Water Quality Report: 2023

Wachusett Reservoir Watershed

Stillwater Basin – Dan Crocker (2023)

July 2024

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

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Abstract

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management manages Wachusett Reservoir and lands within the Watershed 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 water quality and hydrological monitoring activities carried out by the Division in the Wachusett Reservoir Watershed during 2023. 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 2023, Wachusett Reservoir water quality satisfied the requirements of the Filtration Avoidance Criteria established under the United States Environmental Protection Agency Surface Water Treatment Rule.

2023 was a year of climatological extremes. With over 64 inches of precipitation, 2023 was the wettest year since at least 1985. Streamflows and groundwater levels remained unseasonably high throughout the summer and fall months of 2023, winter was extremely warm with little snow, and August was the coldest August on record. These factors provide important context for the interpretation of water quality results discussed in this year's report. Compliance with state surface water quality standards among the tributaries varied, with minor exceedances attributed to higher solute loads measured during storm events, wildlife, and/or natural attributes of the landscape. Excess loading of dissolved salts to the tributaries and Reservoir has continued, as evidenced by specific conductance and chloride results for 2023. Turbidity levels were low throughout the Watershed in 2023, mostly due to the elevated baseflows and the timing of sampling in relation to storm events. Elevated bacteria concentrations remained a problem at Gates Brook 4 and West Boylston Brook, however all tributary monitoring locations, except for Gates Brook 4, met the long-term geometric mean standard, with annual geometric means for *E. coli* below 126 MPN/100mL.

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. The more urbanized subbasins within the watershed continue to experience chronically high chloride concentrations and periodic episodes of elevated bacteria concentrations. Water temperatures rose above the MassDEP recommended threshold for coldwater fishery resources at several monitoring locations, for cumulative durations between 6 and 97 days.

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. Elevated concentrations of silica and total phosphorus, and elevated UV_{254} values were observed at many reservoir sites in 2023 and can be attributed to record precipitation and resulting watershed runoff events experienced in the summer and fall.

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 below levels of concern. No new invasive species were detected in the Reservoir in 2023 and management activities continue to reduce known populations.

The appendices to this report include tributary hydrographs (Appendix A: Continuous Data Hydrographs) and a list of applicable water quality criteria/standards or thresholds of interest (Appendix B: Water Quality Standards and Criteria). Previously compiled background information and historical context for monitoring parameters are included in Appendix C: Watershed Monitoring Parameters and Historical Context to assist in the interpretation of water quality results and serve as a reference for the reader. Quality assurance and quality control (QA/QC) efforts for 2023 are summarized in Appendix D: Quality Assurance and Appendix E: Quality Control. 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 and the Ware River. 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 2023, which satisfy these requirements and continue to ensure availability of safe drinking water to present and future generations.

CITATION

Division of Water Supply Protection. (2024). Water Quality Report: 2023 Wachusett Reservoir Watershed. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management. West Boylston, MA.

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:

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

Derek Liimatainen, Assistant Regional Director of the Wachusett/Sudbury Region, whose staff helps maintain access to sampling sites and maintains boats that are critical for reservoir sampling.

Emily Scheyder, seasonal Aquatic Biologist I for analyzing zooplankton samples and organizing references for this report.

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

Jamie Carr, EQ Section head, for leading the Water Quality Monitoring team and Chloride/Conductivity Working Group and providing report review and comments.

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

Joel Zimmerman, DWSP Watershed Planning Coordinator, 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.

Josh Sjogren, Environmental Analyst II, for field investigations and sampling assistance.

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

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.

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.

Nick Ferry, Environmental Analyst II, for watershed field work and sampling.

Travis Drury, Environmental Analyst II, for watershed field work and sampling, and carrying out the hydrologic and groundwater monitoring programs; Writing, analysis, map production, development and documentation of QA/QC protocols and review of 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.

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

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Abbreviations

The following abbreviations are used in this report:

AIS	Aquatic Invasive Species
Cl	Chloride
CFR	Coldwater Fish Resources
CWTP	Carroll Water Treatment Plant
DBP	Disinfection Byproducts
DCR	Massachusetts Department of Conservation and Recreation
DWSP	Department of Conservation and Recreation, Division of Water Supply Protection
D.O.	Dissolved Oxygen
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
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
OWM	Office of Watershed Management
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/Quality Control
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
USGS	U.S. Geological Survey
VWM	Variable Water-milfoil (*Myriophyllum heterophyllum*)
WFR	Warmwater Fish Resources

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 can 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:

Abbreviation	**Unit of Measurement**
ABU/cm	Absorbance units per centimeter of path length
ASU/mL	Areal standard units per milliliter
BG	Billion Gallons
cfs	Cubic feet per second
CFU	Colony-forming unit
°C	Degrees Celsius
ft	Feet
FNU	Formazin Nephelometric Units
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
UV_{254}	Ultraviolet Absorbance at 254 Nanometers
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 53 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[3], followed by the Interim Enhanced Surface Water Treatment Rule (IESWTR) in 1998[4], 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[5].

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 processes[6]. 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 drivers, 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 hydrologic monitoring activities carried out by DWSP in the Wachusett Reservoir Watershed during 2023.

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[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] National Primary Drinking Water Regulations: Surface Water Treatment Rule (SWTR) - 40 CFR Part 141, Subpart H, 1989
[4] National Primary Drinking Water Regulations: Interim Enhanced SWTR (IESWTR) - 40 CFR Part 141, Subpart P, 1998
[5] Massachusetts Department of Conservation and Recreation [MassDCR] & MWRA, 2004
[6] Ibid

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 2023 and prior years are available upon request.

The remainder of Section 1 provides an overview of the water quality regulations applicable to the water resources of the Wachusett Reservoir Watershed, summarizes DWSP goals and objectives with respect to its water quality monitoring programs and includes an overview of the MWRA water supply system and Wachusett Reservoir Watershed. Section 2 presents methods for water quality monitoring programs in 2023, including an overview of monitoring locations, the parameters monitored and their manner of analysis, documentation of statistical methods and data management tools utilized, and a summary of quality assurance and control measures. 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 always below 5.0 NTU[7]. Massachusetts Department of Environmental Protection (MassDEP) regulations require that turbidity levels at the point of consumption for all public drinking water always remains below 1.0 NTU[8]. Authority to enforce the SWTR has been delegated to MassDEP.

All waters within the Wachusett Watershed are designated as Class A Public Water Supply[9] and thereby are considered Outstanding Resource Waters for the purposes of water quality protection[10]. Massachusetts has developed numerical Class A water quality criteria for several parameters. These are presented in Appendix B: Water Quality Standards and Criteria 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.*[11]

There are other standards that apply to various elements and compounds in public drinking water supplies, such as arsenic, polychlorinated biphenyls (PCBs), haloacetic acids[12] and per- and polyfluoroalkyl

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

substances (PFAS)[13]. 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[14].

1.2 DWSP Monitoring Program Goal and Objectives

MWRA, as an unfiltered public water supplier, 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 those threats. The current WPP was written in 2023 and covers fiscal years 2024 – 2028[15]. 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 DWSP 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:

- Maintain long-term water quality data and statistics.
- Document compliance with the EPA's SWTR requirements and criteria consistent with filtration avoidance.
- Identify streams and water bodies that do not meet water quality standards and initiate specific control measures to mitigate or eliminate pollution sources.

[13] MWRA, 2023
[14] MWRA, n.d.
[15] Division of Water Supply Protection [DWSP], 2023f

- Conduct proactive surveillance of water quality trends to identify emerging issues and support ongoing assessments of threats to water quality.
- Document Quality assurance and quality control (QA/QC) metrics in annual water quality reports.

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. For example, the 1992 Watershed Protection Act 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[16].

Coordination will continue with DCR's Office of Climate Resilience on climate related planning and project implementation, including the initiation of a DWSP specific comprehensive vulnerability assessment that incorporates the impact on important natural resources. DWSP will strive to utilize consistent climate change data and projections across its programs, including data collected internally as well as state level data, to identify current impacts and assess projected impacts. Staff will continue to monitor and evaluate climate change research and scientific literature, data, and recommendations.

1.3 MWRA System and Wachusett Watershed Overview

The Quabbin Aqueduct connects three active water sources that currently serve as a source of drinking water to 50 communities in central and eastern 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 (BG). Wachusett Reservoir holds 65 BG at full capacity (Table 1). The emergency backup Sudbury and Foss Reservoirs hold another 7.7 BG, combined[17].

[16] Watershed Protection, 2017
[17] MWRA, 2021a

Table 1: a) General Information on the Wachusett Reservoir, b) Wachusett Reservoir Watershed

Other protected lands include property identified by MassGIS as Open Space protected in perpetuity less DWSP, fee lands, and WPRs (WPR = Watershed Preservation Restriction, similar to a Conservation Restriction). Acreage may vary from that of from previous years due to increased accuracy of MassGIS data.

a) Wachusett Reservoir General Information

Description	Quantity	Units
Capacity	65.7	Billion gallons
Surface Area at Full Capacity	4,147	Acres
Length of Shoreline	31	Miles
Maximum Depth	122	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[18]

Description	Quantity	Units
Watershed Area	74,909	Acres
Land Area	70,876	Acres
	94.6	% 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	20,400	Acres (includes Watershed Preservation Restrictions)
	28.8	% Total watershed area
Other Protected Area	12,263	Acres
	17.2	% 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, 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 in Clinton, MA and transferred to the John J. Carroll Water Treatment Plant at Walnut Hill in Marlborough, MA via the Cosgrove or Wachusett Aqueduct. The treated water leaves the plant through the MetroWest Water Supply Tunnel

[18] DWSP, 2016

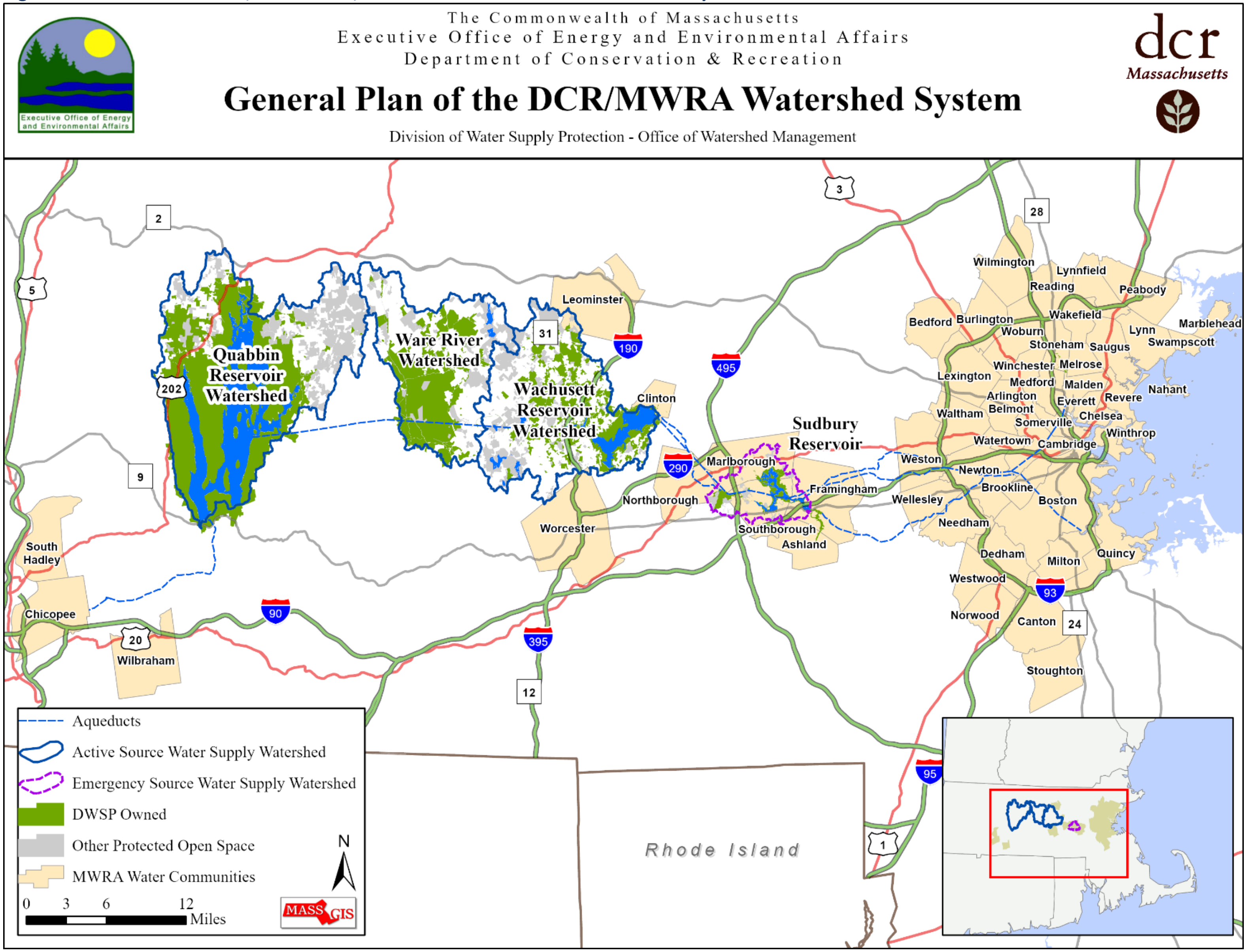
and the Hultman Aqueduct where it enters the storage and distribution system and is ultimately delivered to greater Boston and MetroWest communities and businesses.

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 31 miles, Wachusett Reservoir drains 110 square miles (70,876 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”[19]. 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[20].

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 20,400 acres (28.8%) of watershed area for water supply protection purposes. Including the Reservoir, DWSP owns or controls 32.6% of the entire watershed area, with an additional 17.2% 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 FY24 – 28*[21] and the *2017 Land Management Plan*[22].

[19] Griffith et al., 2009
[20] Ibid
[21] DWSP, 2018a
[22] DWSP, 2018b

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



2 Methods

This section provides an overview of how each element of DWSP water quality and hydrologic monitoring was carried out during 2023, 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. These SOPs 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: Additional research and monitoring activities are conducted by other agencies and organizations related to water quality and hydrology within the Wachusett Watershed, with DWSP funding and direction.

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 2023. 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 2). 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 divide large drainage areas into smaller units. Twice monthly turbidity and bacteria sampling is conducted at all *Primary* and *Secondary* monitoring stations. Field parameters (water temperature, pH, dissolved oxygen, specific conductance) are measured during all routine tributary monitoring visits. Although it is not a natural tributary, Shaft 1 (Quabbin Transfer) is routinely sampled for nutrients 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 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 2023 in the Wachusett Reservoir Watershed

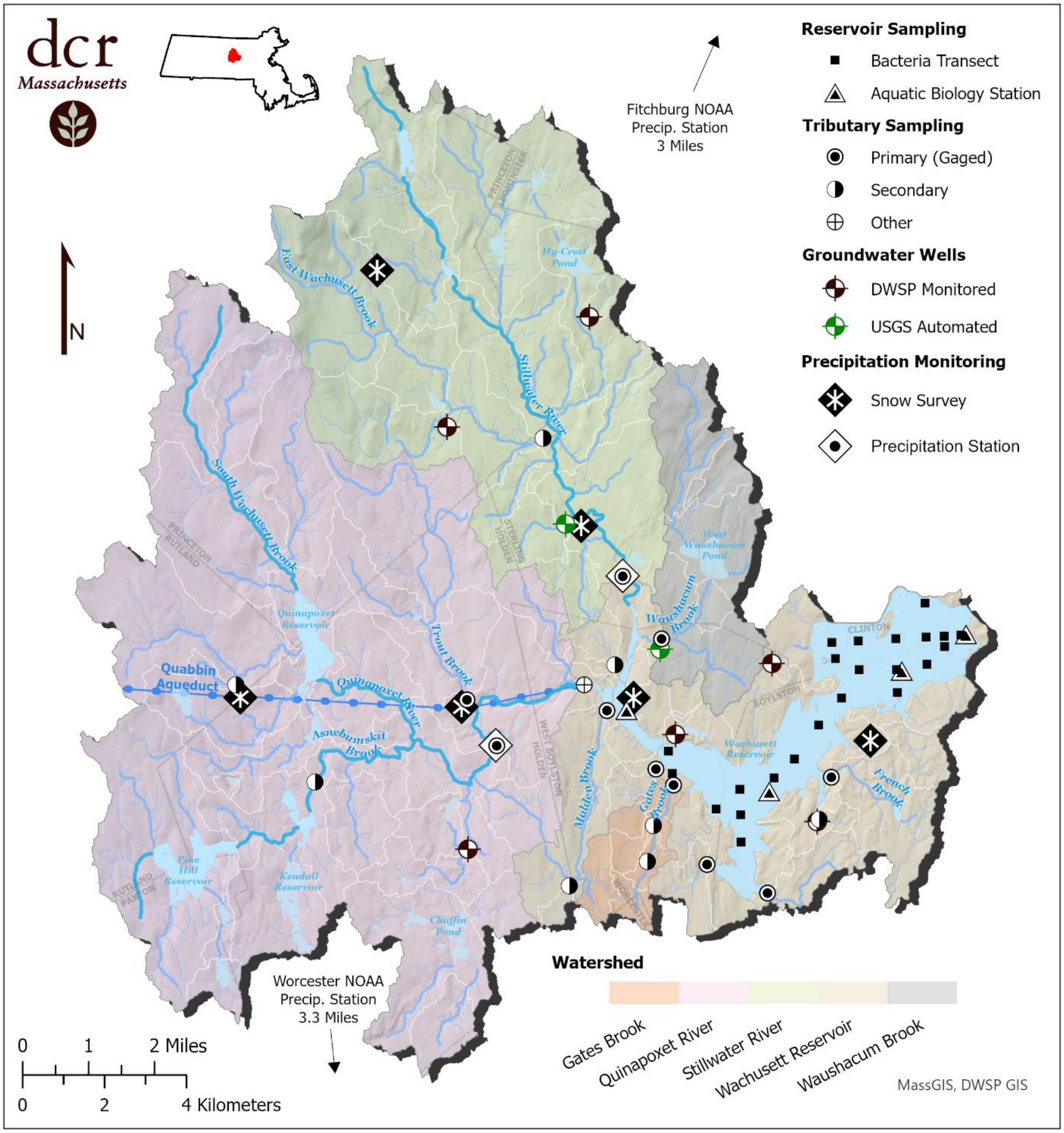


Table 2: Wachusett Tributary Sampling Locations, 2023

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

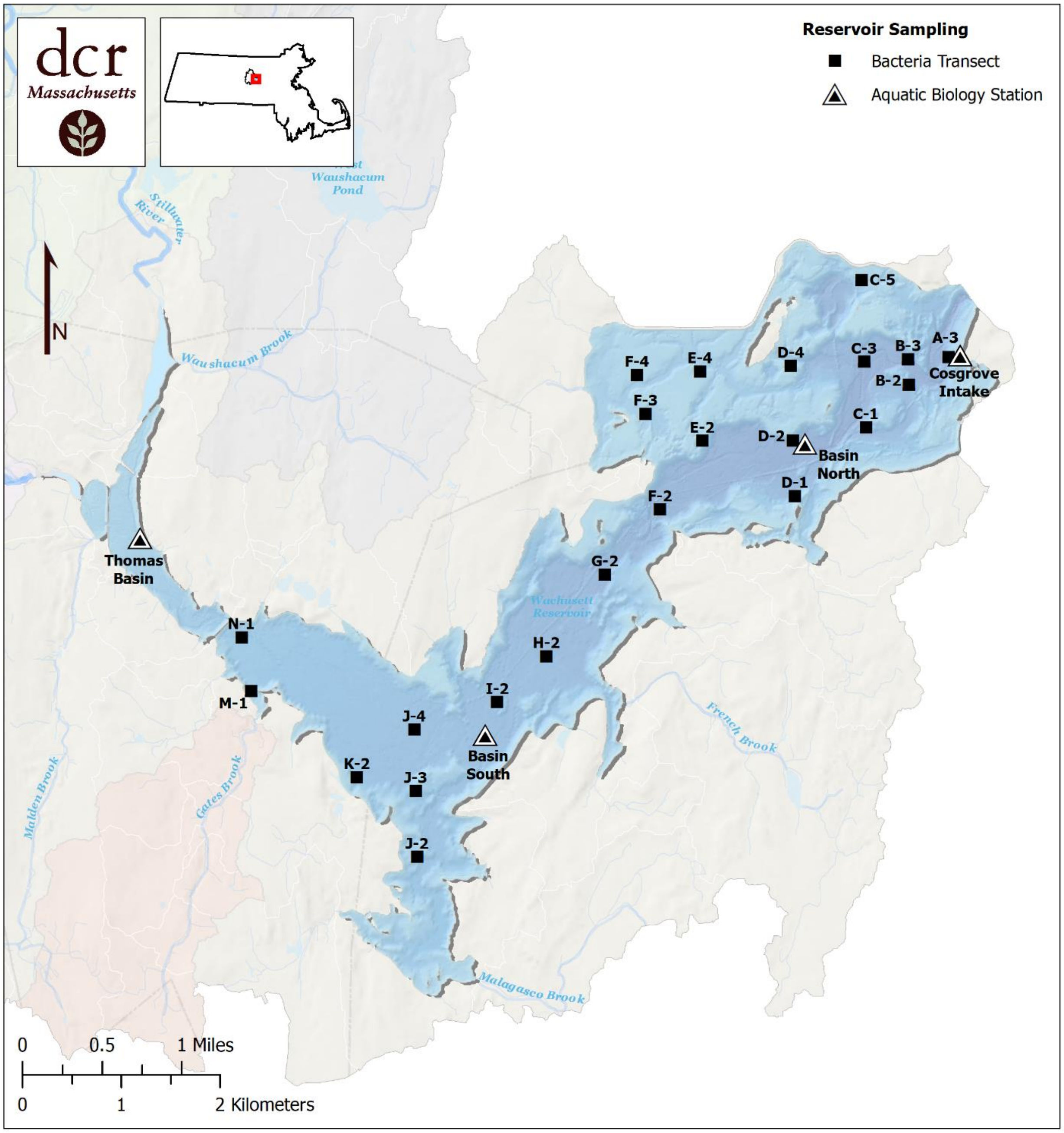


Table 3: Wachusett Reservoir Sampling Locations

Station (Id)	Location Description	Approximate Depth* (m)	Frequency: Plankton/profile	Frequency: 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; * = depth at normal operating elevation of 390.5 ft BCB

2.1.2 Meteorologic and Hydrologic 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. It is important for DWSP to consider this hydrological context when interpreting water quality results, comparing interannual variability, or evaluating trends.

DWSP contracts with the U.S. Geological Survey (USGS) New England Water Science Center 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 4). 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

Station Name	Owner	Gage Number	Period of Record	Data Collected
Worcester	NOAA	USW00094746	1892 - Present	Precipitation, Air temperature
Fitchburg	NOAA	USW00004780	1998-04-01 - Present	Precipitation, Air temperature
Stillwater	USGS	01095220 (MD07)	2000-06-01 - Present	Precipitation
Quinapoxet	USGS	01095375 (MD69)	2012-10-01 - Present	Precipitation
Boylston Brook	DWSP	MD02	2017-01-13 - 2017-08-03	Air temperature
Waushacum Brook	DWSP	MD83	2017-08-03 - 2023-11-03	Air temperature
West Boylston Brook	DWSP	MD05	2023-11-03 - Present	Air temperature
Princeton Forestry	DWSP	FPRN	2017-01-03 - Present	Air temperature

Since 1985, the Wachusett Watershed average annual precipitation is 47.29 inches, with a historical low of 35.36 inches (2001) and high of 64.44 (2023). Average monthly precipitation ranges from 3.00 inches (February) to 4.86 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 track the eastern coast of the USA after originating in and around the equatorial North Atlantic Ocean (e.g., Gulf of Mexico, Caribbean Sea). These events often cause noteworthy responses in stream flows and solute loads and can lead to a series of cascading ecological responses in aquatic environments. Likewise, drought conditions can lead to adverse ecological consequences as some solutes can become concentrated and aquatic habitat can become diminished or degraded.

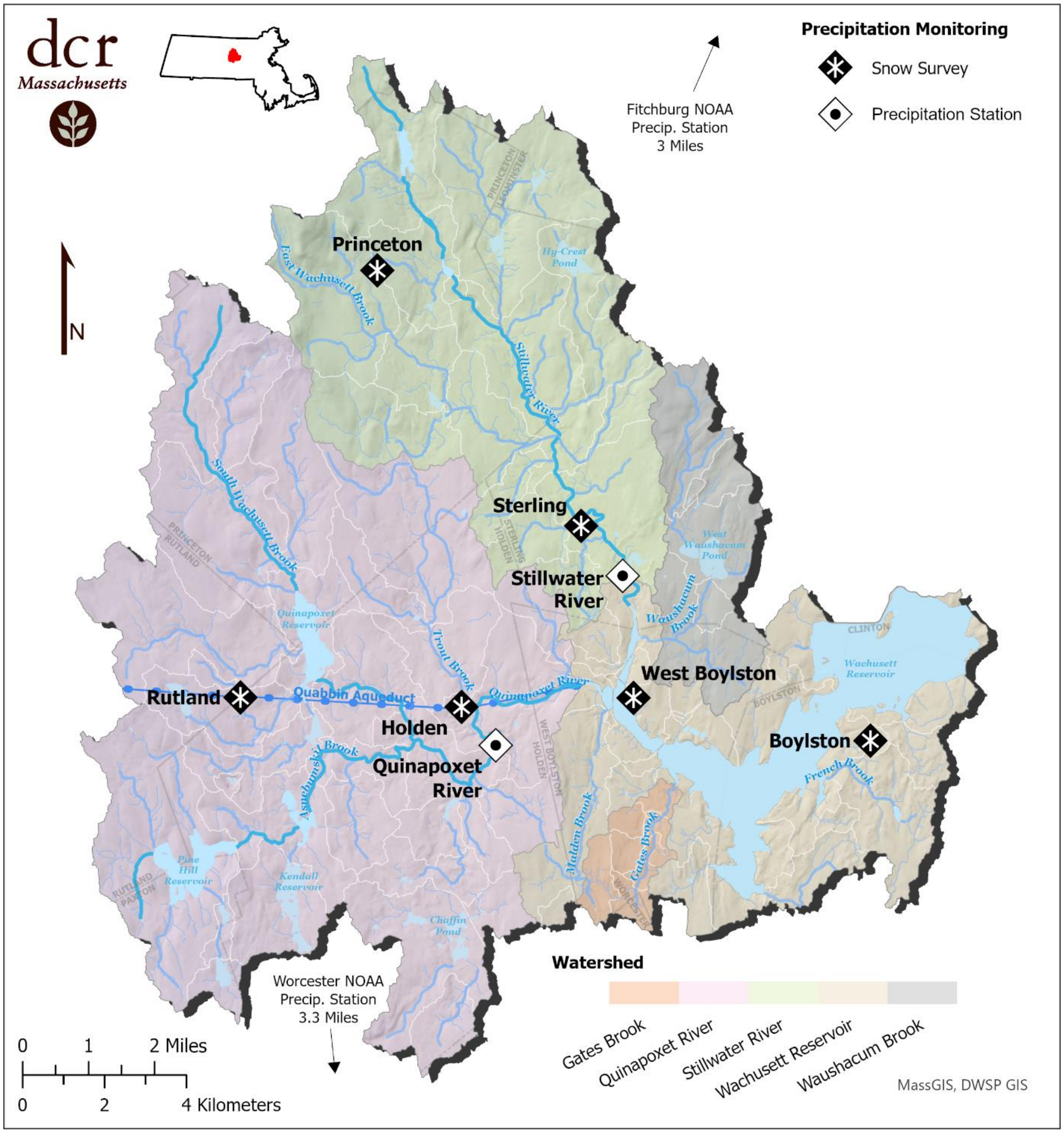
Effectively managing Wachusett Reservoir water storage volume requires an accurate prediction of water inputs to the Reservoir which are derived from new precipitation and/or melting of past precipitation stored in the snowpack. Therefore, DWSP carries out a snowpack monitoring program to track the water 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 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) (see Section 3.1.1.2 for results). 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 parameter 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 Appendix C: Watershed Monitoring Parameters and Historical Context), 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



2.1.2.2 Hydrologic Monitoring

Streamflow

Monitoring of stage (water level) 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. 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 the station was upgraded with new sensors and equipment to collect stage, temperature, and conductivity data at 10-minute increments. All data and details about USGS monitoring methods and equipment for these stations can be found on the National Water Information System (NWIS) website[23]. Responsibility for streamflow monitoring on the other primary tributaries was transferred to DWSP towards the end of 2011.

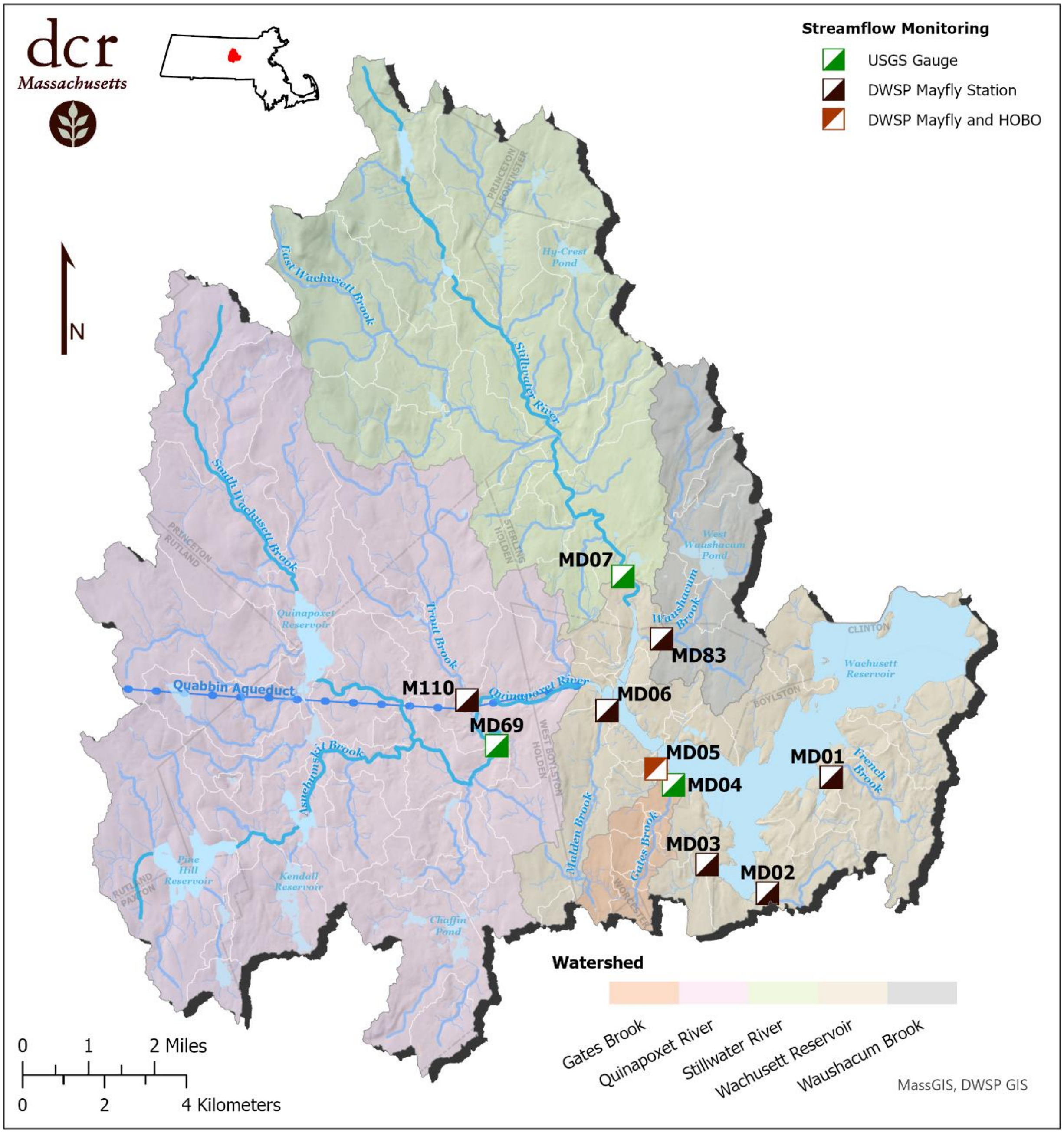
At the seven DWSP flow monitoring stations (Figure 5) visual observations of stream depth (stage) is recorded from staff plates during all sampling visits (typically three times per month). Manual stage measurements were supplemented by continuous depth recordings using HOBO water level data loggers 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.

New real-time monitoring instrumentation was added to the Waushacum Brook monitoring station in 2019 to pilot a viable replacement for aging Onset HOBO dataloggers. The equipment utilizes a Mayfly datalogger[24], 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[25]. 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, water temperature, and water depth. This pilot project was determined to be successful and Mayfly units were deployed at five additional monitoring locations in December 2021. One final Mayfly station was installed at Trout Brook in 2023. Additional details about continuous stream flow monitoring are provided in the DWSP *SOP for the Monitoring of Continuous Stream Flow*[26].

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 enough 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 DWSP *SOP for the Monitoring of Stream Discharge*[27].

[23] https://waterdata.usgs.gov/ma/nwis/current/?type=MWRA&group_key=basin_cd
[24] https://stroudcenter.org/news/digital-mayfly-swarm-is-emerging/
[25] https://monitormywatershed.org/sites/WACH-MD01/
[26] DWSP, 2023c
[27] DWSP, 2021a

Figure 5: Streamflow Monitoring Locations in Wachusett Reservoir Watershed



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 surface 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.

Groundwater Levels

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[28]. 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.

Due to the automation of the Sterling - Rt 140 USGS well in 2022, DWSP no longer reports monthly groundwater levels in that well to USGS. However, in 2023 DWSP continued its groundwater quality monitoring program that began in 2019 to collect additional specific conductance/Cl data in response to observed increases in tributary specific conductance in the Wachusett Watershed (Figure 6). Water levels are measured as part of this groundwater monitoring effort. A total of seven wells are sampled by DWSP, six of which were previously monitored by USGS and have historical water level data. An eighth well (MDW8, USGS Code: 422201071530201) was sampled from 2019 to 2022 but was discontinued before 2023 sampling began because the narrow diameter prevented the collection of the full suite of parameters collected in other wells. The periods of historical data and other summary information about the wells sampled in 2023 by DWSP and USGS are presented in Table 5.

Table 5: Wachusett Groundwater Well Information

DWSP Code	Well Name	USGS Code	Type	Depth (ft)	Elevation (ft)	USGS Period of Record
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 – present
WSW26	West Boylston - Prescott St	422341071464901	Augered	16.8	485	2012 – present

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. USGS maintains automated groundwater observations in the Sterling - Rt 140[29] and West Boylston - Prescott St[30] wells, which record

[28] Bent, 1999
[29] https://waterdata.usgs.gov/monitoring-location/422520071483001/
[30] https://waterdata.usgs.gov/monitoring-location/422341071464901/

groundwater levels every 15 minutes. Additional details about groundwater level monitoring are provided in the DWSP *SOP for the Monitoring of Groundwater (WATWEL)*[31].

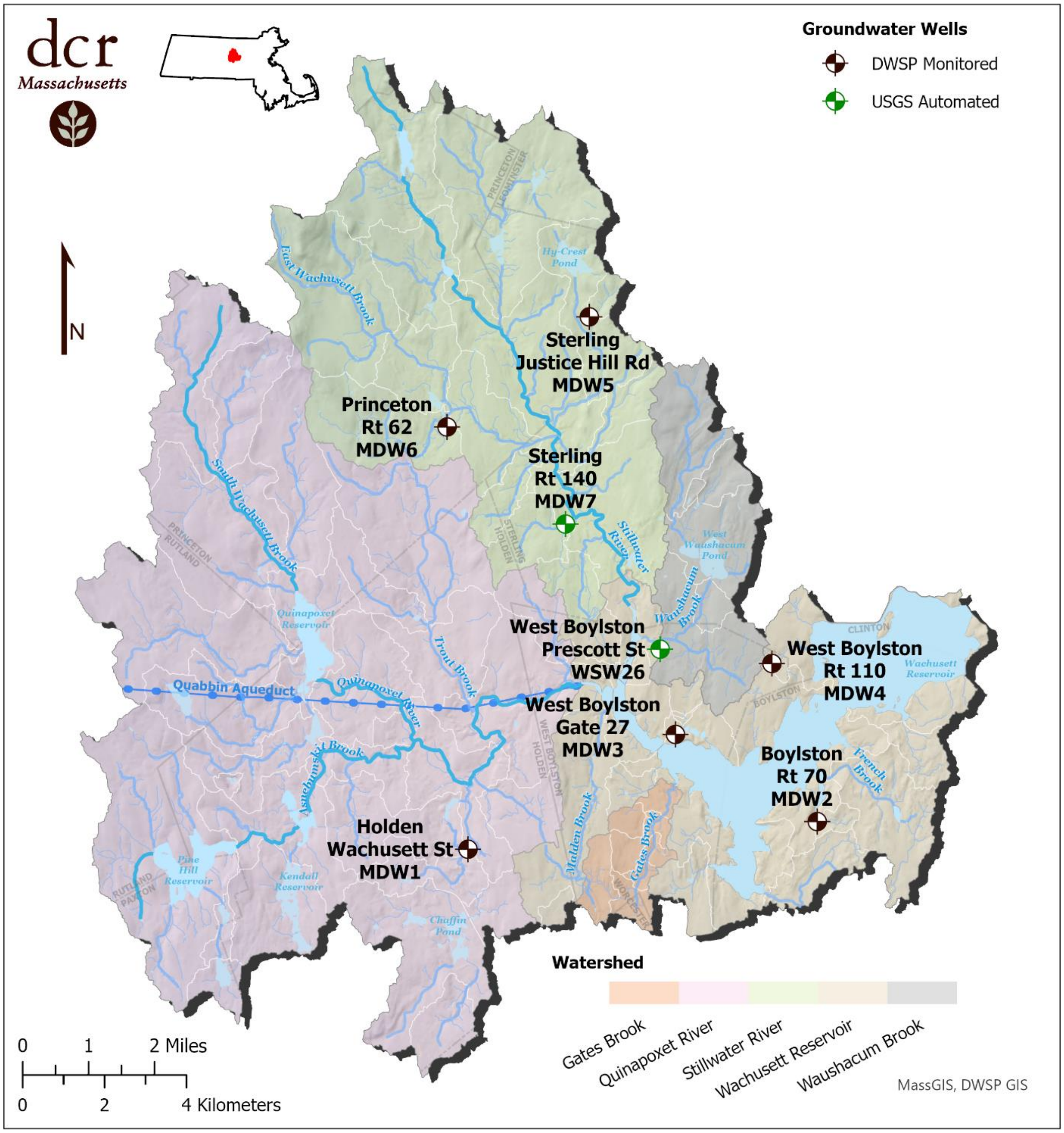
2.1.3 Groundwater Quality Monitoring

Groundwater quality can differ drastically between and within groundwater aquifers. This water resource is a major component of the Wachusett Watershed water budget. DWSP groundwater quality monitoring began in 2019 with specific conductance, temperature, and chloride data collection (Figure 6). MWRA assigned the project code “WATWEL” for groundwater parameters requiring laboratory analysis. This list of parameters was expanded for one year, from May 2021 to April 2022, to include concentrations of alkalinity, sulfate, fluoride, bromide, calcium, magnesium, sodium, and nitrate. In April 2022, DWSP began using a new flow cell which enables the collection of data with a YSI ProQuatro probe. Groundwater quality parameters collected from April 2022 through 2023 were specific conductance, temperature, pH, and dissolved oxygen.

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[32] 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. Additional details about groundwater quality monitoring are provided in the DWSP *SOP for the Monitoring of Groundwater (WATWEL)*[33].

[31] DWSP, 2021b
[32] United States Environmental Protection Agency [USEPA], 2017
[33] DWSP, 2021b

Figure 6: DWSP Groundwater Monitoring Wells in Wachusett Reservoir Watershed*



* Well MDW7 was converted to an automated well by USGS in November 2022

2.1.4 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) (Figure 7). *In situ* measurements for physiochemical parameters (field parameters) are also taken in conjunction with all tributary monitoring visits. Field parameters are measured with a YSI

Professional Plus or ProQuatro 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.

2.1.4.1 Routine Tributary Monitoring

In 2023, routine water quality samples for bacteria, turbidity, and field parameters were collected from eighteen stations on seventeen tributaries. Each tributary station was visited twice per month throughout the entire year (Table 2 – Primary and Secondary). 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 in the field using a HACH 2100Q portable turbidimeter. Samples were occasionally collected from additional locations to investigate water quality problems discovered during environmental assessments or investigations. Follow-up samples were sometimes collected after detecting elevated bacteria concentrations to determine if bacteria sources were persisting. Additional details about routine tributary monitoring are provided in the DWSP *SOP for the Monitoring of Tributary Bacteria and Turbidity (WATTRB)*[34].

2.1.4.2 Nutrient Monitoring

In 2023, 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[35], 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 in Winthrop, MA. Nutrient measurement units are all mg/L except for UV_{254}, which is reported in ABU/cm, and TP which was converted from mg/L to µg/L due to its low concentrations. 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 2023. The Quabbin Transfer was sampled six times in 2023 (June – November). Results from all tributary sampling programs are discussed in Section 3.2. Additional details about how nutrient samples are collected are provided in the DWSP *SOP for the Monitoring of Tributary Nutrients (WATMDC)*[36].

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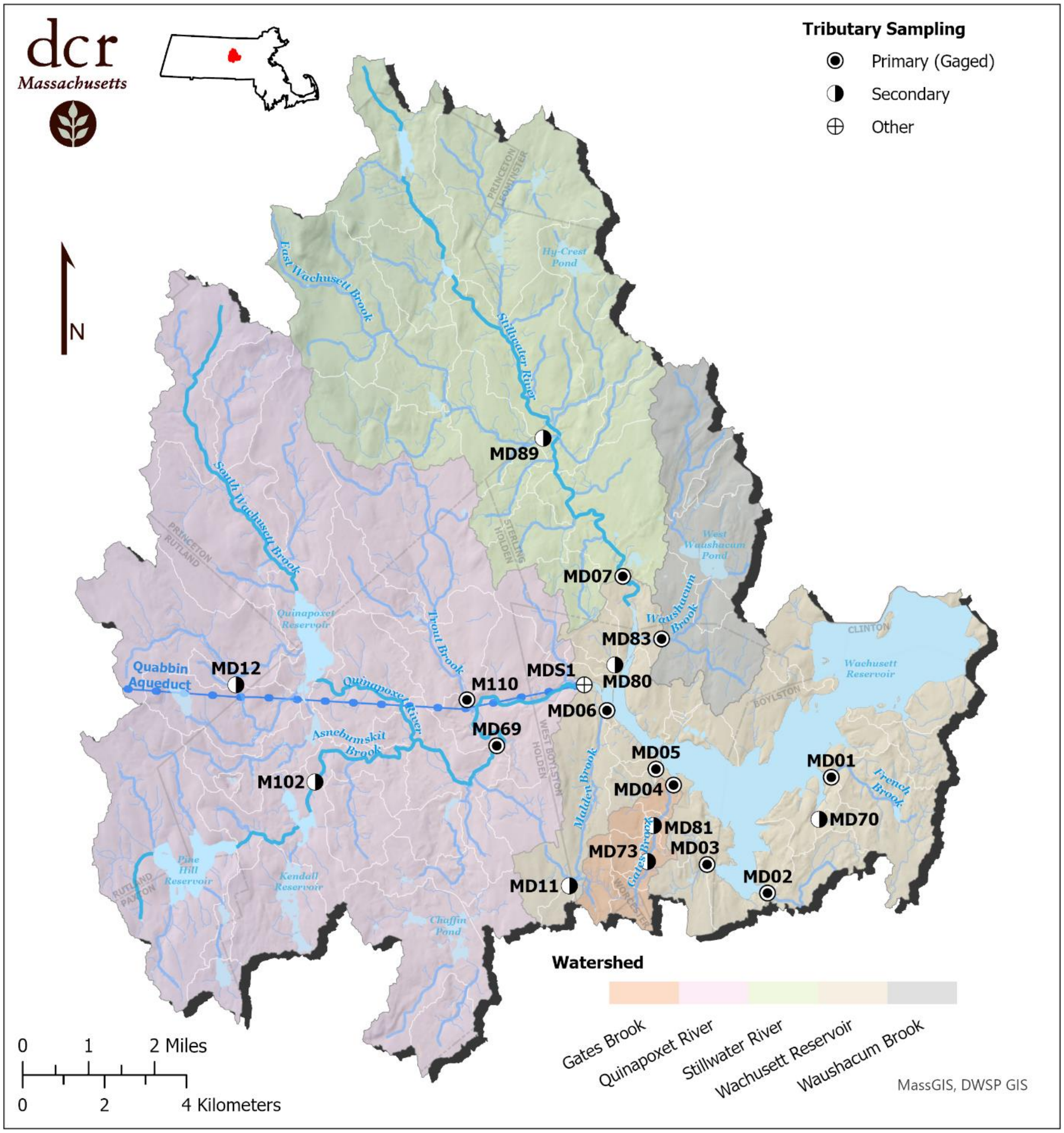
[34] DWSP, 2023b
[35] Alkalinity sampling was resumed at all primary tributary locations in September 2020
[36] DWSP, 2021d

Table 6: 2023 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 2023
Nutrients	WATMDC	NH_3-N, NO_2-N, NO_3-N, TKN, TP, TSS, TOC, UV_{254}, Cl, Alkalinity	Monthly	Primary, Other	126*
Bacteria and Turbidity	WATTRB (Only for bacteria)	*E. coli*, turbidity	Twice per Month	Primary, Secondary	432 (E. coli) 432 (turbidity)
Field Parameters (physical and chemical)	N/A	Water temperature, dissolved oxygen, pH, specific conductance	1-3 times per month/location in conjunction with WATMDC and WATTRB projects	Primary, Secondary, Other	2,604
Field Parameters (hydrology)	N/A	Stage	3 or more times per month	Primary	464
Long-term Forestry	WATBMP	NH_3-N, NO_2-N, NO_3-N, TKN, TP, TSS, TOC, UV_{254} + Field Parameters	Monthly/Quarterly Storms (no storms sampled in 2023)	LTF	1*

Figure 7: Tributary Sampling Locations in the Wachusett Reservoir Watershed



2.1.5 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.

When the Reservoir is thermally stratified and water is being transferred from Quabbin Reservoir, an interflow is established between Shaft 1 and the Cosgrove Intake. This interflow layer is comprised of a higher percentage of water from Quabbin Reservoir, indicated by lower specific conductance values than those of native Wachusett Watershed water. The timing and duration of the interflow has important implications on water quality entering the system. Therefore, tracking the progress of this layer is an important component of reservoir monitoring. More details can be found in this section and in Appendix C: Watershed Monitoring Parameters and Historical Context (Sections C-8 and C-13).

Table 7: 2023 Reservoir Monitoring Program Components

Program Name	MWRA Project Code	Parameter or Analysis	Typical Sampling Frequency	Sample Locations	# Samples Collected in 2023
Profiles	N/A	Water temperature, specific conductance, chlorophyll *a*, phycocyanin, dissolved oxygen, pH	Weekly (May – Sept), biweekly (Oct – April)	Primary: BN3417, CI3409, Secondary: BS3412, TB3427	45
Phytoplankton	N/A	Phytoplankton density	Weekly (May – Sept), biweekly (Oct – April)	Primary: BN3417, CI3409, Secondary: BS3412, TB3427, other	94
Nutrients	MDCMTH	Alkalinity, NH_3-N, NO_3-N, Silica, TKN, TP, UV_{254}	Quarterly (4x)	BN3417, BS3412, TB3427	36*
Bacteria	WATTRN	E. coli	Monthly (minimum)	23 transect stations	322
Macrophytes	N/A	Species present, location, density	Throughout growing season	Entire reservoir	n/a
Zooplankton	N/A	Population screening	Quarterly (4x)	BN3417, BS3412, TB3427	48
Salvelinus namaycush (Lake Trout)	N/A	Species, length, weight	Multiple sample trips during fall spawn	Entire reservoir – spawning locations	See Section 3.4.10

* Samples analyzed for multiple parameters at the MWRA lab at Deer Island

2.1.5.1 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 DWSP *SOP for Collection of Reservoir Profiles*[37].

[37] DWSP, 2020a

A total of 45 profiles were collected from four locations in 2023. 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 2023 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.

2.1.5.2 Nutrient Monitoring

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 November. These samples were collected at three routine locations: Basin North (BN3417), Basin South (BS3412), and Thomas Basin (TB3427). Grab samples were collected from three depths representative of specific stratification layers during the stratified period and from the surface, middle, and bottom of the water column during periods of isothermy. These collections resulted in a total of 252 nutrient samples which were analyzed by MWRA staff at the Deer Island Central Laboratory for the following: NH_3-N, NO_3-N, TKN, Silica, TP, and UV_{254}. Details of the sampling protocol are provided in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics[38] and in the DWSP *SOP for Collection of Reservoir Nutrients*[39].

2.1.5.3 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.

2.1.5.4 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 C-18, Table C-1), or decrease when conditions such as ice cover physically prevent sampling. Monitoring by

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[38] Worden & Pistrang, 2003
[39] DWSP, 2020b

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 DWSP SOPs: *SOP for Collection of Reservoir Profiles*[40], *Phytoplankton Collection and Reporting*[41] and *Microscopic Enumeration of Phytoplankton*[42].

