Water Quality Report: 2022

Wachusett Reservoir Watershed

August Drought, Trout Brook – Dan Crocker (2022)

June 2023

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

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Abstract

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management manages Wachusett Reservoir and lands within the Watershed in order to assure the availability of safe drinking water to present and future generations. The Division's Environmental Quality Section implements a comprehensive water quality and hydrologic monitoring program to screen for potential pollutants, measure the effectiveness of watershed management programs, better understand the responses of the Reservoir to a variety of physical, chemical, and biological inputs, assess the ecological health of the Reservoir and the watershed system, and demonstrate compliance with state and federal water quality standards. As part of this program, Environmental Quality Section staff perform field work, manage and interpret water quality data, and prepare reports of findings. This report is a summary and discussion of water quality monitoring methods and results from water quality and hydrological monitoring activities carried out by the Division in the Wachusett Reservoir Watershed during 2022. 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 2022, Wachusett Reservoir water quality satisfied the requirements of the Filtration Avoidance Criteria established under the United States Environmental Protection Agency Surface Water Treatment Rule.

Compliance with state surface water quality standards among the tributaries varied, with minor exceedances attributed to higher solute loads measured during storm events and during low flow conditions, wildlife, 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 2022. Turbidity was elevated throughout the Watershed in 2022, though mean annual values were heavily influenced by three storm events and the prolonged summertime drought. Elevated bacteria concentrations remain a problem at Asnebumskit Brook, Gates Brook 4, and West Boylston Brook, however all tributaries 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, with the exception of impairments from dissolved salts in a few small subbasins and water temperatures rising above the MassDEP recommended threshold for coldwater fishery resources at several monitoring locations, for cumulative durations between 13 and 121 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. The high percentage of water transferred from Quabbin Reservoir to Wachusett Reservoir and the low input of native Wachusett Watershed water due to the 2022 drought resulted in lower specific conductance, UV_{254} and silica in Wachusett Reservoir.

Patterns typical of oligotrophic water bodies were observed in the phytoplankton population which remains dominated by diatoms and/or chrysophytes for much of the year. Organisms that can produce undesirable tastes and odors were only briefly present above internally defined thresholds and

cyanobacteria concentrations remained below levels of concern. No new invasive species were detected in the Reservoir in 2022 and management activities continue to reduce known populations.

The appendix to this report includes summary information on mean daily flows of tributaries where flow is monitored and a list of applicable water quality criteria/standards or thresholds of interest. Previously compiled background information and historical context for monitoring parameters is also included in the appendix to assist in the interpretation of water quality results and serve as a reference for the reader. Some of the ancillary data presented in this report have been compiled with the help of outside agencies (e.g., U.S. Geological Survey) and other workgroups within Division of Water Supply Protection whose efforts are acknowledged below.

Plain Language Summary

Water used by people and businesses in metro-Boston comes from the Quabbin and Wachusett Reservoirs 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 2022, which satisfy these requirements and continue to ensure availability of safe drinking water to present and future generations.

CITATION

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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
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
OWM	Office of Watershed Management
NH_3-N	Ammonia-nitrogen
NH_4-N	Ammonium-nitrogen
NO_2-N	Nitrite-nitrogen
NO_3-N	Nitrate-nitrogen
NOAA	National Oceanographic and Atmospheric Administration
SMCL	Secondary Maximum Contaminant Level
SOP	Standard Operating Procedure
STF	Short-term Forestry [Monitoring]
SWE	Snow Water Equivalent
SWTR	Surface Water Treatment Rule
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
THM	Trihalomethane
TSS	Total Suspended Solids
UMass	University of Massachusetts
U.S.	United States
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 is able to transmit through a water sample in absorbance units per centimeter of path length (ABU/cm).

The following units of measurement are used in this report:

ABU/cm	Absorbance units per centimeter of path length
ASU/mL	Areal standard units per milliliter
cfs	Cubic feet per second
CFU	Colony-forming unit
°C	Degrees Celsius
ft	Feet
in	Inches
µS/cm	Microsiemens per centimeter
MG	Million gallons
MGD	Million gallons per day
µg/L	Microgram per liter
mg/L	Milligram per liter
m	Meters
MPN	Most probable number (equivalent to CFU)
Nm	Nanometers
NTU	Nephelometric turbidity units
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 inputs, and to assess the ecological health of these water resources. A long-term record of water quality statistics provides information regarding potential controls on observed changes in water quality over time and represents a proactive effort to identify emerging threats to water quality.

This annual summary is intended to meet the needs of watershed managers, the interested public, and others whose decisions must reflect water quality considerations. The following pages summarize and discuss water quality monitoring methods, results, and major findings from all water quality and hydrological monitoring activities carried out by DWSP in the Wachusett Reservoir Watershed during 2022. Additionally, some background information is included for context and programmatic status

[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

updates are provided to document changes in monitoring programs. Data generated from water quality monitoring in 2022 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 2022, 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 below 5.0 NTU at all times[7]. Massachusetts Department of Environmental Protection (MassDEP) regulations require that turbidity levels at the point of consumption for all public drinking water remains below 1.0 NTU at all times[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 A along with the SWTR standards. Narrative criteria for Class A waters also exist for some parameters, including nutrients:

> *Unless naturally occurring, all surface waters shall be free from nutrients in concentrations that would cause or contribute to impairment of existing or designated uses and shall not exceed the site-specific criteria developed in a TMDL or as otherwise established by the Department pursuant to 314 CMR 4.00.*[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 substances (PFAS)[13]. The required monitoring for these substances at different stages in the system (i.e.,

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[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
[13] MWRA, 2023

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 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 these threats. The current WPP was written in 2018 and covers fiscal years 2019 – 2023[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.
- Conduct proactive surveillance of water quality trends to identify emerging issues and support ongoing assessments of threats to water quality.

To meet these objectives, DWSP monitoring programs will continue to evolve as necessary by responding to emergent and high priority threats to water quality, making use of the best available scientific

[14] MWRA, n.d.

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

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].

1.3 MWRA System and Wachusett Watershed Overview

The Quabbin Aqueduct connects three active water sources that ultimately serve as a source of drinking water to 50 communities in Massachusetts. The Quabbin Aqueduct connects, from west to east, Quabbin Reservoir, the Ware River Watershed, and Wachusett Reservoir. Quabbin Reservoir is the largest of the sources, with a capacity of 412 billion gallons. Wachusett Reservoir holds 65 billion gallons at full capacity (Table 1). The emergency backup Sudbury and Foss Reservoirs hold another 7.7 billion gallons, combined[17].

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 land area)
Other Protected Area	12,263	Acres
	17.2	(% Total watershed land area)

[16] Watershed Protection, 2017
[17] MWRA, 2021a
[18] DWSP, 2016

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 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 FY19 – 23*[21] and the *2017 Land Management Plan*[22].

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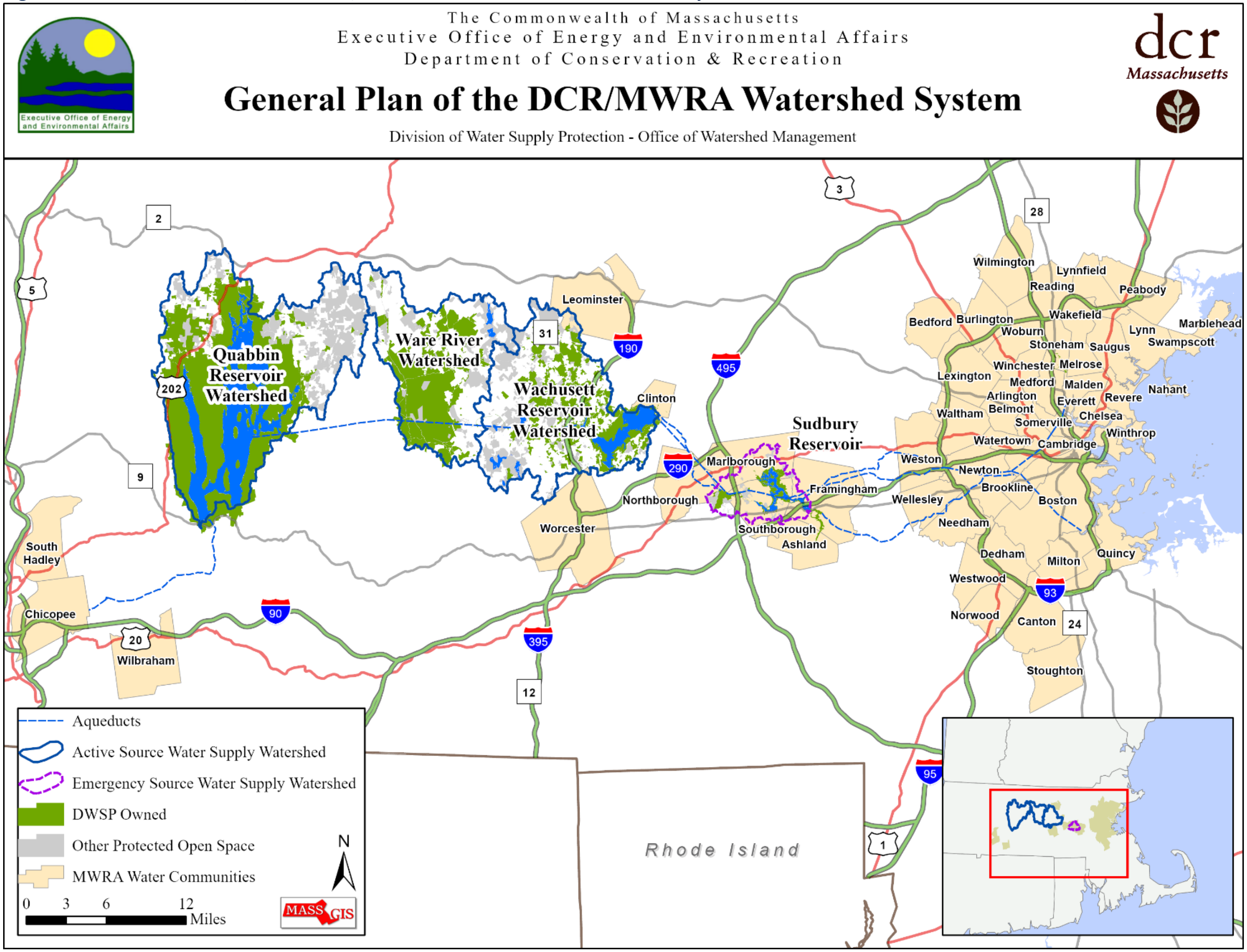
[19] Griffith et al., 2009
[20] Ibid
[21] DWSP, 2018a
[22] DWSP, 2018b

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 2022, 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: Monitoring activities are conducted by other agencies and organizations related to water quality and hydrology within the Wachusett Watershed.

2.1.1 Wachusett Watershed Monitoring Locations

DWSP staff collected routine water quality samples from eight groundwater wells, 20 tributary monitoring stations, and 27 stations on Wachusett Reservoir in 2022. 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 break 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 2022 in the Wachusett Reservoir Watershed

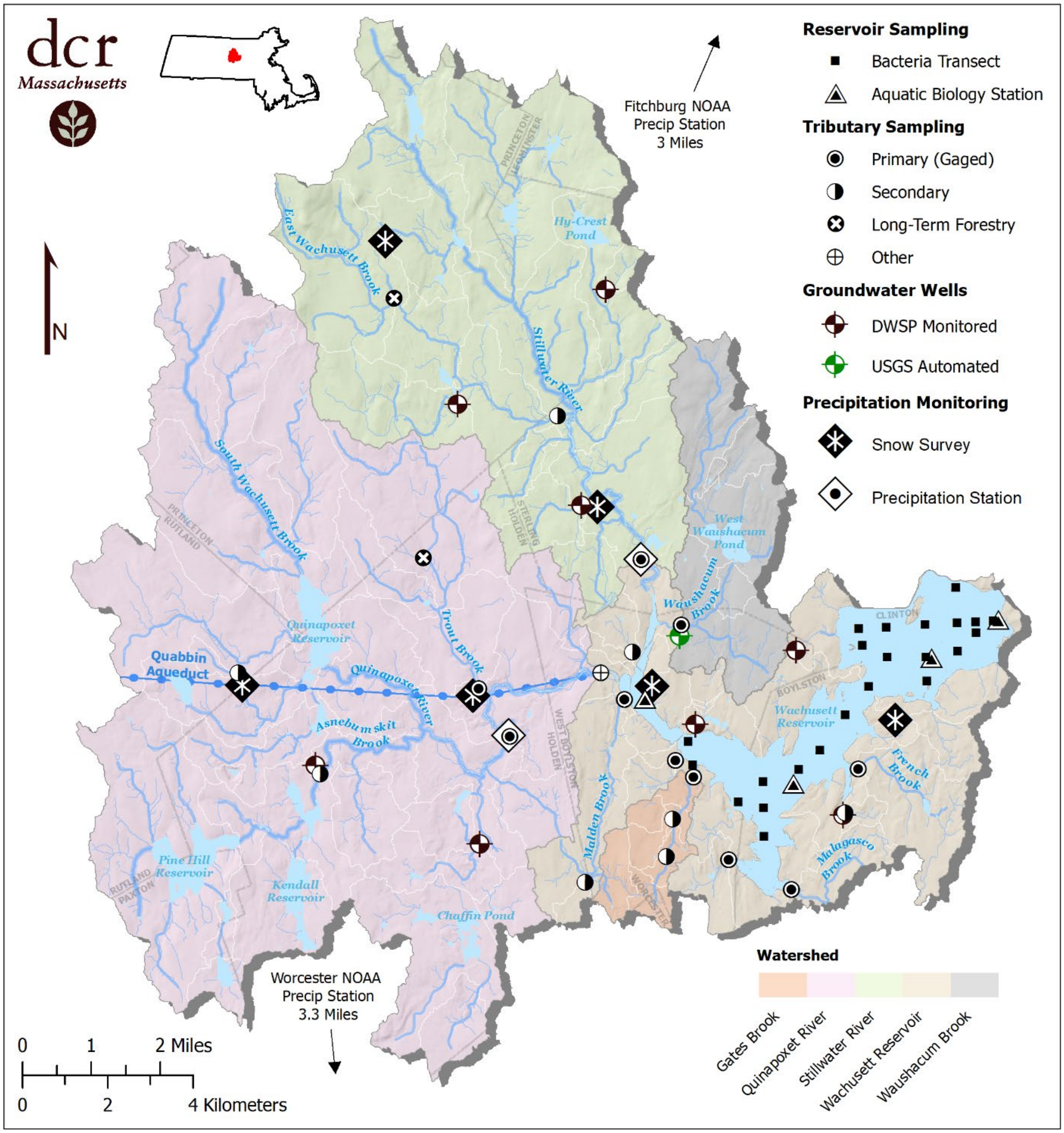


Table 2: Wachusett Tributary Sampling Locations, 2022

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

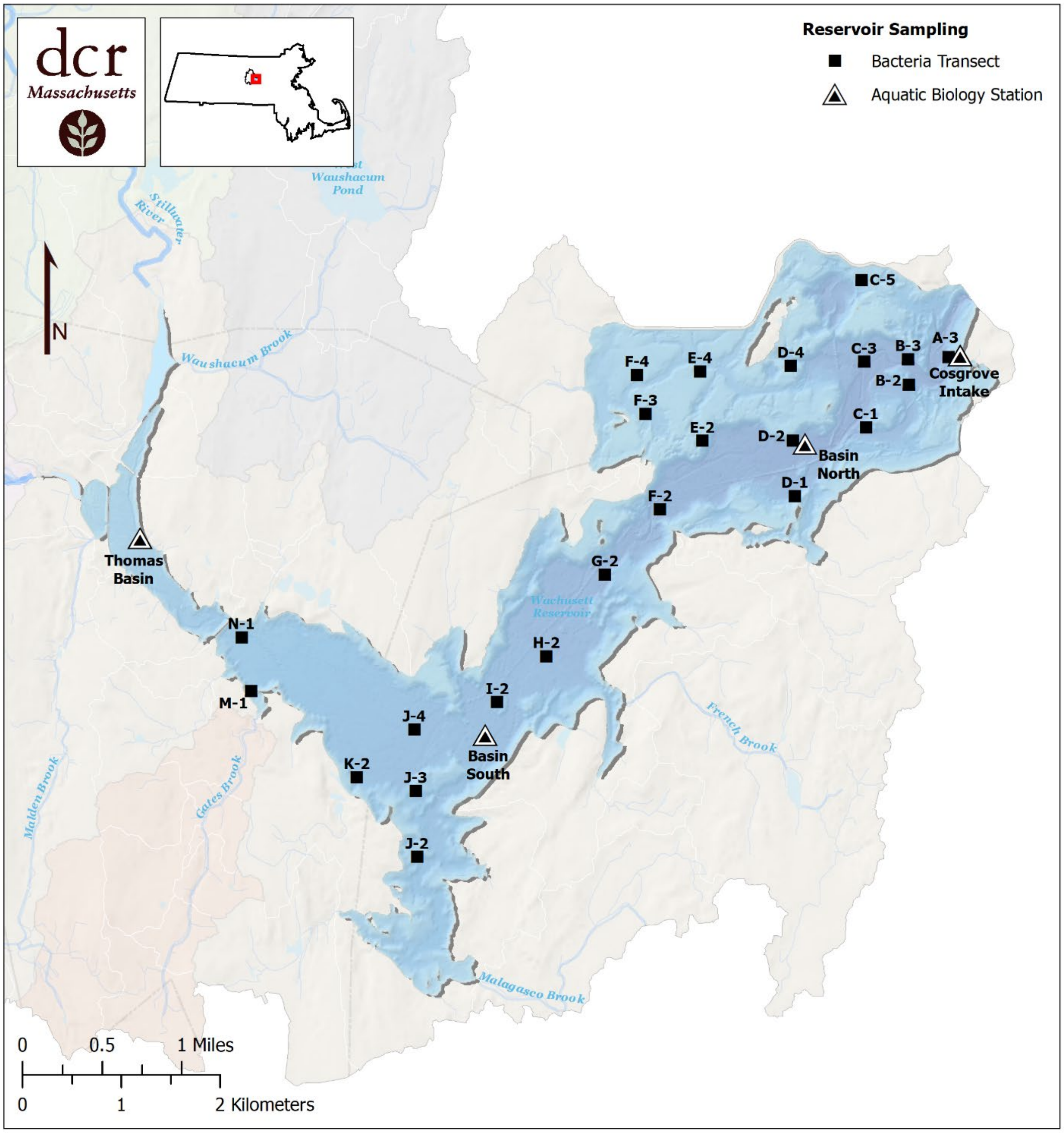


Table 3: Wachusett Reservoir Sampling Locations

Station (Id)	Location Description	Approximate Depth* (m)	Frequency	
			Plankton/profile	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 Meteorological and Hydrological Monitoring

2.1.2.1 Precipitation and Air Temperature

DWSP monitors precipitation and uses this information to provide context for the water quality and hydrological conditions observed in the tributaries, groundwater, and Reservoir. The type, amount, intensity, frequency, and spatial distribution of precipitation (or snowmelt) across the landscape are the dominant drivers of the water quality and hydrologic dynamics. 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

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

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

Since 1985, the Wachusett Watershed average annual precipitation is 46.83 inches, with a historical low of 35.36 inches (2001) and high of 61.20 (2018). Average monthly precipitation ranges from 3.03 inches

(February) to 4.9 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.

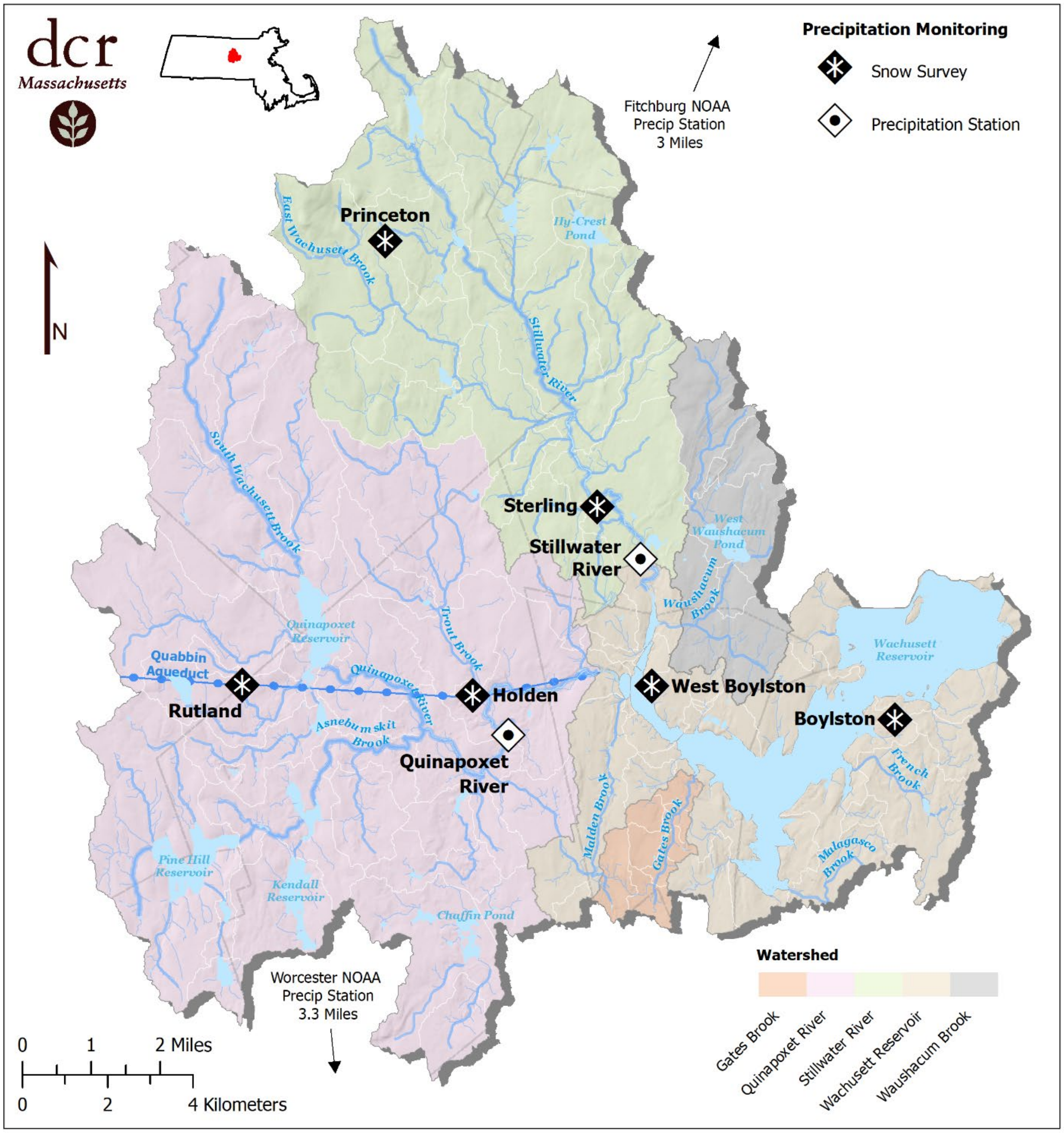
Effectively managing Wachusett Reservoir water storage volume requires an accurate prediction of water inputs to the Reservoir which are derived from new precipitation and/or melting of past precipitation stored in the snowpack. Therefore, DWSP carries out a snowpack monitoring program to track the water 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 in order to capture the variability of snowpack across the Watershed. At each location five snow core samples are taken, the depth of the snow is recorded, and each core is weighed to determine its snow water equivalent (SWE) (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 variable which has important implications for both water quality and the seasonal timing of water inputs to the Reservoir. Air temperatures determine if precipitation falls in liquid or frozen form. It is therefore a key factor in winter snowpack development and controls its subsequent melt. Heat exchange over time between the atmosphere and water at various stages of the water cycle (both gain and loss) drives seasonal water temperature fluctuations in both tributaries and the Wachusett Reservoir. Water temperature plays a significant role in aquatic ecology (see Section A-8), and seasonal ice formation on the Reservoir (see Section 3.4.1).

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

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



2.1.3 Hydrologic Monitoring

2.1.3.1 Streamflow

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. Details about USGS monitoring methods and equipment for these stations can be found 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 seven DWSP flow monitoring stations (Figure 5) visual observations of stream depth (stage) is recorded from staff plates during all sampling visits (typically three times per month). Manual stage measurements were supplemented by continuous depth recordings using HOBO water level data loggers starting in 2013. Unfortunately, data management issues have prevented reliable use of HOBO data prior to 2017. Additionally, prior to 2017, HOBO devices were removed from streams in winter months due to concerns over freezing. This issue was resolved in late 2017 and HOBO devices are now in service year-round. Additional details about continuous stream flow monitoring are provided in the DWSP *SOP for the Monitoring of Continuous Stream Flow*[24].

Reliable stage-discharge relationships (ratings) allow the use of easily acquired stream depths to quickly estimate discharge (flow). Direct flow measurements (discharge measurements) at a range of depths are usually performed several times during the year using a Sontek FlowTracker handheld acoustic doppler velocimeter. A rating equation is calculated after a sufficient number of discharge measurements are obtained at a tributary, which is subsequently used to derive discharge as a function of stage. Additional details about stream discharge measurements are provided in the DWSP *SOP for the Monitoring of Stream Discharge*[25].

Three other stations utilize continuous monitoring equipment maintained by the USGS to collect and transmit real-time data every 10 to 15 minutes. Continuous data (15-minute increments) from the Stillwater and Quinapoxet Rivers have been collected since 1994 and 1996, respectively. Stage data from Gates Brook were collected manually from 1994 until December 2011 when a flow monitoring sensor was installed to collect stage, temperature, and conductivity data at 10-minute increments. All data and other information available for these locations are available from the USGS at the NWIS website for each station.

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[26], 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[27]. Due to the increased interest in collecting additional specific conductance/Cl data this pilot station was outfitted with a Hydros21 CTD sensor manufactured by Meter Group, Inc., which measures specific conductance, temperature, and depth.

This pilot project was determined to be successful and Mayfly units were deployed at five additional monitoring locations in December 2021. One final Mayfly station is scheduled to be installed at Trout Brook in 2023.

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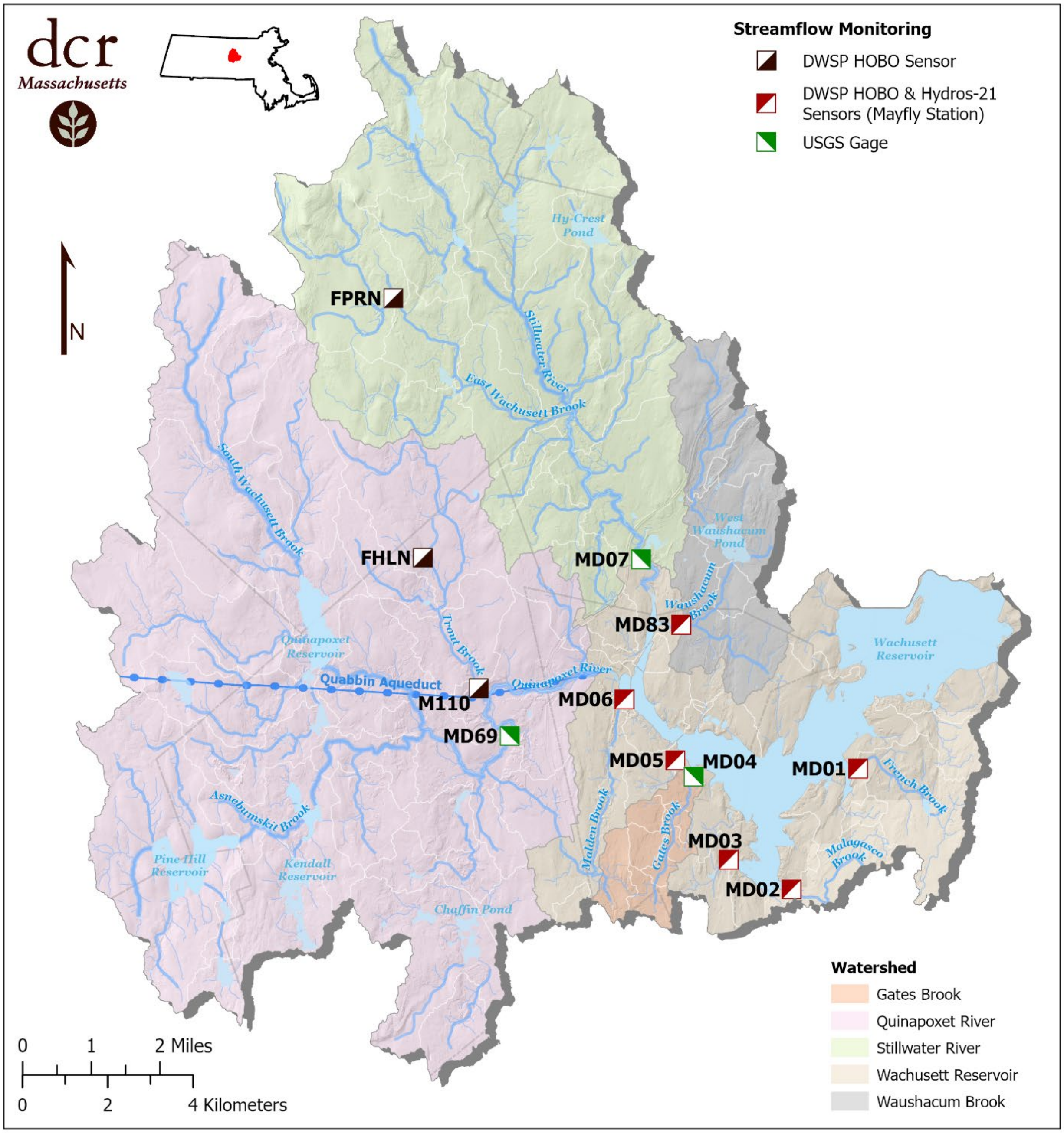
[23] https://waterdata.usgs.gov/ma/nwis/current/?type=MWRA&group_key=basin_cd
[24] DWSP, 2023c
[25] DWSP, 2021a
[26] https://stroudcenter.org/news/digital-mayfly-swarm-is-emerging/
[27] https://monitormywatershed.org/sites/WACH-MD01/

Figure 5: Streamflow Monitoring Locations in Wachusett Reservoir Watershed



2.1.3.2 Reservoir Elevation

Wachusett Reservoir elevation is controlled by MWRA, which manages aqueduct transfers and outflows to maintain a water surface elevation within the normal operating band between 390 and 391.5 ft when the reservoir 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.

2.1.3.3 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.

In 2022, DWSP continued its partnership with USGS to measure monthly groundwater levels from Sterling - Rt 140 and report them to USGS for the National Water Information System and to DCR Office of Water Resources as part of the statewide hydrologic monitoring network. This continued until automated well depth equipment was installed by USGS in November 2022.

An additional seven groundwater wells were sampled monthly in 2022, continuing the expanded groundwater monitoring that began in 2019, primarily due to the increased interest in collecting additional specific conductance/Cl data in the Wachusett Watershed (Figure 30). Water levels are measured as part of this expanded monitoring effort. A total of eight wells are now sampled by DWSP, seven of which were previously monitored by USGS and have historical water level data. The periods of historical data and other summary information about the wells sampled by DWSP can be found in Table 5.

Table 5: Wachusett Groundwater Well Information

DWSP Code	Well Name	USGS Code	Type	Depth (ft)	Elevation (ft)	Historical Period
MDW1	Holden - Wachusett St	422102071501401	Dug	10.5	670	1995 – 2002
MDW2	Boylston - Rt 70	422125071440101	Augered	12.2	475	1995 – 2002
MDW3	West Boylston - Gate 27	N/A	Augered	15.1	403	2019 – present
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
MDW8	Holden - Jefferson	422201071530201	Augered	20.3	815	1995 – 2002
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. Additional water level measurements were collected by DWSP at Sterling - Rt 140 at four-hour intervals using a HOBO water level data logger. USGS also continues to maintain an automated groundwater observation well (West

[28] Bent, 1999

Boylston – Prescott St), which records groundwater levels hourly. Data and information about this USGS monitoring well can be found at the NWIS website[29]. Additional details about groundwater level monitoring are provided in the DWSP *SOP for the Monitoring of Groundwater (WATWEL)*[30].

2.1.4 Groundwater Quality Monitoring

Groundwater quality can differ drastically between and within groundwater aquifers. This water resource is a major component of the Wachusett Watershed water budget, however there is very little recent data about the quality of groundwater in Wachusett Watershed aquifers. As mentioned in the section above, DWSP groundwater monitoring was expanded to seven additional wells due to concern over concentrations of Cl and specific conductance observed in tributaries and the Wachusett Reservoir. Exploratory monitoring of the new wells began in April 2019 with regular monthly monitoring starting in July 2019 and continuing through 2022 (Figure 6). In 2020, three additional parameters were collected monthly in conjunction with well level measurements: specific conductance, Cl, and temperature. MWRA has assigned the project code "WATWEL" for groundwater parameters requiring laboratory analysis. This list of parameters was expanded again in May 2021 to include concentrations of alkalinity, sulfate, fluoride, bromide, calcium, magnesium, sodium, and nitrate. These expanded parameters were collected through April 2022 which provided a full year of data. Also in April 2022, DWSP began using a new flow cell which enables the collection of data with a YSI Quatro probe. From that point on, the groundwater sampling parameters collected 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[31] ensures the samples were representative of the surrounding groundwater. Two wells (Holden – Wachusett St and Sterling – Justice Hill Rd) are dug wells and therefore unable to be fully purged due to the large volumes of water they contain. Additionally, the Holden – Jefferson well has a narrow diameter that prevents purging with a submersible pump. As a result, specific conductance and temperature readings are collected *in situ* without purging and Cl samples were unable to be collected in this well (MDW8). Specific conductance, temperature, pH, and dissolved oxygen are measured with a Yellow Springs Instrumentation (YSI) Professional Plus or ProQuatro meter equipped with a flow cell and samples to be analyzed by MWRA are collected in a 4-liter bulk bottle. The sample is then split into parameter-specific bottles and sent to the MWRA Deer Island Lab for analysis. Additional details about groundwater quality monitoring are provided in the DWSP *SOP for the Monitoring of Groundwater (WATWEL)*[32].

