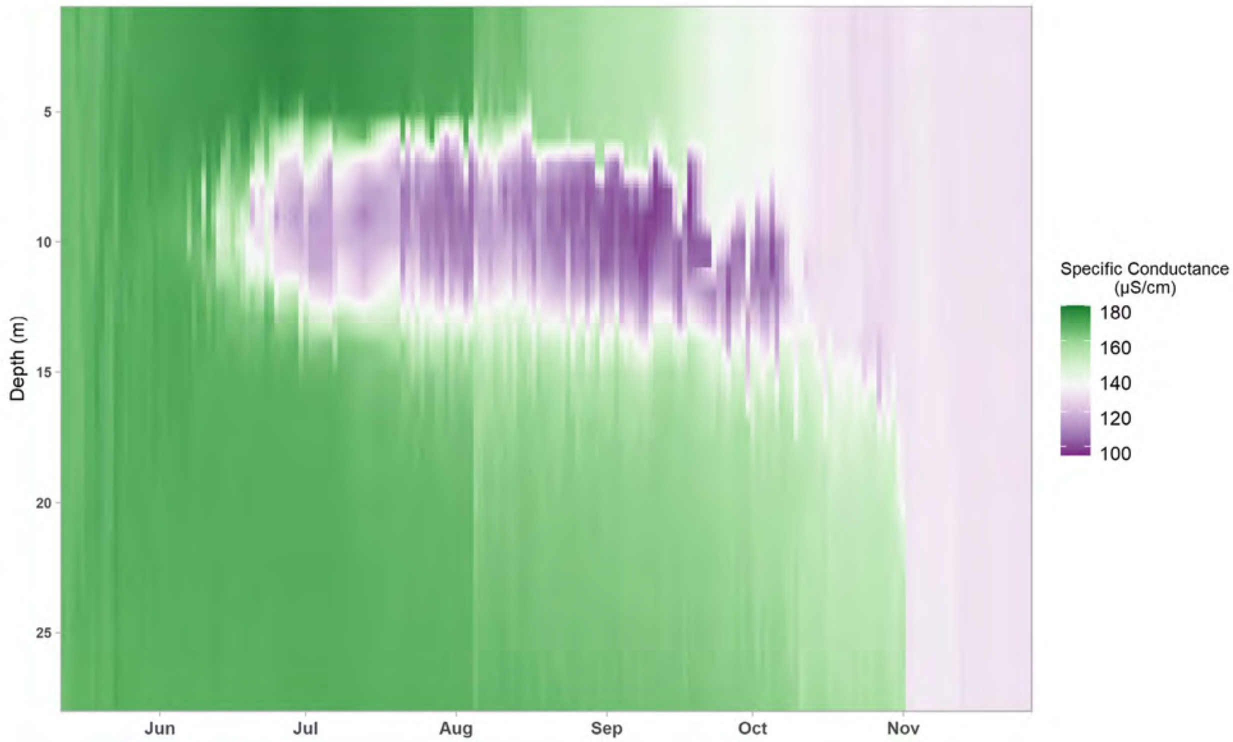
Figure 48: Profiles from Basin North Displaying Specific Conductance at Critical Periods During 2020



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 49).

Figure 49: Specific Conductance Recorded by Basin North Profiling Buoy May – November 2020

The Quabbin interflow layer is clearly visible in the range of 96 to 130 µS/cm between mid-June and October.



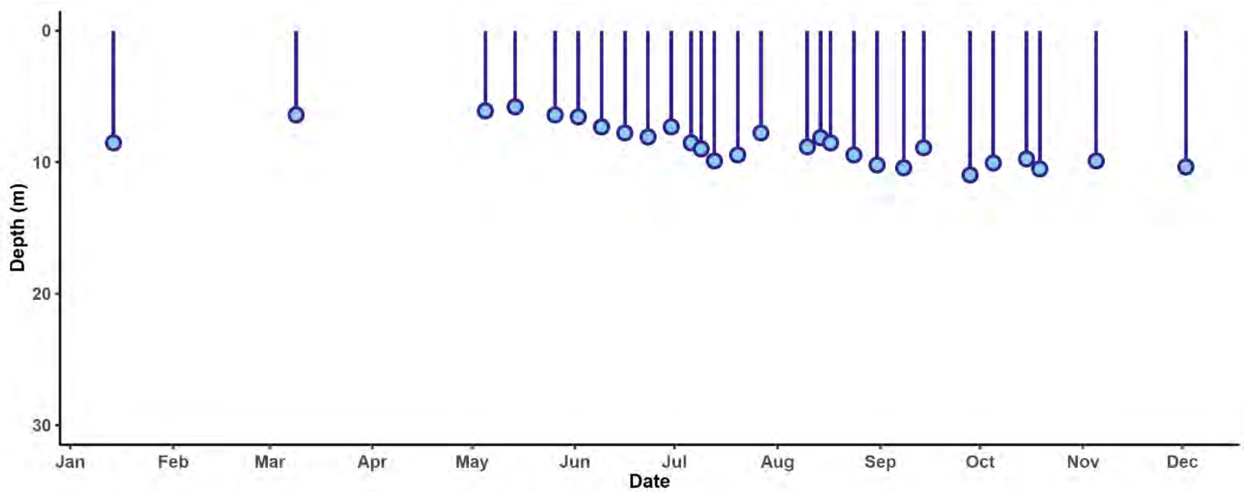
3.4.4 Turbidity

Turbidity in the reservoir was measured with sensors installed on the YSI EXO2 sondes used by DWSP and on the remote profiling buoys. The precision of these sensors is 0.3 FNU, which is approximately 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.

3.4.5 Secchi Disk Depth/Transparency

Secchi disk depth was less than 7 m through early June, influenced by elevated concentrations of diatoms (Figure 50). As the season progressed, Secchi disk depth increased to a seasonal maximum of 9.4 m on July 20. Transparency was reduced by increased chrysophyte density in August but increased again in late September when the annual maximum Secchi disk depth of 11 m was recorded on September 28. The annual mean Secchi disk depth of 8.6 m remained greater than the reference range of 4 m to 6.1 m for the reservoir ecoregion.

Figure 50: 2020 Secchi Disk Transparency at Basin North



3.4.6 Nutrient Dynamics

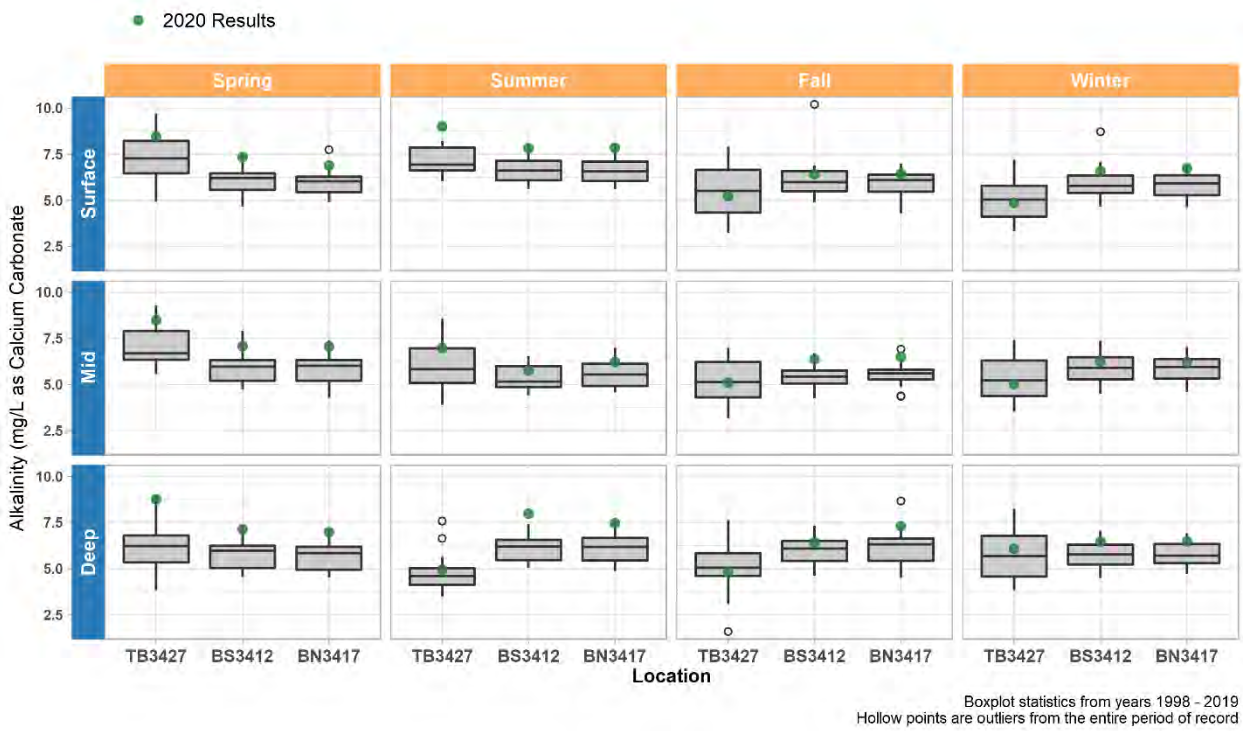
The patterns of nutrient distribution in 2020 quarterly samples generally followed those documented in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics[50]. These patterns consist most importantly of the following: 1) seasonal and vertical variations with low epilimnetic 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 vertical gradients becoming pronounced for nitrate, silica, UV_{254}, and specific conductance downgradient of Thomas Basin and within the interflow, if present.

[50] Worden & Pistrang, 2003

3.4.6.1 *Alkalinity*

Mean alkalinity across all sites and depths in 2020 was 6.71 mg/L as $CaCO_3$ and 86% of results for individual sites were higher than annual means. The overall mean was slightly lower than in 2019, breaking the increasing trend observed since 2015; however, results remain elevated compared to the period of record (Figure 51). The maximum alkalinity of 9.00 mg/L as $CaCO_3$ was recorded in the summer at Thomas Basin while the minimum of 4.82 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.

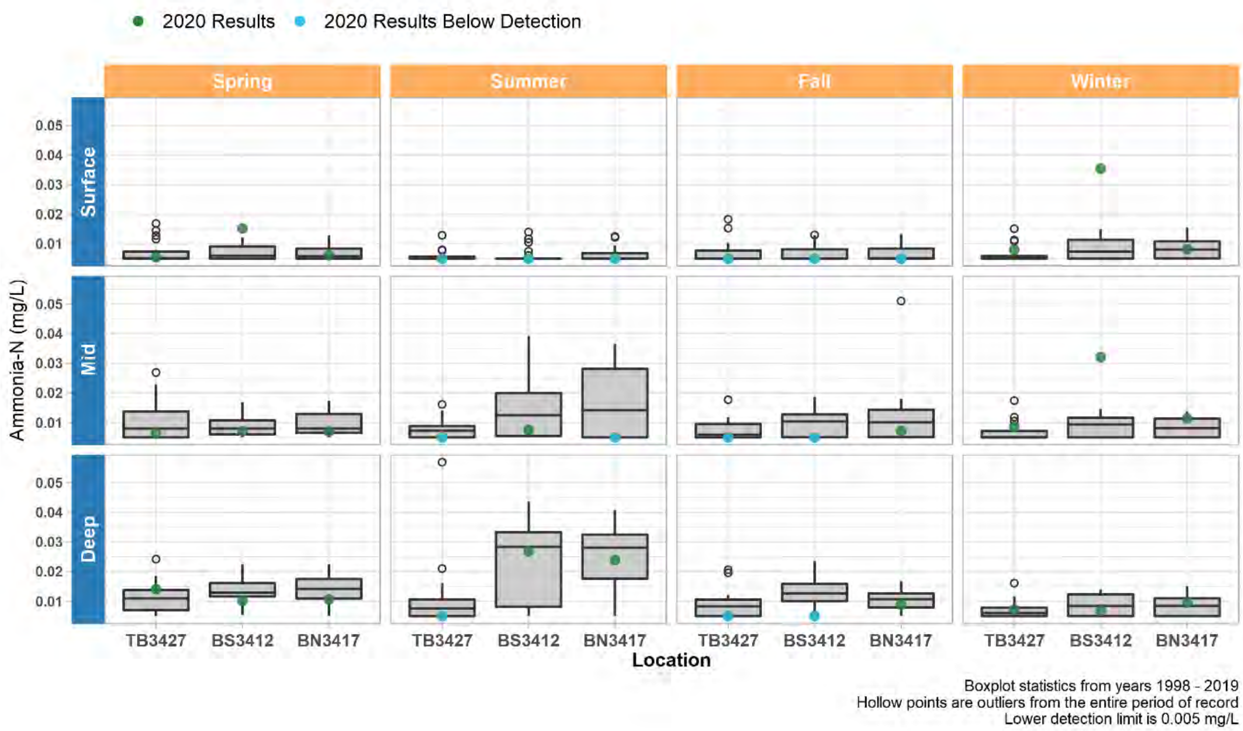
Figure 51: 2020 Alkalinity in Wachusett Reservoir



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

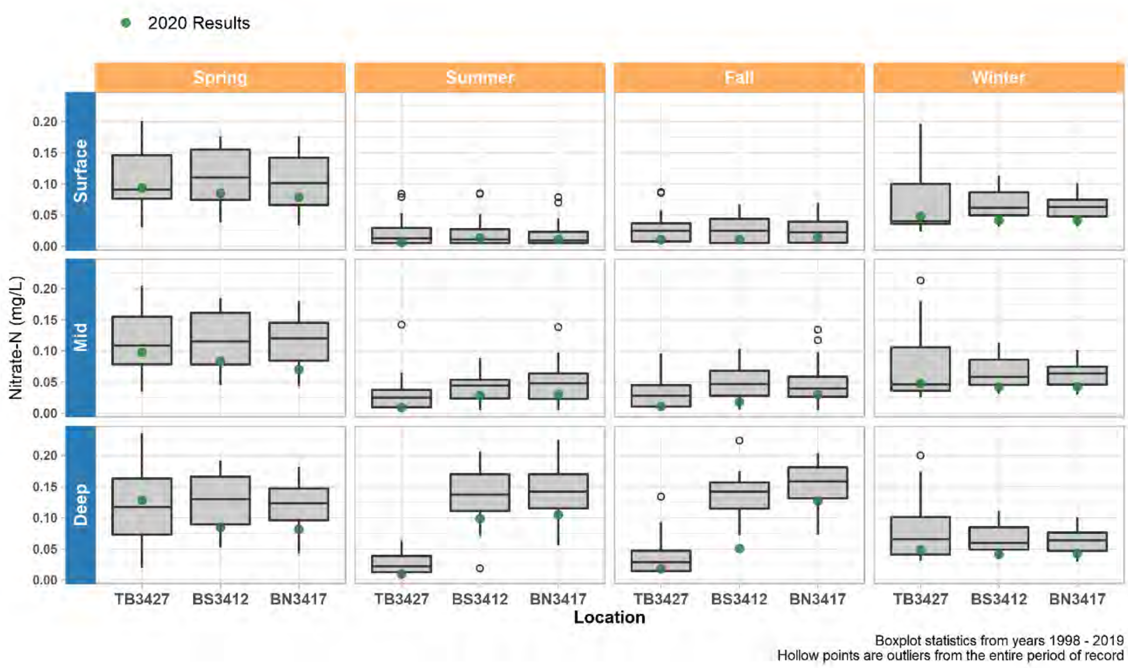
Ammonia-nitrogen (NH_3-N) levels within the reservoir remain low, with concentrations ranging from below the detection limit (0.005 mg/L) to a maximum observed value of 0.035 mg/L in 2020 (Figure 52). Ammonia-nitrogen concentrations were higher at the surface and epilimnion at Basin South than previously recorded values at those sites. However, all values are within the historical range and well below regulatory thresholds reservoir wide (Figure 52).

Figure 52: 2020 Ammonia-Nitrogen in Wachusett Reservoir



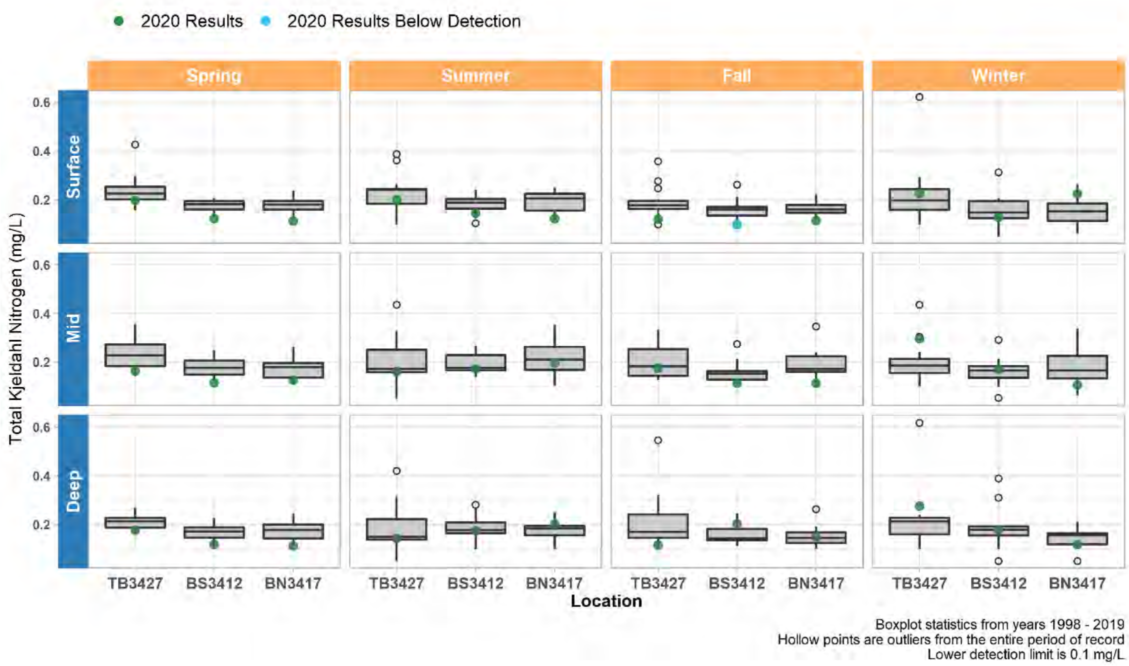
Nitrate-nitrogen (NO_3-N) concentrations also remain low with the majority (83%) of 2020 results falling below historical site medians (Figure 53). The highest concentrations are most often observed in the spring and in the main basin locations at depth during periods of stratification. This pattern continued in 2020, with spring values at all sites falling between 0.070 and 0.128 mg/L. Summer and fall concentrations in the hypolimnion at Basin South and Basin North were similar, ranging between 0.010 and 0.127 mg/L, generally lower than historical medians and well below the SDWA threshold of 10 mg/L (Figure 53).