In 2023, phytoplankton monitoring was carried out on 38 days, resulting in 94 individual samples. Twelve of these samples were analyzed solely for taxa of concern (see Section C-18, Table C-1); the entire phytoplankton community was assessed in the remainder.

2.1.5.5 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 with 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 DWSP *SOP: Collection of Reservoir Zooplankton*[43].

2.1.5.6 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; oversight of aquatic invasive species (AIS) management programs in collaboration with MWRA: and management of *Phragmites australis* along the reservoir shoreline. The *P. australis* management program takes place from June through October and involves physical and mechanical methods of control, coupled with photographic documentation of management progress.

Surveys in 2023 were conducted in support of ongoing management programs including physical AIS management in the Reservoir and management programs in three local pond systems: Clamshell Pond in Clinton, the Lily Ponds in West Boylston, and South Meadow Pond Complex in Clinton and Lancaster.

[40] DWSP, 2020a
[41] DWSP, 2020d
[42] DWSP, 2018c
[43] DWSP, 2020c

2.1.5.7 Fish Monitoring

DWSP staff conduct annual surveys of two important Wachusett Reservoir fish populations, *Osmerus mordax* (Rainbow Smelt) and *Salvelinus namaycush* (Lake Trout). Surveys for *O. mordax* spawning activity are typically carried out in early spring by boat or from shore. DWSP Aquatic Biologists look for evidence of specimens of adults and eggs washed up on shore, as observations of spawning behavior are difficult to obtain. *O. mordax* are considered an important prey species in the Reservoir and there is evidence that *O. mordax* abundance in other waterbodies is correlated with increased *S. namaycush* condition and length at catch[44].

The annual *S. namaycush* mark and recapture study capitalizes on spawning behavior to target *S. namaycush* that move into shallow gravel and cobble substrate spawning areas at night after the water temperature has reached approximately 12 °C (55 °F), typically in October. Gillnets are set in these spawning areas for 30-45 minutes. Fish captured are weighed, measured, injected with a passive integrated transponder (PIT) tag, and marked by clipping the adipose fin before being released. The length and weight data collected during this study are used to develop a length-weight relationship for the Wachusett *S. namaycush* population. When a *S. namaycush* with a clipped adipose fin is recaptured, the PIT tag is scanned to identify the individual fish, which is then measured, weighed, and released. The changes in weight and length collected from recaptured fish helps develop growth rates and track condition for the Wachusett population.

2.1.6 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. Additional monitoring or water quality investigations may arise from recommendations in Environmental Quality Assessments or updates to the Watershed Protection Plan.

2.1.6.1 Forestry Monitoring

Forest management operations, when conducted with proper 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. After many years of short-term forestry monitoring the program was evaluated and then suspended based on statistical evidence that forestry operations on DWSP lands do not pose a threat to water quality, and staff time and resources would be better directed towards higher priority water quality issues.

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[44] Stolarski, 2019.

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. Nine 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 DWSP *SOP for Long-term Forestry Monitoring (WATBMP)*[45].

2.1.6.2 Storm Sampling

Storm 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 considered for extreme precipitation events (2 or more inches of rain) to support UMass modelling efforts. No storms were sampled in 2023. A separate storm 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 DWSP *SOP for Storm Sampling*[46].

2.1.6.3 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 multi-sensor meter at inlet and outlet locations of each forebay at least monthly from July through December. Photographic documentation of vegetation and water level was also recorded using a customized ESRI Field Maps application. These data will be used to assess changes which may occur in water quality and vegetative composition because 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).

[45] DWSP, 2021c
[46] DWSP, 2021d

2.1.6.4 Environmental Quality Assessments

DWSP conducts annual Environmental Quality Assessments (EQA) of a single sanitary district in Wachusett Watershed to assess potential sources of contamination. Each of five separate sanitary districts is comprehensively evaluated by DWSP once every five years. The 2023 EQA report focused on the Waushacum sanitary district. Targeted sampling may be conducted relating to specific recommendations concerning known or suspected water quality issues identified in EQA reports.

2.2 2023 Watershed Monitoring Parameters

In 2023, 25 distinct physical, chemical, and biological parameters were monitored across all water quality and hydrologic monitoring programs throughout the Wachusett Reservoir Watershed (Table 8). Most 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, and/or 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 B-1 in Appendix B: Water Quality Standards and Criteria. Scientific background information and historical context in relation to the Wachusett Watershed is also provided in Appendix C: Watershed Monitoring Parameters and Historical Context to help readers better understand the discussion of water quality and hydrologic monitoring results. Monitoring results for 2023 are presented and discussed in Section 3.

Table 8: 2023 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	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	Nutrients	MWRA Lab	SM 2320 B	X	X	
Blue Green Algae	µg/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	
Chlorophyll	µg/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		
Depth to Water	ft	Field parameter	Field-Sensor	*SOP for Groundwater*			X
Discharge	cfs	Field parameter	Field Sensor/ Calculated	Calculated from stage-discharge rating curve		X	
Dissolved Oxygen	mg/L	Field parameter	Field-Sensor	SM 4500-O G-2001	X	X	X
E. coli	MPN/100 mL	Bacteria	MWRA Lab	9223B 20th Edition (Enzyme Substrate Procedure)	X	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	X
Precipitation	in	Meteorological	Field-Sensor	(USGS/NOAA)			
Secchi Depth	ft	Field parameter	Field-Sensor	SOP for Secchi Measurement[47]	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	Field-Sensor	EPA 180.1		X	
Water Depth	m	Field parameter	Field-Sensor	N/A	X		
Water Temperature	Deg-C	Field parameter	Field-Sensor,	SM 2550 B-2000	X	X	X

[47] DWSP, 2023e

2.3 Statistical Methods and Data Management

All numerical calculations and related graphics were generated using the R programming language[48] and preserved in scripts, which document the exact steps that were utilized to produce the presented results. 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[49]. All seasonal statistics presented in this report, apart from reservoir nutrients (see Section 3.4.7), use the following date cutoffs to determine season:

- December 1 (start of meteorological winter)
- March 1 (start of meteorological spring)
- June 1 (start of meteorological summer)
- September 1 (start of meteorological autumn)

In 2021, DWSP changed how left-censored laboratory results (values that were below lower detection limit thresholds) were stored and analyzed. Previously, left-censored results were recalculated as one-half the detection limit and statistics were calculated using these values. All left-censored results are now stored to be equal to the detection limit, however, statistical methods have been improved to handle the uncertainty associated with censored results. Right-censored laboratory results (values above the upper quantification limit) are assigned a value equal to the limit (this did not change). All censored results are flagged as such in the database.

Annual report statistics (mean, median, geometric mean) are now calculated using methods depending on the prevalence of non-detects within each data grouping. Logic has been embedded in R scripts so that when fewer than four values are detected in a data group, the left-censored results (except for *E. coli*) are set to one-half the detection limit value and the normal statistic is calculated using base R functions. However, when there are four or more uncensored values in a data group, statistics are calculated using functions from the NADA package[50]. A parametric method, Maximum Likelihood Estimation (MLE), is used to compute bacteria geometric means. A non-parametric method, Regression on Order Statistics (ROS), is used with non-bacteria data to calculate means and medians. This change in statistical methods has caused some slight differences from the statistics that were reported in prior annual reports (for some parameters). For parameters where data groupings had no censored results, the statistics will not differ between the 2021 and future reports and prior annual reports.

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[51] 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 2023 and prior years are available upon request.

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[48] R Core Team, 2019
[49] Wickham, 2016
[50] Lee, 2022
[51] Chang et al., 2019

2.4 Quality Assurance and Quality Control

Over the last several years, QA/QC protocols have been incorporated into many aspects of water quality and hydrological monitoring in the Wachusett Reservoir Watershed. Since 2018, and prior to any formalized SOPs, automated data quality and other screening checks were embedded into data processing scripts. In 2019, the first detailed written description of monitoring programs was written, which became the precursor for individual monitoring program SOPs. Between 2020 and 2023 formal SOPs were developed to cover most routine water quality and hydrological monitoring programs. An internal monthly QA/QC report was developed in 2022, which summarized equipment calibration results, pre-sampling calibration verification checks, and potential data outliers that may need to be reviewed by staff. In 2023, field duplicates and blanks were added to the routine tributary monitoring programs and field and lab audits were conducted to ensure that established SOPs are being adhered to by DCR staff. A summary of field blanks and duplicate results was incorporated into the monthly QA/QC report, indicating if any parameter was outside of the acceptable range. The first Wachusett Watershed Quality Assurance Project Plan (QAPP) for water quality and hydrological monitoring programs was completed in June of 2023[52], which serves as the umbrella document for all SOPs and QA/QC procedures.

The implementation of the QAPP and recent modifications to SOPs have resulted in more efficient data processing and field procedures and better data quality control and reliability. In particular, the addition of field blanks and duplicates has allowed for improved detection of data anomalies which may have otherwise gone unnoticed. A full summary of QA/QC efforts for 2023 are provided in Appendix D: Quality Assurance and Appendix E: Quality Control.

[52] DWSP, 2023f

3 Results

This section presents the results of DWSP routine monitoring programs in Wachusett Watershed for 2023, including the reservoir, tributaries, and groundwater. In the tributaries, DWSP staff collected 432 turbidity samples along with 2,086 physiochemical measurements (552 water temperature, 552 specific conductance, 491 dissolved oxygen and 491 pH) in the field at tributary stations and Shaft 1, and 94 phytoplankton samples were taken from the Reservoir 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 755 bacteria samples were collected and delivered to the MWRA Southborough laboratory for *E. coli* analysis (432 from tributaries and 322 from the Reservoir), and 1,416 samples (1,200 tributary, 216 reservoir) were collected and shipped to the MWRA Deer Island laboratory for a total of 2,171 analyses of nutrients and other parameters; these numbers do not include special studies and non-routine samples. 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 five occasions during 2023.

3.1 Meteorologic and Hydrologic Conditions

Climatic patterns (precipitation and temperature) are the primary drivers of the hydrologic cycle and have major implications to water quality and water supply due to their influence on 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 (e.g. drought) or after short and intense weather events. Thus, it is important to compare water quality results to antecedent hydrological and climate conditions to determine if there is a causal link, or if other factors may be responsible for the water quality response.

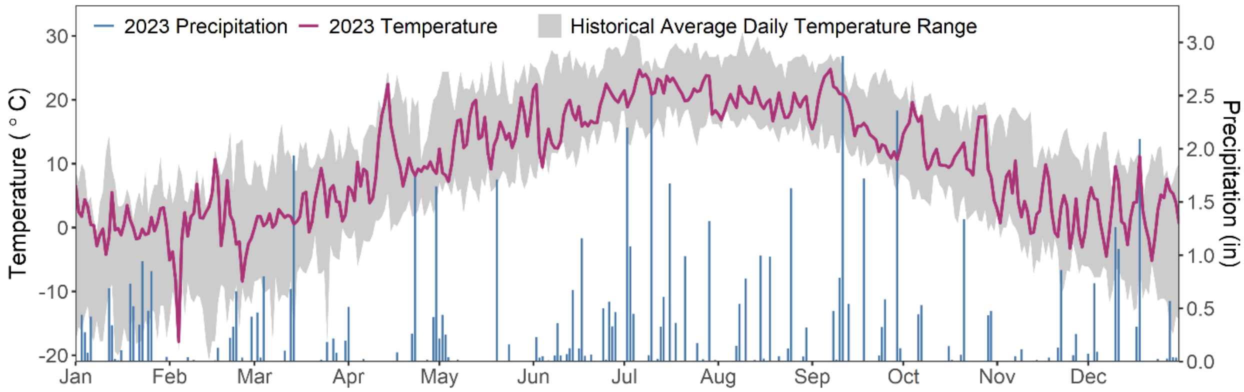
3.1.1 Meteorologic Conditions

3.1.1.1 Air Temperature

Average daily air temperatures in the Wachusett Reservoir Watershed for 2023 ranged from -17.90 °C (February 4) to 24.8 °C (July 3) (Figure 8). The lowest daily minimum temperature (average of all stations) observed in 2023 was -24.9 °C on February 4, while the highest daily maximum temperature was 32.2 °C on April 14 and September 7.

Figure 8: Climatograph of Daily Mean Temperatures and Daily Precipitation Totals for Wachusett Watershed from January 1 through December 31, 2023

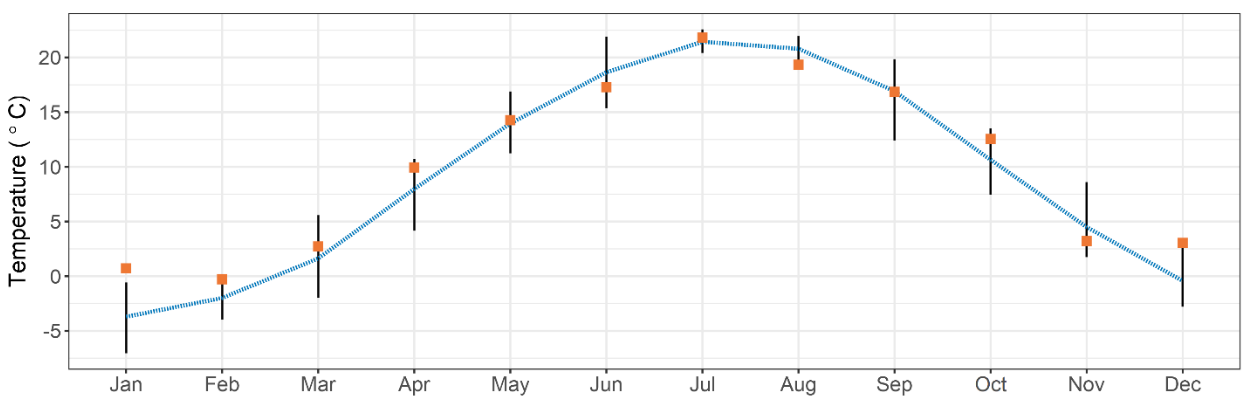
Shaded band represents average daily temperature ranges from 1998 – 2023.



Most monthly average temperatures were within historical ranges. Eight months in 2023 experienced above normal temperatures and four below (Figure 9). The mean annual temperature for 2023 was 10.11 °C, which is 0.65 °C above the historical annual mean temperature (since 1998). January 2023 was the warmest January in the period of record, while August 2023 was the coldest August in the period of record.

Figure 9: Wachusett Reservoir Watershed Monthly Mean Temperatures in 2023

Monthly mean temperatures for 2023 (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.

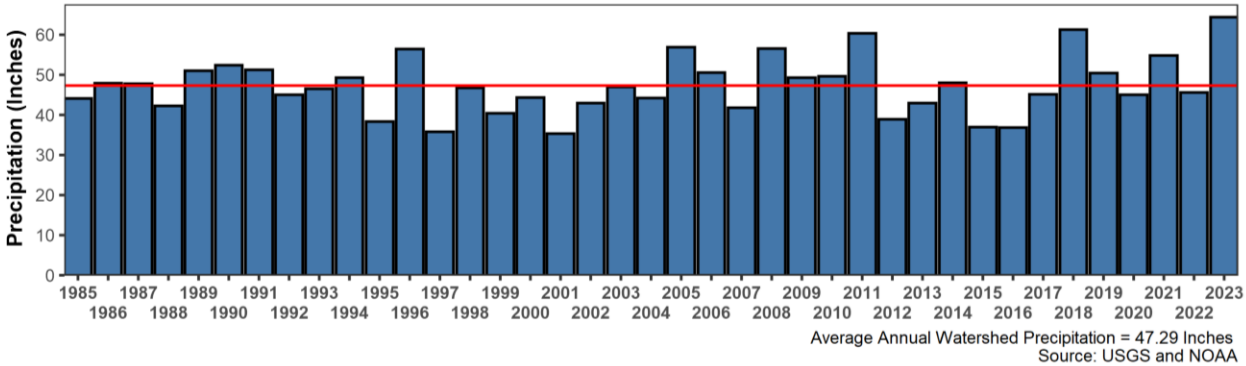


3.1.1.2 Precipitation

As illustrated by Figure 10, in 2023 Wachusett Reservoir Watershed received the highest annual precipitation since 1985, with 64.44 inches of rainfall (17.15 inches above average annual precipitation).

Figure 10: Annual Precipitation for Wachusett Watershed, 1985 to 2023

The red line indicates the long-term average annual total precipitation.



Calendar year cumulative precipitation remained normal to slightly above normal until the end of June. Precipitation was above average for the months July through September, with a combined surplus of nearly 15 inches. October and November precipitation was below normal, but then December precipitation was back up, more than two inches above normal (Figure 11). As a result of the surplus precipitation for most months in 2023, central Massachusetts drought status remained at level 0 – "Normal" for the entirety of 2023[53]. July was the wettest month of 2023 (11.9 inches). Small and medium storms were numerous throughout 2023, with 18 days receiving one inch or more precipitation, 25 days between 0.5 and 1.0 inches, and 13 days between 0.2 and 0.5 inches. Noteworthy storms in 2023 occurred July 2 (2.2 inches), July 10 (2.56 inches), September 29 (2.36 inches), and December 18 (2.09 inches). The most significant precipitation event of the year occurred overnight on September 11-12, when an intense and very localized storm generated between six and ten inches of rainfall in parts of Princeton and Leominster, MA – which is the headwaters of the Stillwater River.

[53] MA Drought Management Taskforce, 2023

Figure 11: Wachusett Watershed Monthly Total (left) and Daily Cumulative Precipitation (right) in 2023

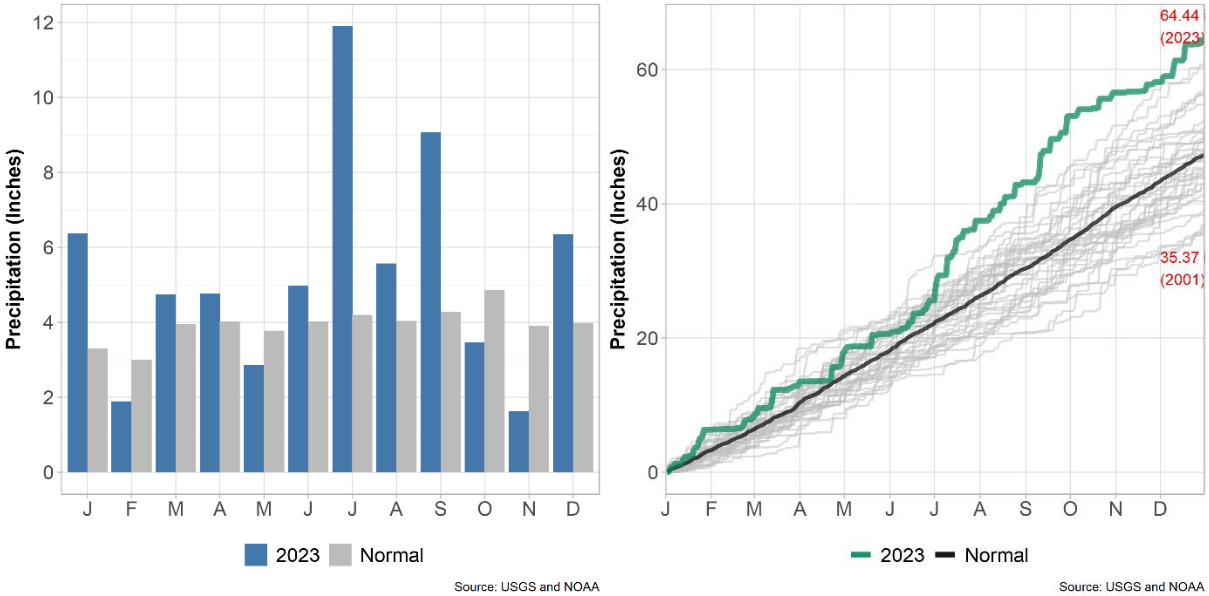


Table 9: Monthly Total Precipitation in 2023 and Statistics for the Period of Record 1985 to 2023

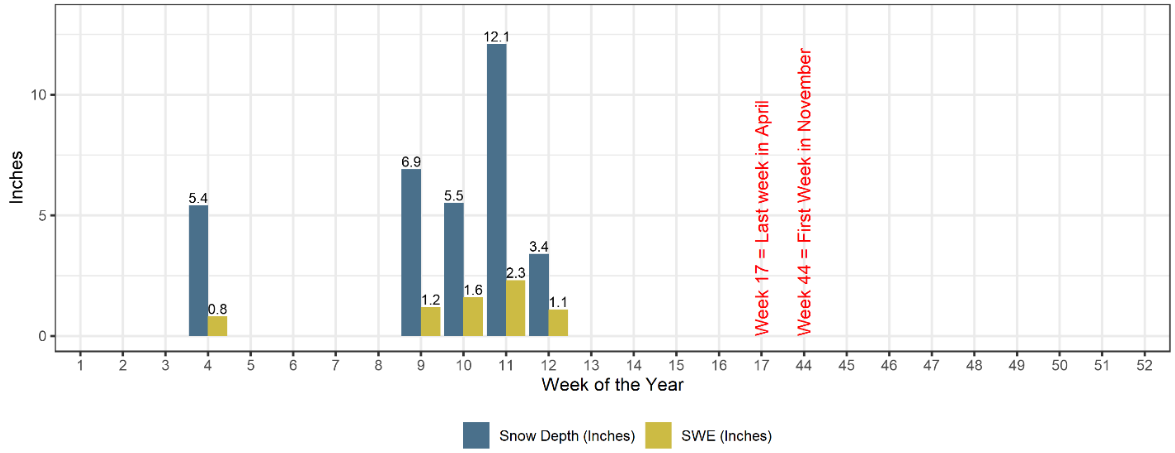
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Precipitation (in)	6.36	1.89	4.74	4.76	2.86	4.97	11.9	5.70	9.89	3.46	1.55	6.35	64.43
Normal (in)	3.30	3.00	3.95	4.01	3.77	4.02	4.19	4.04	4.29	4.86	3.90	3.97	47.29
Departure (in)	3.06	-1.11	0.79	0.75	-0.91	0.95	7.71	1.66	5.60	-1.40	-2.35	2.38	17.13

Snow

Figure 12 shows the snowpack measurement results for calendar year 2023. 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 measurable snowpack in 2023 occurred after a storm on January 22-23, totaling 5.3 inches (Watershed average). Due to warm temperatures and rain, the snowpack had completely melted by the end of January. An ice storm followed by a snowstorm during the last week of February delivered 5-8 inches of snow/ice with a snow-water-equivalent (SWE) of 1.2 inches. A Nor'easter on March 13-14 resulted in snowfall ranging from 5 to 25 inches across the Wachusett Watershed, bringing the snowpack to its maximum depth for the season at 12.1 inches (watershed average), with a SWE of 2.3 inches. By the end of March, the snowpack had substantially melted, preventing any additional measurements. There were no other snowstorms during the remainder of 2023. More detailed information was recorded in snowpack reports that were produced for the weeks that a snowpack survey was conducted.

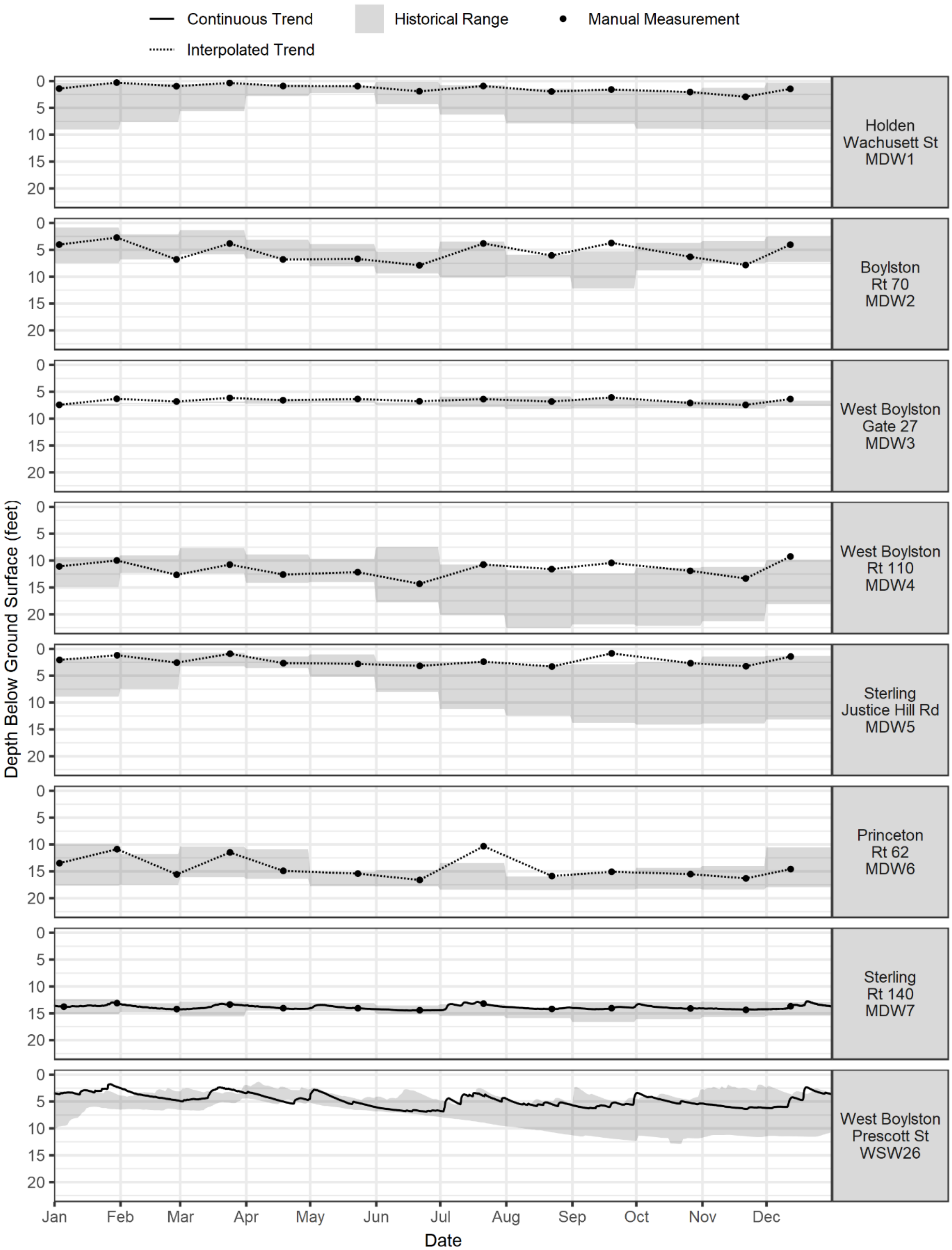
Figure 12: Snowpack Measurements in 2023
SWE = Snow-water-equivalent.



3.1.2 Groundwater Levels

Results of groundwater level monitoring are presented in Figure 13. During the 2023 sampling period, none of the wells were dry on the sampling dates. 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 nine 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 2023 with Historical Ranges for Comparison

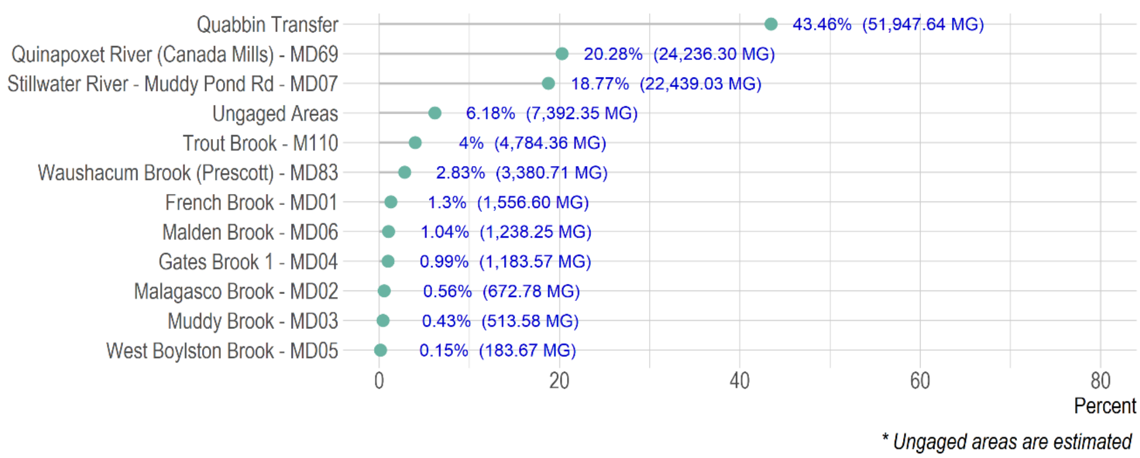


3.1.3 Streamflows, Quabbin Transfer and Withdrawals

The total surface water inflow to Wachusett Reservoir in 2023 was estimated to be 119.53 BG; about 28 BG more than in 2022. The seasonal hydrologic patterns typical of Wachusett Watershed did not follow the usual sequence of high flows in the spring, low summer flows, and a return to moderate flows from the late fall through the winter. The winter snowpack was gone by the end of March and streamflows mostly declined through May. Excess precipitation from June – September, combined with a very cold August kept summertime flows from dropping to the low levels that are customary for the summer season. In fact, many streams that typically dry up intermittently in the summer did not.

Water transfers from the Quabbin Reservoir comprised only 43.46% of the total surface water inflow in 2023, which is only about 2.5 billion less gallons than in 2022, but a 16% lesser share of the total annual surface water inflows to Wachusett Reservoir. Figure 14 shows a breakdown of annual total flow (MG) among all the tributaries as well as ungaged areas and the Quabbin transfer. About 39% 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 in 2023



Total annual discharges for the Quinapoxet and Stillwater Rivers for 2023 were 46% and 58% above average, respectively (Figure 15).

Figure 15: Annual Discharge in the Quinapoxet and Stillwater Rivers (MG) (2007 to 2023)

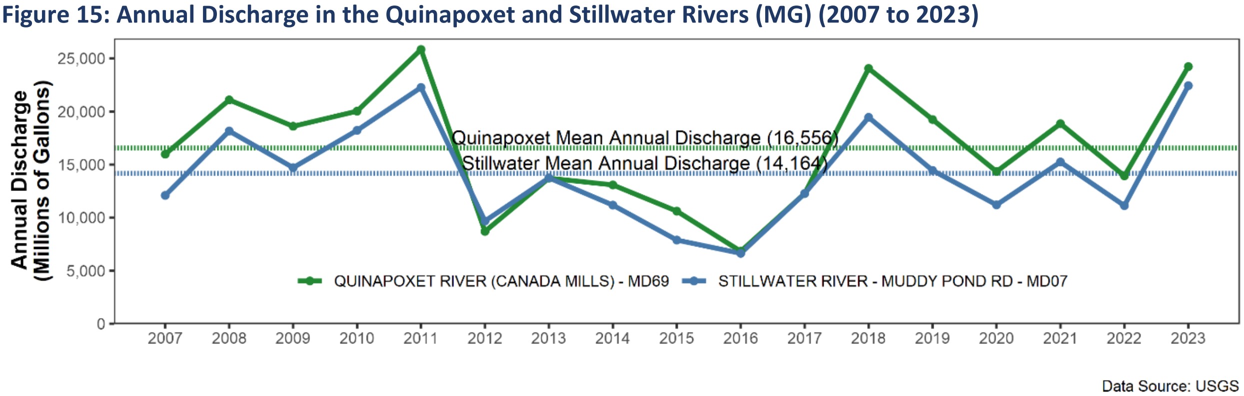


Table 10 provides summary statistics of surface water discharge for 2023. Daily flow rates in the smaller tributaries ranged from 0.07 cfs at West Boylston Brook to 181 cfs at Trout Brook. The maximum instantaneous flows at these tributaries ranged from 18.93 cfs at West Boylston Brook to 377 cfs at Trout Brook.

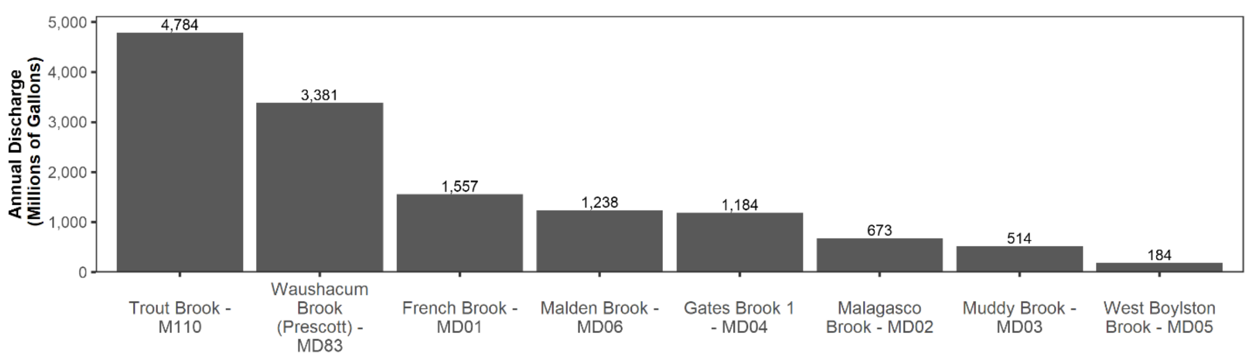
Table 10: 2023 Flow Statistics for Wachusett Reservoir Tributaries

Location	Min Daily Flow (CFS)	Avg Daily Flow (CFS)	Max Daily Flow (CFS)	2023 Peak Inst. Flow (CFS)	Min Month Vol (MG)	Avg Month Vol (MG)	Max Month Vol (MG)	2023 Total Vol (MG)
French Brook - MD01	0.37	6.55	109.96	624.97	24.4	129.7	276.9	1,557
Gates Brook 1 - MD04	1.81	5.02	37.80	91.60	43.6	98.6	143.9	1,184
Malagasco Brook - MD02	0.30	2.83	25.82	35.80	12.0	56.1	166.5	673
Malden Brook - MD06	1.37	5.24	22.30	31.13	39.6	103.2	192.1	1,238
Muddy Brook - MD03	0.35	2.17	13.74	26.20	10.9	42.8	69.3	514
Quinapoxet River - MD69	14.50	102.74	1070.00	1720.00	558.4	2,019.7	4,395.9	24,236
Stillwater River - MD07	13.90	95.12	1040.00	1610.00	921.0	1,869.8	3,923.0	22,439
Trout Brook - M110	2.36	20.14	181.07	377.34	138.8	398.7	873.9	4,784
Waushacum Brook - MD83	0.33	14.24	65.43	102.61	37.6	281.7	481.4	3,381
West Boylston Brook - MD05	0.07	0.77	8.17	18.93	3.5	15.3	27.5	184
Ungaged Areas*	—	—	—	—	—	—	—	7,392
Quabbin Transfer	—	—	—	—	—	—	—	51,948

* Estimated

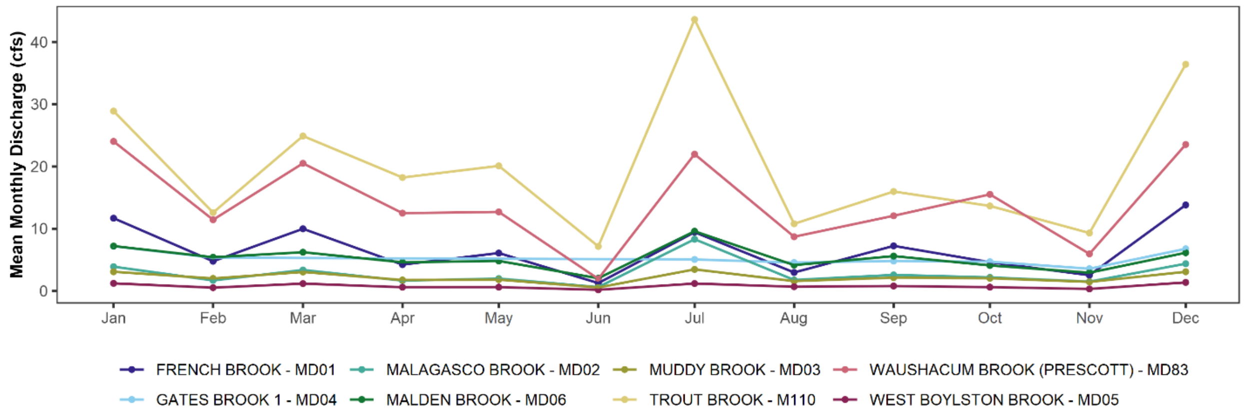
The annual discharge totals for the smaller tributaries are presented in Figure 16. Trout Brook contributed the largest water volume to Wachusett Reservoir of the smaller tributaries with 4,784 MG (~4 %), while Waushacum Brook contributed 3,381 MG (~2.8%) of the surface water inflow to the Reservoir. The other gaged small tributaries combined to contribute less than 5% of the surface water inflows to Wachusett Reservoir. Non-gaged areas contributed approximately 6% of the total inflows (estimated).

Figure 16: Annual Discharge (MG) for Smaller Gaged Wachusett Tributaries in 2023



Monthly tributary flows did not follow their typical seasonal patterns during 2023 (Figure 17). Due to higher-than-normal rainfall, streamflow remained well above typical seasonal levels from July through October. At Trout, Malden, and Malagasco Brooks, mean monthly discharge was highest in July, when this month typically has one of the lowest mean monthly discharges. The prolonged period of high flows, sustained through frequent summer rainstorms did result in elevated turbidity and bacteria levels during 2023.

Figure 17: Mean Monthly Discharge in Smaller Wachusett Tributaries (CFS) in 2023



Monthly discharges in the Quinapoxet River (Figure 18) and Stillwater River (Figure 19) for 2023 followed the same pattern as the smaller tributaries, with above normal discharge from July through October. The highest monthly discharge for both rivers was in July. Complete hydrographs for all flow monitored tributaries are provided in Appendix A.

Figure 18: Monthly Discharge in the Quinapoxet River (MG) 2023

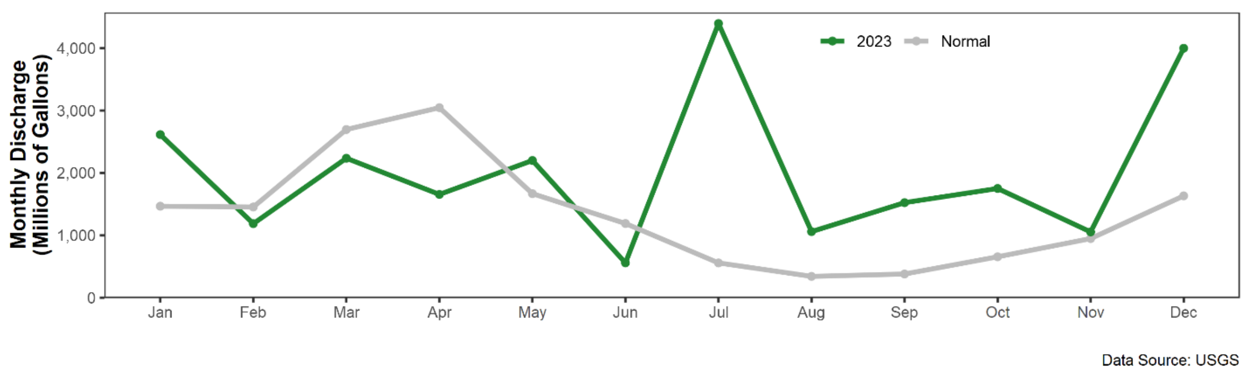
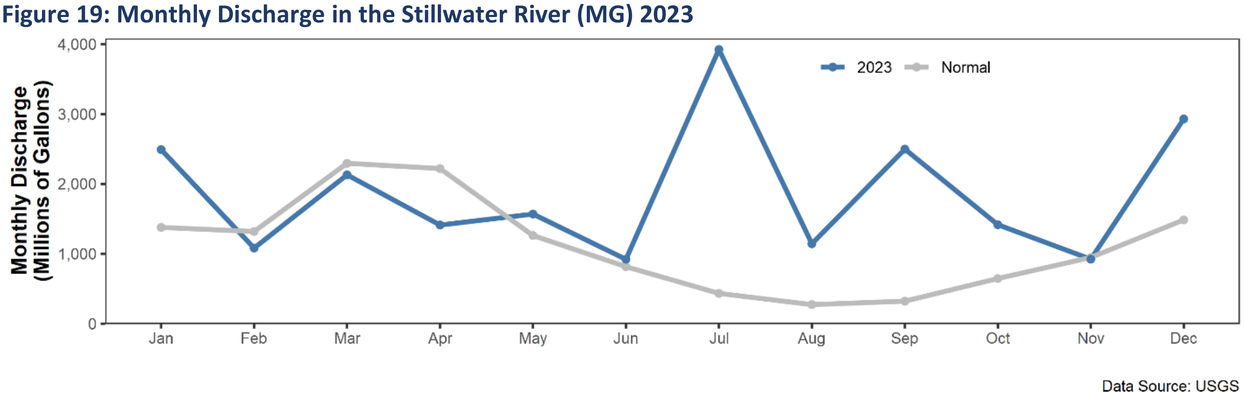


Figure 19: Monthly Discharge in the Stillwater River (MG) 2023



The Quabbin transfer was incrementally ramped up to 300 MGD by mid-May and remained on through mid-December. In 2023, the transfer was on for a total of 216 days, delivering a total volume of 51.9 BG to Wachusett Reservoir at an average transfer rate of 240.5 MGD (Figure 20). This is equivalent to 79.8% of Wachusett Reservoir capacity (65 BG) and is about 6,558 MG more than the average transfer volume between 2005 and 2022 (45,390 MG) (Figure 21). Wachusett Reservoir elevation fell below its standard operating band due to infrastructure work for most of April but remained within or above its operating band during all other times of the year. Despite a reduction in transfer volume during July and August, the reservoir exceeded the operating band for almost five weeks due to high tributary flows (Figure 20). The reservoir elevation peaked at 393.18 ft on July 19, while its lowest point in 2023 was 389.10 ft on April 22.

Figure 20: 2023 Daily Wachusett Reservoir Water Elevation and Daily Quabbin Transfer Rate

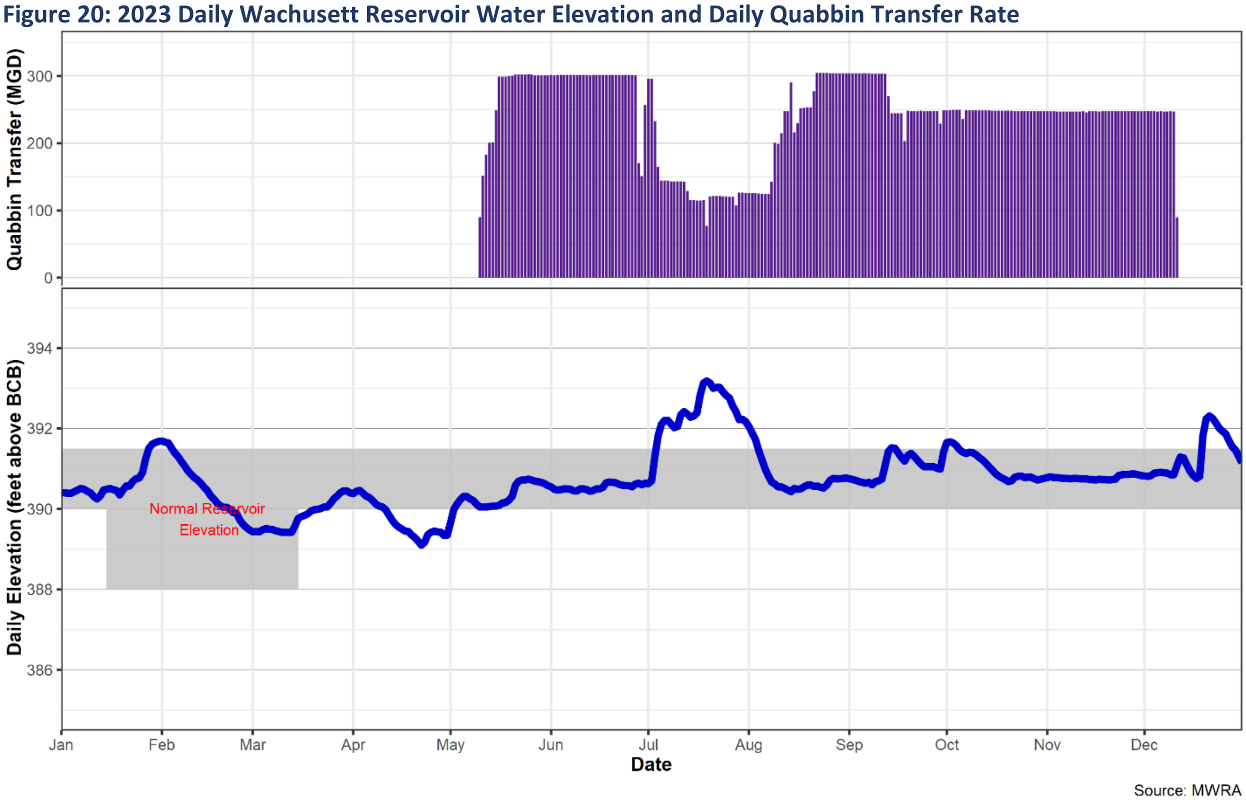
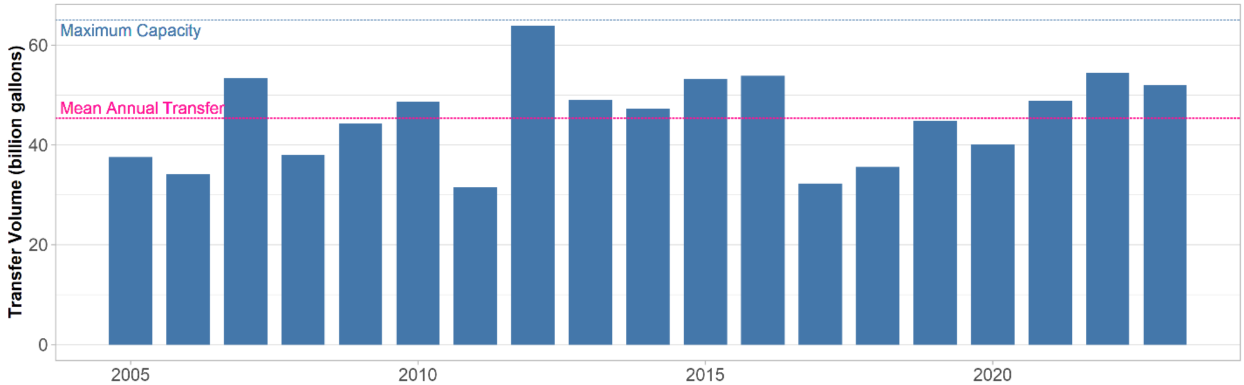


Figure 21: Annual Volume of Quabbin Transfer to Wachusett Reservoir
Maximum capacity of Wachusett Reservoir indicated by line at 65 billion gallons.



Wachusett Reservoir withdrawals by MWRA during 2023 were just under 71 BG, which was the lowest volume since at least 2014, but only about 3.5 BG below the mean withdrawal over these ten years. 2023 was such a wet year that the annual demand could have nearly been satisfied entirely by native Wachusett Watershed water, with over 67 BG of surface inflows from the tributaries. However, MWRA was able to take advantage of excess water in the supply system and transfer an average of 240.5 MGD from Quabbin Reservoir to the Wachusett. While this rate of transfer was not needed to meet demand, it was sustained for its moderating effect on TOC and UV_{254} levels, which were nearing record high levels during the latter half of the year and making it challenging for MWRA to meet disinfection byproduct (DBP) compliance requirements at the treatment plant (see Appendix C-15). In order to stay within the reservoir elevation operating band, MWRA released water over the reservoir spillway to the Nashua River on a continuous basis from the end of May through the end of 2023, totaling more than 45 BG for the year. This was the largest annual water volume released to the Nashua River since at least 2014, and more than double the mean annual release over this time period (21.2 BG).

3.2 Tributary Monitoring

3.2.1 Water Temperature and Dissolved Oxygen

Tributary water temperature and dissolved oxygen results for 2023 are presented below. Records for these parameters prior to 2020 are not included in this analysis due to failure to meet current QC standards for approval. Interannual variation and statistics will be presented once a sufficient record of reliable data has been accumulated.

In 2023, water temperature in Wachusett Watershed tributaries ranged from -1.1 °C at East Wachusett and Trout Brooks to 27.1 °C, at French Brook. At the 10 monitoring locations where temperature sensors were installed, the 7-day mean maximum temperature (purple points) is shown in Figure 22 and Figure 23 for comparison to the MassDEP 20 °C coldwater fish resource (CFR) and 28.3 °C warmwater fish resource (WFR) limits[54]. For the CFR tributaries with temperature sensors, all monitoring locations exceeded the 20 °C limit on at least one day over the summer (Table 11). It is likely that the other three

[54] Massachusetts Surface Water Quality Standards, 2013a

CFR tributaries without temperature sensors also exceeded the 20 °C threshold over multiple days in 2023. Based on manual point measurements and continuous sensor data (where available) no tributaries exceeded the WFR threshold during 2023 (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 2023

Monitoring Location	Days Exceeded
Gates Brook 1 - MD04	7
Malden Brook – MD06	37
Quinapoxet River (Canada Mills) - MD69	97
Stillwater River - Muddy Pond Rd - MD07	79
Trout Brook - M110	62
West Boylston Brook - MD05	6

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 (6.0 mg/L).