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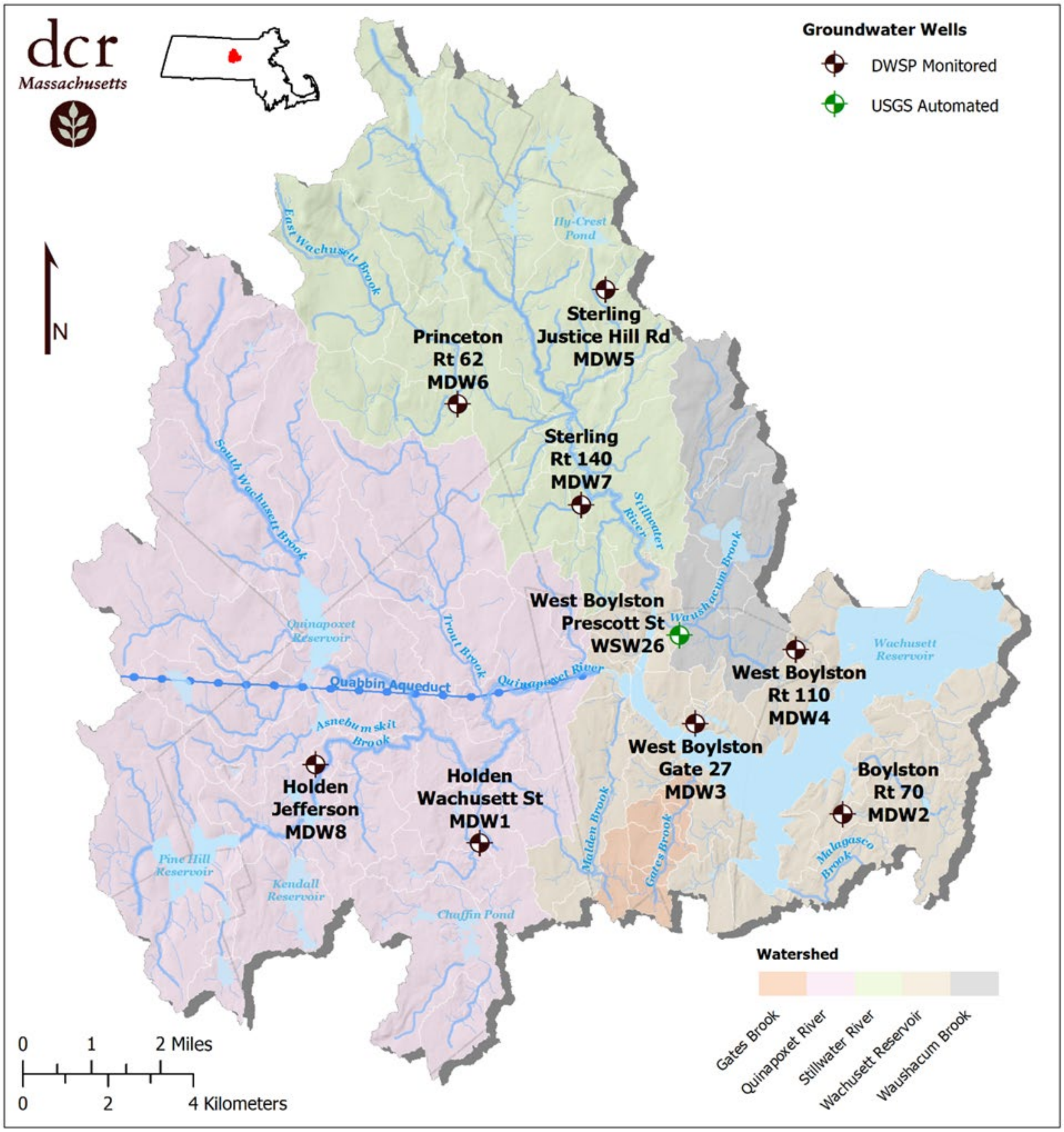
[29] https://waterdata.usgs.gov/ma/nwis/current/?type=MWRA&group_key=basin_cd
[30] DWSP, 2021b
[31] United States Environmental Protection Agency [USEPA], 2017
[32] DWSP, 2021b

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



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

2.1.5 Tributary Monitoring

The principle tributary monitoring programs are divided into two groups: 1) Routine tributary monitoring for bacteria and turbidity (MWRA project code WATTRB) and 2) Nutrient and total suspended solids (TSS) monitoring (MWRA project code WATMDC, referred to as 'nutrient monitoring'). Other tributary monitoring occurs at the two long-term forestry (LTF) project study locations (MWRA project code WATBMP) and short-term forestry (STF) monitoring locations (Figure 7). *In situ* measurements for physiochemical parameters (field parameters) are also taken in conjunction with all tributary monitoring visits (except STF). Field parameters are measured with a YSI Professional Plus 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.

2.1.5.1 Routine Tributary Monitoring

In 2022, 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 assessment investigations. Follow-up samples were also collected when elevated bacteria levels were detected in order to determine if levels persisted. Additional details about routine tributary monitoring are provided in the DWSP *SOP for the Monitoring of Tributary Bacteria and Turbidity (WATTRB)*[33].

2.1.5.2 Nutrient Monitoring

In 2022, 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[34], ammonia-nitrogen (NH_3-N), chloride (Cl), UV absorbance at 254 nm (UV_{254}), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), total Kjeldahl nitrogen (TKN), total organic carbon (TOC), total phosphorus (TP), and total suspended solids (TSS). All samples were analyzed at the MWRA lab on Deer Island. Nutrient measurement units are all mg/L with the exception of UV_{254}, which is reported in ABU/cm and TP which 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 2022. The Quabbin Transfer was sampled six times in 2022. 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)*[35].

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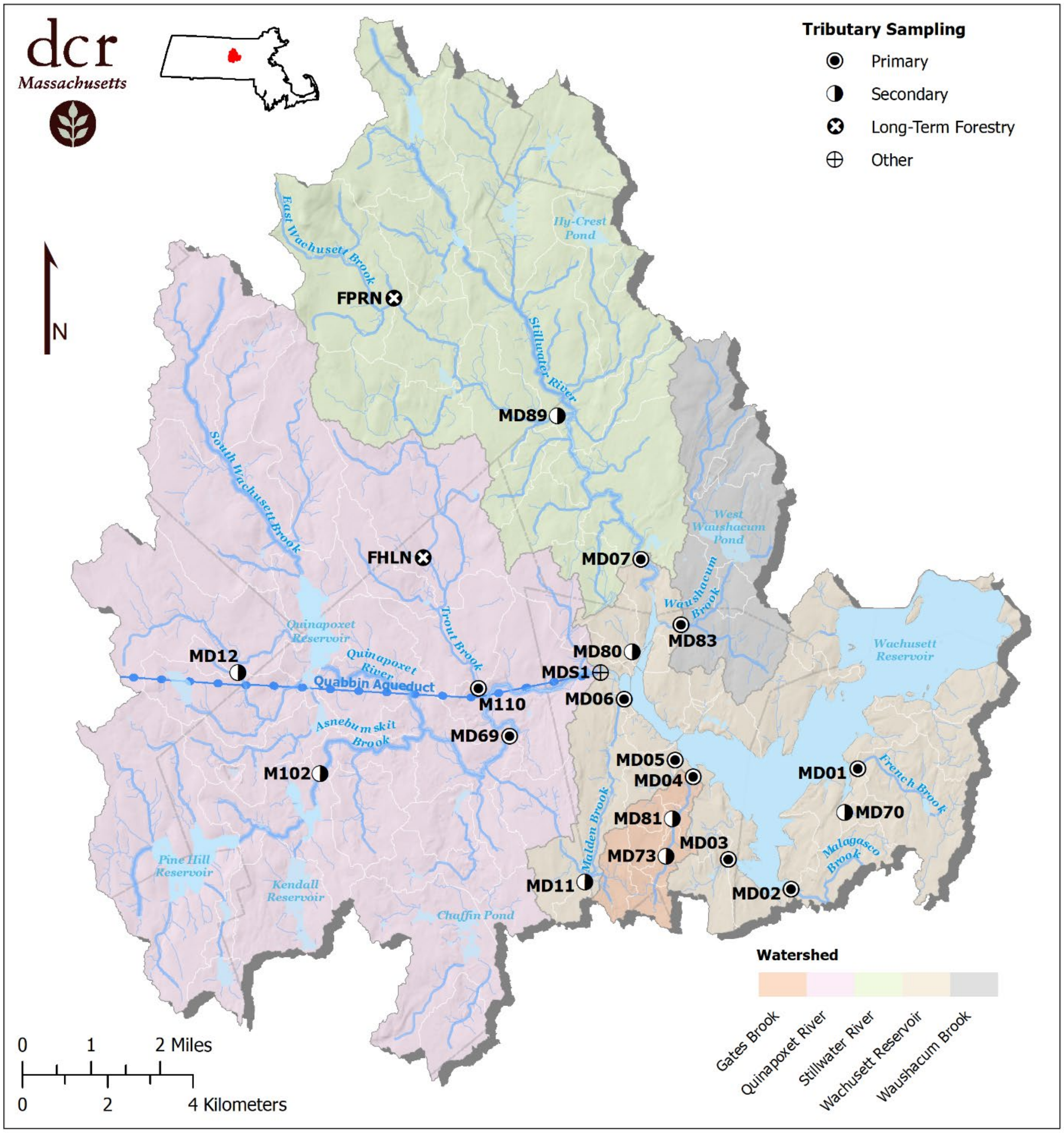
[33] DWSP, 2023b
[34] Alkalinity sampling was resumed at all primary tributary locations in September 2020
[35] DWSP, 2021d

Table 6: 2022 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 2022
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	419 (*E. coli*) 421 (turbidity)
Field Parameters	N/A	Water temperature, dissolved oxygen, pH, specific conductance, stage (where applicable)	1-3 times per month/location in conjunction with WATMDC and WATTRB projects	Primary, Secondary, Other	2,691
		Stage		Primary	461
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 2022)	LTF	9*
Short-term Forestry	N/A	Turbidity	Varied	5 timber harvest lots (not mapped)	12

Figure 7: Tributary Sampling Locations in the Wachusett Reservoir Watershed



2.1.6 Reservoir Monitoring

Monitoring of Wachusett Reservoir includes collection of *in situ* measurements, collection and analysis of water samples for plankton, nutrients, and bacteria, as well as collection or observation of other flora and fauna inhabiting the Reservoir (Table 7). Details of each program are provided below.

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 the Appendix (A-8 and A-13).

Table 7: 2022 Reservoir Monitoring Program Components

Program Name	MWRA Project Code	Parameter or Analysis	Typical Sampling Frequency	Sample Locations	# Samples Collected in 2022
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	44
Phytoplankton	N/A	Phytoplankton density	Weekly (May – Sept), biweekly (Oct – April)	Primary: BN3417, CI3409, Secondary: BS3412, TB3427, other	109
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	344
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

2.1.6.1 Water Quality Profiles

DWSP staff routinely record water column profiles in Wachusett Reservoir using a YSI EXO2 multi-parameter sonde for the following hydrographic parameters: temperature, specific conductance, dissolved oxygen concentration, percent oxygen saturation, chlorophyll *a*, phycocyanin, turbidity, and pH. Data are recorded with a handheld display connected to the sonde with a 33-meter cable, starting at the surface. Measurements are recorded at 0.5 to 1-meter intervals or more frequently, except during periods of isothermy and mixing (generally November through March) when intervals of two or three meters are adequate to characterize the water column. Detailed procedures are contained in the DWSP *SOP for Collection of Reservoir Profiles*[36].

A total of 44 profiles were collected from four locations in 2022. These included 12 profiles collected in conjunction with reservoir nutrient monitoring.

[36] DWSP, 2020a

Three remote sensing profiling buoys have been deployed annually by MWRA starting in 2016. In 2022 these buoys correspond to DWSP routine sampling sites at Basin South and Basin North. An additional profiling buoy was placed outside of Cosgrove Intake. Profiles are collected with YSI EXO2 sondes identical to those used by DWSP. The profilers automatically run every 6 hours (12am, 6am, 12pm, and 6pm) and collect data at 1-m increments. The data can be viewed remotely shortly after collection via the MWRA Operations Management Monitoring System (OMMS) website. Results are frequently used by DWSP to augment the routine profile/plankton sampling program. For example, if elevated chlorophyll *a* values are observed in remote sensing data, DWSP may sample earlier than scheduled to capture associated phytoplankton data. The high frequency profile data also allows for identification and visualization of diurnal patterns and both short and long-term effects of environmental forces such as cooling temperatures during turnover and seiche effects due to wind events.

2.1.6.2 Nutrient Monitoring

Sampling for assessment of nutrient dynamics was conducted in May at the onset of stratification, July in the middle of the stratification, near the end of the stratification period in October, and following turnover in late November. 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 216 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[37] and in the DWSP *SOP for Collection of Reservoir Nutrients*[38].

2.1.6.3 Bacteria Monitoring

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

2.1.6.4 Phytoplankton Monitoring

Routine monitoring for phytoplankton follows a seasonal schedule with samples collected every other week from October through April and at least once per week from May through September. Sampling frequency may intensify in response to increases in density of specific phytoplankton genera (see Section A-18, Table A-2), or decrease when conditions such as ice cover physically prevent sampling. Monitoring by DWSP staff takes place at either Basin North (BN3417) or at the Cosgrove Intake Facility (CI3409) with additional locations sampled as necessary to characterize the phytoplankton community present throughout the Reservoir. Grab samples are typically collected from at least two depths including an epilimnion sample at 3 m and (during stratification) a metalimnion sample. The exact depth of the latter is typically selected based on results of a water column profile collected in conjunction with phytoplankton

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

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*[39], *Phytoplankton Collection and Reporting*[40] and *Microscopic Enumeration of Phytoplankton*[41].

In 2022, phytoplankton monitoring was carried out on 39 days, resulting in 109 individual samples. Twenty of these samples were analyzed solely for taxa of concern (see Section A-18, Table A-2); the entire phytoplankton community was assessed in the remainder. A six-week period of elevated chrysophyte densities was documented through routine monitoring, requiring an increase in monitoring frequency for a total of six weeks in 2022.

2.1.6.5 Zooplankton Monitoring

Quarterly collection of zooplankton samples was conducted in conjunction with nutrient sampling as described above. A total of 48 samples were field preserved 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*[42].

2.1.6.6 Macrophyte Monitoring

Frequent assessments of the aquatic vegetation community in and around Wachusett Reservoir are made as part of the invasive macrophyte control program. Monitoring takes place throughout the growing season, typically May through October, and may include visual surveys conducted via boat, in-water assessments via snorkeling, and collection of vegetation biovolume data with boat-based sonar. Related activities undertaken by DWSP staff include maintenance of floating fragment barriers; inspection of boats and other vessels deployed to the Reservoir by contractors, emergency personnel, and others; 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 2022 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.

2.1.6.7 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

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

O. mordax abundance in other waterbodies is correlated with increased *S. namaycush* condition and length at catch[43].

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.

The *S. namaycush* population in the Reservoir is important as it is on the southern edge of this species' range for natural reproduction, it requires high water quality to survive, and it is the most popular sport-fish in the Reservoir. *S. namaycush* are the most popular sport-fish based on information from the Roving Creel Survey, which is completed every five years, and was conducted in 2022. A creel survey is a survey of anglers designed to collect information on fishing effort, species catch, and fish harvest. The 242-day fishing season ran from the first Saturday in April until November 30 and DWSP and MassWildlife staff interviewed 2,027 anglers during 101 scheduled survey days. The complete results of the 2022 survey will be published in a separate report.

2.1.7 Additional Watershed Monitoring and Special Studies

In addition to routine monitoring of Wachusett Reservoir and its tributaries, DWSP staff conduct several special investigations. These studies vary in duration and depth of scope, but include storm sampling, monitoring of potential short-term and long-term water quality changes following forest management activities, and evaluation of spatial and temporal trends in specific conductance and Cl concentrations of waters impacted by roadway de-icing practices. Additional monitoring or water quality investigations may arise from recommendations in Environmental Quality Assessments, which outline threats to water quality by sub-basin.

2.1.7.1 Forestry Monitoring

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

[43] 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)*[44]. No storm samples were collected in 2022 because an adequate number of pre-harvest samples have been collected. Storm sampling is scheduled to resume once harvest is completed.

Short-term Forestry Monitoring

From 2008 through 2022, DWSP EQ staff monitored for potential impacts of forestry operations on soil and water by conducting periodic inspections of forestry lots and collecting water samples for turbidity analysis from streams affected by logging, primarily at streams which were spanned by a temporary bridge used for transporting equipment and lumber. Elevated dry weather turbidity can be a signal that erosion is occurring above naturally fluctuating background levels and may help identify deficiencies in BMP implementation[45]. Up until 2022, turbidity sampling was frequent and occurred at all steam crossings on timber harvest lots. Methods for turbidity collection and analysis were the same as for other tributaries. In 2021, an analysis of all turbidity data collected for this project was completed for Wachusett Watershed, which concluded that there were no significant impacts to water quality at streams that were crossed during timber harvest operations. Initially, a decision was made to revise the monitoring protocol for short-term forestry monitoring – reducing its frequency and geographic scope beginning in 2022. In early 2023 it was decided that short-term forestry monitoring would be suspended division-wide, as staff time and resources should be allocated towards other areas and activities which present a greater threat to water quality. This will be the final report in which this monitoring project is discussed.

2.1.7.2 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 conducted for extreme precipitation events (2 or more inches of rain) in order to support UMass modelling efforts. No storms were sampled in 2022. 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].

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[44] DWSP, 2021c
[45] DWSP, 2018b
[46] DWSP, 2021d

2.1.7.3 Stormwater Basins

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

2.2 2022 Watershed Monitoring Parameters

In 2022, 32 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. The six parameters marked with an asterisk were added for a short-term groundwater study, from May 2021 to April of 2022.

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 A-1 in the Appendix. Scientific background information and historical context in relation to the Wachusett Watershed is also provided in the appendix to help readers better understand the discussion of water quality and hydrologic monitoring results. Monitoring results for 2022 are presented and discussed in Section 3.

Table 8: 2022 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 $CaCO_3$)	Nutrients	MWRA Lab	SM 2320 B	X	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		
Bromide*	µg/L	Special Study	MWRA Lab	EPA 300.1			X
Calcium*	µg/L	Special Study	MWRA Lab	EPA 200.7 (Rev. 4.4, 1994)			X
Chloride	mg/L	Nutrients	MWRA Lab	EPA 300.0		X	X
Chlorophyll	ug/L	Field parameter	Field-Sensor	*In situ* Fluorometry	X		
Chlorophyll RFU	RFU	Field parameter	Field-Sensor	*In situ* Fluorometry	X		
Chlorophyll volts	volts	Field parameter	Field-Sensor	*In situ* Fluorometry	X		
Discharge	cfs	Field Parameter	Calculated	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	
Fluoride*	mg/L	Special Study	MWRA Lab	SM 4500-F-C 2011			X
UV_{254}	ABU/cm	Nutrients	MWRA Lab	SM 5910B 19th edition	X	X	
Magnesium*	µg/L	Special Study	MWRA Lab	EPA 200.7 (Rev. 4.4, 1994)			X
Nitrate-nitrogen	mg/L	Nutrients	MWRA Lab	EPA 350.1, 353.2	X	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	X		
Sodium*	µg/L	Special Study	MWRA Lab	EPA 200.7 (Rev. 4.4, 1994)			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	
Sulfate*	mg/L	Special Study	MWRA Lab	EPA 300.0			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

* These parameters were analyzed for a special short-term groundwater study

[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 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 2022 and prior years are available upon request.

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

2.4 Quality Assurance and Quality Control

During the 2022 sampling season, several new quality control practices were implemented or formalized in the DWSP sampling programs.

Beginning in July 2019, all YSI meter calibration data were written on paper forms and scanned once per year to back up the information. Beginning in 2022, all YSI meter calibration data are exported from the meters and imported into DWSP's Microsoft SQL Server database. Storing these records digitally facilitates review and analysis of the calibrations, tracking calibration metrics, and detecting potential drift in sensor calibration values. As an additional check on calibration results, a quality control report—automated with R Markdown—is produced after every calibration import which compares calibration results to ideal and acceptable calibration results. The calibration results of the previous six months are plotted to reveal any patterns in calibration results. Calibration result plots for YSI meters are shown Figure 8 for pH, Figure 9 for dissolved oxygen, and Figure 10 for specific conductance.

Figure 8: YSI Meter pH Calibration Values - 2022

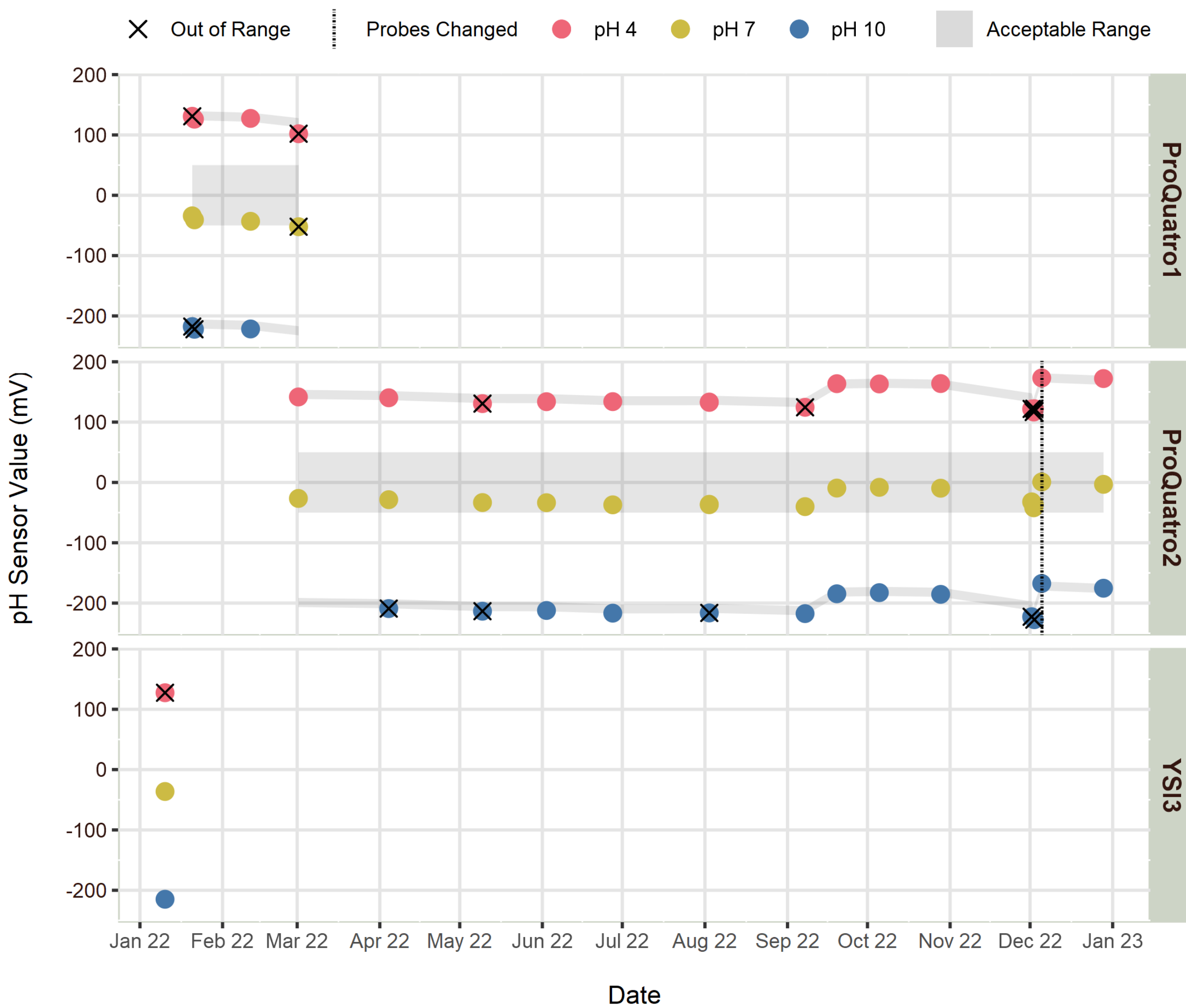


Figure 9: YSI Meter Dissolved Oxygen Calibration Values - 2022

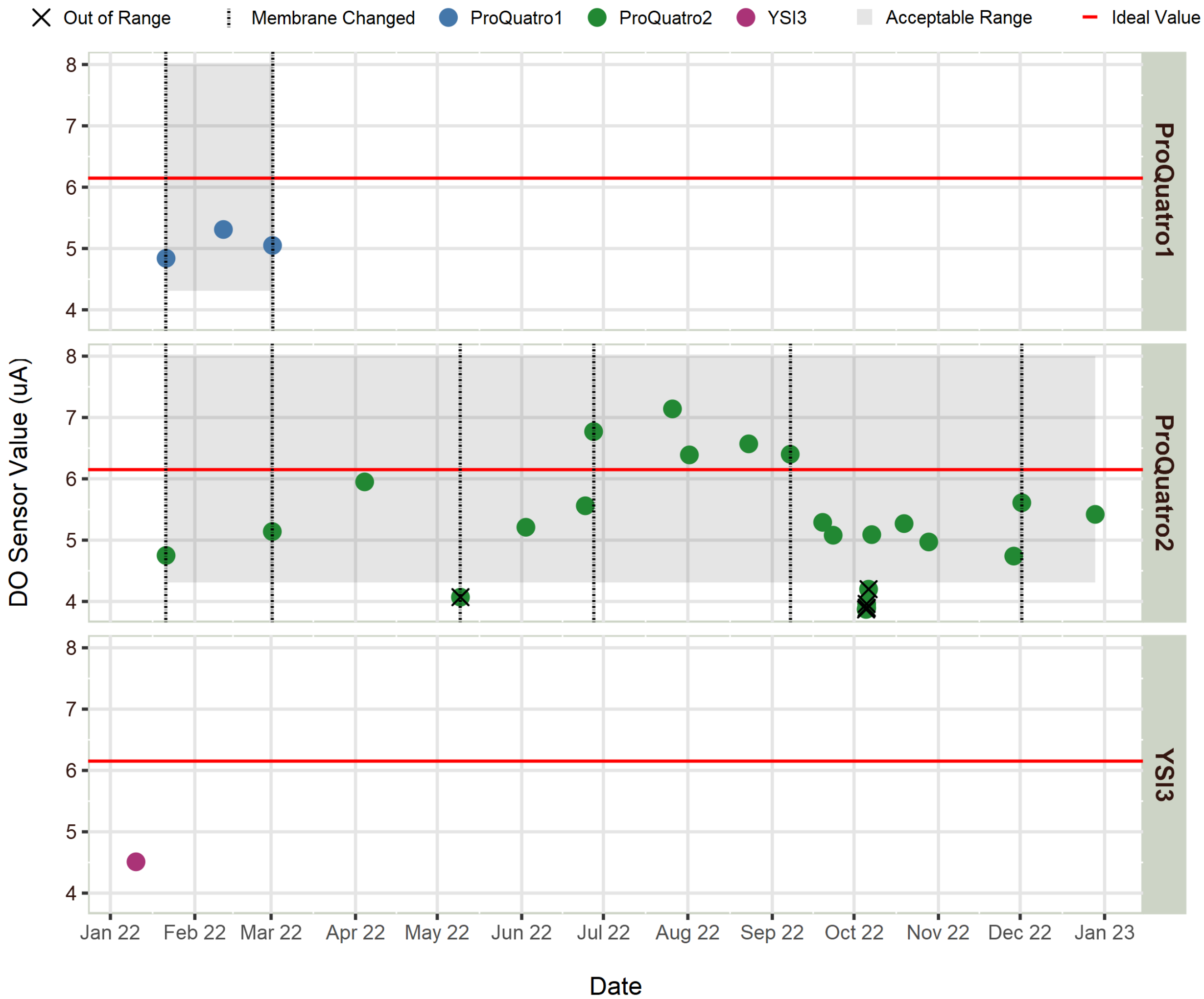
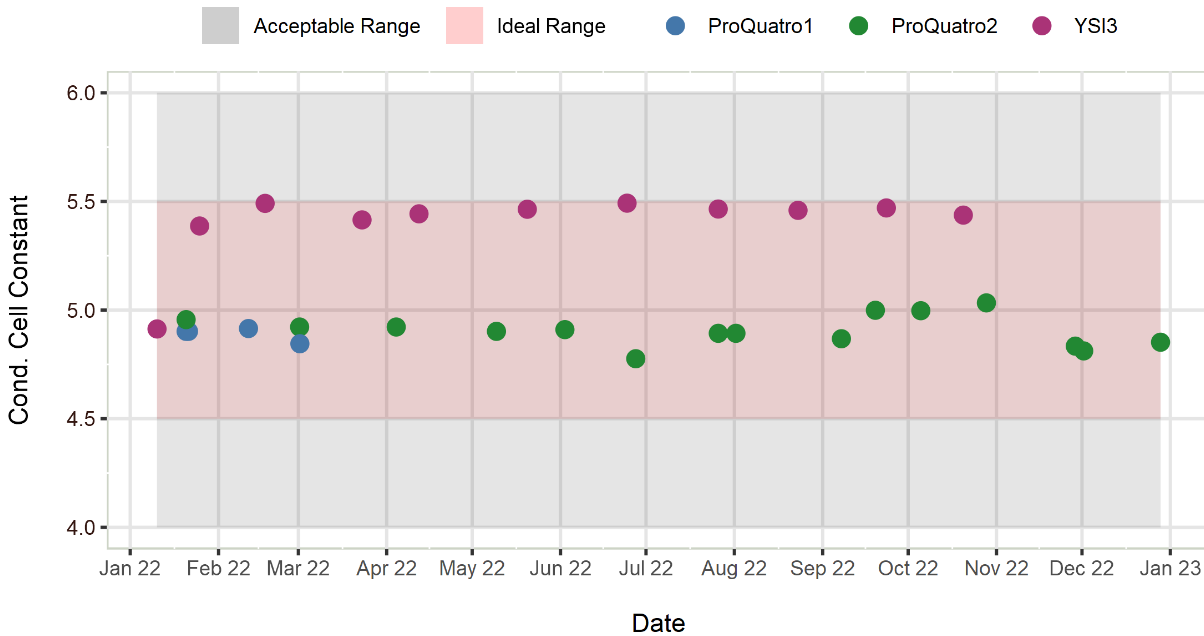
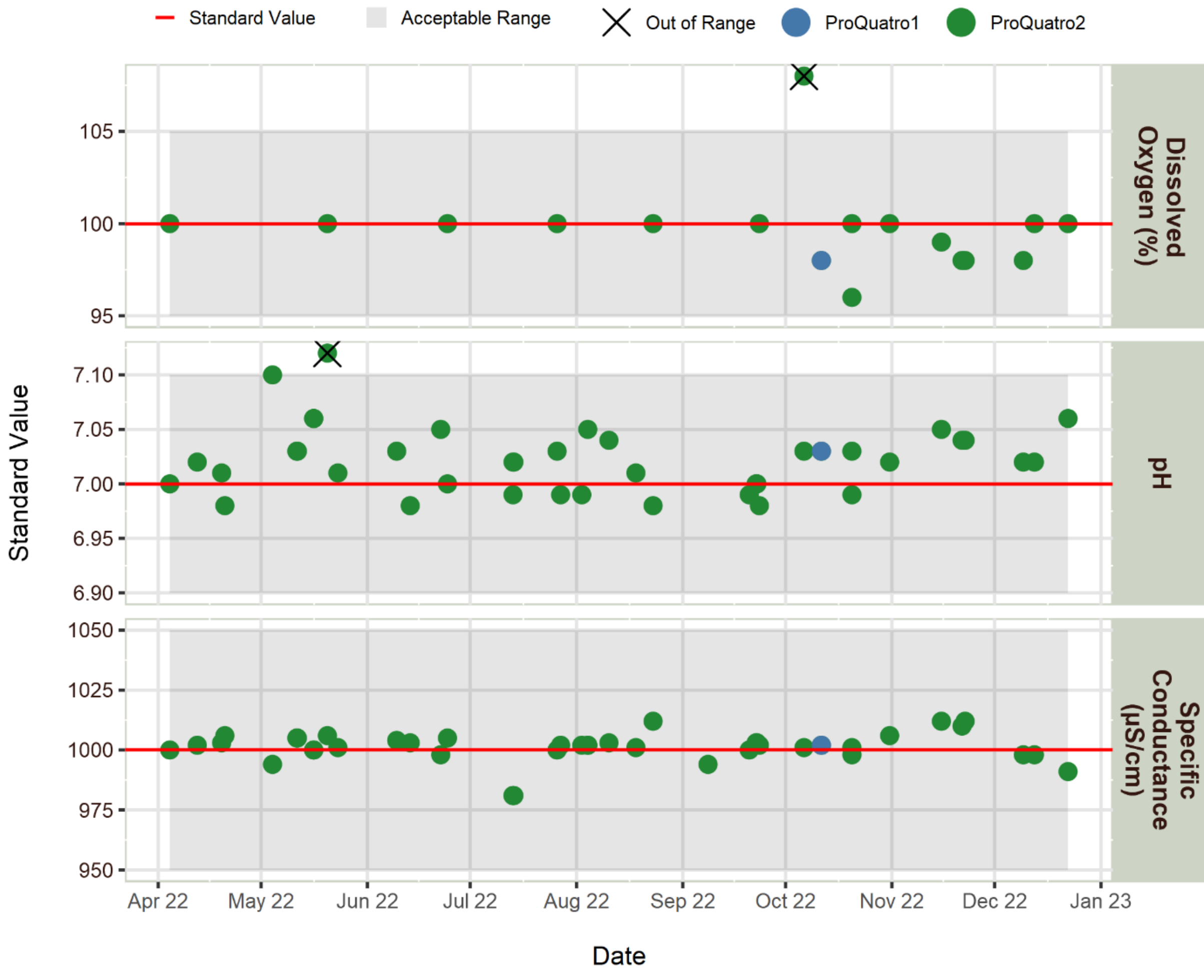


Figure 10: YSI Meter Conductivity Calibration Values - 2022



Beginning in April 2022, a new process was implemented for recording pre-sampling checks on YSI meter parameters. These data are entered into the beginning of the Survey123 form used to record data in the field. If values are out of the acceptable range, DWSP staff will be prompted to recalibrate prior to sampling. Upon import of field data, the pre-sampling checks are imported into a new table in DWSP's database. These data are used to ensure that sample data collected with the YSI meter are accurate each sampling day. Pre-sampling check data are shown in Figure 11.

Figure 11: YSI Meter Pre-Sampling Quality Control Check Values - 2022



Field sampling SOPs have been updated as needed to match the new quality control procedures and to improve overall clarity. Additionally, a Quality Assurance Project Plan for DWSP EQ sampling programs is being drafted with planned approval and implementation by the end of FY 2023.

3 Results

In 2022, DWSP staff analyzed 421 turbidity samples from 17 tributaries and 109 phytoplankton samples from the Reservoir. A total of 2,192 physiochemical measurements (551 each of temperature and specific conductance; 545 of dissolved oxygen and pH) were taken in the field at tributary stations and Shaft 1, with another 44 water column profiles (temperature, specific conductance, dissolved oxygen, percent oxygen saturation, chlorophyll *a*, phycocyanin, and pH) recorded from the Reservoir. A total of 763 bacteria samples were collected and delivered to the MWRA Southborough laboratory for *E. coli* analysis (419 from tributaries and 344 from the Reservoir), and 1,619 samples (1,403 tributary, 216 reservoir) were collected and shipped to the MWRA Deer Island laboratory for a total of 2,382 analyses of nutrients and other parameters; this includes special studies. Daily climate statistics for the Wachusett Watershed were calculated using records from NOAA, USGS, and DWSP monitoring stations. Daily streamflow statistics were calculated from DCR stream gauging stations or obtained from three USGS monitoring stations. Daily Quabbin transfer totals were provided by MWRA. DWSP staff measured watershed snowpack on six occasions during 2022.