Figure 53: 2020 Nitrate-Nitrogen in Wachusett Reservoir



Concentrations for Total Kjeldahl Nitrogen (TKN) fell between 0.1 and 0.297 mg/L, within the historical range (Figure 54) and below the ecoregional threshold of 0.3 mg/L. Concentrations during 2020 at each site were generally lower than or close to historical medians.

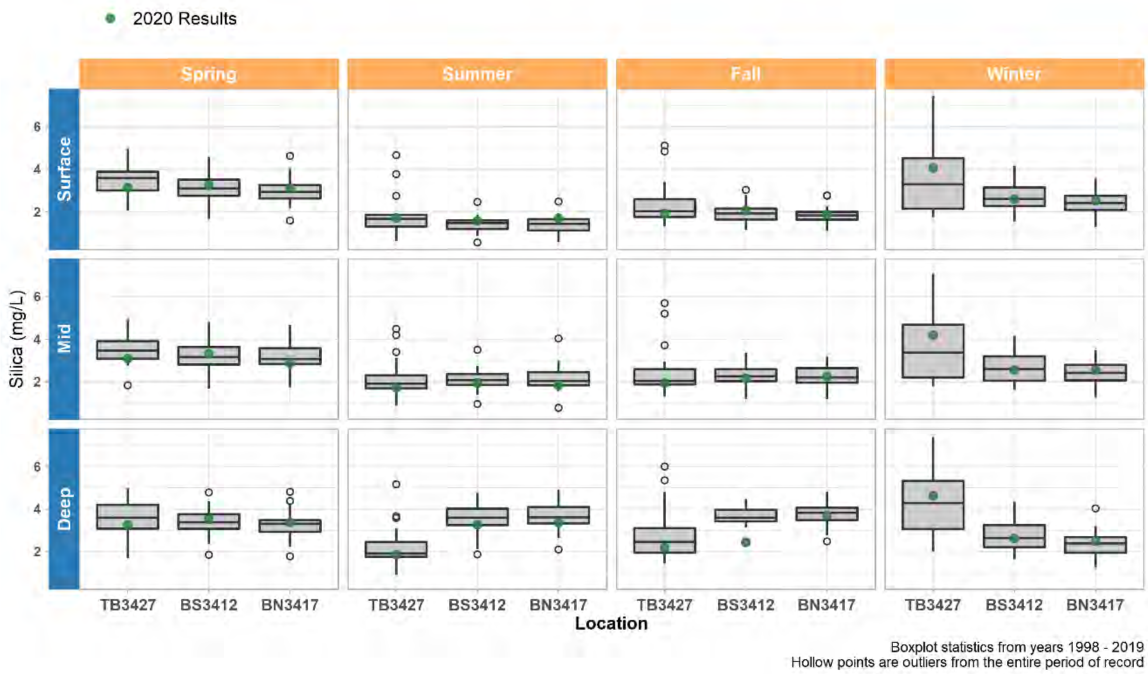
Figure 54: 2020 Total Kjeldahl Nitrogen in Wachusett Reservoir



3.4.6.3 *Silica*

Silica concentrations were between 1.57 and 4.62 mg/L in 2020, well within historical ranges (Figure 55). Concentrations did not exceed the 75th percentile, in contrast with 2019 when 47% of values were above this range. Spring, summer, and fall concentrations of silica at TB3427 were lower than average but increased following fall mixing.

Figure 55: 2020 Silica in Wachusett Reservoir

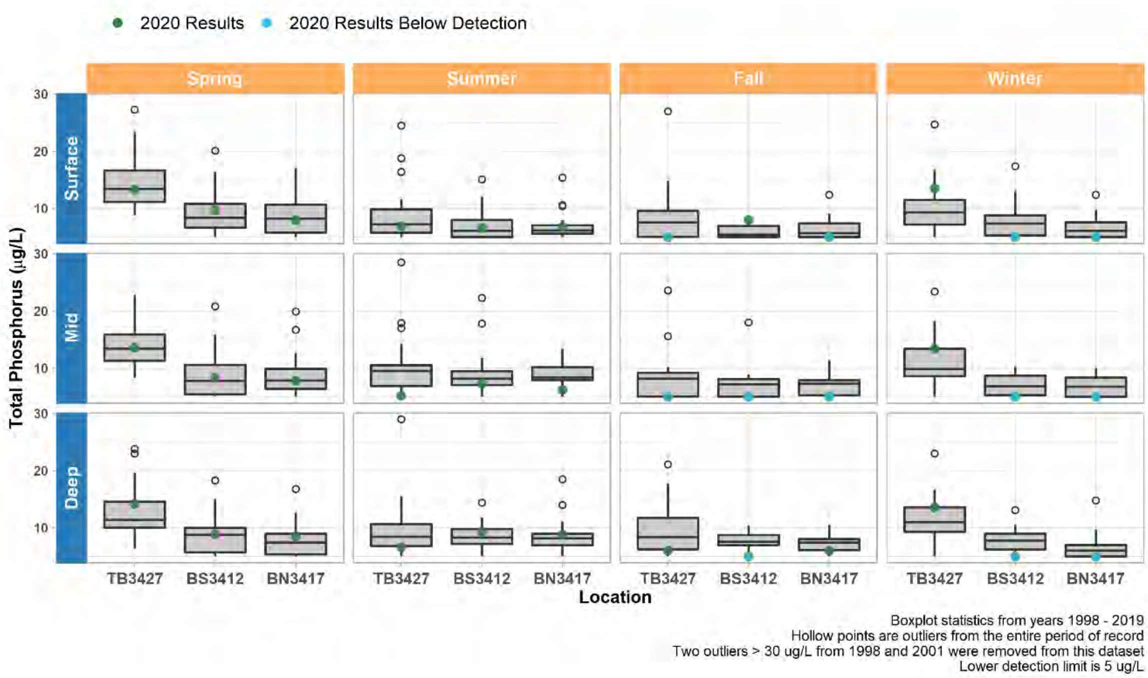


3.4.6.4 *Total Phosphorus*

Total phosphorus (TP) results for 2020 were below the 75th percentile of the historical range (1998 – 2019) except for two surface sites: Thomas Basin (TB3427) winter sample and Basin South (BN3412) fall sample, which had only slightly higher concentrations. The majority of 2020 results were lower than the 10 µg/L threshold for classification as an oligotrophic water body (Figure 56). Results greater than this threshold occurred in the spring and fall in Thomas Basin (TB3427) when flow from Stillwater and Quinapoxet Rivers was greater than Quabbin Transfer volume.

These results reflected expected seasonal patterns with phosphorus transport to the reservoir during the spring season. Phosphorus concentrations were reduced by the summer season and were lower than the detection limit of 5.0 µg/L at most sites (67%) in the fall and winter.

Figure 56: 2020 Total Phosphorus in Wachusett Reservoir

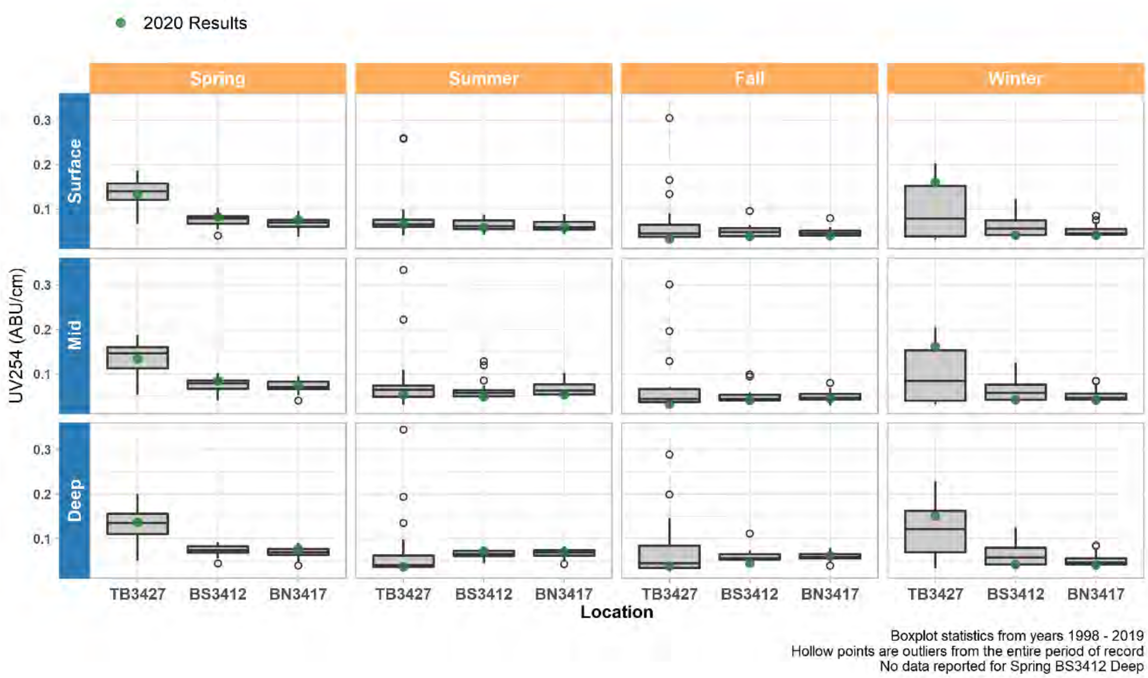


3.4.6.5 *UV Absorbance*

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 0.032 and 0.162 ABU/cm in 2020, which is within the historical range (Figure 57). Except for samples collected at surface and mid depths at TB3427 following fall turnover, values fell below the 75th percentile with approximately 70% falling below site means. UV_{254} results in Thomas Basin continue to be the most variable due to the countering influences of Quabbin Transfer and native watershed water mixing at this location.

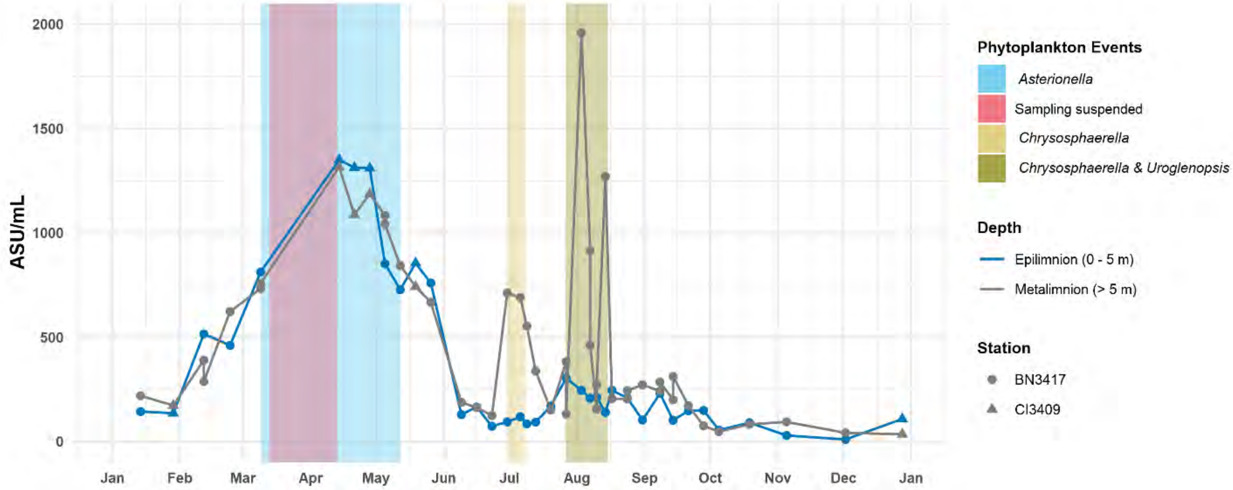
Figure 57: 2020 Wachusett Reservoir UV_{254}



3.4.7 Phytoplankton

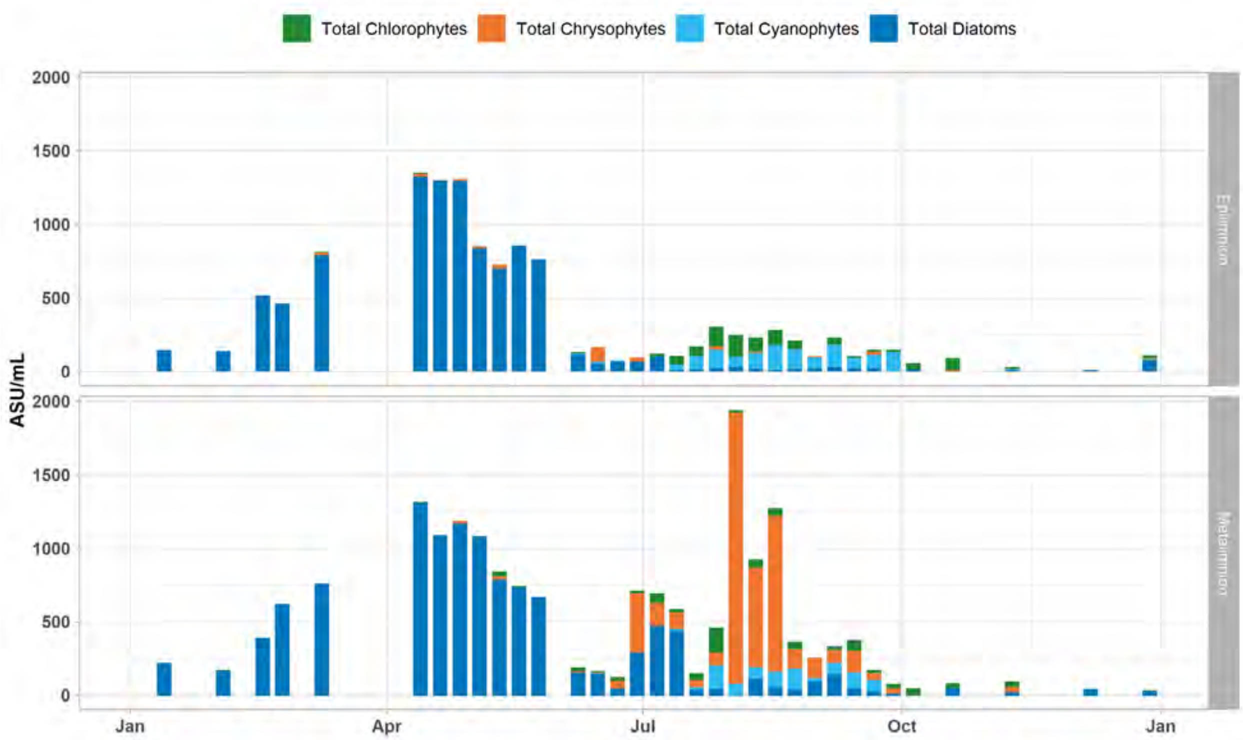
A total of 88 algae samples were collected and analyzed on 37 days during the 2020 season. Ice-free conditions in the north basin of the reservoir allowed collection of samples from Basin North until mid-March when sampling was suspended for five weeks in response to COVID-19. Sampling resumed on April 14 and continued through the end of the year with the last sample collected on December 30. Four notable increases in nuisance phytoplankton genera occurred over this time: a period of elevated *Asterionella* occurred in the spring, an aggregation of *Dolichospermum* was observed in mid-June, two brief periods of *Chrysosphaerella* occurred in July and August, and Uroglenopsis was elevated in early August (Figure 58).

Figure 58: 2020 Wachusett Reservoir Phytoplankton Totals
Epilimnion range is 1 – 5 m, metalimnion range is 5 – 15 m.



The pattern of succession observed in 2020 followed the seasonal changes in phytoplankton community composition and density typically observed in the Wachusett Reservoir. Community composition by group is displayed in Figure 59.

Figure 59: 2020 Phytoplankton Community Composition
Reported as weekly maximums for Basin North and Cosgrove Intake.