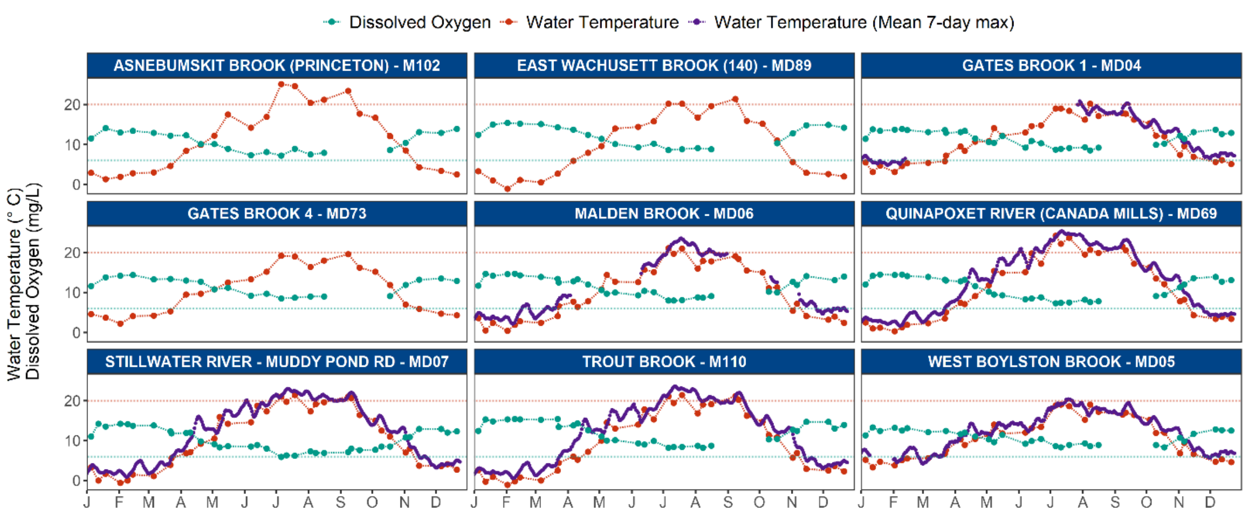
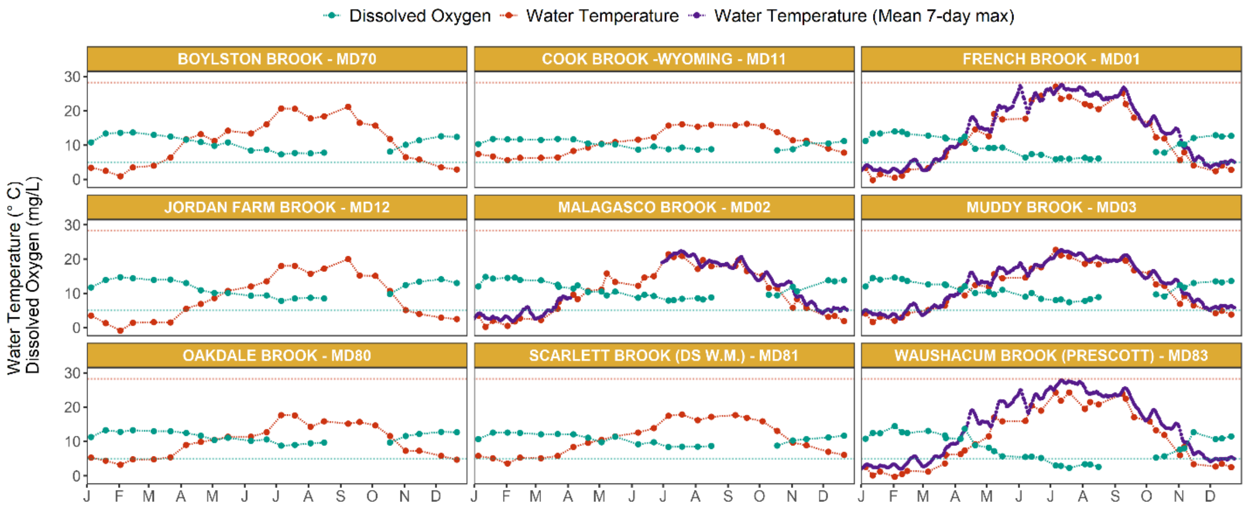


Figure 23: Water Temperature and Dissolved Oxygen for Wachusett Tributaries designated as Warmwater Fish Resources (WFR)

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 2023 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 2.3 mg/L at Waushacum Brook to a high of 15.4 mg/L, also at Waushacum Brook[55]. For CFR monitoring locations D.O. during 2023 monitoring visits met the MassDEP aquatic life criteria (minimum of 6.0 mg/L) at all locations except for the Stillwater River, which fell below this threshold during 1 day in July (Figure 22). For WFR monitoring locations D.O. fell below the MassDEP aquatic life threshold (5.0 mg/L) only at Waushacum Brook (at six visits), which is common for this tributary during the summer months due to the large and shallow wetland area upstream of the monitoring location.

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 previously conducted between 2000 and 2012, and then 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.

[55] Although sensor calibration was confirmed prior to sampling, the recommended dissolved oxygen sensor maintenance schedule was not followed in 2021 and early on in 2022, casting greater uncertainty about results above 15 mg/L.

In 2023, and in the earlier monitoring period, alkalinity concentrations in the tributaries (as $CaCO_3$) correspond well with the underlying bedrock carbonate content. A band of calcpelite, which is composed of 15 – 45% carbonate minerals[56], stretches across the Wachusett Watershed through Gates Brook, West Boylston Brook, and Waushacum Brook subbasins. These three tributaries have the highest 2020 – 2023 mean and median alkalinity concentrations in the Wachusett Watershed. Another narrow swath 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.

Compared to the 2000 – 2012 period, the latest four years of alkalinity data, including 2023, show slight increases at French and West Boylston Brooks and the Stillwater and Quinapoxet Rivers (Table 12). The limited number of recent measurements and range of interannual variability make it difficult to conclude whether the observed increases constitute a significant trend.

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. Data from 2020 – 2023 suggest that most Wachusett tributaries fall below this minimum alkalinity requirement to protect aquatic life. As more data are collected it will become possible to make stronger conclusions about how alkalinity has changed over the years and whether the tributaries exhibit any predictable inter-seasonal patterns.

Table 12: Wachusett Tributary Alkalinity (mg/L) 2000 – 2012 Compared to 2020 – 2023 Results

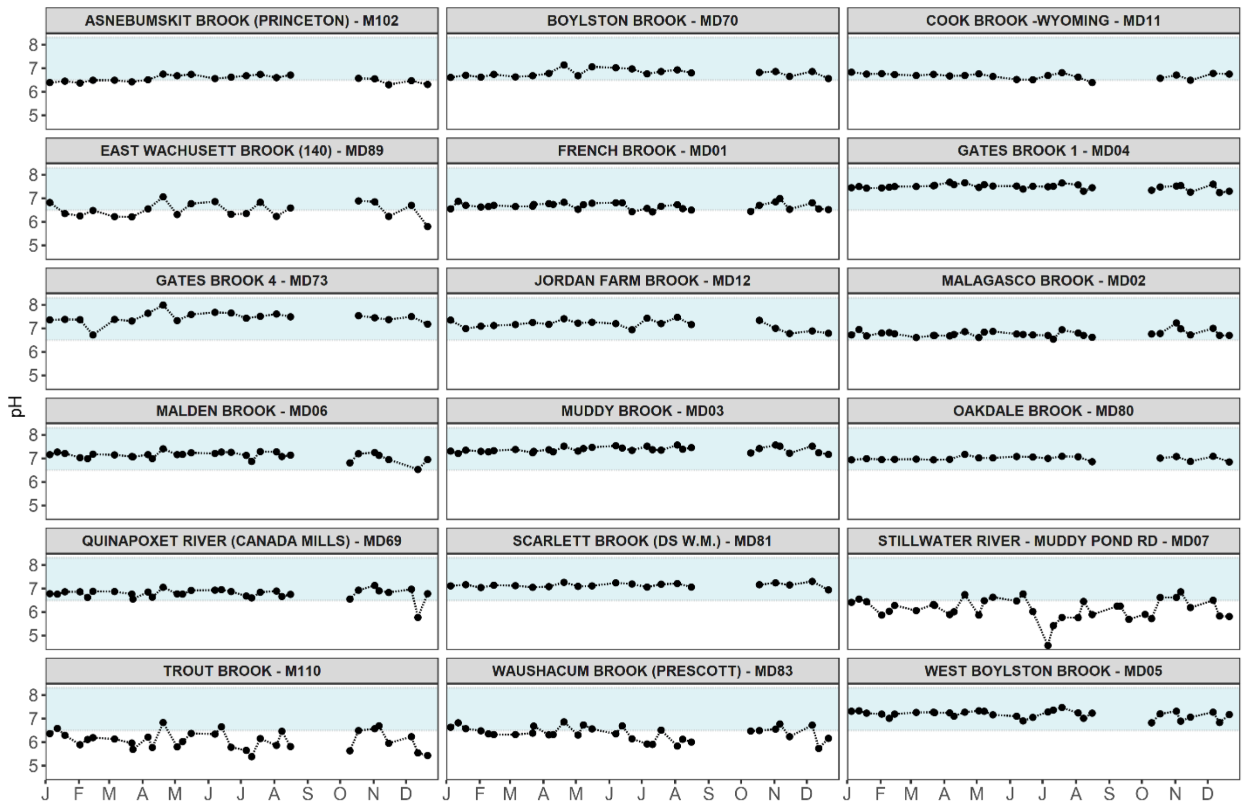
Sample Location	# Samples 2000-2012	# Samples 2020-2023	Mean 2000-2012	Mean 2020-2023	Median 2000-2012	Median 2020-2023
Cook Brook -Wyoming - MD11	61	—	30.85	—	30.80	—
French Brook - MD01	71	40	13.32	15.11	10.80	12.40
Gates Brook 1 - MD04	77	40	43.64	43.16	44.90	43.30
Jordan Farm Brook - MD12	48	—	16.88	—	15.50	—
Malagasco Brook - MD02	78	40	11.63	11.40	11.10	11.15
Malden Brook - MD06	65	40	20.37	20.00	22.0	20.65
Muddy Brook - MD03	78	40	21.66	18.97	22.55	17.60
Quinapoxet River (Canada Mills) - MD69	138	39	8.36	10.16	7.96	9.18
Rocky Brook (E Branch) - MD13	48	—	1.48	—	0.56	—
Shaft 1 (Quabbin transfer) - MDS1	—	13	—	3.92	—	3.90
Stillwater River - Muddy Pond Rd - MD07	138	40	7.94	10.00	6.85	7.77
Trout Brook - M110	—	35	—	4.36	—	3.84
Waushacum Brook (Prescott) - MD83	—	40	—	29.97	—	26.75
West Boylston Brook - MD05	78	40	31.63	34.73	32.8	33.80

[56] Grady & Mullaney, 1998

Across all tributary monitoring locations, pH values in 2023 ranged from 4.58 at the Stillwater River to 7.99 at Gates Brook 4. Tributary pH values below the recommended range (6.5 – 8.3)[57] are common in Wachusett Watershed and were observed at eight monitoring locations at least once in 2023. The monitoring locations where pH was not detected below the recommended range include Boylston, Gates Brook 1, Jordan Farm, Malagasco, Malden, Muddy, Oakdale, Scarlett, and West Boylston Brooks. In 2023, seasonal variation in pH levels across monitoring locations was generally muted when compared with 2022. The record precipitation in 2023 is presumed to have influenced the observed pH levels in 2023, however, the short period of record for stream pH data limits the ability to compare 2023 pH results to prior results during similar seasons or hydrologic conditions.

Figure 24: 2023 Results for pH in Wachusett Tributaries

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



The extent and magnitude of different anthropogenic and geogenic influences on Wachusett tributary chemistry has not yet been researched, however, DWSP will be investigating those influences as part of its goal to better understand the sources and ramifications of freshwater salinization observed in the Watershed.

[57] Massachusetts Surface Water Quality Standards, 2013b

3.2.3 Specific Conductance and Chloride

In 2023, tributary specific conductance ranged from to 35.2 µS/cm at Jordan Farm Brook to 2,100 µS/cm at Gates Brook 4. Values of less than 100 µS/cm were recorded in 86% of all samples from Trout Brook (31 of 36), 25% of samples at East Wachusett Brook (6 of 24), 14% of samples at the Stillwater River (5 of 36), and a single result at Jordan Farm Brook. This represents just 8% of all specific conductance samples from Wachusett tributaries during 2023. Measurements greater than 904 µS/cm, the proxy chronic Cl toxicity threshold[58], were recorded in 9.8% of all samples from 2023. For individual tributaries, this threshold was exceeded in 75% of samples from Gates Brook 4 (MD73), 47% of samples from Gates Brook 1 (MD04), 34% of samples from West Boylston Brook, and 29% of samples from Oakdale Brook. Extremely high specific conductance (>1,800 µS/cm) was observed only once at Gates Brook 4 on March 6 (2,100 µS/cm).

Except for Jordan Farm Brook, all monitoring locations experienced a decrease in specific conductance from 2022, with levels closer to 2021, which had similar surplus precipitation. High frequency specific conductance data (where available) was also used to calculate annual means, and the results were very similar to the grab data, which consisted of only 24-36 measurements, depending on the location. This is discussed in further detail below, in Section 3.2.3.1.

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

The last column (2023) represents annual mean specific conductance values calculated from high frequency sensors at USGS and Mayfly water quality stations.*

Location	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2023*
Asnebumskit Brook - M102	215	254	336	279	249	267	243	195	254	205	—
Boylston Brook - MD70	373	579	542	594	686	661	679	546	611	530	—
Cook Brook -Wyoming - MD11	493	475	526	640	624	524	489	478	609	543	—
East Wachusett Brook - MD89	133	166	174	171	151	169	180	140	164	124	—
French Brook - MD01	227	321	447	364	290	318	347	250	298	252	250
Gates Brook 1 - MD04	759	942	1,081	1,272	1,211	1,154	1,075	940	1,027	883	986
Gates Brook 4 - MD73	1,018	1,276	1,371	1,696	1,558	1,451	1,253	1,149	1,437	1,131	—
Jordan Farm Brook - MD12	128	124	181	175	183	193	169	178	187	196	—
Malagasco Brook - MD02	313	447	473	450	432	525	558	345	444	331	329
Malden Brook - MD06	220	288	334	364	365	371	382	311	340	308	309
Muddy Brook - MD03	203	273	320	344	333	340	351	296	350	303	307
Oakdale Brook - MD80	686	872	982	1,136	1,166	989	878	954	870	827	—
Quinapoxet River - MD69	195	255	304	296	250	261	268	211	291	228	227
Scarlett Brook (DS W.M.) - MD81	514	635	620	771	747	897	632	487	692	550	—
Stillwater River - MD07	142	182	213	170	162	174	200	152	197	133	128
Trout Brook - M110	74	74	86	96	92	87	86	82	99	80	—**
Waushacum Brook - MD83	284	339	396	420	395	408	421	334	375	332	327
West Boylston Brook - MD05	739	1,137	1,227	1,700	1,274	1,266	1,221	901	1,131	796	799

Note: Table cells are shaded to aid in visually comparing 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.

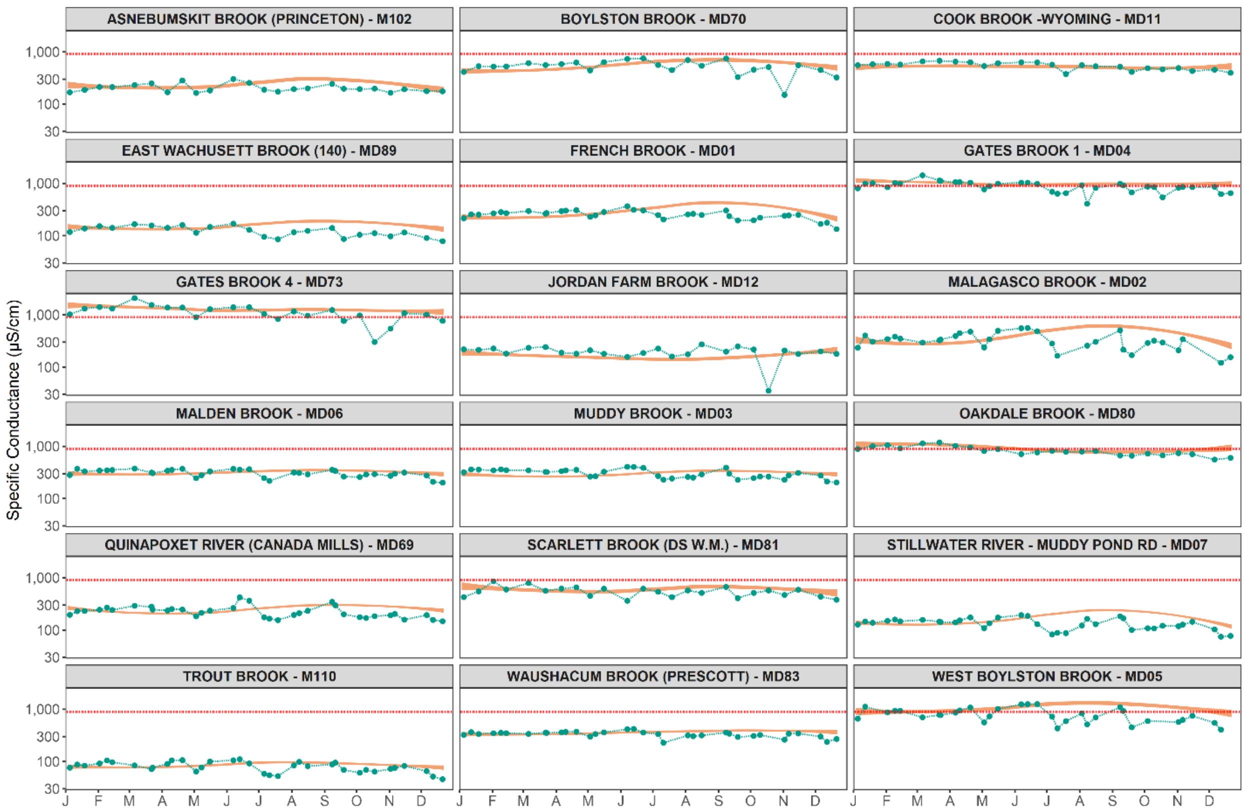
**The Trout Brook Mayfly station was installed in October 2023 and data did not cover enough of the year to make this calculation.

[58] MassDEP, 2018

Most tributary locations had annual mean specific conductance towards the low end of the ranges observed during the nine years prior. Seasonal patterns of specific conductance in 2023 deviated from historical patterns due to the surplus precipitation during most of the year. Gates Brook was the only tributary with specific conductance above the chronic chloride toxicity threshold (904 µS/cm), which indicates possible negative impacts to aquatic life.

Figure 25: Specific Conductance Measurements at Wachusett Tributaries

The green points show specific conductance results for 2023, with the orange band representing a LOESS smooth function 95% confidence interval for the period 2014-2022. 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[59].

3.2.3.1 Specific Conductance at USGS and Mayfly Monitoring Stations

High frequency specific conductance data available from the three USGS monitoring stations and the seven Mayfly monitoring stations (DWSP) capture more of the variability of specific conductance throughout the year, which is not reflected in the grab measurements collected two or three times per

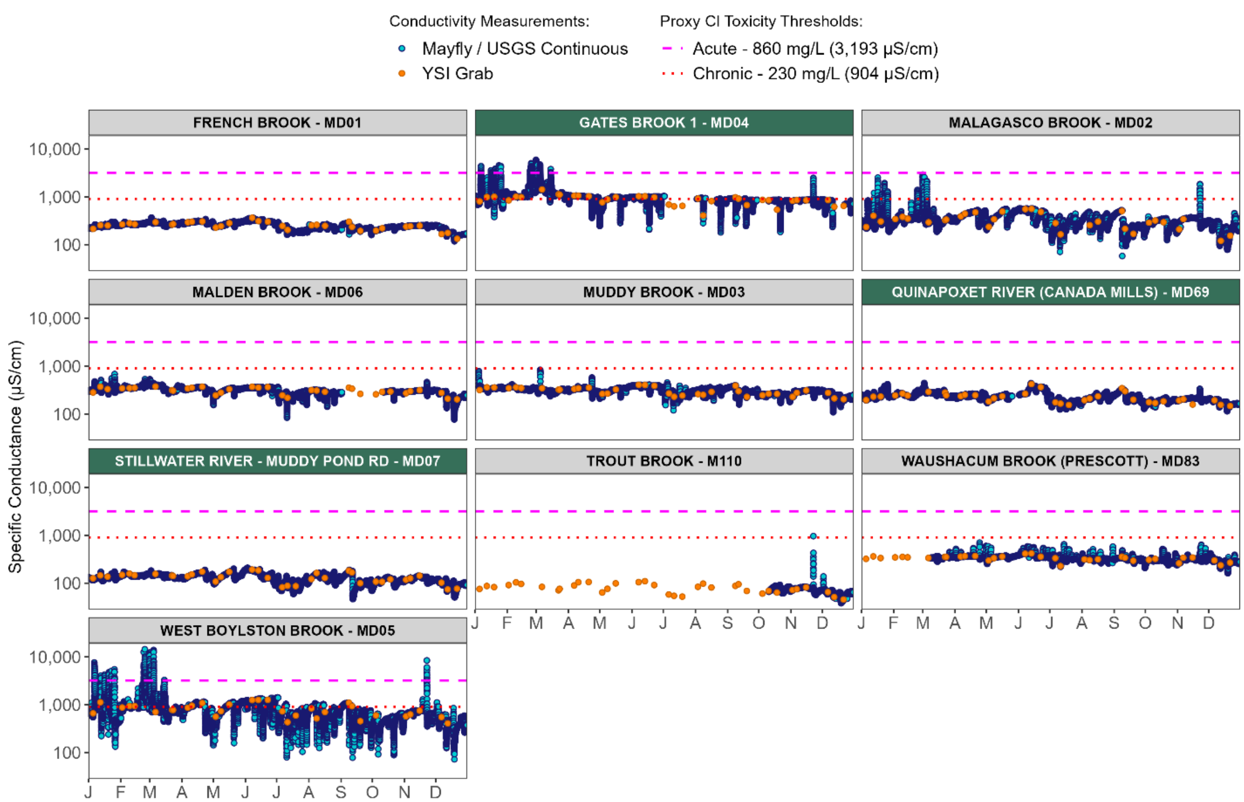
[59] Soper, 2021

month. In subbasins that are more impacted by historical and current road salt applications (West Boylston, Gates, Malagasco Brooks), the groundwater specific conductance levels are elevated and there is a distinctive pattern visible in the high frequency data. During the cold months, runoff (rain or snowmelt) is often laden with dissolved road salt which causes rapid spikes in specific conductance. In-stream specific conductance returns to baseline levels when overland runoff stops and baseflow becomes dominant again. In the warm months, after the salting season is over, overland runoff is not carrying dissolved salts and the specific conductivity is extremely low in comparison to the baseflow. These periods are visible in the high frequency data as rapid declines in specific conductance caused by dilution, with levels returning to baseline conditions as runoff stops. This pattern is less prominent in subbasins that are less impacted by salt applications (French, Trout, Waushacum Brooks).

Annual mean specific conductance values calculated from high frequency data was remarkably similar to the mean values calculated from the grab data, except for Gates Brook 1 (Table 13). However, the grab samples did not capture the extremes in specific conductivity on the tributaries most impacted by decades of high application rates of road salt. West Boylston Brook provides the starkest example of why high frequency data is necessary to fully understand the short-term dynamics of dissolved salts. While the annual mean specific conductance in West Boylston Brook was around 800 µS/cm, runoff events in the summer were as low as 71.8 µS/cm, whereas winter runoff events reached over 14,000 µS/cm. These pulses of water with extremely high concentrations of dissolved salts often result in chloride levels that exceed the 860 mg/L acute toxicity threshold for aquatic life (using the proxy specific conductance threshold of 3,193 µS/cm)

Figure 26: Mayfly and USGS Station Conductivity Measurements with YSI Grabs in 2023

The panel labels with a green background are the USGS Monitoring Stations. The Trout Brook Mayfly station was not installed until October 2023. All other gaps in continuous data indicate missing data.



3.2.3.2 Chloride

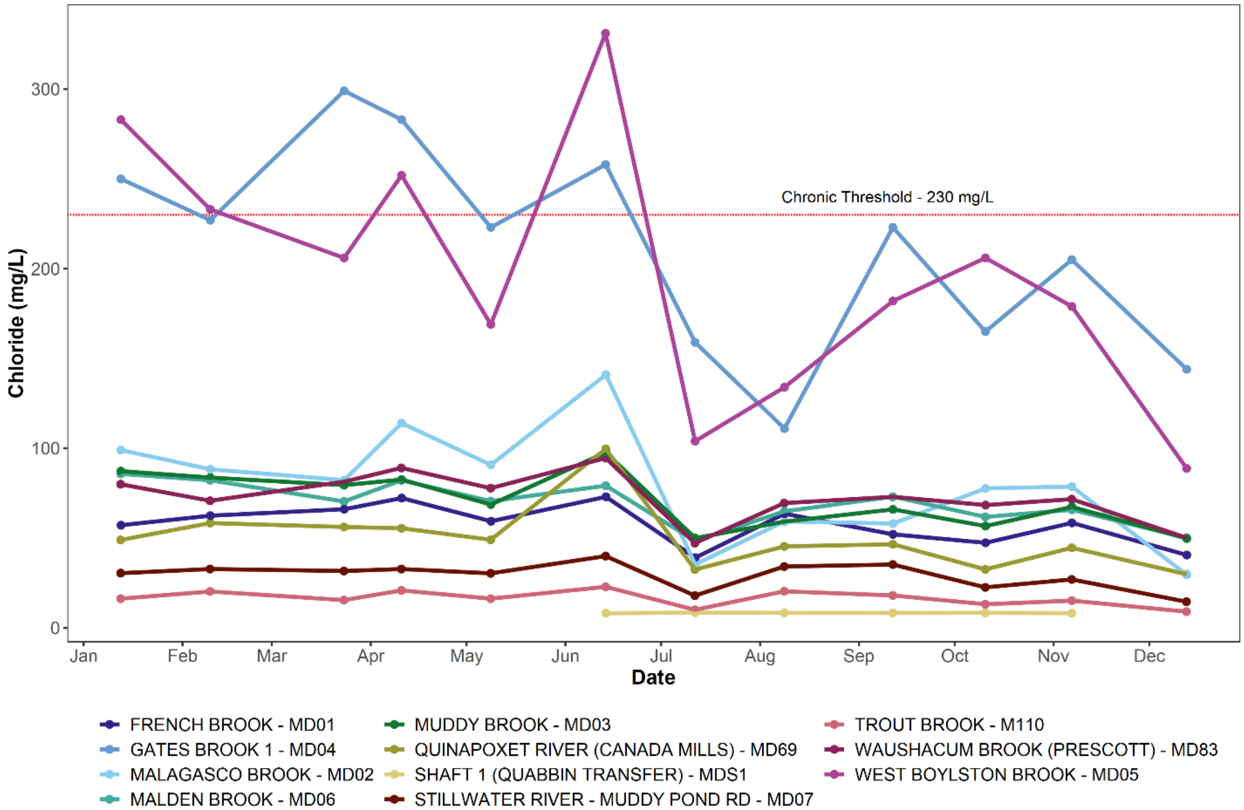
Chloride (Cl) concentrations in 2023 were generally lower than 2022 concentrations across all Wachusett tributary monitoring locations (Table 14). Annual mean chloride was lower in 2023 compared to 2022 and the five-year average. For 2023, Gates Brook 1 had the highest mean annual Cl concentration (212 mg/L) while West Boylston Brook had the second highest mean annual Cl concentration (197 mg/L). Trout Brook and the Stillwater River continued to have the lowest mean annual Cl concentrations at 20 and 37 mg/L, respectively. These statistics, although comprised of only 12 samples per monitoring location each year, do follow similar patterns reflected by the high frequency specific conductivity statistics, but only when aggregated by longer durations of time. As illustrated by Figure 26, the full range of concentrations is not reflected in the monthly grab data. Therefore, the actual short-term variability in chloride must be inferred through the high frequency specific conductance measurements.

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 for aquatic life (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 secondary maximum contaminant level (SMCL) for Cl (250 mg/L), which only applies to finished drinking water for public systems, would also be exceeded part of the year at West Boylston Brook and nearly Gates Brook if these tributaries were sole drinking water sources, and the five-year mean Cl concentration of these tributaries is above the SMCL concentration. Fortunately, these two tributaries are not directly used for drinking water and contribute less than 2% of the total inflow to Wachusett Reservoir; the overall Wachusett Reservoir Cl concentration is well below this threshold. Still, Cl concentrations at Gates Brook 1 and West Boylston Brook are detrimental to aquatic life and contribute to the overall load of dissolved salts to the Wachusett Reservoir, which has undesirable consequences for drinking water treatment processes.

Table 14: Chloride Concentration (mg/L) Summary for Wachusett Tributaries in 2023

Sample Location	Count	Minimum (mg/L)	Median mg/L)	Maximum (mg/L)	Mean (mg/L)	2019 - 2023 Mean (mg/L)
French Brook - MD01	12	39	59	73	58	68
Gates Brook 1 - MD04	12	111	223	299	212	265
Malagasco Brook - MD02	12	30	80	141	80	114
Malden Brook - MD06	12	48	70	86	70	80
Muddy Brook - MD03	12	50	68	98	71	78
Quinapoxet River (Canada Mills) - MD69	12	30	48	100	50	56
Shaft 1 (Quabbin Transfer) - MDS1	6	8	8	9	8	8
Stillwater River - Muddy Pond Rd - MD07	12	15	31	40	29	37
Trout Brook - M110	12	9	16	23	17	19
Waushacum Brook (Prescott) - MD83	12	47	72	95	73	84
West Boylston Brook - MD05	12	89	194	331	197	293

Figure 27: Chloride Concentrations in the Wachusett Tributaries During 2023



A discussion of other work completed in 2023 related to Cl and conductivity is provided in Section 3.2.9.2. Chloride monitoring in groundwater is discussed in Section 3.3.

3.2.3.3 Salt Loading

The current Watershed Protection Plan (FY24 – 28) includes a multi-prong approach to reduce road salt applications in the watershed, which should ultimately lead to less salt loading to the tributaries and reservoir. In addition to tracking salt applications by municipalities, MassDOT, and others, DWSP has expanded its chloride/specific conductance monitoring with the installation of Mayfly monitoring stations that measure water temperature, water depth, and specific conductance at 15-minute intervals. Combined with the three USGS stations, DWSP now collects high frequency specific conductance measurements from all 10 primary tributaries, representing about 90-95% of surface water inflows to the Wachusett Reservoir (not including the Quabbin Transfer).

From year to year, watershed salt application amounts (inputs) will vary with winter weather severity, and salt loads in the tributaries (output) will vary with the timing and magnitude of precipitation, runoff, changes to aquifer storage, and baseflow contributions to streams. Over the long-term, DWSP's goal is to track the success of salt reduction programs by documenting decreasing salt application rates (inputs), followed by decreasing salt loading rates (outputs). As this program is newly developed, the period of record of information and data is insufficient to analyze any input/output trends. Until sufficient data are available for trend analysis, annual reports will focus on documenting the year-to-year variability.

For each tributary, a linear regression was fit to the relationship between specific conductance and chloride grab samples. The regression equations and high frequency specific conductance measurements were then used to derive time-series chloride concentrations at each tributary in 15-minute intervals. Chloride concentrations and associated flow rates, in cubic feet per second, were used to calculate a daily chloride load for each tributary. This daily load of chloride was then used to estimate a daily salt load, assuming that nearly all the chloride present in tributaries comes from dissolved road salt (NaCl). Annual salt loads, shown in Table 15 below, were computed by summing the daily loads for each year.

Table 15: Salt Load Estimates (tons) for Wachusett Tributaries, 2022-2023

Location	2022	2023	Percent Change
West Boylston Brook - MD05	236	192	-18%
Muddy Brook - MD03	145	239	65%
Malagasco Brook - MD02	164	327	99%
Trout Brook - M110	282	482	71%
French Brook - MD01	340	577	70%
Malden Brook - MD06	373	599	61%
Waushacum Brook (Prescott) - MD83	948	1,629	72%
Gates Brook 1 - MD04	1,339	1,734	29%
Stillwater River - Muddy Pond Rd - MD07	2,224	3,558	60%
Quinapoxet River (Canada Mills) - MD69	4,823	7,139	48%
WACHUSETT TRIBUTARY TOTAL	**10,874**	**16,476**	**52%**

Compared with 2022, there was a 52% increase in salt loads in the tributaries for 2023, with individual tributaries showing load changes between -18% and 99%. This is despite the fact that the mean 2023 Chloride concentration was lower than the mean 2022 Chloride at all tributaries (Table 14). This increase in salt loads can likely be attributed mostly to the additional 25 BG of water flowing in the tributaries during 2023, which represents an 85% increase in tributary discharge.

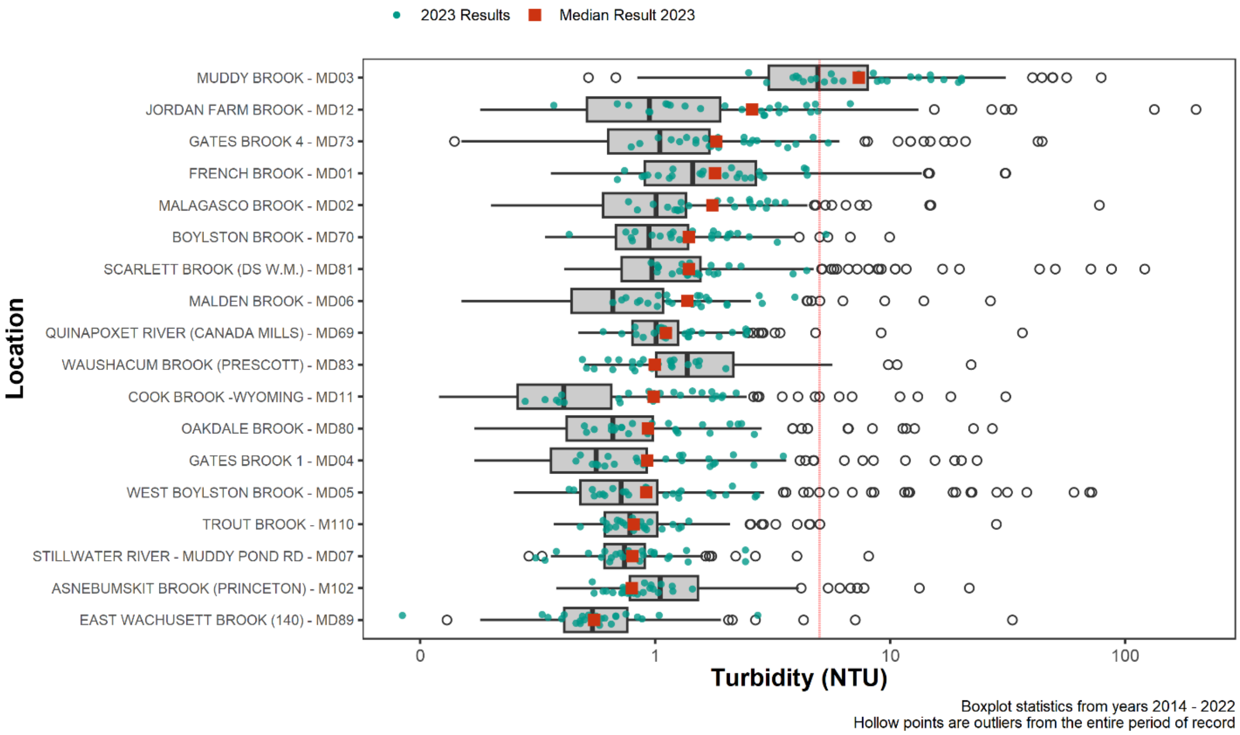
3.2.4 Turbidity

Turbidity results in Wachusett tributaries in 2023 ranged from 0.08 NTU at East Wachusett Brook to 20.1 NTU at Muddy Brook. There were 19 samples with turbidity levels of 5.0 NTU or higher, which were predominantly collected from Muddy Brook (16 samples), where elevated concentrations of fine particulate matter are historically persistent and naturally occurring. Wet weather sampling on April 20 and September 19 accounted for 5 of the 20 turbidity results above 5.0 NTU, with the remaining high turbidity results spread throughout the year.

Except for Asnebumskit and Waushacum Brooks, 2023 annual median turbidity was higher than the 2014 – 2022 median at all sampling locations, and at six monitoring locations, above the 75th percentile. Annual median turbidity values ranged from 0.55 NTU at East Wachusett Brook to 6.82 NTU in Muddy Brook (Table 16). Turbidity levels were 0.40 NTU higher (on average) during or after wet weather conditions (> 0.2 inches of rainfall within 24 hours of sample) (Table 17).

Figure 28: 2023 Turbidity Levels with 2014 – 2022 Statistics

The red vertical line is at 5.0 NTU, the SWTR raw water regulated limit at drinking water intakes.



Annual mean turbidity in 2023 ranged from 0.65 NTU at the East Wachusett Brook to 8.72 NTU at Muddy Brook (Table 16), with mean values lower than in 2022 at every monitoring location. Apart from Waushacum Brook, which experienced its lowest annual mean turbidity in the last ten years (1.02 NTU), all annual mean values were within historically observed ranges.

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 (green circle points)
8) Annual median result (red square point)

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

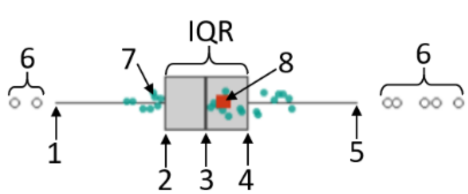


Table 16: Annual Mean Turbidity at Wachusett Tributaries (NTU)

Sample Location	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Asnebumskit Brook (Princeton) - M102	—	1.47	1.14	1.63	1.07	1.12	1.16	1.49	2.92	0.85
Boylston Brook - MD70	0.90	0.98	0.92	1.06	1.13	1.44	1.09	1.92	2.24	1.66
Cook Brook -Wyoming - MD11	1.23	0.63	0.28	1.75	0.55	0.42	0.91	1.38	1.82	1.09
East Wachusett Brook (140) - MD89	0.56	0.60	0.47	0.86	0.65	0.57	0.54	0.92	2.14	0.65
French Brook - MD01	1.61	2.16	1.93	1.56	1.73	2.55	6.86	2.08	3.73	2.03
Gates Brook 1 - MD04	0.70	0.53	0.57	1.16	1.23	0.85	1.00	2.38	2.61	1.22
Gates Brook 4 - MD73	1.43	0.91	0.89	2.73	1.88	1.68	1.63	2.90	4.65	2.24
Jordan Farm Brook - MD12	1.21	1.61	0.51	1.68	2.22	2.44	1.65	8.43	15.16	2.58
Malagasco Brook - MD02	1.10	0.90	0.82	1.13	1.27	1.21	1.08	2.32	5.71	1.92
Malden Brook - MD06	0.79	0.84	0.52	0.75	0.95	0.96	0.96	1.48	2.73	1.48
Muddy Brook - MD03	5.87	5.46	5.48	9.12	6.86	6.83	5.36	7.92	11.53	8.72
Oakdale Brook - MD80	1.15	0.63	0.43	2.12	1.18	0.79	1.28	1.31	2.68	1.15
Quinapoxet River (Canada Mills) - MD69	0.97	1.09	1.00	1.01	1.11	1.17	1.14	1.48	3.12	1.29
Scarlett Brook (DS W.M) - MD81	5.47	1.05	1.38	3.65	1.91	2.24	1.17	1.71	5.12	1.66
Stillwater River - Muddy Pond Rd - MD07	0.74	0.76	0.75	0.70	0.80	0.83	0.86	0.97	1.36	0.86
Trout Brook - M110	0.97	1.22	0.60	0.76	0.81	0.90	0.97	1.15	2.27	0.85
Waushacum Brook (Prescott) - MD83	1.64	1.29	2.04	1.74	1.67	1.63	2.09	1.21	3.11	1.02
West Boylston Brook - MD05	3.21	0.86	1.09	3.59	2.22	1.27	1.29	1.98	4.35	1.15

Table 17: Turbidity Statistics in Wachusett Tributaries for 2023 (NTU)

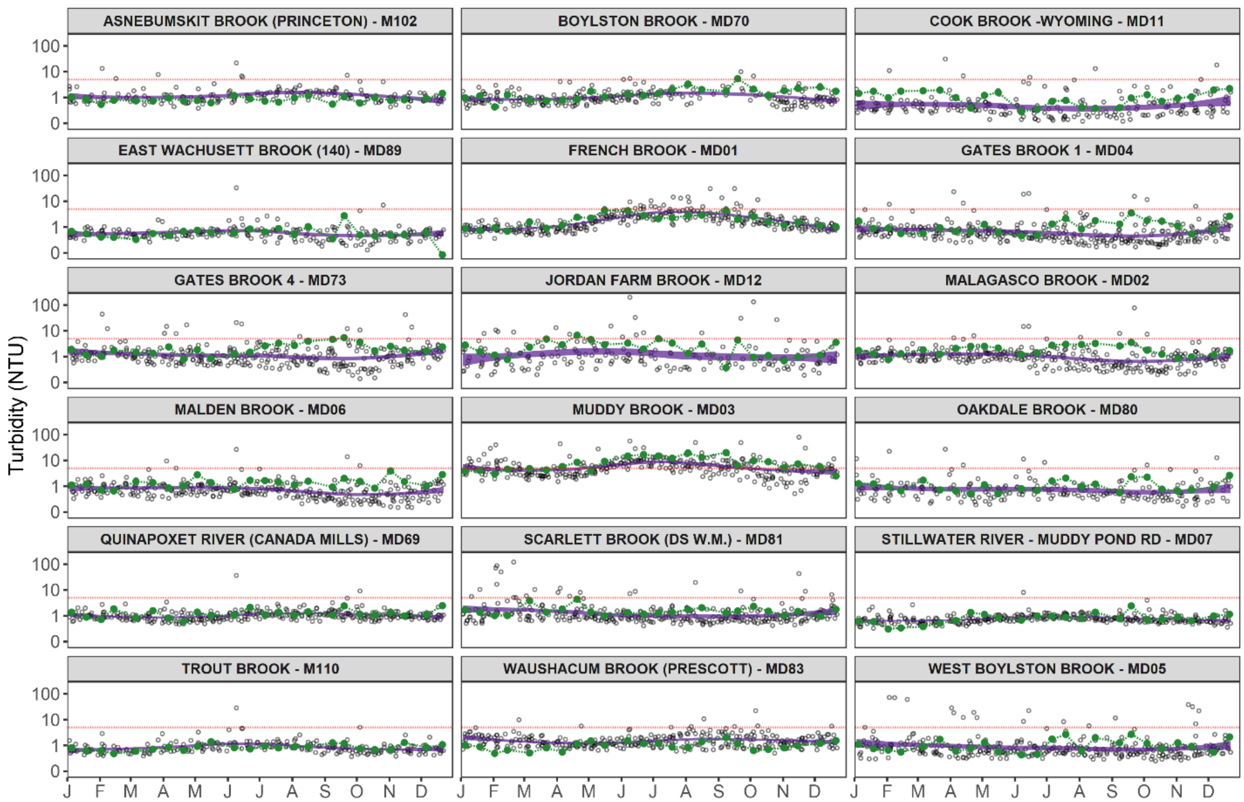
Wet weather samples were collected soon after or during precipitation events of 0.2 inches or more.

Sample Location	Minimum	Maximum	Annual Median	Dry Median	Wet Median
Asnebumskit Brook (Princeton) - M102	0.54	1.44	0.80	0.78	0.84
Boylston Brook - MD70	0.43	5.33	1.39	1.27	1.77
Cook Brook -Wyoming - MD11	0.28	2.21	0.98	0.99	0.95
East Wachusett Brook (140) - MD89	0.08	2.73	0.55	0.50	0.75
French Brook - MD01	0.69	4.44	1.79	1.58	2.23
Gates Brook 1 - MD04	0.46	3.51	0.92	0.83	1.71
Gates Brook 4 - MD73	0.79	5.45	1.82	1.70	3.33
Jordan Farm Brook - MD12	0.37	6.76	2.58	1.98	3.07
Malagasco Brook - MD02	0.77	3.57	1.75	1.39	2.60
Malden Brook - MD06	0.66	3.93	1.37	1.37	1.44
Muddy Brook - MD03	2.50	20.1	6.82	7.35	6.29
Oakdale Brook - MD80	0.50	2.64	0.93	0.77	1.23
Quinapoxet River (Canada Mills) - MD69	0.60	2.47	1.10	1.09	1.39
Scarlett Brook (DS W. M.) - MD81	0.96	4.41	1.39	1.38	1.40
Stillwater River - Muddy Pond Rd - MD07	0.31	2.42	0.78	0.73	0.88
Trout Brook - M110	0.48	1.39	0.81	0.75	0.90
Waushacum Brook (Prescott) - MD83	0.49	2.00	1.00	0.82	1.18
West Boylston Brook - MD05	0.43	2.70	0.92	0.73	1.29
All Wachusett Tributaries	**0.63**	**4.31**	**1.54**	**1.45**	**1.85**

Figure 29 shows the variability in turbidity by location for 2023 compared to the prior nine years. Despite the record rainfall in 2023, there were very few observations of turbidity above 5 NTU. At most sampling locations, turbidity values were normal and close to historical seasonal levels. The excess rainfall during the summer and early fall months did seem to impact some tributaries more than others. Gates Brook 1, Gates Brook 4, Malden Brook, Muddy Brook, Malagasco Brook, and West Boylston Brook turbidity levels were noticeably higher than the typical levels during that time period. Jordan Farm Brook experienced higher than normal turbidity levels during the spring months, however elevated turbidity on this tributary is usually the result of agricultural operations within the drainage area.

Figure 29: Turbidity Results at Wachusett Tributaries

The green points show turbidity results for 2023, while the hollow points show results from years 2014 – 2022, 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 2023 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 for 2023 was 1.80 NTU and the median was 1.54 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 81.0 mg/L at Gates Brook 1. Only 17 of 126 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 2023 were mostly consistent with the previous nine years, with no unidirectional patterns over time (Table 18). Gates Brook 1 and Malagasco Brook annual means were both highly influenced by a single sample collected during wet weather on August 8, where TSS levels were observed at 81.0 and 71.5 mg/L, respectively. For locations where there were three or fewer detected results each year, the results below detection were multiplied by 0.5 prior to the calculation of summary statistics. Since most samples (90%) were below detection limits, the values presented below have a high degree of uncertainty relative to their magnitude.

Table 18: Total Suspended Solids Annual Mean Concentrations in Wachusett Tributaries (mg/L)

Sample Location	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
French Brook - MD01	4.66	3.02	3.84	3.00	3.92	7.03	12.43	4.87	4.40	3.92
Gates Brook 1 - MD04	4.20	2.48	3.25	2.21	2.56	3.08	3.33	2.50	2.50	9.25
Malagasco Brook - MD02	2.83	2.80	3.10	3.58	2.93	4.25	3.48	3.13	2.50	9.29
Malden Brook - MD06	3.60	4.27	3.13	2.50	2.77	2.82	2.83	2.50	3.88	3.46
Muddy Brook - MD03	2.82	2.50	6.74	11.99	6.12	4.23	7.16	3.29	3.00	4.98
Quinapoxet River (Canada Mills) - MD69	2.33	2.49	3.13	2.50	2.75	2.50	2.50	2.50	2.92	2.83
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	1.75	2.82	2.45	2.50	2.50	2.50	2.50
Stillwater River - Muddy Pond Rd - MD07	2.33	2.50	3.88	2.43	2.49	2.50	2.71	2.50	2.50	2.50
Trout Brook - M110	—	2.91	2.94	2.50	2.92	2.75	2.50	2.50	2.50	2.50
Waushacum Brook (Prescott) - MD83	2.44	2.50	2.89	2.43	5.06	3.00	2.79	3.00	3.17	2.78
West Boylston Brook - MD05	9.98	2.49	2.77	4.33	4.88	2.96	15.96	4.88	2.50	3.63

Dash (—) = No data

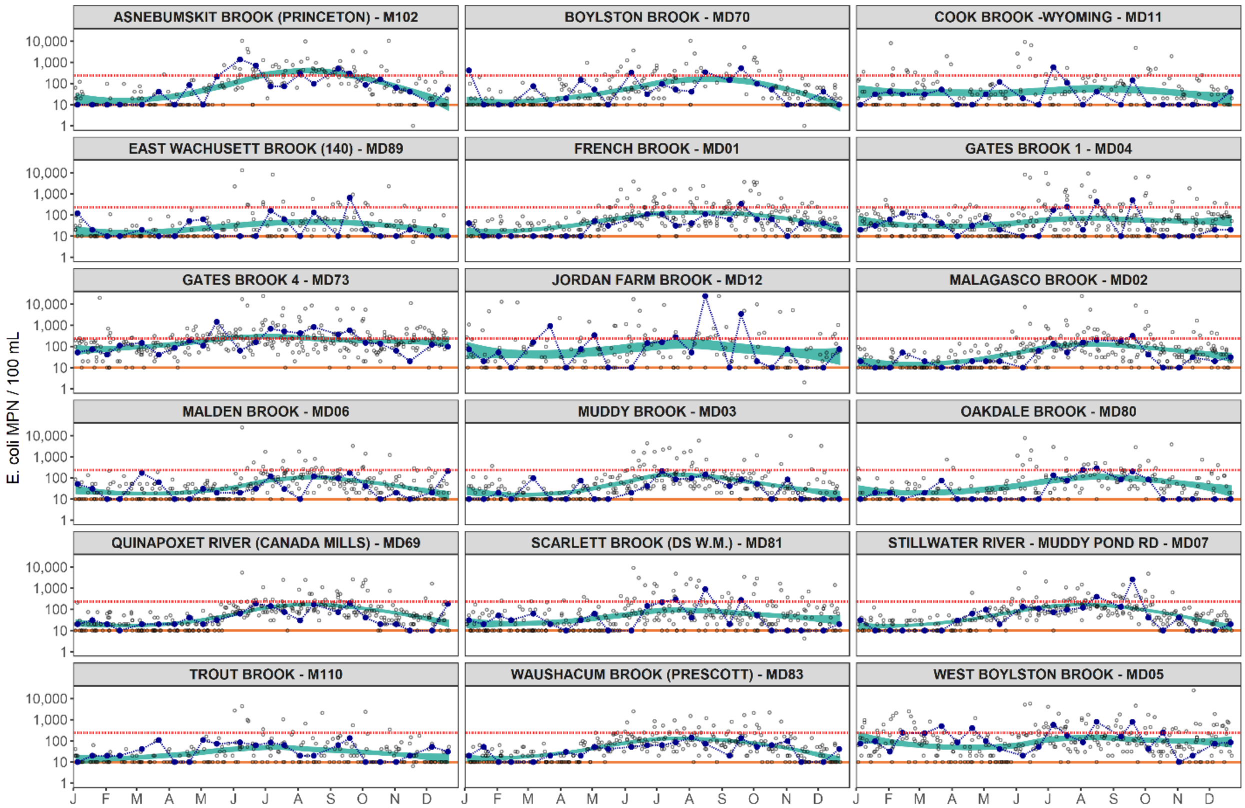
3.2.6 *E. coli* Bacteria in Tributaries

Bacteria samples collected from the tributary stations during 2023 contained a wide range of *E. coli* concentrations, from less than the lower detection limit (10 MPN/100 mL) in approximately 30% of all samples, to a high of > 24,200 MPN/100 mL at Jordan Farm Brook immediately after a storm on August 16. As in previous years, the highest concentrations were mostly recorded during or following precipitation. Three of the five samples that exceeded 1,000 MPN/100 mL were collected within 24 hours of a 1-inch precipitation event. The only dry weather samples that exceeded 1,000 MPN/100 mL were collected from Gates Brook 4 on May 16 and Asnebumskit Brook on June 7.