3.1 Hydrology and Climate

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

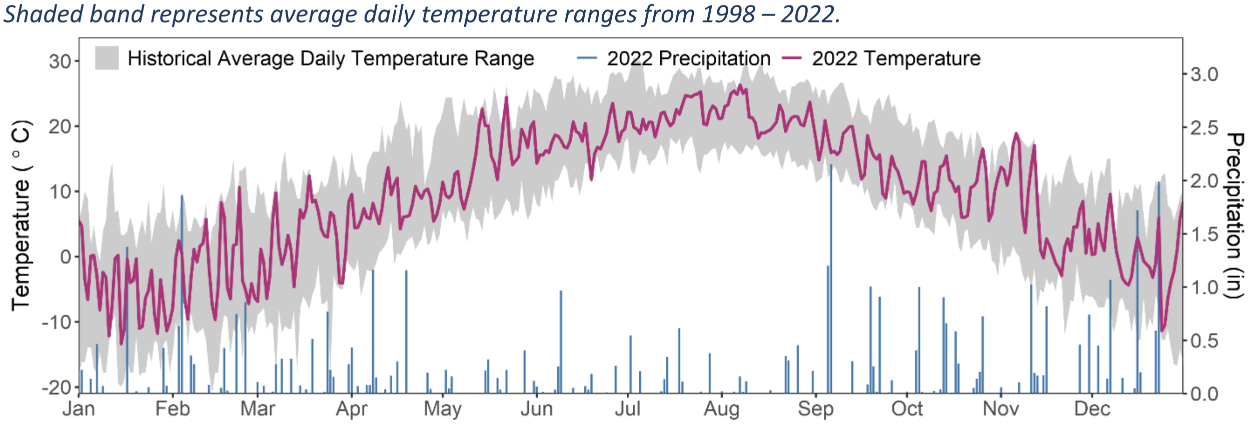
3.1.1 Climatic Conditions

3.1.1.1 Air Temperature

Average daily air temperatures in the Wachusett Reservoir Watershed for 2022 ranged from -7.61 °C (January 21) to 22.74 °C (July 22) (Figure 12). The lowest daily minimum temperature (average of all stations) observed in 2022 was -20.9 °C on February 14, while the highest daily maximum temperature was 30.6 °C on July 3.

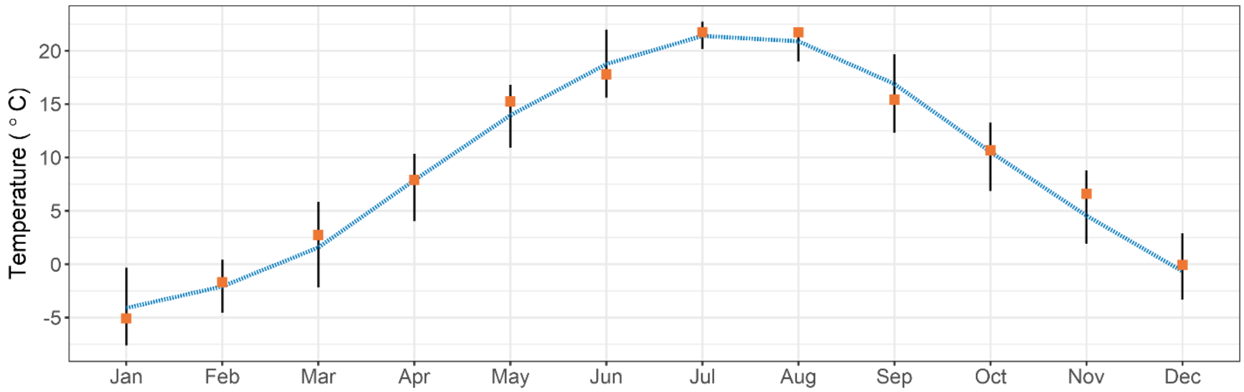
Figure 12: Climatograph of Daily Mean Temperatures and Daily Precipitation Totals for Wachusett Watershed from January 1 through December 31, 2022

Shaded band represents average daily temperature ranges from 1998 – 2022.



All monthly average temperatures were within historical ranges. Nine months in 2022 had above normal temperatures and three below (Figure 13). The mean annual temperature for 2022 was 9.49 °C, which is 0.3 degrees above the historical annual mean temperature (since 1998).

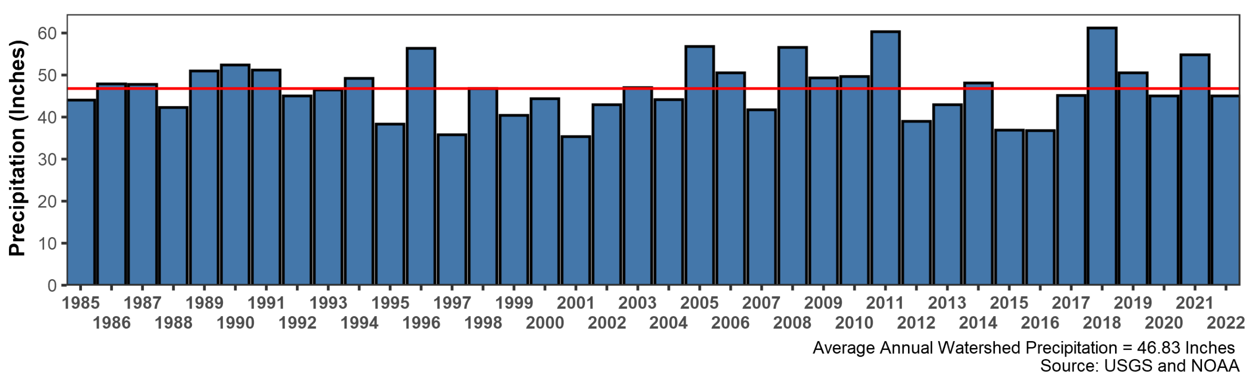
Figure 13: Wachusett Reservoir Watershed Monthly Mean Temperatures for 2022
Monthly mean temperatures for 2022 (orange squares) are shown in relation to the long-term average monthly temperatures (blue dashed line). The vertical black lines indicate the minimum and maximum monthly mean temperatures over the period of record, which began in 1998.



3.1.1.2 Precipitation

As illustrated by Figure 14, Wachusett Reservoir Watershed received slightly below average precipitation in 2022, with 45.06 inches of rainfall (1.77 inches below average annual precipitation).

Figure 14: Annual Precipitation for Wachusett Watershed, 1985 to 2022
The red line indicates the long-term average annual total precipitation.



Calendar year cumulative precipitation remained near or above normal through the middle of May, at which point rain events became small and infrequent, with monthly precipitation deficits greater than 1.5 inches during the months May through August. A mild (level 1) drought was declared for the Central Massachusetts Region on June 15. The drought status was updated to significant (level 2) on July 12 and then to Critical (level 3) on July 21[52]. Drought status was finally lowered back down to Mild on October 7, after above average rainfall in September (6.07 inches) and cooler temperatures. August was the driest month of the year with only 1.70 inches of precipitation. December was the wettest month of 2022 (6.65 inches). Noteworthy storms in 2022 occurred February 4 (1.86 inches), September 5-6 (3.35 inches), and December 23 (1.99 inches). Small and medium storms were numerous throughout 2022, with 12 days receiving one inch or more precipitation, 16 days between 0.5 and 1.0 inches, and 24 days between 0.2 and 0.5 inches.

Figure 15: Wachusett Watershed Monthly Total (left) and Daily Cumulative Precipitation (right) for 2022

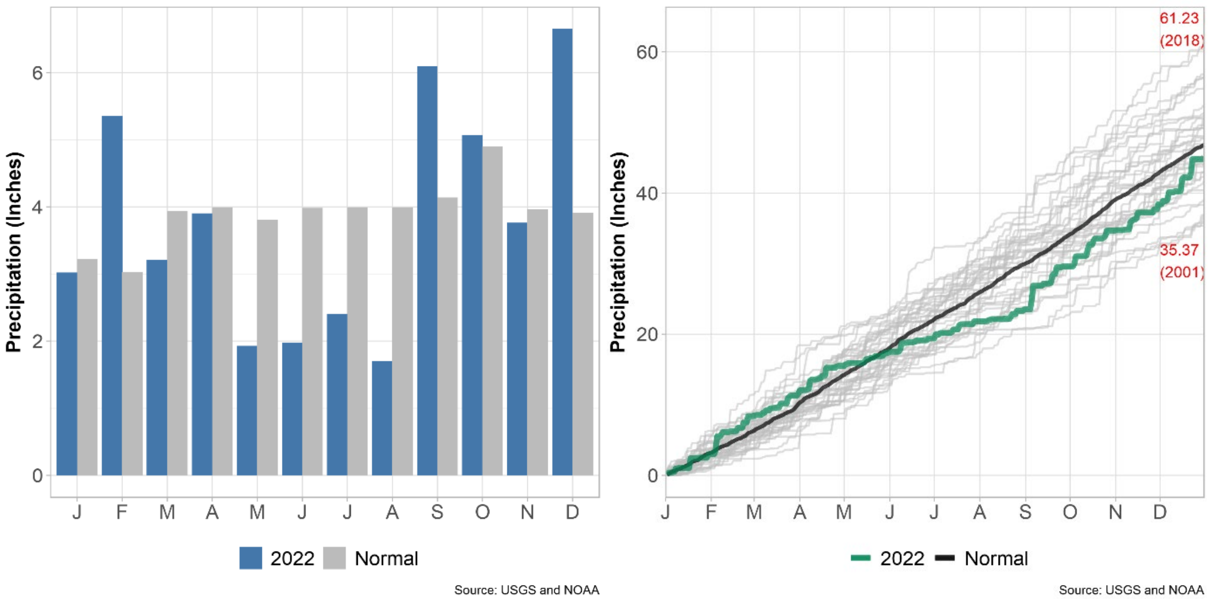


Table 9: Monthly Total Precipitation for 2022 and Statistics for the Period of Record 1985 to 2022

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Precipitation (in)	3.02	5.35	3.21	3.90	1.93	1.98	2.40	1.70	6.09	5.07	3.76	6.65	45.06
Normal (in)	3.22	3.03	3.93	3.99	3.80	3.98	3.99	3.99	4.14	4.90	3.96	3.91	46.83
Departure (in)	-0.20	2.32	-0.72	-0.09	-1.87	-2.00	-1.59	-2.29	1.95	0.17	-0.20	2.74	-1.77
Years	38	38	38	38	38	38	38	38	38	38	38	38	

Snow

Figure 16 shows the snowpack measurement results for calendar year 2022. 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.

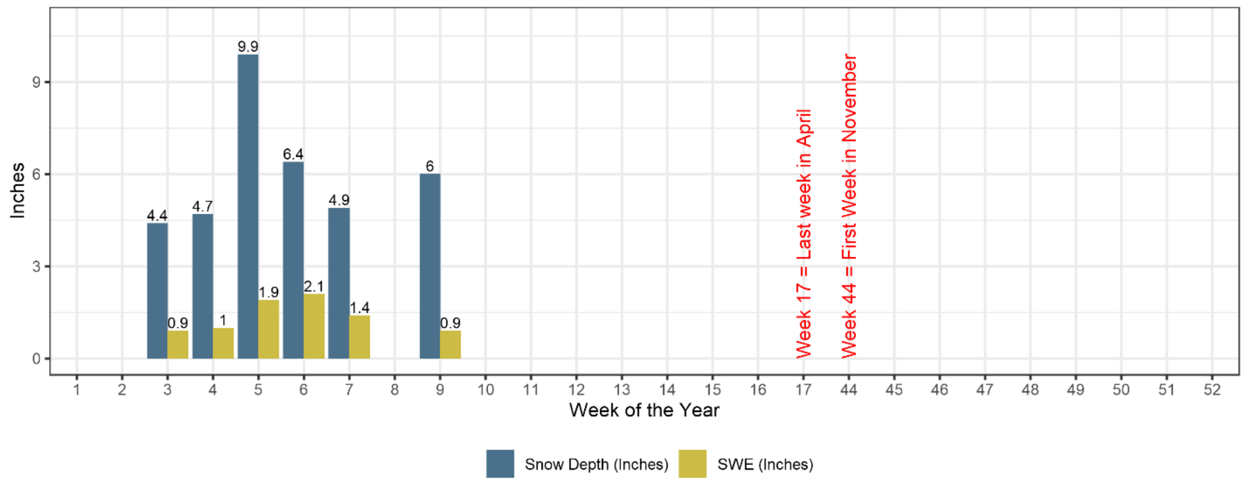
The first measurable snowpack in 2022 occurred after a storm on January 17, totaling 4.4 inches (Watershed average). Snowpack depth and SWE increased slightly the following week, followed by a

[52] MA Drought Management Taskforce, 2022

period of compaction. A blizzard with high winds on January 29 resulted in variable snowfall across the landscape, delivering between 7 and 15 inches of snow throughout the Watershed. Snowpack decreased by February 8 due to warm temperatures and rain, however the snow trapped some of the rain, and despite the snowmelt watershed average SWE increased to 2.1 inches, reaching its peak for the season. The snowpack completely melted between February 15 and 24 and then one final snowstorm of 5-6 inches occurred on February 25. By the following week warm temperatures had diminished the snowpack and no measurements could be taken. No additional snowpack measurements were taken during the last months of the year, as no significant snow had accumulated. More detailed information was recorded in snowpack reports that were produced for the weeks that a snowpack survey was conducted.

Figure 16: Snowpack Measurements in 2022

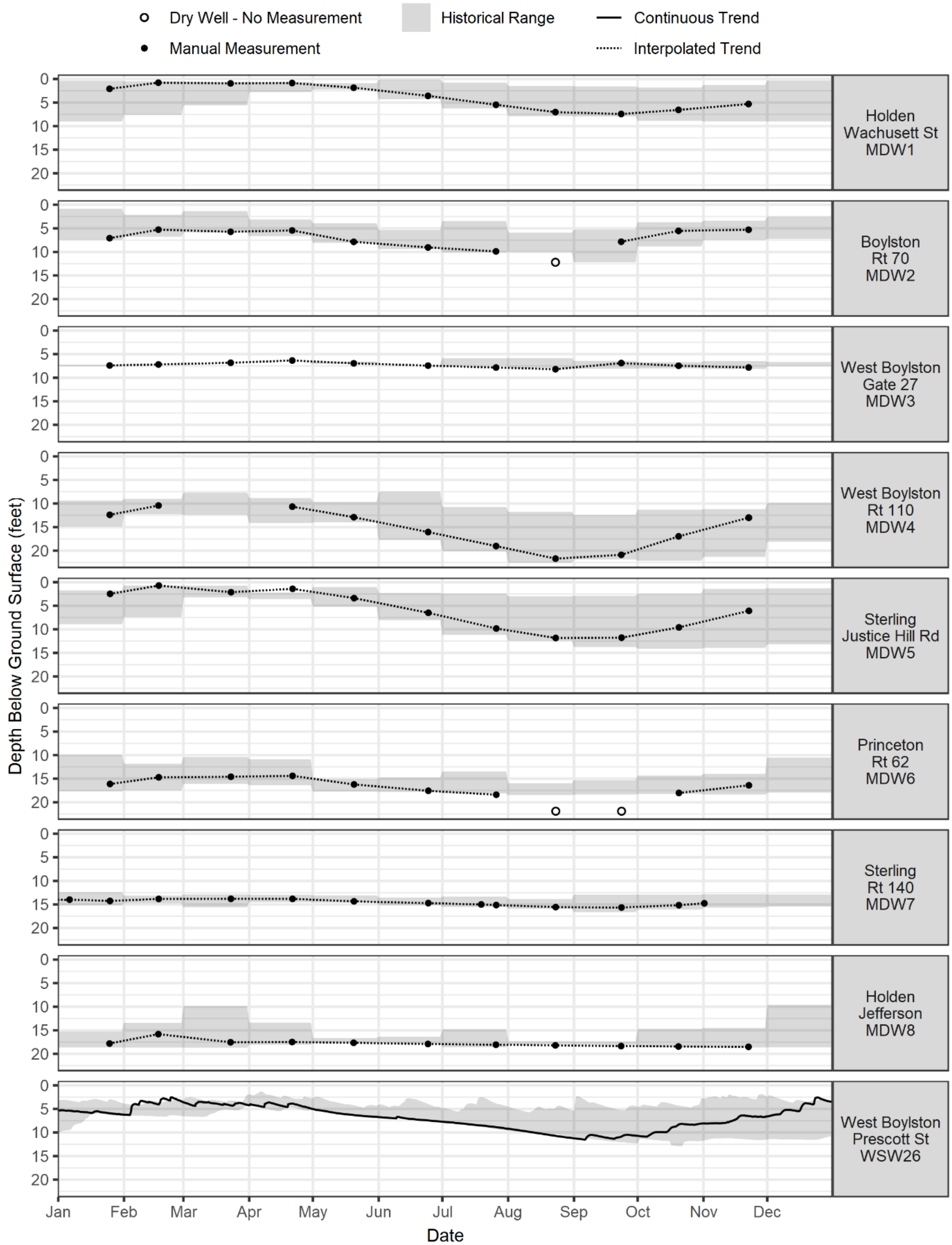
SWE = Snow-water-equivalent.



3.1.2 Groundwater Levels

Results of groundwater level monitoring are presented in Figure 17. During the 2022 sampling period, the Boylston – Rt 70 well was dry during the August sampling event and the Princeton Rt 62 well was dry in August and September. The missing March point data point for West Boylston – Rt 110 was due to a data recording error. 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 17: Wachusett Groundwater Depth Measurements in 2022 with Historical Ranges for Comparison

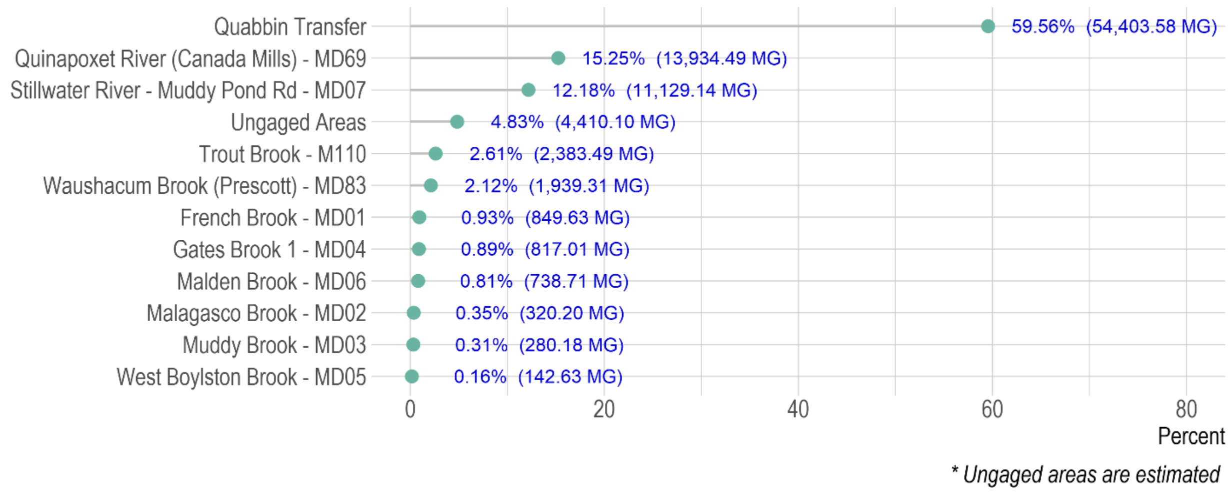


3.1.3 Streamflow and Quabbin Transfer

The total surface water inflow to Wachusett Reservoir in 2022 was estimated to be 91.35 billion gallons; about 10% less than in 2021. The seasonal hydrologic patterns typical of Wachusett Watershed returned in 2022, however summer and fall flows dropped to extremely low levels due to the prolonged drought conditions. Fortunately, fall precipitation was sufficient to recharge aquifers and increase streamflows closer to normal ranges by the end of the year.

Water transfers from the Quabbin Reservoir comprised nearly 60% of the total surface water inflow in 2022, which is about 5.6 billion more gallons than in 2021, but nearly a 12% greater share of the total annual surface water inflows to Wachusett Reservoir. Figure 18 shows a breakdown of annual total flow (MG) among all the tributaries as well as ungaged areas and the Quabbin transfer. About 27% of surface water inputs came from the Quinapoxet and Stillwater Rivers, while about 13% was contributed by the smaller tributaries and ungaged areas.

Figure 18: Wachusett Reservoir Surface Water Inflows for 2022



Total annual discharges for the Quinapoxet and Stillwater Rivers for 2022 were 13% and 18% below average, respectively (Figure 19).

Figure 19: Annual Discharge in the Quinapoxet and Stillwater Rivers (MG) (2007 to 2022)

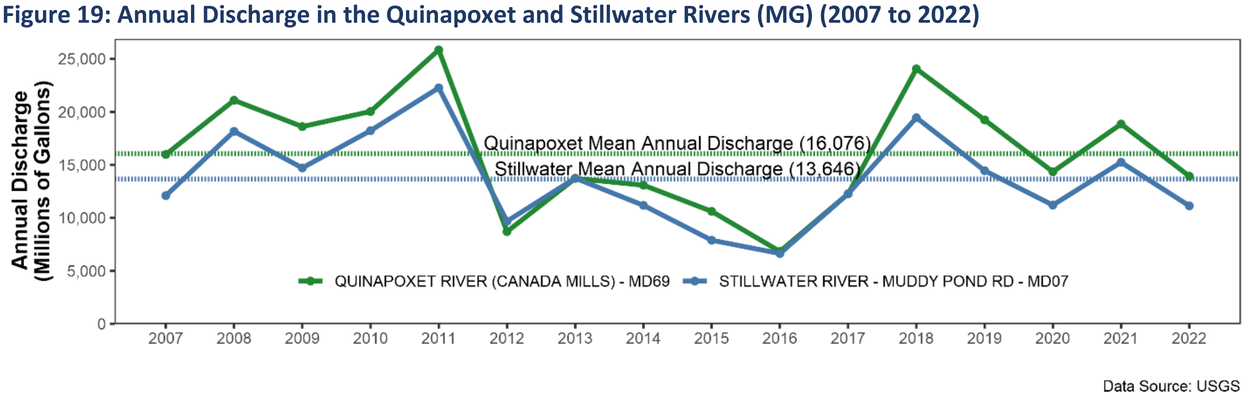


Table 10 provides summary statistics of surface water discharge for 2022. Daily flow rates in the smaller tributaries ranged from 0.00 cfs (dry) at French Brook to 115.5 cfs at Trout Brook. The maximum instantaneous flows at these tributaries ranged from 11.1 cfs at Muddy Brook to 172.4 cfs at Trout Brook.

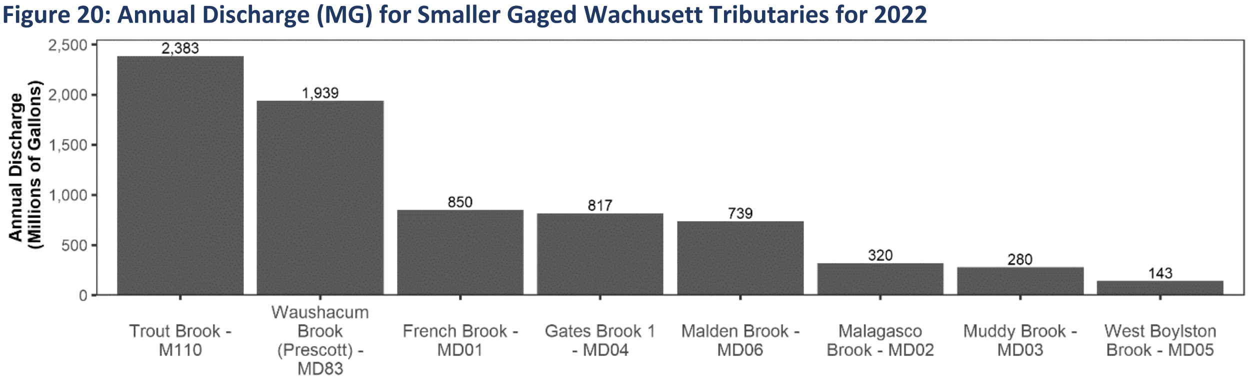
Table 10: 2022 Flow Statistics for Wachusett Reservoir Tributaries

Location	Min Daily Flow (CFS)	Avg Daily Flow (CFS)	Max Daily Flow (CFS)	2022 Peak Inst. Flow (CFS)	Min Month Vol (MG)	Avg Month Vol (MG)	Max Month Vol (MG)	2022 Total Vol (MG)
French Brook - MD01	0.00	3.65	53.0	97.3	0.4	70.8	210.1	850
Gates Brook 1 - MD04	0.33	3.46	33.1	72.0	13.5	68.1	150.6	817
Malagasco Brook - MD02	0.01	1.38	14.3	19.2	1.0	26.7	75.3	320
Malden Brook - MD06	0.32	3.16	14.0	18.8	13.0	61.6	128.8	739
Muddy Brook - MD03	<0.01	1.20	7.5	11.1	0.4	23.4	55.1	280
Quinapoxet River - MD69	1.20	59.07	461.0	640.0	54.7	1,161.2	3,796.7	13,934
Stillwater River - MD07	0.20	47.18	538.0	767.0	17.6	927.6	2,788.7	11,129
Trout Brook - M110	<0.01	10.25	115.5	172.4	0.4	198.6	577.3	2,383
Waushacum Brook - MD83	< 0.01	8.32	49.8	93.0	0.2	161.6	434.5	1,939
West Boylston Brook - MD05	0.01	0.61	6.6	13.8	1.8	11.9	27.1	143
Ungaged Areas*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4,410
Quabbin Transfer	N/A	N/A	N/A	N/A	N/A	N/A	N/A	54,404

* Estimated

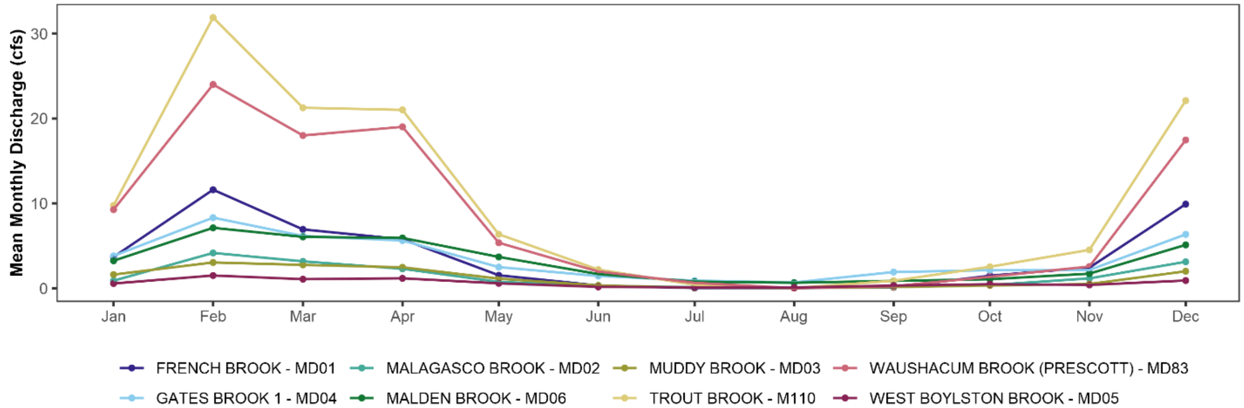
The annual discharge totals for the smaller tributaries are presented in Figure 20. Trout Brook contributed the largest water volume to Wachusett Reservoir of the smaller tributaries with 2,383 MG (~2.6 %), while Waushacum Brook contributed 1,939 MG (~2.1%) of the surface water inflow to the Reservoir. The other gaged small tributaries combined to contribute less than 3.4% of the surface water inflows to Wachusett Reservoir. Non-gaged areas contributed approximately 5% of the total inflows (estimated).

Figure 20: Annual Discharge (MG) for Smaller Gaged Wachusett Tributaries for 2022



Monthly tributary flows followed their typical seasonal patterns during 2022 (Figure 21). June through November flows were much lower than normal, with mean daily discharges dropping to less than 0.01 cfs at the lowest levels. French Brook dried up completely, which may be the first time this has happened in the last 20 years. The low summertime flows did have an impact on water quality, as nutrients and other pollutants could be concentrated as surface waters evaporated. Additionally, water samples collected during extreme low flows could have inadvertently contained additional sediment due to the shallow water depths, which at times were not deep enough to submerge the sample bottles.

Figure 21: Mean Monthly Discharge in Smaller Wachusett Tributaries (CFS) in 2022



Monthly discharges in the Quinapoxet and Stillwater Rivers for 2022 were above normal in February and December (Stillwater only), but below normal in all other months of the year. Discharge dropped to record lows in August, with the Stillwater and Quinapoxet Rivers mean daily discharge dropping to 0.20 and 1.20 cfs, respectively, during the height of the drought.

Figure 22: Monthly Discharge in the Quinapoxet River (MG) 2022

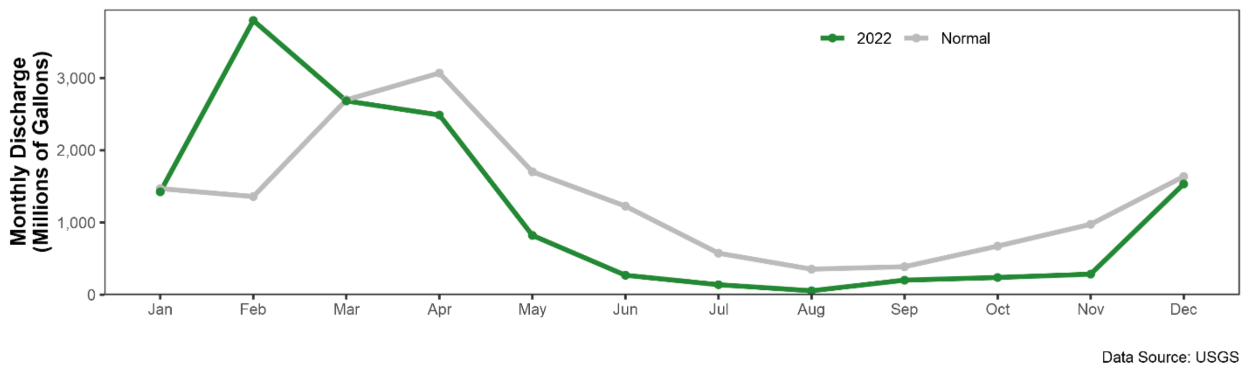
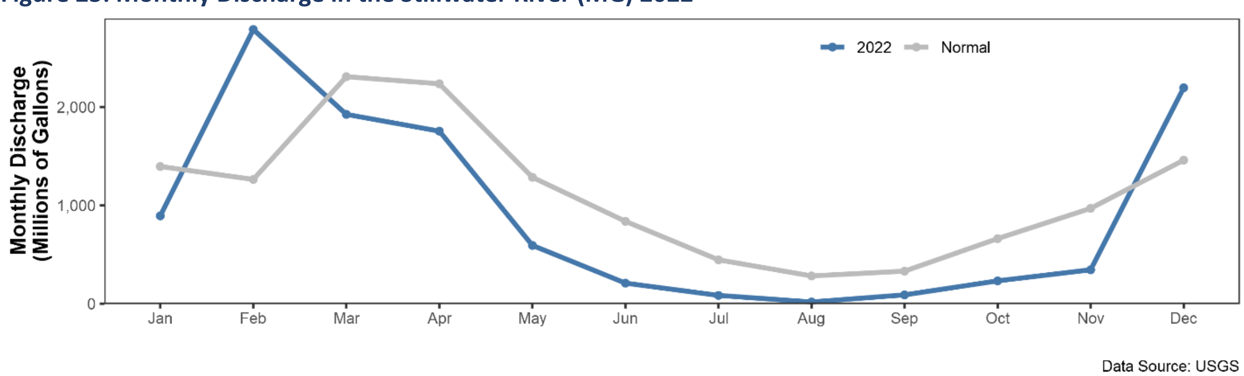


Figure 23: Monthly Discharge in the Stillwater River (MG) 2022



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

The Quabbin transfer was flowing at approximately 120 MGD between January 1, 2022 and February 3, and then again on February 22. The typical seasonal transfer began on May 17 and water was transferred to Wachusett Reservoir on a nearly continuous basis through mid-December. In 2022, the transfer was on for a total of 243 days and delivered a total volume of 54.4 billion gallons to Wachusett Reservoir with an average transfer rate of 223.9 MGD (Figure 24). This is equivalent to 83.7% of Wachusett Reservoir capacity (65 billion gallons) and is about 9,378 MG more than the average transfer volume between 2005 and 2021 (45,025.7 MG) (Figure 25). Wachusett Reservoir elevation was kept below its standard operating band from the end of April through the end of December (Figure 24). This change in reservoir operations was due to ongoing maintenance work on the dam bastion as well as a defined effort to boost the ratio of Quabbin water versus native Wachusett water in the Reservoir for water quality improvements. The reservoir elevation peaked at 391.61 ft on February 27, while its lowest point in 2022 was 388.03 ft on May 20.