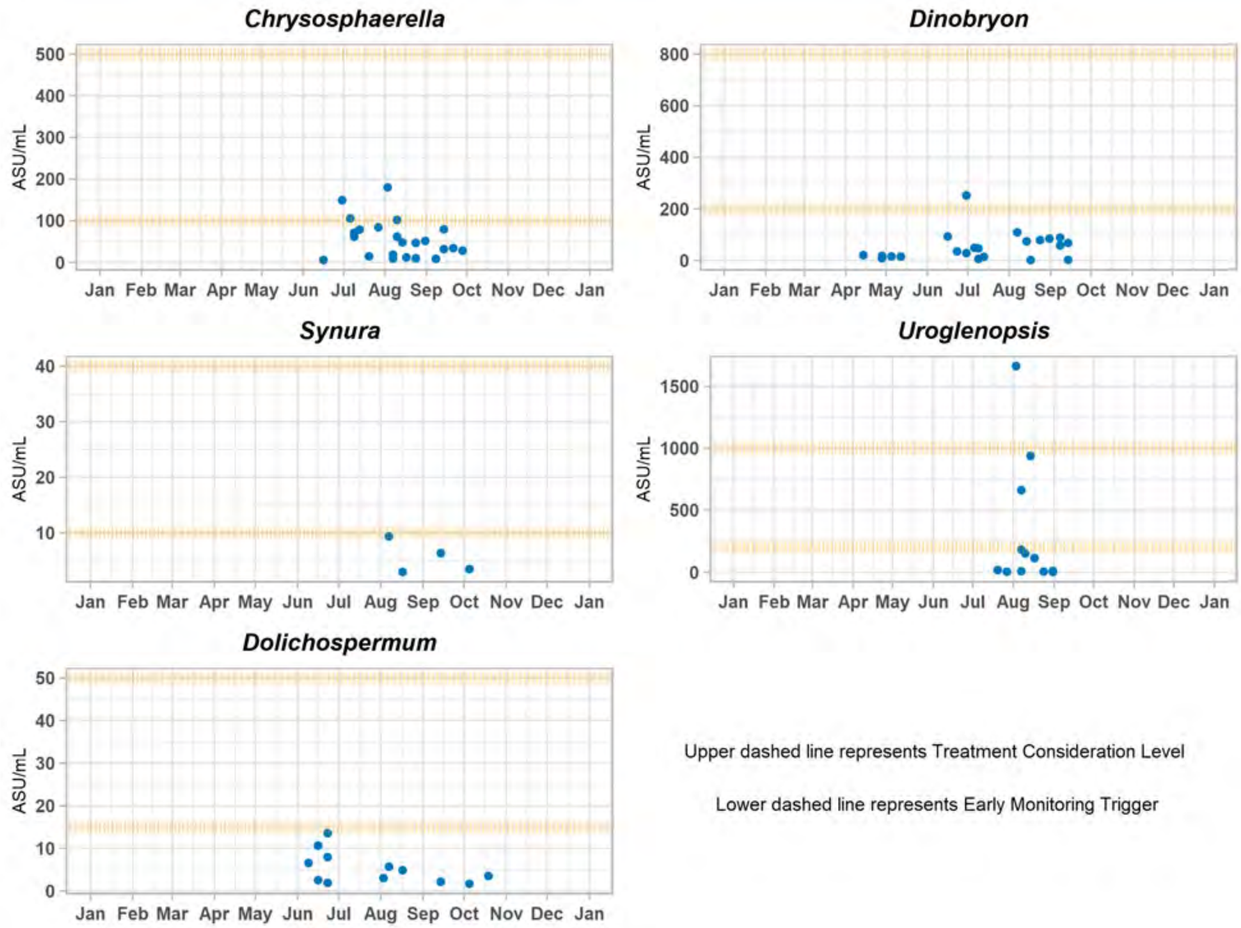


Total densities for reservoir phytoplankton in January and February were less than 250 ASU/mL. Densities started to increase with the increase in diatoms, particularly *Asterionella* in late February and early March. At this point, sampling was suspended due to COVID-19. *Asterionella* likely continued to increase since, when sampling resumed on April 14, the maximum annual density of 1,210 ASU/mL was recorded at

Cosgrove Intake at 7 m. The maximum diatom density was also recorded on this date with 1,323 ASU/mL observed at Cosgrove Intake at 3 m. Maximum densities for diatoms in 2020 may have been higher during the non-sampling period.

Phytoplankton densities decreased through May and densities below 200 ASU/mL were recorded until June 30 when *Asterionella*, *Dinobryon*, and *Chrysosphaerella* briefly appeared in the metalimnion, each above 150 ASU/mL. The early monitoring trigger of 200 ASU/mL for *Dinobryon* was briefly exceeded during this period (Figure 60).

Figure 60: 2020 Occurrence of Nuisance Phytoplankton Taxa in Wachusett Reservoir



Elevated *Dolichospermum* was observed within the epilimnion in early to mid-June. A localized aggregation of *Dolichospermum* occurred during this period in Pine Cove (42.356138, -71.760354) when a surface scum was observed by a member of the public on June 21. Within 28 hours of the initial observation, the scum had disappeared. All *Dolichospermum* values collected from Basin North and Cosgrove Intake during this period and the remainder of the year were below the early monitoring trigger of 15 ASU/mL (Figure 60).

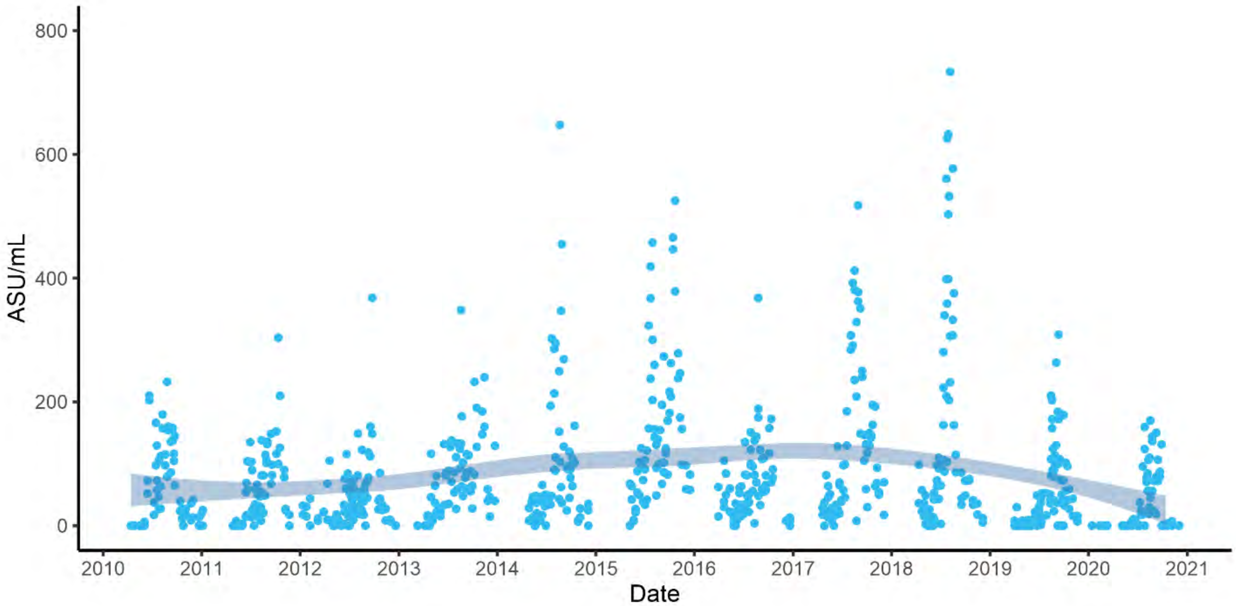
Phytoplankton densities briefly rose again when *Uroglenopsis* increased in early August. This taxa was present at very low densities in July and increased abruptly on August 3 to 1,663 ASU/mL at Basin North within the interflow at 7 m. Densities above early monitoring and treatment thresholds persisted in the interflow for 11 days. *Uroglenopsis* concentrations dissipated through the end of August and were below countable densities for the remainder of the year.

Chrysosphaerella density also rose above the early monitoring threshold of 100 ASU/mL within the interflow on August 3 with a density of 180 ASU/mL and August 10 with a density of 102.03 ASU/mL. Densities then fell below the early monitoring threshold, but *Chrysosphaerella* persisted into early October.

Overall cyanobacteria levels were lower throughout 2020 than those recorded in recent years (Figure 61). The maximum total cyanobacteria density of 170 ASU/mL was recorded on August 17 and the dominant cyanobacteria taxa on that day was *Anathece*. Maximum cyanobacteria concentrations over the past five years were all greater than this 2020 maximum, with an average of approximately 490 ASU/mL.

Figure 61: Total Cyanophytes at Basin North 2010 – 2020

The blue band represents a LOESS smooth function 95% confidence interval for the same period.



3.4.8 Zooplankton

A total of 48 zooplankton samples were collected in conjunction with the 2020 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. As in previous years, frequently observed zooplankton in these samples include Cladocerans in the Bosminidae, Daphniidae, Holopedidae families (including *Holopedium gibberum*), and the Leptodoridae family (including *Leptodora kindti*), as well as an abundance of copepods of the orders Calanoida and Cyclopoida.

3.4.9 Fish

Monitoring programs conducted in 2020 include the continuation of the Lake Trout mark-recapture study, the annual investigations for evidence of spawning Rainbow Smelt, and electrofishing in Gates Brook. Each of these monitoring programs involved coordination with MassWildlife.

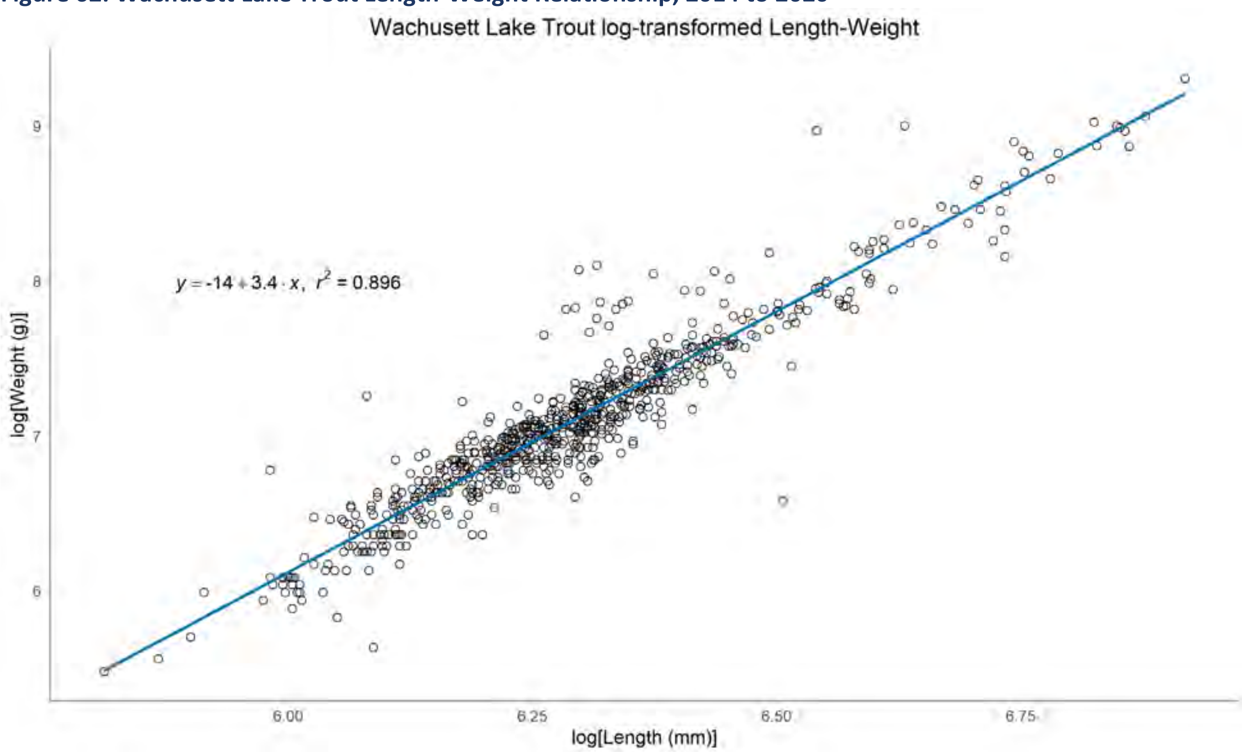
3.4.9.1 *Lake Trout (Salvelinus namaycush)*

The Wachusett Reservoir Lake Trout mark-recapture study continued in 2020. The mark-recapture study began in 2014 to investigate the status, life history, and sustainable yield of the Wachusett Reservoir Lake

Trout population. Lake Trout are an important coldwater predator in the Wachusett Reservoir food web and are the most popular game fish for anglers. As more information on the Lake Trout population is collected, DWSP and MassWildlife will be able to evaluate both the effects of angling pressure and the susceptibility to climate change [51].

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 62). 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 62: Wachusett Lake Trout Length-Weight Relationship, 2014 to 2020



To date, 760 Lake Trout have been captured during fall sampling efforts between 2014 and 2020, and 600 of these individuals have been tagged and released (Table 33). Thirty-three tagged fish have been recaptured, five of which have been recaptured at least twice. Due to equipment malfunctions, no fish were tagged in 2020 bringing the total number of caught but untagged fish up to 168. Despite the inability to read or deploy tags in 2020, the goal of catching 100 Lake Trout was met in just three nights, and the data collected contribute to the development of the length-weight relationship for the Wachusett Lake Trout population.

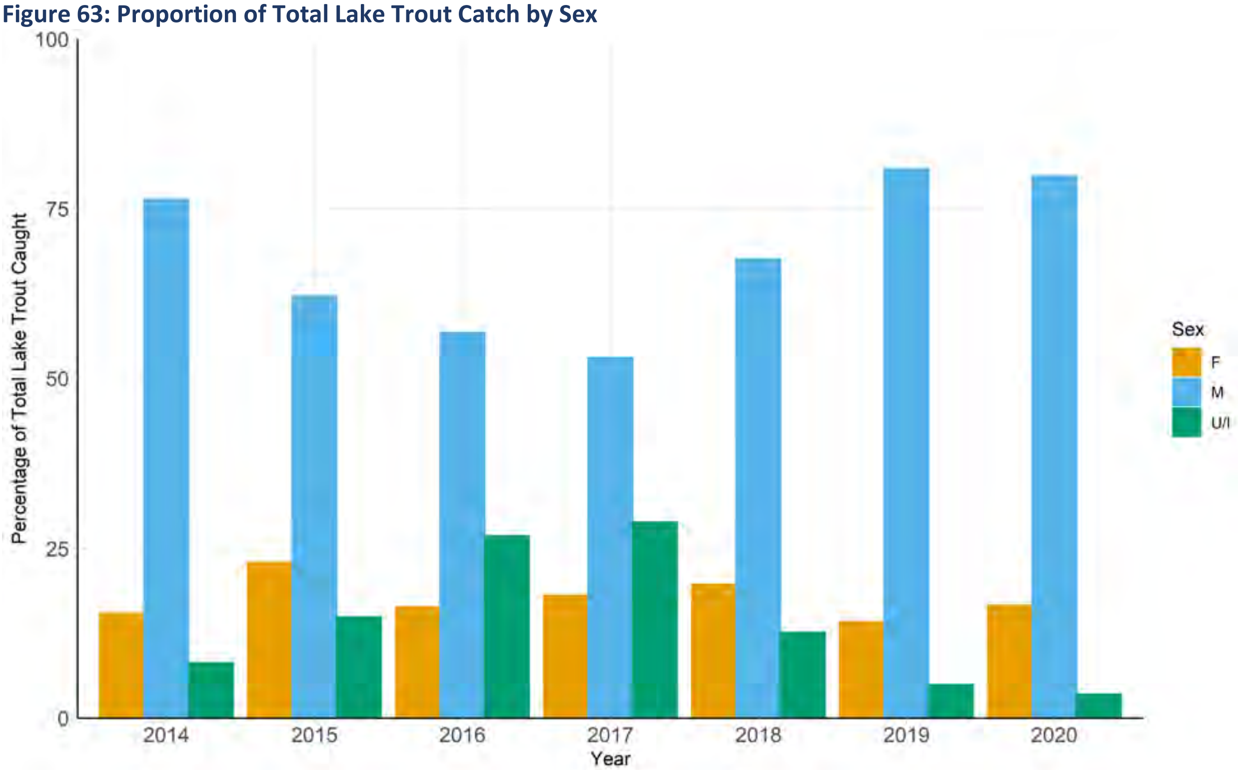
[51] Thill, 2014

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
2020	114	NA	1,367	540	114
Total	**760**	**600**	**1,452**	**545**	**168**

In 2020, 80% of Lake Trout captured in Wachusett Reservoir were males, 17% were females, and the remainder were immature or of unknown sex. The proportions of the total catch in 2020 were consistent with the results of previous years (Figure 63). Evidence suggests that male Lake Trout are caught more frequently in gill nets set during the spawn because they spend more time on the spawning grounds searching for females[52]. Studies have also shown that females spend less time on the spawning grounds searching for a mate, and thus are less likely to be captured in gill nets[53].

Figure 63: Proportion of Total Lake Trout Catch by Sex



3.4.9.2 *Other Fish Species*

As a part of annual monitoring for Rainbow Smelt spawning activity, DWSP and MassWildlife biologists investigated several tributaries and portions of the reservoir shoreline for Rainbow Smelt schools, eggs, and specimens. DWSP staff searched for evidence of smelt spawning at Dover Point and Malagasco Brook

[52] Binder et al., 2016

[53] Binder et al., 2014

on March 18, 2020; nothing was found to indicate spawning had occurred. On April 5 and 6 reports came into the DWSP Watershed Rangers and MassWildlife that at least one hundred Rainbow Smelt had washed ashore inside Gate 14. MassWildlife staff collected specimens for aging on April 6. Rainbow Smelt are a coldwater fish species with preferences for deep, oligotrophic lakes, and are considered a valuable prey item for salmonids. This coldwater species is likely an important component of the Wachusett Reservoir food web and efforts to monitor the Wachusett Reservoir population will continue annually.