In 2023, most Wachusett Watershed tributaries exceeded the MA Class A surface water quality standard single sample *E. coli* limit of 235 MPN/100 mL on at least one monitoring occasion (Figure 30 and Table 19). The Quinapoxet River and Trout, Muddy, Malden, and Waushacum Brooks were the only tributaries where bacteria levels were not observed above 235 MPN/100 mL. Most tributaries exhibit a seasonal increase in bacteria levels during the summer months when there are more favorable physical, chemical, and biological conditions for bacterial growth and survival, of which temperature is a dominant driver. This pattern persisted at most monitoring locations in 2023.

Figure 30: *E. coli* Concentrations in Wachusett Tributaries

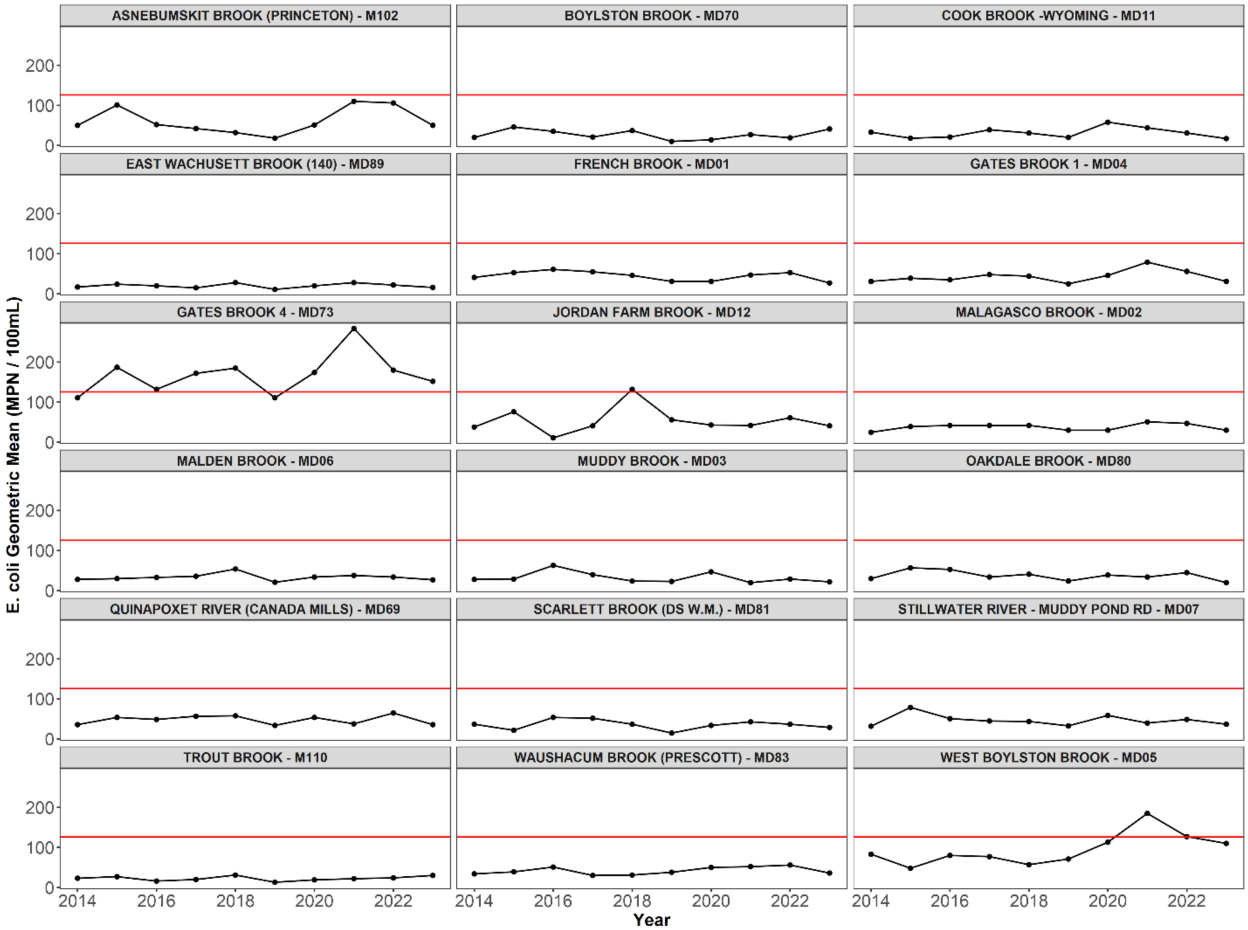
The blue points show E. coli *results for 2023, while the hollow points show results from years 2014 – 2022, with the green band representing a LOESS smooth function 95% confidence interval for the same period. The red dashed line is the MassDEP Class A surface water quality standard single sample limit: 235 MPN/100 mL and the orange dashed horizontal line represents the detection limit of 10 MPN/100 mL.*



Aside from Gates Brook and West Boylston Brook, annual geometric mean concentrations of *E. coli* over the past 10 years do not show any significant (visually) increasing trend (Figure 31), and 2023 annual geometric means were lower than the prior 10-year geometric mean at all locations except for Trout, Boylston, and West Boylston Brooks. Compared with 2022, annual geometric means were lower in 2023 at all monitoring locations except for Trout and Boylston Brooks.

Figure 31: Annual Geometric Mean *E. coli* for Wachusett Reservoir Tributaries (MPN/100 mL)

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 geometric mean standard for *E. coli of* 126 MPN/100 mL in 2022 (Table 19). East Wachusett Brook had the lowest 2022 geometric mean (16 MPN/100 mL). Gates Brook 4 continues to have the highest geometric mean (158 MPN/100 mL). Bacterial source investigations were completed in 2018 and again in 2023. In 2018, the source of elevated bacteria concentrations was geographically linked to a large population of roosting birds. In 2023, the investigation led to a bacterial source geographically linked with wildlife activity (raccoon/rats) in the stream corridor. The investigation in 2023 concluded that the animals were likely using dumpsters from food service businesses as a food source. Efforts were made to inform the business owners of the issue and remind them of proper management of food waste, which may persuade wildlife to relocate due to lower food availability. The Gates Brook 4 bacteria results will be reviewed frequently to determine if the problem persists and warrants additional mitigation actions.

Table 19: Annual *E. coli* Geometric Mean in Wachusett Tributaries (MPN/100 mL)
GMEAN = Geometric Mean.

Sample Location	GMEAN 2020	GMEAN 2021	GMEAN 2022	GMEAN 2023	%>235 2020	%>235 2021	%>235 2022	%>235 2023
Asnebumskit Brook (Princeton) - M102	51	110	106	50	30	29	39	21
Boylston Brook - MD70	14	27	19	41	8	12	20	17
Cook Brook -Wyoming - MD11	58	44	31	17	16	29	17	4
East Wachusett Brook (140) - MD89	20	28	22	16	5	17	17	4
French Brook - MD01	31	47	53	27	5	12	26	4
Gates Brook 1 - MD04	46	79	56	31	5	21	12	12
Gates Brook 4 - MD73	174	284	180	152	30	50	29	29
Jordan Farm Brook - MD12	43	42	61	41	18	21	32	21
Malagasco Brook - MD02	30	51	47	30	5	12	17	4
Malden Brook - MD06	34	38	34	27	5	12	12	0
Muddy Brook - MD03	47	20	29	22	20	8	12	0
Oakdale Brook - MD80	39	34	45	20	5	8	17	8
Quinapoxet River (Canada Mills) - MD69	54	38	65	36	10	12	17	0
Scarlett Brook (DS W. M) - MD81	34	43	37	29	10	25	8	12
Stillwater River - Muddy Pond Rd - MD07	59	40	49	37	10	8	12	8
Trout Brook - M110	19	22	24	30	5	8	8	0
Waushacum Brook (Prescott) - MD83	50	52	56	36	10	12	17	0
West Boylston Brook - MD05	113	185	127	110	25	29	25	29

2023 geometric means were lower than both the five-year average and ten-year average geometric means for 15 of 18 monitoring locations (Table 20). Boylston Brook was the only tributary with a geometric mean substantially higher than normal, whereas other tributaries had 2023 geometric means closer to their historical averages.

Table 20: Trends in Geometric Mean *E. coli* Concentrations (MPN/100 mL)

Sample Location	2023 GEOMETRIC MEAN	5 YEAR GEOMETRIC MEAN	10 YEAR GEOMETRIC MEAN
Asnebumskit Brook (Princeton) - M102	50	67	61
Boylston Brook - MD70	41	22	27
Cook Brook -Wyoming - MD11	17	34	31
East Wachusett Brook (140) - MD89	16	19	20
French Brook - MD01	27	38	44
Gates Brook 1 - MD04	31	47	43
Gates Brook 4 - MD73	152	180	169
Jordan Farm Brook - MD12	41	49	54
Malagasco Brook - MD02	30	38	38
Malden Brook - MD06	27	31	34
Muddy Brook - MD03	22	28	32
Oakdale Brook - MD80	20	32	38
Quinapoxet River (Canada Mills) - MD69	36	45	48
Scarlett Brook (DS W. M) - MD81	29	32	36
Stillwater River - Muddy Pond Rd - MD07	37	44	47
Trout Brook - M110	30	22	22
Waushacum Brook (Prescott) - MD83	36	46	42
West Boylston Brook - MD05	110	121	95

In 2023, wet weather samples continued to have higher bacteria concentrations than dry weather samples (Table 21). For all sampling locations, except for West Boylston Brook, exceedances of the MassDEP Class A water quality single sample regulatory limit (235 MPN/100 mL) were more likely to occur during wet conditions, and 11 locations did not have a single dry weather exceedance of this standard.

Table 21: Wet and Dry Weather *E. coli* Metrics in Wachusett Watershed Tributaries During 2023 (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	48	52	23.5	0	17.6	28.6	17	7
Boylston Brook - MD70	27	117	17.6	0	5.9	42.9	17	7
Cook Brook -Wyoming - MD11	12	32	47.1	14.3	5.9	0	17	7
East Wachusett Brook (140) - MD89	10	63	41.2	14.3	0	14.3	17	7
French Brook - MD01	20	55	35.3	0	0	14.3	17	7
Gates Brook 1 - MD04	21	82	23.5	0	0	42.9	17	7
Gates Brook 4 - MD73	127	235	0	0	17.6	57.1	17	7
Jordan Farm Brook - MD12	30	106	23.5	14.3	5.9	57.1	17	7
Malagasco Brook - MD02	23	59	11.8	0	0	14.3	17	7
Malden Brook - MD06	18	61	35.3	0	0	0	17	7
Muddy Brook - MD03	16	33	41.2	0	0	0	17	7
Oakdale Brook - MD80	15	44	29.4	14.3	5.9	14.3	17	7
Quinapoxet River (Canada Mills) - MD69	30	59	11.8	0	0	0	17	7
Scarlett Brook (DS W. M) - MD81	19	92	35.3	0	0	42.9	17	7
Stillwater River - Muddy Pond Rd - MD07	24	122	17.6	0	0	28.6	17	7
Trout Brook - M110	25	42	17.6	0	0	0	17	7
Waushacum Brook (Prescott) - MD83	31	51	0	0	0	0	17	7
West Boylston Brook - MD05	86	200	0	0	29.4	28.6	17	7

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 (126 MPN/100 mL) has been met by most Wachusett tributaries in the last five years, and the tributaries which occasionally surpass this 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). DWSP may pursue microbial source identification using genetic methodologies if high bacteria levels persist. Despite the several wet-weather related spikes, *E coli* concentrations for 2023 continued to indicate good sanitary quality at most Wachusett Reservoir tributaries.

3.2.7 Nutrient Dynamics

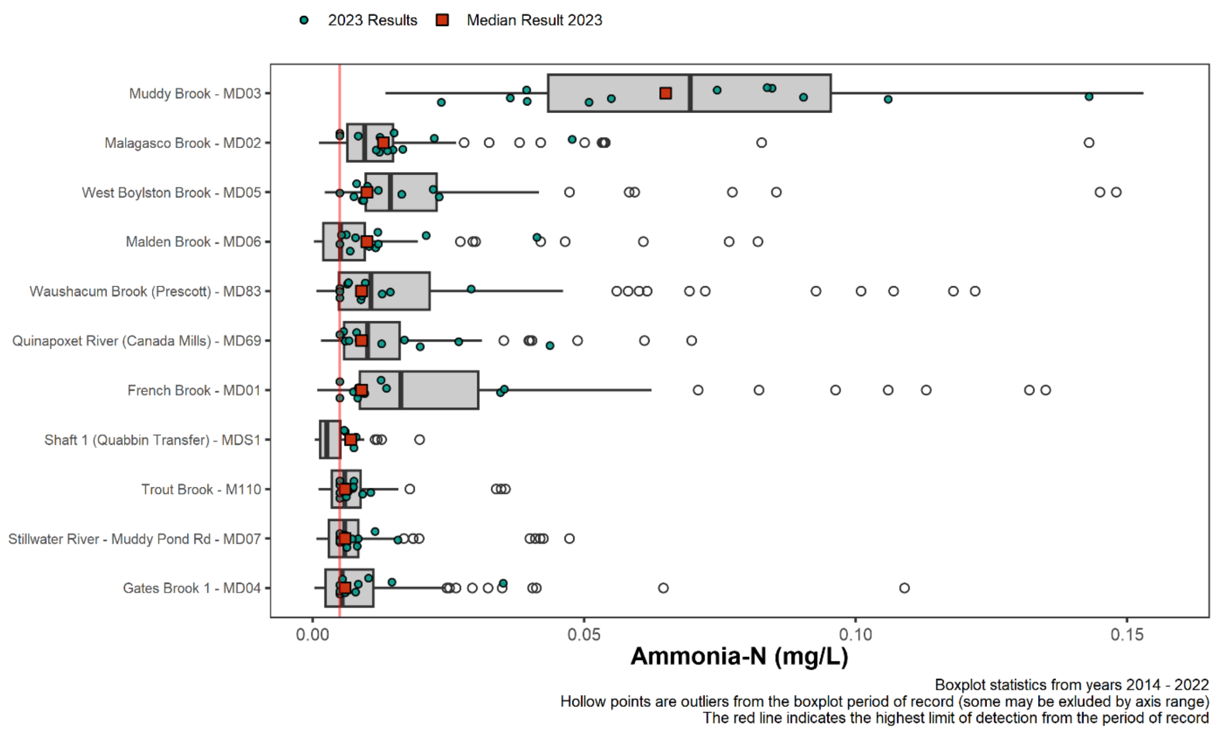
Results for monthly tributary nutrient monitoring in Wachusett tributaries are presented below. Sampling results for Quabbin transfer water are not discussed but are included in the tables and figures because transfer water is a large percentage of the annual inflow to Wachusett Reservoir and has a significant 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 2023, Ammonia-nitrogen (NH3-N) concentrations were below the limit of detection in 17.6% of samples, while the detected results were mostly within historical 25 – 75th percentile concentrations. Muddy Brook continues to have the highest median annual concentration of NH3-N (Figure 32). The Muddy Brook sample location is immediately downgradient to a closed landfill in West Boylston, which is a potential source of elevated NH3-N, although this has yet to be investigated.

Figure 32: 2023 Ammonia-Nitrogen Concentrations with 2014 - 2022 Statistics



Due to the high number of non-detection lab results (<0.005 mg/L) the values presented in Table 22 for NH_3-N have an inherent high level of uncertainty relative to their magnitude. Trout Brook and the Stillwater River had the lowest annual mean NH_3-N concentrations in 2023 (0.007 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 22: Ammonia-Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
French Brook - MD01	0.034	0.041	0.018	0.012	0.029	0.026	0.201	0.023	0.028	0.013
Gates Brook 1 - MD04	0.014	0.012	0.013	0.008	0.008	0.012	0.006	0.005	0.006	0.009
Malagasco Brook - MD02	0.015	0.028	0.012	0.014	0.011	0.014	0.009	0.014	0.027	0.016
Malden Brook - MD06	0.009	0.016	0.004	0.005	0.012	0.006	0.009	0.008	0.012	0.012
Muddy Brook - MD03	0.067	0.076	0.060	0.078	0.086	0.094	0.055	0.084	0.072	0.069
Quinapoxet River (Canada Mills) - MD69	0.017	0.021	0.011	0.015	0.012	0.011	0.009	0.012	0.014	0.014
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	0.004	0.003	0.006	0.003	0.008	0.002	0.007
Stillwater River - Muddy Pond Rd - MD07	0.012	0.011	0.007	0.006	0.006	0.005	0.007	0.010	0.007	0.007
Trout Brook - M110	—	0.012	0.007	0.008	0.006	0.008	0.007	0.007	0.006	0.007
Waushacum Brook (Prescott) - MD83	0.024	0.023	0.010	0.013	0.011	0.029	0.028	0.017	0.023	0.010
West Boylston Brook - MD05	0.049	0.021	0.016	0.037	0.027	0.034	0.016	0.013	0.013	0.012

Nitrite-Nitrogen

Nitrite-nitrogen (NO_2-N) is rarely detected in Wachusett Reservoir tributaries, therefore results are not displayed below. In 2023, there were only three NO_2-N concentrations above the 0.005 mg/L detection limit: One at West Boylston Brook (0.0053 mg/L), and two at Malagasco Brook (0.0055 and 0.008 mg/L). The typical tributary NO_2-N concentrations are not a concern for any designated use, however, nitrite's eventual conversion to nitrate in aquatic systems does contribute to the overall nutrient loading of the Wachusett tributaries and Reservoir. All NO_2-N results for 2023 were below the EPA MCL of 1.0 mg/L.

Nitrate-Nitrogen

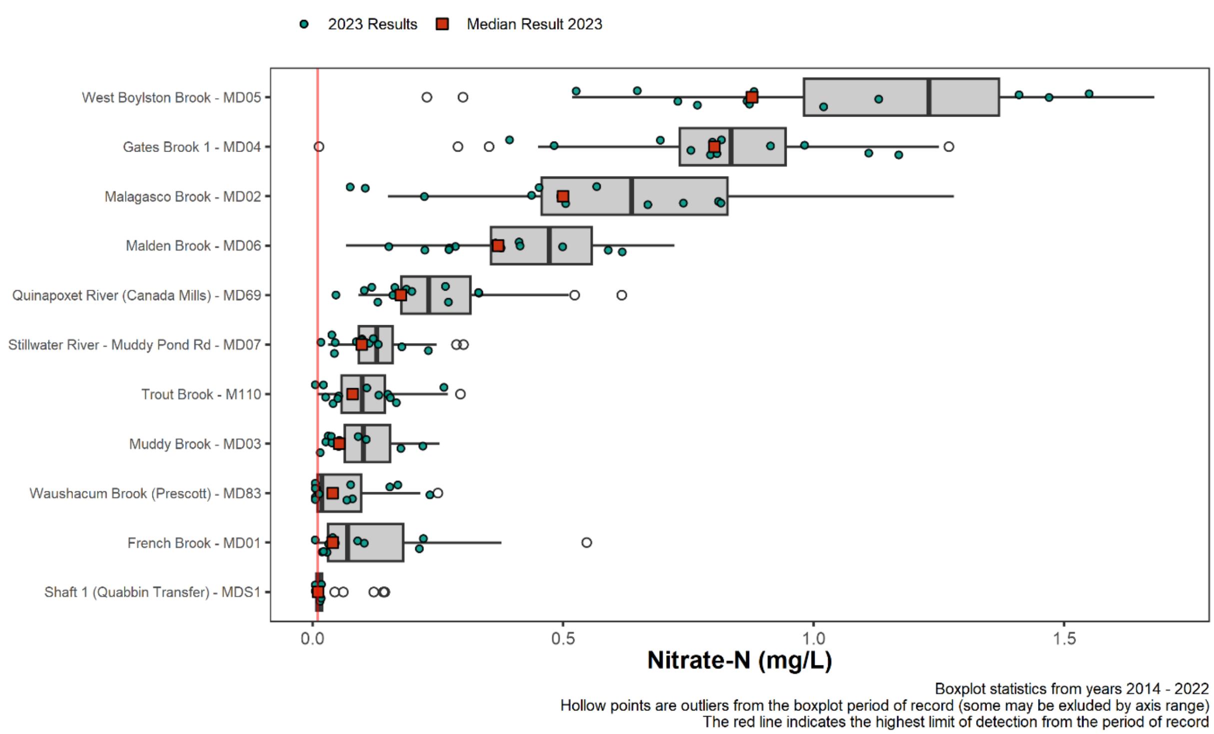
Annual mean nitrate-nitrogen (NO_3-N) concentrations for 2023 ranged from 0.068 mg/L at Waushacum Brook to 0.99 mg/L at West Boylston Brook (Table 23), with individual measurements from below detection (< 0.005 mg/L) to 1.55 mg/L at West Boylston Brook. The mean annual NO_3-N concentrations at individual tributaries have been stable over the last several years, with 2023 mean concentrations tracking very close to long term averages. All annual median NO3-N concentrations for 2023 were below the historical medians from the 2014 – 2022 period (Figure 33).

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

Sample Location	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
French Brook - MD01	0.167	0.093	0.153	0.110	0.134	0.119	0.096	0.070	0.078	0.072
Gates Brook 1 - MD04	0.856	0.786	0.762	0.907	0.846	0.886	0.747	0.809	0.801	0.810
Malagasco Brook - MD02	0.583	0.704	0.615	0.684	0.599	0.626	0.619	0.608	0.605	0.491
Malden Brook - MD06	0.443	0.534	0.443	0.488	0.452	0.463	0.424	0.412	0.424	0.373
Muddy Brook - MD03	0.135	0.134	0.139	0.108	0.110	0.095	0.098	0.070	0.125	0.075
Quinapoxet River (Canada Mills) -	0.251	0.291	0.208	0.320	0.239	0.277	0.275	0.186	0.241	0.192
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	0.020	0.053	0.020	0.010	0.009	0.006	0.011
Stillwater River - Muddy Pond Rd -	0.136	0.155	0.122	0.134	0.108	0.127	0.133	0.124	0.123	0.100
Trout Brook - M110	—	0.110	0.101	0.101	0.101	0.097	0.093	0.132	0.125	0.097
Waushacum Brook (Prescott) - MD83	0.045	0.053	0.022	0.030	0.069	0.073	0.059	0.057	0.060	0.068
West Boylston Brook - MD05	1.142	1.250	1.198	1.284	1.069	1.170	1.094	1.115	1.214	0.989

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 nutrient 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). 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.

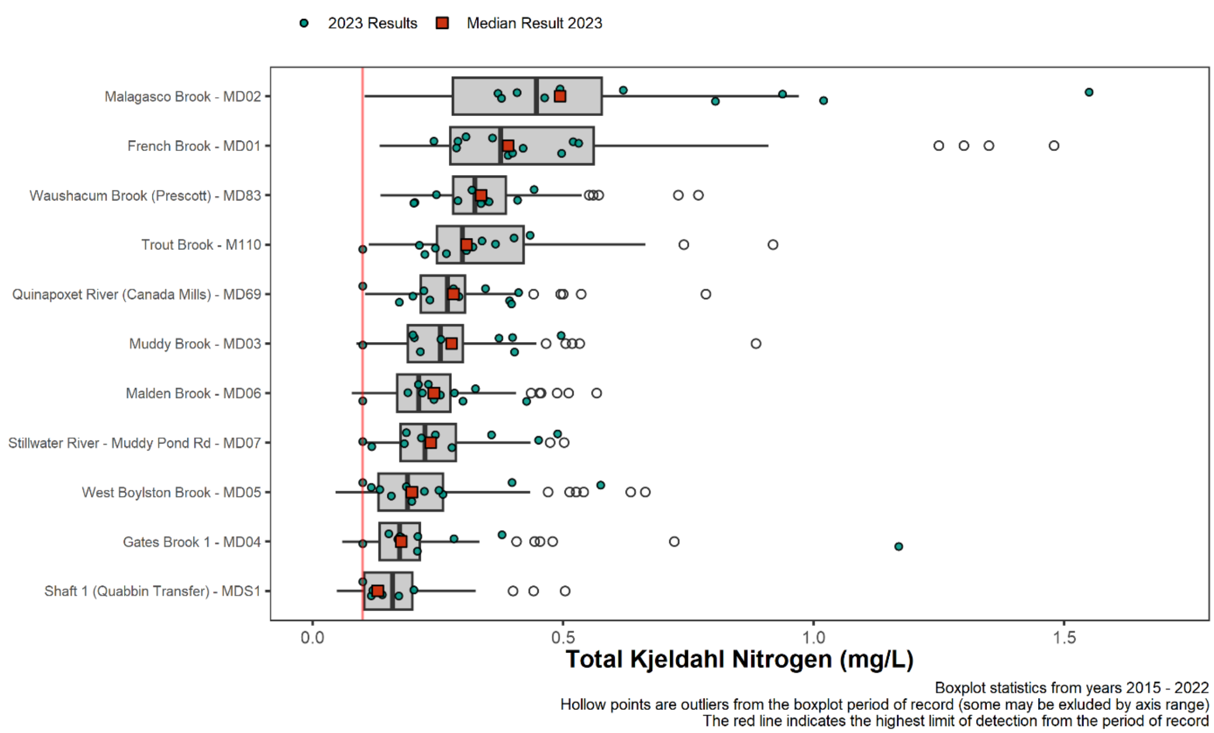
Figure 33: 2023 Nitrate-Nitrogen Concentrations with 2014 - 2022 Statistics



Total Kjeldahl Nitrogen

Annual mean Total Kjeldahl Nitrogen (TKN) concentrations were relatively consistent up until 2019. The previous three years, including 2023, had higher annual means than the prior five years (2005 – 2018), at most monitoring locations. In 2023, Gates, Malagasco, and Malden Brooks mean annual TKN concentrations were the highest observed levels on record. Malden and West Boylston Brooks had the lowest mean annual TKN concentrations: 0.287 and 0.234 mg/L, respectively. Median TKN concentrations for 2023 were higher than the period of record median at most tributaries, however none were above the 75th percentile historical concentration. Individual TKN sample concentrations in 2023 ranged from below detection (0.1 mg/L), at eight monitoring locations, to 1.55 mg/L at Malagasco Brook (Figure 34).

Figure 34: 2023 Total Kjeldahl Nitrogen Concentrations with 2014 - 2022 Statistics



Although mean and median annual TKN concentrations observed in 2023 were slightly higher than normal, they are generally reflective of local ecoregional background concentrations (0.1 – 0.3 mg/L). The four tributaries with the highest median 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 within their drainage areas, which are highly productive environments where organic compounds containing nitrogen and carbon are constantly breaking down and entering surface waters.

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

Sample Location	2015	2016	2017	2018	2019	2020	2021	2022	2023
French Brook - MD01	0.391	0.356	0.358	0.480	0.421	0.796	0.419	0.504	0.386
Gates Brook 1 - MD04	0.158	0.210	0.162	0.163	0.217	0.209	0.216	0.176	0.287
Malagasco Brook - MD02	0.376	0.344	0.465	0.472	0.389	0.394	0.563	0.479	0.685
Malden Brook - MD06	0.231	0.222	0.207	0.246	0.198	0.231	0.254	0.251	0.257
Muddy Brook - MD03	0.252	0.229	0.270	0.267	0.248	0.317	0.291	0.256	0.294
Quinapoxet River (Canada Mills) - MD69	0.290	0.288	0.246	0.265	0.260	0.258	0.301	0.301	0.280
Shaft 1 (Quabbin Transfer) - MDS1	—	—	0.102	0.208	0.190	0.194	0.152	0.158	0.138
Stillwater River - Muddy Pond Rd - MD07	0.206	0.266	0.228	0.228	0.201	0.227	0.253	0.288	0.259
Trout Brook - M110	0.257	0.310	0.351	0.345	0.381	0.329	0.360	0.345	0.298
Waushacum Brook (Prescott) - MD83	0.281	0.361	0.303	0.324	0.338	0.354	0.356	0.426	0.317
West Boylston Brook - MD05	0.178	0.188	0.175	0.248	0.269	0.376	0.238	0.227	0.234

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. This anomaly was discussed in the 2020 Annual Water Quality Report. Overall, mean annual TKN concentrations are close to the ecoregional reference conditions are not indicative of any water quality problems. Interannual variation is likely in part attributable to variation in precipitation and runoff. Other reasons for the variation and patterns observed in TKN concentrations have yet to be explored.

Total Nitrogen

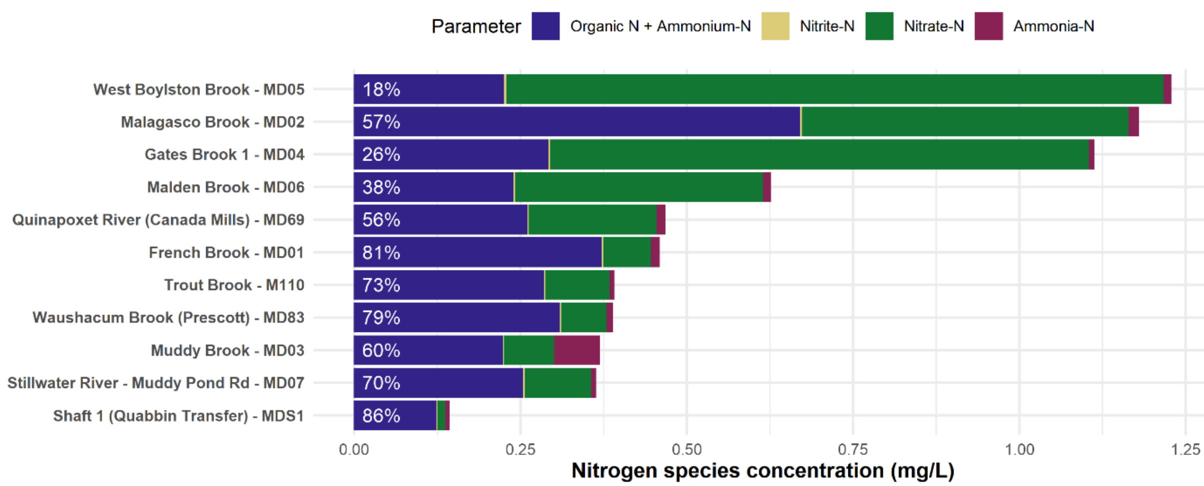
Total Nitrogen (TN) concentrations in 2023 ranged from 0.11 mg/L at the Trout Brook to 2.06 mg/L at Malagasco Brook, with mean annual concentrations for 2023 ranging from 0.36 mg/L at the Stillwater River to 1.19 mg/L at West Boylston Brook. Except for French Brook in 2020, TN concentrations have been stable at each tributary since 2015 (Table 25).

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

Sample Location	2015	2016	2017	2018	2019	2020	2021	2022	2023
French Brook - MD01	0.488	0.514	0.473	0.619	0.545	0.905	0.494	0.587	0.448
Gates Brook 1 - MD04	0.952	0.977	1.085	1.014	1.109	0.963	1.030	0.984	1.078
Malagasco Brook - MD02	1.074	0.966	1.154	1.075	1.020	0.995	1.176	1.089	1.159
Malden Brook - MD06	0.770	0.670	0.708	0.705	0.666	0.661	0.671	0.680	0.620
Muddy Brook - MD03	0.391	0.376	0.384	0.382	0.348	0.420	0.366	0.387	0.362
Quinapoxet River (Canada Mills) - MD69	0.587	0.501	0.571	0.508	0.542	0.539	0.501	0.547	0.468
Shaft 1 (Quabbin Transfer) - MDS1	—	—	0.152	0.271	0.217	0.208	0.170	0.189	0.158
Stillwater River - Muddy Pond Rd - MD07	0.367	0.394	0.367	0.335	0.333	0.366	0.382	0.416	0.358
Trout Brook - M110	0.448	0.412	0.455	0.452	0.481	0.434	0.497	0.472	0.388
Waushacum Brook (Prescott) - MD83	0.339	0.388	0.339	0.398	0.416	0.418	0.418	0.491	0.381
West Boylston Brook - MD05	1.438	1.391	1.472	1.326	1.444	1.452	1.358	1.446	1.192

Figure 35 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, French, Malagasco and Waushacum Brooks, usually have higher proportions of organic nitrogen (see discussion of TKN in Appendix C: Watershed Monitoring Parameters and Historical Context) 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 35: 2023 Mean Total Nitrogen Concentrations at Wachusett Tributaries
Percentages indicate the organic nitrogen fraction of total nitrogen at each sample location.

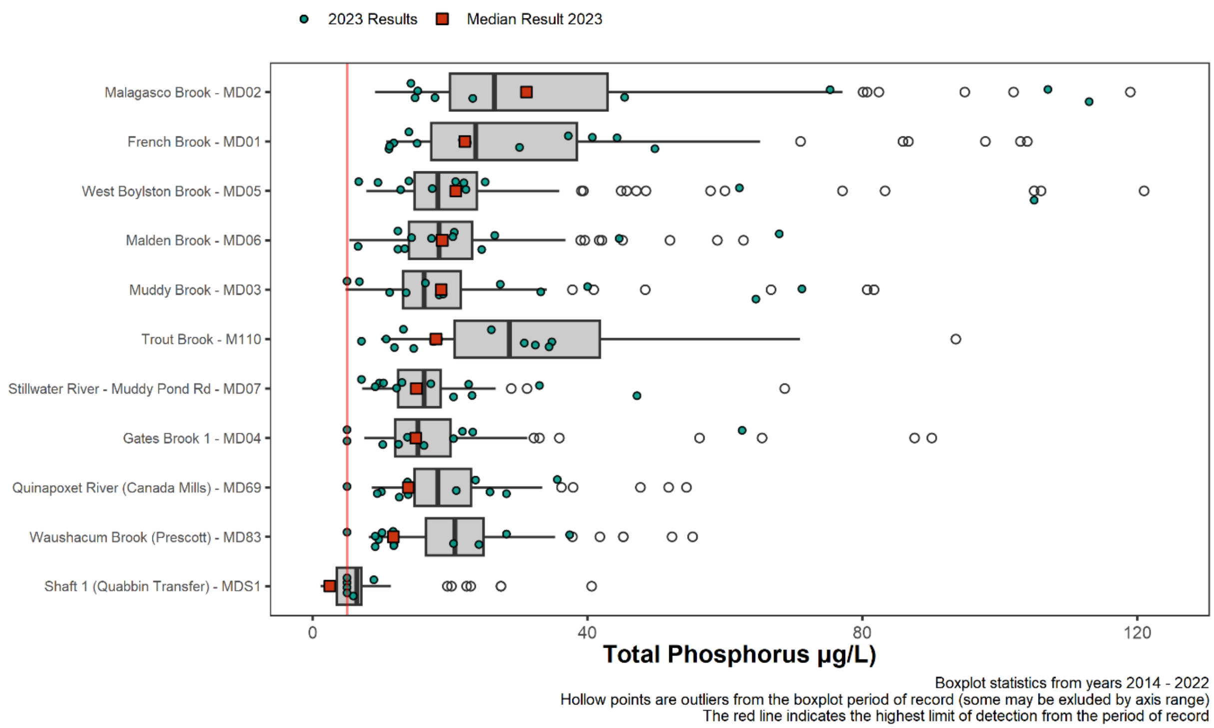


Concentrations of TN within Wachusett tributaries are mostly within the range of ecoregional background concentrations (0.42 – 0.59 mg/L), which are suggested reference conditions for numerical criteria development. West Boylston, Gates and Malagasco Brooks all exceed these concentrations, likely because of either urban/suburban development, golf courses, or agriculture. The Quinapoxet River and Malden and French Brook TN concentrations are also somewhat elevated above naturally occurring background conditions. The Quinapoxet River drainage area is large with many potential nitrogen sources, including significant urban/suburban landscapes and their associated uses. 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

Total phosphorus (TP) concentrations measured in Wachusett tributaries during 2023 ranged from < 5.0 µg/L at four tributaries to 113 µg/L at Malagasco Brook (Figure 36). Annual median TP concentrations were below the 2014-2022 median at about half of the monitoring locations, with the remaining under the 75th percentile. Annual mean concentrations ranged from 15.66 µg/L at Waushacum Brook to 44.42 µg/L at Malagasco Brook (Table 26). When comparing 2023 annual mean TP concentrations to the prior nine years, there was very little consistency across monitoring locations. Malagasco Brook experienced a record high mean concentration, while Waushacum and Trout Brooks experienced record low mean concentrations, and the rest were somewhere in the middle. Because phosphorus strongly adsorbs to soil particles, higher TP concentrations are typically observed during storm events when soil particles are eroded off the land and carried to tributaries with surface runoff, or during extremely low flows when fine bed load particles can be collected in samples. Given the record rainfall observed in 2023, these results are not surprising.

Figure 36: 2023 Total Phosphorus Concentrations with 2014 – 2022 Statistics



Mean annual TP concentrations in 2023 for most Wachusett tributaries were within typical ecoregional background concentrations (12 – 23.75 µg/L). Three tributaries (French, Trout, and Malagasco Brooks) have long-term median TP concentrations above 23 µg/L, which could be reflective of local background conditions (high percentage of wetlands), or possibly the result of anthropogenic sources. All 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 2023 was 20.79 µg/L. However, the Quabbin transfer contribution lowers the flow-weighted TP concentration to 11.76 µg/L for all surface water delivered to Wachusett Reservoir. The drainage areas to these tributaries should be targeted for nutrient reduction opportunities, specifically evaluating the impacts of septic systems, golf courses, urban stormwater runoff, and agricultural operations on phosphorus concentrations in surface waters.

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

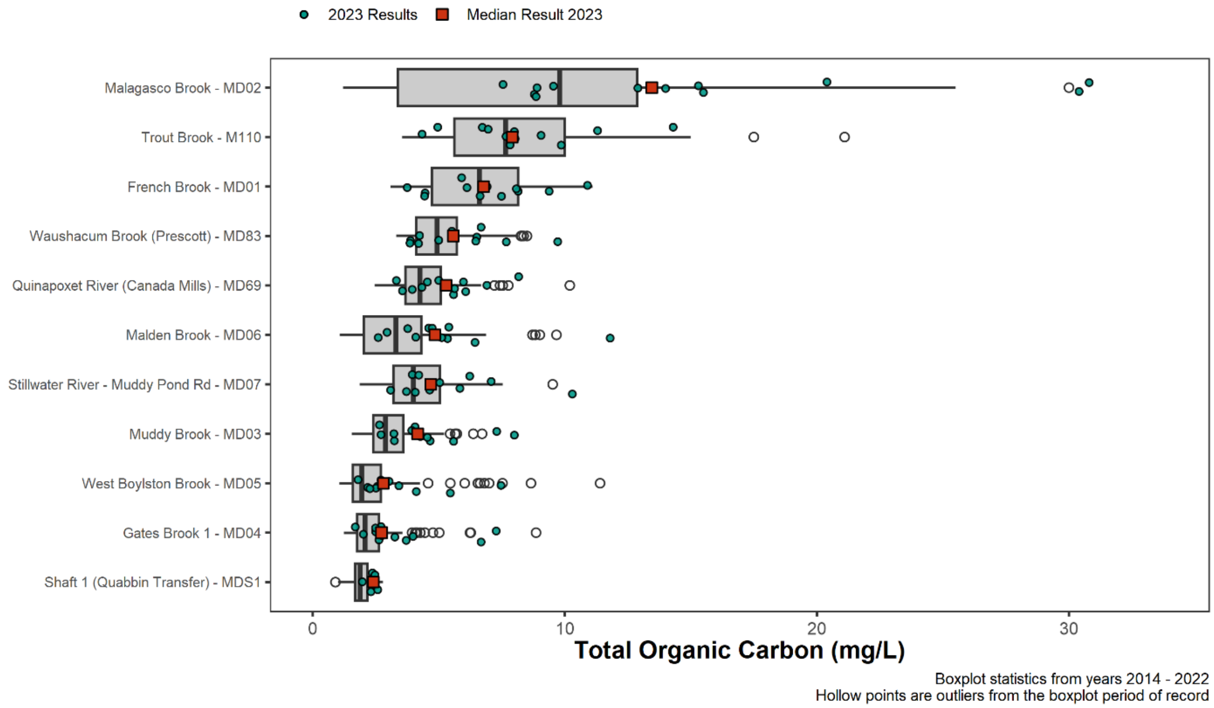
Sample Location	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
French Brook – MD01	31.4	32.3	28.7	22.9	26.2	44.3	53.7	25.6	32.6	25.8
Gates Brook 1 - MD04	24.9	14.8	17.3	15.3	18.8	22.9	20.9	15.9	15.2	19.1
Malagasco Brook - MD02	34.0	37.8	25.1	37.3	35.6	30.1	30.2	38.5	29.5	44.4
Malden Brook - MD06	24.6	23.8	19.5	15.6	19.9	17.9	20.6	20.0	20.2	23.4
Muddy Brook - MD03	18.5	18.4	20.1	20.5	20.7	19.3	30.9	18.8	15.2	27.1
Quinapoxet River (Canada Mills) - MD69	20.4	24.0	21.2	17.4	19.0	17.5	22.6	16.7	21.2	17.8
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	7.8	12.4	7.3	9.7	6.2	6.7	4.1
Stillwater River - Muddy Pond Rd - MD07	17.5	18.9	18.5	14.7	16.0	15.0	18.4	14.6	15.2	18.8
Trout Brook - M110	—	50.0	37.6	30.5	29.4	28.9	35.0	27.8	26.3	21.0
Waushacum Brook (Prescott) - MD83	24.6	21.9	26.3	19.8	19.0	20.7	26.5	17.9	22.9	15.7
West Boylston Brook - MD05	36.8	20.5	18.2	19.5	30.8	24.7	32.2	27.0	17.2	28.9

3.2.7.3 Total Organic Carbon and UV_{254}

In 2023, Total Organic Carbon (TOC) sample concentrations in the Wachusett tributaries ranged from 1.69 mg/L at Gates Brook 1 to 30.8 mg/L at Malagasco Brook (Figure 36; Table 27). The overall mean concentration for 2023 was 6.13 mg/L, which is 24% higher than the long-term mean concentration since 2014 (4.94 mg/L). Over the 2014 – 2023 period, six tributaries (including the Stillwater River) had their highest annual mean TOC concentration in 2023. The highest mean annual TOC concentrations were recorded from Malagasco Trout and French Brooks, with the lowest concentrations Gates and West Boylston Brooks (Figure 37). Most tributaries had median TOC concentrations in 2023 near or above the 75^{th} percentile from the 2014 – 2022 period of record. Trout and French Brooks were the only tributaries that had 2023 median TOC concentrations close to their historical median (Figure 37).

The 2023 flow-weighted mean TOC concentration for all tributaries and Quabbin transfer was 3.86 mg/L. Without the Quabbin transfer, the flow-weighted mean concentration would have been 6.82 mg/L, or 77% higher. 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. French Brook also has a high percentage of wetlands in its drainage area, which are probably a dominant source of carbon to the stream.

Figure 37: 2023 Total Organic Carbon Concentrations with 2014 - 2022 Statistics



A recent internal analysis of UV_{254} revealed a weak increasing trend at Waushacum Brook and weak decreasing trends in Boylston, French, and Trout Brooks. These trends are strongly influenced by precipitation, which if decoupled from the variation of UV_{254}, result in no significant increasing trends and two additional significant decreasing trends (Gates Brook 1 and West Boylston Brook). Correlations between UV_{254} levels and TOC are strong, so it is likely that TOC trends are similar.

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

Sample Location	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
French Brook - MD01	6.74	5.88	6.06	6.81	7.14	5.51	7.59	6.81	7.11	6.85
Gates Brook 1 - MD04	2.52	1.86	2.34	2.27	2.45	2.46	2.55	2.82	2.53	3.47
Malagasco Brook - MD02	10.80	7.79	8.83	10.82	10.81	7.20	6.80	12.11	9.99	15.25
Malden Brook - MD06	4.21	2.29	3.08	3.50	3.67	2.82	3.50	4.58	3.46	5.15
Muddy Brook - MD03	3.01	2.44	2.93	3.53	3.49	2.73	3.06	4.00	2.98	4.52
Quinapoxet River (Canada Mills) - MD69	4.76	4.11	4.92	4.53	4.73	3.61	3.92	5.33	4.68	5.26
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	1.89	1.55	1.79	2.04	2.11	2.36	2.36
Stillwater River - Muddy Pond Rd - MD07	4.58	3.89	3.84	4.54	4.79	3.34	3.65	4.64	4.22	5.24
Trout Brook - M110	—	9.54	8.50	9.43	9.31	6.51	7.06	7.73	6.58	8.25
Waushacum Brook (Prescott) - MD83	5.33	4.50	4.97	5.36	4.91	4.27	4.98	5.60	6.12	5.78
West Boylston Brook - MD05	3.20	1.76	1.88	2.26	2.71	2.80	3.07	2.73	2.36	3.37

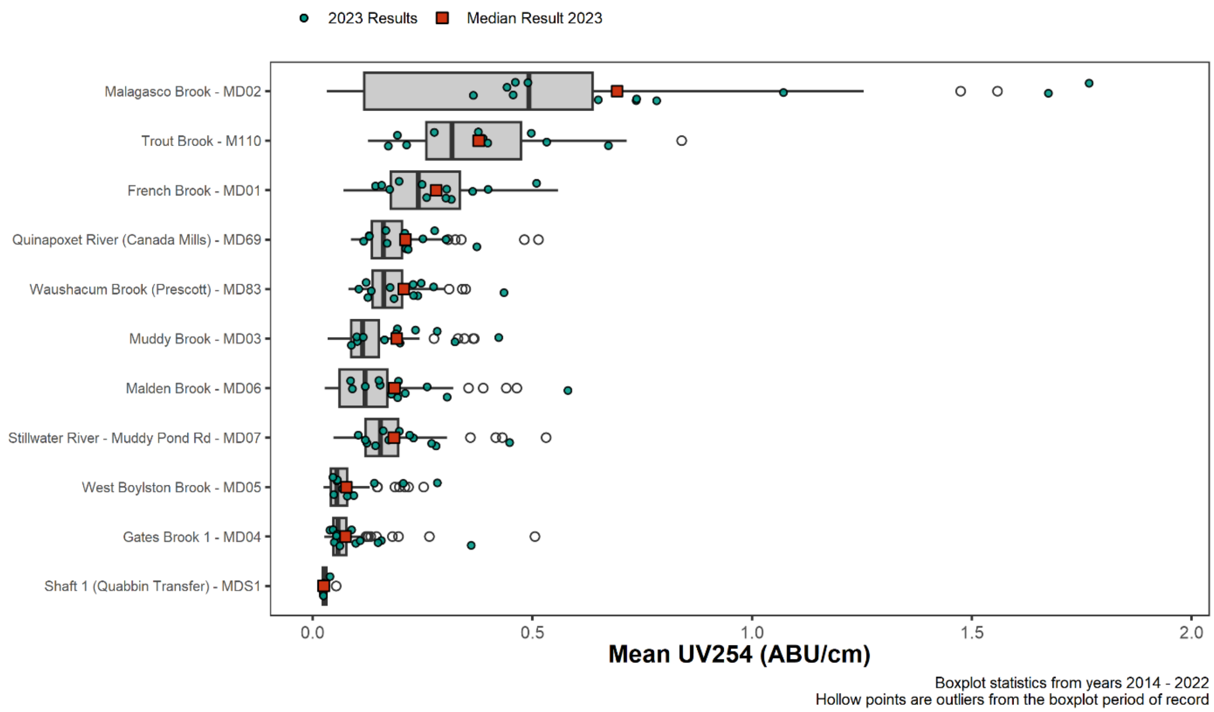
TOC concentrations between 2 and 4 mg/L are considered low for surface waters, and the 2023 flow-weighted mean TOC concentration of 3.86 mg/L is not a concern for aquatic life. However, this concentration is higher than optimal from a drinking water treatment perspective. Although tributary TOC concentrations are within ranges that could be reflecting typical background concentrations, more research needs to be conducted to determine the sources and controls of natural organic matter that is entering the tributaries. Until those sources and controls are better understood, recommendations for reduction cannot be made. Quabbin water will continue to play an important role in overall TOC concentrations in the Reservoir. The slight upward trend in Shaft 1 TOC concentration may be the dominant driver of any upward trend in TOC observed in the Wachusett Reservoir.