Figure 24: 2022 Daily Wachusett Reservoir Water Elevation and Daily Quabbin Transfer Rate

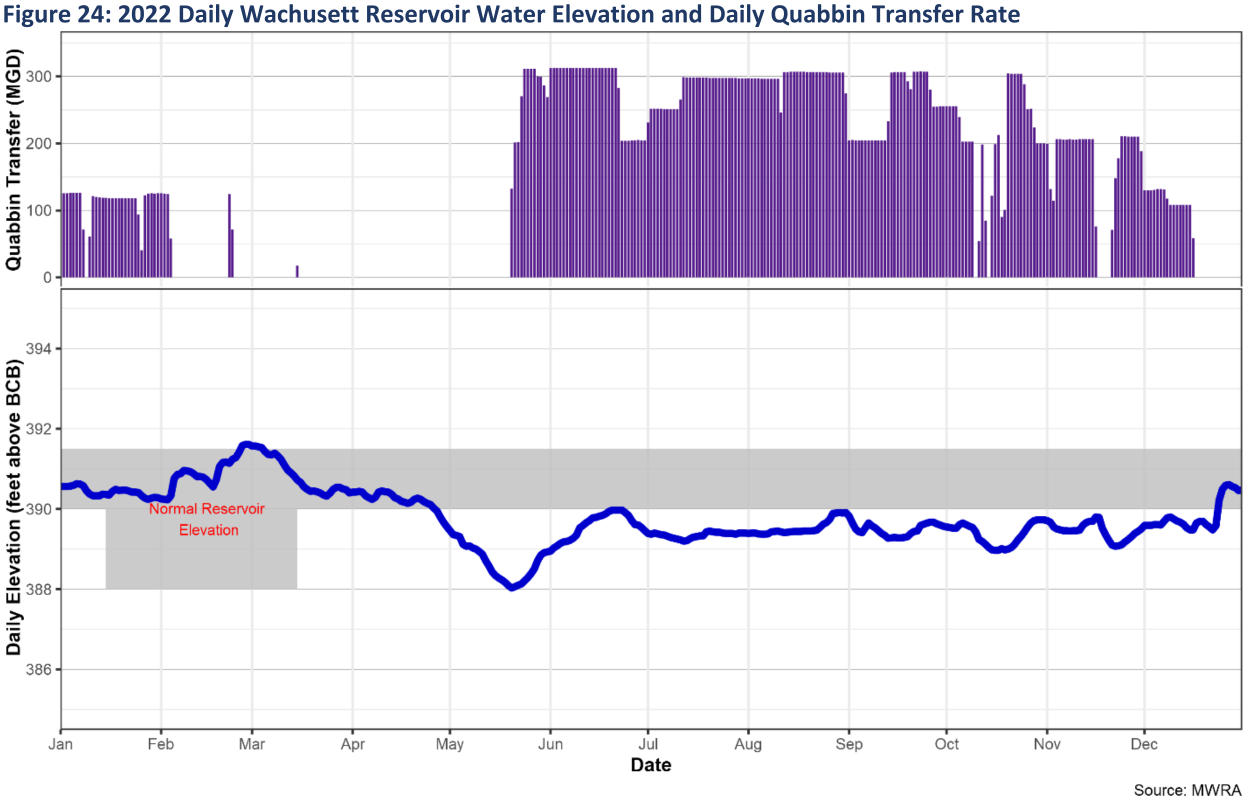
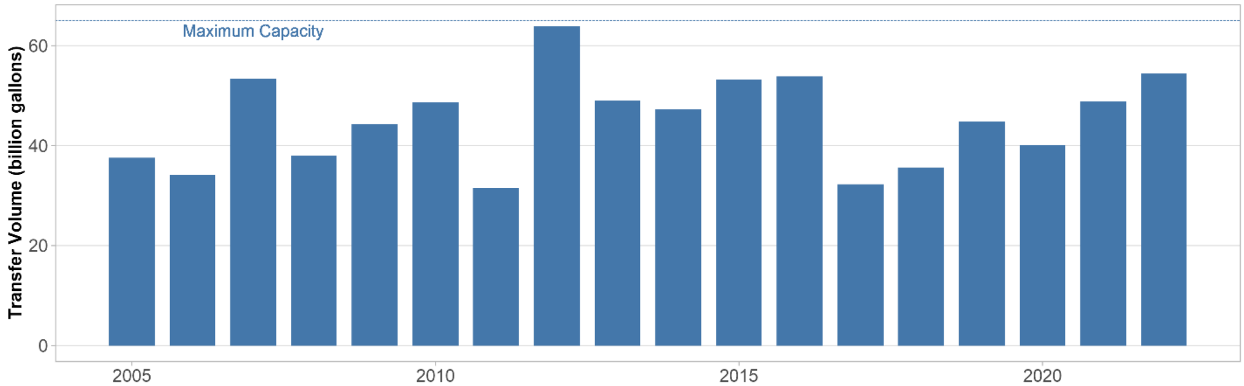


Figure 25: Annual Volume of Quabbin Transfer to Wachusett Reservoir
Maximum capacity of Wachusett Reservoir indicated by line at 65 billion gallons.



3.2 Tributary Monitoring

3.2.1 Water Temperature and Dissolved Oxygen

Tributary water temperature and dissolved oxygen results for 2022 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 2022, water temperature in Wachusett Watershed tributaries ranged from -0.9 °C at Trout Brook to 28.1 °C, at French Brook. At the 10 monitoring locations where temperature sensors were installed, the 7-day mean maximum temperature (purple line) is shown in Figure 26 and Figure 27 for comparison to the MassDEP 20 °C coldwater fish resource (CFR) and 28.3 °C warmwater fish resource (WFR) limits[53]. For the CFR tributaries with temperature sensors, all monitoring locations except for West Boylston Brook exceeded the 20 °C limit on at least one day over the summer (Table 11). It is likely that the other three CFR tributaries without temperature sensors also exceeded the 20 °C threshold over multiple days in 2022. Based on manual point measurements and continuous sensor data (where available) no tributaries exceeded the WFR threshold during 2022 (Figure 27). 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.

[53] Massachusetts Surface Water Quality Standards, 2013a

Table 11: Coldwater Fish Resource Tributaries that Exceeded the MassDEP Water Temperature Recommended Limit of 20 °C (mean 7-day maximum temperature) in 2022

Monitoring Location	Days Exceeded
Gates Brook 1 - MD04	14
Malden Brook - MD06	13
Quinapoxet River (Canada Mills) - MD69	121
Stillwater River - Muddy Pond Rd - MD07	97
Trout Brook - M110	31

Figure 26: 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).

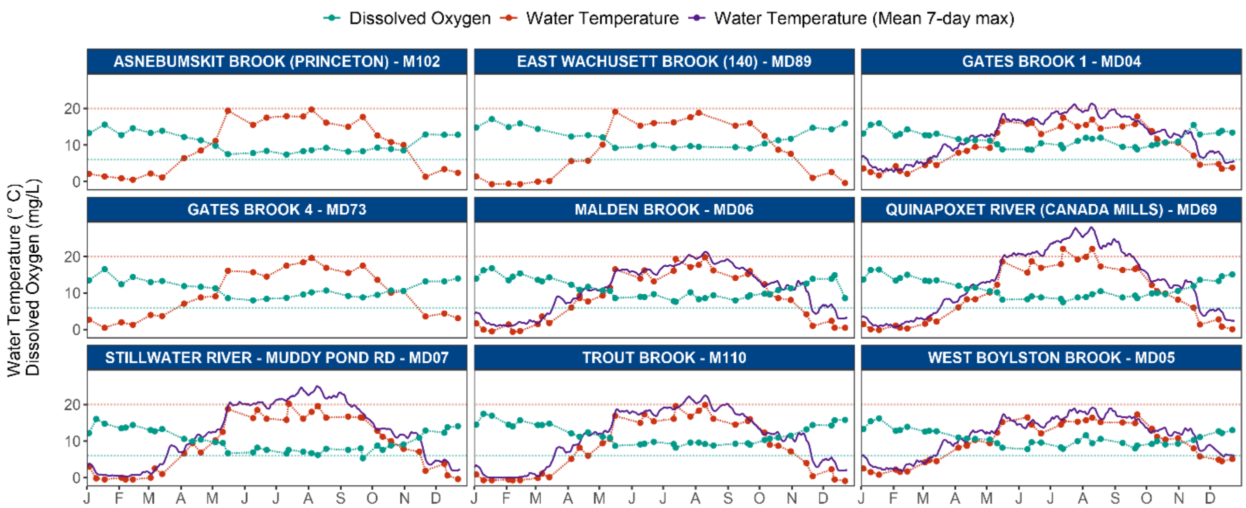
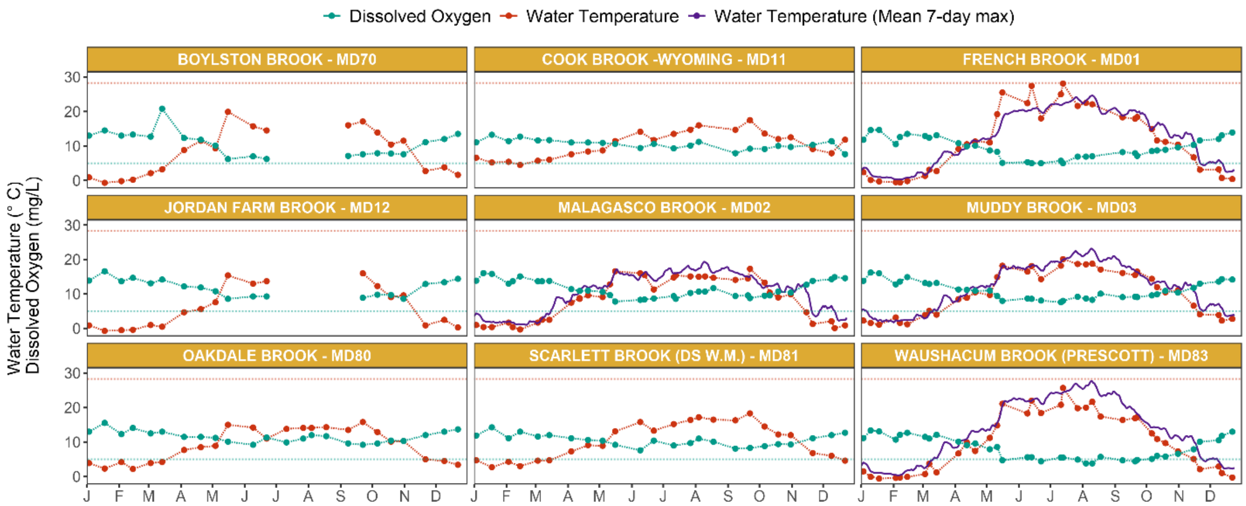


Figure 27: Water Temperature and Dissolved Oxygen for Wachusett Tributaries designated as Warmwater Fish Resources (WFR)

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 2022 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 3.8 mg/L at Waushacum Brook to a high of 17.47 mg/L at Trout Brook[54]. For CFR monitoring locations D.O. during 2022 monitoring visits was measured above the MassDEP aquatic life threshold (6.0 mg/L) at all locations except for the Stillwater River, which fell below this threshold briefly in the end of September (Figure 26). For WFR monitoring locations D.O. fell below the MassDEP aquatic life threshold (5.0 mg/L) only at Waushacum Brook (at eight 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.

In 2022, 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

[54] 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.

of 15 – 45% carbonate minerals[55], stretches across the Wachusett Watershed through Gates Brook, West Boylston Brook, and Waushacum Brook subbasins. These three tributaries have the highest 2020 – 2022 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 three years of alkalinity data, including 2022, show slight increases at French Brook 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 or not the observed increases constitute a significant trend.

An increasing trend in Wachusett Reservoir alkalinity has been documented, however the causes of increasing alkalinity are not yet fully understood and any findings from internal research on this topic will be presented in future water quality reports.

There are no drinking water criteria for alkalinity, however the EPA recommends a minimum concentration of 20 mg/L for the protection of aquatic life. Data from 2020 – 2022 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 – 2022 Results

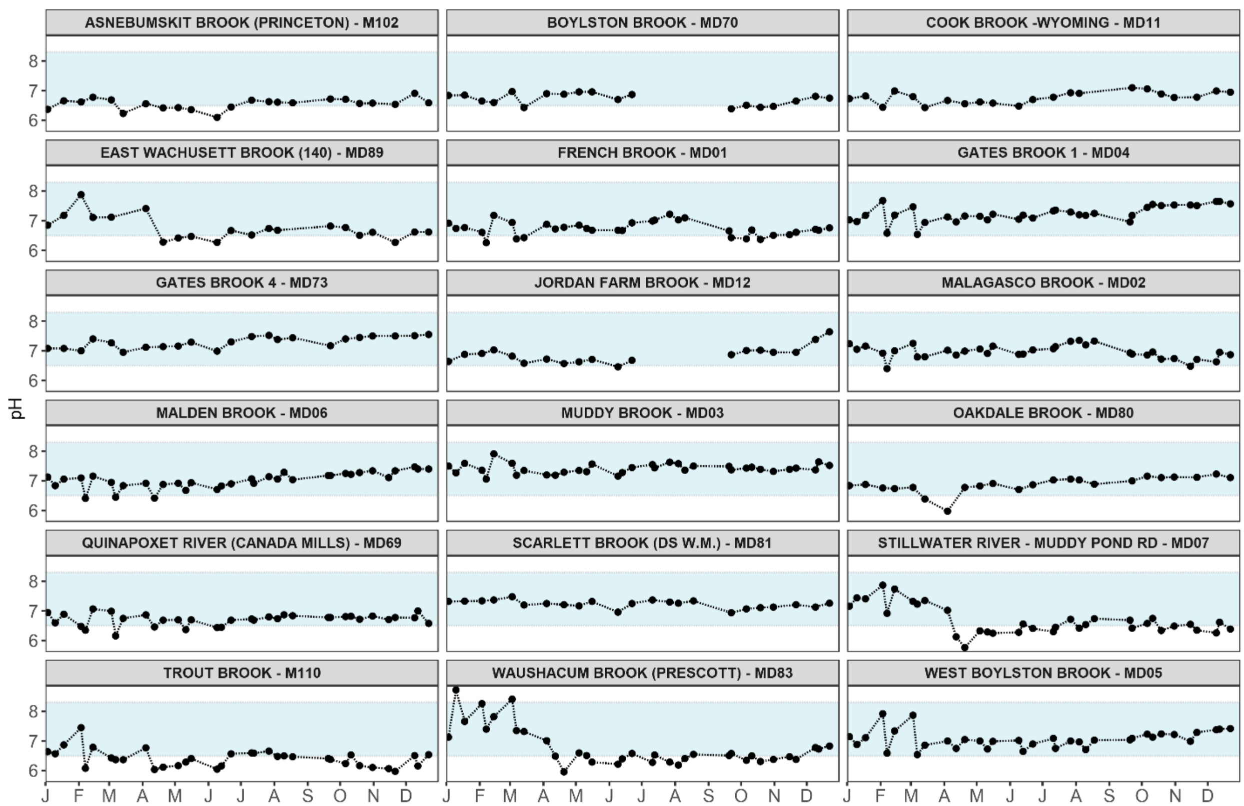
Sample Location	# Samples 2000-2012	# Samples 2020-2022	Mean 2000-2012	Mean 2020-2022	Median 2000-2012	Median 2020-2022
Cook Brook -Wyoming - MD11	61	—	30.9	—	30.8	—
French Brook - MD01	71	28	13.3	15.9	10.8	12.1
Gates Brook 1 - MD04	77	28	43.6	43.7	44.9	43.8
Jordan Farm Brook - MD12	48	—	16.9	—	15.5	—
Malagasco Brook - MD02	78	28	11.6	11.5	11.1	11.4
Malden Brook - MD06	65	28	20.4	20.4	22.0	20.8
Muddy Brook - MD03	78	28	21.7	19.2	22.6	17.9
Quinapoxet River (Canada Mills) - MD69	138	27	8.4	10.5	8.0	10.0
Rocky Brook (E Branch) - MD13	48	—	1.5	—	0.6	—
Shaft 1 (Quabbin transfer) - MDS1	—	7	—	3.9	—	3.9
Stillwater River - Muddy Pond Rd - MD07	138	28	7.9	11.0	6.9	8.2
Trout Brook - M110	—	23	—	4.9	—	4.0
Waushacum Brook (Prescott) - MD83	—	28	—	31.5	—	27.6
West Boylston Brook - MD05	—	12	—	39.9	—	39.6

[55] Grady & Mullaney, 1998

Across all tributary monitoring locations, pH values in 2022 ranged from 5.57 at the Stillwater River to 8.72 at Waushacum Brook. Waushacum Brook exceeded the MassDEP recommended range for the protection of aquatic life (6.5 – 8.3)[56] on two occasions[57]. Tributary pH values below the recommended range are common in Wachusett Watershed and were observed at 13 monitoring locations at least once in 2022. The tributaries where pH was not detected below the recommended range include Gates, Muddy, Scarlett, and West Boylston Brooks. In 2022 seasonal variation in pH was most pronounced at Waushacum and East Wachusett Brooks and the Stillwater River, which saw a notable decline in pH in May coinciding with the onset of drought conditions. Fluctuating conditions in the hyporheic zone likely help to drive stream chemistry changes responsible for the acidity patterns observed in Wachusett tributaries. However, with only a few years of reliable data for stream pH, and a lack of any other monitoring of the hyporheic zone, it is difficult to attribute 2022 observations to previously documented phenomena under similar seasons or hydrologic conditions.

Figure 28: 2022 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 is not certain, however, DWSP will be investigating them as part of its goal to better understand the sources and ramifications of freshwater salinization observed in the Watershed.

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[56] Massachusetts Surface Water Quality Standards, 2013b

[57] pH probe calibration was out of range from January through May, with the exception of the last half of February (Figure 8)

3.2.3 Specific Conductance and Chloride

In 2022, tributary specific conductance ranged from to 69.2 µS/cm at Trout Brook to 4,980 µS/cm at West Boylston Brook. Values of less than 100 µS/cm were recorded in 53% of all samples from Trout Brook (19 of 36), and at no other tributary in Wachusett Watershed. This represents just 3.5% of all specific conductance samples for the year from Wachusett tributaries. Measurements greater than 904 µS/cm, the proxy chronic Cl toxicity threshold[58], were recorded in 15.8% of all samples from 2022. For individual tributaries, this threshold was exceeded in 91% of samples from Gates Brook 4 (MD73), 75% of samples from Gates Brook 1 (MD04), 59% of samples from West Boylston Brook, and 33% of samples from Oakdale Brook. Extremely high specific conductance (>1,800 µS/cm) was observed at Gates Brook 4 on January 18, and again on February 3 at Cook, West Boylston, Scarlett, and Gates Brooks 1 and 4. On February 3, Specific Conductivity at West Boylston Brook and Gates Brook 4 were both above the MassDEP proxy acute Cl toxicity threshold of 3,193 µS/cm[59], at 4,980 and 4,458 µS/cm, respectively. The Gates Brook USGS monitoring station recorded a maximum instantaneous specific conductance on January 17 of 6,280 µS/cm, during a snow event with temperatures hovering around freezing. Road salt applications likely resulted in melting of snow and ice in the roadways and subsequent stormwater runoff and chloride loading to tributaries. Wachusett tributary annual mean specific conductance levels for 2022 were all higher than last year, except for Oakdale Brook. This is likely due to the long-lasting drought through the summer and the influence of a larger than normal proportion of saltier groundwater comprising the baseflow in these tributaries (Table 13).

[58] MassDEP, 2018
[59] Ibid.

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

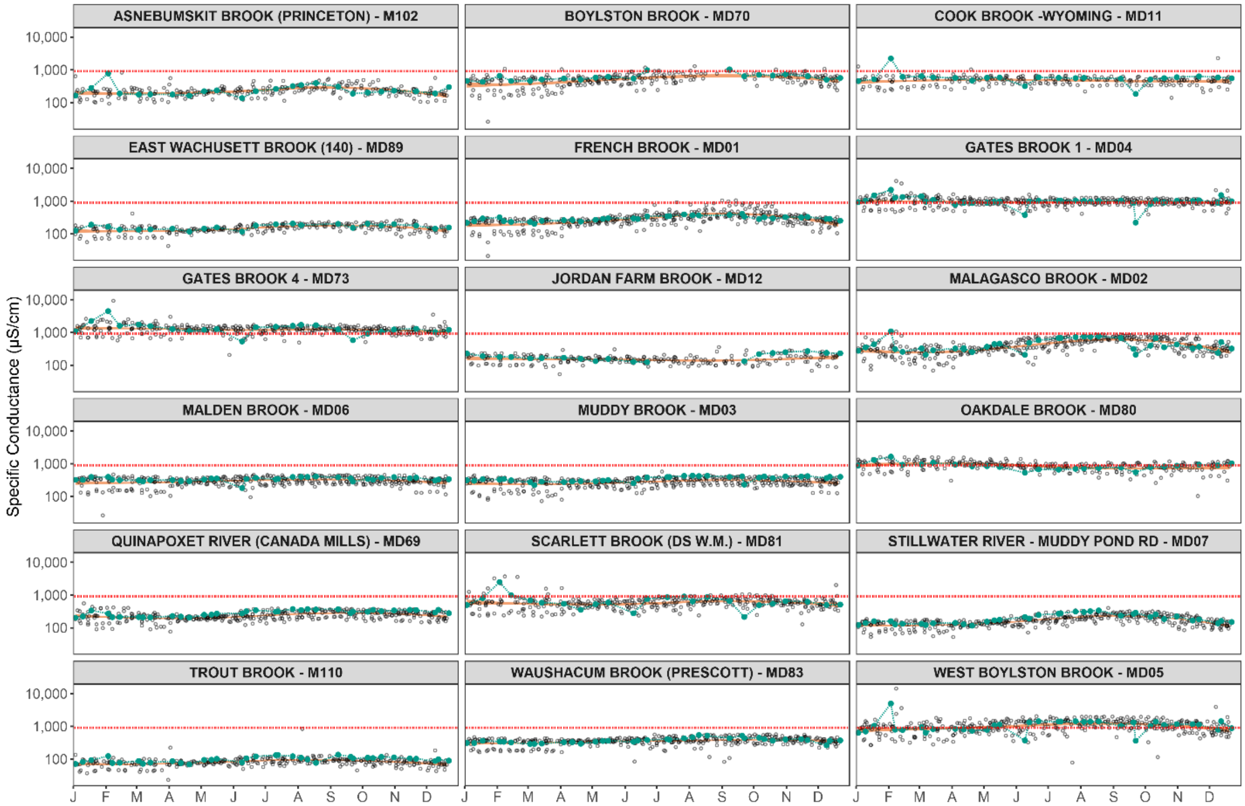
Location	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Asnebumskit Brook (Princeton) - M102	183	215	254	336	279	249	267	243	195	254
Boylston Brook - MD70	278	373	579	542	594	686	661	679	546	611
Cook Brook -Wyoming - MD11	329	493	475	526	640	624	524	489	478	609
East Wachusett Brook (140) - MD89	123	133	166	174	171	151	169	180	140	164
French Brook - MD01	207	227	321	447	364	290	318	347	250	298
Gates Brook 1 - MD04	715	759	942	1,081	1,272	1,211	1,154	1,075	940	1,027
Gates Brook 4 - MD73	1,006	1,018	1,276	1,371	1,696	1,558	1,451	1,253	1,149	1,437
Jordan Farm Brook - MD12	122	128	124	181	175	183	193	169	178	187
Malagasco Brook - MD02	350	313	447	473	462	451	525	558	345	444
Malden Brook - MD06	199	220	288	334	364	365	371	382	311	340
Muddy Brook - MD03	174	203	273	320	344	333	340	351	296	350
Oakdale Brook - MD80	666	686	872	982	1,136	1,166	989	878	954	870
Quinapoxet River (Canada Mills) - MD69	172	195	255	304	296	250	261	268	211	291
Scarlett Brook (DS W.M.) - MD81	484	514	635	620	771	747	897	632	487	692
Stillwater River - Muddy Pond Rd - MD07	144	142	182	213	170	162	174	200	152	197
Trout Brook - M110	84	74	74	86	96	92	87	86	82	99
Waushacum Brook (Prescott) - MD83	315	284	339	396	420	395	408	421	334	375
West Boylston Brook - MD05	667	739	1,137	1,227	1,700	1,274	1,266	1,221	901	1,131

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

Most tributary locations had annual mean specific conductance within the ranges observed during the nine years prior. However, in 2022 Trout Brook had the highest annual mean specific conductance on record. Seasonal patterns of specific conductance in 2022 followed historical patterns, however several locations were sampled during wet weather, either catching high conductivity in wintertime runoff or low conductivity from warm season runoff absent of dissolved road salt. Specific conductance levels at two tributaries remain indicative of chronic elevated dissolved salt concentrations (above 904 µS/cm) which are likely having negative effects on aquatic life: Gates Brook (two stations) and West Boylston Brook. Oakdale Brook annual mean specific conductance was back below the 904 µS/cm threshold in 2022 but remains very high.

Figure 29: Specific Conductance Measurements at Wachusett Tributaries

The green points show specific conductance results for 2022, while the hollow points show results from years 2013 – 2021, with the orange band representing a LOESS smooth function 95% confidence interval for the same period. The red dashed line is the MassDEP proxy chronic Cl toxicity threshold of 904 µS/cm.



Roadway deicing products (primarily rock salt) are the dominant source of dissolved ions detected in Wachusett tributaries. As expected, the more developed subbasins with more roads have a higher need for roadway deicing during the winter months, therefore they are experiencing the greatest increases in specific conductance. This topic is discussed in greater detail in a publication by UMass researchers[60].

3.2.3.1 Chloride

Chloride (Cl) concentrations in 2022 were generally higher than 2021 concentrations across most sampling locations (Table 14). Since monitoring for chloride began, and again in 2022, West Boylston Brook had the highest mean annual Cl concentration (314 mg/L), followed by Gates Brook 1 (267 mg/L). Trout Brook and the Stillwater River continued to have the lowest mean annual Cl concentrations at 25 and 42.6 mg/L, respectively. Unfortunately, the Trout Brook 2022 mean annual chloride concentration was the highest of the five years that chloride has been monitored at this tributary.

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)

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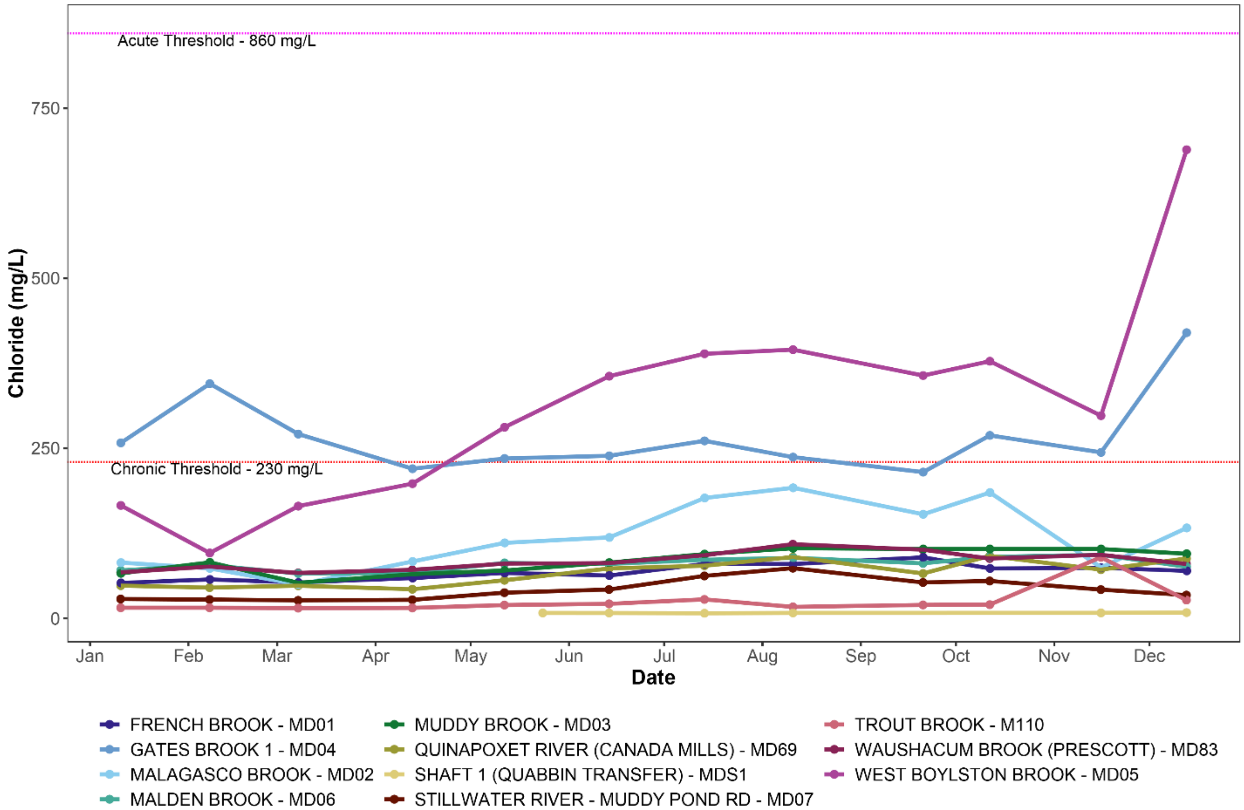
[60] Soper, 2021

several times a year after roadway deicing. The MassDEP SMCL for Cl (250 mg/L), which only applies to finished drinking water for public systems, would also be exceeded at West Boylston Brook (and nearly Gates Brook) if these tributaries were sole drinking water sources. Fortunately, these two tributaries are not directly used for drinking water and contribute less than 2% of the total inflow to Wachusett Reservoir; the overall Wachusett Reservoir Cl concentration is well below this threshold. Still, Cl concentration at Gates Brook 1 and West Boylston Brook are detrimental to many species of aquatic plants and animals and contribute to the overall increase in dissolved salts in the Wachusett Reservoir, which has undesirable consequences for drinking water treatment processes.

Table 14: Chloride Concentration (mg/L) Summary for Wachusett Tributaries During 2022

Sample Location	Count	Minimum (mg/L)	Median mg/L)	Mean (mg/L)	Maximum (mg/L)	Std. Dev (mg/L)
French Brook - MD01	12	52	68	68	90	12
Gates Brook 1 - MD04	12	215	251	268	420	59
Malagasco Brook - MD02	12	50	115	119	192	49
Malden Brook - MD06	12	66	80	80	93	9
Muddy Brook - MD03	12	52	88	85	103	18
Quinapoxet River (Canada Mills) - MD69	12	43	69	67	92	18
Shaft 1 (Quabbin Transfer) - MDS1	6	8	8	8	9	0
Stillwater River - Muddy Pond Rd - MD07	12	26	40	43	74	15
Trout Brook - M110	12	15	20	25	90	21
Waushacum Brook (Prescott) - MD83	12	67	81	84	109	13
West Boylston Brook - MD05	12	96	327	314	689	156

Figure 30: Chloride Concentrations in the Wachusett Tributaries During 2022



A discussion of other work completed in 2022 related to Cl and conductivity is provided in Section 3.2.9.2. Chloride monitoring in groundwater is discussed in Section 3.3.

3.2.3.2 Mayfly Data

Mayfly monitoring stations were operational most of 2022 at French, Malagasco, Malden, West Boylston and Waushacum Brooks. The Muddy Brook station was offline most of 2022 due to battery charging problems. Data collected by the Mayfly stations during 2022 was reviewed: Water level records were compared to manual measurements of stage and specific conductivity measurements were compared to YSI specific conductance measurements (Figure 31 and Figure 32). For stage, the Mayfly stations were typically within one-hundredth of a foot (1-2%) of manual stage readings. Mayfly Specific conductivity was typically within 5% of YSI specific conductivity, except for West Boylston Brook and Malagasco Brook, with average differences of 13% and 22%, respectively (Table 15). Due to high sediment loads, the Mayfly at West Boylston Brook is located downstream of the weir pool where the staff gage is located for monitoring water level. Therefore, the HOBO datalogger at West Boylston Brook is used for water level measurements rather than the Mayfly.

The Mayfly sensor performance for stage was within the acceptable range for accuracy and precision specifications at all locations. For specific conductance, the Mayfly sensor performance was acceptable at all locations except for Malagasco Brook. The Malagasco Brook Mayfly sensor will be inspected and tested again to determine if a replacement sensor should be installed so that accuracy and precision tolerances will be met in the future.