On September 15 and September 22, DWSP staff assisted MassWildlife with backpack electroshocking surveys of Gates Brook and the Stillwater River, respectively. The Gates Brook survey began just upstream of the USGS sampling station, and the Stillwater survey was completed at several locations upstream of Stillwater Basin. Both surveys were a part of an ongoing study on Landlocked Atlantic Salmon (*Salmo salar*). Species identity, total length, and weight data were collected during both surveys. Two coldwater fish species were observed at both Gates Brook and the Stillwater River.

3.4.10 Bacteria

Reservoir bacteria samples were collected on 13 days in 2020. Partial ice cover on Wachusett Reservoir prevented sampling for bacteria at locations south of the Narrows on two occasions (January 31 and February 24). Location E4 was also inaccessible due to ice on January 31. Elevated *E. coli* concentrations were observed in January and February despite active bird harassment. Harassment was able to confine the roosting bird populations to the southern parts of the reservoir, as evidenced by the lower bacteria results observed in Basin North. Bacteria levels had declined by the end of February and remained low until the fall, apart from an isolated high count at F3 on August 11. Elevated concentrations of bacteria were again recorded in November and December at the southern end of the reservoir. The highest result in 2020 at location A3 (closest to the Cosgrove Intake) was 10 MPN/100 mL on September 9. All reservoir transect bacteria results for 2020 are provided in Table 34.

Table 34: Reservoir Bacteria Transect Results for 2020 – *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
Jan 7	1	1	1	1	1	1	1	3	2	19	1	2	18	1	1	5	9	12	34	27	27	19	18
Jan 31	6	4	3	4	8	4	6	4	4	10	—	4	1	1	—	—	—	—	—	—	—	—	—
Feb 12	3	4	3	3	4	2	3	4	4	5	4	8	9	1	10	21	24	5	14	24	5	8	4
Feb 24	1	1	2	1	1	2	—	5	1	2	1	4	2	1	—	—	—	—	—	—	—	—	—
Mar 9	1	1	2	2	2	1	3	5	1	4	1	2	2	1	1	4	4	1	2	4	2	3	6
Jul 13	1	2	1	1	1	2	1	4	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1
Aug 11	1	1	1	1	1	1	2	1	1	4	1	1	36	2	1	1	1	1	1	1	1	1	1
Sep 9	10	1	1	2	2	1	2	1	2	1	1	8	8	1	5	1	1	1	1	1	1	1	1
Sep 21	1	1	1	1	1	1	1	1	1	1	1	1	3	2	1	1	1	1	1	2	1	2	1
Oct 16	1	2	1	1	1	1	2	1	1	1	1	1	1	1	2	4	1	2	4	5	4	9	11
Oct 29	1	1	1	2	1	1	1	8	1	2	3	1	3	1	1	2	1	1	2	8	3	2	1
Nov 13	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	5	5	6	2	9	2	5
Nov 25	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	5	12	8	19	24	25	6	21

* 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 366 samples collected at CWTP in 2020 contained less than the standard, with a maximum concentration of 10 MPN/100 mL. Most samples (66%) did not contain any detectable bacteria. DWSP has put considerable time and effort into implementing a rigorous bird harassment program, and the results in 2020 continued to prove that the efforts are effective at maintaining low numbers of both birds and bacteria.

3.4.11 Special Studies and Investigations – Reservoir

3.4.11.1 *Investigation of Reservoir Stratification*

Worden and Pistrang[54] describe the Quabbin Interflow as "spreading through the metalimnion into all portions of the basin having sufficient depth including South Bay, Andrews Harbor, west of Cemetery Island, and against the dam." Additionally, profiles collected from routine sample sites (BS3412, BN3417, TB3427, etc.) which are close to the former Nashua River riverbed show that the thermocline and interflow depth are closely related. This correlation is expected based on the temperature of water entering from Shaft 1 and epilimnion/metalimnion temperatures in Wachusett Reservoir during summer months. However, data on these correlations had not been formally documented elsewhere in the reservoir and it was unknown how the interflow layer influenced stratification in areas of the reservoir more distant from the former Nashua River riverbed (considered the main flow path of the reservoir).

A preliminary investigation of stratification and interflow depth across Wachusett Reservoir was carried out on September 25, 2019. A total of eleven profiles were collected at pre-selected locations to include sites with a range of maximum depths and distances from the main flow path through the reservoir (Figure 64). Analysis of these data were carried out in 2020.

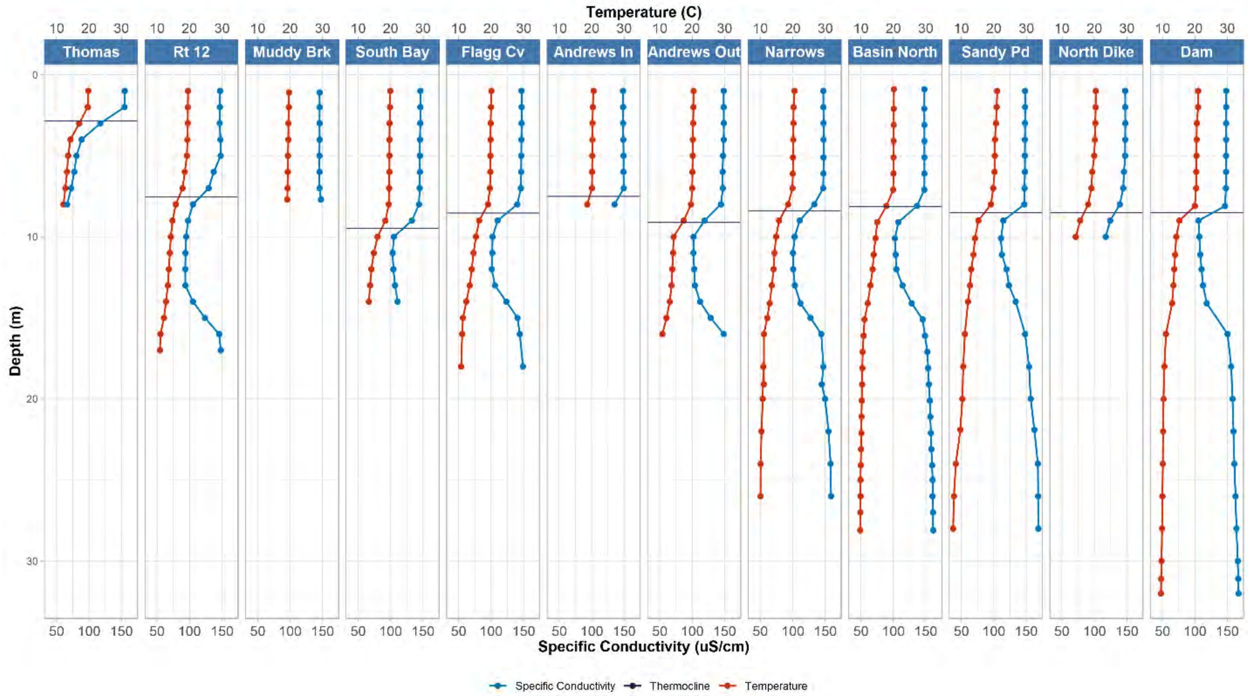
For all sites where a thermocline was present, seasonal thermocline depth, defined as the deepest density gradient found in the profile, was correlated ($r^2 = 0.8$) with the top of the interflow, defined as the depth after the greatest percent drop in specific conductivity (at least 20% decrease except for Inner Andrews Harbor, which was only slightly impacted by the interflow near the bottom). The Muddy Brook sample site was too shallow for a thermocline to form, and therefore no interflow layer was present. In locations where a thermocline and sufficient depth were present, the interflow formed a distinct layer between approximately 8 and 16 m. Below 16 m, specific conductivity rose to levels typical of native Wachusett Watershed water. Where maximum depth was less than ~16m, this deep layer of native water was not present (i.e., South Bay and North Dike). The intensity of the interflow, measured by the lowest specific conductivity reading in each profile, appears most closely related to proximity to Shaft 1, with the lowest values occurring at the Rt 12, Flagg Cove, and Narrows sample sites.

Additional spatial and temporal data collection will be necessary to quantify this relationship across the reservoir and through the year. This information will further understanding of the hydrodynamics in the reservoir and how these interactions may influence phytoplankton habitat.

[54] Worden & Pistrang, 2003

Figure 64: Wachusett Reservoir Temperature and Specific Conductivity Profiles

Profiles were collected September 25, 2019.



3.5 Macrophyte Monitoring and Management

Aquatic invasive species (AIS) have serious drinking water quality implications including increases in water color, turbidity, phytoplankton growth, and trihalomethane (THM) precursors. Macrophytes function 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.

The *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.[55] It is updated periodically to reflect changes in AIS composition within and in proximity to the reservoir.

[55] Trahan-Liptak & Carr, 2016

Table 35. Aquatic Invasive Species in or Near 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
Pistia stratiotes	Water lettuce		x

AIS were first recorded in Wachusett Reservoir in the late 1990s and have been actively managed since 2002. Early years of management focused on *Myriophyllum spicatum* (Eurasian water-milfoil) and *Cabomba caroliniana* (fanwort). In recent years, *Myriophyllum heterophyllum* (variable water-milfoil) was added as a target species. 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.

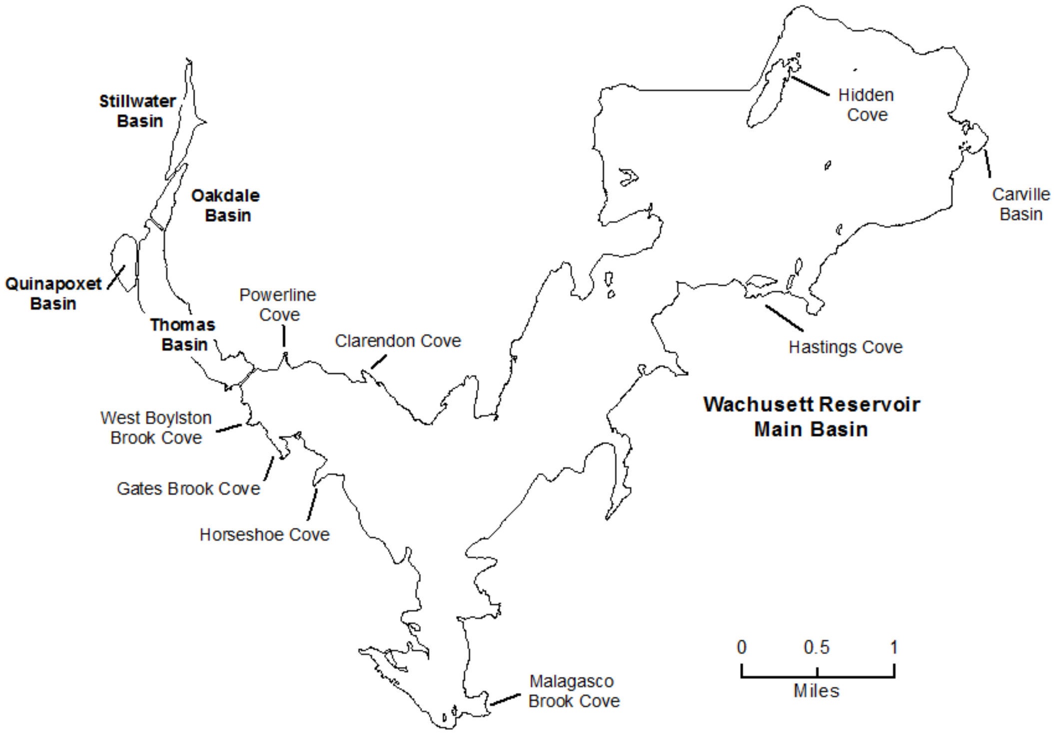
The following sections of this report provide details of AIS management activities undertaken in the reservoir, elsewhere in the watershed, and near the reservoir during 2020 and those planned for 2021.

3.5.1 Wachusett Reservoir – Invasive Macrophyte Control Program

M. spicatum was first identified in the Wachusett Reservoir system in August 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 *M. spicatum* 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.

Removal of *M. spicatum* and *C. caroliniana* via hand-harvesting was initiated in Oakdale Basin in 2002. Despite these efforts, *M. spicatum* and *C. caroliniana* gradually spread throughout Thomas Basin and into several coves of the main basin (Figure 65). As new infestations are identified, these areas are also targeted in annual removal efforts. Diver Assisted Suction Harvesting (DASH) was first implemented in 2012 and has continued as the primary control strategy for dense patches of plant growth. Hand-harvesting is used in areas where target species growth is less dense. 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. Likewise, management of VLM reservoir-wide, including in Quinapoxet Basin, was initiated in 2020 following successful management of this historically present species. 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.

Figure 65: Locations of 2020 AIS Management in the Wachusett Reservoir System



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, 2016 and planned for 2021).

Highlights of management in 2020 include:

- Low density of *M. spicatum* and *C. caroliniana* continued in the upper basins (Figure 66).
- Removal of *M. heterophyllum* in all managed areas of the reservoir (Figure 66). This milfoil species was previously thought to be too well-established for successful management; however, significant biovolume reductions in test areas (e.g., Hastings Cove (Figure 67)) demonstrate this plant can be managed with DASH. As shown in Figure 66, diver effort (Diver Hours) increased due to inclusion of *M. heterophyllum* and the increased effort required to search for single stems of invasive plants among native vegetation.
- The first year of full-scale DASH operations in Quinapoxet Basin targeting *M. heterophyllum* which has been present since at least 1989. A total of 68,298 gallons of biomass were removed over 240 diver-days (Figure 68).
- *M. heterophyllum* was not detected in Hidden Cove following two years of management.

- Transition from reporting biomass removal in gallons to reporting number of individual plant stems removed by species in Stillwater Basin

Figure 66: ***M. spicatum, C. caroliniana,*** **and** ***M. heterophyllum*** **Removed from Wachusett Reservoir 2003 to 2020**
Panel A and B: Plot includes totals removed from Oakdale, Thomas, and Powerline Coves, Panel B: Plot includes totals for M. heterophyllum *stems and gallons which are used depending on plant density.*