Measurements of UV_{254} absorbance for Wachusett tributaries in 2023 demonstrated variability comparable to TOC concentrations (Figure 38, Table 28). The highest UV_{254} absorbance level was from Malagasco Brook (1.77 ABU/cm) and the lowest was from Gates Brook 1 (0.039 ABU/cm). Aside from Waushacum Brook, mean annual UV_{254} absorbance levels were higher in 2023 compared with 2022 (Table 28). Eight of ten tributaries had median UV_{254} levels for 2023 near or above the 75^{th} percentile historical value. Trout and French Brooks were the only tributaries with 2023 median UV_{254} levels similar to their respective long-term medians (Figure 38).

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

Sample Location	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
French Brook - MD01	0.251	0.226	0.199	0.248	0.313	0.237	0.311	0.309	0.279	0.281
Gates Brook 1 - MD04	0.068	0.051	0.065	0.057	0.084	0.095	0.068	0.084	0.062	0.106
Malagasco Brook - MD02	0.479	0.372	0.304	0.510	0.618	0.380	0.302	0.672	0.511	0.803
Malden Brook - MD06	0.153	0.078	0.100	0.126	0.156	0.116	0.133	0.206	0.116	0.211
Muddy Brook - MD03	0.108	0.101	0.103	0.133	0.151	0.117	0.107	0.215	0.102	0.201
Quinapoxet River (Canada Mills) - MD69	0.167	0.162	0.162	0.197	0.210	0.152	0.153	0.221	0.169	0.213
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	0.020	0.026	0.032	0.027	0.030	0.027	0.028
Stillwater River - Muddy Pond Rd - MD07	0.152	0.167	0.125	0.193	0.215	0.144	0.141	0.195	0.142	0.206
Trout Brook - M110	—	0.432	0.316	0.437	0.421	0.335	0.327	0.413	0.279	0.373
Waushacum Brook (Prescott) - MD83	0.158	0.146	0.153	0.169	0.186	0.163	0.179	0.207	0.210	0.209
West Boylston Brook - MD05	0.075	0.050	0.057	0.053	0.091	0.081	0.077	0.079	0.056	0.103

Figure 38: 2023 UV_{254} Absorbance with 2014 - 2022 Statistics



TOC concentrations and UV_{254} absorbance levels observed in 2023 were high compared to historical results, particularly in the latter half of the year. Record high precipitation is the presumed dominant driver of the elevated concentrations of organics observed in 2023. The formation of disinfection byproducts from reactive organic compounds remains a top water treatment concern, particularly in 2023, due to these elevated levels of organic compounds in the Wachusett Reservoir water. Collecting flow targeted and or higher resolution TOC or UV_{254} absorbance data at the tributary monitoring locations could help provide a better understanding of the factors controlling dissolved organic matter loads[60]. Monthly measurements limit the ability to discern which factors may be responsible for the transport of organic matter through Wachusett subbasins, as deviations from long-term statistics can be heavily influenced by a single sample taken during anomalous hydrologic conditions.

3.2.8 Special Studies and Investigations – Tributaries

3.2.8.1 Long-Term Forestry Water Quality Monitoring

In 2023, dry weather monitoring at the LTF monitoring locations (Holden (FHLN) and Princeton (FPRN)) was completed only for the month of January. At that time, it was determined that additional dry weather data was not needed to characterize dry weather water quality at these locations during the pre-harvest phase. Storm event sampling remained on hold through 2023 for the same reason.

[60] Leonard, et. al. 2022

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 be completed at the Princeton site by the end of summer 2024, as stipulated in the timber sale contract. Post-harvest monitoring will begin in 2024 as soon as the timber harvest has been completed.

3.2.8.2 Conductivity and Chloride

Since 2018, the Conductivity/Chloride working group has been meeting quarterly to address the increasing specific conductance observed in the Quabbin and Wachusett Reservoirs and many of their tributaries. In 2023, members of the Chloride/Conductivity working group met quarterly to discuss progress on tasks and brainstorm possible new initiatives and partnerships. This effort involves staff across all sections of DWSP working on several distinct initiatives within the following categories:

- Education, training and outreach
- Data collection
- Modeling, literature review, partnerships
- Salt reduction grant program
- DWSP salt use
- Interagency Salt Reduction Working Group

Several tasks initiated under this program have now been completed and progress is being made in each category listed above. Additional information about DWSP's watershed system salt reduction efforts[61] is provided on the DCR web page, which includes links to educational videos, signage and brochures. Therefore, the discussion in this report will be limited to water quality monitoring activities conducted in the Wachusett Reservoir Watershed.

Conductivity Blitz

In April of 2021, a short-term monitoring initiative was started to gain a better spatial understanding of elevated chloride/specific conductance levels within the Wachusett Reservoir Watershed. The goal of this monitoring effort, referred to as a "conductivity blitz," was to collect specific conductance measurements at as many surface water locations across the Watershed as possible. Measurements were taken in streams, wetlands, and ponds, avoiding storm runoff so that measurements reflect baseflow water chemistry as much as possible. The conductivity blitz could not be completed in 2022 due to drought conditions, which dried up most intermittent streams in the watershed. Dry locations were revisited in 2023 and all anticipated sampling was completed. This information will be used to help identify chloride/specific conductance hotspots within subbasins. Hotspot areas will be investigated to identify probable chloride sources and appropriate mitigation strategies can then be targeted in these locations.

Real-time Conductivity Monitoring

Real-time conductivity monitoring has been ongoing for many years at the three USGS stations in the Wachusett Watershed. Mayfly monitoring stations have now been installed at the other seven primary

[61] https://www.mass.gov/info-details/dcr-watershed-system-salt-reduction#:~:text=DWSP%20is%20committed%20to%20finding,winter%20snow%20and%20ice%20management.

monitoring locations: French, Malagasco, Muddy, Malden, Trout, Waushacum and West Boylston Brooks (Figure 39). See Section 2.1.2.2 for background information on Mayfly monitoring stations.

The increased temporal resolution of real-time monitoring (15-minute increments) of specific conductivity captures rapid fluctuations in specific conductivity that are missed by regular sampling programs, which only record discrete specific conductivity measurements three times per month. This information will improve the understanding of the timing and magnitude of chlorides delivered to the tributaries after the application of deicing products on roadways and allow DWSP to monitor for the effectiveness of chloride reduction initiatives over time. The data collected at these stations is summarized in Section 3.2.3.

Figure 39: Mayfly Station at French Brook

3.2.8.3 Stormwater Basins

Monitoring of the stormwater basins located on either side of the Rt 12/140 causeway has been conducted since July 2019. In 2023, 13 monitoring visits were conducted approximately monthly and during a range of weather conditions. Basins holding water were also monitored for developing mosquito larvae, visually and through collected water samples. No larvae were found through either method.

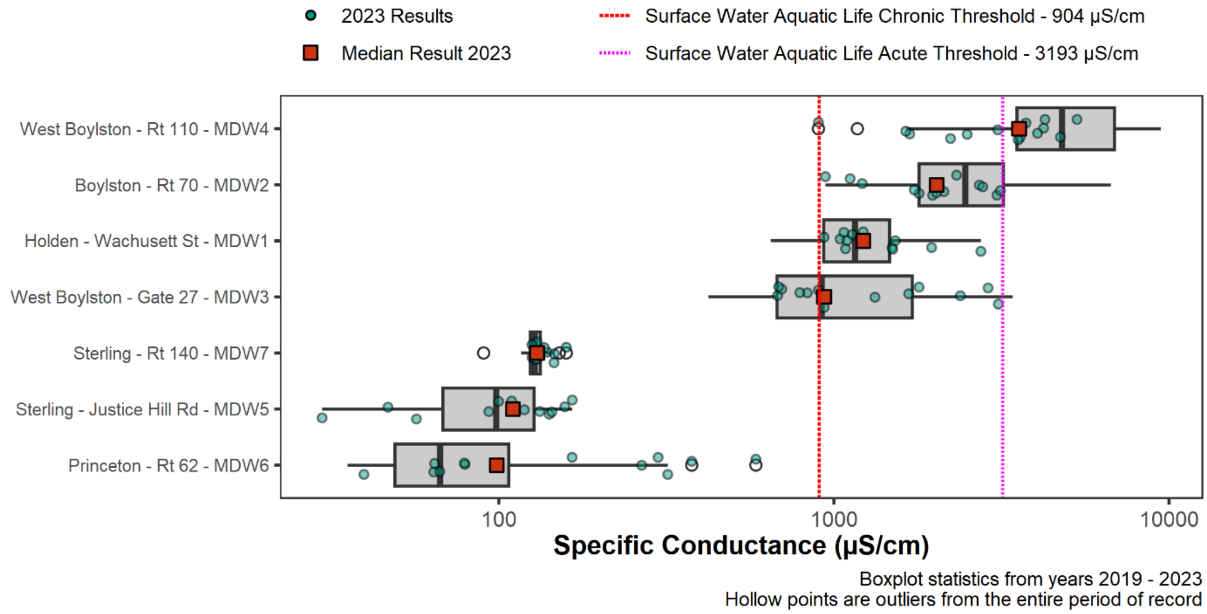
3.3 Groundwater Quality Monitoring

Groundwater monitoring continued in 2023 after launching in 2019 (see Figure 6), and the data collected so far have provided preliminary insights on the groundwater levels and specific conductance in Wachusett Watershed aquifers. Results of well monitoring in 2023 continued to indicate a wide range in specific conductance concentrations in Wachusett Watershed groundwater (Figure 40). The mean specific conductance in West Boylston - 110 was over an order of magnitude higher than the mean in Sterling – Justice Hill Rd, with values from the other wells between those two extremes (Table 29). Median specific conductance results in 2023 were below the historical mean in the two wells with the highest specific conductance results. This may be due to dilution of the groundwater conductivity from the elevated precipitation in 2023.

The ranges and medians of specific conductance results are shown in the box plot in Figure 40 with logarithmic Y-axes due to the high and low extremes in values. Elevated conductivity levels in the Wachusett Watershed are assumed to be primarily attributable to the long-term application of deicing road salt, but due to the particularly elevated specific conductance 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, no additional sources of Cl have been determined, but investigations will continue to seek potential sources.

Figure 40: Specific Conductance Results in Wachusett Watershed Wells in 2023

The chronic and acute thresholds are surface water criteria for aquatic life, provided here only for comparison.



The ranges and medians of dissolved oxygen and pH are shown in the box plots Figure 41 and Figure 42.

Figure 41: Dissolved Oxygen Results in Wachusett Watershed Wells in 2023

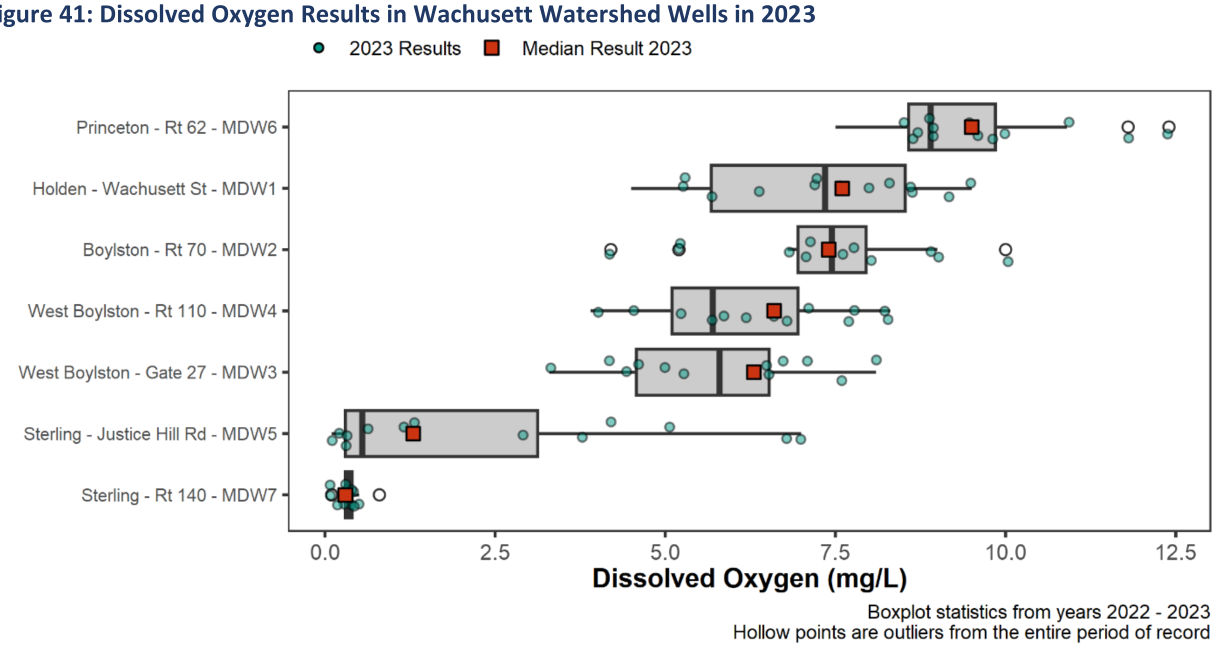


Figure 42: pH Results in Wachusett Watershed Wells in 2023

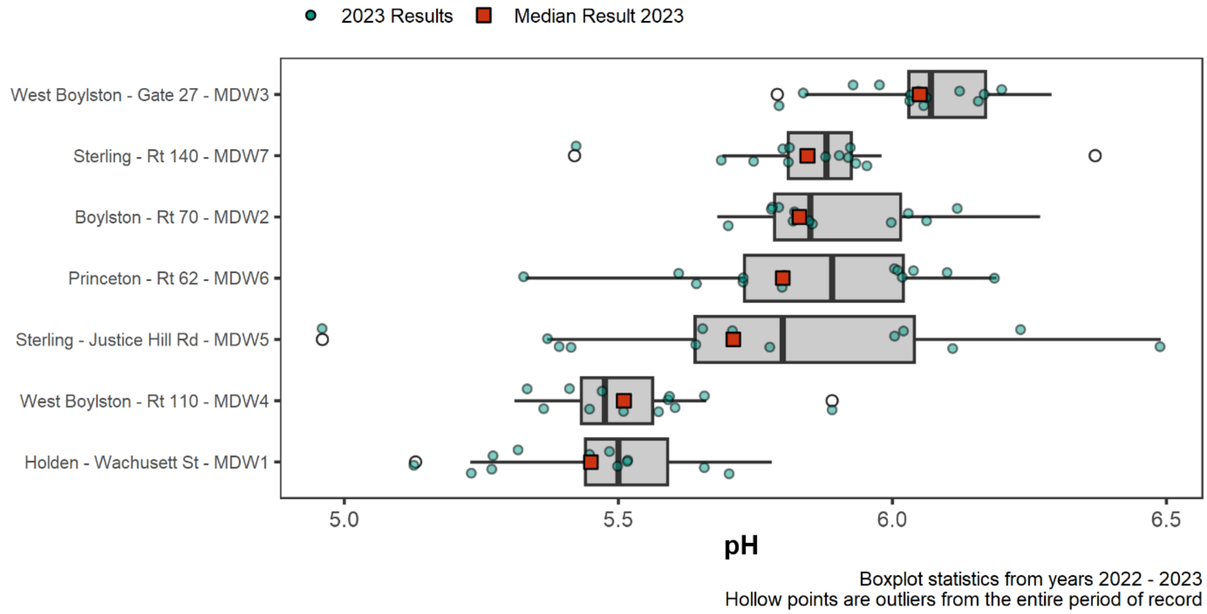


Table 29: Groundwater Monitoring Summary for 2023

Well	Mean Water Depth Below Ground Surface (ft)	Mean Specific Conductance (µS/cm)	Mean Dissolved Oxygen (mg/L)	Mean pH
Sterling - Justice Hill Rd - MDW5	2.3	108.2	2.6	5.8
Sterling - Rt 140 - MDW7	13.8	135.5	0.3	5.8
Princeton - Rt 62 - MDW6	14.3	192.6	9.7	5.8
Holden - Wachusett St - MDW1	1.4	1,387.2	7.5	5.4
West Boylston - Gate 27 - MDW3	6.7	1,436.5	5.8	6
Boylston - Rt 70 - MDW2	5.4	2,073.1	7.3	5.9
West Boylston - Rt 110 - MDW4	11.5	3,250.8	6.5	5.5

Well monitoring will continue in 2024 to determine if seasonal or long-term trends are present in groundwater specific conductance concentrations. In June 2024, five years of specific conductance results will be available for seasonal trend analyses.

The wide ranges of specific conductance results in groundwater 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 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 above average watershed runoff and storm events. These conditions resulted in low annual mean Secchi depth, elevated silica concentrations throughout the reservoir during the growing season, and seasonal site maximum total phosphorus concentrations. 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

Reservoir temperatures in 2023 supported MassDEP aquatic life use standards for coldwater and warmwater fisheries. Recorded reservoir temperatures ranged from 2.0 °C to 27.2 °C.

Ice was present in isolated cove areas, but the entire reservoir did not freeze over the winter of 2022 – 2023 (Figure 43). 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 April 24 (Figure 44). Surface temperatures continued to warm, attaining a maximum recorded temperature of 26.8 °C at Basin North at 0.5 m on July 24. Cooling of the epilimnion started in late September when the combination of cooling air temperatures and wind energy pushed the thermocline deeper. However, cooling was gradual due to warm fall temperatures. Turnover occurred on November 16 (as recorded by MWRA profile buoys) and the water column continued to cool for the remainder of the season.

Figure 43: Ice Cover Duration for Wachusett Reservoir for the Period of Record (1992 – 2023)

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

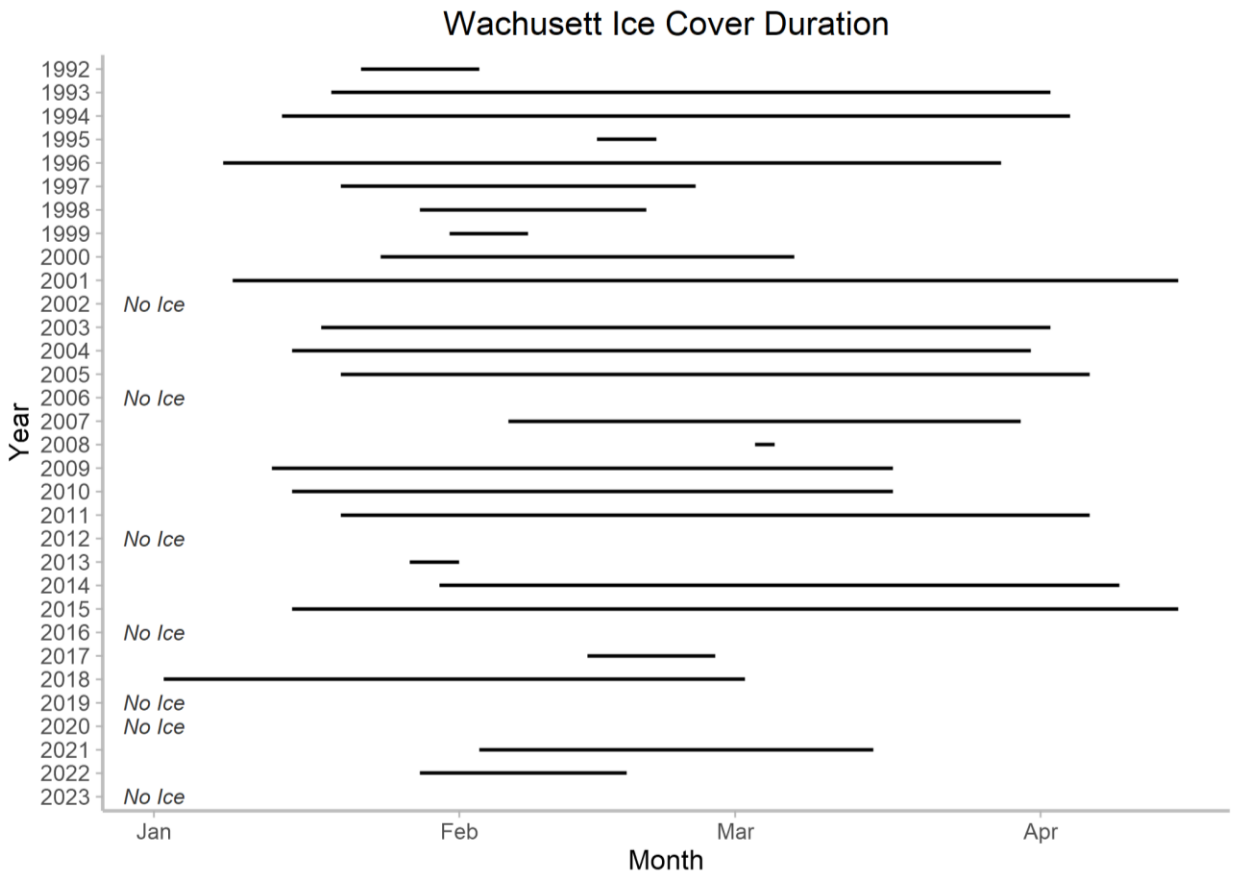
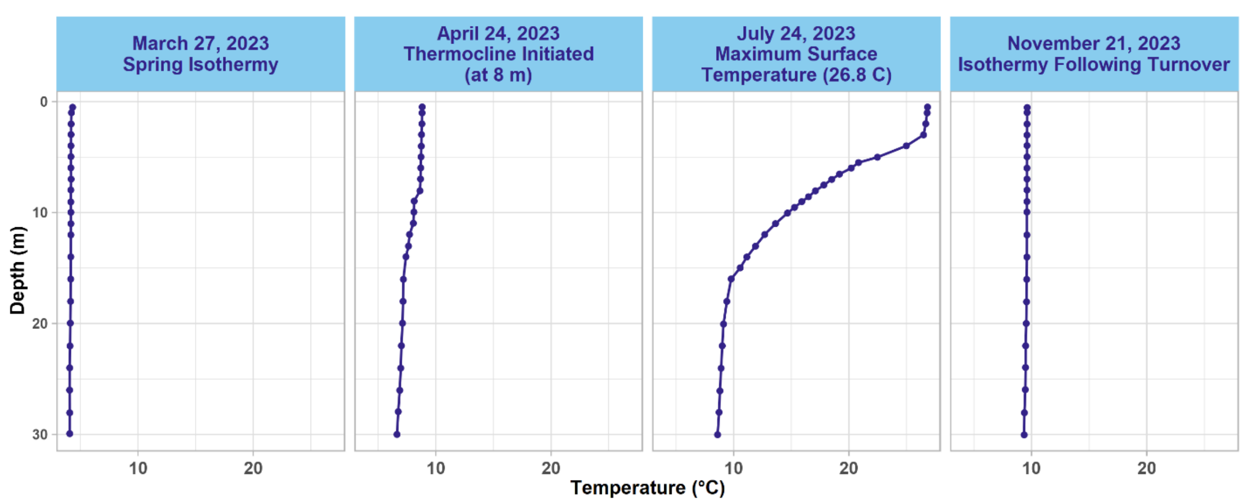
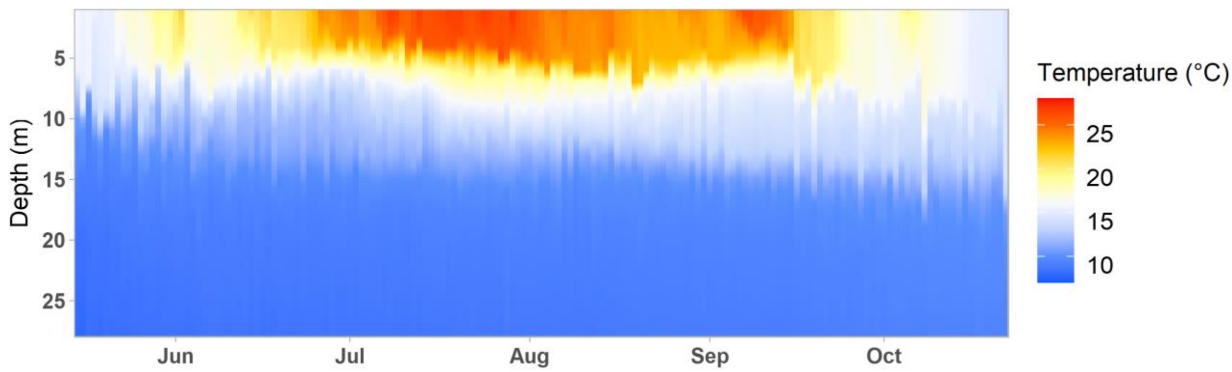


Figure 44: Profiles from Basin North Displaying Water Temperature at Critical Periods During 2023



The high temporal resolution data obtained from MWRA remote sensing buoys provide an opportunity to visualize reservoir temperature changes over the entire season (Figure 45). Cooling of the epilimnion in September was followed by a period of warming and then subsequent cooling until turnover occurred on November 16.

Figure 45: Water Temperature Recorded by Basin North Profiling Buoy May – December 2023
Plot of data recorded daily at 12 pm.

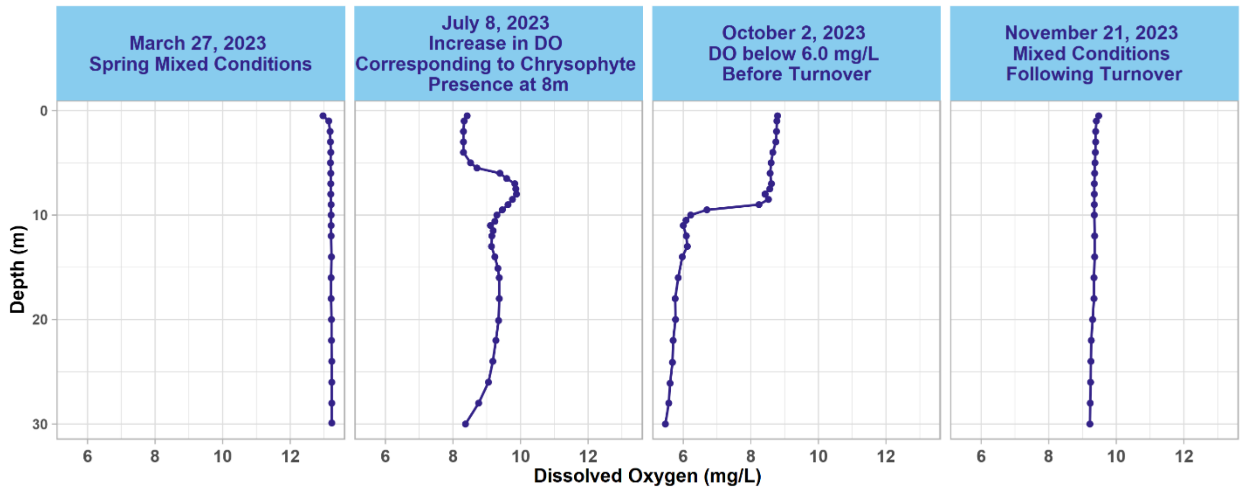


3.4.2 Dissolved Oxygen

Expected patterns in dissolved oxygen were observed through the 2023 season. MassDEP aquatic life use criteria of 6.0 mg/L for coldwater communities and 5.0 mg/L for warmwater communities were met for most of the year. Concentrations below 6.0 mg/L were recorded in the hypolimnion in October and November prior to turnover but did not fall below 5.5 mg/L based on profiles collected at Basin North (Figure 46).

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 through mid-May. 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 5.5 mg/L at 30 m on October 2. Despite decreased oxygen at depth, the mean dissolved oxygen concentration remained above 7.0 mg/L, maintaining concentrations required to support coldwater species. Once turnover occurred on November 16 (as recorded by MWRA profile buoys), dissolved oxygen was again dispersed through the water column and was approximately 9.3 mg/L from the surface to the bottom on November 21. Elevated dissolved oxygen below the thermocline associated with increased phytoplankton activity occurred in early July when an aggregation of *Chrysosphaerella* was present within the interflow around 8 m.

Figure 46: Profiles from Basin North Displaying Dissolved Oxygen at Critical Periods During 2023

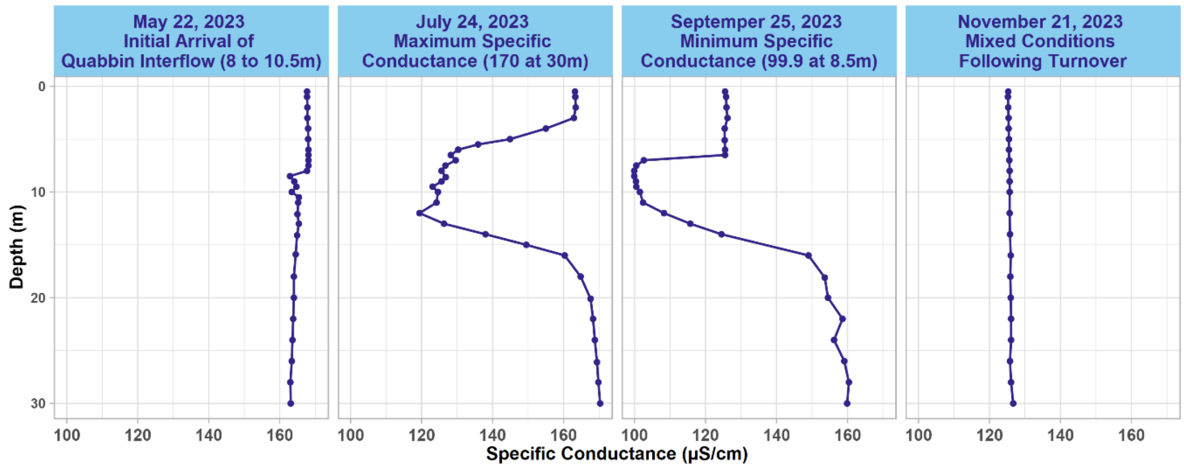


3.4.3 Specific Conductance

The annual maximum specific conductance observed at Basin North was lower than observed in 2022; however, the mean and minimum values were higher. All specific conductance values were lower than historical peak values observed in 2018, indicating that recent increased volumes of water transferred from Quabbin Reservoir (Figure 20) may be successful in diluting dissolved salts in Wachusett Reservoir. The maximum value of 170.0 µS/cm was recorded at 30 m on July 24. The annual mean was 143 µS/cm. Annual minimum specific conductance values ranging from 102.6 to 99.9 were recorded between 7 and 11 m on September 25.

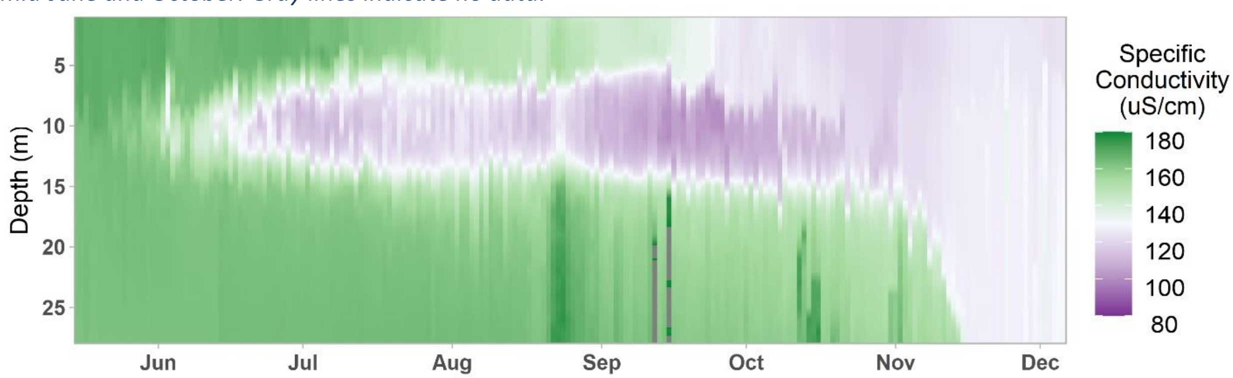
Arrival of the Quabbin interflow at Basin North was first observed on May 22 with a slight decrease in specific conductance detected between 9 and 10.5 m. By June 5, a definitive decrease in specific conductance between 7.5 and 12 m indicated the establishment of the Quabbin interflow within the Wachusett metalimnion. Following this date, specific conductance within the metalimnion continued to decrease, reaching a minimum of 99.9 µS/cm at 8 and 8.5 m on September 25. On this date, the interflow encompassed approximately 9.5 m between depths of 6.5 m and 16 m. Warm temperatures through the end of September maintained stratification and a strong interflow layer until early October when a 2.5 °C change in surface temperature occurred over three days. This shift pushed the thermocline and top of the interflow deeper. The interflow layer continued to decrease as stratification lessened through October, mixing higher conductivity water found in the Wachusett epilimnion with the lower conductivity hypolimnion and Quabbin interflow. By mid-November, the Reservoir was fully mixed, with a mean specific conductance of 126 µS/cm on November 21 (Figure 47).

Figure 47: Profiles from Basin North Displaying Specific Conductance at Critical Periods During 2023



Formation of the Quabbin interflow and the stark differences between interflow specific conductance and that of native Wachusett Watershed water throughout the year is shown below using the high-resolution data obtained from the MWRA profiling buoy in Basin North (Figure 48).

Figure 48: Specific Conductance Recorded by Basin North Profiling Buoy May – December 2023
Plot of data recorded daily at 12 pm. The Quabbin interflow layer is visible in the range of 99 to 130 µS/cm between mid-June and October. Gray lines indicate no data.



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 NTU (Nephelometric Turbidity unit), which is the typical result observed in the Reservoir. Therefore, turbidity values observed *in situ* are used for observational purposes only. Data for regulatory compliance are collected by MWRA at various points throughout the distribution system once water leaves the Reservoir.

3.4.5 pH

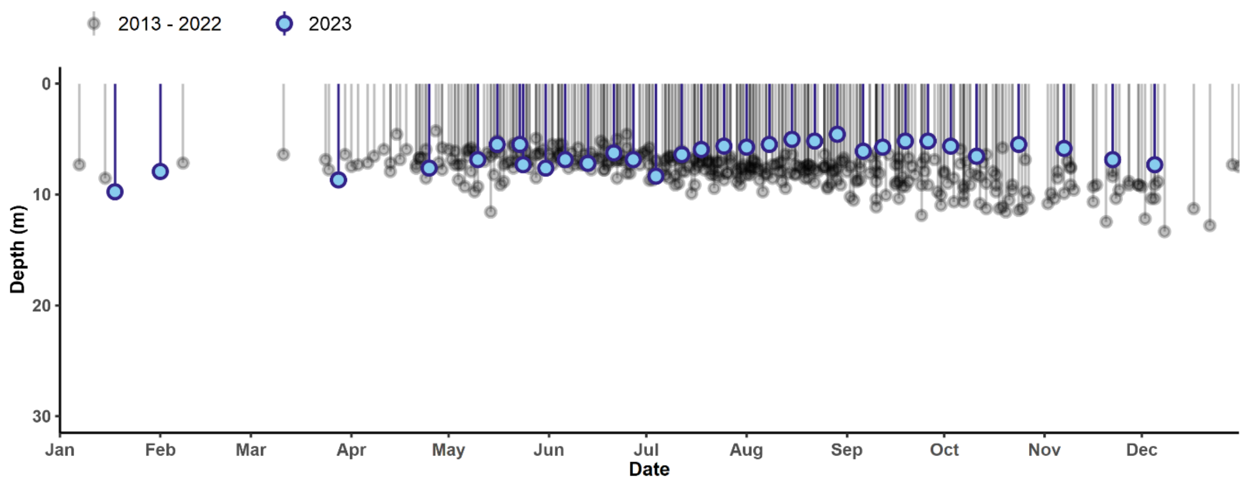
Reservoir pH varies slightly seasonally and vertically through the water column corresponding with changes in photosynthesis and respiration. In 2023, pH ranged from neutral to slightly acidic with a maximum value of 7.8 and minimum value of 6.02. Slight acidity was observed below depths of 10 m from late July through October as phytoplankton senesced and subsequent carbon release occurred at depth.

pH greater than 7.5 was observed in the epilimnion and corresponded to brief periods of increased photosynthesis.

3.4.6 Secchi Disk Depth/Transparency

Secchi disk depths in 2023 ranged from 4.6 m to 9.7 m. The maximum value was recorded on January 17 (Figure 49). Transparency decreased in the spring with increasing density of diatoms and spring runoff events. The growing season maximum Secchi depth of 8.4 m was recorded on July 3 during a period of low plankton density (See Section 3.4.8). The minimum value of 4.6 m was recorded on August 28 and was associated with a period of elevated phytoplankton density in the epilimnion. The annual mean Secchi disk depth of 6.45 m remained greater than the reference range of 4 m to 6.1 m for the reservoir ecoregion but was the lowest annual mean value since 2005. Significant rainfall and resulting runoff events likely contributed to decreased water clarity throughout the season.

Figure 49: 2023 Secchi Disk Transparency at Basin North
Y-axis shows maximum depth at Basin North of 30m



3.4.7 Nutrient Dynamics

The patterns of nutrient distribution in 2023 seasonal samples generally followed those documented in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics[62]. 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.

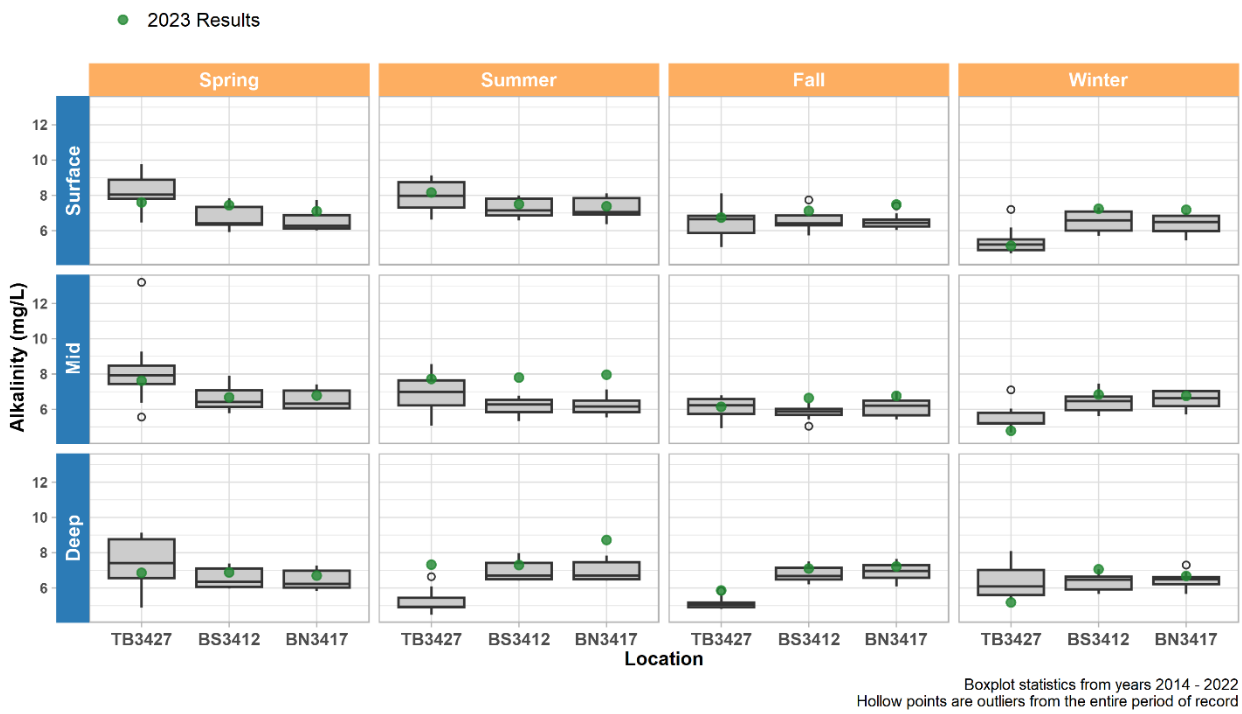
[62] Worden & Pistrang, 2003

3.4.7.1 Alkalinity

As with many analytes, differences in alkalinity across Wachusett Reservoir sites and depths is influenced by the percent of water originating from the Wachusett watershed versus that transferred from Quabbin Reservoir. Annual maximum alkalinity values typically occur at sites where the primary influence was native Wachusett watershed water whereas minimum values are typically recorded from locations or times when the Quabbin interflow was the primary source of water.

Mean alkalinity across all sites and depths in 2023 was 6.98 mg/L as $CaCO_3$, slightly lower than the mean recorded for 2022. The annual maximum alkalinity value of 8.72 mg/L as $CaCO_3$ was recorded in the hypolimnion at Basin North during the summer and annual minimum of 4.78 mg/L as $CaCO_3$ was recorded at the Thomas Basin mid-depth in November. The six lowest values were also recorded at Thomas Basin in fall and winter when the Quabbin transfer was the dominant water source.

Figure 50: 2023 Alkalinity as $CaCO_3$ in Wachusett Reservoir



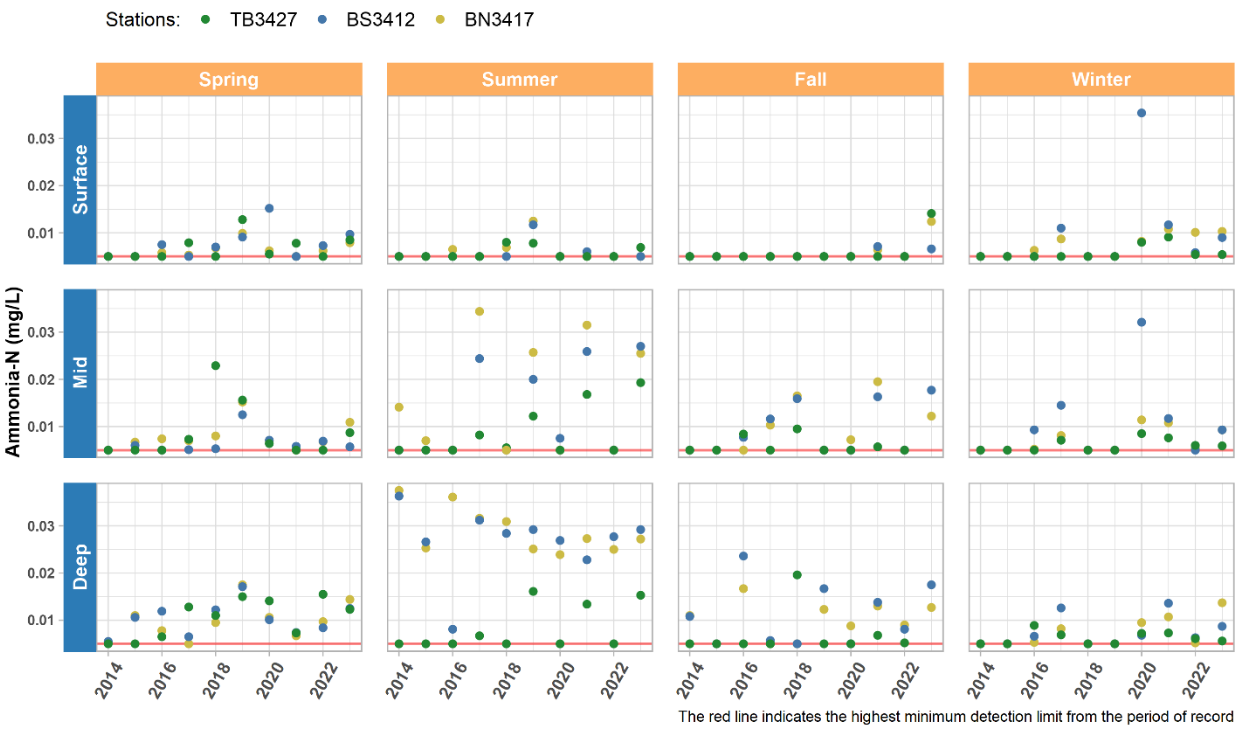
3.4.7.2 Nitrogen Species (Ammonia-Nitrogen, Nitrate-Nitrogen, and Total Kjeldahl Nitrogen)

Ammonia-Nitrogen

In 2023, overall Ammonia-Nitrogen (NH_3-N) results were elevated, with 22% of results exceeding the seasonal site historical maximum and another 24% exceeding the 75th percentile. Due to problems with laboratory calibrations during the 2023 season (see discussion in Appendix C), results for the year, are questionable. Values within the historical range were retained while values that exceeded the historical maximum for each site were removed from analysis.

Ammonia-Nitrogen levels within the Reservoir remained low, with all values below regulatory thresholds. Typical patterns were observed with the highest values present at mid and deep sample depths during the summer and fall when ammonia builds in the hypolimnion (Figure 51).

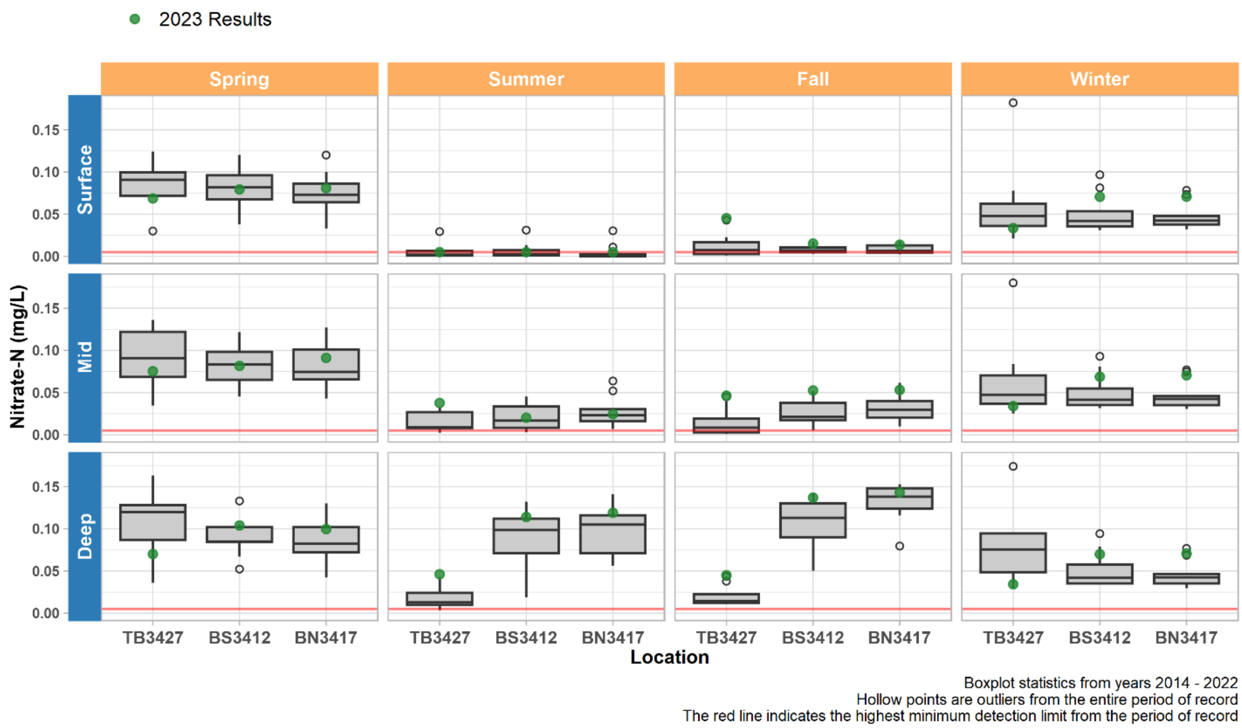
Figure 51: 2023 Ammonia-Nitrogen in Wachusett Reservoir



Nitrate-Nitrogen

Annual nitrate-nitrogen (NO_3-N) concentrations were well below the SDWA threshold of 10 mg/L, ranging from below detection (0.005 mg/L, 3 samples) to 0.143 mg/L (Figure 52). The highest concentrations are most often observed in the spring and in main basin locations at depth during periods of stratification. This pattern continued in 2023, with spring values at all sites falling between 0.067 and 0.104 mg/L and the highest annual concentrations, between 0.114 and 0.143, were recorded in the hypolimnion during stratification at Basin South and Basin North.