Figure 31: Manual Stage Observations (red) Compared to 15-minute Mayfly Sensor Water Level Measurements (black) at Malden Brook - MD06 During 2022

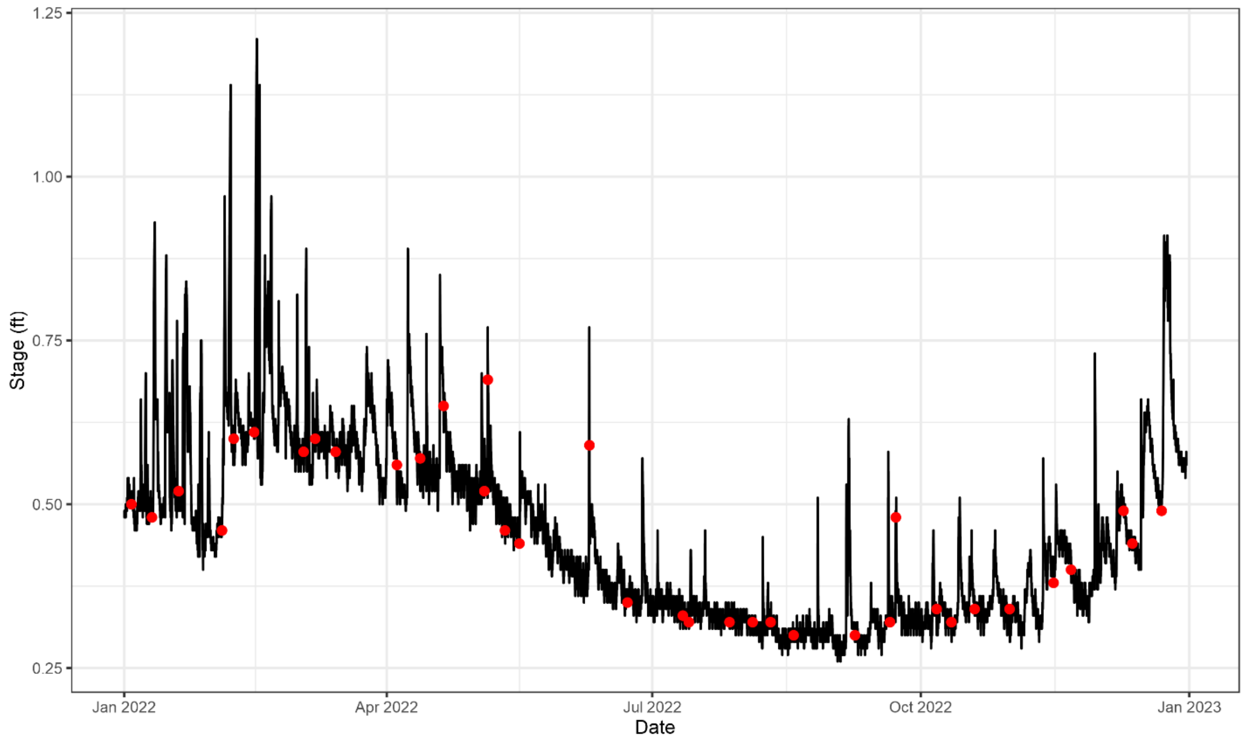


Figure 32: YSI Specific Conductance Measurements (purple) Compared to Mayfly Sensor Specific Conductance (black) at Malden Brook – MD06 During 2022

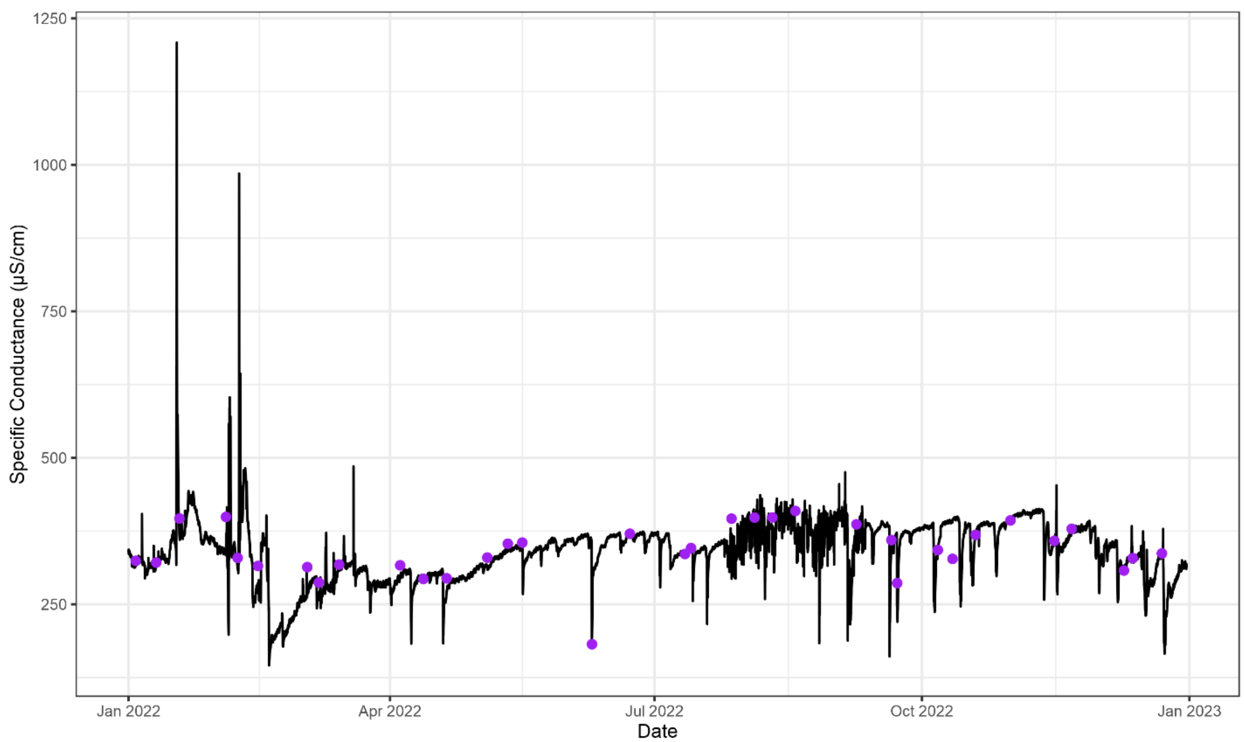


Table 15: Mayfly Stage Measurements Compared to Manual Staff Plate Readings and Specific Conductance Compared to YSI Measurements During 2022

Location	Parameter	N	Mean Absolute Difference	Mean Percent Difference
MD01	Staff Gauge Height	30	0.01	1
MD02	Staff Gauge Height	36	0.01	2
MD05	Staff Gauge Height	34	0.03	5
MD06	Staff Gauge Height	36	0.01	2
MD83	Staff Gauge Height	31	0.01	2
MD01	Specific Conductance	28	5.15	2
MD02	Specific Conductance	36	88.97	22
MD05	Specific Conductance	34	128.69	13
MD06	Specific Conductance	35	18.01	5
MD83	Specific Conductance	30	14.63	4

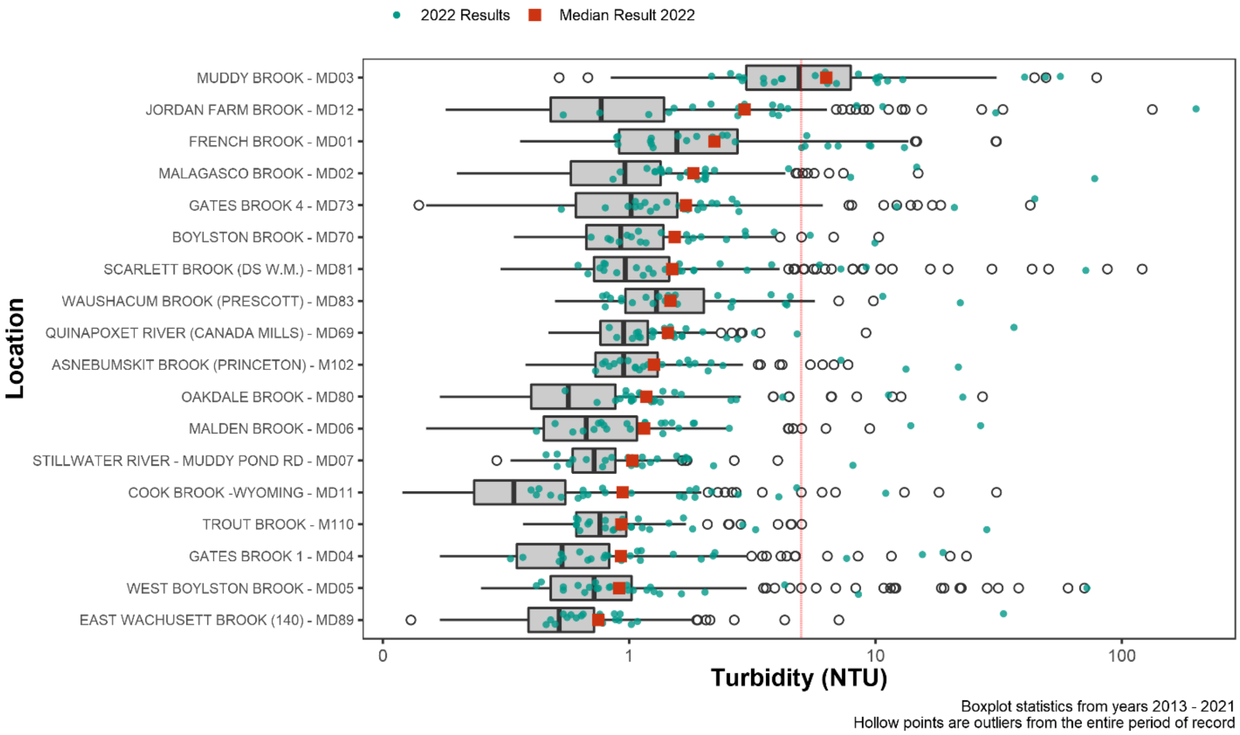
Given the quality of water level data collected by the Mayfly sensors during 2022, the HOBO sensors that were collecting redundant information at some monitoring locations will be removed during 2023. The high frequency specific conductance measurements at the Mayfly stations now allows for more accurate loading estimates of dissolved ions in Wachusett tributaries. As illustrated in Figure 32, the high frequency measurements are able to capture spikes and rapid fluctuations in specific conductance that were not detected with only three measurements per month taken during sample visits. These data will be used in conjunction with chloride measurements to estimate loading of roadway deicing salts to Wachusett Watershed tributaries. DWSP plans to track annual salt loads over time to detect trends and link changes in loading to salt application rates within the Watershed.

3.2.4 Turbidity

Turbidity results in Wachusett tributaries in 2022 ranged from 0.33 NTU at Gates Brook 1 to 200 NTU at Jordan Farm Brook. There were 57 samples with turbidity levels of 5.0 NTU or higher, which were predominantly collected from Muddy Brook (14 samples), where elevated concentrations of fine particulate matter are historically persistent and naturally occurring. Wet weather sampling on February 3, June 9 and September 22 accounted for 35 of the 57 turbidity results above 5.0 NTU, with the remaining high turbidity results spread throughout the year.

Figure 33: 2022 Turbidity Levels with 2013 – 2021 Statistics

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



Annual mean turbidity in 2022 ranged from 1.36 NTU at the Stillwater River to 15.16 NTU at Jordan Farm Brook, with 10-year record high annual means occurring at all tributaries except for Scarlett Brook (Table 15).

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)

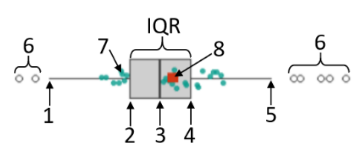


Table 15: Annual Mean Turbidity at Wachusett Tributaries (NTU)

Sample Location	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Asnebumskit Brook (Princeton) - M102	0.94	—	1.47	1.14	1.63	1.07	1.12	1.16	1.49	2.85
Boylston Brook - MD70	1.48	0.90	0.98	0.92	1.06	1.13	1.44	1.09	1.92	2.24
Cook Brook -Wyoming - MD11	0.37	1.23	0.63	0.28	1.75	0.55	0.42	0.91	1.38	1.82
East Wachusett Brook (140) - MD89	0.55	0.56	0.60	0.47	0.86	0.65	0.57	0.54	0.92	2.14
French Brook - MD01	2.55	1.61	2.16	1.93	1.56	1.73	2.55	6.86	2.08	3.73
Gates Brook 1 - MD04	0.67	0.70	0.53	0.57	1.16	1.23	0.85	1.00	2.38	2.61
Gates Brook 4 - MD73	1.22	1.43	0.91	0.89	2.73	1.88	1.68	1.63	2.90	4.65
Jordan Farm Brook - MD12	1.39	1.21	1.61	0.51	1.68	2.22	2.44	1.65	8.43	15.16
Malagasco Brook - MD02	1.45	1.10	0.90	0.82	1.17	1.27	1.21	1.08	2.32	5.71
Malden Brook - MD06	0.99	0.79	0.84	0.52	0.75	0.95	0.96	0.96	1.48	2.73
Muddy Brook - MD03	6.90	5.87	5.46	5.48	9.12	6.86	6.83	5.36	7.92	11.53
Oakdale Brook - MD80	0.77	1.15	0.63	0.43	2.12	1.18	0.79	1.28	1.31	2.68
Quinapoxet River (Canada Mills) - MD69	0.94	0.97	1.09	1.00	1.01	1.11	1.17	1.14	1.48	3.12
Scarlett Brook (DS W.M.) - MD81	1.91	5.47	1.05	1.38	3.65	1.91	2.24	1.17	1.71	5.12
Stillwater River - Muddy Pond Rd - MD07	0.76	0.74	0.76	0.75	0.70	0.80	0.83	0.86	0.97	1.36
Trout Brook - M110	0.82	0.97	1.22	0.60	0.76	0.81	0.90	0.97	1.15	2.27
Waushacum Brook (Prescott) - MD83	1.31	1.64	1.29	2.04	1.74	1.67	1.63	2.09	1.21	3.11
West Boylston Brook - MD05	1.22	3.21	0.86	1.09	3.59	2.22	1.27	1.29	1.98	4.35

2022 annual median turbidity was higher than the 2013 – 2021 median at all sampling locations, and in several cases, above the 75th percentile. Annual median turbidity values ranged from 0.75 NTU at East Wachusett Brook to 6.31 NTU in Muddy Brook (Table 16). Turbidity levels were 0.57 NTU higher (on average) during or after wet weather conditions (> 0.2 inches of rainfall within 24 hours of sample) (Table 16).

Table 16: Turbidity Statistics in Wachusett Tributaries for 2022 (NTU)

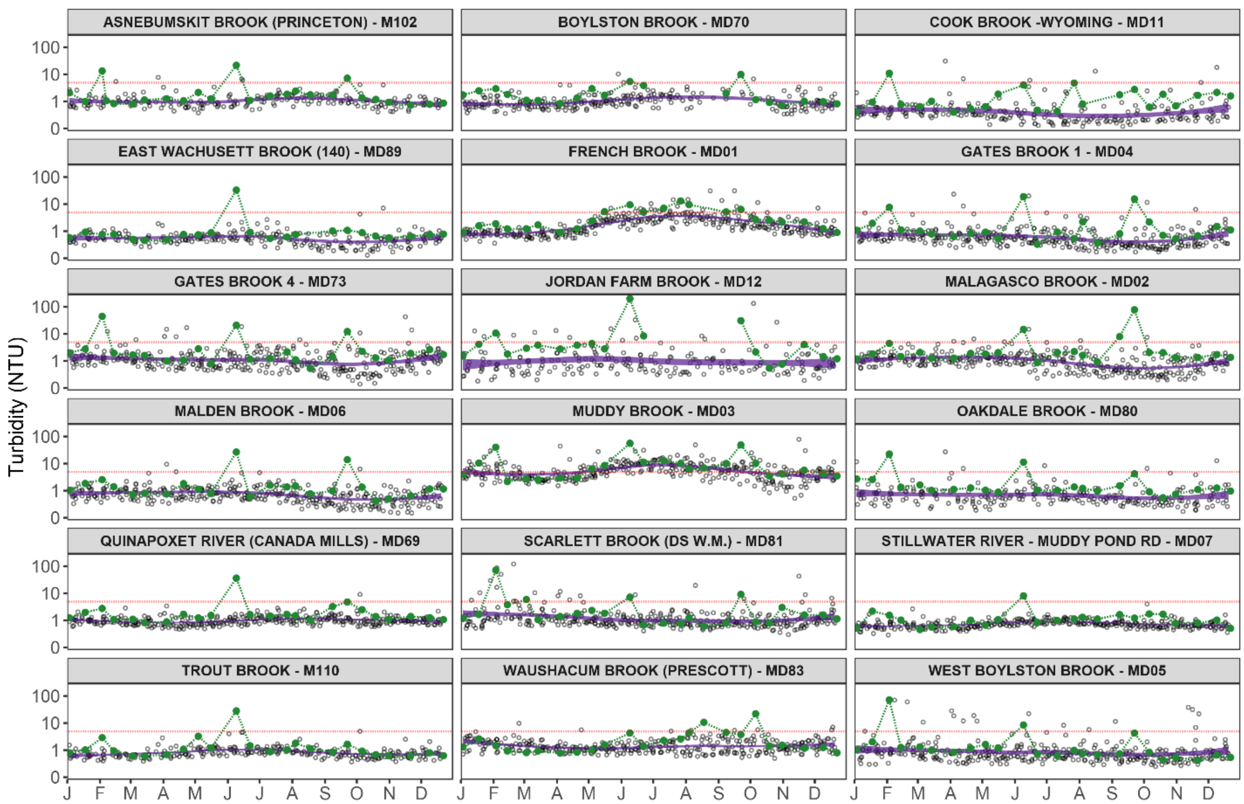
Wet weather samples were collected soon after or during precipitation events of 0.2 inches or more.

Sample Location	Minimum	Maximum	Annual Median	Dry Median	Wet Median
Asnebumskit Brook (Princeton) - M102	0.73	21.70	1.26	1.14	1.31
Boylston Brook - MD70	0.70	9.94	1.53	1.09	1.74
Cook Brook -Wyoming - MD11	0.40	11.00	0.94	0.79	1.60
East Wachusett Brook (140) - MD89	0.46	33.10	0.75	0.62	0.78
French Brook - MD01	0.89	13.10	2.22	2.20	2.39
Gates Brook 1 - MD04	0.33	18.80	0.92	0.79	1.11
Gates Brook 4 - MD73	0.53	44.30	1.70	1.42	2.27
Jordan Farm Brook - MD12	0.54	200.00	2.94	2.85	3.82
Malagasco Brook - MD02	0.86	77.60	1.82	1.45	2.02
Malden Brook - MD06	0.42	26.70	1.15	0.81	1.35
Muddy Brook - MD03	2.16	56.30	6.31	5.69	8.53
Oakdale Brook - MD80	0.55	22.60	1.18	1.12	1.27
Quinapoxet River (Canada Mills) - MD69	0.83	36.50	1.44	1.26	1.70
Scarlett Brook (DS W. M) - MD81	0.62	71.40	1.50	1.25	1.83
Stillwater River - Muddy Pond Rd - MD07	0.46	8.09	1.03	0.99	1.22
Trout Brook - M110	0.61	28.30	0.93	0.86	1.09
Waushacum Brook (Prescott) - MD83	0.78	22.10	1.47	1.40	1.50
West Boylston Brook - MD05	0.42	72.10	0.91	0.74	1.22
All Wachusett Tributaries	**0.68**	**42.98**	**1.67**	**1.47**	**2.04**

Figure 34 shows the variability in turbidity by location for 2022 compared to the prior nine years. Turbidity spikes can be seen across most sampling locations in February, July, and September, when sampling was conducted during storm events. At most sampling locations, aside from the storm related spikes, turbidity values were normal and close to historical seasonal levels. Three tributaries had noticeable deviations from historical trends. Cook Brook experienced higher than normal turbidity in the latter half of 2022, Waushacum Brook experienced elevated turbidity levels between August and October, and Jordan Farm Brook experienced elevated turbidity for the first nine months of 2022. The cause of elevated turbidity at Jordan Farm Brook is suspected to be agricultural operations, however there is no obvious reason for the elevated turbidity at Waushacum and Cook Brooks, other than drought conditions lowering stream depth to the point where bed load may have been picked up during sample collection.

Figure 34: Turbidity Results at Wachusett Tributaries

The green points show turbidity results for 2022, while the hollow points show results from years 2013 – 2021, 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 2022 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 2022 was 4.28 NTU and the median was 1.67 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 18.0 mg/L at French Brook. Only 8 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 2022 were consistent with the previous nine years, with no unidirectional patterns over time (Table 17). For locations where there were three or fewer detected results in a given 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 17: Total Suspended Solids Annual Mean Concentrations in Wachusett Tributaries (mg/L)

Sample Location	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
French Brook - MD01	5.45	4.66	3.02	3.84	3.00	3.92	7.03	12.43	4.87	4.40
Gates Brook 1 - MD04	2.23	4.20	2.48	3.25	2.21	2.56	3.08	3.33	2.50	2.50
Malagasco Brook - MD02	4.40	2.83	2.80	3.10	3.58	2.93	4.25	3.48	3.13	2.50
Malden Brook - MD06	2.45	3.60	4.27	3.13	2.50	2.77	2.82	2.83	2.50	3.88
Muddy Brook - MD03	4.11	2.82	2.50	6.74	11.99	6.12	4.23	7.16	3.29	3.00
Quinapoxet River (Canada Mills) - MD69	2.77	2.33	2.49	3.13	2.50	2.75	2.50	2.50	2.50	2.92
Shaft 1 (Quabbin transfer) - MDS1	—	—	—	—	1.75	2.82	2.45	2.50	2.50	2.50
Stillwater River - Muddy Pond Rd - MD07	2.38	2.33	2.50	3.88	2.43	2.49	2.50	2.71	2.50	2.50
Trout Brook - M110	—	—	2.91	2.94	2.50	2.92	2.75	2.50	2.50	2.50
Waushacum Brook (Prescott) - MD83	3.83	2.44	2.50	2.89	2.43	5.06	3.00	2.79	3.00	3.17
West Boylston Brook - MD05	2.84	9.98	2.49	2.77	4.33	4.88	2.96	15.96	4.88	2.50

Dash (—) = No data

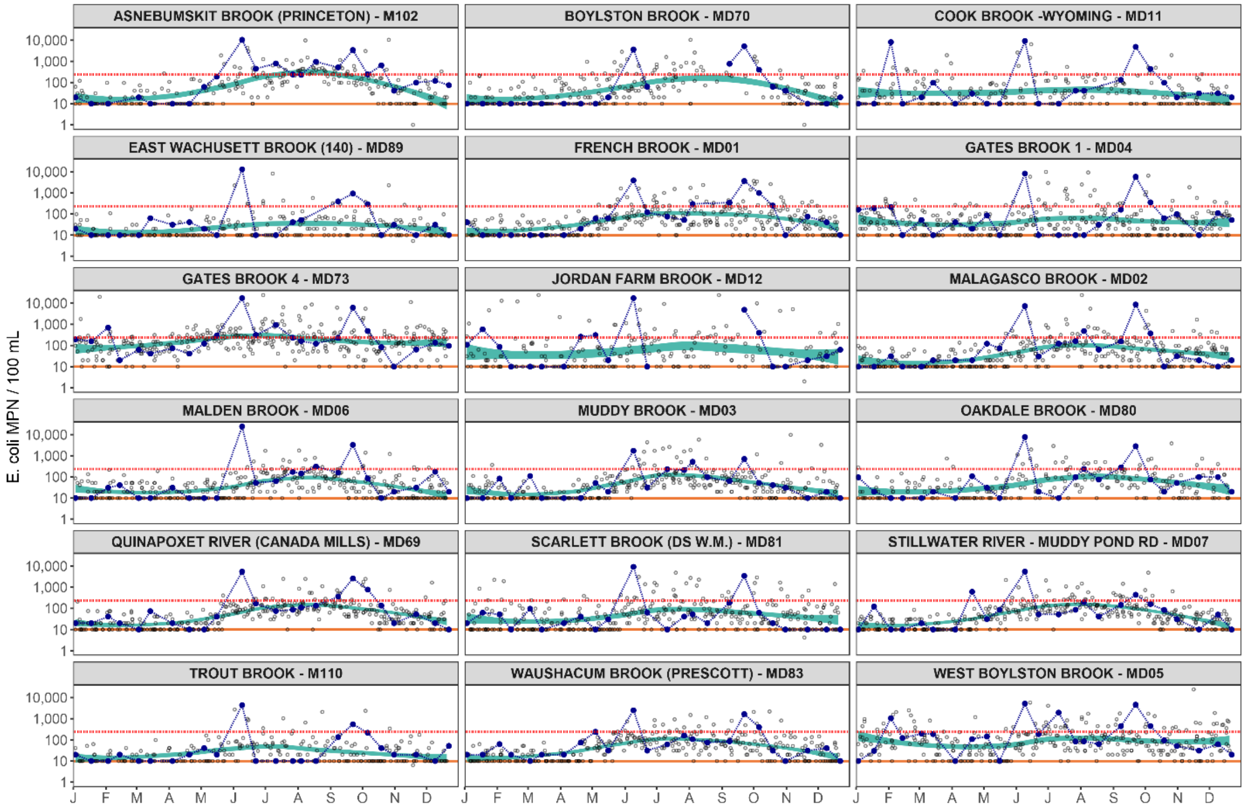
3.2.6 *E. coli* Bacteria in Tributaries

Bacteria samples collected from the tributary stations during 2022 contained a wide range of *E. coli* concentrations, from less than the lower detection limit (10 MPN/100 mL) in approximately 29% of all samples, to a high of > 24,200 MPN/100 mL at Malden Brook during a storm on June 9. As in previous years, the highest concentrations were mostly recorded during or following precipitation. Thirty-two of the 35 samples that exceeded 1,000 MPN/100 mL were collected during the storm events on June 9 and September 22. The only dry weather sample that exceeded 1,000 MPN/100 mL was collected from West Boylston Brook on July 11.

In 2022, all Wachusett Reservoir tributaries exceeded the MA Class A surface water quality standard single sample limit of 235 MPN/100 mL on at least one monitoring occasion (Figure 35 and Table 18). 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. The elevated bacteria concentrations on June 9 and September 22 are especially prominent, likely due to drought conditions and streamflows dominated by stormwater runoff, with little baseflow to dilute the high bacterial loads.

Figure 35: *E. coli* Concentrations in Wachusett Tributaries

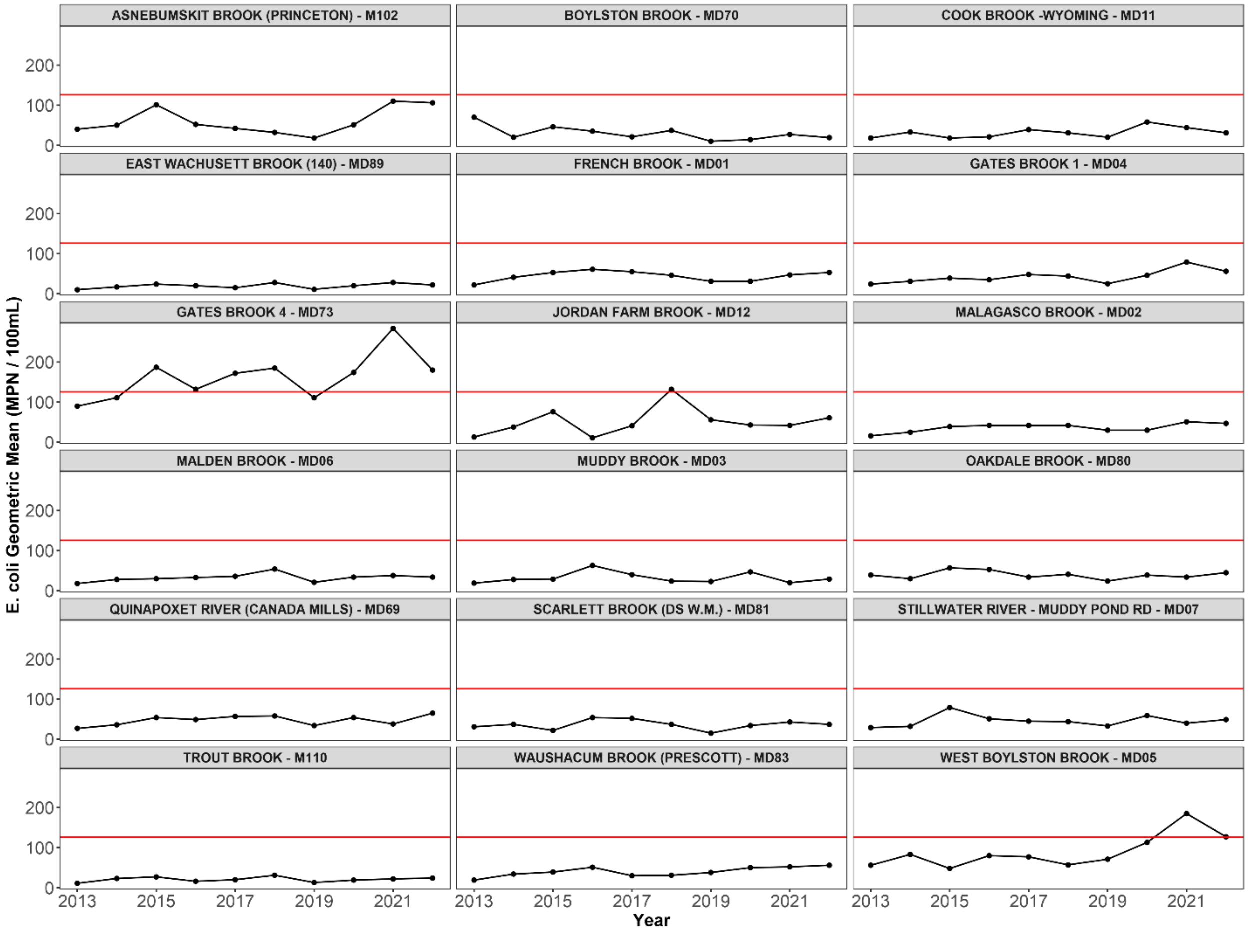
The blue points show E. coli results for 2022, while the hollow points show results from years 2013 – 2021, with the green band representing a LOESS smooth function 95% confidence interval for the same period. The red dashed line is the MassDEP Class A surface water quality standard single sample limit: 235 MPN/100 mL and the orange dashed horizontal line represents the detection limit of 10 MPN/ 100mL.



Aside from West Boylston Brook, annual geometric mean concentrations of *E. coli* over the past 10 years do not show any discernible trend and 2022 annual geometric means were similar to previous years across all sample locations (Figure 36). Annual geometric mean at West Boylston Brook has increased in the past two consecutive years, and although lower than in 2020 and 2021, it still exceeded the longer term geometric mean standard (126 MPN/100 mL) in 2022.

Figure 36: 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 and West Boylston Brook, met the MassDEP Class A surface water geometric mean standard for *E. coli of* 126 MPN/100 mL in 2022 (Table 18). Bolyston Brook had the lowest 2022 geometric mean (19 MPN/100 mL). As in recent years, Gates Brook 4 had the highest geometric mean (180 MPN/100 mL). The source of high bacteria concentrations at Gates Brook 4 (avian wildlife) were previously investigated and a discussion of this investigation was included in the 2018 Annual Water Quality Report[61].

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61 DWSP, 2019

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

Sample Location	GMEAN 2019	GMEAN 2020	GMEAN 2021	GMEAN 2022	%>235 2019	%>235 2020	%>235 2021	%>235 2022
Asnebumskit Brook (Princeton) - M102	18	51	110	106	12	30	29	39
Boylston Brook - MD70	10	14	27	19	10	8	12	20
Cook Brook -Wyoming - MD11	20	58	44	31	0	16	29	17
East Wachusett Brook (140) - MD89	11	20	28	22	0	5	17	17
French Brook - MD01	31	31	47	53	8	5	12	26
Gates Brook 1 - MD04	25	46	79	56	8	5	21	12
Gates Brook 4 - MD73	111	174	284	180	21	30	50	29
Jordan Farm Brook - MD12	56	43	42	61	25	18	21	32
Malagasco Brook - MD02	30	30	51	47	8	5	12	17
Malden Brook - MD06	21	34	38	34	4	5	12	12
Muddy Brook - MD03	23	47	20	29	8	20	8	12
Oakdale Brook - MD80	24	39	34	45	4	5	8	17
Quinapoxet River (Canada Mills) - MD69	34	54	38	65	4	10	12	17
Scarlett Brook (DS W. M) - MD81	15	34	43	37	4	10	25	8
Stillwater River - Muddy Pond Rd - MD07	33	59	40	49	4	10	8	12
Trout Brook - M110	13	19	22	24	4	5	8	8
Waushacum Brook (Prescott) - MD83	38	50	52	56	0	10	12	17
West Boylston Brook - MD05	71	113	185	127	17	25	29	25

2022 geometric means were higher than both the five-year average and ten-year average geometric means for 11 of 18 tributaries (Table 19). Asnebumskit Brook and West Boylston Brook were the only tributaries to have a 2022 geometric mean substantially higher than normal, whereas other tributaries had 2022 geometric means closer to their historical averages.

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

Sample Location	2022 GEOMETRIC MEAN	5 YEAR MEAN	10 YEAR MEAN
Asnebumskit Brook (Princeton) - M102	106	63	60
Boylston Brook - MD70	19	21	30
Cook Brook -Wyoming - MD11	31	37	31
East Wachusett Brook (140) - MD89	22	22	20
French Brook - MD01	53	42	44
Gates Brook 1 - MD04	56	50	43
Gates Brook 4 - MD73	180	187	163
Jordan Farm Brook - MD12	61	67	51
Malagasco Brook - MD02	47	40	36
Malden Brook - MD06	34	36	33
Muddy Brook - MD03	29	29	32
Oakdale Brook - MD80	45	37	40
Quinapoxet River (Canada Mills) - MD69	65	50	47
Scarlett Brook (DS W. M) - MD81	37	33	36
Stillwater River - Muddy Pond Rd - MD07	49	45	46
Trout Brook - M110	24	22	21
Waushacum Brook (Prescott) - MD83	56	45	40
West Boylston Brook - MD05	127	111	90

In 2022, wet weather samples continued to have higher bacteria concentrations than dry weather samples (Table 20). For all sampling locations, except for Asnebumskit 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 seven locations did not have a single dry weather exceedance of this standard.

Table 20: Wet and Dry Weather *E. coli* Metrics in Wachusett Watershed Tributaries During 2022 (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	105	110	17	9	42	36	12	11
Boylston Brook - MD70	11	33	44	27	11	27	9	11
Cook Brook -Wyoming - MD11	22	47	25	36	0	36	12	11
East Wachusett Brook (140) - MD89	20	30	33	27	8	27	12	11
French Brook - MD01	37	77	8	18	17	36	12	11
Gates Brook 1 - MD04	22	179	15	0	0	27	13	11
Gates Brook 4 - MD73	100	359	0	0	15	46	13	11
Jordan Farm Brook - MD12	12	222	13	9	0	55	8	11
Malagasco Brook - MD02	36	65	15	18	8	27	13	11
Malden Brook - MD06	54	16	8	27	8	18	13	11
Muddy Brook - MD03	32	26	31	36	8	18	13	11
Oakdale Brook - MD80	34	67	23	9	15	18	13	11
Quinapoxet River (Canada Mills) - MD69	54	81	0	0	8	27	13	11
Scarlett Brook (DS W. M) - MD81	22	73	15	0	0	18	13	11
Stillwater River - Muddy Pond Rd - MD07	33	77	8	18	0	27	13	11
Trout Brook - M110	12	60	23	0	0	18	13	11
Waushacum Brook (Prescott) - MD83	35	97	8	0	0	36	13	11
West Boylston Brook - MD05	109	152	0	0	15	36	13	11

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). In 2022, staff conducted a focused sanitary survey in West Boylston Brook subbasin, but no definitive bacterial source could be identified. Additional information about this sanitary investigation in West Boylston Brook subbasin is provided in Appendix B. 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 2022 continued to indicate good sanitary quality at most Wachusett Reservoir tributaries.

3.2.7 Nutrient Dynamics

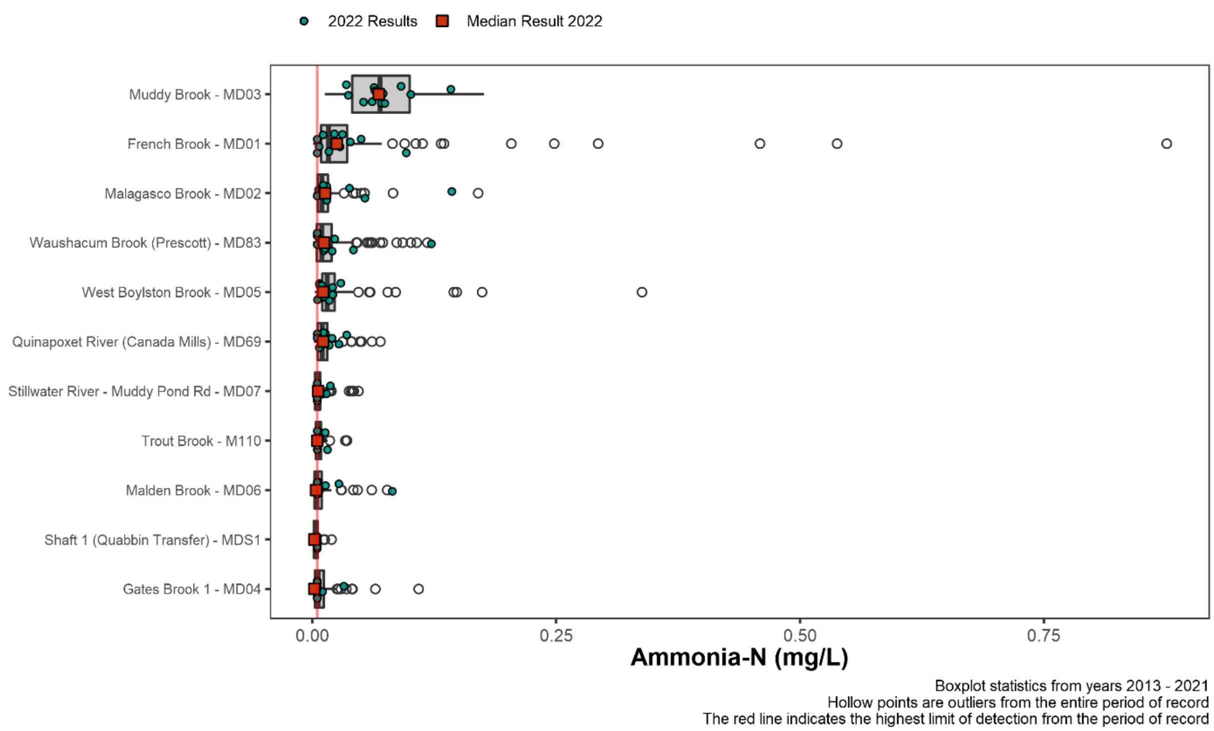
Results for monthly tributary nutrient monitoring in Wachusett tributaries are presented below. Sampling results for Quabbin transfer water are not discussed but are included in the tables and figures because transfer water is a large percentage of the annual inflow to Wachusett Reservoir and has a significant 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 2022, Ammonia-nitrogen (NH_3-N) concentrations were below the limit of detection in 27% 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 NH_3-N (Figure 37). 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 37: 2022 Ammonia-Nitrogen Concentrations with 2013 - 2021 Statistics



Due to the high number of non-detection lab results (<0.005 mg/L) the values presented in Table 21 for NH_3-N have an inherent high level of uncertainty relative to their magnitude. Gates Brook and Trout Brook had the lowest annual mean NH_3-N concentrations in 2022 (0.006 mg/L).