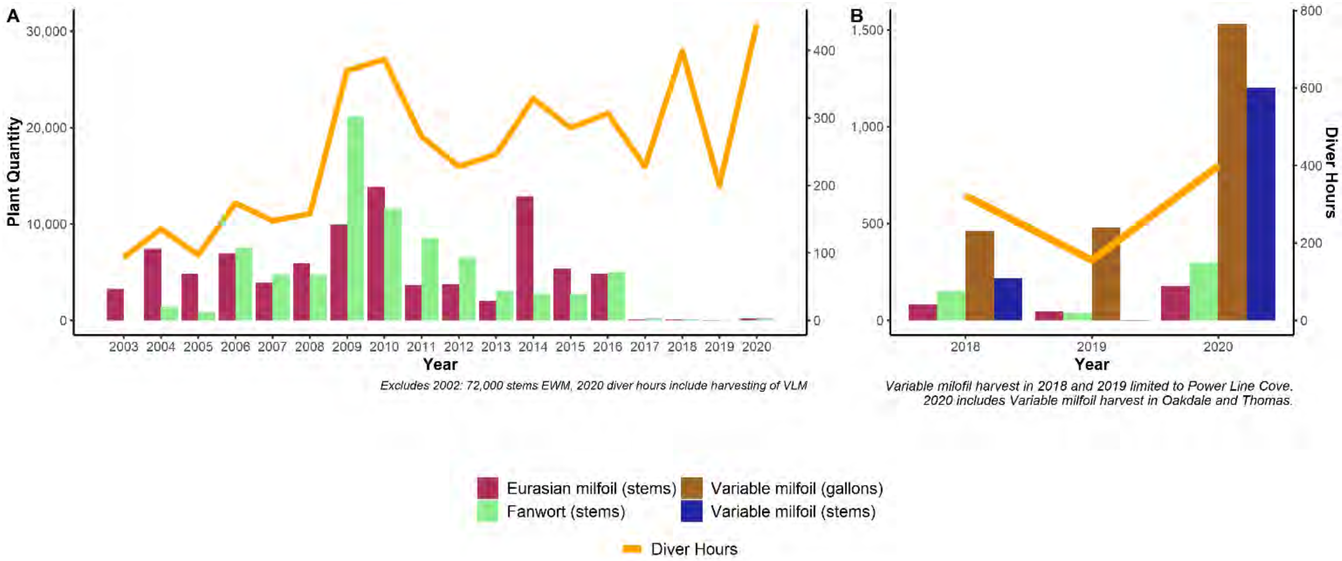


Figure 67: ***M. heterophyllum*** **Plants Removed from Hastings Cove**

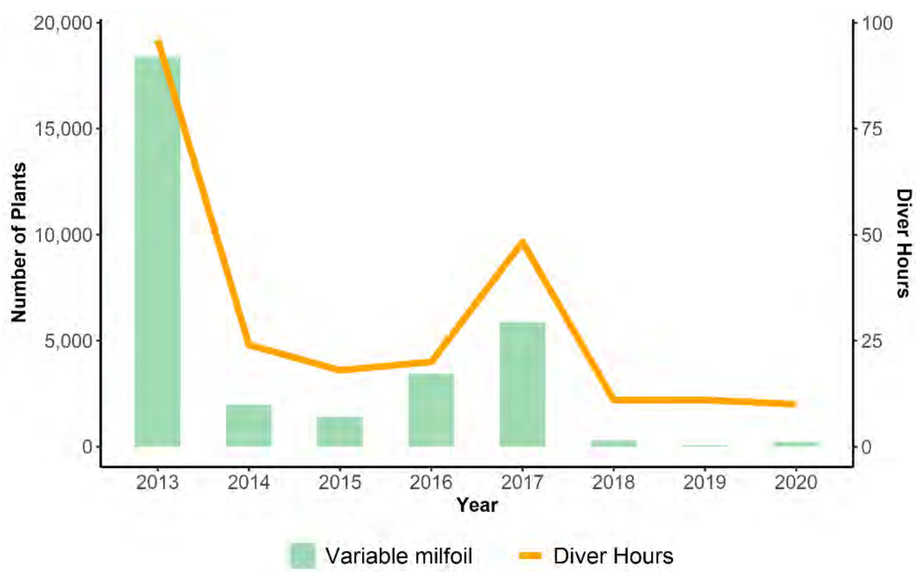
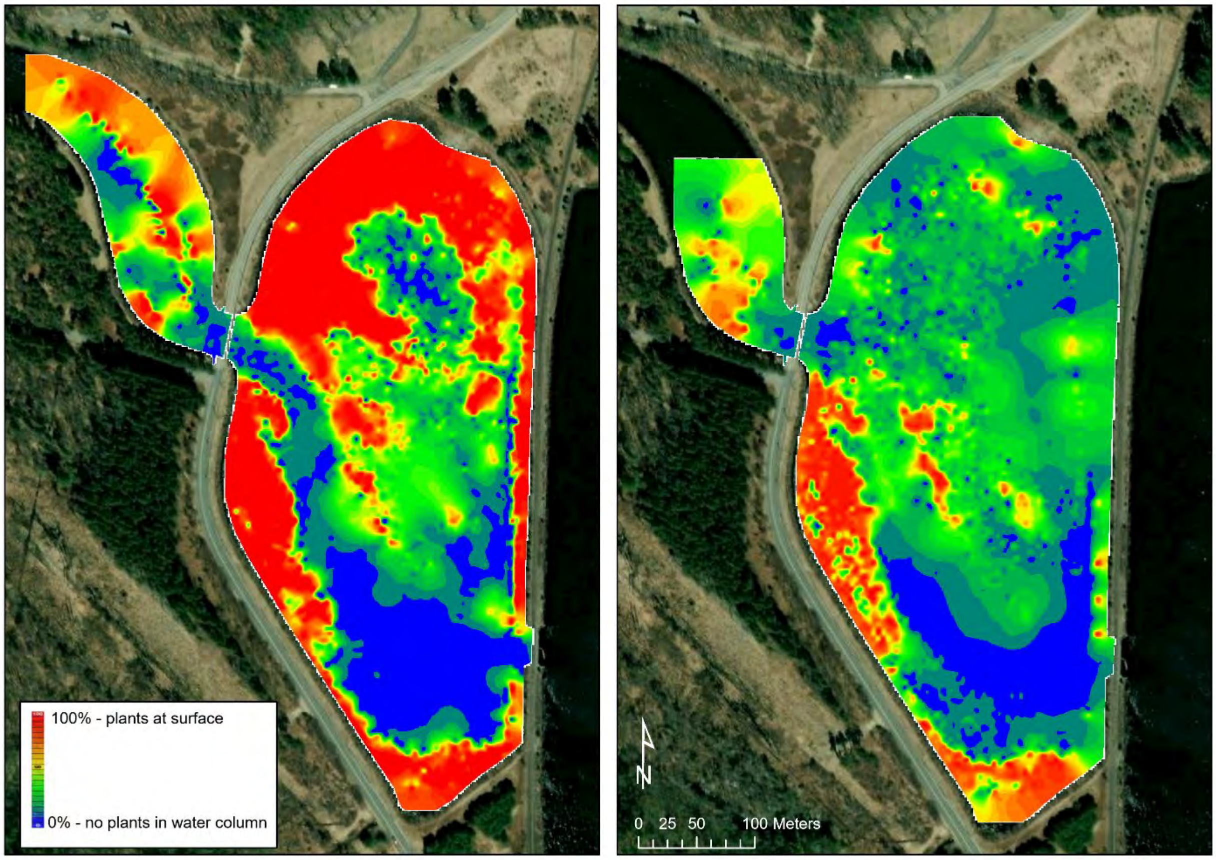


Figure 68: Biovolume in Quinapoxet Basin Before (left) and After (right) DASH in 2020



3.5.2 Wachusett Reservoir – Additional Management Activities

3.5.2.1 *Contracted Aquatic Macrophyte Surveys*

2020 was the seventh year in a row that MWRA 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 2020 survey and increases in distribution and density were not observed, with the following exception: *Glossostigma cleistanthum* (mudmat) was observed at six additional sites in 2020, the fourth year of increases.

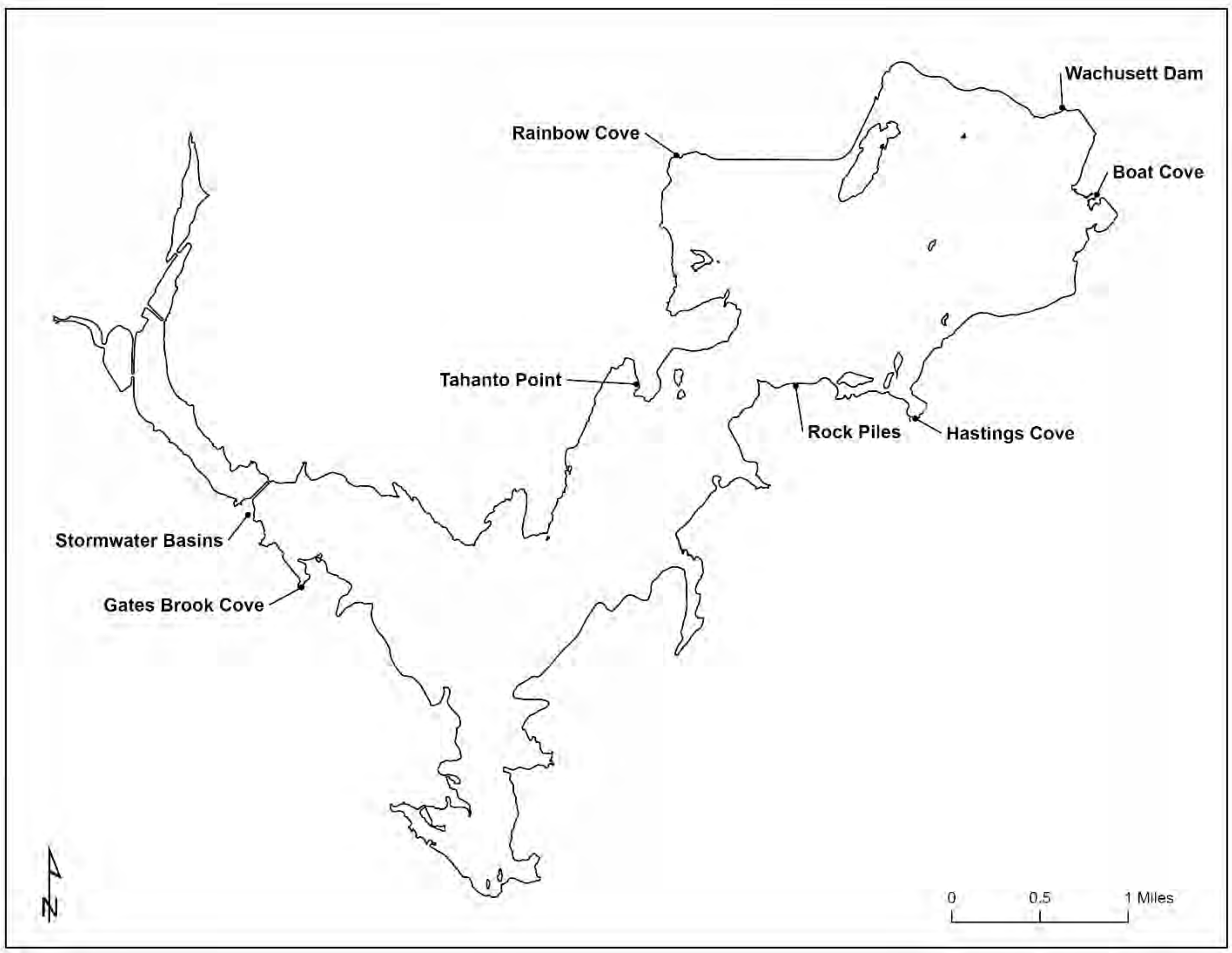
3.5.2.2 *Phragmites Management*

DWSP EQ staff surveyed and managed *Phragmites australis* (common reed) at 17 locations around the Wachusett Reservoir shoreline in 2020 (Table 36, Figure 69). Mechanical methods, including cutting and hand-harvesting, were the primary methods used. *P. australis* management progress was tracked with a series of photographs, taken at the same location before and after each management event. A full directory of *P. australis* photographs from previous years is stored on the DCR DWSP shared network drive. *P. australis* management typically occurs monthly from June to October. The goal of a monthly management frequency is to both prevent *P. australis* from going to seed and to reduce the above and below ground biomass of all stands. Additional background on *P. australis* management at Wachusett Reservoir can be found in previous Annual Water Quality Reports.

Table 36: *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
Rock Piles	112	2018	Cutting, Hand pull
Dam	6	2018	Cutting, Hand pull

Figure 69: *Phragmites australis* Stand Locations Around Wachusett Reservoir



In 2020, *P. australis* management occurred on September 3. This management effort was a drastic reduction compared to 2019, when five management days were completed; this was due primarily to COVID-19 precautions. Overall, the reservoir stands appeared to have reduced regrowth compared to previous years; individual plant height and stem density appeared to be reduced, and the number of seed heads was limited. The low number of seed heads was an interesting note this late in the growing season and may be indicative of the decreasing condition of the stands. Seed heads typically form July to September[56]. In Hastings Cove a significant thatch of cut *P. australis* stems was observed and there also appeared to be a higher incidence of individual stems within the terrestrial areas along the shoreline. It is not possible to determine if these stems grew from rhizomes or from seed.

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.
- Photographs are taken before and after each management event.

2020 Program highlights

- No *P. australis* found at Tahanto Point, the Dam, Rock Piles, Hastings Cove A, Hastings Cove F.
- Cuts completed in 2020 for established stands: Hastings Cove, Boat Cove, Rainbow Cove.
- Hand pulling effort at small expansion locations and edges of stands: Hastings Cove, Gates Cove.

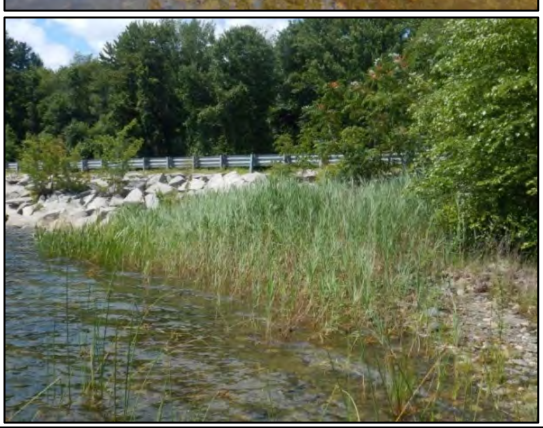
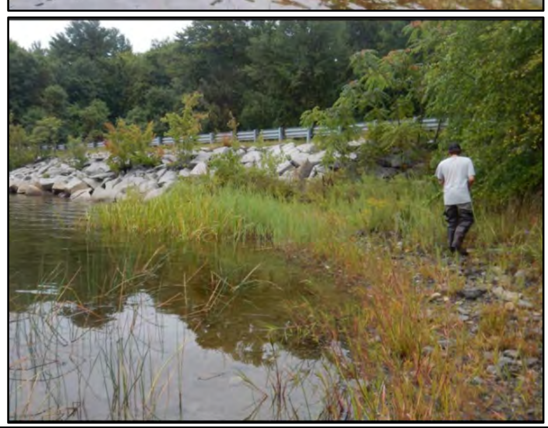
Future plans

- Management in 2021 is anticipated to return to a full management program with monthly monitoring and removal as necessary.
- Physical barrier methods may be employed at smaller stands such as Tahanto Point.
- Utilize ESRI applications such as Survey123 and Collector to track management progress.
- Survey for pioneer infestations during the 2021 Reservoir Shoreline Surveys for AIS.

---

[56] MassDCR, 2002

Figure 70: Photo Documentation of *Phragmites* Management Progression

Location	2015-2017, Before Management Program	2020, Prior to Annual Cutting
Boat Cove Site A		
Hastings Cove Site C		
Hastings Cove Site B		
Rainbow Cove		

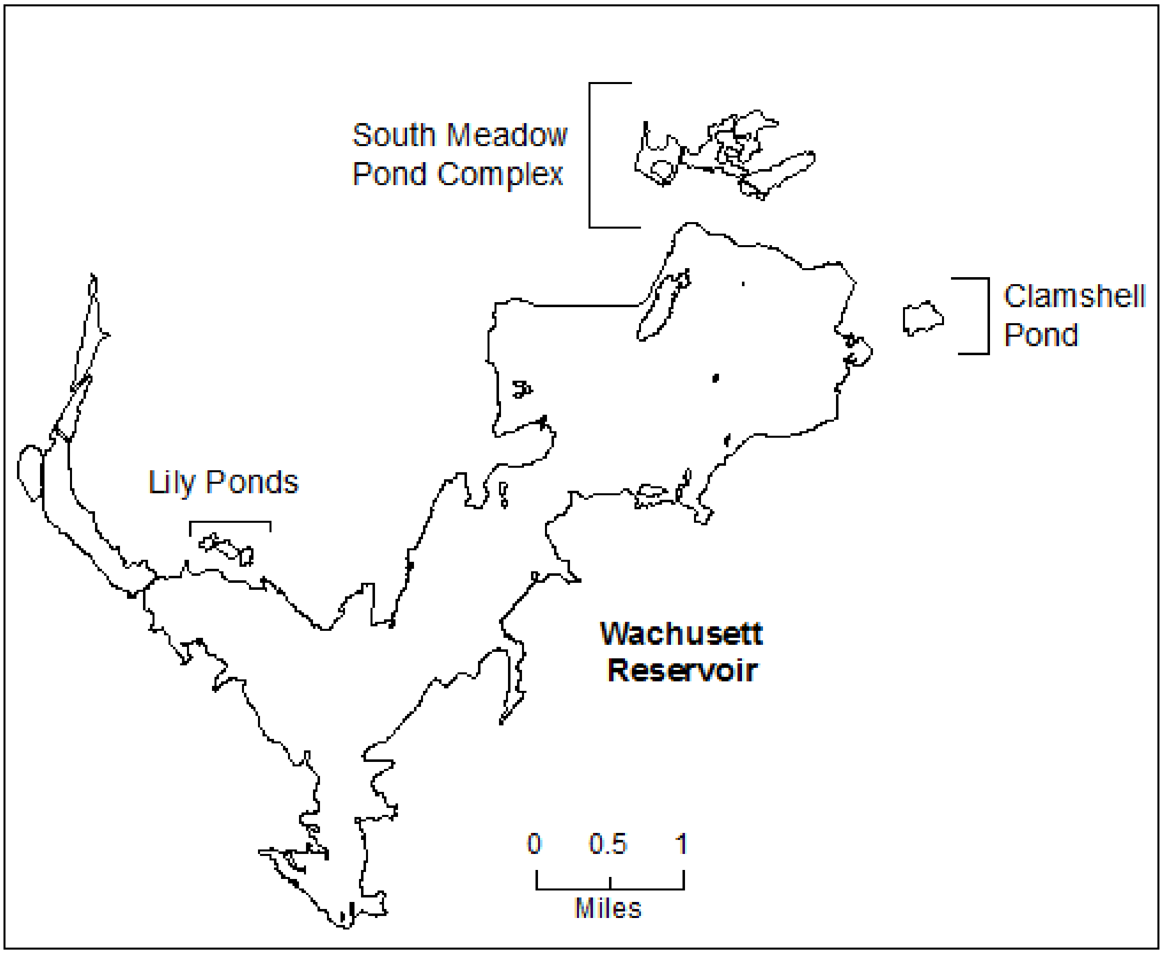
3.5.3 Supplemental Invasive Macrophyte Control Activities

Additional activities were conducted in 2020 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 71). Although technically outside of the Wachusett Reservoir watershed, three 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 ongoing.

Figure 71: Locations of Local Ponds Managed for AIS



South Meadow Pond Complex

Hydrilla was first discovered in the South Meadow Pond Complex, located just 1,970 feet (600 m) north of Wachusett Reservoir, in August 2010. A rapid response plan was initiated with the first herbicide treatment conducted in fall 2010. Herbicide treatments have continued on an annual basis with management of *P. crispus* added to the treatment program upon its discovery in 2015.

Results of treatment are monitored through pre- and post-management surveys conducted by the contractors and DCR and a tuber sampling program conducted by the contractors since 2010. Tuber density has decreased such that less than one tuber per square meter is reported annually; however, these tubers continue to produce vegetation, requiring continued annual maintenance.

In 2020 *P. crispus* was managed with an application of diquat on June 10 to approximately 15 acres of South Meadow Pond. Three treatments with fluridone herbicide were conducted to manage *Hydrilla* on June 25, August 5, and September 9. Tuber density continues to be low; however, five tubers were collected from three sites in October, indicating that plants persist and continue to produce reproductive structures.