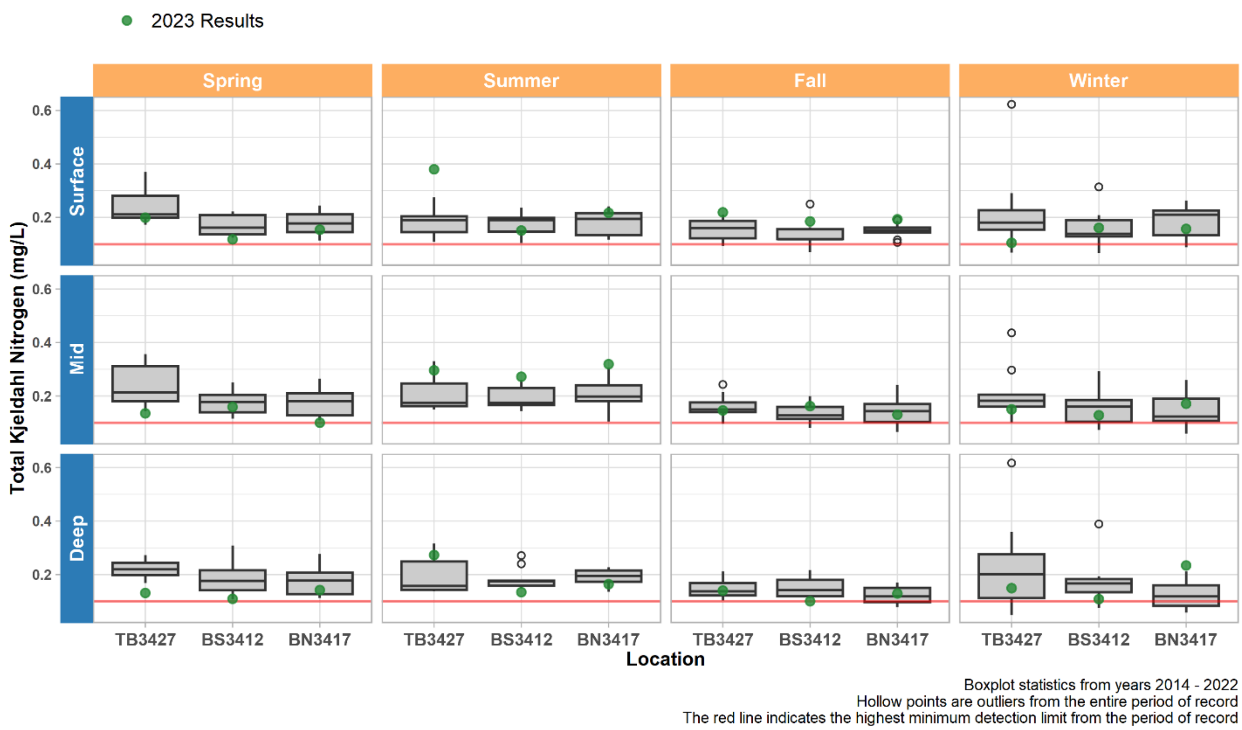
Figure 52: 2023 Nitrate-Nitrogen in Wachusett Reservoir



Total Kjeldahl Nitrogen

Concentrations for Total Kjeldahl Nitrogen (TKN) ranged from below the detection limit (0.1 mg/L, 2 samples) to 0.38 mg/L (Figure 53), within the historical range. The maximum TKN concentration for the year was recorded at the surface of Thomas Basin. Site and depth and seasonal maximums were recorded for the following samples: summer and fall Thomas Basin surface, summer Basin South and Basin North mid-depths, and winter Basin North deep depth. These values largely coincide with relatively high specific conductance values (for these sites/timeframes), indicating a higher percentage of native Wachusett water present in these locations following periods of elevated precipitation and subsequent tributary discharge.

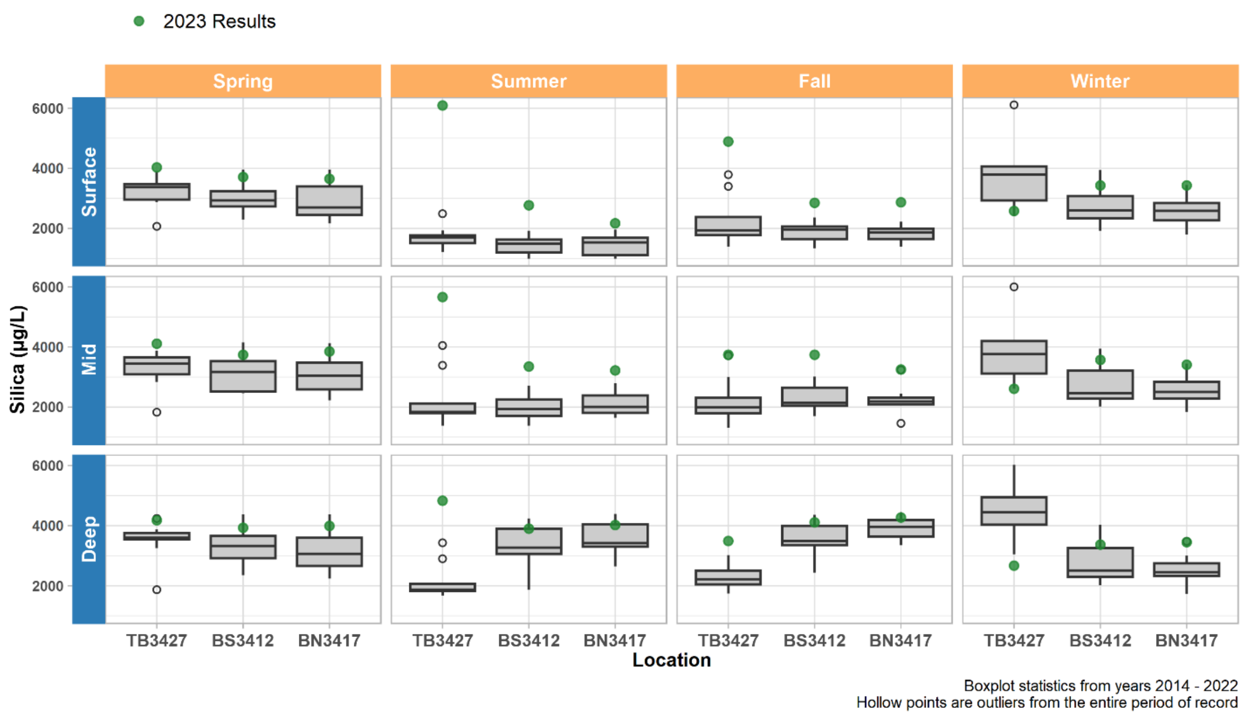
Figure 53: 2023 Total Kjeldahl Nitrogen in Wachusett Reservoir



3.4.7.3 Silica

Silica concentrations were between 2,170 and 6,090µg/L in 2023 (Figure 54). Silica is typically transported to the Reservoir through watershed runoff in spring where it is taken up by diatoms and other organisms requiring this nutrient. This pattern was observed in 2023 data where most spring values fell within or above the 75th percentile of historical data. Silica was elevated at most sites and depths, especially Thomas Basin through the summer and fall, likely due to anomalous precipitation events. Concentrations decreased following turnover and the summer period of primary productivity, but remained within or above the 75th percentile at Basin South and Basin North. Seasonal site maximums were recorded for 44% of samples in 2023, including most locations heavily influenced by the Quabbin transfer. An upward trend in TOC and UV_{254} has been observed at Shaft 1 as well as within the Quabbin Reservoir (See Section 3.2.7.3).

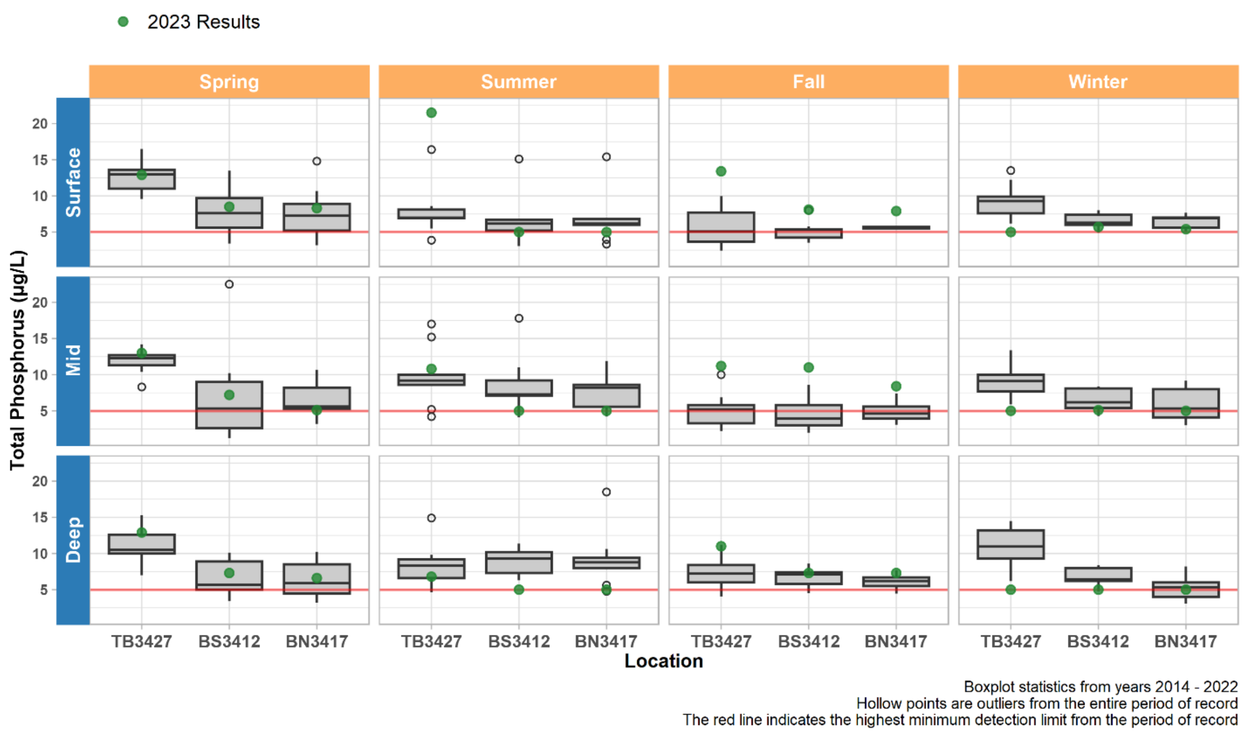
Figure 54: 2023 Silica in Wachusett Reservoir



3.4.7.4 Total Phosphorus

Total phosphorus (TP) results for 2023 followed typical spatial and temporal patterns and were within historical range although several seasonal site maximums were recorded. While 75% of results were lower than the 10 µg/L threshold for classification as an oligotrophic water body, 67% of samples collected from Thomas Basin and one sample from Basin South fell above this threshold (values between 10.8 and 21.5 µg/L) (Figure 55). Seasonal site maximums were recorded for all fall samples collected from the surface and mid-depths. Anomalous rain events in the summer and early fall likely contributed to these elevated concentrations. TP results following turnover returned to typical ranges across the reservoir with results ranging from below the detection limit (5.0 µg/L at six sites) to 5.7 µg/L.

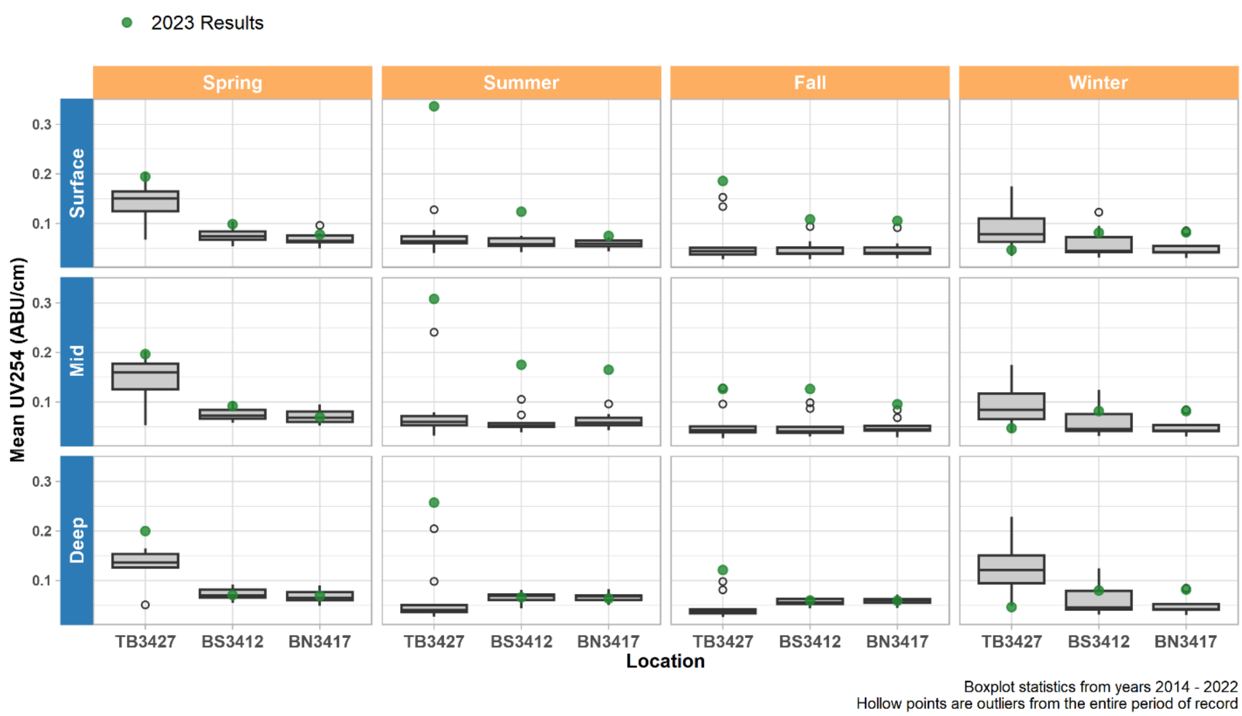
Figure 55: 2023 Total Phosphorus in Wachusett Reservoir



3.4.7.5 UV Absorbance

Measurements of UV_{254} were elevated for much of 2023, ranging from 0.046 to 0.337 ABU/cm (Figure 56). All three Thomas Basin summer samples exceeded the historic maximum for all reservoir sites. Seasonal site records were recorded at 14 locations, most from the surface and mid-depths in the summer and fall as well as the bottom sampled depth in spring, summer, and fall at Thomas Basin. The timing of these elevated values follows anomalous rain events and above average rainfall in general, likely contributing to both increased mobilization of organics into the reservoir as well as a decrease in water volume transferred from Quabbin Reservoir which typically reduces UV_{254} measurements in the reservoir.

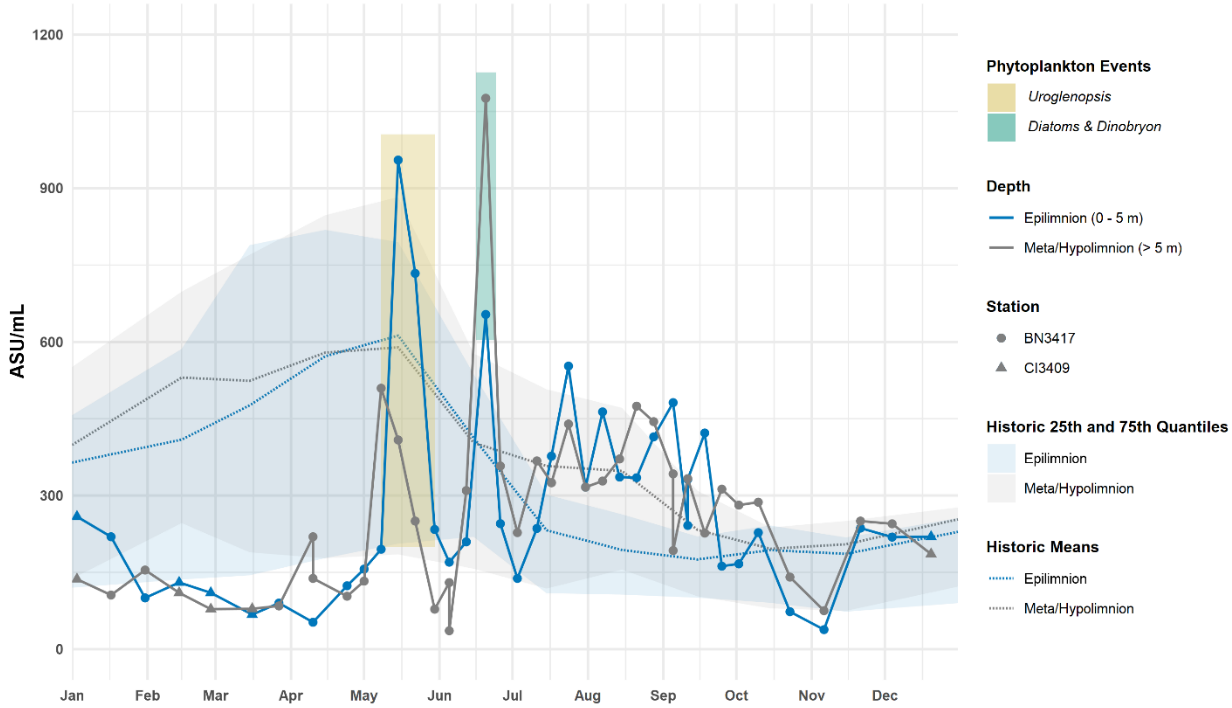
Figure 56: 2023 Wachusett Reservoir UV_{254}



3.4.8 Phytoplankton

A total of 94 phytoplankton samples were collected and analyzed on 38 days during the 2023 season. Ice-free conditions allowed collection of samples every other week through the winter, from January to May. Weekly sampling took place from May until October when productivity slowed and sampling every other week resumed through December 20. As in the previous two years, spring diatom densities were low in 2023 compared to the period of record. Four of the five taxa of special concern were enumerated throughout the year, but none exceeded the new Alert Levels established in 2023. The routine sample schedule was therefore adhered to for the duration of the year (Figure 57, Figure 59).

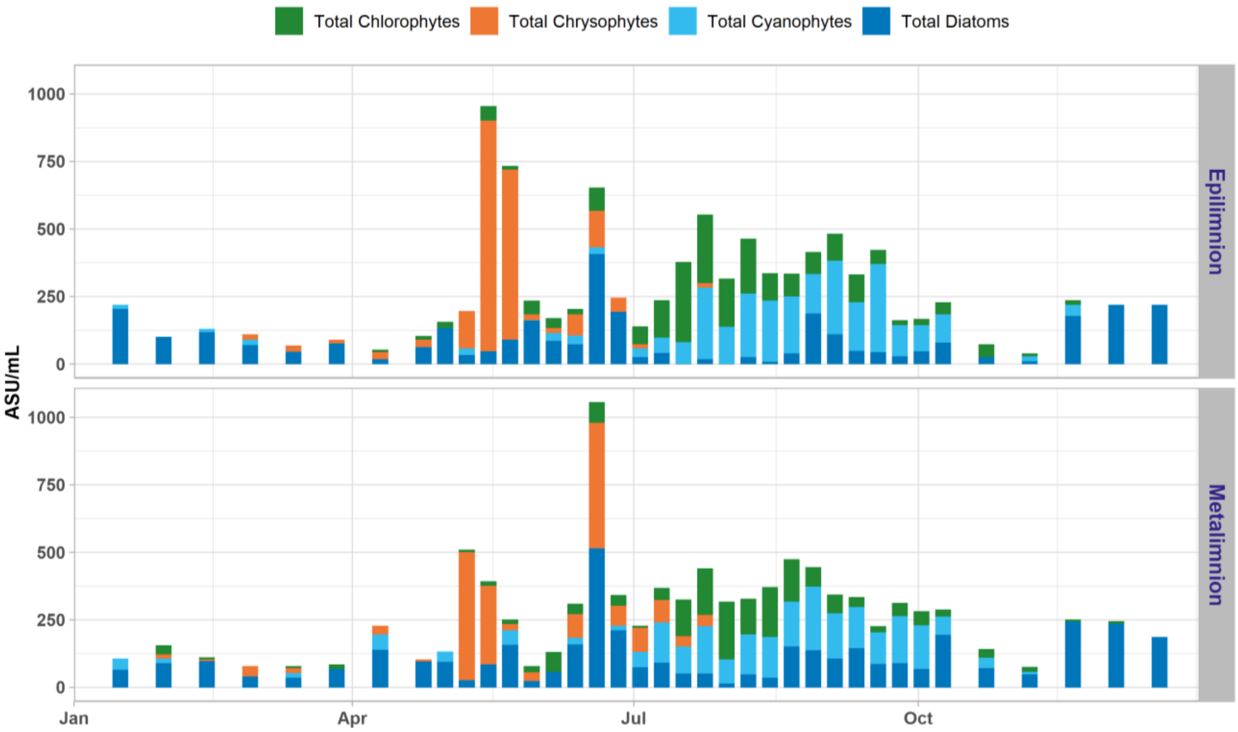
Figure 57: 2023 Wachusett Reservoir Phytoplankton Totals
Epilimnion range is 2 – 5 m, metalimnion range is 5 – 15 m.



The pattern of succession observed in 2023 followed the seasonal changes in phytoplankton community composition and density typically observed in the Wachusett Reservoir. Community composition by group is displayed in Figure 58.

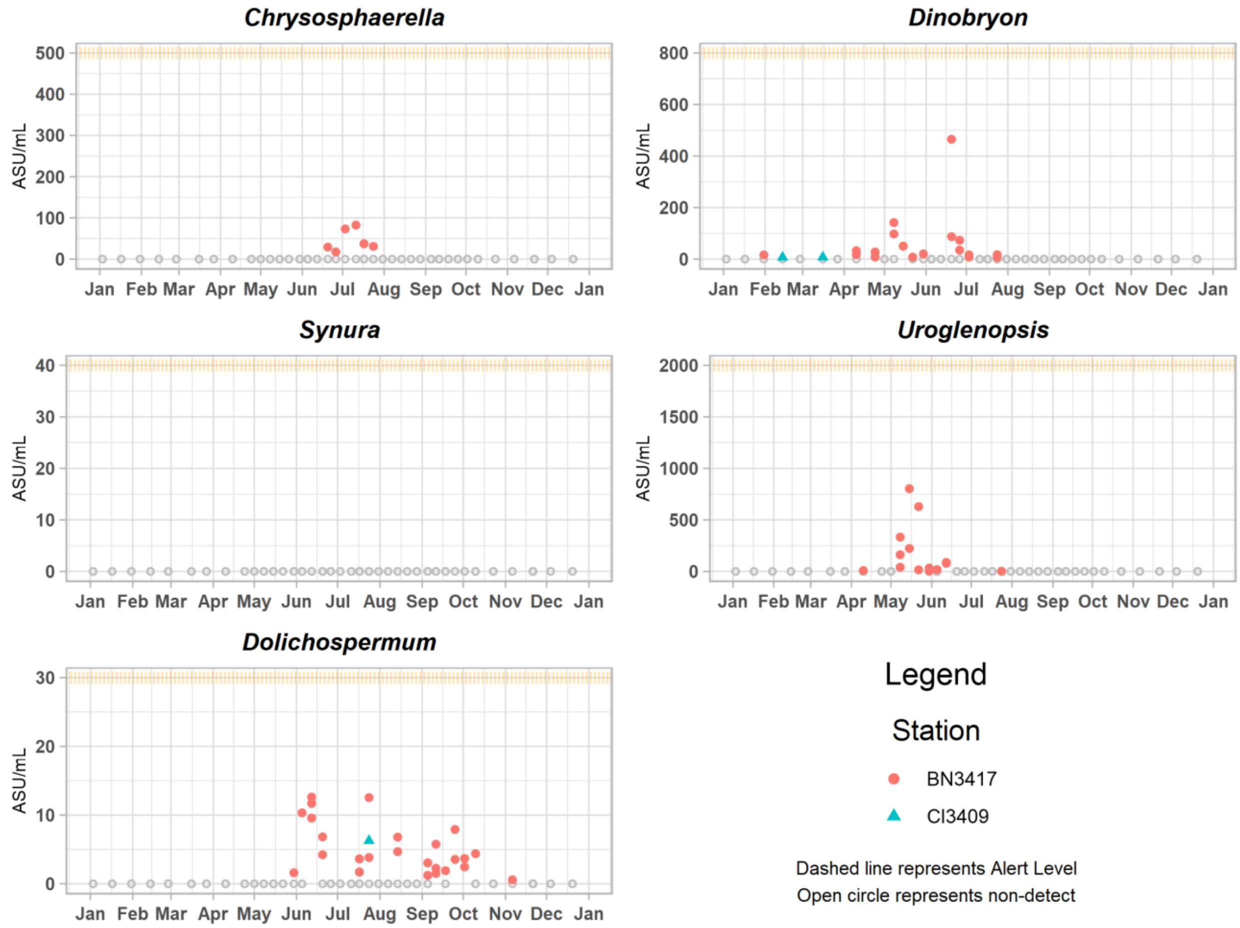
Figure 58: 2023 Phytoplankton Community Composition

Reported as weekly maximums for Basin North and/or Cosgrove Intake.



Diatoms dominated the phytoplankton community and low total densities were recorded from January through May, with some cyanophytes and chrysophytes present. Total densities remained below 300 ASU/mL until May when chrysophytes *Dinobryon* and *Uroglenopsis* increased in density (Figure 59). *Uroglenopsis* comprised 85% of the phytoplankton community at 3m when the maximum value for that taxa was observed at Basin North on May 22. *Uroglenopsis* decreased in density but remained present above the strengthening thermocline until late June. *Dinobryon* was present in most spring and early summer samples, with a maximum density of 465 ASU/mL occurring on June 20 at 5.5m. The maximum diatom density was also recorded on that day, bringing the grand total phytoplankton density at Basin North 5.5m to 1,076 ASU/mL; the maximum recorded phytoplankton density for the year. Following this later than typical diatom peak, total densities decreased in July and remained below 550 ASU/mL for the remainder of the year.

Figure 59: 2023 Observed Concentrations of Nuisance Phytoplankton Taxa in Wachusett Reservoir



Dolichospermum was present in samples sporadically from June through November but remained below the 30 ASU/mL threshold with a maximum density of 12.6 ASU/mL recorded at Basin North 3m on June 12 (Figure 59). Two brief cyanobacteria aggregation events were observed in the reservoir during 2023; one was reported by a member of the public and one was observed by aquatic biologists during routine surveys. On June 13, DWSP staff were notified that a potential cyanobacteria bloom was observed by a member of the public the previous day along the shoreline of Pine Point. Aquatic biologists responded and found a small (less than 100 ft^2) aggregation of *Dolichospermum* along the shoreline. Several other areas of the reservoir were surveyed and no additional aggregations were observed. On the afternoon of October 5, an aggregation primarily comprised of *Dolichospermum* and *Worochinia* was observed by aquatic biologists in the boat cove and nearby shoreline. Surveys were conducted the following day and no additional accumulations were reported. No adverse effects to drinking water quality were reported during these brief events.

Cyanobacteria levels were slightly higher than those observed in recent years with densities between 100 and 271 ASU/mL maintained from mid-July through mid-October. The maximum total cyanobacteria density of 326 ASU/mL was recorded from Basin North 3m on September 18. *Aphanocapsa* was the dominant taxa on this date with a density of 123 ASU/mL.

3.4.9 Zooplankton

A total of 48 zooplankton samples were collected in conjunction with the 2023 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 and none have been recorded in the Reservoir to date.

3.4.10 Fish

Monitoring programs in 2023 were limited to the *Salvelinus namaycush* (Lake Trout) mark-recapture study. High flow conditions in the watershed prevented opportunities for electrofishing stretches of the Stillwater River for *Salmo salar* (Atlantic Salmon) that typically occur in cooperation with MassWildlife. MassWildlife did survey Gates Brook for *Salmo salar* and *Salvelinus fontinalis* (Eastern Brook Trout) on October 10.

The Wachusett Reservoir *S. namaycush* mark-recapture study continued in 2023. This annual study began in 2014, when MassWildlife and DWSP partnered to investigate the status, life history, and sustainable yield of the Wachusett Reservoir *S. namaycush* population. This study is similar to the ongoing effort at Quabbin Reservoir.

S. namaycush 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 *S. namaycush* population is collected, DWSP and MassWildlife will be able to evaluate both the effects of angling pressure and the susceptibility to climate change [63].

To date, 1,146 *S. namaycush* have been captured during fall sampling efforts between 2014 and 2023, and 895 of these individuals have been assigned a unique ID, tagged, and released (Table 30). From 2014-2023, there have been 65 recapture events of 58 individually tagged fish, five of which have been recaptured at least twice. In 2023, there were nine recapture events, 107 fish that had not been previously caught were tagged, and 125 fish were caught in total. Nine fish were caught but not tagged due to mortality or inability to insert a tag. The data collected contribute to the development of the length-weight relationship for the Wachusett *S. namaycush* population. The 2023 mean weight was the second lowest on record and mean length was tied for lowest on record (Table 30).

[63] Thill, 2014

Table 30: *S. namaycush* Annual Caught and Tagged Results

Year	Caught	Tagged	Recaps	Caught Mean Weight (g)	Caught Mean Length (mm)	Not Tagged
2014	110	100	2	1,974	582	6
2015	161	137	10	1,427	547	14
2016	67	56	4	1,312	553	7
2017	83	66	10	1,016	515	7
2018	71	59	6	1,402	541	6
2019	162	142	8	1,422	538	12
2020	114	NA	NA	1,367	540	114
2021	134	123	7	1,172	535	4
2022	119	105	9	1,282	533	5
2023	125	107	9	1,057	515	9
Total	1,146	895	65	1,352	539	186

In 2023, 76% of *S. namaycush* captured in Wachusett Reservoir were males, 21% were females, and 3% were immature. The proportions of the total catch in 2023 were consistent with the results of previous years (Figure 60). Results show that reservoir females are often larger and heavier at capture than males (Figure 61). Evidence suggests that male *S. namaycush* are caught more frequently in gill nets set during the spawn because they spend more time on the spawning grounds searching for females [64]. 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[65].

64 Binder et al., 2016
65 Binder et al., 2014

Figure 60: Proportion of Total *S. namaycush* Catch by Sex

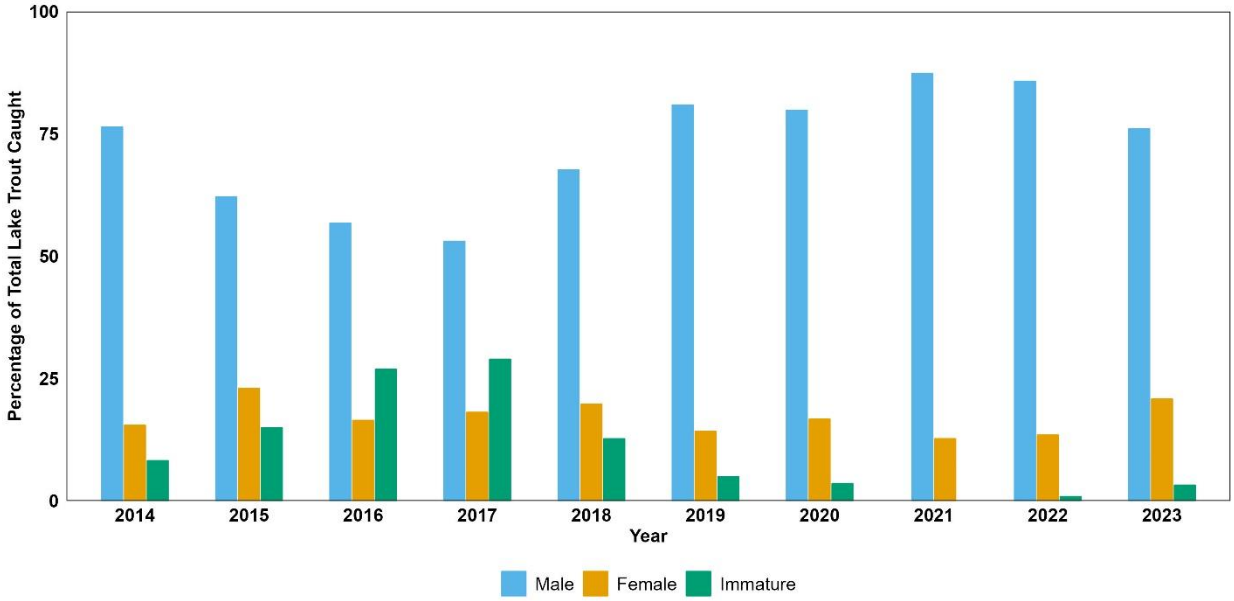
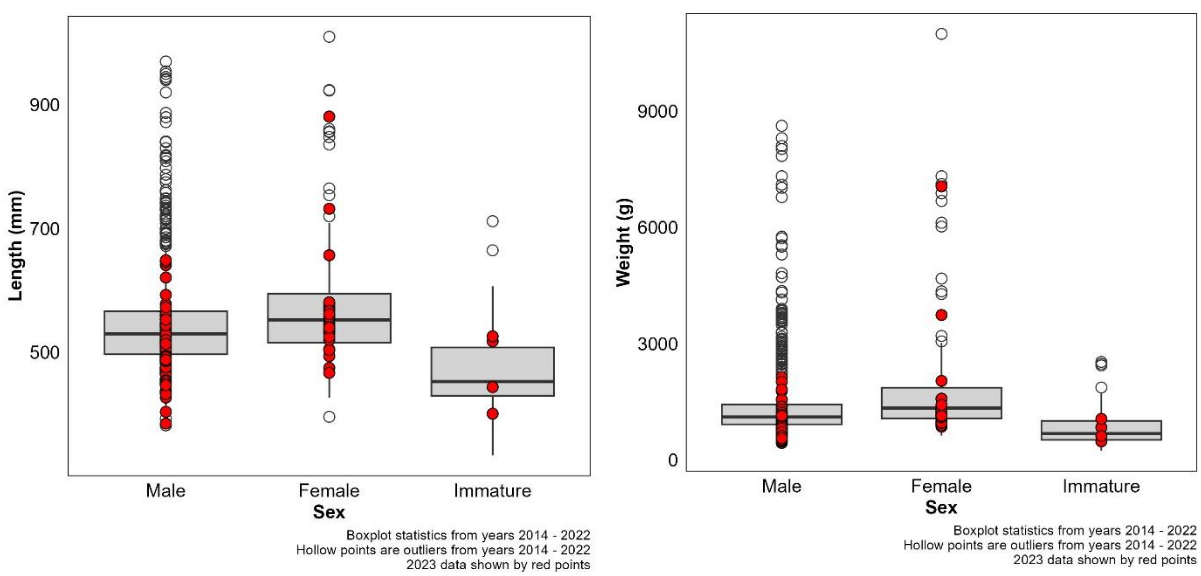


Figure 61: Wachusett *S. namaycush* Length (left) and Weight (right)



3.4.11 Bacteria

In 2023, *E. coli* samples were collected at 23 transect points in Wachusett Reservoir three times in January and once per month February through December (Table 31). Elevated *E. coli* concentrations were most common during the winter months at transects points south of the narrows (transects G – N, Figure 3). *E. coli* was also higher than usual on sampling days in July through September, most likely due to the numerous rainfall events during this period. The highest bacteria levels observed at transect location A3, which is closest to the Cosgrove Intake, were on August 9th (25 MPN/100 mL) and September 13th (8 MPN/100 mL). Harassment was able to confine the roosting bird populations to the southern parts of the

Reservoir, as evidenced by the predominantly lower bacteria results observed in Basin North (transects A - F), even during colder months when birds were most numerous. All reservoir bacteria transect results for 2023 are provided in Table 31.

Table 31: Reservoir Bacteria Transect Results for 2023 – *E. coli* (MPN/100 mL); Sampled at 0.1 – 0.3 m
Result values of 1 were below the method detection limit, which was 1 MPN/100 mL.

Date	A3 (Cosgrove)	B2	B3	C1	C3	C5	D1	D2	D4	E2	E4	F2	F3	F4	G2	H2	I2	J2	J3	J4	K2	M1	N1
Jan 04	1	1	1	1	1	1	1	1	1	2	1	2	2	1	4	5	3	6	11	45	21	24	56
Jan 17	1	1	1	1	1	1	11	3	1	16	2	4	3	4	6	6	14	8	9	27	27	11	29
Jan 31	1	1	1	1	1	1	2	3	1	6	1	1	2	1	3	5	2	4	10	15	27	14	11
Feb 22	2	1	1	1	1	2	2	3	1	5	1	2	4	1	3	3	3	7	38	19	38	12	15
Mar 29	2	1	3	2	1	1	4	8	1	5	2	5	1	1	3	2	1	1	1	3	2	1	1
Apr 20	1	1	1	1	1	1	1	15	1	1	1	1	15	1	1	1	1	1	1	1	1	2	2
May 10	1	1	1	1	1	1	1	1	1	10	2	1	1	1	1	1	1	1	1	1	1	1	1
Jun 14	1	1	1	1	1	2	1	1	1	6	1	1	2	1	1	1	1	2	1	1	1	5	1
Jul 05	3	1	1	2	2	29	3	1	1	3	5	6	1	2	3	2	5	1	1	9	3	11	3
Aug 09	25	2	3	1	1	2	1	1	5	8	4	1	5	3	1	1	4	1	1	1	1	25	4
Sep 13	8	5	3	4	5	2	2	3	4	4	1	4	4	6	3	2	15	1	2	9	6	12	8
Oct 11	1	1	1	3	1	2	1	1	1	1	1	2	4	1	4	1	2	2	3	1	3	1	6
Nov 08	1	2	4	2	1	1	1	1	4	5	1	1	1	1	1	1	1	1	4	1	4	2	1
Dec 14	3	1	2	1	6	1	1	1	1	5	2	1	8	9	2	4	11	1	15	38	16	31	24

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. One sample (May 8) was not analyzed due to a laboratory accident. The SDWA regulations for drinking water require that a minimum of ninety percent of all source water samples (in any six-month period) contain less than 20 MPN/100 mL fecal coliform. All 364 samples from CWTP analyzed in 2023 contained less than the standard, with a maximum concentration of 14 MPN/100 mL on two days: March 2 and September 20. Most samples (55%) did not contain any detectable bacteria. DWSP has put considerable time and effort into implementing a rigorous bird harassment program, and the results in 2023 continued to prove that the efforts are effective at maintaining low numbers of both birds and bacteria.

3.5 Macrophyte Monitoring and Management

Aquatic invasive species (AIS) have serious drinking water quality implications including potential 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[66]. It is updated periodically to reflect changes in AIS composition within and in proximity to the Reservoir.

Table 32. 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	
Hydrilla verticillata	Hydrilla		x
Myriophyllum heterophyllum	Variable leaved water-milfoil (VLM)	x	x
Myriophyllum spicatum	Eurasian water-milfoil (EWM)	x	x
Najas minor	Brittle naiad		x
Nymphoides peltata	Yellow-floating heart		x
Phragmites australis	Common reed	x	x
Potamogeton crispus	Curly-leaf pondweed		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 2023 as well as those planned for 2024.

3.5.1 Wachusett Reservoir – Invasive Macrophyte Control Program

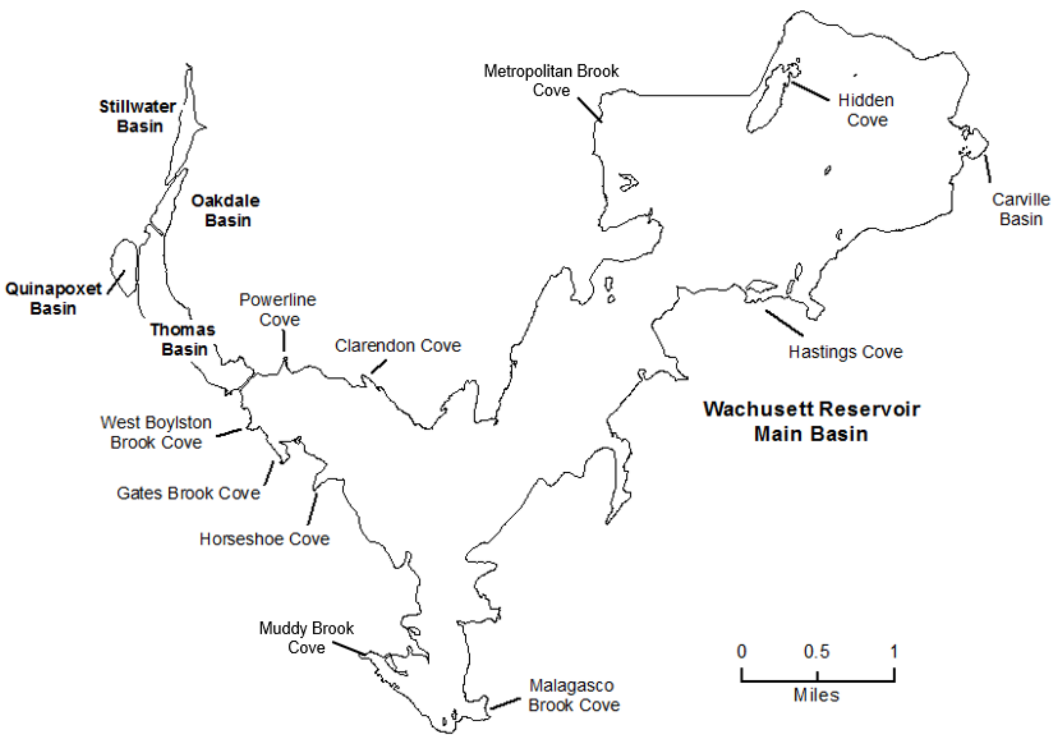
M. spicatum was first identified in the Wachusett Reservoir system in August 1999. The plants were initially isolated to Stillwater Basin; however, over the next several years, distribution extended southerly, in the direction of water flow, progressing through Oakdale Basin, into Thomas Basin and the upper coves of the Main Basin west of the Route 12/140 causeway in West Boylston. *C. caroliniana* 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 62). As new infestations are identified, these areas are also

66 Trahan-Liptak & Carr, 2016

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 *Myriophyllum heterophyllum* 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 62: Locations of 2023 AIS Management in the Wachusett Reservoir System



The main components of this program are as follows:

- Deployment and maintenance of floating fragment barriers
- Utilizing hand-harvesting and DASH
- Assurance checks of select areas harvested with DASH
- Routine scouting within the Reservoir and Watershed by DWSP aquatic biologists to ensure early detection of pioneering infestations
- Immediate removal of pioneer infestations upon detection
- Point-intercept vegetation surveys by independent contractors (GEI Consultants, 2023)
- Scouting the entire littoral zone of Wachusett Reservoir every five years (completed in 2012, 2016 and 2021)

Highlights of management in 2023 include the following:

- Low density of *M. spicatum* and *C. caroliniana* continued in the upper basins (Figure 63).
- Removal of *M. heterophyllum* continued in all managed areas of the Reservoir and harvest decreased in the upper basins, including Quinapoxet, for the first year since it was added as a managed species (Figure 64).
- A total of approximately 22,280 gallons of biomass were removed from Quinapoxet Basin.
- *C. caroliniana* has not been observed in Quinapoxet Basin since 2018 and *M. spicatum* density remains low (Figure 65).
- *C. caroliniana* was not encountered in Thomas Basin for the first year since management began and just three stems were removed from Oakdale Basin.

Figure 63: *M. spicatum*, *C. caroliniana*, and *M. heterophyllum* Removed from Wachusett Reservoir 2003 to 2023
Plot shows totals removed from Oakdale, Thomas, and Powerline Coves

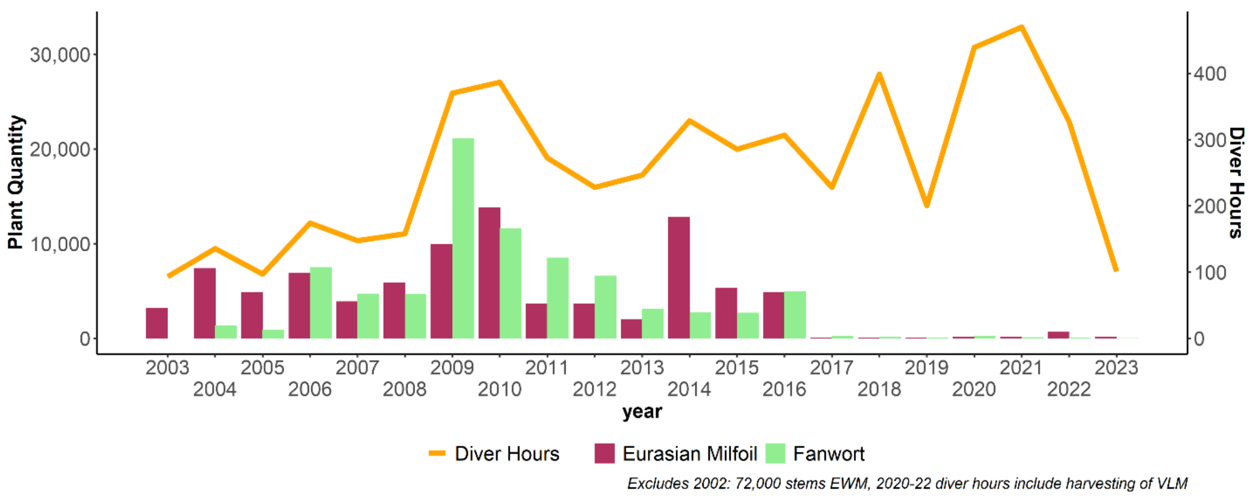


Figure 64: Invasive Species Removed from Wachusett Reservoir 2018 to 2023
Plot shows totals removed from Oakdale, Thomas, and Powerline Coves and includes totals for M. heterophyllum *stems and gallons which are reported depending on plant density.*

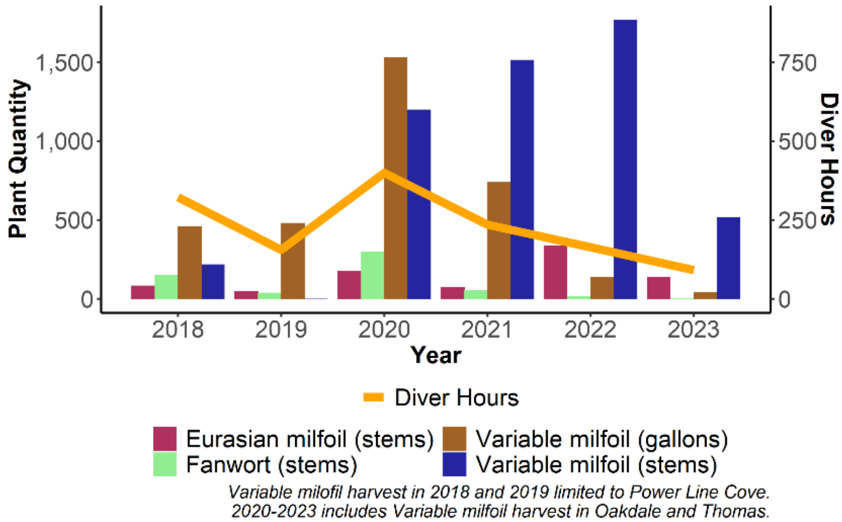
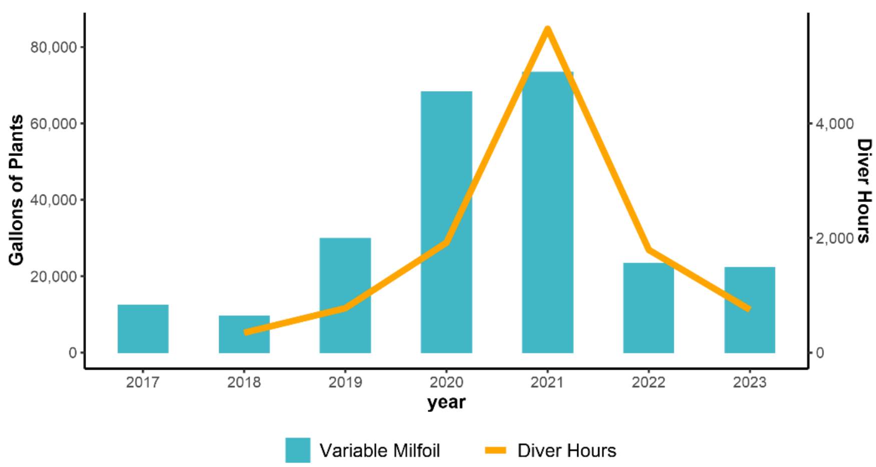


Figure 65: *M. heterophyllum* Removed from Quinapoxet Basin 2017 – 2023



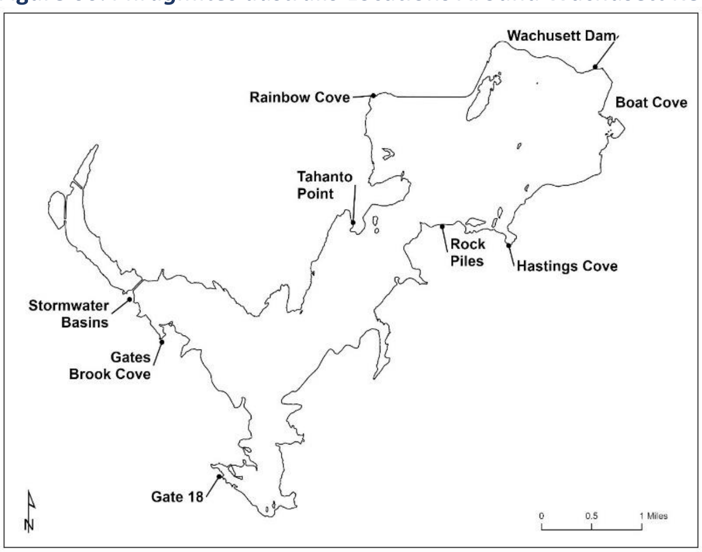
3.5.2 *Phragmites* Management

DWSP EQ staff surveyed and managed *Phragmites australis* at 20 locations around the Wachusett Reservoir shoreline in 2023 (Table 33, Figure 66). Manual and mechanical removal were the primary management methods used. Management progress was tracked with a series of photographs, taken at the same location before and after each management event. Historical *P. australis* photographs have been preserved in DWSP files and additional background on *P. australis* management at Wachusett Reservoir can be found in prior Annual Water Quality Reports. *P. australis* monitoring and/or management typically occurs monthly from June to October; the goal of monthly monitoring is to schedule management actions to prevent *P. australis* from going to seed and to reduce the above and below ground biomass of all stands. Surveys were completed on June 6, July 26, and September 14. Active management in 2023 included one event on September 28.