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

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

Sample Location	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
French Brook - MD01	0.051	0.034	0.041	0.018	0.012	0.029	0.026	0.201	0.023	0.028
Gates Brook 1 - MD04	0.010	0.014	0.012	0.013	0.008	0.008	0.012	0.006	0.005	0.006
Malagasco Brook - MD02	0.014	0.015	0.028	0.012	0.014	0.011	0.014	0.009	0.014	0.027
Malden Brook - MD06	0.007	0.009	0.016	0.004	0.005	0.012	0.006	0.009	0.008	0.012
Muddy Brook - MD03	0.065	0.067	0.076	0.060	0.078	0.086	0.094	0.055	0.084	0.072
Quinapoxet River (Canada Mills) - MD69	0.012	0.017	0.021	0.011	0.015	0.012	0.011	0.009	0.012	0.014
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	0.004	0.003	0.006	0.003	0.008	0.002
Stillwater River - Muddy Pond Rd - MD07	0.007	0.012	0.011	0.007	0.006	0.006	0.005	0.007	0.010	0.007
Trout Brook - M110	—	—	0.012	0.007	0.008	0.006	0.008	0.007	0.007	0.006
Waushacum Brook (Prescott) - MD83	0.014	0.024	0.023	0.010	0.013	0.011	0.029	0.028	0.017	0.023
West Boylston Brook - MD05	0.014	0.049	0.021	0.016	0.037	0.027	0.034	0.016	0.013	0.013

Nitrite-Nitrogen

Nitrite-nitrogen (NO_2-N) is rarely detected in Wachusett Reservoir tributaries, therefore results are not displayed below. In 2022, there were only three NO_2-N concentrations above the 0.005 mg/L detection limit: 0.0051 mg/L at French Brook, 0.0064 mg/L at Malagasco Brook, and 0.0059 mg/L at Muddy Brook - all on June 13. 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 2022 were below the EPA MCL of 1.0 mg/L.

Nitrate-Nitrogen

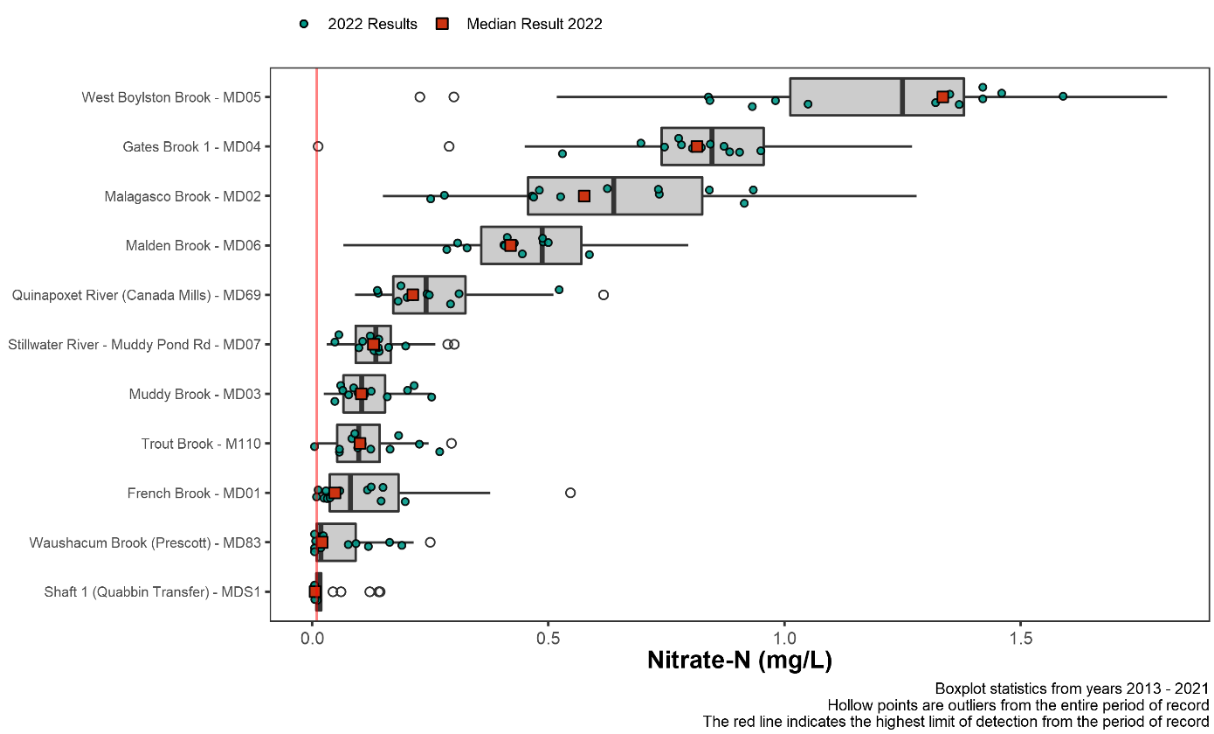
Annual mean nitrate-nitrogen (NO_3-N) concentrations for 2022 ranged from 0.06 mg/L at Waushacum Brook to 1.21 mg/L at West Boylston Brook (Table 22), with individual measurements from below detection (< 0.005 mg/L) to 1.59 mg/L at West Boylston Brook. The average annual NO_3-N concentrations at individual tributaries have been stable over the last several years, with 2022 concentrations tracking very close to long term averages. Apart from Trout Brook and West Boylston Brook, all annual median NO_3-N concentrations for 2022 were below the historical medians from the 2013 – 2021 period (Figure 38).

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

Sample Location	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
French Brook - MD01	0.16	0.17	0.09	0.15	0.11	0.13	0.12	0.10	0.07	0.08
Gates Brook 1 - MD04	0.92	0.86	0.79	0.76	0.93	0.85	0.89	0.75	0.81	0.80
Malagasco Brook - MD02	0.68	0.58	0.70	0.62	0.68	0.60	0.63	0.62	0.61	0.61
Malden Brook - MD06	0.55	0.44	0.53	0.44	0.49	0.45	0.46	0.42	0.41	0.42
Muddy Brook - MD03	0.14	0.14	0.13	0.14	0.11	0.11	0.10	0.10	0.07	0.13
Quinapoxet River (Canada Mills) -	0.25	0.25	0.29	0.21	0.32	0.24	0.28	0.28	0.19	0.24
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	0.02	0.05	0.02	0.01	0.01	0.01
Stillwater River - Muddy Pond Rd -	0.16	0.14	0.16	0.12	0.13	0.11	0.13	0.13	0.12	0.12
Trout Brook - M110	—	—	0.11	0.10	0.10	0.10	0.10	0.09	0.13	0.13
Waushacum Brook (Prescott) - MD83	0.04	0.05	0.05	0.02	0.03	0.07	0.07	0.06	0.06	0.06
West Boylston Brook - MD05	1.39	1.14	1.25	1.20	1.28	1.07	1.17	1.09	1.12	1.21

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.

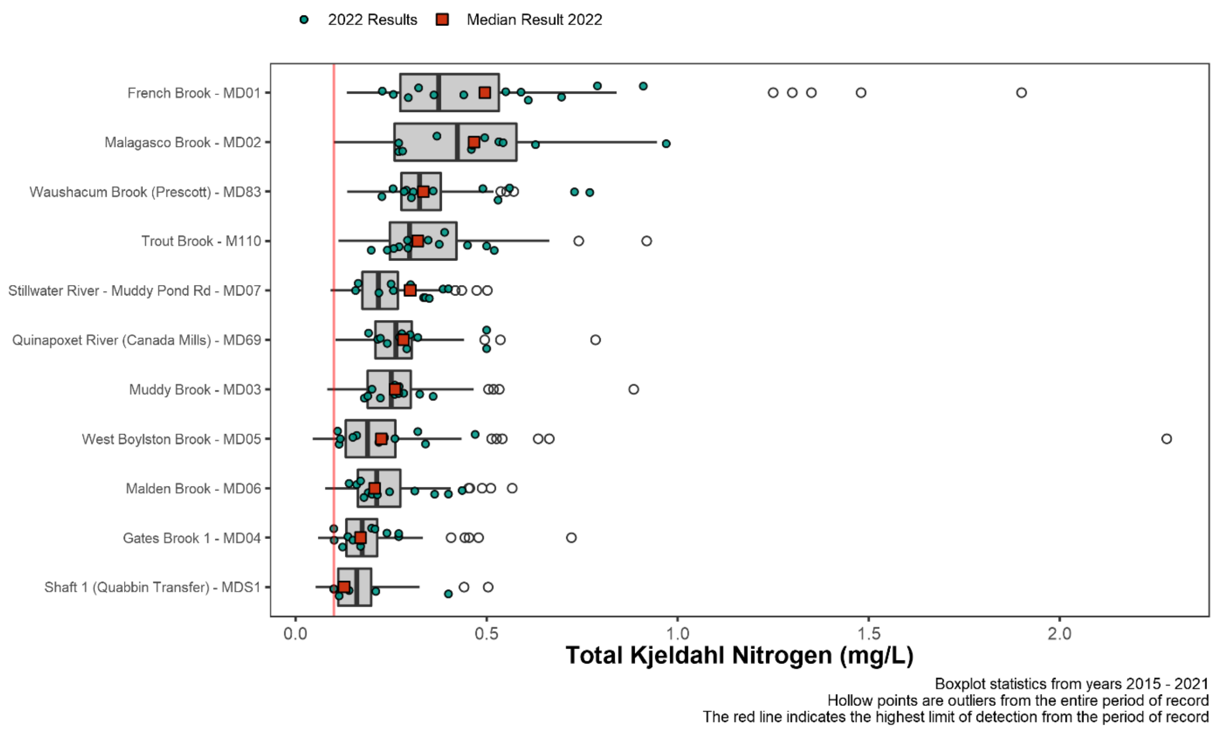
Figure 38: 2022 Nitrate-Nitrogen Concentrations with 2013 - 2021 Statistics



Total Kjeldahl Nitrogen

Annual mean Total Kjeldahl Nitrogen (TKN) concentrations have remained relatively consistent since 2015, when monitoring for this parameter in Wachusett tributaries began. However, in 2022 Malden and Waushacum Brooks and the Quinapoxet and Stillwater River's mean annual TKN concentrations were at their highest observed levels on record, though not significantly higher than in previous years. Gates and West Boylston Brooks continued to have the lowest mean annual TKN concentrations in 2022: 0.18 and 0.23 mg/L, respectively. Median TKN concentrations for 2022 were higher than the period of record median at most tributaries, with the Stillwater River 2022 median above the 75th percentile historical concentration. Individual TKN sample concentrations in 2022 ranged from below detection (0.1 mg/L) at Gates Brook 1 to 0.97 mg/L at Malagasco Brook (Figure 39).

Figure 39: 2022 Total Kjeldahl Nitrogen Concentrations with 2015 - 2021 Statistics



The mean and median annual TKN concentrations observed in 2022 were slightly higher than normal, but generally reflective of local ecoregional background concentrations (0.1 – 0.3 mg/L). The four tributaries with the highest mean TKN concentrations (French, Malagasco, Trout, and Waushacum Brooks) frequently contain slightly higher concentrations, between 0.3 and 0.75 mg/L. These four tributaries all have significant proportions of wetlands within their subbasins, which are highly productive environments where organic compounds containing nitrogen and carbon are constantly breaking down and entering surface waters.

Table 23: Total Kjeldahl Nitrogen Annual Mean Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2015	2016	2017	2018	2019	2020	2021	2022
French Brook - MD01	0.39	0.36	0.36	0.48	0.42	0.80	0.42	0.50
Gates Brook 1 - MD04	0.16	0.21	0.16	0.16	0.22	0.21	0.22	0.18
Malagasco Brook - MD02	0.38	0.34	0.47	0.47	0.39	0.39	0.56	0.48
Malden Brook - MD06	0.23	0.22	0.21	0.25	0.20	0.23	0.25	0.25
Muddy Brook - MD03	0.25	0.23	0.27	0.27	0.25	0.32	0.29	0.26
Quinapoxet River (Canada Mills) - MD69	0.29	0.29	0.25	0.27	0.26	0.26	0.30	0.30
Shaft 1 (Quabbin Transfer) - MDS1	—	—	0.10	0.21	0.19	0.19	0.15	0.16
Stillwater River - Muddy Pond Rd - MD07	0.21	0.27	0.23	0.23	0.20	0.23	0.25	0.29
Trout Brook - M110	0.26	0.31	0.35	0.35	0.38	0.33	0.36	0.35
Waushacum Brook (Prescott) - MD83	0.28	0.36	0.30	0.32	0.34	0.35	0.36	0.43
West Boylston Brook - MD05	0.18	0.19	0.18	0.25	0.27	0.38	0.24	0.23

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.

Total Nitrogen

Total Nitrogen (TN) concentrations in 2022 ranged from 0.27 mg/L at the Stillwater River to 1.83 at West Boylston Brook, with mean annual concentrations for 2022 ranging from 0.39 mg/L at Muddy Brook to 1.45 mg/L at West Boylston Brook. With the exception of French Brook in 2020, TN concentrations have been stable at each tributary since 2015. Waushacum Brook and the Stillwater River did have their highest mean annual TN concentration on record, however these concentrations were only slightly higher than in previous years (Table 24).

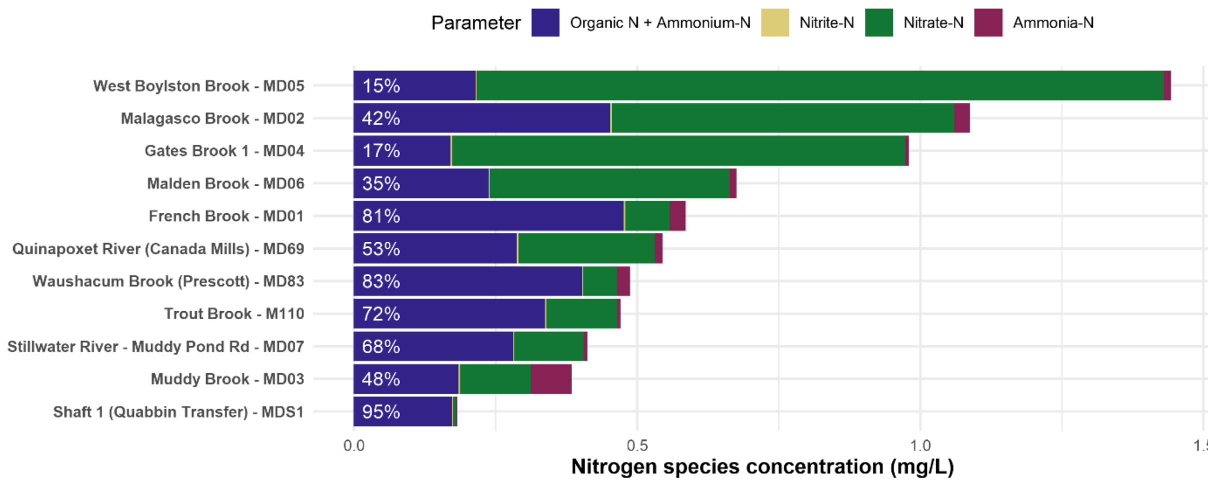
Table 24: Total Nitrogen Mean Annual Concentrations at Wachusett Tributaries (mg/L)

Sample Location	2015	2016	2017	2018	2019	2020	2021	2022
French Brook - MD01	0.49	0.51	0.47	0.62	0.55	0.91	0.49	0.59
Gates Brook 1 - MD04	0.95	0.98	1.09	1.01	1.11	0.96	1.03	0.98
Malagasco Brook - MD02	1.07	0.97	1.15	1.08	1.02	1.00	1.18	1.09
Malden Brook - MD06	0.77	0.67	0.71	0.71	0.67	0.66	0.67	0.68
Muddy Brook - MD03	0.39	0.38	0.38	0.38	0.35	0.42	0.37	0.39
Quinapoxet River (Canada Mills) - MD69	0.59	0.50	0.57	0.51	0.54	0.54	0.50	0.55
Shaft 1 (Quabbin Transfer) - MDS1	—	—	0.15	0.27	0.22	0.21	0.17	0.19
Stillwater River - Muddy Pond Rd - MD07	0.37	0.39	0.37	0.34	0.33	0.37	0.38	0.42
Trout Brook - M110	0.45	0.41	0.46	0.45	0.48	0.43	0.50	0.47
Waushacum Brook (Prescott) - MD83	0.34	0.39	0.34	0.40	0.42	0.42	0.42	0.49
West Boylston Brook - MD05	1.44	1.39	1.47	1.33	1.44	1.45	1.36	1.45

Figure 40 shows the relative proportion of all nitrogen species in the Wachusett tributaries, which differ considerably based on the landscape characteristics of each tributary subbasin. Less developed subbasins, such as Trout Brook, French Brook, and Waushacum Brook, usually have higher proportions of organic nitrogen (see discussion of TKN in the Appendix, Section A.4) while more developed subbasins, such as West Boylston Brook and Gates Brook, have much lower proportions of organic nitrogen. This phenomenon is a function of the availability of organic nitrogen source material and inorganic nitrogen uptake by plants. On a per unit area basis, less developed subbasins have greater amounts of organic nitrogen within the landscape and more nutrient uptake by plants. The ratios of various nitrogen species play a significant role in aquatic ecology, both in the tributaries and Reservoir, in terms of algal production and bacteria growth and survival.

Figure 40: 2022 Mean Total Nitrogen Concentrations at Wachusett Tributaries

Percentages indicate the organic nitrogen fraction of total nitrogen at each sample location.

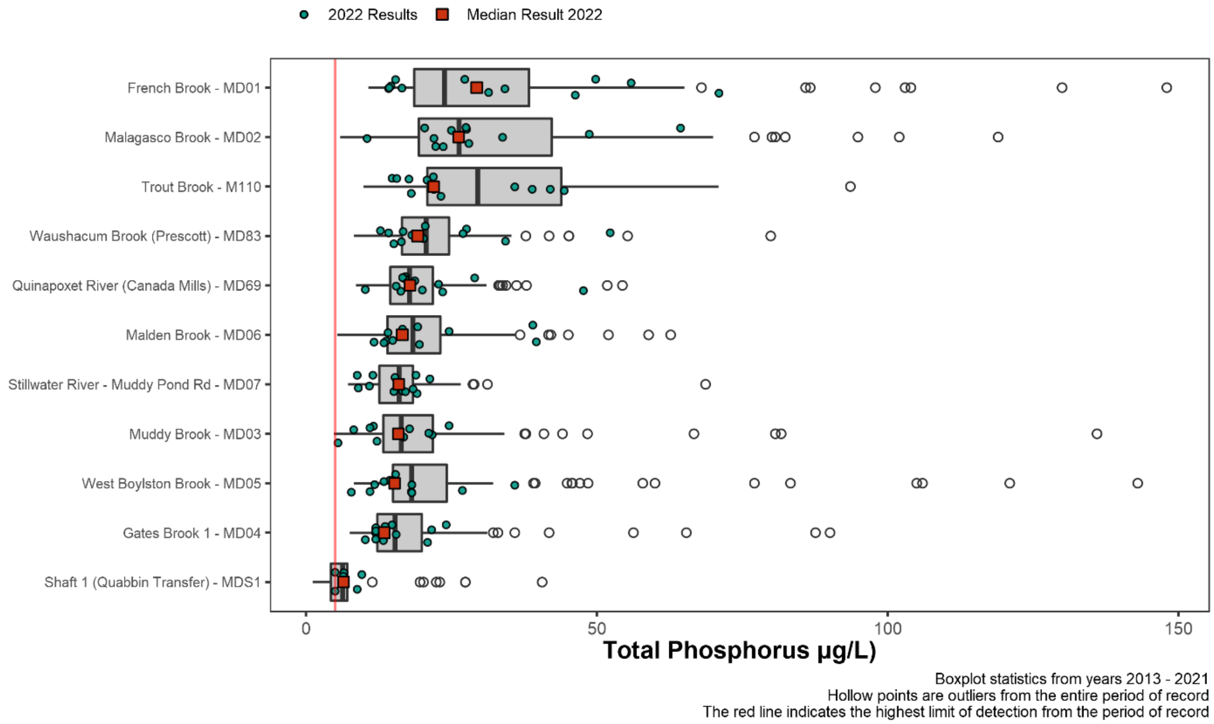


Concentrations of TN within Wachusett tributaries are mostly within the range of ecoregional background concentrations (0.42 – 0.59 mg/L), which are suggested reference conditions for numerical criteria development. West Boylston, Gates and Malagasco Brooks all exceed these concentrations, likely because 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 in Wachusett Reservoir Watershed Tributaries

Total phosphorus (TP) concentrations measured in Wachusett tributaries during 2022 ranged from 5.5 µg/L at Muddy Brook to 71 µg/L at French Brook (Figure 41). Annual mean concentrations ranged from 15.17 µg/L at the Gates Brook to 32.58 µg/L at French Brook (Table 25). Annual median TP concentrations were below the 2013-2021 median at most tributaries. The Stillwater and Quinapoxet Rivers and Malagasco Brook had 2022 annual median TP concentrations almost the same as the median over the prior nine years, while French Brook was the only tributary with an annual median TP concentration significantly higher, although still below the 75th percentile for the nine years prior (Figure 41). 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.

Figure 41: 2022 Total Phosphorus Concentrations with 2013 - 2021 Statistics



Mean annual TP concentrations in 2022 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 of these subbasins have on-lot waste disposal systems (septic) on developed parcels. Furthermore, French Brook subbasin contains a golf course which covers 10% of the drainage area and Malagasco Brook contains a nursery operation which covers 8% of its drainage area. The flow weighted mean TP concentration for all tributaries for 2022 was 27.24 µg/L. However, the Quabbin transfer contribution lowers the flow-weighted TP concentration to 11.01 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 25: Total Phosphorus Annual Mean Concentrations at Wachusett Tributaries (µg/L)

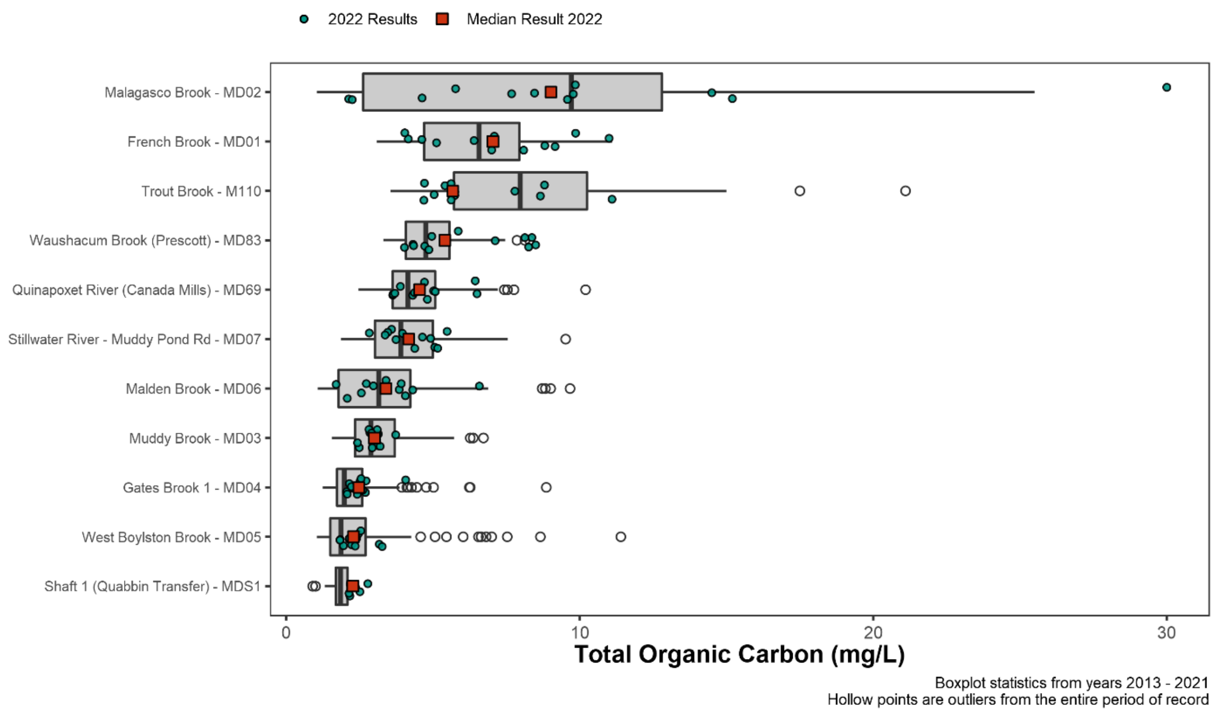
Sample Location	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
French Brook - MD01	32	31	32	29	23	26	44	54	26	33
Gates Brook 1 - MD04	17	25	15	17	15	19	23	21	16	15
Malagasco Brook - MD02	26	34	38	25	37	36	30	30	39	29
Malden Brook - MD06	18	25	24	20	16	20	18	21	20	20
Muddy Brook - MD03	21	19	18	20	21	21	19	31	19	15
Quinapoxet River (Canada Mills) - MD69	19	20	24	21	17	19	18	23	17	21
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	8	12	7	10	6	7
Stillwater River - Muddy Pond Rd - MD07	15	18	19	19	15	16	15	18	15	15
Trout Brook - M110	—	—	50	38	31	29	29	35	28	26
Waushacum Brook (Prescott) - MD83	23	25	22	26	20	19	21	26	18	23
West Boylston Brook - MD05	19	37	21	18	20	31	25	32	27	17

3.2.8 Total Organic Carbon and UV254 in Wachusett Reservoir Watershed Tributaries

In 2022, Total Organic Carbon (TOC) sample concentrations in the Wachusett tributaries ranged from 1.7 mg/L at Malden Brook to 9.99 mg/L at Malagasco Brook (Figure 42; Table 26). The overall mean concentration for 2022 was 4.88 mg/L, which is 5% higher than the long-term mean concentration since 2013 (4.66 mg/L). Waushacum Brook had the highest annual mean TOC concentration since at least 2013, while the Quabbin transfer had the highest mean TOC concentration since monitoring at this location began in 2017. Eight tributaries had median TOC concentrations for 2022 between 0.02 and 0.07 mg/L higher than the 2013 – 2021 median, with only Trout and Malagasco Brooks having their annual median concentrations lower than their 2013 – 2021 median. (Figure 42).

The 2022 flow-weighted mean TOC concentration for all tributaries and Quabbin transfer was 3.10 mg/L. Without the Quabbin transfer, the flow-weighted mean concentration would have been 7.66 mg/L, or 147% higher. The highest mean annual TOC concentrations were recorded from Malagasco and French Brooks, with the lowest concentrations Gates and West Boylston Brooks (Figure 42). 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 42: 2022 Total Organic Carbon Concentrations with 2013 - 2021 Statistics



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

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

Sample Location	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
French Brook - MD01	6.21	6.74	5.88	6.06	6.81	7.14	5.51	7.59	6.81	7.11
Gates Brook 1 - MD04	2.10	2.52	1.86	2.34	2.27	2.45	2.46	2.55	2.82	2.53
Malagasco Brook - MD02	6.40	10.80	7.79	8.83	10.82	10.81	7.20	6.80	12.11	9.99
Malden Brook - MD06	2.81	4.21	2.29	3.08	3.50	3.67	2.82	3.50	4.58	3.46
Muddy Brook - MD03	2.96	3.01	2.44	2.93	3.53	3.49	2.73	3.06	4.00	2.98
Quinapoxet River (Canada Mills) - MD69	4.28	4.76	4.11	4.92	4.53	4.73	3.61	3.92	5.33	4.68
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	1.89	1.55	1.79	2.04	2.11	2.36
Stillwater River - Muddy Pond Rd - MD07	3.55	4.58	3.89	3.84	4.54	4.79	3.34	3.65	4.64	4.22
Trout Brook - M110	—	—	9.54	8.50	9.43	9.31	6.51	7.06	7.73	6.58
Waushacum Brook (Prescott) - MD83	4.72	5.33	4.50	4.97	5.36	4.91	4.27	4.98	5.60	6.12
West Boylston Brook - MD05	2.11	3.20	1.76	1.88	2.26	2.71	2.80	3.07	2.73	2.36

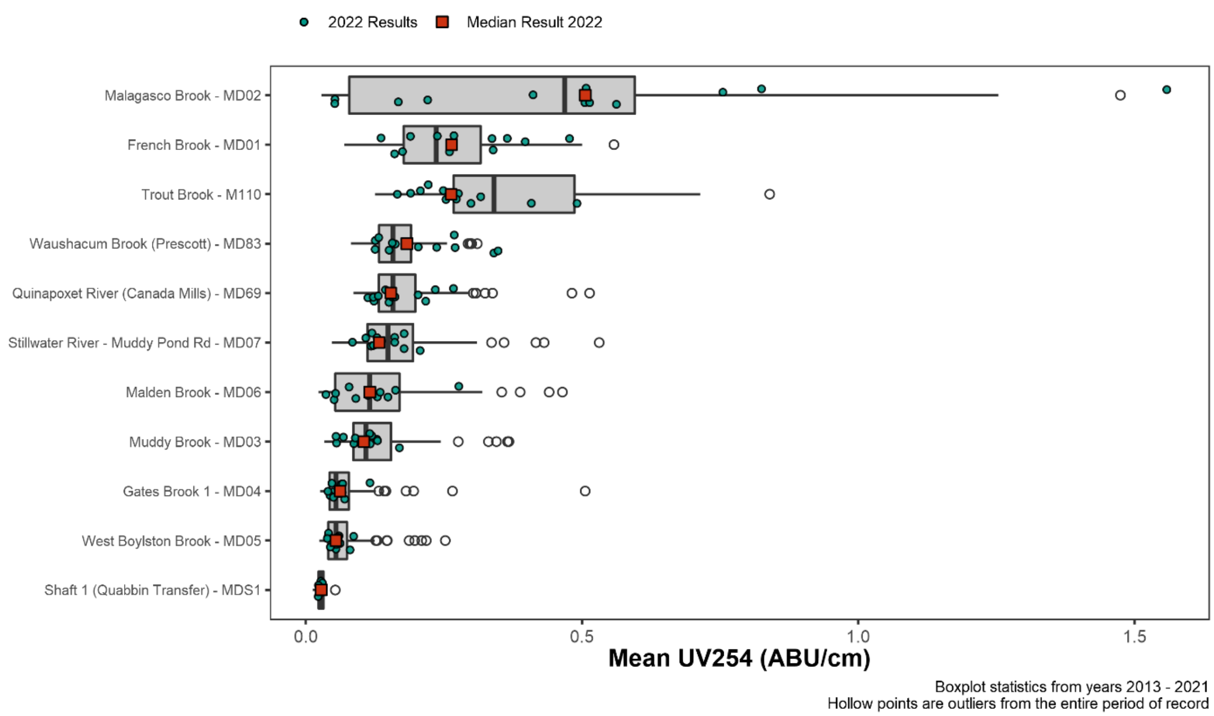
TOC concentrations between 2 and 4 mg/L are considered low for surface waters, and the 2022 flow-weighted mean TOC concentration of 3.10 mg/L is not a concern for aquatic life. However, this concentration is higher than optimal from a drinking water treatment perspective. Although tributary TOC concentrations are within ranges that could be reflecting typical background concentrations, more research needs to be conducted to determine what portion of tributary organic carbon is of natural origin versus anthropogenic origin. Until those sources and relative quantities are better understood, recommendations for reduction cannot be made. 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 2022 demonstrated variability comparable to TOC concentrations (Figure 43, Table 27). The highest UV_{254} absorbance level was from Malagasco Brook (1.56 ABU/cm) and the lowest was from Malden Brook (0.037 ABU/cm). Aside from Waushacum Brook, UV_{254} absorbance levels were lower in 2022 compared with 2021, but similar to the long term mean and median over the prior nine years. Trout Brook was the only tributary with annual median UV_{254} levels outside the 25-75th percentile range (below), and the annual mean UV_{254} was the lowest since this parameter was first measured at this tributary in 2015.

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

Sample Location	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
French Brook - MD01	0.229	0.251	0.226	0.199	0.248	0.313	0.237	0.311	0.309	0.279
Gates Brook 1 - MD04	0.057	0.068	0.051	0.065	0.057	0.084	0.095	0.068	0.084	0.062
Malagasco Brook - MD02	0.317	0.479	0.372	0.304	0.510	0.618	0.380	0.302	0.672	0.511
Malden Brook - MD06	0.102	0.153	0.078	0.100	0.126	0.156	0.116	0.133	0.206	0.116
Muddy Brook - MD03	0.108	0.108	0.101	0.103	0.133	0.151	0.117	0.107	0.215	0.102
Quinapoxet River (Canada Mills) - MD69	0.156	0.167	0.162	0.162	0.197	0.210	0.152	0.153	0.221	0.169
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	0.020	0.026	0.032	0.027	0.030	0.027
Stillwater River - Muddy Pond Rd - MD07	0.140	0.152	0.167	0.125	0.193	0.215	0.144	0.141	0.195	0.142
Trout Brook - M110	—	—	0.432	0.316	0.437	0.421	0.335	0.327	0.413	0.279
Waushacum Brook (Prescott) - MD83	0.138	0.158	0.146	0.153	0.169	0.186	0.163	0.179	0.207	0.210
West Boylston Brook - MD05	0.052	0.075	0.050	0.057	0.053	0.091	0.081	0.077	0.079	0.056

Figure 43: 2022 UV_{254} Absorbance with 2013 - 2021 Statistics



Even though TOC concentrations and UV_{254} absorbance levels observed in 2022 were generally consistent with historical results, the formation of disinfection byproducts from reactive organic compounds remains a top water treatment concern. Collecting targeted and or higher resolution TOC and UV_{254} absorbance data could enable analyses that could lead to a better understanding of export control points for dissolved organic matter loads[62]. 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.