Clamshell Pond

DWSP initiated management of *Egeria densa* (Brazilian elodea) and *Trapa natans* (water chestnut) present in Clamshell Pond in 2016. These species had been present in the 25-acre pond, located approximately 1,300 feet (400 m) northeast of Wachusett Reservoir, since at least 2008, but DWSP was not aware of the infestations until records were made available in online databases[57].

E. densa was treated with the contact herbicide diquat in June 2018 and *E. densa* has not been observed in Clamshell Pond in subsequent surveys. During surveys, DWSP biologists also monitor the *T. natans* population and remove plants, as necessary. In 2020, four *T. natans* plants were removed during the June survey and five plants were removed during the August survey. Volunteers from the Raucher Farm Management Subcommittee periodically survey the pond and did not report any *T. natans* in 2020.

Lily Ponds

Najas minor (Brittle Naiad) and *M. spicatum* were identified in the Lily Ponds in 2015. Due to the ponds' locations, approximately 600 feet (180 m) from the reservoir shoreline, a rapid response plan was initiated in fall 2015 and management has continued annually. *M. spicatum* has not been observed since the initial diquat treatment in 2015. *N. minor* persists, in each pond, likely due to a seed bed which persists in the sediments.

DWSP biologists observed *N. minor* in each of the three ponds in August 2020 and an herbicide treatment was conducted on September 1. Approximately 4.5 acres were treated across all three water bodies.

3.5.3.2 *Watershed Pond Monitoring*

DWSP staff completed aquatic macrophyte surveys in a selection of the Wachusett Watershed ponds. Watershed pond surveys occur every five years and were completed in addition to the surveys associated with watershed ponds under management for AIS. The focus of the watershed pond surveys was to

[57] United States Geological Survey [USGS], 2021

document AIS presence. The watershed pond surveys also contributed information to historic databases of both native and non-native macrophytes and served as baseline surveys for ponds where historic data do not exist.

Surveys were conducted by paddling the littoral zone of each waterbody. The data collected during surveys included species present, location, depth at observation location, biovolume, and density. Survey information was recorded using the ESRI applications Collector and Survey123. Most observations were made from above the water; however, a throw rake was used when water clarity and depth did not allow for plant identification from the surface.

In 2020, a total of 14 ponds within the watershed were surveyed. These water bodies were selected based on proximity to the reservoir, size, public access, and known presence of invasive vegetation based on historical data (Table 37).

Non-native aquatic vegetation was documented in 11, or 85%, of the 14 ponds surveyed. The most common non-native species, occurring in 12 waterbodies, was *M. heterophyllum*, a species that has been present within Wachusett Reservoir for several decades. *M. spicatum* was observed in three watershed ponds, while *C. caroliniana* was observed in four ponds. These species have been present in the upper basins of Wachusett Reservoir and have been managed on an annual basis since the early 2000s (Section 3.5.1). A fourth non-native species that has not been observed in Wachusett Reservoir, *N. minor* (European Naiad or Brittle Naiad), was documented in six watershed ponds. *N. minor* has been managed in the Lily Ponds since 2015.

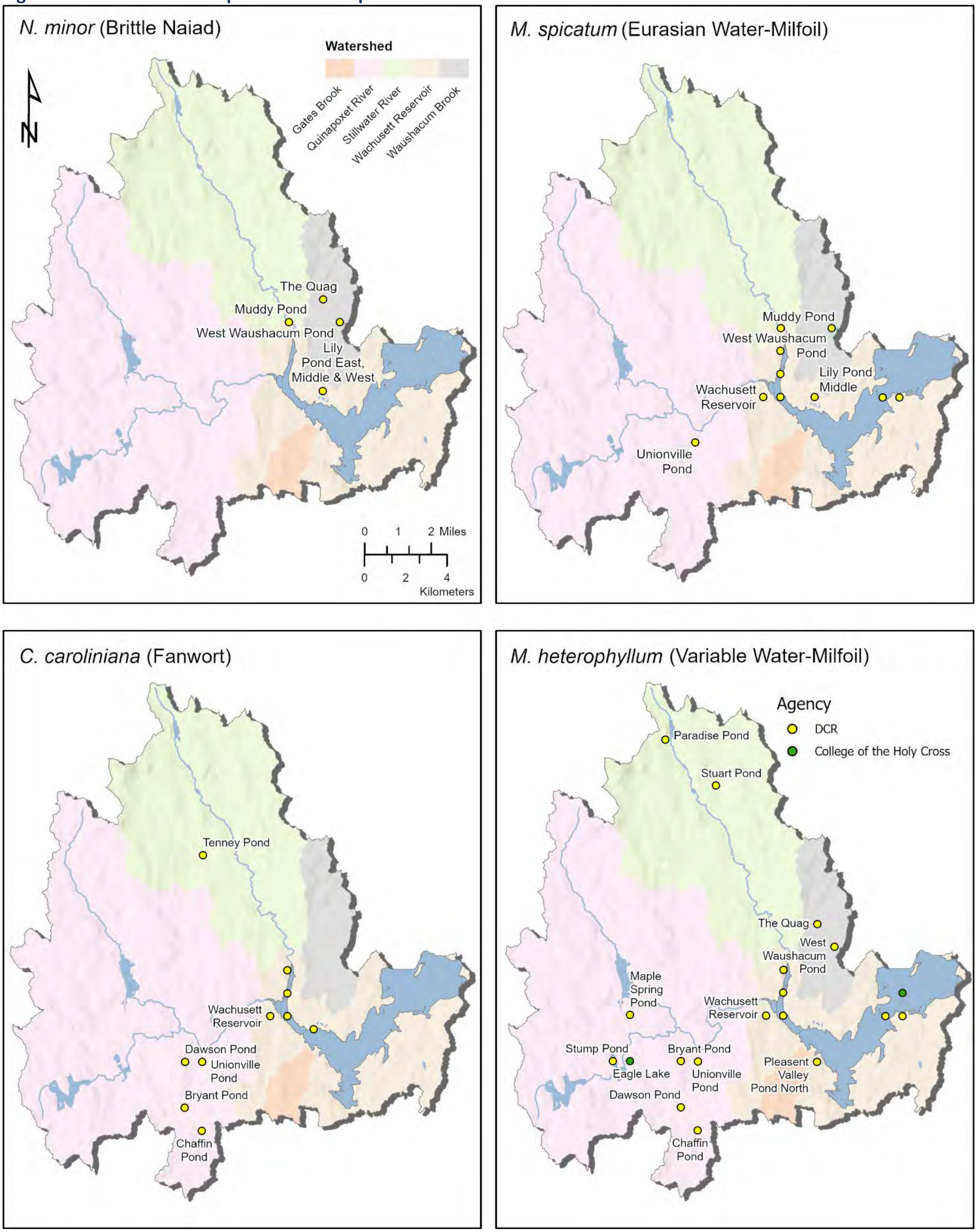
Table 37: Wachusett Watershed Ponds Surveyed in 2020 for Non-native Aquatic Vegetation

Name	Town	Proximity to Wachusett Reservoir (miles)*	Acres	Number of Invasive Vegetation Species Observed in 2020
Pleasant Valley Pond North	West Boylston	0.08	2.0	1
Pleasant Valley Pond South	West Boylston	0.16	2.3	0
Lily Pond East	West Boylston	0.21	4.7	1
Lily Pond Middle	West Boylston	0.21	7.5	2
Lily Pond West	West Boylston	0.26	4.3	1
Carrolls Pond	West Boylston	1.28	1.5	0
Edwards Pond	West Boylston	1.29	0.9	0
Muddy Pond	Sterling	1.31	25.8	2
The Quag	Sterling	2.27	34.7	2
West Waushacum Pond	Sterling	2.39	118.2	2
Unionville Pond	Holden	5.41	20.0	2
Chaffin Pond	Holden	7.59	83.9	2
Dawson Pond	Holden	8.57	24.6	2
Paradise Pond	Princeton	10.1	61	2

* straight line distance to closest reservoir shoreline

Occurrences of AIS in the Wachusett Reservoir watershed are depicted in the maps below, based on DWSP data and other sources, including the MA DEP AIS Database (Figure 72).

Figure 72: Occurrence of Aquatic Invasive Species in Wachusett Reservoir Watershed



3.5.3.3 *New Occurrences of AIS*

On September 30, DWSP Natural Resources (NR) Biologist Hillary Siener notified DWSP Aquatic Biologists of a potential AIS occurrence in the Stillwater River. Photos and a description of the plants were provided in an email from NR and suggested *Pistia stratiotes* (water lettuce). DWSP Aquatic Biologists conducted a follow up survey on October 1 and confirmed the plants were *P. stratiotes*. Rosettes were found on the Stillwater River just south of the Route 62 bridge in Sterling (Figure 73), between the bridge and the first beaver dam downstream of the bridge. There were four beaver dams within one half-mile downstream of the Route 62 bridge on 10/1/2020. These structures were likely impediments to movement of these floating plants farther downstream.

Approximately 10-20 rosettes were removed from this area and placed in sample bags within 20 minutes. After removing these the survey continued upstream until reaching Wilder Brook. No *P. stratiotes* was found in any section of the Stillwater River upstream of the Route 62 bridge. The survey continued downstream of the initial launch point until Riverview Road, but no additional *P. stratiotes* was observed.

P. stratiotes, commonly known as water lettuce, is a perennial, free-floating, rosette-forming, freshwater macrophyte. It is not currently listed on the Massachusetts list of prohibited plants[58]; however, it is listed as a noxious weed or an invasive species in several states in the United States, including California, Alabama, Mississippi, Louisiana, Wisconsin, Florida, Texas, South Carolina, and Connecticut. Currently, *P. stratiotes* is not winter hardy or capable of overwintering outside of USDA Zones 8-10; however, there have been cases of *P. stratiotes* overwintering in some mild climates with warm water refuge (Sajna, 2007). Massachusetts is in USDA Zones 5-7. *P. stratiotes* can spread quickly through sexual reproduction via small flowers found in the middle of the rosettes, but more commonly spreads through asexual reproduction or "budding" of daughter plants connected to the mother plant via stolons. *P. stratiotes* is free-floating, but it is equipped with a root system that collects floating particles. *P. stratiotes* is sold as a popular backyard pond plant. *P. stratiotes* is also considered poisonous if eaten in large quantities as the leaves contain calcium oxalate crystals.

This location on the Stillwater River will be revisited by DWSP to monitor for future invasive species activity, as it is likely that this incident was an aquarium or pond dump related to the proximity of the site to Route 62. Local greeneries in the area may be contacted and encouraged to limit sales of *P. stratiotes* and/or provide clients educational materials on the detriments of releasing these and all non-native species.

Figure 73: *Pista stratiotes* Found and Subsequently Removed from the Stillwater River.

[58] Forman-Orth, 2021

4 Conclusions and Recommendations

4.1 Wachusett Tributary Water Quality

Routine tributary monitoring results for bacteria and turbidity in 2020 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 stormwater 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 2020 which warrant additional investigation or management action.

Water temperature data for 2020 was reviewed and discussed for the first time in more than two decades. While this parameter does not have direct implications for the sanitary quality of drinking water supplies, it is an important parameter for aquatic life considerations and plays an important role in regulating many biogeochemical processes (such as algal and bacteria growth), which do ultimately impact the quality of the drinking water supply. Tributary water temperatures followed predictable seasonal patterns, with summertime high temperatures rising above the MassDEP recommended threshold for coldwater species (20 °C) in several tributaries. All tributaries remained within the recommended temperature range for warm water species. To help reduce stress on coldwater species and improve other aspects of tributary water quality, DWSP should continue to actively promote the pre-treatment of stormwater, most importantly through the reduction of direct discharges of stormwater collected from impervious surfaces and the promotion of forested stream buffer zones.

In the fall of 2020, monitoring for alkalinity in Wachusett tributaries resumed to determine the cause of the rising alkalinity trend observed in Wachusett Reservoir in recent years. Alkalinity was previously sampled in tributaries between 2000 and 2012, and the few results collected in 2020 were compared with the earlier alkalinity concentrations. The 2020 data show a significant increase in alkalinity has occurred in the Stillwater and Quinapoxet Rivers since 2012. Additionally, Quabbin Reservoir has experienced a slight, but steady, rise in alkalinity in recent years, with concentrations rising from under 3 mg/L to over 4 mg/L in 2020. The combined inputs of the Quabbin Transfer and Quinapoxet and Stillwater rivers appear to be the cause of rising alkalinity observed in Wachusett Reservoir. Monitoring for alkalinity in the tributaries will continue for at least the next year to determine if the results from 2020 are representative of all seasons, or if there is intra-annual variability. The causes and implications of rising alkalinity will also be explored in greater depth.

Monitoring for tributary pH was conducted for over a decade (prior to 2000) and it was previously concluded the pH did not vary seasonally or over time. As of mid-2019 more rigorous sensor calibration and maintenance protocols were established for tributary pH sensors and results could be relied upon for accuracy. The tributary pH results for 2020 provide evidence that there is inter-seasonal variation in pH levels for most Wachusett tributaries. Summertime pH tends to rise due to the buffering provided by growing vegetation and increased contact and chemical interaction within soils. During the winter, stream pH acidity increases, often dropping below the recommended lower pH threshold for aquatic life (6.5) at several tributary monitoring locations, with the lowest value reaching 5.77. These lower pH levels are reflecting the pH of precipitation, which is around 5.1, because wintertime hydrologic pathways do not have the same opportunity for buffering reactions in vegetation and soils. The pH values and seasonal patterns observed in Wachusett tributaries are reflective of natural conditions and are not a water quality concern for the drinking water supply at this time.

Routine tributary and groundwater monitoring results for dissolved salts and specific conductance in 2020 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 ongoing planning efforts at DWSP and UMass. Mitigation strategies are still being developed through the Chloride/Conductivity working group, while strategies for expanded monitoring in groundwater and surface waters are being researched by Environmental Quality staff. In 2020, the first round of targeted chloride mitigation grants was funded, and grants were awarded to three watershed towns totaling $58,592. However, the town of Princeton was unable to move ahead with their project by the fiscal year deadline, so their FY2021 grant award of $20,000 will be rolled into the FY2022 program. These grants will help Wachusett watershed towns reduce chloride contamination from road salt through either improved efficiency or tools for better salt storage and management. The Chloride/Conductivity working group did not meet in 2020 due to the COVID-19 pandemic, however, information is still being gathered to better understand salt loading in Wachusett and how it is impacting drinking water quality and the water treatment process. This problem is not expected to be resolved quickly, as dissolved salts do not readily break down in the environment, they have accumulated in soils and aquifers, and many tons continue to be spread throughout the watershed every year. Expanded monitoring for Cl and specific conductance throughout the Wachusett Watershed has been planned for 2021 and results from those initiatives will be presented in the 2021 Annual Water Quality Report.

Routine tributary nutrient monitoring results for 2020 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. French Brook experienced higher than normal nitrogen concentrations due to extreme low flows during the summer and late fall. 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 and within ecoregional background ranges, however a few of the smaller tributaries had mean and median concentrations in 2020 that were slightly elevated. French Brook was most notable, with a mean annual TP concentration of 44 µg/L. Seven of ten primary tributaries had median TP concentrations for 2020 above the 2011 – 2019 median. Fortunately, elevated concentrations mostly occurred under extreme low flow conditions, so TP loads to the reservoir would have been relatively small. 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} absorbance levels in Wachusett tributaries for 2020 were slightly greater than in 2019, but still the third lowest (annually) since 2011. Although the organic carbon concentrations 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. In the absence of numerical nutrient criteria for nutrients in Wachusett Watershed tributaries, the most effective regulatory drivers to control nutrient pollution lie in the Watershed Protection Act, MA Wetlands Protection Act, and Municipal Separate Storm Sewer System (MS4) requirements of the National Pollutant Discharge Elimination System (NPDES) program.

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.

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 results of these conditions were also similar to previous years.

Specific conductance remains elevated compared to historical values and the increasing trend in alkalinity continued in 2020. Enhanced monitoring and mitigation programs (see Section 4.1) are being implemented to address these trends and monitoring within the reservoir will continue to provide a reference for detection of downstream changes resulting from these modifications within the watershed.

Density thresholds for cyanobacteria, specifically *Dolichospermum* have not been exceeded since 2018; however, two surface aggregations of this genera have been observed in the past two years. These surface scums appear to be short-lived (visible for less than 48 hours) and have occurred in small areas, such as isolated in coves more than 1.5 miles away from the Cosgrove Intake. DWSP biologists continue to work with rangers and other DWSP staff to monitor for and document these events when possible. New monitoring techniques, including remote sensing with wildlife cameras, are also being tested to enhance understanding of these events and their potential effects on water quality.

4.3 Proposed Wachusett Watershed Monitoring Programs

4.3.1 Hydrological and Climate Monitoring

Continuous monitoring station upgrades are planned for six tributaries in 2021, using the same equipment that was tested at the pilot station on Waushacum Brook. Mayfly dataloggers and Hydros-21 conductivity, temperature, and depth sensors will be installed at the following locations: Trout Brook, Malden Brook, French Brook, Malagasco Brook, Muddy Brook, and West Boylston Brook. Existing HOBO U20 depth and temperatures will remain in place until the new stations are tested and are recording accurate data.

Monitoring Element	Current Program	Proposed Changes
Real-time flow monitoring	10 tributaries (3 by USGS)	Change sensor from HOBO to Hydros-21
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

Groundwater will continue to be monitored for specific conductance, temperature, and chloride as in 2020. Due to highly elevated specific conductance and chloride levels in multiple wells, particularly West Boylston - Rt 110 - MDW4, additional monthly samples will be collected for eight parameters—alkalinity, bromide, calcium, fluoride, magnesium, nitrate, sodium, and sulfate—in the seven wells currently sampled for chloride. Collection and analysis of these parameters began in May 2021, and it is hoped that the added information will assist in determining if road salt is the only source of extra chloride or if other sources are contributing to the levels present in the groundwater.