Table 33: Shoreline *Phragmites australis* at Wachusett Reservoir

Stand ID	Initial Area (ft^2)	First Documented	2023 Management Method
Boat Cove A	1071	2013	Cutting, Hand pull
Boat Cove B	1640	2013	Cutting
Boat Cove C	316	2013	Cutting, Hand pull
Boat Cove D	50	2022	Cutting
Gates Brook	1314	2014	None
Hastings Cove A	422	2009	Absent
Hastings Cove B	6034	2009	Cutting
Hastings Cove C	1635	2009	Cutting
Hastings Cove D	504	2009	Hand pull
Hastings Cove E	190	2009	Hand pull
Hastings Cove F	146	2009	Absent
Rainbow Cove	896	2009	Cutting
Tahanto Point A	860	2016	Absent
Tahanto Point B	511	2016	Hand pull
Storm Water Basins (x3)	19	2017	None
Rock Piles	112	2018	Absent
Dam	6	2018	Absent
Gate 18 Storm Water Basins	10	2021	None

Figure 66: *Phragmites australis* Locations Around Wachusett Reservoir



The reduction in management effort in 2023 is indicative of the progress made in reducing apparent above ground biomass. Overall, the Reservoir stands continued to show diminished regrowth compared to previous years; individual plant height appears to be reduced at most survey locations. As in 2022, Hastings Cove and Rainbow Cove had a higher incidence of individual stems within the terrestrial areas along the shoreline compared to other stands. *P. australis* was not observed at Tahanto Point A, the Wachusett Dam, Rock Piles, and two Hastings Cove locations. The stand at Boat Cove A appears drastically reduced. Management in 2024 will include monthly monitoring from June to October, with management as needed.

3.5.3 Wachusett Reservoir – Vegetation Monitoring

MWRA contracted with GEI Consultants to carry out point-intercept surveys of DWSP/MWRA source and emergency reservoirs. No new AIS were discovered in Wachusett Reservoir during the 2023 survey and substantial increases in distribution and density were not observed. *Glossostigma cleistanthum* (mudmat) was observed at 28 more locations in 2023 than in 2022, totaling 67 locations throughout the reservoir. Water quality impacts from this minute non-native species are assumed to be limited. GEI reported that *Elodea* species remained the most frequently encountered native aquatic genus in Wachusett Reservoir. Overall, GEI reports that aquatic plant cover, density, and biovolume have remained stable over the past several years[67].

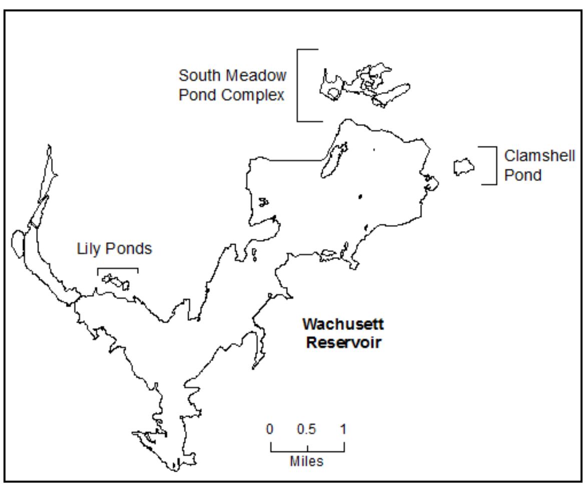
3.5.4 Supplemental Invasive Macrophyte Control Activities

Additional activities were conducted in 2023 outside of Wachusett Reservoir in conjunction with the main components of the in-reservoir invasive control program.

3.5.4.1 Management of AIS Outside of Wachusett Reservoir

AIS, including several novel species not found in Wachusett Reservoir have been identified in water bodies close to the Reservoir (Figure 67). Although Clamshell Pond and the South Meadow Pond Complex are outside of the Wachusett Reservoir Watershed, each of these waterways 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 and monitoring of these ponds by DWSP is ongoing.

Figure 67: Locations of Local Ponds Managed for AIS



[67] GEI, 2023

South Meadow Pond Complex

Hydrilla was first discovered in August 2010 in the South Meadow Pond Complex, located just 1,970 feet (600 m) north of Wachusett Reservoir. A rapid response plan was initiated with the first herbicide treatment conducted in fall 2010. Herbicide treatments have continued annually with management of *P. crispus* added to the treatment program upon its discovery in 2015. *Najas minor* was discovered in 2022 and was subsequently added to the treatment program.

Results of treatment are monitored through pre- and post-management surveys conducted by the contractors and DCR and a tuber sampling program conducted by 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 management.

In 2023, TRC was contracted to conduct a detailed assessment of the aquatic plant community and *Hydrilla* tuber density, and to provide recommendations for ongoing management. Based on these surveys, *P. crispus* was managed with an application of diquat on May 10 to approximately three acres of South Meadow Pond. Approximately nine acres of *Hydrilla* were mapped as part of summer survey efforts and subsequently treated with the contact herbicide endothall. These *Hydrilla* beds were distributed throughout the pond complex. Two additional invasive species, *Nymphoides peltata* and *Trapa natans*, were observed, bringing the known submerged AIS total present in South Meadow Pond to six (*Hydrilla, M. heterophyllum, N. minor, N. peltata*, *P. crispus*, and *T. natans*). The single observed specimen of *T. natans* was removed, *N. peltata* will be integrated into the ongoing management program, and *N. minor* was not observed in 2023.

Based on results of the 2023 surveys, TRC has recommended at least four years of intensive management for the AIS present in South Meadow Pond using a combination of early season contact herbicide treatments to target *P. crispus* and carefully regulated complex-wide systemic treatments targeting *Hydrilla* with incidental control of *N. minor*, *N. peltata*, and *M. heterophyllum* anticipated. Monitoring for species not observed in 2023 will continue. The key component of this management program will be the systematic use of a systemic herbicide (fluridone) throughout the treatment period, a likely factor in lack of successful management in prior years.

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[68].

E. densa was treated with the contact herbicide diquat in June 2018; it has not been observed in Clamshell Pond in any subsequent surveys. During surveys, DWSP biologists also monitor the *T. natans* population and remove plants, as necessary. In 2023, surveys were completed on May 23 and August 24. *T. natans* was not observed during the May survey, but three *T. natans* plants were removed during the August

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

survey. The native macrophyte community consisted of dense submerged vegetation including *Potamogeton robinsii* (Fern-leaf Pondweed) and *P. ampifolius* (Big-leaf Pondweed), and dense floating vegetation including *Brasenia schreberi* (watershield), *Nymphaea odorata* (white water lily), and *Nuphar variegata* (yellow water lily). *Schoenoplectus subterminalis* (water bulrush) was also observed along the shoreline. *P. robbinsii* was the primary species collected by a rake toss. *Utricularia vulgaris* (common bladderwort) was also distributed throughout the pond. These findings are similar to previous years.

Lily Ponds

Najas minor 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* remains in each pond, likely due to a seed bed which persists in the sediment.

In 2023, *N. minor* in all three ponds was managed in late June via application of the systemic herbicide fluridone. Herbicide concentration samples collected on August 1, approximately four weeks post treatment, showed concentrations across the three ponds ranged from 5.8 to 12.1 ppb. *N. minor* was not observed in subsequent surveys.

4 Conclusions and Recommendations

4.1 Wachusett Tributary Water Quality

In 2023, many water quality and hydrological statistics fell outside of normal ranges due to extreme climatological conditions. 2023 was the wettest year in the Wachusett Watershed since at least 1985, with 64.44 inches of rainfall. Additionally, the winter months January, February, and December were either the warmest on record or tied with a prior year, while August 2023 was the coldest August in the period of record. Typical hydrological patterns did not occur in 2023, as streamflows and groundwater levels remained higher than normal through the summer and early fall. The numerous precipitation events, including the extreme precipitation of September 12 in the Stillwater River headwaters, resulted in elevated solute concentrations during episodes of overland runoff and flooding, as well as low solute concentrations during subsequent periods of baseflow dominant streamflow.

Tributary water temperatures followed typical seasonal patterns, with summertime high temperatures rising above the MassDEP recommended threshold for coldwater species (20 °C) in several tributaries for durations spanning 6 – 97 days (though not necessarily consecutive). Although CFR temperature standards were not met at all monitoring locations, areas of groundwater exfiltration and deeper pools (which are unmonitored) do provide thermal refuge for temperature sensitive species. All tributaries remained within the recommended temperature range for warm water species. Dissolved oxygen levels remained in the recommended ranges at all CFR tributaries and all WFR tributaries, except for the Stillwater River (CFR) at one monitoring visit and at Waushacum Brook (WFR) on six monitoring visits. The summertime low dissolved oxygen in Waushacum Brook is common, and likely due to the large and often stagnant wetland area just upstream of the sample location. The single low dissolved oxygen measured in the Stillwater River was 5.9 mg/L; only 0.1 mg/L below the CFR threshold. 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.

Bacteria concentrations in 2023 (*E. coli* geometric means) were lower than in 2022 at every Wachusett Reservoir tributary except for Boylston and Trout Brooks. Cooler summer temperatures and elevated base flows due to excess precipitation helped to dilute concentrations and slow bacteria growth. Consistent with previous years, bacteria concentrations were higher during periods of wet weather. The frequent medium size storms (1 -2 inches) resulted in most tributaries exceeding the 235 MPN/ 100 mL Class A surface water standard at least once during the year. Elevated bacteria concentrations persisted at Gates Brook 4 and West Boylston Brook throughout much of 2023, however the annual geometric mean at West Boylston Brook fell below the 126 MPN/mL long-term threshold. The elevated bacteria in Gates Brook was investigated in the late spring and summer, and the source was linked to wildlife activity near food service businesses located along Rt. 12 in West Boylston. The businesses owners were asked to be diligent in their waste management practices, as to eliminate food sources that may be attracting wildlife to the area.

Despite the record rainfall in 2023, mean turbidity in the Wachusett tributaries was lower than in the previous two years. The lack of extreme low flows during 2023 meant that stream water columns were deep enough to avoid collecting water samples close to the stream bed, which often results in elevated turbidity. The extreme precipitation event in the Stillwater River headwaters on September 12 delivered a significant amount of sediment and debris into the upper basins of the Reservoir, with smaller particles (silt and clay) reaching the Cosgrove Intake. The implications of this event are difficult to predict, but the large pulse of nutrients, sediment and organic matter to the upper basins could certainly affect algal dynamics in the 2024 growing season as well as macrophyte growth and spatial distribution.

Although there were occasional elevated bacteria and turbidity results during 2023, Wachusett tributary sanitary quality continues to be excellent overall, providing source water that meets all drinking water compliance standards for bacteria and turbidity.

Alkalinity and pH monitoring continued in 2023, without any remarkable observations to note. The seasonal variation in pH was less pronounced in 2023 compared to prior years, possibly due to the stability of baseflow contributions to streamflows along with the frequent precipitation throughout the year. 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.

In 2023, all monitoring locations experienced a decrease in specific conductance from 2022, except for Jordan Farm Brook, with levels closer to 2021, which had similar surplus precipitation. The increased temporal resolution of specific conductance measurements obtained from the Mayfly monitoring stations and USGS stations provided greater insight into the true variability of specific conductance levels of the primary Wachusett tributaries. While the mean annual values of the high-resolution results were similar to the grab results, the grab samples collected 2-3 times per month did not capture the high and low spikes that occurred during runoff events. Salt loads were estimated for the first time for all primary tributaries. Although mean annual specific conductivity and chloride concentrations were generally lower in 2023 compared to 2022, the total annual salt loads in the primary Wachusett tributaries combined to be 52% higher in 2023 compared with 2022. This is likely attributed to an 85% increase in tributary discharge from 2022 to 2023.

Routine tributary and groundwater monitoring results for dissolved salts and specific conductance in 2023 continue to be elevated across several Wachusett Watershed subbasins. Chloride concentrations in Gates and West Boylston Brooks continued to be above chronic chloride toxicity threshold during several periods throughout 2023. High temporal resolution specific conductivity data collected from several of the Mayfly and USGS monitoring stations show continued evidence of chloride spikes above the acute toxicity threshold for aquatic life occurring after road salt applications.

Elevated Cl/conductivity in the Wachusett Reservoir and tributaries continues to be a high priority concern for DWSP and is the focus of additional research in collaboration with UMass, ongoing mitigation, and planning efforts at DWSP. An expanded groundwater monitoring report was completed in 2022, which summarizes and interprets Wachusett Watershed groundwater quality data and offer recommendations for future groundwater monitoring and research. The conductivity blitz for surface waters was completed in 2023. High frequency conductivity monitoring (10–15-minute measurement intervals) at three USGS stations and seven Mayfly stations provided greater insight into the variability and rapid fluctuations of dissolved ion concentrations that are not captured by routine measurements taken only three times per month. These data will enable DWSP to calculate estimated loads of dissolved salts delivered to the Wachusett Reservoir from approximately 87% of the watershed land area. This data will provide the Conductivity/Chloride working group a means to evaluate the success of chloride reduction efforts over time and develop geographically targeted strategies to reduce chloride loads throughout the Wachusett Watershed.

Routine tributary nutrient monitoring results for 2023 were consistent with historical data and demonstrate continued adherence to drinking water quality standards. Total Nitrogen concentrations have been generally consistent across all primary tributaries since 2015. Aside from Muddy Brook and the Stillwater River, the fraction of organic forms of nitrogen in 2023 was higher than in 2022, likely as a result of the frequent rain storms throughout the year. The observed concentrations of nitrogen compounds during 2023 continued to be well below regulatory standards and are not sufficiently elevated to be a water quality concern. Annual mean TP concentrations for 2023 were mostly within the ranges observed over the previous nine years. The 2023 mean annual TP concentrations for Waushacum and Trout Brooks were the lowest in the past 10 years, while the Malagasco Brook mean annual TP concentration was the highest. The observed TP concentrations in Wachusett tributaries for 2023 were generally low and mostly within ecoregional background ranges. Three tributaries (French, Trout, and Malagasco Brooks) have long-term median TP concentrations above 23 µg/L, which could be indicative of phosphorus loading beyond background levels. If time and resources allow, additional assessments could be conducted to determine sources of excess nitrogen in Malagasco and Malden Brooks and phosphorous in French, Malagasco, and Trout Brooks.

In 2023, TOC concentrations and UV_{254} levels were elevated in comparison to recent years, with six tributaries recording their highest mean annual TOC concentration on record. The overall mean TOC concentration for 2023 was 6.13 mg/L, which is 24% higher than the long-term mean concentration since 2014 (4.94 mg/L). A recent internal trend analysis for UV_{254}, which strongly correlates to TOC concentrations, found that variation in UV_{254} is highly influenced by precipitation patterns. Thus, the high level of watershed carbon export, reflected by tributary TOC concentrations and UV_{254} levels, was a predictable consequence of the record rainfall during 2023. The long-term trends for UV_{254} in Wachusett tributaries are mixed, with some slightly decreasing and some slightly increasing. The only statistically significant trends were from French, Malagasco, and Trout Brooks, which were all decreasing. However, higher resolution UV_{254} data available for Cosgrove Intake showed a statistically significant and slightly increasing trend. The formation of disinfection byproducts from reactive organic compounds, especially during the latter half of 2023, posed increased water treatment challenges for MWRA and remains a top water treatment concern. DCR staff should continue efforts to better understand the drivers of temporal and spatial variability of carbon loading to Wachusett Watershed tributaries and continue to research management practices or changes to reservoir operations that could help reduce the reactive carbon loads to the Wachusett Reservoir.

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 slightly elevated beyond the 75^{th} percentile, were isolated events, or can be tied to specific factors such as abnormally high rainfall.

Results of routine water quality profiles were comparable 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.

The annual maximum specific conductance observed at Basin North was lower than observed in 2022; however, the mean and minimum values were higher. Overall, specific conductance has decreased since the historical highs observed in 2018, potentially due to dilution from increased Quabbin transfers. Elevated concentrations of silica and total phosphorus, and elevated UV_{254} values were recorded for many sites throughout the year. These values largely coincide with relatively high specific conductance values (for these sites/timeframes), indicating a higher percentage of native Wachusett water present in these locations following periods of elevated precipitation and subsequent tributary discharge. As is typical, overall concentrations improved following turnover and the anomalous weather events experienced in this year are not expected to adversely affect water quality for the long term. However, as the region experiences climate change, these and other atypical events may become more common, leading to long-term impacts to water quality.

4.3 Proposed Wachusett Watershed Monitoring Programs

4.3.1 Hydrological and Climate Monitoring

Continuous monitoring with Mayfly dataloggers and Hydros-21 CTD sensors will continue for 2024 at seven primary tributary monitoring locations: French, Malagasco, Muddy, Malden, Trout, Waushacum and West Boylston Brooks. These stations measure conductivity, temperature, and depth at 15-minute increments with real-time raw data access via the internet. The existing HOBO U20 depth and temperature logger will remain in place at West Boylston Brook (for water depth/discharge only).

Groundwater levels will continue to be manually measured monthly at seven wells. USGS will continue to operate and maintain real-time monitoring stations at the Sterling and West Boylston wells as part of the Climate Response Network.

Snowpack measurements will continue during the winter months as in prior years. Prior to the 2022/2023 snow season, the location of the Boylston was moved closer to the access road parking area on Rt. 70 and given the location ID “BOY70”.

Monitoring Element	Current Program	Proposed Changes
Real-time flow monitoring	10 tributaries (3 by USGS)	No Change
Precipitation	2 USGS Stations, 2 NOAA Stations	No change
Snowpack (seasonally)	Weekly, 6 locations	No change
Groundwater levels	Monthly manual, 7 wells	No change

4.3.2 Groundwater Quality Monitoring

Using a flow cell to collect field parameter data, specific conductance, temperature, dissolved oxygen, and pH sampling that began in 2022 will continue in 2024. No samples will be collected for lab analysis under the WATWEL project in 2024. DWSP will continue to seek out additional wells in the watershed with existing data collected by other organizations or wells that can be added to the routine sampling program.

Monitoring Element	Current Program	Proposed Changes
Groundwater Quality	Monthly – Seven wells for specific conductance, temperature, dissolved oxygen and pH	No change

4.3.3 Tributary Monitoring

Routine tributary monitoring projects (WATMDC and WATTRB) and field parameter collection will continue at the same frequency and with the same parameters as in 2023. Real-time conductivity monitoring has will be continued at all primary tributary monitoring locations.

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, dissolved oxygen, pH, stage)	3x per month in conjunction with other projects	No change
Real-time conductivity monitoring (USGS or DWSP – using Mayfly)	3 USGS Stations, 7 DCR Stations	No change

4.3.4 Special Projects and Other Sampling

4.3.4.1 Long-term Forestry Study

It is anticipated that monitoring for long-term effects of water quality at forestry locations will resume in 2024 after the experimental lot (Princeton) is harvested. Sufficient dry and wet weather data has been collected to establish hydrologic and water quality relationships between the paired watersheds. The completion of a preliminary summary report for the pre-harvest phase is still pending.

4.3.4.2 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 Reservoir water on Wachusett Reservoir water quality.

4.3.4.3 Follow-up Bacteria Monitoring and Microbial Source Tracking

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. Samples may be sent in for DNA analysis if upstream tracking cannot determine the cause of elevated bacteria levels.

4.3.4.4 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.

4.3.4.5 Groundwater Isotope Sampling

Stable isotope sample collection was suspended in 2022 but may resume after a review of the data from existing isotope samples.

4.3.4.6 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. Sampling will depend on staff availability.

4.4 Reservoir Monitoring for 2024

Reservoir monitoring programs will continue as carried out in 2024. 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 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 2024.

Movement of water and contaminants through the Reservoir remains of significant interest. Sampling of the reservoir surface will continue regularly. Monthly, twice monthly, 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	No change
Secchi Disk Depth	Biweekly Oct – April at BN3417 or CI3409	No change
Phytoplankton	Regular phytoplankton sampling will continue; the frequency of additional monitoring for taste and odor taxa to be decided in concert with MWRA based on alert thresholds	No change (Updated Phytoplankton Action Plan in 2023)
Nutrients	Quarterly	No change
Zooplankton	Quarterly	No change
Fish	Fall *S. namaycush* 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

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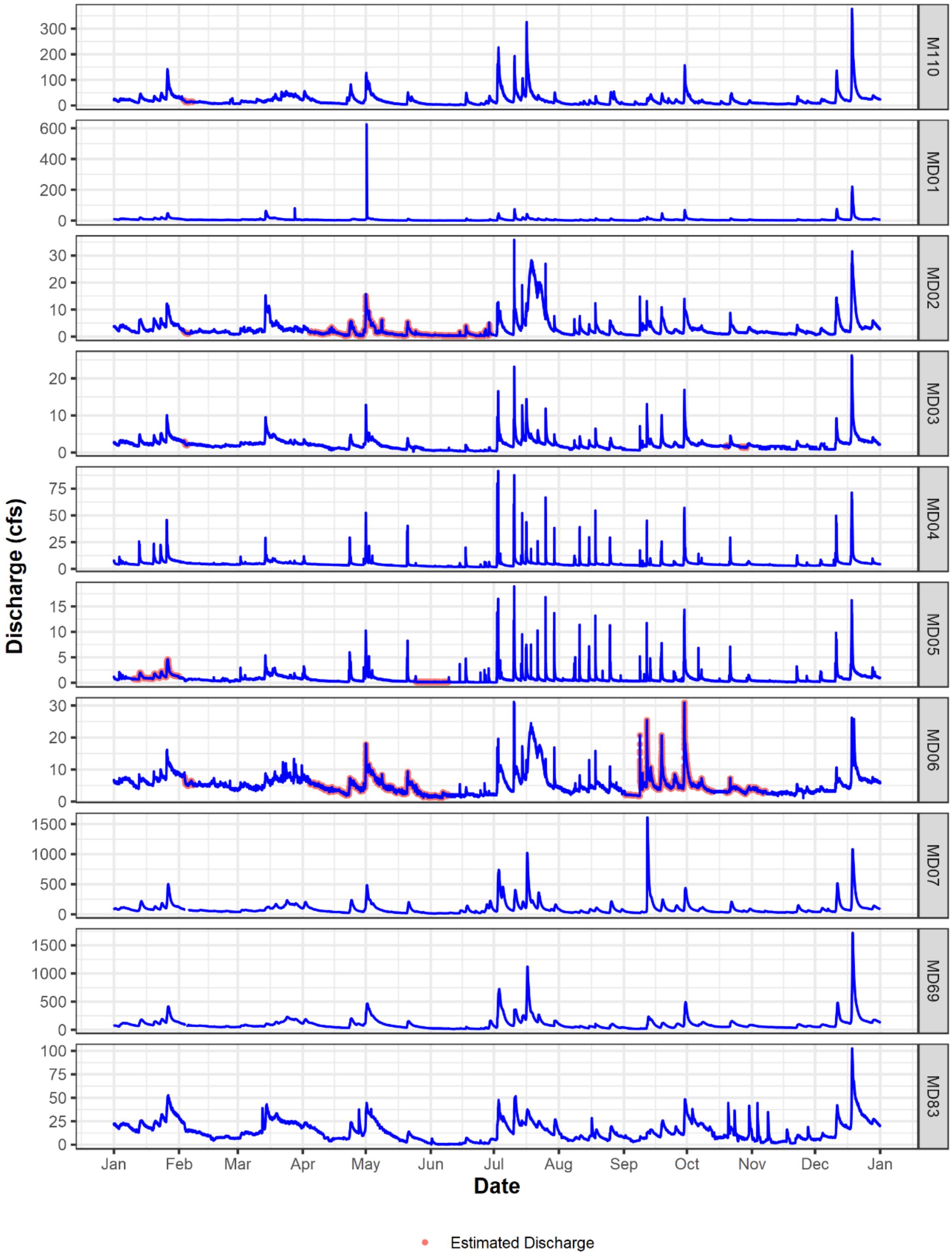
Appendix A: Continuous Data Hydrographs

Figure A-1: Hydrographs for Wachusett Watershed Tributaries During 2023

Data points represent measurements collected at 15-minute intervals (10-minute intervals at MD04).



Appendix B: Water Quality Standards and Criteria

Table B-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

Parameter	Standard/Criteria	Regulatory reference	Threshold Value	Notes
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
Total Phosphorus	Ecoregional reference – (Streams/Rivers)	EPA recommended criteria	5.00 – 23.75 µg/L	25^{th} Percentile subecoregion 58 – 25^{th} Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA recommended criteria	7.0 – 8.0 µg/L	25^{th} Percentile subecoregion 58 – 25^{th} Percentile subecoregion 59
Total Kjeldahl Nitrogen	Ecoregional reference – (Streams/Rivers)	EPA recommended criteria	0.10 – 0.30 mg/L	25^{th} Percentile subecoregion 58 – 25^{th} Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA recommended criteria	0.33 – 0.43 mg/L	25^{th} Percentile subecoregion 58 – 25^{th} Percentile subecoregion 59
Total Nitrogen	Ecoregional reference – (Streams/Rivers)	EPA recommended criteria	0.42 – 0.59 mg/L	25^{th} Percentile subecoregion 58 – 25^{th} Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA recommended criteria	0.27 – 0.40 mg/L	25^{th} Percentile subecoregion 58 – 25^{th} 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

Appendix C: Watershed Monitoring Parameters and Historical Context

C-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)[69]. 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[70]. 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[71]. 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 nearly half of all Wachusett tributary samples taken to date, with a maximum single result of 0.876 mg/L. Ammonia concentrations in the Reservoir have been below detection (0.005 mg/L) in approximately one-third 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[72]. 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.

C-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[73]. 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

[69] USGS, 1999
[70] Mallin et al., 2006
[71] USEPA & Tetra Tech Inc, 2013
[72] World Health Organization [WHO], 1996
[73] USGS, 1999

mg/L (ecoregion 58)[74] and 0.31 mg/L (ecoregion 59)[75], 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 Sections 3.2.7.1 and 3.4.7.2), therefore it can be assumed that these background concentrations are primarily composed of NO_3-N. At elevated concentrations, nitrates can cause significant water quality problems including increases in aquatic plant growth, reductions in dissolved oxygen concentrations, changes in plant and animal species composition, and loss of biodiversity[76].

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 Sections 3.2.7.1 and 3.4.7.2). The EPA MCL for NO_3-N is 10 mg/L[77]. Several other studies (mostly in Europe) have linked high levels of nitrate consumption, though in some cases below the EPA MCL, to various cancers[78]. 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.

C-3 Nitrite-Nitrogen

Nitrite-nitrogen (NO_2-N) is a short-lived nitrogen compound 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[79], and is particularly lethal to infants[80]. In order to protect human health, the EPA has established the MCL for NO_2-N in drinking water at 1.0 mg/L[81]. 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.

C-4 Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) is the sum of organic nitrogen plus NH3-N and ammonium-nitrogen (NH4-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

[74] USEPA, 2001a
[75] USEPA, 2000
[76] Camargo & Alonso, 2006
[77] Safe Drinking Water Act of 1974, 2019
[78] Ward et al., 2018
[79] Ibid
[80] Walton, 1951
[81] Safe Drinking Water Act of 1974, 2019

value (all seasons) of 0.10 mg/L (ecoregion 58)[82] and 0.30 mg/L (ecoregion 59)[83], 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 water bodies. There are no water quality standards for TKN, however this metric includes NH3-N, which is toxic at low concentrations and has specific regulatory thresholds (see Sections 3.2.7.1 and 3.4.7.2). Sampling 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.

C-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 C-1 – C-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)[84] and 0.59 mg/L (ecoregion 59)[85], 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.

C-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

[82] USEPA, 2001a
[83] USEPA, 2000
[84] USEPA, 2001a
[85] USEPA, 2000

decomposition of plant and animal tissue[86]. Through various human activities, additional phosphorous is released to both soil and water, often in highly concentrated quantities. Many agricultural operations intentionally add phosphorus to soils using chemical fertilizers and/or organic animal waste solids (manure). Concentrated animal feeding operations create large quantities of animal waste that can unintentionally release phosphorous to soils and groundwater when improperly managed. Sewage treatment discharges to streams and septic system effluent leaching to groundwater both usually contain elevated levels of phosphorous. Furthermore, human activities that accelerate erosion processes on the land surface and within streams can increase the release of phosphorous from soils and sediment into water bodies.

Lakes with TP concentrations exceeding 20-30 µg/L may experience nuisance algal growth[87]. Background concentrations of TP in rivers and streams of the Wachusett Watershed ecoregions were found to range between 2 µg/L and 907.5 µg/L, with the 25th percentile value (all seasons) of 5 µg/L (ecoregion 58)[88] and 23.75 µg/L (ecoregion 59)[89], 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 is to maintain concentrations as close to naturally occurring local background concentrations as practical.

C-7 Silica

Silica (or Silicon dioxide, SiO_2) is a necessary compound 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[90]. Silicate minerals are extremely abundant on Earth, comprising much of the material in the Earth’s crust. Silica 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.

[86] USGS, 2012
[87] Vollenweider, 1976
[88] USEPA, 2001a
[89] USEPA, 2000
[90] Reynolds, 2006

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

C-8 Water Temperature

Temperature is a critical physical property that controls 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 temperature[91]. 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 Wachusett 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.

C-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

[91] Massachusetts Surface Water Quality Standards, 2013c

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. The 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 *Salvelinus namaycush* (Lake Trout) and *Salmo salar* (Landlocked Salmon).

C-10 Alkalinity and pH

The Hydrogen ion activity (pH) of a stream is largely a function of the local groundwater hydrogeology and the effectiveness of the stream water in buffering the effects of acid precipitation. pH is an 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[92]. 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 Massachusetts Acid Rain Monitoring Project has collected more than 1,610 statewide pH samples across Massachusetts over many years and has found that average surface water pH values increase in the summer and decrease in the winter[93]. 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[94]. 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[95]. 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[96]. 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 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

[92] USEPA, 2021
[93] Godfrey et al., 1996
[94] Turk, 1983
[95] National Atmospheric Deposition Program, 2021
[96] Hornbeck et al., 1977

application of road salt for deicing[97], which may present other threats to aquatic life and degrade overall water quality.

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[98]. 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[99].

C-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[100], dysentery, typhoid fever, and cholera[101]. *Escherichia coli* (*E. coli*) is a species in the fecal coliform group, which originates from fecal material of humans and other warm-blooded animals[102]. Some strains of *E. coli* can be deadly, especially for small children or people with weakened immune systems[103]. Studies have found that the presence of *E. coli* is often correlated with the presence of many other pathogenetic microorganisms[104], thus it has been selected as a useful indicator of pathogen contamination in waters. Human exposure to pathogens usually occurs through recreational contact or direct consumption of drinking water that was not adequately disinfected.

[97] Kaushal et al., 2020
[98] USEPA, 2013
[99] Kaushal et al., 2005
[100] USGS, n.d.-a
[101] Myers et al., 2014
[102] USEPA, 1986
[103] USEPA & Tetra Tech Inc., 2013
[104] Myers et al., 2014

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[105]. 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[106]. 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[107]. Results for pathogen testing at the intake are briefly discussed Section 3.4.11 and in greater detail in separate reports published by MWRA[108].

C-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[109, 110]. Freshwater systems in Massachusetts naturally contain low levels of mineral salts in solution[111]. Elevated levels of specific conductance and associated dissolved solutes (e.g., sodium, chloride) may stress sensitive biota, threaten ecosystems[112, 113], and degrade drinking water quality[114, 115, 116]. 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[117], resulting in the mobilization of base cations (e.g., calcium, potassium, magnesium) to streams thereby altering natural biogeochemical cycles. Contamination of drinking water

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105 Ibid
106 Massachusetts Surface Water Quality Standards, 2013d
107 Massachusetts Surface Water Quality Standards, 2013e
108 MWRA, 2021b
109 Granato et al., 2015
110 Rhodes et al., 2001
111 Granato et al., 2015
112 Jackson & Jobbágy, 2005
113 Corsi et al., 2010
114 Kaushal et al., 2005
115 Daley et al., 2009
116 Kelly et al., 2010
117 Kaushal et al., 2017

supplies with excess chloride (Cl) may increase the corrosivity of affected waters[118], which can increase the mobilization of lead and copper from older infrastructure. 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[119,120]. In the snowbelt region of the U.S., road salt is the dominant source of chloride to many natural water systems[121, 122, 123].

Sodium chloride is the main component of road salt and brine applied to roads, parking lots and driveways to lower the freezing point of water to prevent ice accumulation on travel surfaces, thereby increasing safety while walking or driving a vehicle. DWSP has documented a long-term increasing trend in specific conductance and the concentration of chloride in surface water in the Wachusett watershed and reservoir, and this increase can mostly be attributed to historical road salt application. Since many aquatic organisms are sensitive to increases in Cl, community composition is likely to shift in response[124]. 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*[125].

DWSP has expanded the water quality monitoring program on several fronts and worked with research partners at UMass to learn more about patterns of chloride in the watershed. Groundwater monitoring was started in 2019 and currently includes monthly monitoring at seven wells. Results have revealed concerning levels of chlorides at some locations and provided initial information about patterns and sources of chloride in the watershed[126]. Real-time continuous monitoring mayfly stations have been installed on several tributaries without USGS gages that will allow for daily chloride loading estimates to be calculated at all primary tributaries (See Chlorides 3.2.3.3)

DWSP is collaborating with other agencies, including MassDOT to implement a Road Salt Reduction program by sharing knowledge and information about road salt use in the watershed with the ultimate goal of reducing salt loading on both DWSP and municipal properties in preparation for more frequent and intense storms resulting from a changing climate.

The EPA established aquatic life criteria for Cl in 1988 at chronic (4-day average) and acute (1-hour average) concentrations of 230 and 860 mg/L, respectively[127]. 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”[128]. MassDEP also established an Office of Research and Standards Guideline (ORSG) of 20

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[118] Stets et al., 2018
[119] Panno et al., 2006
[120] Lautz et al., 2014
[121] Kaushal et al., 2005
[122] Kelly et al., 2008
[123] Mullaney et al., 2009
[124] Van Meter & Swan, 2014
[125] June-Wells et al., 2013
[126] DWSP, 2023a
[127] USEPA, 1988
[128] MassDEP, 2018

mg/L sodium in drinking water and a secondary maximum contaminant level (SMCL) for Cl of 250 mg/L[129]. MassDEP does not currently enforce regulatory standards for specific conductance in drinking water.

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. For example, average specific conductance values from the largest tributaries to Wachusett Reservoir, the Stillwater and Quinapoxet Rivers, during 2019 were 174 µS/cm and 261 µS/cm, respectively, while the average for water entering via the Quabbin Aqueduct was 49 µS/cm. This difference in specific conductance can be used to track movement of native and Quabbin water through the 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.

C-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 or disturbed land surfaces. In Massachusetts, and around the U.S., excessive TSS is one of the most prevalent causes of water quality impairment[130, 131].

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, land cover types, and changing 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[132,133]. 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[134]. 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

[129] Massachusetts Drinking Water Regulations, 2020b
[130] Murphy, 2020
[131] MassDEP, 2024
[132] Southwood, 1977
[133] Wohl et al., 2015
[134] Murphey, 2007

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 (by passing through stormwater control measures) to reduce 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 drinking water supplies, it is desirable to have low TSS concentrations, as high TSS levels often lead to aesthetic issues (taste/odor), mostly due to organic suspended solids. Although TSS is often cited as the reason for water quality impairments, there are no state or federal standards for TSS in streams since other standards (turbidity, bacteria) are more useful predictors of drinking water quality. However, MassDEP does enforce specific stormwater management standards, which address both water volume and TSS loads from development projects exceeding certain size thresholds[135]. 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.

TSS concentrations in Wachusett tributaries are below the method detection limit 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.

C-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)[136]. 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 C-13, 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 because 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.

[135] Wetlands Protection, 2017; Water Quality Certification, 2017
[136] Swenson & Baldwin, 1965

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[137]. 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)[138] and 1.68 NTU (ecoregion 59)[139], 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.

C-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[140].

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 the Wachusett Watershed waters is to maintain background natural concentrations of TOC, preferably below 2 mg/L.

C-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 can 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 (C-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.

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[137] Massachusetts Drinking Water Regulations, 2020c
[138] USEPA, 2001a
[139] USEPA, 2000
[140] Mulholland & Kuenzler, 1979

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 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[141].

C-17 Chlorophyll *a* and Phycocyanin

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

There are currently no MA statutory action levels for algal pigments in surface waters, including drinking water sources. The EPA Office of Water does include chlorophyll *a* in its Ambient Water Quality Criteria Recommendations which are specific to the fourteen U.S. nutrient Ecoregions. The reference condition ranges listed for Wachusett Watershed's subecoregions 58 and 59 are 2.1 – 6 µg/L and 1.38 – 2.7 µg/L, respectively[142].

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.

C-18 Phytoplankton

Algae are a large, diverse group of organisms present in nearly every ecosystem from sandy deserts to artic permafrost to freshwater reservoirs[143]. 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

[141] DWSP, 2018b
[142] USEPA, 2001b
[143] Reynolds, 2006

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 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, also referred to as to 'Alert Levels' for five organisms (Table C-1). 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. The joint MWRA-DCR Phytoplankton Action Plan was revised in early 2023 to account for changes in treatment options and methods of detection. Installation of remote sensing tools allow for near real-time monitoring of water quality and quick response to changing conditions. As climate change influences the region, new water quality concerns such as nutrient pulses, increased water temperature, and changes in phytoplankton communities including increases in cyanobacteria, may arise. The revisions to DCR and MWRA's response plan allow for flexibility in identifying and investigating immediate and future phytoplankton-related water quality concerns.

Table C-1: Alert Levels for Select Phytoplankton Genera

Nuisance Organism Group	Nuisance Organism	Alert Levels (ASU/mL) for taxa densities at routine monitoring sites (BN3417 or CI3409)
Cyanophyte	*Dolichospermum*	30
Chrysophyte	*Synura*	40
	Chrysosphaerella	500
	Uroglenopsis	2,000
	Dinobryon	800

C-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[144, 145]. 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[146].

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[147]. *B. longimanus* was identified in Lake Winnipesaukee, NH in 2023[148]. 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.

C-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[149]. 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*[150]. 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[151].

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[144] Hintz et al., 2019
[145] Richardson, 2008
[146] Havel & Shurin, 2004
[147] USGS, n.d.-b
[148] NH DES, 2023
[149] Dodson, 2005
[150] DWSP, 2023e
[151] USEPA, 2001b

Appendix D: Quality Assurance

Sample Completeness

As detailed in the Quality Assurance Project Plan (QAPP) for Wachusett Watershed Water Quality Monitoring, sample completeness is an indicator of data quality. This metric is used to evaluate whether an adequate number of samples were collected to meet project objectives. For both laboratory and field parameters, 80-100% of planned samples must be collected to meet DWSP objectives for routine tributary monitoring. The tables below show the number of samples collected and expected by Parameter (Table D-1) and by monitoring location (Table D-2).

Table D-1: Sample Completeness by Parameter

Parameter	Collected	Expected	Percent Complete
Alkalinity	120	120	100%
Ammonia-N	120	120	100%
Chloride	120	120	100%
Dissolved Oxygen	491	552	89%
E. coli	432	432	100%
Mean UV_{254}	120	120	100%
Nitrate-N	120	120	100%
Nitrite-N	120	120	100%
Specific Conductance	552	552	100%
Staff Gauge Height	360	360	100%
Total Kjeldahl Nitrogen	120	120	100%
Total Organic Carbon	120	120	100%
Total Phosphorus	120	120	100%
Total Suspended Solids	120	120	100%
Turbidity NTU	432	432	100%
Water Temperature	552	552	100%
pH	491	552	89%

Table D-2: Sample Completeness by Monitoring Location

Location	Collected	Expected	Percent Complete
M102	138	144	96%
M110	340	348	98%
MD01	340	348	98%
MD02	340	348	98%
MD03	340	348	98%
MD04	340	348	98%
MD05	340	348	98%
MD06	338	348	97%
MD07	348	348	100%
MD11	138	144	96%
MD12	138	144	96%
MD69	340	348	98%
MD70	138	144	96%
MD73	138	144	96%
MD80	138	144	96%
MD81	138	144	96%
MD83	340	348	98%
MD89	138	144	96%

Sample completeness was achieved for all parameters and at all locations for the 2023 calendar year. Reasons for failing to collect 100% of samples include: field personnel errors; laboratory mishaps; samples becoming damaged, contaminated, or lost during transit; equipment malfunction; or data management mistakes. For 2023, cases where the percent complete was below 100 are explained below, by location (Table D-3).

Table D-3: Missing Samples for 2023

Monitoring Location	Reason for missing sample(s) (number of samples)
All primary/secondary locations except MD07	YSI field parameter data collected on 9/8, 9/11, 9/19 and 10/4 was erased due to a software glitch (n = 120). Data for location MD07 was unaffected. Temperature and specific conductivity results were preserved from paper field sheet records.
Malden Brook – MD06	Field parameters were not logged on YSI and dissolved oxygen and pH were lost (n = 2). Temperature and specific conductivity results were preserved on paper field sheets.
Field Duplicate (WFD2)	No YSI field parameters were logged or recorded on 3/6 (n = 4)
Field Duplicate (WFD3)	No YSI field parameters were logged or recorded on 7/11 (n = 4)

Extra Samples

In 2023, EQ staff collected 67 extra samples over 13 days to investigate potential water quality threats or to confirm the location or persistence of a previously identified water quality issue (Table D-4). All but five of these samples were collected in relation to three different issues. The bacteria samples collected between the end of May and July (not including June 28) were collected to investigate a persistent source of bacteria impacting Gates Brook, upstream of the Gates Brook 4 sampling site (MD73). This investigation was described in Section 3.2.6 with additional details logged in file EQ2023-023. On June 28, the West Boylston manganese treatment facility off Thomas St. in West Boylston was backflushing filters into a wastewater line that connected to the sewer main on Thomas St. Excess pressure or a clog forced some of this backflush water out of a manhole on Thomas St, which flowed along the road and ultimately into Quinapoxet Basin. The EQ Staff response was primarily concerned over bacteria, as this appeared to be a sewage release. Bacteria samples were sent to the lab, however once the source of the release was linked to the manganese facility, additional analysis for manganese and phosphorus were conducted with the remaining sample aliquots. The samples collected between September 12 and September 14 were in response to an extreme precipitation event local to the Stillwater River headwaters. Turbidity and bacteria samples were collected to help assess potential water quality impacts related to the flood waters entering the reservoir from the Stillwater River.

Table D-4: Extra Samples Collected During 2023

Location	Date-Time (ET)	Parameter	Result	Units	Location Description	Latitude (DD)	Longitude (DD)	Sample Notes	EQ File #
MISC	2023-05-01 13:00	*E. coli*	218	MPN/100 mL	Downstream of MD01	42.3666361	-71.729167	Bacteria sample - culvert block release	EQ2023-019
MISC	2023-05-01 13:00	Turbidity NTU	4.7	NTU	Downstream of MD01	42.3666361	-71.729167	Turbidity sample - culvert block release	EQ2023-019
MD73	2023-05-23 8:45	*E. coli*	399	MPN/100 mL				Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MD75	2023-05-23 8:54	*E. coli*	121	MPN/100 mL				Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-05-23 9:04	*E. coli*	63	MPN/100 mL	Gates Brook - Prescott St. (M754)	42.3432524	-71.800727	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-05-23 9:11	*E. coli*	41	MPN/100 mL	Gates Brook - Prescott St. below sewer pump station	42.3442686	-71.800729	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MD75	2023-06-07 10:07	*E. coli*	18	MPN/100 mL				Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-07 10:12	*E. coli*	161	MPN/100 mL	Gates Brook downstream of Danielian Dr.	42.3405024	-71.789103	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-07 10:19	*E. coli*	1,140	MPN/100 mL	Southeast Trib to Gates Brook downstream of Chapman Ave.	42.34133546	-71.78672699	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-07 10:24	*E. coli*	663	MPN/100 mL	Gates Brook downstream of Kings Mountain Dr.	42.345298	-71.784222	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023

Location	Date-Time (ET)	Parameter	Result	Units	Location Description	Latitude (DD)	Longitude (DD)	Sample Notes	EQ File #
MISC	2023-06-14 10:12	*E. coli*	620	MPN/100 mL	Southeast Trib to Gates Brook downstream of Tyson Terrace	42.33918603	-71.78644253	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-14 10:20	*E. coli*	121	MPN/100 mL	Southeast Trib to Gates Brook downstream of W. Boylston St.	42.340437	-71.786518	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-14 10:22	*E. coli*	1,280	MPN/100 mL	Southeast Trib to Gates Brook downstream of Chapman Ave.	42.34133546	-71.78672699	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-22 11:50	*E. coli*	8,160	MPN/100 mL	Southeast Trib to Gates Brook downstream of Chapman Ave.	42.34133546	-71.78672699	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-22 11:53	*E. coli*	1,660	MPN/100 mL	Drainage spur under Magnolia Ave	42.340298	-71.7869247	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-22 11:55	*E. coli*	148	MPN/100 mL	Southeast Trib to Gates Brook downstream of W. Boylston St.	42.340437	-71.786518	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-22 11:58	*E. coli*	331	MPN/100 mL	Southeast Trib to Gates Brook downstream of Tyson Terrace	42.33918603	-71.78644253	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-06-28 12:50	*E. coli*	10	MPN/100 mL	Manhole on Thomas St.	42.38694	-71.7951618	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:50	Manganese	246	µg/L	Manhole on Thomas St.	42.38694	-71.7951618	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:50	Phosphorus	479	µg/L	Manhole on Thomas St.	42.38694	-71.7951618	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:52	*E. coli*	3,450	MPN/100 mL	Roadway gutter along Thomas St.	42.3866407	-71.795836	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:52	Manganese	752	µg/L	Roadway gutter along Thomas St.	42.3866407	-71.795836	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:52	Phosphorus	756	µg/L	Roadway gutter along Thomas St.	42.3866407	-71.795836	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:55	*E. coli*	201	MPN/100 mL	Quinapoxet Basin shoreline	42.3862068	-71.7963704	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:55	Manganese	154	µg/L	Quinapoxet Basin shoreline	42.3862068	-71.7963704	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:55	Phosphorus	207	µg/L	Quinapoxet Basin shoreline	42.3862068	-71.7963704	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:58	*E. coli*	63	MPN/100 mL	Railroad bridge over Quinapoxet Basin	42.3825431	-71.7938314	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:58	Manganese	14	µg/L	Railroad bridge over Quinapoxet Basin	42.3825431	-71.7938314	Release from Mn treatment facility filter backflushing	EQ2023-024
MISC	2023-06-28 12:58	Phosphorus	60	µg/L	Railroad bridge over Quinapoxet Basin	42.3825431	-71.7938314	Release from Mn treatment facility filter backflushing	EQ2023-024

Location	Date-Time (ET)	Parameter	Result	Units	Location Description	Latitude (DD)	Longitude (DD)	Sample Notes	EQ File #
MISC	2023-07-06 9:00	*E. coli*	8,660	MPN/100 mL	Downstream of Chapman Ave	42.34133546	-71.78672699	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-07-06 9:10	*E. coli*	11,200	MPN/100 mL	Upstream of Chapman Ave	42.34119745	-71.78668579	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-07-06 9:22	*E. coli*	677	MPN/100 mL	Southeast Trib to Gates Brook downstream of W. Boylston St.	42.340437	-71.786518	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-07-06 9:33	*E. coli*	4,350	MPN/100 mL	Drainage spur under Magnolia Ave	42.340298	-71.7869247	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-07-19 10:22	*E. coli*	350	MPN/100 mL	Upstream Chapman Ave	42.34119745	-71.78668579	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-07-19 10:25	*E. coli*	1,070	MPN/100 mL	Upstream of chapman Ave Fairchild culvert	42.34082482	-71.78676868	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-07-19 10:35	*E. coli*	657	MPN/100 mL	Upstream of Gerardos	42.340454	-71.786851	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-07-19 10:45	*E. coli*	754	MPN/100 mL	Drainage spur under Magnolia Ave	42.340298	-71.7869247	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-09-08 11:53	*E. coli*	226	MPN/100 mL	At log with game camera	42.34051192	-71.78698066	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MISC	2023-09-08 11:56	*E. coli*	591	MPN/100 mL	Upstream Chapman Ave	42.34119745	-71.78668579	Elevated bacteria at Gates 4 - upstream source tracking	EQ2023-023
MD12	2023-09-12 9:23	*E. coli*	3,650	MPN/100 mL				Extreme precipitation Event follow-up	EQ2023-033
MD12	2023-09-12 9:23	Turbidity NTU	5.4	NTU				Extreme precipitation Event follow-up	EQ2023-033
M102	2023-09-12 9:32	*E. coli*	657	MPN/100 mL				Extreme precipitation Event follow-up	EQ2023-033
M102	2023-09-12 9:32	Turbidity NTU	2.0	NTU				Extreme precipitation Event follow-up	EQ2023-033
MISC	2023-09-12 9:45	Turbidity NTU	30.0	NTU	B - Backwater eddy - Reservoir - Oakdale Basin NE of 140 Causeway	42.38709	-71.79026	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MD69	2023-09-12 9:49	*E. coli*	1,080	MPN/100 mL				Extreme precipitation Event follow-up	EQ2023-033
MD69	2023-09-12 9:49	Turbidity NTU	6.4	NTU				Extreme precipitation Event follow-up	EQ2023-033
MISC	2023-09-12 9:50	Turbidity NTU	24.8	NTU	A - To the side of the flow - Reservoir - Thomas Basin SW of 140 Causeway	42.38712	-71.79064	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033

Location	Date-Time (ET)	Parameter	Result	Units	Location Description	Latitude (DD)	Longitude (DD)	Sample Notes	EQ File #
MISC	2023-09-12 9:55	Turbidity NTU	26.9	NTU	C - To the side of the flow - Reservoir - Oakdale Basin NW of 140 Causeway	42.38723	-71.7905	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MISC	2023-09-12 10:00	Turbidity NTU	27.2	NTU	D - In visible flow - Reservoir - Oakdale Basin NW of 140 Causeway	42.38729	-71.79048	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MD07	2023-09-12 10:15	Staff Gauge Height	8.65	ft				Extreme precipitation Event follow-up	EQ2023-033
MD07	2023-09-12 10:15	Turbidity NTU	13.7	NTU				Extreme precipitation Event follow-up	EQ2023-033
MD07	2023-09-12 10:15	Discharge	1,270	cfs				Extreme precipitation Event follow-up	EQ2023-033
MD07	2023-09-12 11:38	*E. coli*	3,130	MPN/100 mL				Extreme precipitation Event follow-up	EQ2023-033
MD07	2023-09-12 11:38	Turbidity NTU	11.3	NTU				Extreme precipitation Event follow-up	EQ2023-033
MISC	2023-09-13 9:40	Turbidity NTU	5.7	NTU	B - Backwater eddy - Reservoir - Oakdale Basin NE of 140 Causeway	42.38709	-71.79026	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MISC	2023-09-13 9:45	Turbidity NTU	5.0	NTU	A - To the side of the flow - Reservoir - Thomas Basin SW of 140 Causeway	42.38712	-71.79064	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MISC	2023-09-13 9:55	Turbidity NTU	5.0	NTU	C - To the side of the flow - Reservoir - Oakdale Basin NW of 140 Causeway	42.38723	-71.7905	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MISC	2023-09-13 10:00	Turbidity NTU	4.7	NTU	D - In visible flow - Reservoir - Oakdale Basin NW of 140 Causeway	42.38729	-71.79048	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MD07	2023-09-13 10:15	Turbidity NTU	2.6	NTU				Extreme precipitation Event follow-up	EQ2023-033
MISC	2023-09-13 12:54	Turbidity NTU	4.6	NTU	B - Backwater eddy - Reservoir - Oakdale Basin NE of 140 Causeway	42.38709	-71.79026	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MISC	2023-09-13 12:55	Turbidity NTU	5.1	NTU	A - To the side of the flow - Reservoir - Thomas Basin SW of 140 Causeway	42.38712	-71.79064	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MISC	2023-09-13 12:58	Turbidity NTU	4.1	NTU	C - To the side of the flow - Reservoir - Oakdale Basin NW of 140 Causeway	42.38723	-71.7905	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033

Location	Date-Time (ET)	Parameter	Result	Units	Location Description	Latitude (DD)	Longitude (DD)	Sample Notes	EQ File #
MISC	2023-09-13 13:05	Turbidity NTU	4.0	NTU	D - In visible flow - Reservoir - Oakdale Basin NW of 140 Causeway	42.38729	-71.79048	Turbidity sample - Visible elevated turbidity in Oakdale Basin	EQ2023-033
MD07	2023-09-14 13:12	Turbidity NTU	2.5	NTU				Extreme precipitation Event follow-up	EQ2023-033
MISC	2023-10-06 10:00	*E. coli*	384	MPN/100 mL	Upstream of Farm Rd	42.342075	-71.520893	Sewer main leak follow-up - Southborough	EQ2023-040
MISC	2023-10-06 10:05	*E. coli*	473	MPN/100 mL	Downstream of Farm Rd	42.3416	-71.52036	Sewer main leak follow-up - Southborough	EQ2023-040
MISC	2023-10-06 10:40	*E. coli*	657	MPN/100 mL	Downstream of Farm Rd	42.339945	-71.518592	Sewer main leak follow-up - Southborough	EQ2023-040

Sample Flags and Data Excluded from Analysis

Water quality data are flagged for various reasons during different stages of data review. Some flags are added to records automatically upon import to databases, while others are added manually. Flags are added to records any time results have been altered or any time a result may be influenced by a known factor or condition, which may require further review to determine if the record is reliable or should be excluded from analysis and reporting. If, after a detailed evaluation, sufficient evidence exists to support the determination that a record is likely to be unreliable or inaccurate, then the result will also be given Flag 123 (remove from analysis) in addition to the specific flag that best describes the underlying reason for lacking confidence in the result. Table D-5 lists the records from 2023 that were flagged and removed from analysis. Table D-6 is a summary of all other data that were flagged, where evidence to justify exclusion from analyses was insufficient. Typically, these results were within historical 25th – 75th percentile values for their respective parameter and location.