3.2.9 Special Studies and Investigations – Tributaries

3.2.9.1 Forestry Water Quality Monitoring

Long-term forestry monitoring

In 2022, monthly dry weather monitoring at the LTF monitoring locations (Holden (FHLN) and Princeton (FPRN)) continued as part of the pre-harvest phase. Storm event sampling remained on hold through 2022 because sufficient data for storm events in the pre-harvest phase has been acquired (21 events prior to 2019).

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. Monthly dry weather monitoring for this project will also be put on hold in 2023, and sampling will resume after the harvest is complete. It is expected that timber harvesting will commence at the Princeton site in 2023.

Short-term forestry monitoring

In 2022, 12 lot visits were made across four distinct forestry lots in various stages of harvest. During 2022, pre-harvest monitoring was completed at proposed stream crossings on lots WA-21-148 and WA-19-95. Harvest was completed at lot WA-19-241 on June 1, 2022, however no turbidity samples were collected during the harvest phase because staff were not informed that harvest was occurring. Five post-harvest monitoring visits were made to this site in 2022, however the stream was dry during three visits, so only two turbidity samples were collected. Four post-harvest visits were made to lot WA-18-211. Due to the reduced monitoring protocol established for 2022, only 15 turbidity samples were collected from stream crossing sampling locations across all harvest phases (Table 28).

Table 28: Short-term Forestry Monitoring in 2022

Metric	Pre-harvest	Harvest - Active	Harvest - Suspended	Post-harvest	Total
Lot Visits	5	0	0	9	12
Crossing Observations	5	0	0	13	18
Turbidity Samples Collected	5	0	0	10	15

Turbidity results ranged from 0.26 NTU at WA-18-211 to 4.42 NTU at WA-19-241 (Figure 44). Turbidity results were less than 1.0 NTU for 73% of samples in 2022. No samples were above 5.0 NTU.

Overall mean turbidity values for 2022 were low and representative of background water quality conditions (Table 29). The turbidity results for 2022 indicate that sediment erosion control practices at Wachusett forestry operations continue to adequately protect water quality.

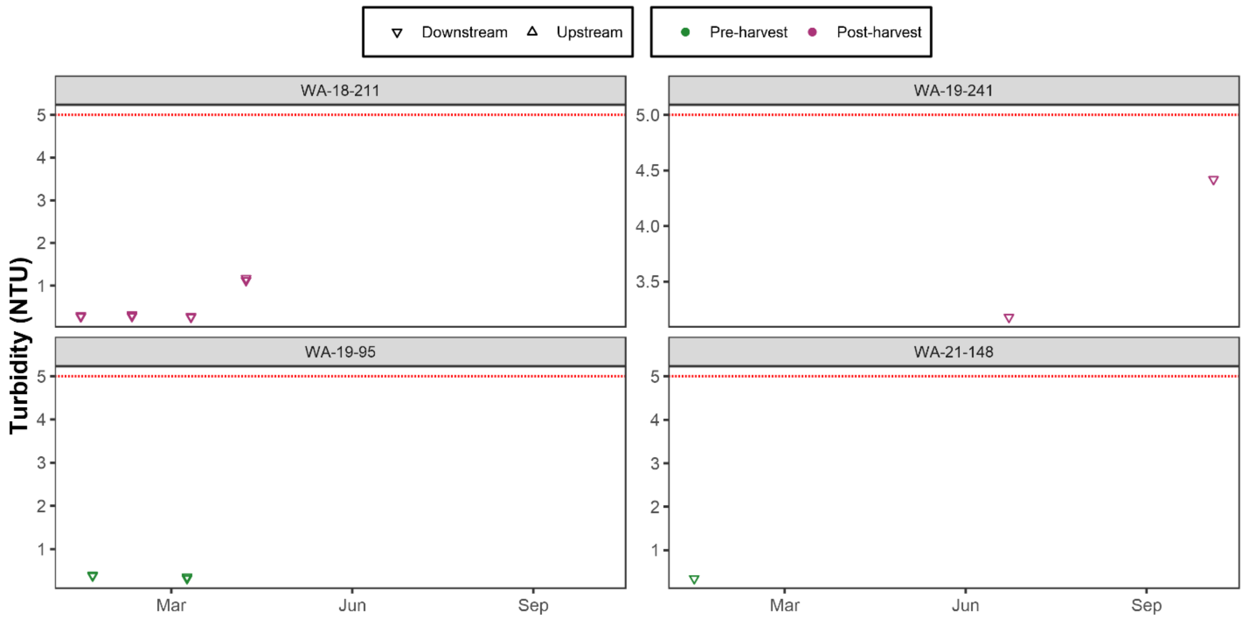
[62] Leonard, et. al. 2022

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

Sample Location	Pre-harvest	Harvest (Active and Suspended)	Post-Harvest
Upstream	—	—	—
Downstream	0.36	—	1.16

Figure 44: Turbidity Results at Short-term Forestry Monitoring Locations in 2022

Upstream and downstream designations are only applicable during harvest periods when stream crossings were installed. Only the downstream location was sampled during pre- and post-harvest monitoring periods. The red dashed line is the SWTR threshold of 5.0 NTU.



3.2.9.2 Conductivity and Chloride

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 2022, members of the Chloride/Conductivity working group met quarterly to discuss progress on tasks and brainstorm possible new initiatives and partnerships. This effort now has nearly 20 staff involved across all sections of DWSP working on over 30 distinct tasks within the following categories:

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

Several tasks initiated under this program have now been completed and progress is being made in every category listed above. DWSP has taken on a leadership role in the formation of a new inter-agency salt reduction working group, which will be working to enact statewide action to promote salt reduction initiatives and increased collaboration. A summary of this program is provided to MassDEP on an annual basis and is beyond the scope of this report, 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 new 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," is 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 was expected to be finished by the fall of 2022, however the drought conditions during the summer and early fall months dried up many intermittent streams in the headwaters, preventing the collection of measurements at most targeted locations. This project will resume in the summer of 2023 with the goal of collecting measurements at the locations that were dry in 2022.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.

Expanded Groundwater Monitoring

In May 2021 groundwater monitoring was expanded to include several other parameters that can be analyzed in relation to chloride levels in order to discern various sources of chlorides that have become dissolved in groundwater, such as halite (road salt), fertilizers, septic systems, alternative deicers or water-rock interactions. This expansion of groundwater monitoring was a short-term effort that was incorporated into the WATWEL project. The project was concluded in April 2022 after 12 samples were collected at each monitoring well. A separate report, *2021-2022 Expanded Well Parameter Report,* provides an analysis of the data to assist in determining sources of elevated conductivity in the shallow groundwater[63].

Real-time Conductivity Monitoring

Real-time specific conductivity monitoring was expanded in December 2021, with Mayfly logger stations installed at French, Malagasco, Muddy, Malden and West Boylston Brooks (Figure 45). The increased temporal resolution of real-time monitoring (15-minute increments) of specific conductivity will capture rapid fluctuations in specific conductivity that are missed by our 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 will be summarized in future water quality reports.

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[63] DWSP, 2023

Figure 45: Mayfly Station at French Brook

3.2.9.3 Stormwater Basins

Monitoring of the stormwater basins located on either side of the Rt 12/140 causeway has been conducted since July 2019. In 2022, 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.

3.2.9.4 Cyanobacteria Bloom in West Waushacum Pond

DWSP detected a cyanobacteria bloom on West Waushacum Pond in Sterling on September 14. The bloom, which was initially discovered using the EPA's Cyanobacteria Assessment Network Application, a web application that provides estimations of cyanobacteria density using satellite imagery, was confirmed by a site visit, visual inspection, and microscopic identification. *Dolichospermum* was the dominant cyanobacteria of concern in this bloom. Although water contact is prohibited on this DWSP owned waterbody, advisory signs were posted to further discourage contact by humans or pets. A trail cam was positioned in a downwind cove to monitor visual, diurnal changes for the duration of the bloom. The local board of health, MA DPH, DEP, and MWRA were all notified. Additionally, DPH listed West Waushacum Pond on their advisory list on September 15. By October 22, visual signs of the cyanobacteria bloom, including water color, and the accumulation of cyanobacteria on the shoreline, had improved, and the advisory was lifted by DPH. The DWSP advisory signs were subsequently removed.

3.3 Groundwater Quality Monitoring

Groundwater monitoring continued in 2022 after launching in 2019 (see Figure 6), and the data collected so far have provided preliminary insights on the groundwater levels, specific conductance, and Cl in Wachusett Watershed aquifers. Chloride samples were discontinued after the April 2022 sampling event and linear regressions of chloride and specific conductance were presented in the *2021-2022 Expanded Well Parameter Report* which will enable DWSP to estimate groundwater chloride concentrations going forward. Results of well monitoring in 2022 continued to indicate a wide range in specific conductance and Cl concentrations in Wachusett Watershed groundwater (Figure 46). The means of both parameters in West Boylston - 110 were two orders of magnitude higher than the means in Sterling – Justice Hill Rd, with values from the other wells between those two extremes (Table 30).

The ranges and medians of specific conductance and Cl results are shown in the box plots in Figure 46 and Figure 47 with logarithmic Y-axes due to the high and low extremes in values. Elevated Cl 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 and Cl levels in West Boylston – Rt 110, DWSP launched a supplementary investigation in 2019 to determine additional sources impacting the groundwater at that location. To date, no additional sources of Cl have been determined, but investigations will continue to seek potential sources.

Figure 46: Chloride Results in Wachusett Watershed Wells in 2022

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

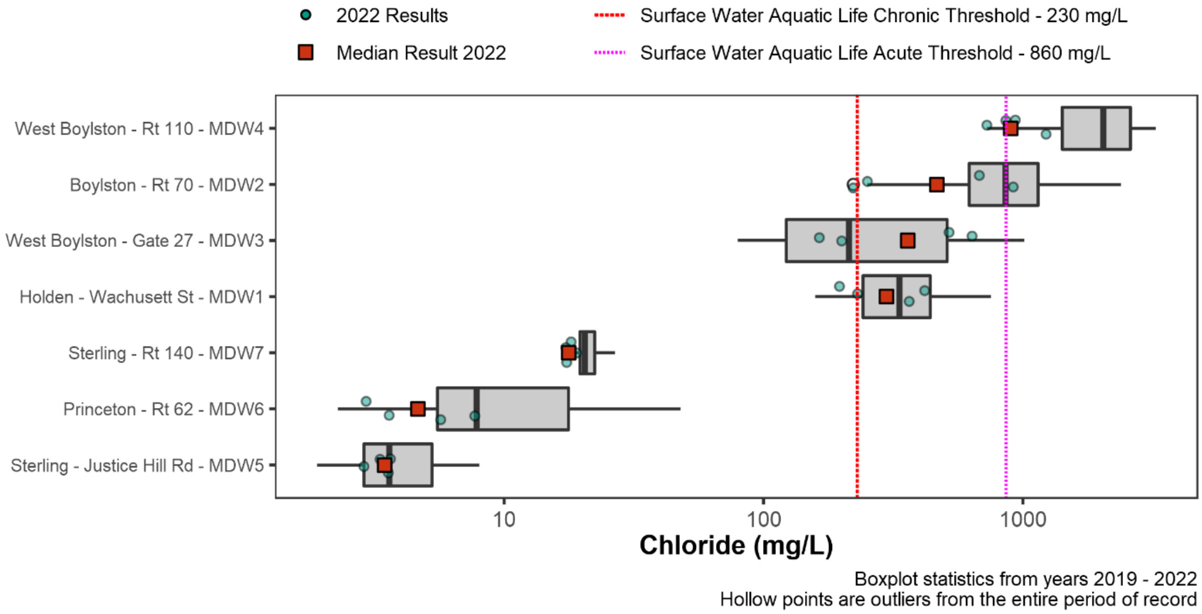
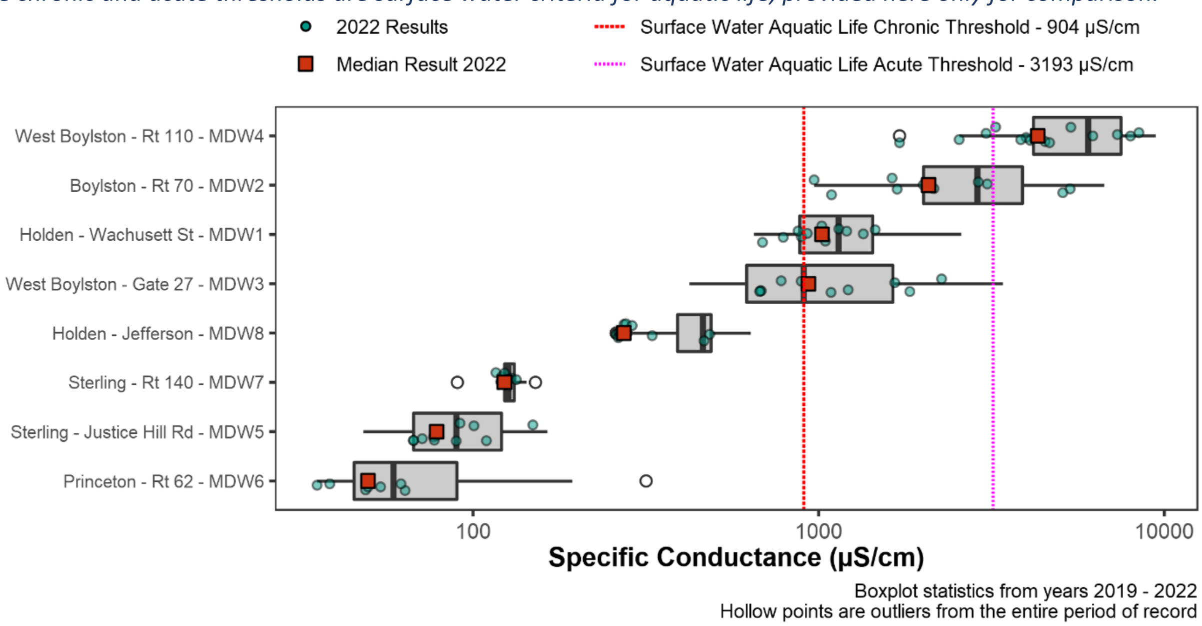


Figure 47: Specific Conductance Results in Wachusett Watershed Wells in 2022

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 48 and Figure 49. These data were only first collected in April 2022, so they contain less than a full year of data and do not have any historical data with which to compare them.

Figure 48: Dissolved Oxygen Results in Wachusett Watershed Wells in 2022

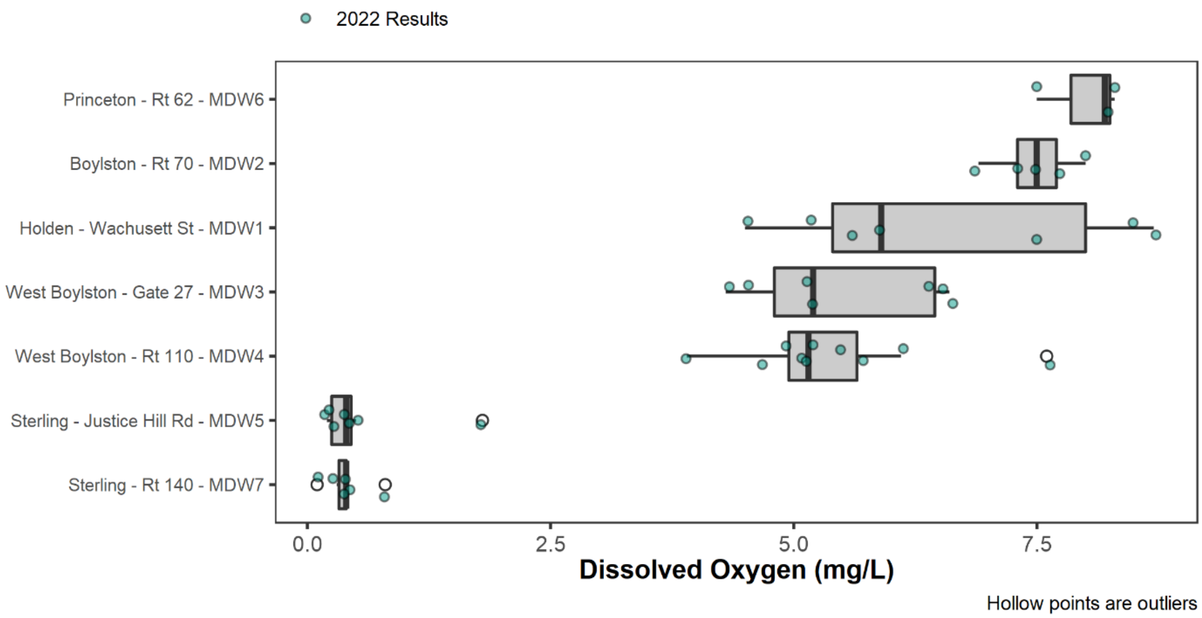


Figure 49: pH Results in Wachusett Watershed Wells in 2022

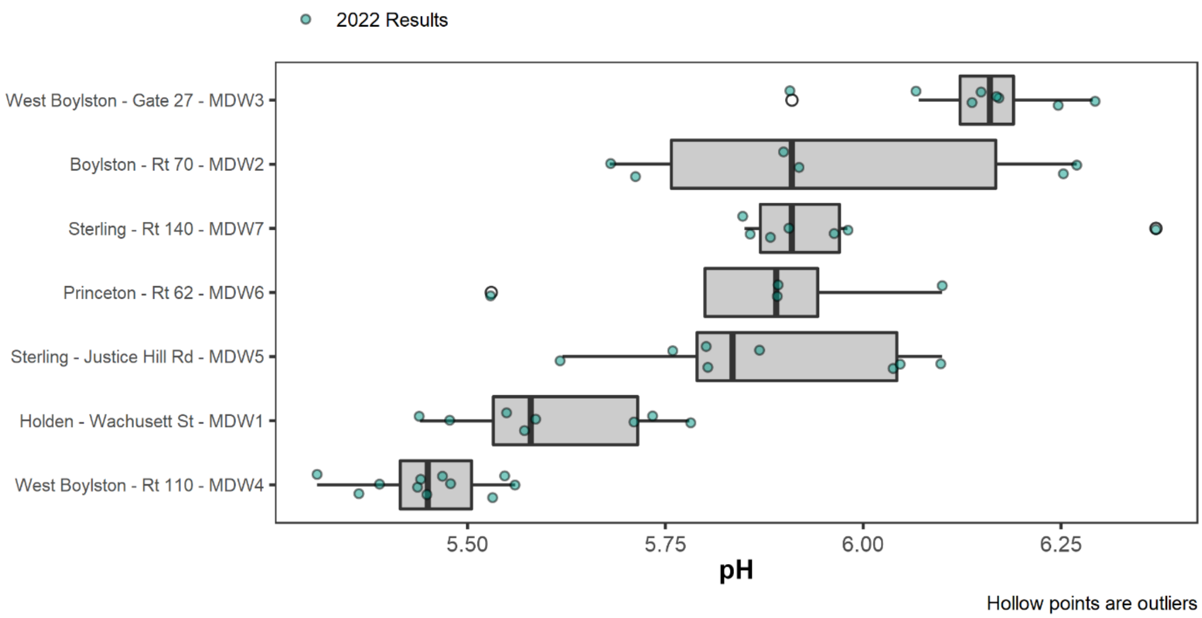


Table 30: Groundwater Monitoring Summary for 2022

Well	Mean Water Depth Below Ground Surface (ft)	Mean Specific Conductance (µS/cm)	Mean Chloride (mg/L)	Mean Dissolved Oxygen (mg/L)	Mean pH
Princeton - Rt 62 - MDW6	16.1	50.3	5.0	8.0	5.9
Sterling - Justice Hill Rd - MDW5	6.0	88.9	3.4	0.5	5.9
Sterling - Rt 140 - MDW7	14.6	124.0	18.0	0.4	6.0
Holden - Jefferson - MDW8	17.8	312.8	-	-	-
Holden - Wachusett St - MDW1	3.8	1,035.1	302.8	6.6	5.6
West Boylston - Gate 27 - MDW3	7.3	1,154.8	380.0	5.5	6.1
Boylston - Rt 70 - MDW2	6.9	2,593.5	517.8	7.5	6.0
West Boylston - Rt 110 - MDW4	14.9	4,784.6	937.8	5.4	5.5

Well monitoring will continue in 2023 to determine if seasonal or long-term trends are present in groundwater specific conductance concentrations.

Although there are water quality standards or thresholds that are applicable to groundwater that is not used as a drinking water source, Cl concentrations observed in Holden - Wachusett St, Boylston - Rt 70, and West Boylston - Rt 110 exceed all established surface water quality thresholds for drinking water (EPA SMCL 250 mg/L for taste and odor) and aquatic life (230 mg/L chronic/860 mg/L acute). Cl concentrations in West Boylston - Rt 110 are almost an order of magnitude higher than the highest tributary concentrations. The wide ranges of Cl concentrations in groundwater also demonstrate how certain hotspot areas can go undetected when only monitoring surface waters because of the blending of various ground/surface waters from an entire drainage area that occur within tributaries. Unfortunately, there is limited capacity to expand the spatial extent of the groundwater sampling program due to the lack of additional monitoring wells. However, there are other methods that may provide increased spatial resolution of groundwater impairment, such as monitoring baseflow at first order tributaries that are not currently routinely monitored.

3.4 Reservoir Monitoring

In general, results of reservoir monitoring programs followed expected trends and fell within or close to historical values. Notable deviations are likely related to the high percentage of water transferred from Quabbin Reservoir to Wachusett Reservoir and the low input of native Wachusett Watershed water due to the 2022 drought. These conditions resulted in lower specific conductance, UV_{254} and silica. A brief period during which chrysophyte algae exceeded early monitoring thresholds was documented in 2022. Details on these and all other water quality and aquatic life monitoring programs are presented below.

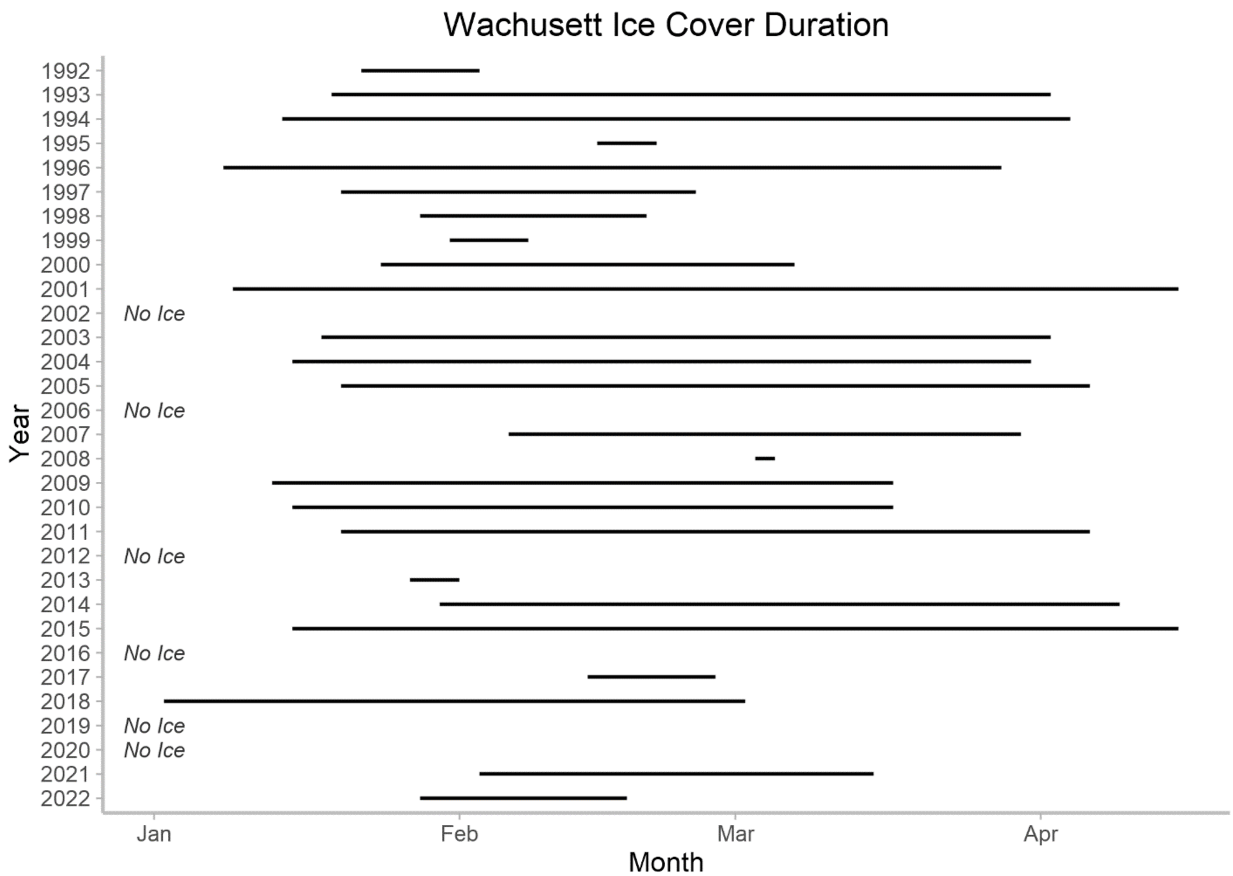
Unless otherwise noted, results reported in this section were obtained by DWSP aquatic biologists via hand-held instruments *in situ*, microscopy, or via samples processed by an MWRA lab (see Section 2.1).

3.4.1 Water Temperature

Reservoir temperatures in 2022 supported MassDEP aquatic life use standards for coldwater and warmwater fisheries. Recorded reservoir temperatures ranged from 1.4 °C to 27.4 °C.

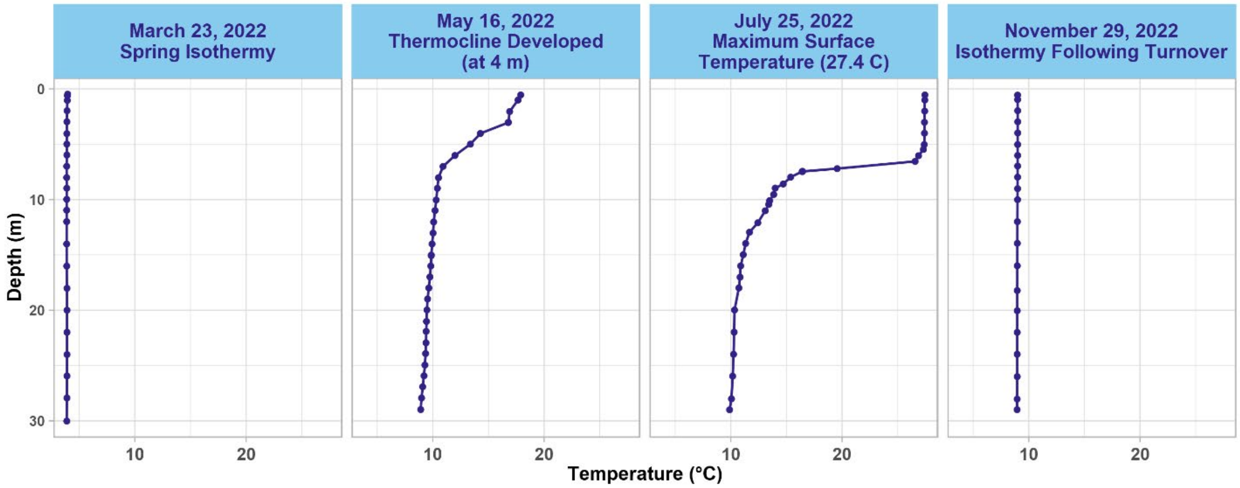
Ice was present for a total of 21 days between January 27 and February 17 (Figure 50). Warming started in May and the presence of a thermocline, as indicated by a 1 °C temperature decrease over one meter in depth, was first recorded on May 16 (Figure 51). Surface temperatures continued to warm, attaining a maximum recorded temperature of 27.4 °C at Basin North from 0.5 m to 5 m on July 25. Cooling of the epilimnion started in September when the combination of cooling air temperatures and wind energy pushed the thermocline deeper. However, cooling was gradual due to warm fall temperatures, including a 3.7 °C warmer than normal November[64]. Turnover occurred on November 17 (as recorded by MWRA profile buoys) and the water column continued to cool for the remainder of the season.

Figure 50: Ice Cover Duration for Wachusett Reservoir for the Period of Record (1992 – 2022)
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.



[64] Northeast Regional Climate Center, 2022

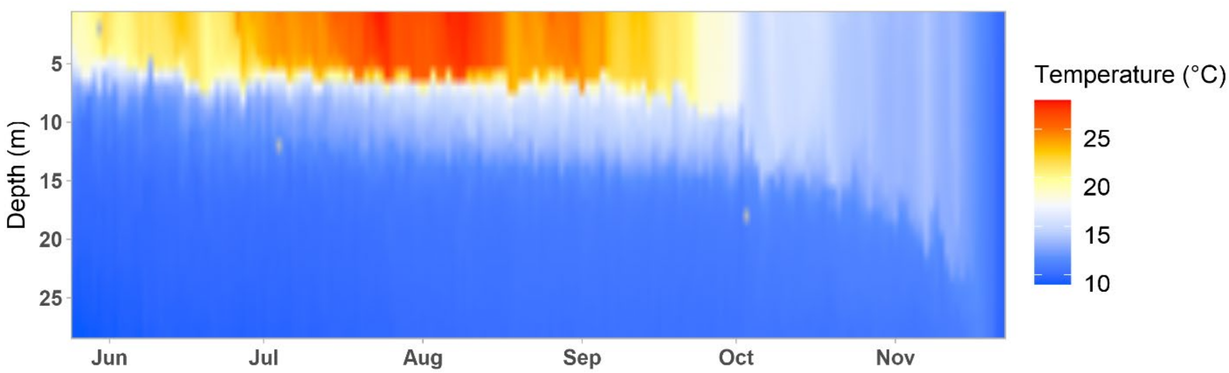
Figure 51: Profiles from Basin North Displaying Water Temperature at Critical Periods During 2022



The high temporal resolution data obtained from MWRA remote sensing buoys provide an opportunity to visualize reservoir temperature changes over the entire season (Figure 52). A brief period of stratification occurred in late May, dissipated, and then strengthened through June and the remainder of the summer.

Figure 52: Water Temperature Recorded by Basin North Profiling Buoy May – November 2022

Plot of data recorded daily at 12 pm.

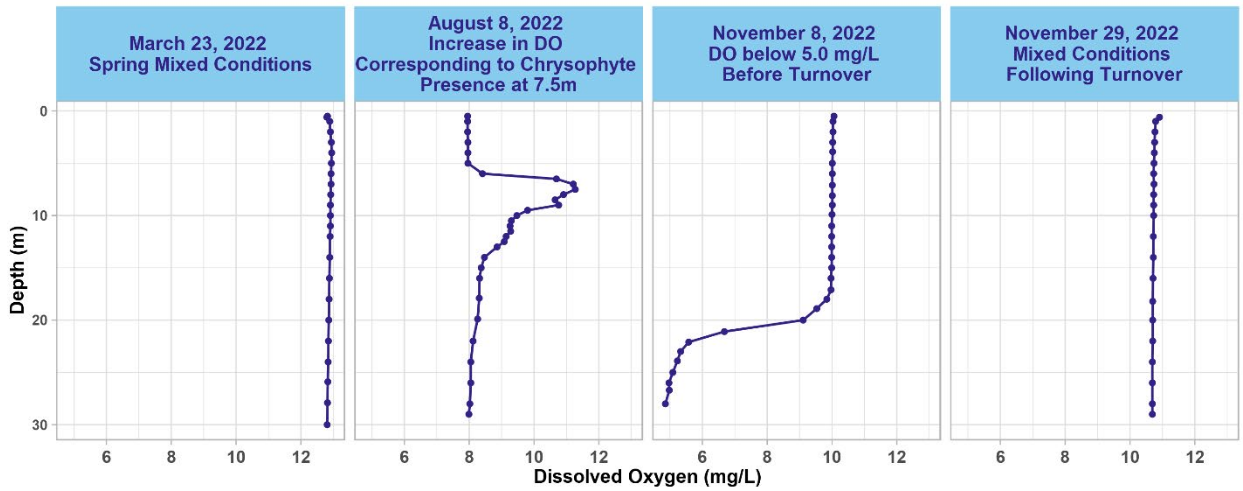


3.4.2 Dissolved Oxygen

Expected patterns in dissolved oxygen were observed through the 2022 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. Dissolved oxygen below 5.0 mg/L occurred briefly between October 26 and turnover in mid-November at depths below 25 m but did not fall below 4.64 mg/L based on profiles collected at Basin North (Figure 53).

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 4.64 mg/L at 30 m on October 26. Despite decreased oxygen at depth, the mean dissolved oxygen concentration remained above 6.0 mg/L, maintaining concentrations required to support coldwater species. Once turnover occurred on November 17 (as recorded by MWRA profile buoys), dissolved oxygen was again dispersed through the water column and was approximately 10.7 mg/L from the surface to the bottom on November 29. Elevated dissolved oxygen below the thermocline associated with increased phytoplankton activity occurred several times throughout the summer, including in early August when an aggregation of *Chrysosphaerella* was present within the interflow between 6.5 and 10 m.

Figure 53: Profiles from Basin North Displaying Dissolved Oxygen at Critical Periods During 2022

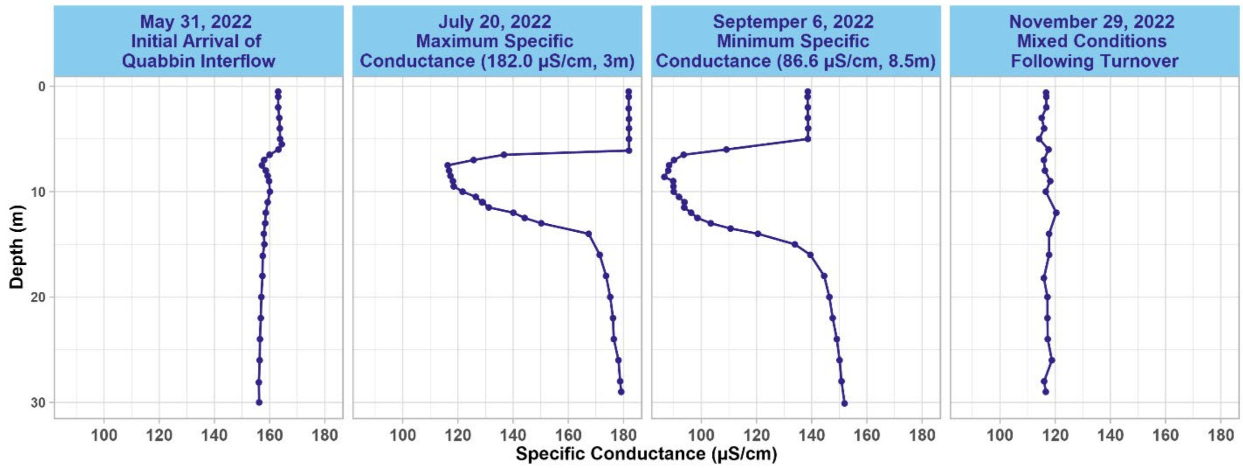


3.4.3 Specific Conductance

Annual mean specific conductance observed in the Reservoir continued to decrease, aided by an increase in Quabbin transfer volume and duration; however, the annual maximum was higher than observed the past three years. The maximum value of 182.0 µS/cm was recorded in the epilimnion between the surface and 5 m at Basin North on July 20. The annual mean was 139 µS/cm. The annual minimum specific conductance was lower than the previous five years at 86.6 µS/cm, recorded at 8.5 m on September 6.