Monitoring Element	Current Program	Proposed Changes
Groundwater Quality (WATWEL)	Monthly – Eight wells for specific conductance and temperature; Seven wells for chloride	Add monthly alkalinity, bromide, calcium, fluoride, magnesium, nitrate, sodium, and sulfate samples to wells being sampled for Cl.

4.3.3 Tributary Monitoring

Routine tributary monitoring (WATMDC and WATTRB) and field parameters will continue at the same frequency and with the same parameters as in 2020. Real-time conductivity monitoring will be expanded to cover all primary tributary monitoring locations when all non-USGS stations are upgraded with the Hydros-21 CTD sensors and Mayfly dataloggers. It is anticipated that station upgrades will occur in the early fall of 2021.

Monitoring Element	Current Program	Proposed Changes
Nutrients, Cl, UV absorbance, TSS, Alkalinity (WATMDC)	Monthly, 10 primary tributaries + Quabbin Transfer (MDS1)	No change
Bacteria and Turbidity (WATTRB)	2x per month, 18 Locations	No change
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	Add all remaining primary sampling locations. Equipment upgrades

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 in 2020 at the same frequency as in prior years, dependent on harvest stage. All new data will still be imported into the EQ Water Quality database and will also remain accessible on ArcGIS online. Recent analysis has determined that the previous threshold for requiring summary and assessment reports (mean annual turbidity of 5.0 NTU) is likely to never occur, and therefore no reports will be written. Due to the low threat to water quality from forestry operations, internal DWSP discussions will take place in 2020 to determine how best to modify the short-term forestry monitoring program to make the best use of staff resources given the current priorities in water quality monitoring. Any changes implemented as a result of that discussion will be presented in the 2021 Annual Water Quality Report.

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. The completion of a preliminary summary report for the first six years of monitoring is still pending, however sufficient flow data at the Princeton weir has been collected to allow for analysis to proceed. The experimental lot (Princeton) has been sold and harvest is expected to begin in 2021. Quarterly storm sampling is scheduled to resume in 2021 as soon as the timber harvest begins.

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 remains 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.

4.3.4.8 *Surface Water Conductivity Blitz*

In May of 2021, a new short-term (1-year) monitoring initiative was launched to gather more information about the geographic variability of elevated conductivity (and chloride by proxy) of surface waters in Wachusett Watershed. Conductivity and other field parameters will be measured at as many surface water locations across the watershed as possible, with emphasis on areas that have not been monitored in the past and areas that are significantly impacted by freshwater salinization. The results of this ‘Conductivity Blitz’ will be compiled and analyzed in 2022.

4.4 Reservoir Monitoring for 2021

Reservoir monitoring programs will continue as carried out in 2020. 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 2021. The reservoir's littoral zone will be surveyed in its entirety in 2021. This assessment is carried out every five years (starting in 2012) and includes visual surveys of macrophyte composition made while traversing the littoral area, collection of biovolume data, and in-water surveys in select areas of concern.

The Lake Trout mark-recapture study is anticipated to continue for a seventh 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 regularly. Monthly, biweekly, or weekly bacterial transect sampling will be completed during ice-free periods to help further understand the effect of avian populations and water movement on fecal bacteria (*E. coli*) levels throughout the reservoir and fecal coliform levels at Cosgrove Intake.

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

5 References

Bent, G. C. (1999). Streamflow, base flow, and ground-water recharge in the Housatonic River Basin, western Massachusetts and parts of Eastern New York and Northwestern Connecticut. *USGS Numbered Series.* United States Department of the Interior, United States Geological Survey. https://doi.org/10.3133/wri984232

Binder, T. R., Thompson, H. T., Muir, A. M., Riley, S. C., Marsden, J. E., Bronte, C. R., & Krueger, C. C. (2014). New insight into the spawning behavior of lake trout, *Salvelinus namaycush*, from a recovering population in the Laurentian Great Lakes. *Environmental Biology of Fishes, 98*(1), 173–181. https://doi.org/10.1007/s10641-014-0247-6

Binder, T. R., Riley, S. C., Holbrook, C. M., Hansen, M. J., Bergstedt, R. A., Bronte, C. R., He, J., & Krueger, C. C. (2016). Spawning site fidelity of wild and hatchery lake trout (*Salvelinus namaycush*) in northern Lake Huron. *Canadian Journal of Fisheries and Aquatic Sciences, 73*(1), 18–34. https://doi.org/10.1139/cjfas-2015-0175

Camargo, J. A., & Alonso, Á. (2006). Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. *Environment International*, *32*(6), 831–849. https://doi.org/10.1016/j.envint.2006.05.002

Chang, W., Cheng, J., Allaire, J., Xie, Y., & McPherson, J. (2019). *shiny: Web application framework for R. R package version 1.3.1. Comprehensive R Archive Network (CRAN)*. https://cran.r-project.org/package=shiny

Corsi, S. R., Graczyk, D. J., Geis, S. W., Booth, N. L., & Richards, K. D. (2010). A fresh look at road salt: Aquatic toxicity and water-quality impacts on local, regional, and national scales. *Environmental Science and Technology*, *44*(19), 7376–7382. https://doi.org/10.1021/es101333u

Daley, M. L., Potter, J. D., & McDowell, W. H. (2009). Salinization of urbanizing New Hampshire streams and groundwater: Effects of road salt and hydrologic variability. *Journal of the North American Benthological Society*, *28*(4), 929–940. https://doi.org/10.1899/09-052.1

Division of Water Supply Protection. (2008). *Water quality report: 2007 Wachusett Reservoir Watershed*. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

Division of Water Supply Protection. (2016). *Wachusett EQ Land Cover* [data]. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

Division of Water Supply Protection. (2018a). *Watershed Protection Plan FY19-FY23*. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

Division of Water Supply Protection. (2018b). *2017 Land management plan*. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

Division of Water Supply Protection. (2019). *Water quality report: 2018 Wachusett Reservoir Watershed*. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

Dodson, S. (2005). *Introduction to limnology*. New York, NY, USA. McGraw-Hill. pp46

Forman-Orth, J. (2021). *Massachusetts Prohibited Plant List.* https://www.mass.gov/service-details/massachusetts-prohibited-plant-list

Grady, S. J., & Mullaney, J. R. (1998). Natural and human factors affecting shallow water quality in surficial aquifers in the Connecticut, Housatonic, and Thames River basins. *Water-Resources Investigations Report*. United States Department of the Interior, United States Geological Survey. https://doi.org/10.3133/wri984042

Granato, G. E., DeSimone, L. A., Barbaro, J. R., & Jeznach, L. C. (2015). *Methods for evaluating potential sources of chloride in surface waters and groundwaters of the conterminous United States*. United States Department of the Interior, United States Geological Survey. https://doi.org/http://dx.doi.org/10.3133/ofr20151080

Griffith, G.E., Omernik, J.M., Bryce, S.A., Royte, J., Hoar, W.D., Homer, J., Keirstead, D., Metzler, K.J., and Hellyer, G. (2009). *Ecoregions of New England* [color poster with map, descriptive text, summary tables, and photographs]: Reston, Virginia, U.S. Geological Survey (map scale 1:1,325,000)

Godfrey, P. J., Mattson, M. D., Walk, M.-F., Kerr, P. A., Zajicek, O. T., & Ruby III, A. (1996). *The Massachusetts Acid Rain Monitoring Project: Ten Years of Monitoring Massachusetts Lakes and Streams with Volunteers*. Water Resource Research Center.

Havel, J. E., & Shurin, J. B. (2004). Mechanisms, effects, and scales of dispersal in freshwater zooplankton. *Limnology and Oceanography, 49*(4 II), 1229–1238. https://doi.org/10.4319/lo.2004.49.4_part_2.1229

Hintz, W. D., Jones, D. K., & Relyea, R. A. (2019). Evolved tolerance to freshwater salinization in zooplankton: Life-history trade-offs, cross-tolerance and reducing cascading effects. *Philosophical Transactions of the Royal Society B: Biological Sciences, 374*(1764). https://doi.org/10.1098/rstb.2018.0012

Hornbeck, J.W., Likens, G.E. & Eaton, J.S. (1977). Seasonal patterns in acidity of precipitation and their implications for forest stream ecosystems. *Water, Air, and Soil Pollution 7*, 355–365. https://doi.org/10.1007/BF00284130.

Jackson, R. B., & Jobbágy, E. G. (2005). From icy roads to salty streams. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(41), 14487–14488. https://doi.org/10.1073/pnas.0507389102

June-Wells, M., Gallagher, F., Gibbons, J., & Bugbee, G. (2013). Water chemistry preferences of five nonnative aquatic macrophyte species in Connecticut: A preliminary risk assessment tool. *Lake and Reservoir Management, 29*(4), 303–316. https://doi.org/10.1080/10402381.2013.857742

Kaushal, S., Groffman, P., Likens, G., Belt, K., Stack, W., Kelly, V., Band, L., & Fisher, G. (2005). Increased salinization of fresh water in the northeastern United States. *Proceedings of the National Academy of Sciences of the United States of America, 102(*38). 13517-13520. https://doi.org/10.1073/pnas.0506414102

Kaushal, S. S., Duan, S., Doody, T. R., Haq, S., Smith, R. M., Newcomer Johnson, T. A., Newcomb, K. D., Gorman, J., Bowman, N., Mayer, P. M., Wood, K. L., Belt, K. T., & Stack, W. P. (2017). Human-accelerated weathering increases salinization, major ions, and alkalinization in fresh water across land use. *Applied Geochemistry*, *83*, 121–135. https://doi.org/10.1016/j.apgeochem.2017.02.006

Kaushal, S., Wood, k., Galella, J., Gion A., Haq, S., Goodling, P., Haviland, K., Reimer. J., Morel, C., Wessel, B., Nguyen, W., Hollingsworth, J., Mei, K., Leal, J., Widmer, J., Sharif, R., Mayer, P., Newcomer-Johnson, T., Newcomb, K., Smith, E., & Belt, K. (2020). Making 'chemical cocktails' – Evolution of urban geochemical processes across the periodic table of elements. *Applied geochemistry*, *119*. https://doi.org/10.1016/j.apgeochem.2020.104632

Kelly, V. R., Lovett, G. M., Weathers, K. C., Findlay, S. E. G., Strayer, D. L., Burns, D. J., & Likens, G. E. (2008). Long-term sodium chloride retention in a rural: Legacy effects of road salt on streamwater concentration. *Environmental Science and Technology*, *42*(2), 410–415. https://doi.org/10.1021/es071391l

Kelly, W. R., Panno, S. V., Hackley, K. C., Hwang, H. H., Martinsek, A. T., & Markus, M. (2010). Using chloride and other ions to trace sewage and road salt in the Illinois Waterway. *Applied Geochemistry*, *25*(5), 661–673. https://doi.org/10.1016/j.apgeochem.2010.01.020

Lautz, L. K., Hoke, G. D., Lu, Z., Siegel, D. I., Christian, K., Kessler, J. D., & Teale, N. G. (2014). Using discriminant analysis to determine sources of salinity in shallow groundwater prior to hydraulic fracturing. *Environmental Science and Technology*, *48*, 9061–9069. https://doi.org/dx.doi.org/10.1021/es502244v

Mallin, M. A., Johnson, V. L., Ensign, S. H., & MacPherson, T. A. (2006). Factors contributing to hypoxia in rivers, lakes, and streams. *Limnology and Oceanography, 51*(1, part 2), 690–701. https://doi.org/10.4319/lo.2006.51.1_part_2.0690

Massachusetts Department of Conservation and Recreation & Massachusetts Water Resources Authority. (2004). *Memorandum of understanding between the Commonwealth of Massachusetts Department of Conservation and Recreation and the Massachusetts Water Resources Authority*. Commonwealth of Massachusetts.

Massachusetts Department of Conservation and Recreation. (2002). *Common Reed: An Invasive Wetland Plant.* Massachusetts Department of Conservation and Recreation, Office of Water Resources, Lakes and Ponds Program.

Massachusetts Department of Environmental Protection. (2018). *Massachusetts consolidated assessment and listing methodology (CALM) guidance manual for the 2018 reporting cycle*. Massachusetts Department of Environmental Protection, Massachusetts Division of Watershed Management.

Massachusetts Drinking Water Regulations. 310 CMR 22.00, Massachusetts Register (2020a).

Massachusetts Drinking Water Regulations: 310 C.M.R. 22.07D, Massachusetts Register (2020b).

Massachusetts Drinking Water Regulations: 310 CMR 22.08(1), Massachusetts Register (2020c).

Massachusetts Drought Management Task Force. (2020). *Drought Status*. Massachusetts executive Office of Energy and Environmental Affairs, Drought Management Task Force. https://www.mass.gov/info-details/drought-status#past-drought-declarations-maps-and-history-

Massachusetts Surface Water Quality Standards. 314 CMR 04.06, Massachusetts Register (2013a).

Massachusetts Surface Water Quality Standards. 314 CMR 04.05(5), Massachusetts Register (2013b).

Massachusetts Surface Water Quality Standards. 314 CMR 04.05(3)(a)2, Massachusetts Register (2013c).

Massachusetts Surface Water Quality Standards. 314 CMR 04.05(3)(a)4.c, Massachusetts Register (2013d).

Massachusetts Surface Water Quality Standards. 314 CMR 04.05(3)(a)4.a, Massachusetts Register (2013e).

Massachusetts Water Resources Authority. (2012, July 12). *Potential contaminants tested for in the MWRA water system*. http://www.mwra.com/watertesting/watertestlist.htm

Massachusetts Water Resources Authority. (2014, April 23). *Sudbury aqueduct history*. http://www.mwra.com/04water/html/history-sudbury-aqueduct.html

Massachusetts Water Resources Authority. (2021a, Aug 2). *Water supply and demand*. http://www.mwra.state.ma.us/04water/html/wsupdate.htm

Massachusetts Water Resources Authority. (2021b, July22). *Monthly water quality test results*. http://www.mwra.com/monthly/wqupdate/qual3wq.htm

Massachusetts Water Resources Authority. (n.d.). *Water quality test results*. http://www.mwra.com/watertesting/watertests.htm

Mulholland, P. J., & Kuenzler, E. J. (1979). Organic carbon export from upland and forested wetland watersheds. *Limnology and Oceanography, 24*(5), 960-966. https://doi.org/10.4319/lo.1979.24.5.0960

Mullaney, J., Lorenz, D., & Arntson, A. (2009). Chloride in Groundwater and Surface Water in Areas Underlain by the Glacial Aquifer System, Northern United States. *U.S. Geological Survey Scientific*

Investigations Report 2009–5086, 41. United States Department of the Interior, United States Geological Survey.

Murphy, S. (2007, April 23). *General information on total suspended solids*. Boulder Area Sustainability Information Network [BASIN]. http://bcn.boulder.co.us/basin/data/FECAL/info/TSS.html

Myers, D., Stoeckel, D., Bushon, R., Francy, D., & Brady, A. (2014). Fecal Indicator bacteria. *In U.S. Geological Survey Techniques of Water-Resources Investigations, 9*(2.1), pp. 5–73. United States Department of the Interior, United States Geological Survey. https://doi.org/https://doi.org/10.3133/twri09A7.1

National Atmospheric Deposition Program (NRSP-3). (2021). NADP Program Office, Wisconsin State Laboratory of Hygiene, 465 Henry Mall, Madison, WI 53706. http://nadp.slh.wisc.edu/data/ntn/plots/ntntrends.html?siteID=MA08. Accessed June 25, 2021.

National Primary Drinking Water Regulations: Long Term 2 Enhanced Surface Water Treatment Rule, 68 Fed. Reg. 47640 (2003) (to be codified at 40 C.F.R. pt. 141 and 142).

Panno, S. V., Hackley, K. C., Hwang, H. H., Greenberg, S. E., Krapac, I. G., Landsberger, S., & O'Kelly, D. J. (2006). Characterization and identification of Na-Cl sources in ground water. *Ground Water, 44*(2), 176–187. https://doi.org/10.1111/j.1745-6584.2005.00127.x

R Core Team. (2019). *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Reynolds, C. (2006). *Ecology of phytoplankton*. Cambridge University Press.

Rhodes, A. L., Newton, R. M., & Pufall, A. (2001). Influences of land use on water quality of a diverse New England watershed. *Environmental Science and Technology*, *35*(18), 3640–3645. https://doi.org/10.1021/es002052u

Richardson, A. J. (2008). In hot water: Zooplankton and climate change. *ICES Journal of Marine Science, 65*(3), 279–295. https://doi.org/10.1093/icesjms/fsn028

Safe Drinking Water Act of 1974, Pub. L. No. 116-92, 58 Stat. 682. (2019).

Soper, J. (2020). *Analysis of road salt loading and transport in the Wachusett Reservoir Watershed*. [Unpublished master's thesis]. University of Massachusetts Amherst.