Table D-5: Flagged data for 2023 that were also censored (removed from analyses with flag code 123)

Sample #	Site	Date-Time ET	Parameter	Result	Units	Flag	Comment
90839	MD83	1/12/2023 9:30	Total Kjeldahl Nitrogen	0.355	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
90849	MD07	1/12/2023 9:45	Total Kjeldahl Nitrogen	0.273	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
90869	M110	1/12/2023 10:00	Total Kjeldahl Nitrogen	0.311	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
90859	MD69	1/12/2023 10:15	Total Kjeldahl Nitrogen	0.492	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
90879	MD06	1/12/2023 10:45	Total Kjeldahl Nitrogen	0.763	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
90889	MD05	1/12/2023 11:15	Total Kjeldahl Nitrogen	0.778	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
90899	MD04	1/12/2023 11:40	Total Kjeldahl Nitrogen	0.685	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
90929	MD03	1/12/2023 12:00	Total Kjeldahl Nitrogen	0.423	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
90939	MD02	1/12/2023 12:15	Total Kjeldahl Nitrogen	0.649	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
90949	MD01	1/12/2023 12:45	Total Kjeldahl Nitrogen	0.558	mg/L	128 - Sampled with failed blank	TKN lab results extremely high with failed blank. Lab issue likely.
104902	MD05	1/19/2023 11:15	Specific Conductance	863	µS/cm	103 - Questionable Data (MWRA Code S)	RPD with Mayfly greater than 30
91109	MD05	2/9/2023 11:45	Total Phosphorus	157	µg/L	127 - Sampled with failed duplicate	TP duplicate off by order of magnitude. Likely either an analysis error or recording error at the lab.

Sample #	Site	Date-Time ET	Parameter	Result	Units	Flag	Comment
91129	MD04	2/9/2023 12:00	Total Phosphorus	343	µg/L	127 - Sampled with failed duplicate	TP duplicate off by order of magnitude. Likely either an analysis error or recording error at the lab.
105762	MD05	3/22/2023 11:15	Dissolved Oxygen	21.4	mg/L	103 - Questionable Data (MWRA Code S)	Maybe air bubble on probe
105763	MD05	3/22/2023 11:15	Oxygen Saturation	175	%	103 - Questionable Data (MWRA Code S)	Maybe air bubble on probe
107170	MD83	7/19/2023 8:30	Specific Conductance	262.9	µS/cm	103 - Questionable Data (MWRA Code S)	105 µS/cm below Mayfly, RPD>30
107215	MD06	7/19/2023 11:00	Specific Conductance	148.9	µS/cm	103 - Questionable Data (MWRA Code S)	About 100 µS/cm below Mayfly, RPD >30
107255	MD02	7/19/2023 12:30	Specific Conductance	239.9	µS/cm	103 - Questionable Data (MWRA Code S)	Conductivity lower than usual at multiple sites on this same day. RPD > 30 from Mayfly
107265	MD01	7/19/2023 13:00	Specific Conductance	79.5	µS/cm	103 - Questionable Data (MWRA Code S)	Conductivity too low compared to normal offset from Mayfly conductivity - likely an air bubble on the electrodes
107528	MD02	8/3/2023 12:30	Specific Conductance	36.5	µS/cm	103 - Questionable Data (MWRA Code S)	Mayfly 399.6 µS/cm. 166% RPD
92441	MD04	8/8/2023 11:10	Total Phosphorus	278	µg/L	103 - Questionable Data (MWRA Code S)	Highest TP result in POR, order of magnitude higher than typical. Likely a data recording error.
92461	MD02	8/8/2023 11:45	Total Phosphorus	319	µg/L	103 - Questionable Data (MWRA Code S)	Highest TP result in POR, order of magnitude higher than typical. Likely a data recording error.
92876	MD07	10/10/2023 9:45	Ammonia-N	0.0635	mg/L	127 - Sampled with failed duplicate	Flag automatically added at import
92876	MD07	10/10/2023 9:45	Ammonia-N	0.0635	mg/L	128 - Sampled with failed blank	NH3-N lab result extremely high with failed blank. Lab recording issue (decimal place) likely.
92896	MD69	10/10/2023 10:15	Ammonia-N	0.089	mg/L	127 - Sampled with failed duplicate	Flag automatically added at import
92896	MD69	10/10/2023 10:15	Ammonia-N	0.089	mg/L	128 - Sampled with failed blank	NH3-N lab result extremely high with failed blank. Lab recording issue (decimal place) likely.
92906	MD06	10/10/2023 10:30	Ammonia-N	0.0693	mg/L	127 - Sampled with failed duplicate	Flag automatically added at import
92906	MD06	10/10/2023 10:30	Ammonia-N	0.0693	mg/L	128 - Sampled with failed blank	NH3-N lab result extremely high with failed blank. Lab recording issue (decimal place) likely.
92916	MDS1	10/10/2023 10:39	Ammonia-N	0.0739	mg/L	127 - Sampled with failed duplicate	Flag automatically added at import
92916	MDS1	10/10/2023 10:39	Ammonia-N	0.0739	mg/L	128 - Sampled with failed blank	NH3-N lab result extremely high with failed blank. Lab recording issue (decimal place) likely.
92926	MD05	10/10/2023 11:00	Ammonia-N	0.0663	mg/L	127 - Sampled with failed duplicate	Flag automatically added at import

Sample #	Site	Date-Time ET	Parameter	Result	Units	Flag	Comment
92926	MD05	10/10/2023 11:00	Ammonia-N	0.0663	mg/L	128 - Sampled with failed blank	NH3-N lab result extremely high with failed blank. Lab recording issue (decimal place) likely.
108209	MD05	10/10/2023 11:00	Specific Conductance	679	µS/cm	103 - Questionable Data (MWRA Code S)	RPD with Mayfly greater than 30
92936	MD04	10/10/2023 11:10	Ammonia-N	0.0647	mg/L	127 - Sampled with failed duplicate	Flag automatically added at import
92936	MD04	10/10/2023 11:10	Ammonia-N	0.0647	mg/L	128 - Sampled with failed blank	NH3-N lab result extremely high with failed blank. Lab recording issue (decimal place) likely.
92996	MD83	10/10/2023 12:15	Ammonia-N	0.0764	mg/L	127 - Sampled with failed duplicate	Flag automatically added at import
92996	MD83	10/10/2023 12:15	Ammonia-N	0.0764	mg/L	128 - Sampled with failed blank	NH3-N lab result extremely high with failed blank. Lab recording issue (decimal place) likely.
108325	MD83	10/18/2023 8:15	Specific Conductance	224.1	µS/cm	127 - Sampled with failed duplicate	Flag added with automatic script
108325	MD83	10/18/2023 8:15	Specific Conductance	224.1	µS/cm	103 - Questionable Data (MWRA Code S)	RPD with Mayfly greater than 30
108380	MD05	10/18/2023 10:45	Specific Conductance	227.6	µS/cm	127 - Sampled with failed duplicate	Flag added with automatic script
108380	MD05	10/18/2023 10:45	Specific Conductance	227.6	µS/cm	103 - Questionable Data (MWRA Code S)	RPD with Mayfly greater than 30
108420	MD01	10/18/2023 12:00	Specific Conductance	173.6	µS/cm	127 - Sampled with failed duplicate	Flag added with automatic script
108420	MD01	10/18/2023 12:00	Specific Conductance	173.6	µS/cm	103 - Questionable Data (MWRA Code S)	Greater than 30 RPD from Mayfly
108732	MD02	11/15/2023 12:00	Dissolved Oxygen	23.4	mg/L	125 - Sensor calibration issues	DO Sensor loose, Possible moisture intrusion
108733	MD02	11/15/2023 12:00	Oxygen Saturation	186	%	125 - Sensor calibration issues	DO Sensor loose, Possible moisture intrusion
108735	MD02	11/15/2023 12:00	Specific Conductance	239.5	µS/cm	103 - Questionable Data (MWRA Code S)	RPD with Mayfly greater than 30
109106	MD02	12/6/2023 11:30	Specific Conductance	168.1	µS/cm	103 - Questionable Data (MWRA Code S)	Greater than 30 RPD from Mayfly
108979	MD05	12/21/2023 11:00	Specific Conductance	450.3	µS/cm	103 - Questionable Data (MWRA Code S)	RPD with Mayfly greater than 30

Table D-6: Data quality flags in 2023 (not excluded from analysis)

Flag	Parameter	# Samples
103 - Questionable Data (MWRA Code S)	Specific Conductance	1
111 - Above rating curve	Discharge	1
126 - Analyzed outside hold time (MWRA Code T)	Nitrate-N	11
127 - Sampled with failed duplicate	Ammonia-N	36
	Chloride	10
	Dissolved Oxygen	125
	E. coli	36
	Oxygen Saturation	53
	pH	53
	Specific Conductance	69
	Total Phosphorus	10
128 - Sampled with failed blank	Alkalinity	11
	Ammonia-N	46
	Mean UV254	10

Appendix E: Quality Control

Equipment Calibration

YSI meters are calibrated at least seven days prior to usage to ensure the devices are measuring accurately. If individual probes fail to calibrate, they are cleaned or replaced and then recalibrated until the probe calibration values fall within acceptable ranges. Figure E-1 through Figure E-3 show all of the calibration values for both YSI meters for 2023. Turbidimeter calibrations began the year at three-month intervals (manufacturer recommendation), but then increased to monthly in April in order to increase confidence that the meter calibration was still valid (Table E-1).

Figure E-1: YSI Meter pH Calibration Values - 2023

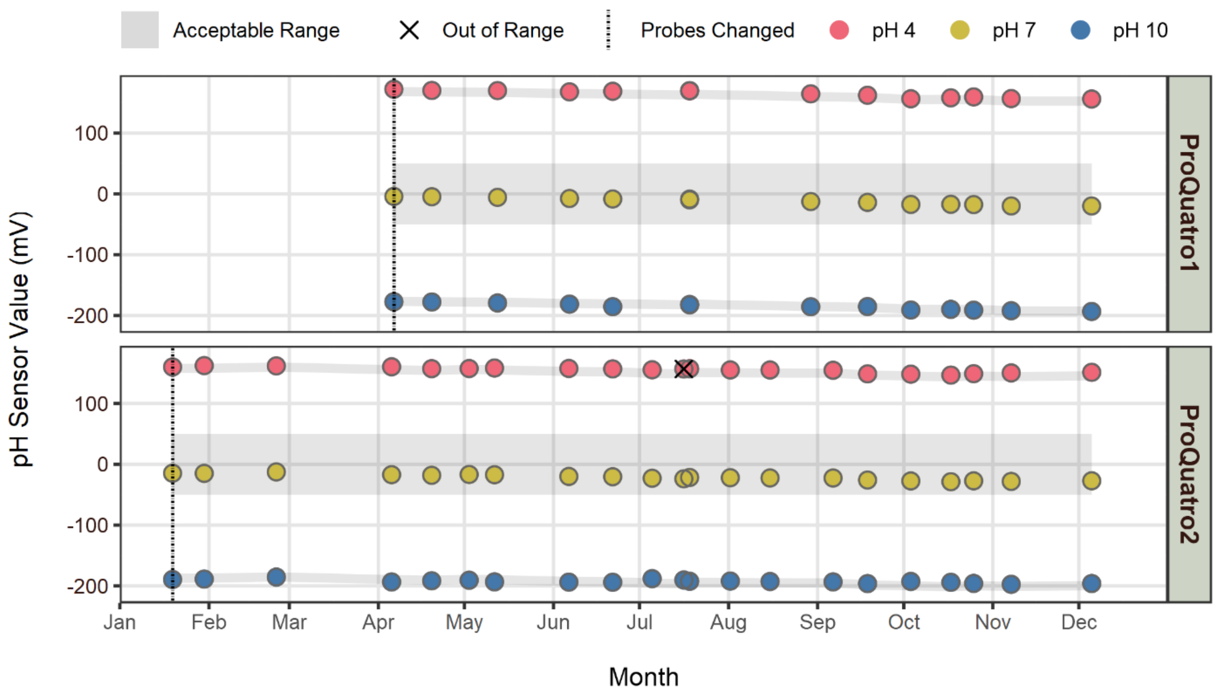


Figure E-2: YSI Meter Dissolved Oxygen Calibration Values - 2023

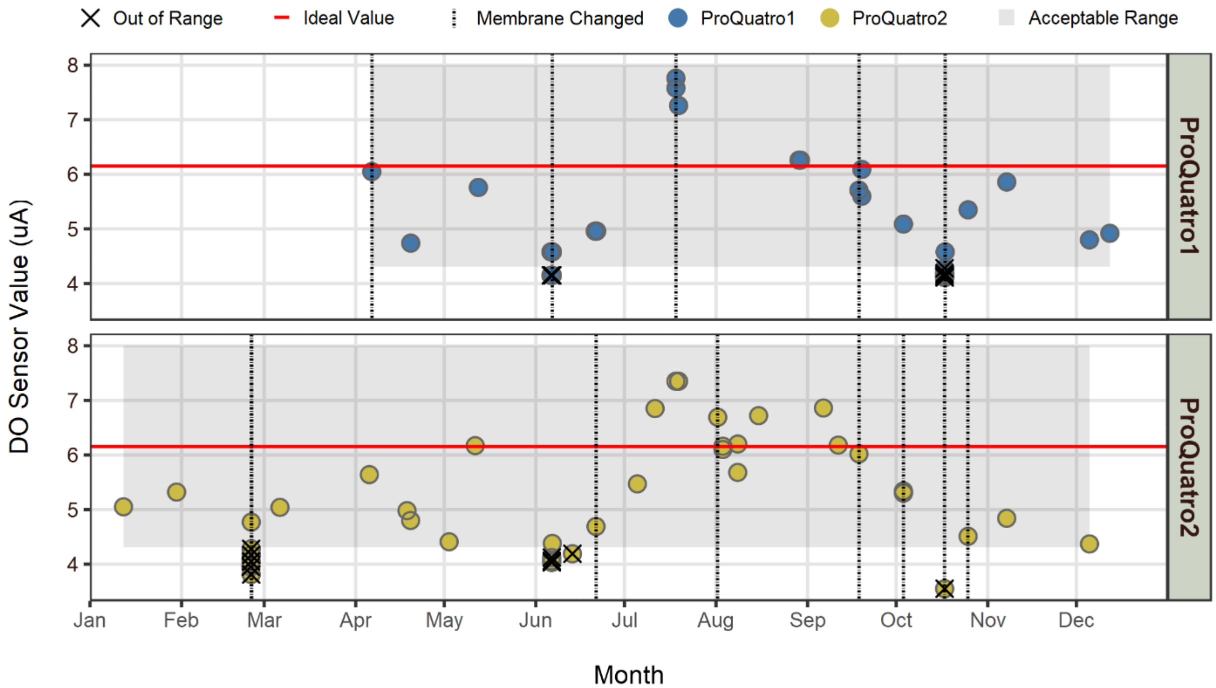


Figure E-3: YSI Meter Conductivity Calibration Values - 2023

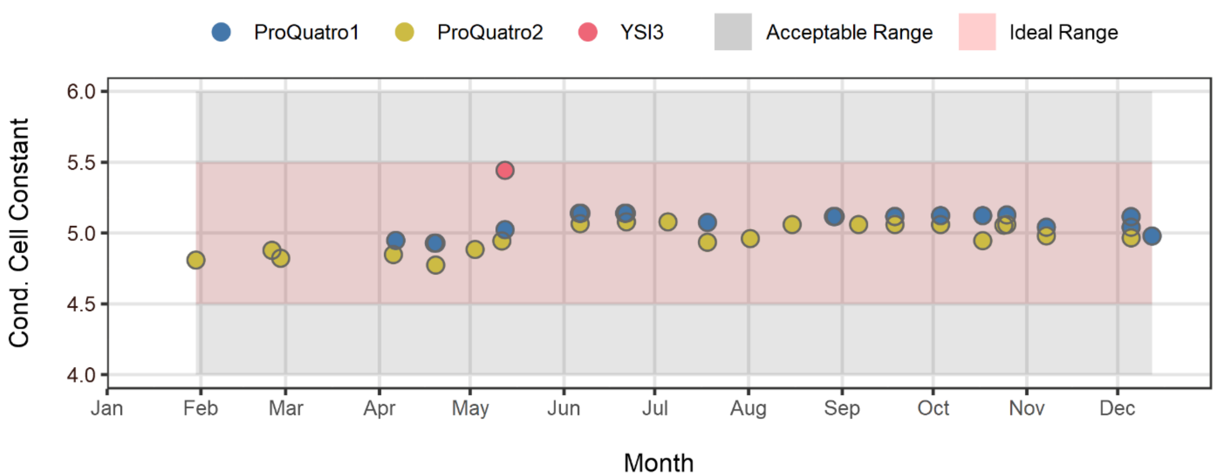
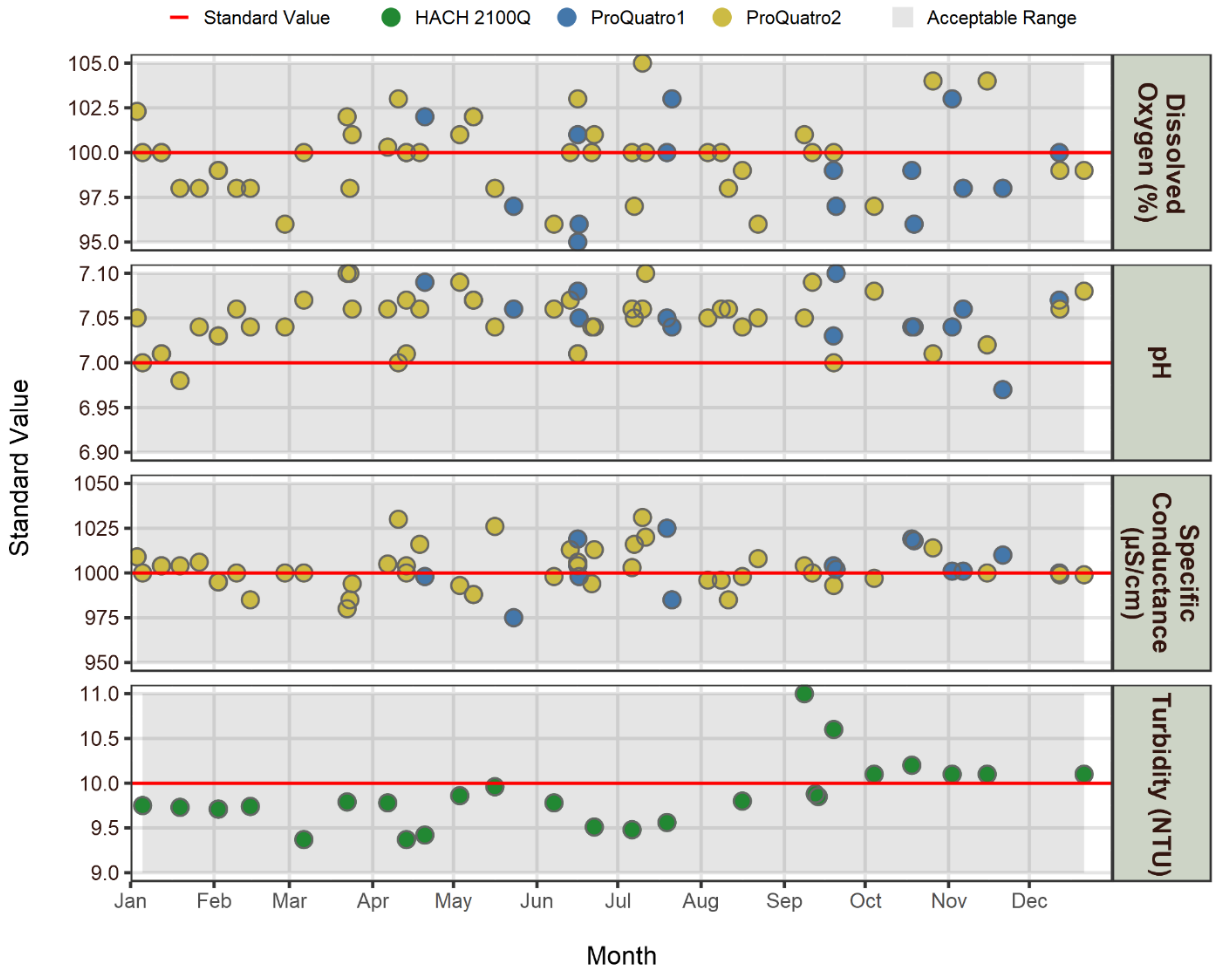


Table E-1: Hach 2100Q Calibration Records for 2023

WACHUSETT TURBIDIMETER CALIBRATION LOG - HACH 2100Q						
YEAR: 2023		Calibration Standards			Calibration Verification*	
Date YYYY-MM-DD	Staff	20 NTU	100 NTU	800 NTU	Expected Value (NTU)	Result (NTU)
		Enter calibration values below				
2023-01-19	DG	20.1	100	797	10.0	9.73
2023-04-06	DC	19.9	101	NA	10.0	9.78
2023-05-02	DC	20	101	802	10.0	9.85
2023-06-06	DC	20	99.3	805	10.0	9.71
2023-07-06	DC	20.1	99.3	789	10.0	9.48
2023-08-15	JSj	19.5	99.7	796	10.0	9.73
2023-09-12	TD	19.8	98.7	793	10.0	9.88
2023-09-18	NF	20.3	102	808	10.0	9.33
2023-10-03	NF	19.8	98.1	838	10.0	10
2023-11-13	NF	20.2	102	801	10.0	10.1
2023-12-21	NF	20.1	101	790	10.0	10.1
*Use 10 NTU Standard						

YSI meters and the HACH 2100Q portable turbidimeter calibrations are checked prior to every use. If any individual probe or meter calibration check falls outside of the acceptable range, the probe/meter will be successfully recalibrated before using in the field. Results for calibration checks in 2023 are displayed in Figure E-4.

Figure E-4: YSI Meter Pre-Sampling Quality Control Check Values - 2023



Blanks

As detailed in the Quality Assurance Project Plan (QAPP) for Wachusett Watershed Water Quality Monitoring, sample blanks were collected alongside tributary samples in 2023. During routine tributary sampling, one blank is collected for each parameter per sampling event. A summary of criteria for the evaluation of blanks is shown in Table E-2. A summary of tributary blanks is shown in Table E-3. A visualization of blank results is shown in Figure E-5.

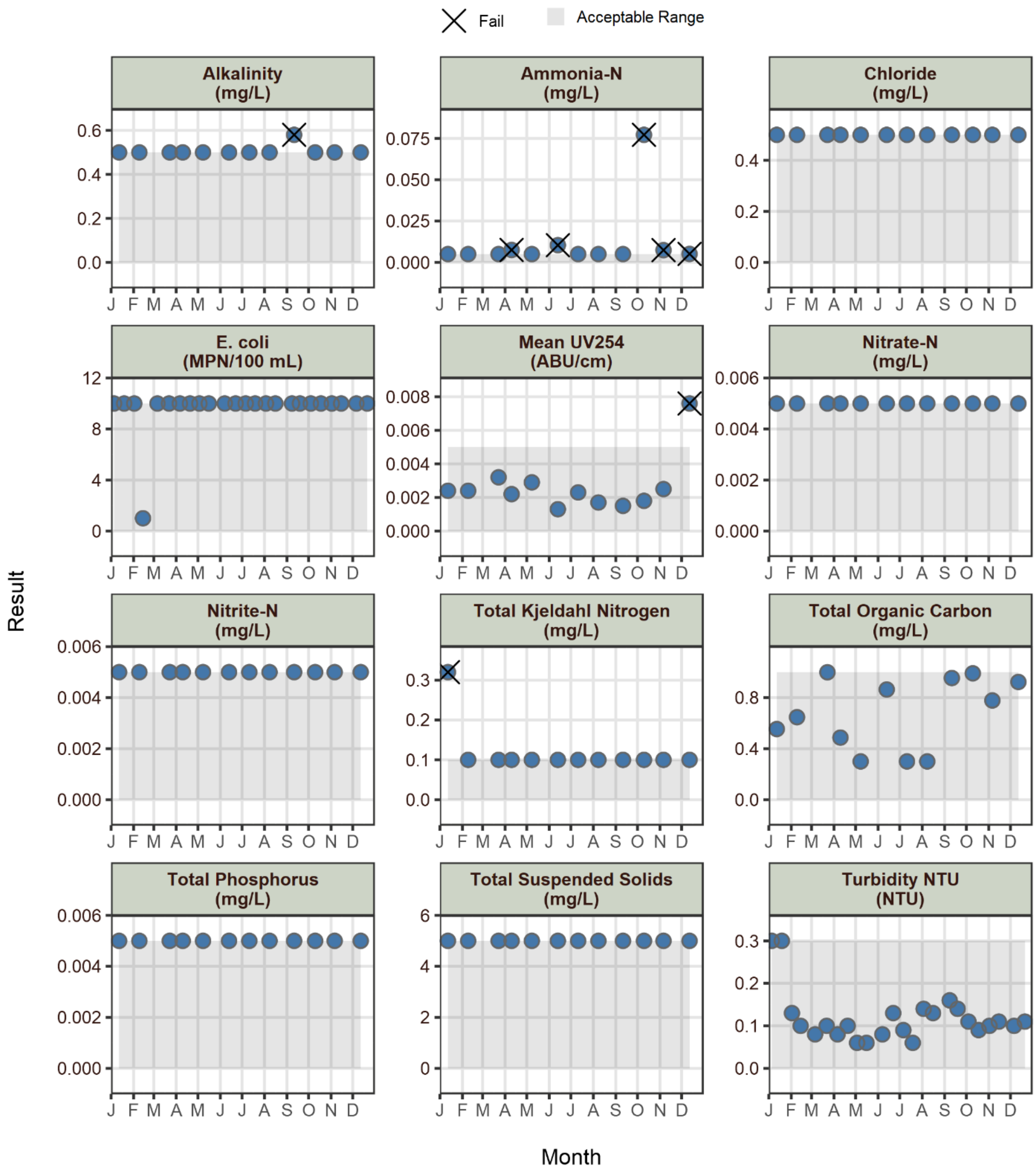
Table E-2: Blank Evaluation Criteria

Parameter	Acceptable Maximum Blank Result	Units
Alkalinity	0.5	mg/L
Ammonia-N	0.005	mg/L
Chloride	0.5	mg/L
E. coli	10	MPN/100 mL
Mean UV_{254}	0.005	ABU/cm
Nitrate-N	0.005	mg/L
Nitrite-N	0.005	mg/L
Total Kjeldahl Nitrogen	0.1	mg/L
Total Organic Carbon	1	mg/L
Total Phosphorus	0.005	mg/L
Total Suspended Solids	5	mg/L
Turbidity	0.3	NTU
Alkalinity	0.5	mg/L

Table E-3: Tributary Blank Results Summary for 2023

Parameter	Count	Expected	% Complete	Count Pass	Count Fail	% Fail
Alkalinity	12	12	100%	11	1	8%
Ammonia-N	12	12	100%	7	5	42%
Chloride	12	12	100%	12	0	0%
E. coli	24	24	100%	24	0	0%
Mean UV_{254}	12	12	100%	11	1	8%
Nitrate-N	12	12	100%	12	0	0%
Nitrite-N	12	12	100%	12	0	0%
Total Kjeldahl Nitrogen	12	12	100%	11	1	8%
Total Organic Carbon	12	12	100%	12	0	0%
Total Phosphorus	12	12	100%	12	0	0%
Total Suspended Solids	12	12	100%	12	0	0%
Turbidity NTU	24	24	100%	24	0	0%

Figure E-5: Tributary Blank Results for 2023



All failed blank results were flagged with flag 130 (QC Blank out of range) and all associated results of the same parameter on the same day were automatically flagged with flag 128 (Sampled with failed blank). As part of the year end QA/QC process, a detailed review was conducted for sample results of the same parameter and same sample day as the failed blanks. This review identified probable sample analysis errors or result recording errors on two occasions.

The TKN blank from January 12, 2023 was the only failing TKN blank for the year, and only blank above the method detection limit. Inspection of the other TKN samples results on this day revealed that six out of the ten other TKN results reported were the highest values ever recorded in the period record for each respective location. Furthermore, there was no event or preceding increasing trend that would lend credence to these results. Total phosphorus results, which often trend with TKN levels, did not show a similar increase on this day. It was determined that all TKN samples (including the QC duplicate) samples should be flagged with flag 123 (Remove from analysis), which informs analysts to filter these records out when performing any data analysis or summary.

NH_3-N was the most frequent parameter to exceed its QC blank threshold (0.005 mg/L), with a failure rate of 42% (5 out of 12 samples). Four of the failed blanks were marginally above the failure threshold. This matter was discussed in a regular working group consisting of DCR and MWRA water quality and lab staff. MWRA confirmed that an ammonia analyzer calibration issue persisted between the months of April and November, coinciding with the failed blanks. Maintenance was performed on the analyzer and the issue has since been resolved.

The failed blank result from October 10, 2023, however, was much higher than normal (0.0772 mg/L), more than an order of magnitude above the method detection limit. This result was also higher than six of the tributary results for this day and five of the results on this day were the highest NH_3-N results ever recorded at their respective sample locations. A closer look at these results, including laboratory analysis records, revealed a possible explanation. The first four NH_3-N results from this day were within ranges historically observed at their respective sample locations. The fourth location, Muddy Brook - MD03, typically has the highest NH_3-N concentrations of all sample locations, often an order of magnitude above other locations. All five of the record high results recorded on this day were analyzed after the Muddy Brook sample. It is possible that the lab analyst simply mis-recorded these results, by entering numbers off by one order of magnitude, which were similar to the Muddy Brook result. Since there is no way to confirm this error and correct the result, it was decided to flag all results analyzed after the Muddy Brook sample with flag 123 (Remove from analysis).

Although all turbidity blank sampled passed during 2023, it should be noted that the first two blank results for the year were significantly higher than following blank results. Staff suspected that the turbidity analysis for these two blank samples may have been elevated due to scratches observed on the sample cuvette. Scratches on the glass cuvette can scatter light and will reduce light transmission through the water sample, causing a higher turbidity output than would be representative of the water sample. The sample cuvette was replaced at the end of January and the subsequent blank results were much lower. This prompted an update to our equipment management protocols, which now specify that the turbidity cuvette will be replaced annually or if the blank result compared to the blank result with a new cuvette deviates by a margin greater than the accuracy tolerance of the HACH 2100Q device. Additionally, the calibration log for the turbidimeter has been modified to track all cuvette replacement dates.

The review of other instances of failed blanks did not elicit any evidence to suggest sample contamination or other laboratory sample analysis or result recording errors. These failed blanks and associated records remain flagged in the database and the related records will be used in future analyses, unless flagged for exclusion for a different reason.

Duplicates

As detailed in the Quality Assurance Project Plan (QAPP) for Wachusett Watershed Water Quality Monitoring, sample duplicates were collected alongside tributary samples in 2023. During routine bacteria and turbidity monitoring, two duplicates are collected for each parameter. One duplicate for each parameter is collected during tributary nutrient sampling. A summary of tributary duplicates is shown in Table E-4. A visualization of duplicate results of parameters collected in the field is shown in Figure E-6 and laboratory analyte duplicates are shown in Figure E-7.

Table E-4: Tributary Duplicate Result Summary for 2023

Parameter	Count	Expected	% Complete	Count Pass	Count Fail	% Fail
Alkalinity	12	12	100%	12	0	0%
Ammonia-N	12	12	100%	8	4	33%
Chloride	12	12	100%	11	1	8%
Dissolved Oxygen	51	60	85%	44	7	14%
E. coli	48	48	100%	46	2	4%
Mean UV254	12	12	100%	12	0	0%
Nitrate-N	12	12	100%	12	0	0%
Nitrite-N	12	12	100%	12	0	0%
Oxygen Saturation	51	60	85%	48	3	6%
pH	51	60	85%	48	3	6%
Specific Conductance	58	60	97%	54	4	7%
Total Kjeldahl Nitrogen	12	12	100%	11	1	8%
Total Organic Carbon	12	12	100%	12	0	0%
Total Phosphorus	12	12	100%	10	2	17%
Total Suspended Solids	12	12	100%	12	0	0%
Turbidity	48	48	100%	44	4	8%
Water Temperature	58	60	97%	58	0	0%

Figure E-6: Tributary Field Parameter Duplicate Results for 2023

Temperature, pH, and dissolved oxygen are shown as the absolute difference of results with < 0.2 acceptable. Oxygen saturation and specific conductance are shown as relative percent difference with < 5 acceptable. Turbidity is shown as relative percent difference with < 30 acceptable.

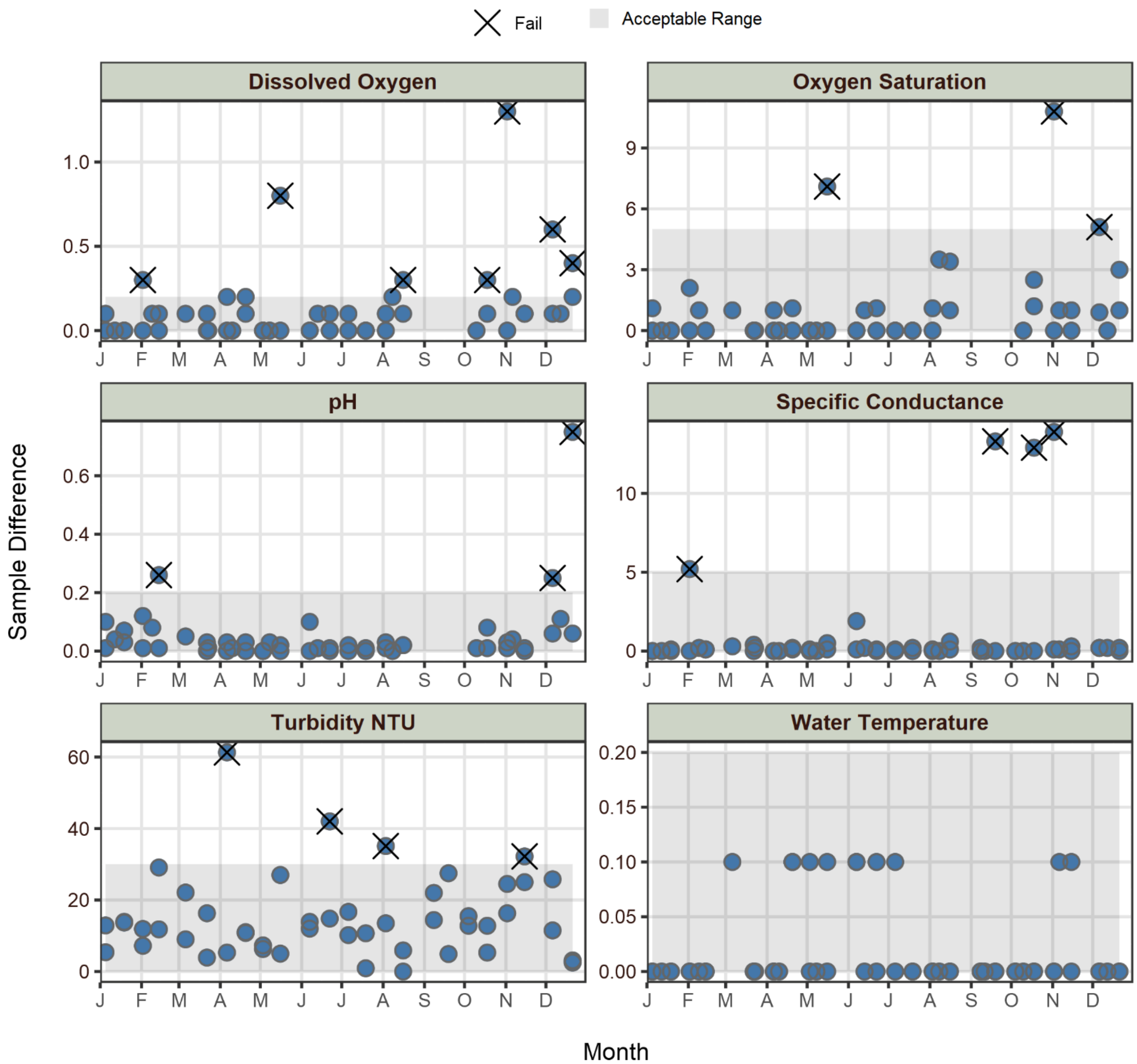
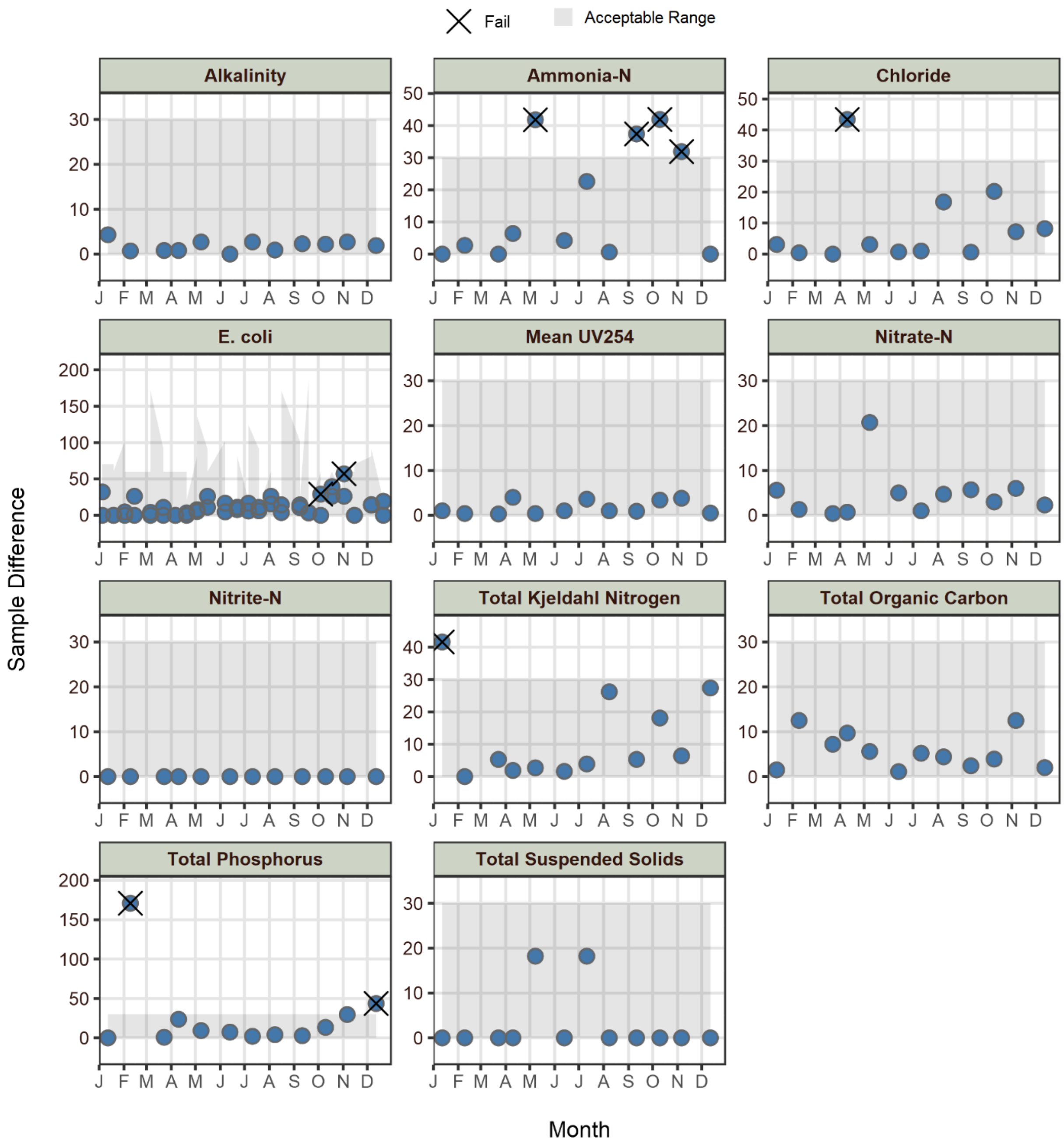


Figure E-7: Tributary Laboratory Analyte Duplicate Results for 2023

E. coli *must be within 50 MPN/100 mL or the relative percent difference of log_{10} values must be < 30 for < 50 MPN, < 20 for 50-500 MPN, < 10 for 500-5000 MPN, or < 5 for > 5000 MPN.*

The remaining parameters are shown as relative percent difference with < 30 acceptable.



All failed duplicate results were flagged with flag 129 (QC Duplicate out of range) and all associated results of the same parameter on the same day were automatically flagged with flag 127 (Sampled with failed duplicate). As part of the year end QA/QC process, a detailed review was conducted for sample results of the same parameter and same sample day as the failed blanks. This review identified probable sample analysis errors or result recording errors on three occasions.

For the failed NH_3-N duplicates, three out of four regular results and their associated duplicates were very low and within ranges typically observed at their respective monitoring locations. However, the failed duplicate on October 10, 2023 was an outlier case that merited additional flagging for reasons described in Appendix D: Quality Assurance, above. The duplicate result, as well as most other NH_3-N results from this day were flagged with flag 123 (Remove from analyses).

The only failed TKN duplicate for 2023 was from the same day as the only failed blank for TKN (January 12, 2023), which was closely reviewed as described above in Appendix D: Quality Assurance. The data review resulted in a determination that all TKN results from this day were inconsistent with prior results and it was probable that there was an error in laboratory analysis or result recording. All TKN results for this day, including the duplicate, were flagged with flag 123 (Remove from analyses).

The failed TP duplicate result on February 9 was about one order of magnitude lower than the tributary result, with a RPD of 170.9%. While the duplicate result was close the historical minimum result at this location (West Boylston Brook), the regular sample would have been the highest result on record. It is highly unlikely that two samples from the same tributary collected within minutes of each other would differ by such a wide margin. Furthermore, the TP result for the next sample collected at Gates Brook 1 was also more than an order of magnitude higher than the winter seasonal median at that monitoring location. Due to the extremely high duplicate RPD and the anomalous results at Gates Brook 1 and West Boylston Brook, these two regular sample results were flagged for flag 103 (Questionable Data (MWRA Code S)) and flag 123 (Remove from analyses).

The review of other instances of failed duplicates did not elicit any evidence to suggest sample contamination or other laboratory sample analysis or result recording errors. These failed duplicates and associated records remain flagged in the database and the related records will be used in future analyses, unless flagged for exclusion based on another rationale.

Field and Laboratory Audits

In order to ensure continued adherence to established procedures as described in the QAPP and relevant SOPs, audits are performed at least on an annual basis for most routine field and laboratory activities. 2023 was the first year that audits were performed, however they were not completed for all monitoring programs, as implementation of the QAPP was still in the beginning phases in 2023. Completed audits from 2023 are listed in the QAPP checklist below (Figure E-8). Upon discovery of a deviation from established procedures, corrective action will be implemented on a case-by-case basis. Minor response actions may be taken immediately to align procedures with those in the relevant SOPs.

For 2023, one lab audit and four field audits were completed in December. Audit results were all either “Good” or “Excellent”. Any deviations from SOPs were documented on individual audit forms and were determined to be minor - not affecting the quality of the data collected. Staff were immediately notified of any deviation from SOPs and instructed to review specific SOPs when appropriate.

Figure E-8: 2023 QAPP Checklist Indicating Date of Audits and Follow-up Actions

WACHUSETT QAPP CHECKLIST

dcr
Massachusetts

Sampling Year: 2023 **QAQC Officer:** Dan Crocker

Field Audits	**Date Complete**
Tributary - WATTRB	12/6/2023
Tributary Nutrients - WATMDC	12/12/2023
Groundwater - WATWEL	12/12/2023
Reservoir Transects - WATTRN	12/14/2023
Discharge Measurements	NA
Snowpack Measurements	NA
Reservoir Nutrieints (MDCMTH)	NA
Reservoir Profiles	NA
Zooplankton	NA
Phytoplankton	NA

Laboratory Audits	**Date Complete**
Field probe calibration: *YSI Pro Quatro*	12/5/2023
Laboratory equipment calibration	NA
Laboratory turbidity analysis (If samples not analysed in the field)	NA

Audit Follow-up Actions	
Staff informed of deviations from SOPs for projects:	*WATMDC, YSI Pro Quatro Calibrations*
Staff retrained in techniques for projects:	*NA*
Staff re-read SOPs for projects:	*WATMDC, YSI Pro Quatro Calibrations*
Other:	

Annual Data Checks	**Date Complete**
Data completeness (80-100% of planned measurements)	5/6/2024
Review samples flagged as 127 (sampled alongside failed duplicate)	3/28/2024
Review samples flagged as 128 (sampled alongside failed blank)	3/28/2024

Signatures

Daniel Crocker 5/7/24

QAQC Officer's Signature Date