Southwood, T. R. E. (1977). Habitat, the templet for ecological strategies? *Journal of Animal Ecology*, *46*(2), 336–365. https://doi.org/10.2307/3817

Stets, E. G., Lee, C. J., Lytle, D. A., & Schock, M. R. (2018). Increasing chloride in rivers of the conterminous U.S. and linkages to potential corrosivity and lead action level exceedances in drinking water. *Science of the Total Environment*, *613–614*, 1498–1509. https://doi.org/10.1016/j.scitotenv.2017.07.119

Swenson, H. A., & Baldwin, H. L. (1965). *A Primer on Water Quality.* United States Department of the Interior, United States Geological Survey. https://doi.org/10.3133/7000057

Thill, M. (2014). *Lake trout and climate change in the Adirondacks*. *Survey report for the Adirondack Chapter of The Nature Conservancy.* https://www.adirondackcouncil.org/vs-uploads/pdf/1418761722_adirondacks-lake-trout-report-old.pdf

Trahan-Liptak, J., & Carr, J. (2016). *Aquatic invasive species summary: Historical update and ongoing actions.* Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

Turk, J. T. (1983). An Evaluation of Trends in the Acidity of Precipitation and the Related Acidification of Surface Water in North America. *U.S Geological Survey Water Supply Paper 2249*. United States Department of the Interior, United States Geological Survey.

United States Environmental Protection Agency & Tetra Tech Inc. (2013). Monitoring for microbial pathogens and indicators. *Tech Notes, 9,* 1-29. https://www.epa.gov/sites/production/files/2016-05/documents/tech_notes_9_dec2013_pathogens.pdf

United States Environmental Protection Agency. (1986). *Bacteriological ambient water quality criteria for marine and fresh recreational waters*. U.S. Environmental Protection Agency, Office of Research and Development. https://doi.org/EPA-A440/5-84-002

United States Environmental Protection Agency. (1988). *Ambient aquatic life water quality criteria for chloride.* P. 1–24. U.S. Environmental Protection Agency, Office of Research and Development.

United States Environmental Protection Agency. (2000). *Ambient water quality criteria recommendations: Rivers and streams in nutrient ecoregion XIV*. U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology.

United States Environmental Protection Agency. (2001a). *Ambient water quality criteria recommendations: Rivers and streams in nutrient ecoregion VIII*. U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology.

United States Environmental Protection Agency. (2001b). *Ambient water quality criteria recommendations: Lakes and reservoirs in nutrient ecoregion XIV*. U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology.

United States Environmental Protection Agency. (2013). *Aquatic life ambient water quality criteria for ammonia - Freshwater 2013.* United States Environmental Protection Agency, Office of Water, Office of Science and Technology.

United States Environmental Protection Agency. (2017). *Low Stress (low flow) Purging and Sampling Procedure for the Collection of Groundwater Samples from Monitoring Wells* (Standard No. EQASOP-GW4). U.S Environmental Protection agency – Region 1, Quality assurance Unit. https://www.epa.gov/sites/default/files/2017-10/documents/eqasop-gw4.pdf

United States Environmental Protection Agency. (2021). *Causal Analysis/Diagnosis Decision Information System (CADDIS)*: *Caddis Volume 2 - pH*. United States Environmental Protection Agency, Office of Research and Development, Washington, DC. https://www.epa.gov/caddis-vol2/caddis-volume-2-sources-stressors-responses-ph. Accessed June 15, 2021

United States Geological Survey. (1999). *The quality of our nation's waters - Nutrients and pesticides. U.S. Geological Survey Circular 1225*. p.82. United States Department of the Interior, United States Geological Survey.

United States Geological Survey. (2012). Phosphorus and groundwater: Establishing links between agricultural use and transport to streams. *In National Water-Quality Assessment Program*. United States Department of the Interior, United States Geological Survey.

United States Geological Survey. (2021). *NAS - Nonindigenous Aquatic Species Database*. United States Department of the Interior, United States Geological Survey. https://nas.er.usgs.gov/

United States Geological Survey. (n.d.-a). *Bacteria and E. Coli in water*. United States Department of the Interior, United States Geological Survey. https://www.usgs.gov/special-topic/water-science-school/science/bacteria-and-e-coli-water?qt-science_center_objects=0#qt-science_center_objects

United States Geological Survey. (n.d.-b). *Harpacticoid introduction.* United States Department of the Interior, United States Geological Survey. https://www.glsc.usgs.gov/greatlakescopepods/Introduction.php?GROUP=Harpacticoid

Van Meter, R. J., & Swan, C. M. (2014). Road salts as environmental constraints in urban pond food webs. *Urban Ecosystems, 14*(4), 723-736. https://doi.org/10.1007/s11252-011-0180-9

Vollenweider, R. A. (1976). Advances in defining critical loading levels for phosphorus in lake eutrophication. *Memorie Dell'Istituto Italiano Di Idrobiologia Dott Marco de Marchi, 33*, 53–83.

Walton, G. (1951). Survey of literature relating to infant methemoglobinemia due to nitrate-contaminated water. *American Journal of Public Health, 41*(8 Pt 1), 986–996. https://doi.org/10.2105/ajph.41.8_pt_1.986

Ward, M. H., Jones, R. R., Brender, J. D., de Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M., & van Breda, S. G. (2018). Drinking water nitrate and human health: An updated review. *International Journal of Environmental Research and Public Health, 15*(7), 1–31. https://doi.org/10.3390/ijerph15071557

Water Quality Certification. 314 CMR 9.06(6)(a) (2017).

Watershed Protection. 313 CMR 11.00, Massachusetts Register (2017).

Wetlands Protections. 310 CMR 10.05(6)(k), Massachusetts Register (2014).

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis.* Springer-Verlag New York.

Wohl, E., Bledsoe, B. P., Jacobson, R. B., Poff, N. L., Rathburn, S. L., Walters, D. M., & Wilcox, A. C. (2015). The natural sediment regime in rivers: Broadening the foundation for ecosystem management. *BioScience*, *65*(4), 358–371. https://doi.org/10.1093/biosci/biv002

Worden, D., & Pistrang, L. (2003). *Nutrient and plankton dynamics in Wachusett Reservoir: Results of the DCR/DWSP's 1998-2002 monitoring program, a review of plankton data from Cosgrove Intake, and an evaluation of historical records*. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

World Health Organization. (1996). Ammonia in drinking water: Health criteria and other supporting information. *Guidelines for drinking-water quality*, *2*(2), 1–4.

Appendix

Figure A-1: Hydrographs for Small Tributaries in Wachusett Watershed During 2020
Discharge data are interpolated from measurements collected at 15-minute intervals.

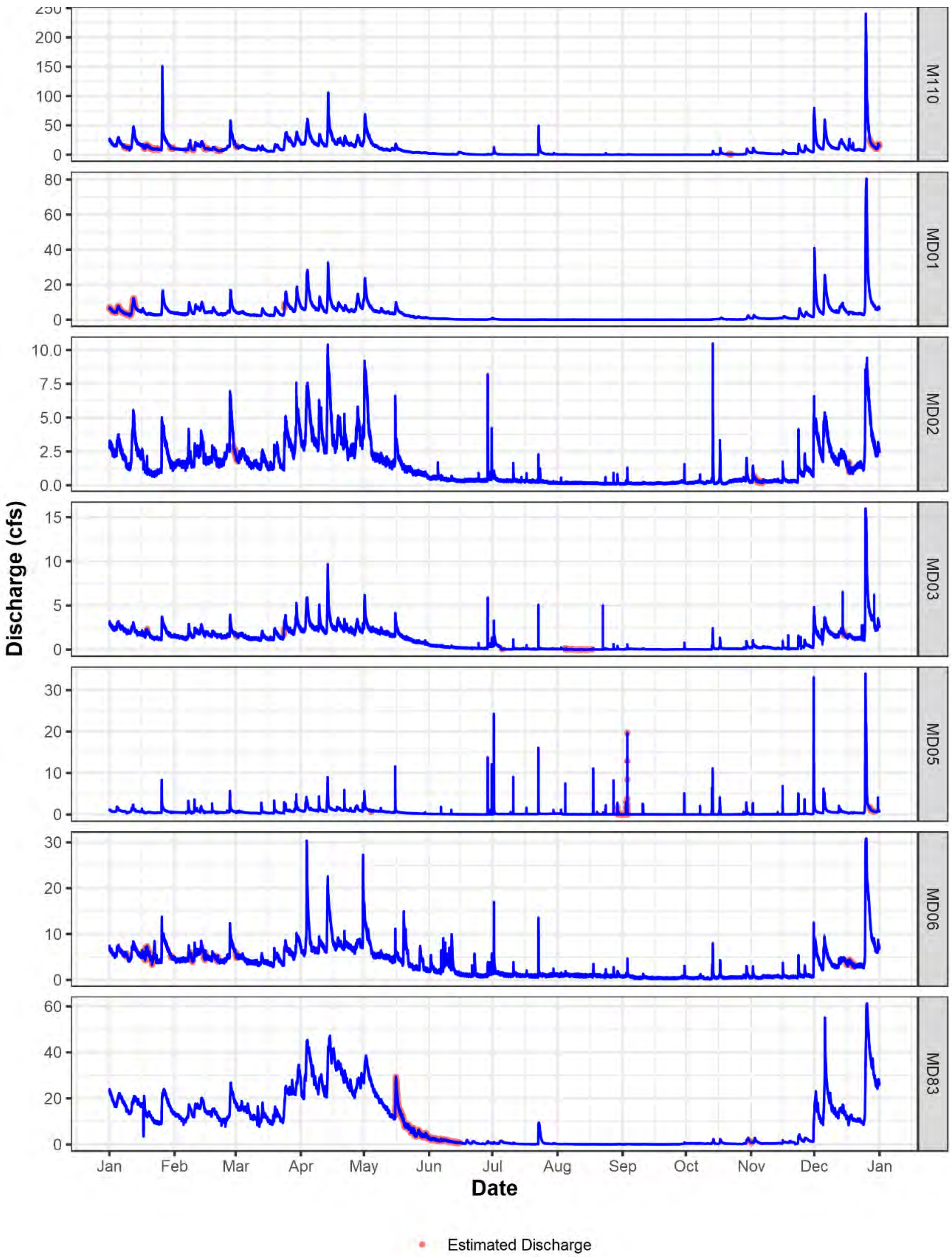


Table A-1: Water Quality Standards/Criteria Applicable to Wachusett Watershed Surface Waters

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/100 mL	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/100 mL	
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	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA Recommended criteria	0.014 – 0.05 mg/L	25th Percentile subecoregion 58 – 25th 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

2020 Watershed Monitoring Parameters and Historical Context

A.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)[59]. 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[60]. 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[61]. 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[62]. Possible 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.

A.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[63]. 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 (Nitrite) 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)[64] and 0.31 mg/L (ecoregion 59)[65], 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

[59] USGS, 1999
[60] Mallin et al., 2006
[61] USEPA & Tetra Tech Inc, 2013
[62] World Health Organization [WHO], 1996
[63] USGS, 1999
[64] USEPA, 2001a
[65] USEPA, 2000

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 dissolved oxygen concentrations, changes in plant and animal species composition, and loss of biodiversity[66].

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[67]. Several other studies (mostly in Europe) have linked high levels of nitrate consumption, though in some cases below the EPA MCL, to various cancers[68]. 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.

A.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[69], and is particularly lethal to infants[70]. In order to protect human health, the EPA has established the MCL for NO_2-N in drinking water at 1.0 mg/L[71]. Although nitrite concentrations are rarely above the detection limit (0.005 mg/L) in Wachusett tributaries, this parameter continues to be monitored 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.

A.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)[72] and 0.30 mg/L (ecoregion 59)[73], 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

---

66 Camargo & Alonso, 2006
67 Safe Drinking Water Act of 1974, 2019
68 Ward et al., 2018
69 Ibid
70 Walton, 1951
71 Safe Drinking Water Act of 1974, 2019
72 USEPA, 2001a
73 USEPA, 2000

for TKN in the Wachusett Reservoir watershed began in 2015 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.

A.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 A.1 – A.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)[74] and 0.59 mg/L (ecoregion 59)[75], 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.

A.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[76]. 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

[74] USEPA, 2001a
[75] USEPA, 2000
[76] USGS, 2012

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[77]. 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)[78] and 23.75 µg/L (ecoregion 59)[79], 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. 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, preferably below 20 µg/L in tributaries and below 10 µg/L in the reservoir.

A.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[80]. 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.

A.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, which can contribute to 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

[77] Vollenweider, 1976
[78] USEPA, 2001a
[79] USEPA, 2000
[80] Reynolds, 2006

temperature[81]. 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 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.

A.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*).

A.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. pH is an

[81] Massachusetts Surface Water Quality Standards, 2013c

important driver of many chemical and biological processes in aquatic environments and can influence the solubility, transport and bioavailability of other substances found in the water[82]. Aquatic life can become stressed or killed when pH deviates from historical ranges. Low pH can increase corrosion rates of metal drinking water pipes, leaching high concentrations of metals into drinking water and degrading infrastructure.

The pH in Wachusett Reservoir is determined ultimately by surface water inputs and 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. The Class A water quality standard is a range between 6.5 – 8.3 (or no change from background levels). For the Wachusett Reservoir and its tributaries the water quality goal for pH is to maintain compliance with the Class A water quality standards.

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[83]. Alkalinity in Wachusett Reservoir is much lower than this threshold. Increases in alkalinity observed over the past 30 years, especially in the last five years, are likely linked to the observed increases in specific conductance caused by regional salinization[84].

A.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, septicemia[85], dysentery, typhoid fever, and cholera[86]. *Escherichia coli* (*E. coli*) is a species in the fecal coliform group, which originates from fecal material of humans and other warm-blooded animals[87]. Some strains of *E. coli* can be deadly, especially for small children or people with weakened immune systems[88]. Studies have found that the presence of *E. coli* is often correlated with the presence of many other pathogenetic microorganisms[89], thus it has been selected as a useful indicator of pathogen contamination in waters.

---

[82] USEPA, 2021
[83] USEPA, 2013
[84] Kaushal et al., 2005
[85] USGS, n.d.-a
[86] Myers et al., 2014
[87] USEPA, 1986
[88] USEPA & Tetra Tech Inc., 2013
[89] Myers et al., 2014

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[90]. 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[91]. 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% of the samples taken in any six-month period[92]. Results for pathogen testing at the intake are briefly discussed Section 3.4.10 and in greater detail in separate reports published by MWRA[93].

A.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[94, 95]. Freshwater systems in Massachusetts naturally contain low levels of mineral salts in solution[96]. Elevated levels of specific conductance and associated dissolved solutes (e.g., sodium, chloride) may stress sensitive biota, threaten ecosystems[97, 98], and degrade drinking water quality[99, 100, 101]. Contamination of drinking water supplies with excess chloride (Cl) may increase the corrosivity of affected waters[102], posing a risk to communities with infrastructure containing lead fixtures.

---

[90] Ibid
[91] Massachusetts Surface Water Quality Standards, 2013d
[92] Massachusetts Surface Water Quality Standards, 2013e
[93] MWRA, 2021b
[94] Granato et al., 2015
[95] Rhodes et al., 2001
[96] Granato et al., 2015
[97] Jackson & Jobbágy, 2005
[98] Corsi et al., 2010
[99] Kaushal et al., 2005
[100] Daley et al., 2009
[101] Kelly et al., 2010
[102] Stets et al., 2018

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[103], 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[104]. 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"[105]. 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[106]. 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[107,108]. In the snowbelt region of the U.S., road salt is the dominant source of salinity to many natural water systems[109, 110, 111].

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[112]. 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*[113].

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. Over 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 since 2019.

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

103 Kaushal et al., 2017
104 USEPA, 1988
105 MassDEP, 2018
106 Massachusetts Drinking Water Regulations, 2020b
107 Panno et al., 2006
108 Lautz et al., 2014
109 Kaushal et al., 2005
110 Kelly et al., 2008
111 Mullaney et al., 2009
112 Van Meter & Swan, 2014
113 June-Wells et al., 2013

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 Wachusett Reservoir. During periods of isothermy, values typically range from 100 to 180 µS/cm depending on the volume of water received from Quabbin Reservoir 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.

A.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 much of the aquatic habitat and nutrient dynamics at the reach scale[114,115]. 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[116]. 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, which can negatively affect aquatic life in those places as well as 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

[114] Southwood, 1977
[115] Wohl et al., 2015
[116] Murphey, 2007

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[117]. 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 can occasionally 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.

A.14 Turbidity

Turbidity is another term for water clarity, which is determined by measuring the scatter of light in the water and reported by DWSP in Nephelometric Turbidity Units (NTU)[118]. 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 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 5.0 NTU. MassDEP regulations specify that turbidity levels may exceed 1.0 NTU only if it does not interfere with effective disinfection[119]. 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)[120] and 1.68 NTU (ecoregion 59)[121], 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.

---

[117] Wetlands Protection, 2017; Water Quality Certification, 2017
[118] Swenson & Baldwin, 1965
[119] Massachusetts Drinking Water Regulations, 2020c
[120] USEPA, 2001a
[121] USEPA, 2000

A.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[122].

While organic carbon is not a directly regulated drinking water quality parameter, carbon sources are precursors to disinfection byproducts (DBP) called trihalomethanes (THMs) 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.

A.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 (A.15).

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[123].

A.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

[122] Mulholland & Kuenzler, 1979
[123] DWSP, 2018b

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[124].

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.

A.18 Phytoplankton

Algae are a large, diverse group of organisms present in nearly every ecosystem from sandy deserts to artic permafrost to freshwater reservoirs[125]. 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 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. These management options for Wachusett Reservoir 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

[124] USEPA, 2001b
[125] Reynolds, 2006

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 A-2). 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 A-2: 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

A.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[126, 127]. 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[128].

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[129]. 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.

[126] Hintz et al., 2019
[127] Richardson, 2008
[128] Havel & Shurin, 2004
[129] USGS, n.d.-b

A.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[130]. 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[131].

[130] Dodson, 2005
[131] USEPA, 2001b