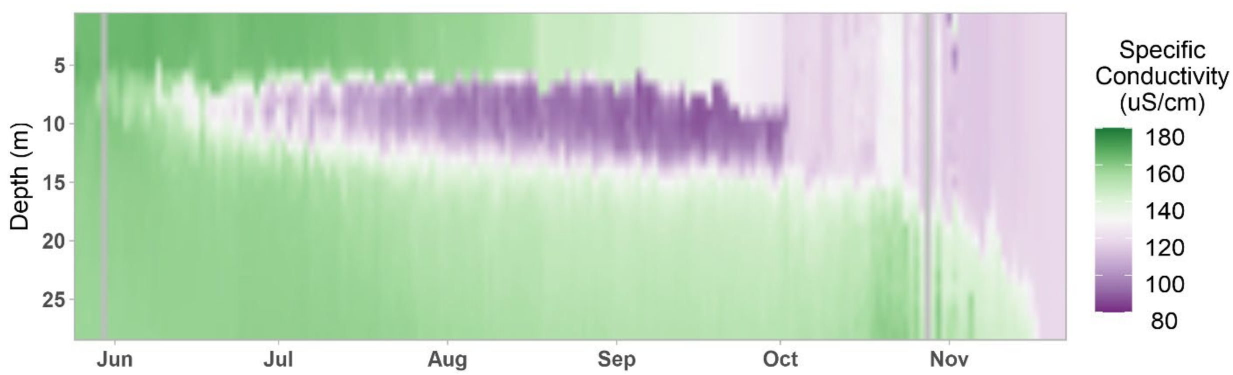
Arrival of the Quabbin interflow at Basin North was first observed on May 31 with a slight decrease in specific conductance observed at a depth of 7 m. By June 21, a definitive decrease in specific conductance between 6 and 11 m indicated the establishment of the Quabbin interflow within the Wachusett metalimnion. Following this date, specific conductance within the metalimnion continued to decrease, reaching a minimum of 86.6 µS/cm at 8.5 m on September 6. On this date, the interflow encompassed approximately 9 m between depths of 6 m and 15 m. Due to a wind event associated with the remnants of Hurricane Ian in late September, the interflow layer dissipated earlier than is typical. As the reservoir epilimnion temperature decreased in mid-October, higher conductivity water found in the Wachusett epilimnion continued mixing with the lower conductivity hypolimnion and Quabbin interflow, reducing the difference in specific conductance between the epilimnion and hypolimnion. By late November, the Reservoir was fully mixed, with a mean specific conductance of 117 µS/cm on November 29 (Figure 54).

Figure 54: Profiles from Basin North Displaying Specific Conductance at Critical Periods During 2022



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 55).

Figure 55: Specific Conductance Recorded by Basin North Profiling Buoy May – November 2022
Plot of data recorded daily at 12 pm. The Quabbin interflow layer is visible in the range of 86 to 130 µS/cm between mid-June and October.



3.4.4 Turbidity

Turbidity in the Reservoir was measured with sensors installed on the YSI EXO2 sondes used by DWSP and on the remote profiling buoys. The precision of these sensors is 0.3 FNU, which is approximately the typical result observed in the Reservoir. Therefore, turbidity values observed *in situ* are used for observational purposes only. Data for regulatory compliance are collected by MWRA at various points throughout the distribution system once water leaves the Reservoir.

3.4.5 pH

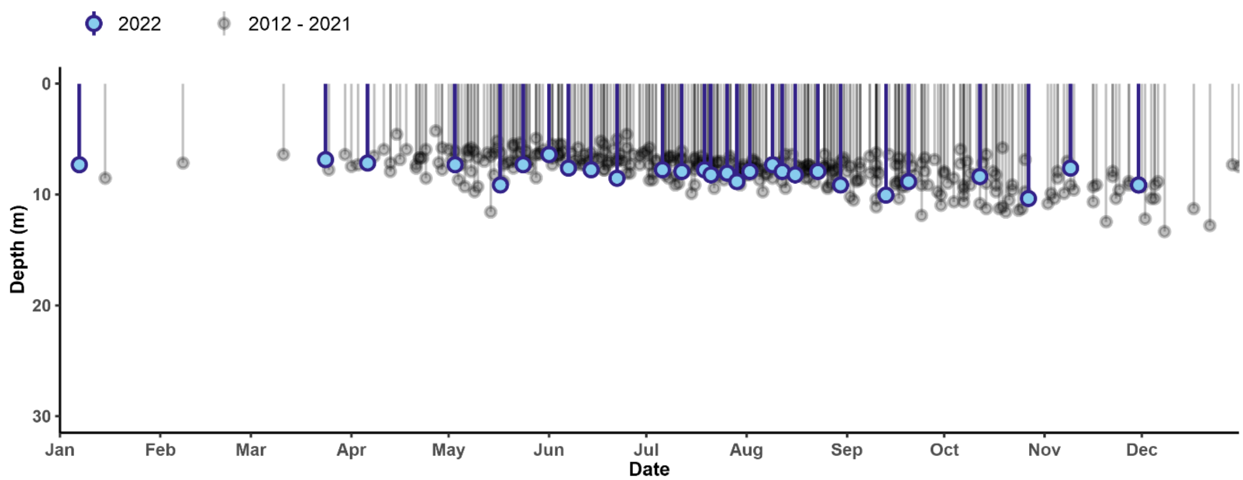
Reservoir pH varies slightly seasonally and vertically through the water column corresponding with changes in photosynthesis and respiration. In 2022, pH ranged from neutral to slightly acidic with a maximum value of 7.9 and minimum value of 5.5. Values less than 6 were recorded below depths of 10 m from late July through October as phytoplankton die off and subsequent carbon release occurred at depth.

pH greater than 7.5 was observed in the epilimnion during spring and early summer, corresponding to elevated diatom density and increased photosynthesis.

3.4.6 Secchi Disk Depth/Transparency

Secchi disk depths in 2022 ranged from 6.4 m to 10.4 m. The maximum value was recorded on October 26 as the growing season came to a close and surface waters mixed with the interflow (Figure 56). Transparency increased briefly in mid-May but remained between approximately 7.5 and 8.5 m through August due to elevated chrysophyte densities. The annual mean Secchi disk depth of 8.1 m remained greater than the reference range of 4 m to 6.1 m for the reservoir ecoregion.

Figure 56: 2022 Secchi Disk Transparency at Basin North



3.4.7 Nutrient Dynamics

The patterns of nutrient distribution in 2022 quarterly samples generally followed those documented in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics[65]. 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.

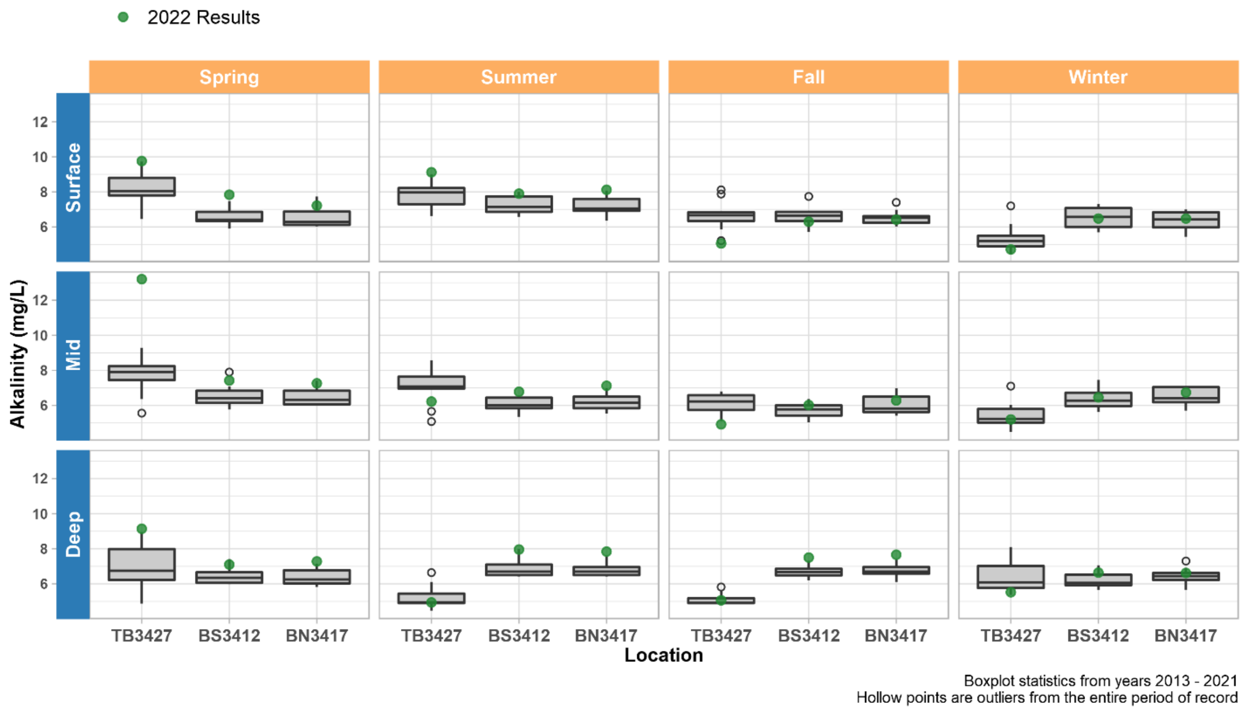
3.4.7.1 Alkalinity

Mean alkalinity across all sites and depths in 2022 was 7.01 mg/L as $CaCO_3$. Alkalinity continued to be elevated overall compared to the period of record (Figure 57). The 2022 maximum alkalinity of 13.2 mg/L as $CaCO_3$ was significantly higher than previous maximums. This value was recorded in May at Thomas Basin which is downstream of several tributaries where elevated alkalinity values have been recorded, likely due to geology of the area. The Quabbin transfer was not established in May, therefore water quality in Thomas Basin was more heavily influenced by spring flow from these tributaries (see Section 3.2.2).

[65] Worden & Pistrang, 2003

Conversely, the annual minimum alkalinity of 4.72 mg/L as $CaCO_3$ was recorded at Thomas Basin in the winter during a period when water at this location was heavily influenced by the Quabbin transfer.

Figure 57: 2022 Alkalinity as $CaCO_3$ in Wachusett Reservoir

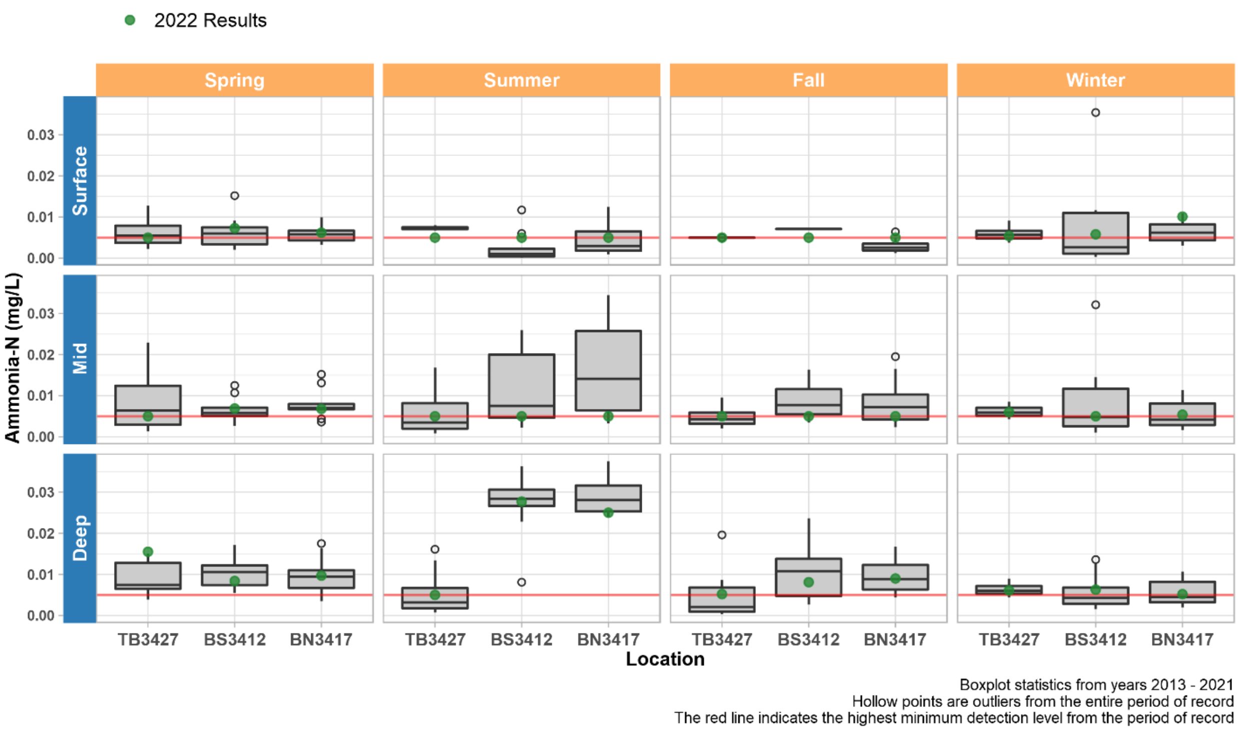


3.4.7.2 Nitrogen Species (Ammonia-Nitrogen, Nitrate-Nitrogen, and Total Kjeldahl Nitrogen)

Ammonia-nitrogen

Ammonia-nitrogen (NH_3-N) levels within the Reservoir remained low, with concentrations ranging from below the detection limit (0.005 mg/L, 44% of samples) to a maximum observed value of 0.028 mg/L (Figure 58). Highest values were present at mid and deep sample depths during the summer when ammonia builds in the hypolimnion. All values were within the historical range and well below regulatory thresholds reservoir-wide (Figure 58). Approximately half (47.8%) of results since 2013 have been lower than the detection limit.

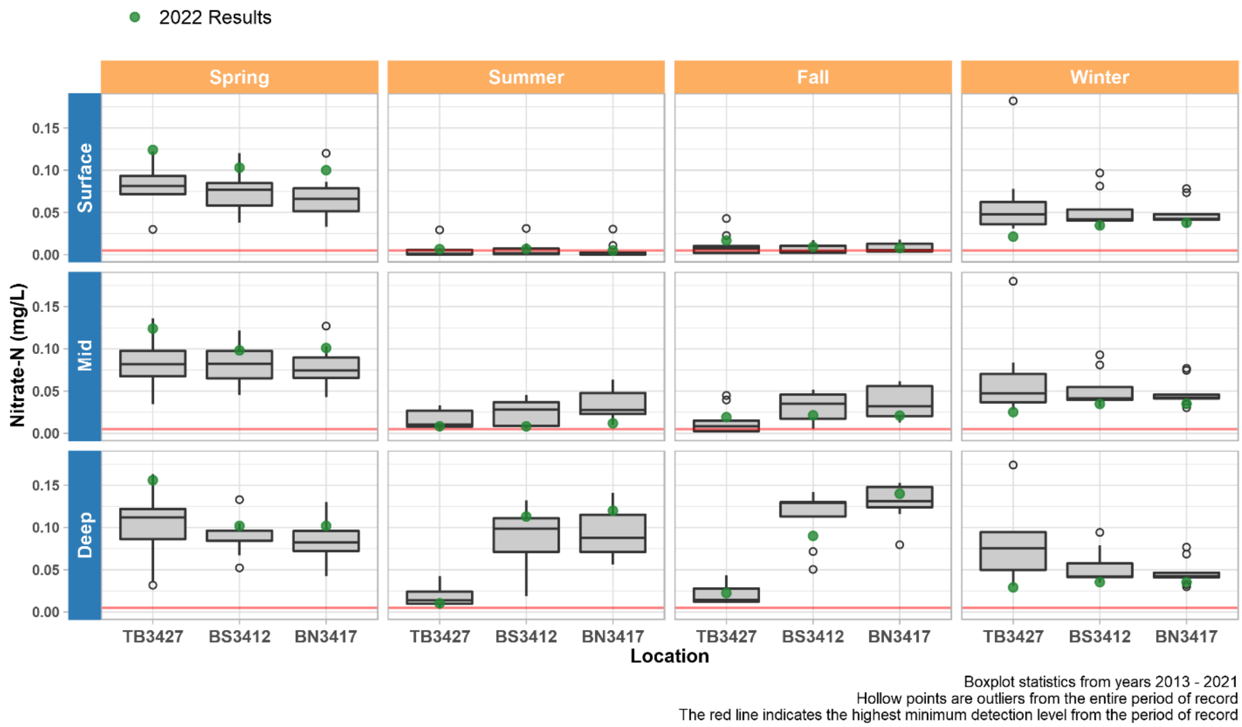
Figure 58: 2022 Ammonia-nitrogen in Wachusett Reservoir



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, 1 sample) to 0.156 mg/L (Figure 59). 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 2022, with spring values at all sites falling between 0.098 and 0.156 mg/L and elevated concentrations were recorded in the hypolimnion at the height of stratification at Basin South and Basin North.

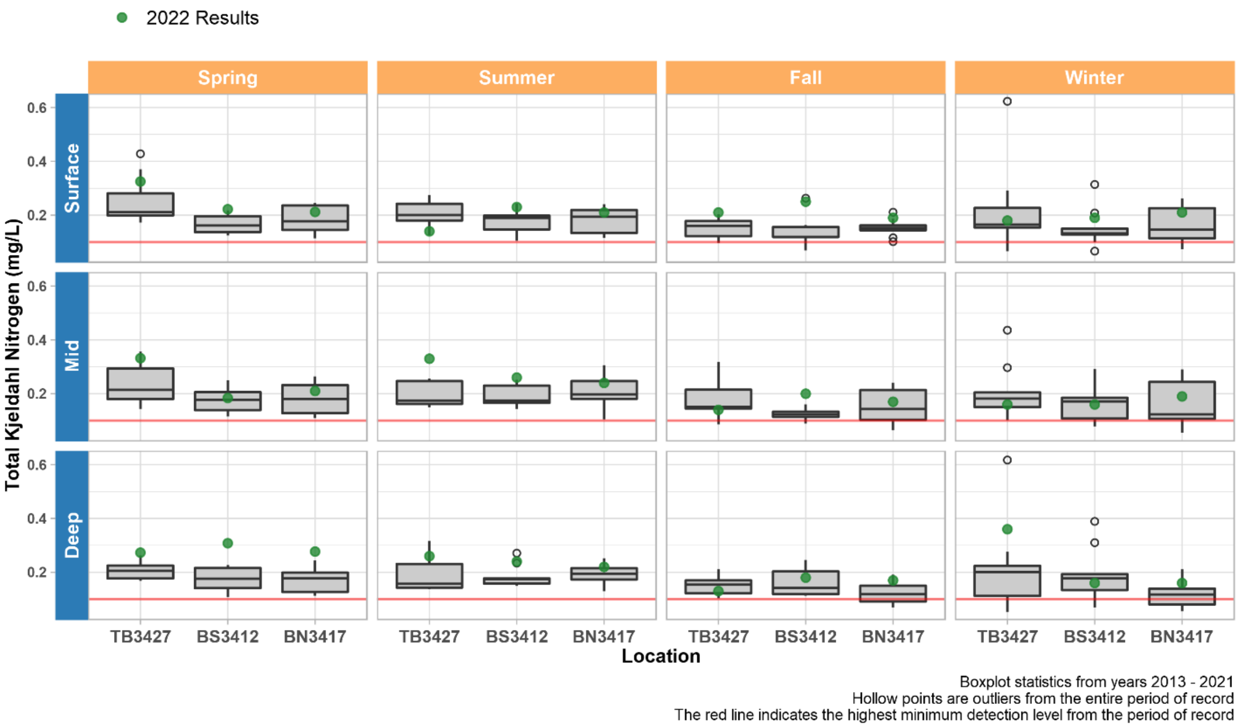
Figure 59: 2022 Nitrate-Nitrogen in Wachusett Reservoir



Total Kjeldahl Nitrogen

Concentrations for Total Kjeldahl Nitrogen (TKN) fell between 0.13 and 0.36 mg/L (Figure 60). Increased TKN at Thomas Basin in the spring was likely due to elevated precipitation and subsequent tributary discharge in April. Concentrations generally remained above historical medians at all sites for the summer sample event but decreased in the fall and winter.

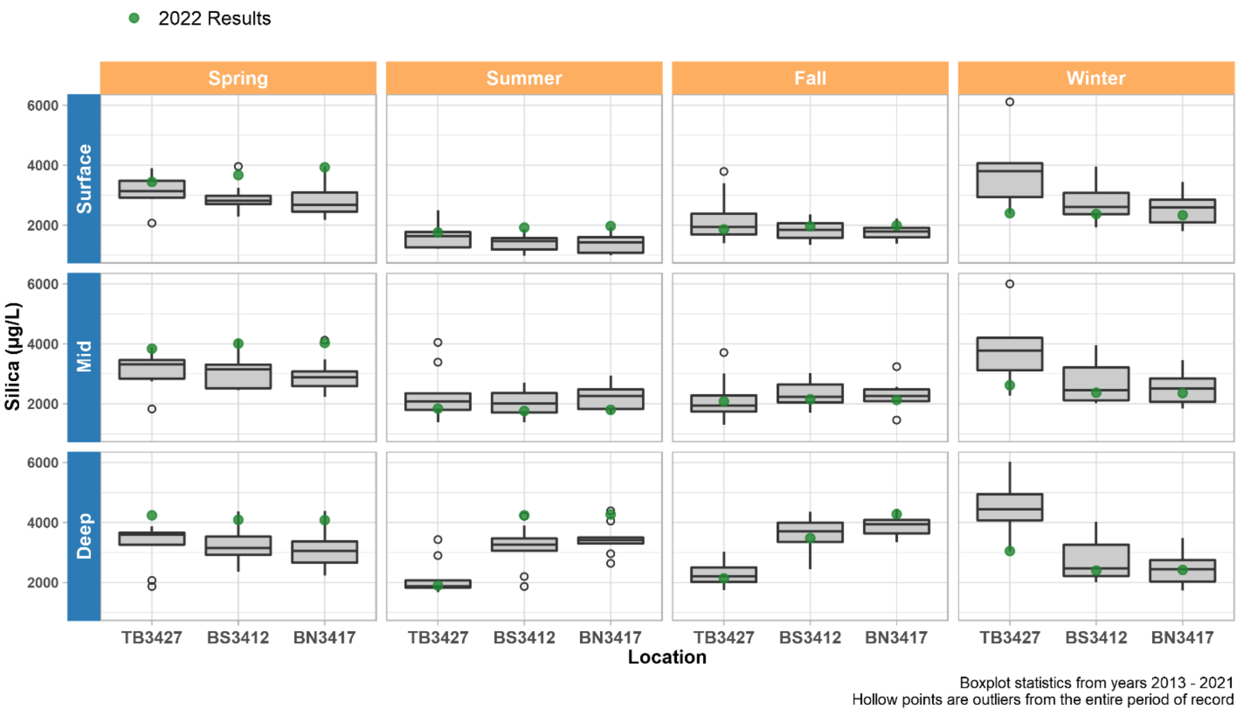
Figure 60: 2022 Total Kjeldahl Nitrogen in Wachusett Reservoir



3.4.7.3 Silica

Silica concentrations were between 1,760 and 4,280 ug/L in 2022 (Figure 61). 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 2022 data where most spring values fell within the 75th percentile. Diatom concentrations were relatively low in 2022, but increased Quabbin transfer volume likely resulted in the decreases in silica observed in 2022 summer, fall and winter data. Water at the Basin South and Basin North deep sites maintained elevated silica values as a higher percentage of native watershed water remained isolated in the hypolimnion through summer and fall.

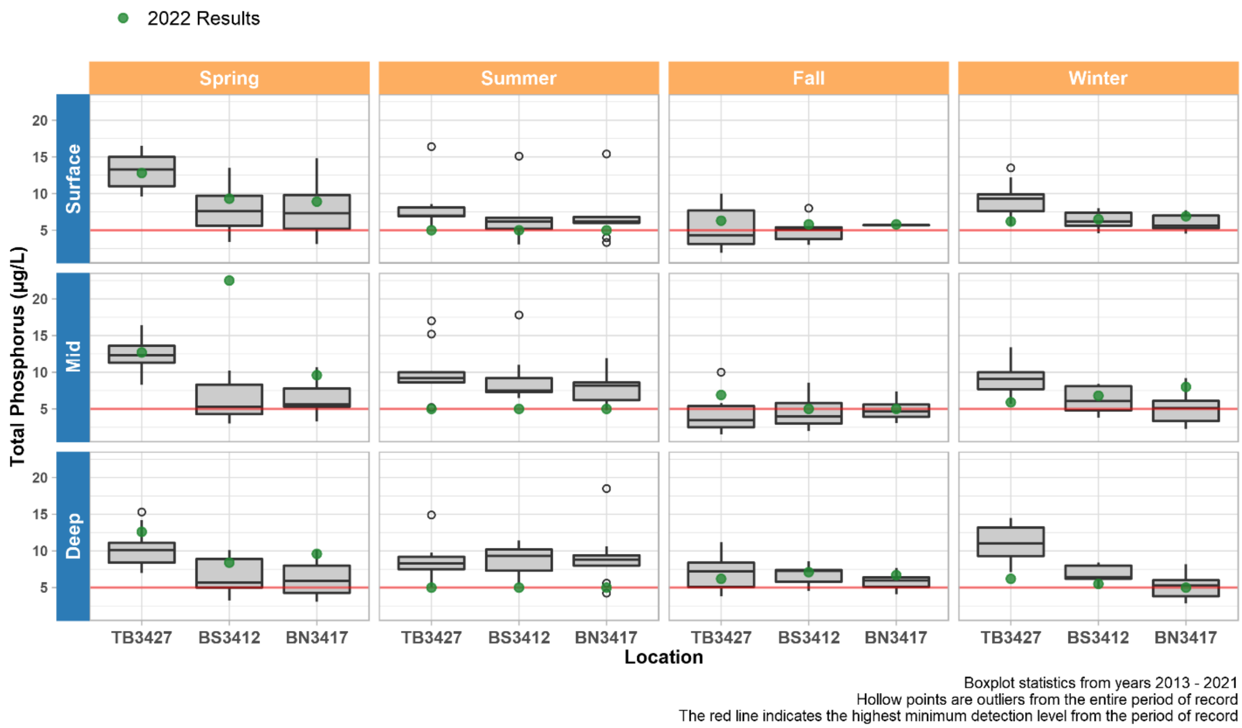
Figure 61: 2022 Silica in Wachusett Reservoir



3.4.7.4 Total Phosphorus

Total phosphorus (TP) results for 2022 were within historical ranges and lower than the 10 µg/L threshold for classification as an oligotrophic water body except for four spring samples (Figure 62). Three of these were collected at Thomas Basin (mean TP of 12.7 ug/L) where water from Stillwater and Quinapoxet Rivers was dominant. The fourth, collected from the Basin South mid-depth is an outlier for the period of record across all sites, at 22.5 ug/L. Spring TP values were above annual medians at all sites but fell to undetectable levels at all sites in the summer and remained at 8.0 ug/L or below for the remainder of the year.

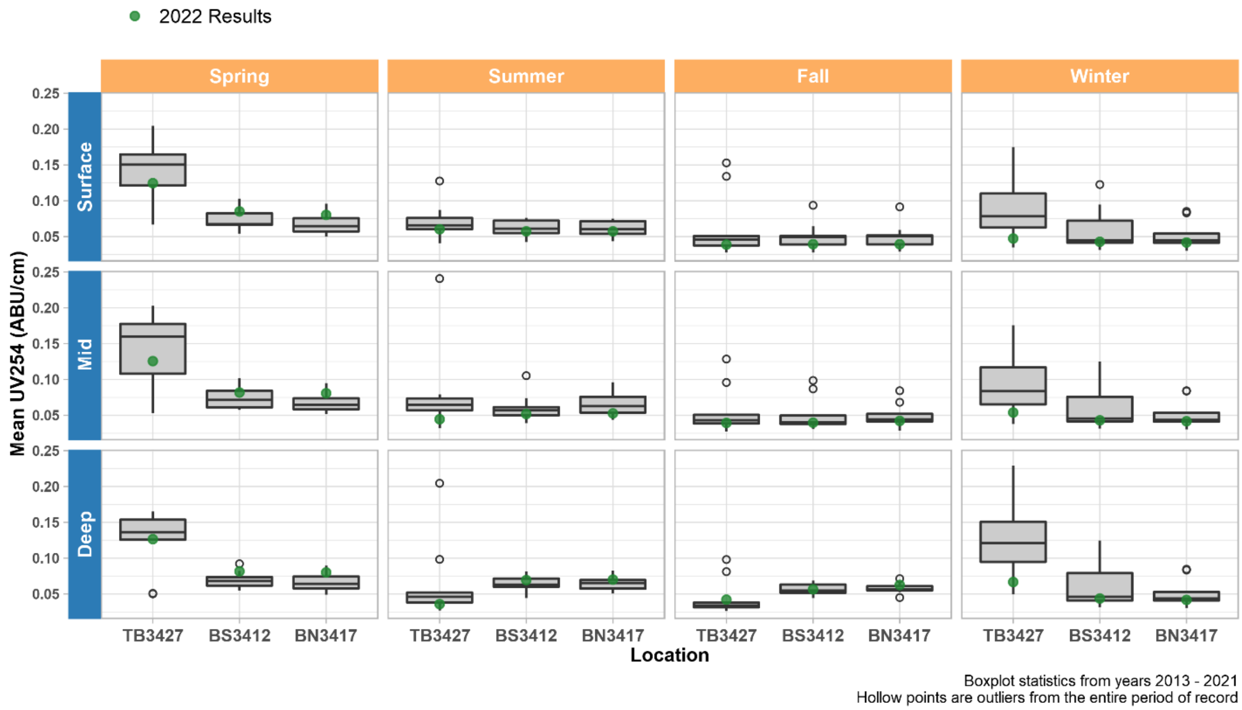
Figure 62: 2022 Total Phosphorus in Wachusett Reservoir



3.4.7.5 UV Absorbance

Measurements of UV_{254} were within historical ranges, between 0.036 and 0.127 ABU/cm. Due to 2022 drought conditions in the region, the influence of the Quabbin transfer was greater in 2022 than in recent years, reducing the influence of organic inputs from the Watershed, therefore bringing UV_{254} values below annual medians at many locations (Figure 63).

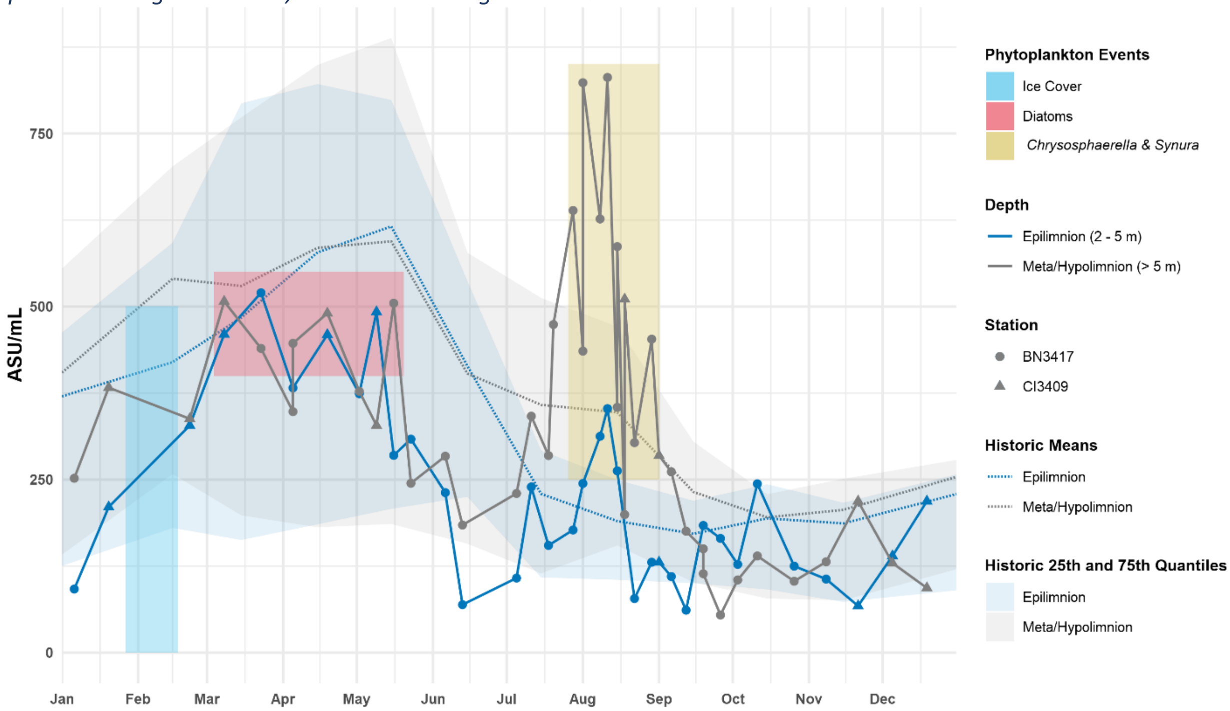
Figure 63: 2022 Wachusett Reservoir UV_{254}



3.4.8 Phytoplankton

A total of 109 phytoplankton samples were collected and analyzed on 39 days during the 2022 season. Ice-free conditions in the north basin of the Reservoir allowed collection of samples from Basin North in January. Ice-in occurred on January 27 resulting in suspension of sampling until February 22. Sampling continued through the end of the year with the last sample collected on December 19. As in 2021, spring diatom densities were low in 2022 compared to the period of record. A six-week period of elevated chrysophyte densities was documented with concentrations of *Chrysosphaerella*, *Synura*, and *Dinobryon* each occurring above monitoring thresholds at least once between July 11 and August 22 (Figure 64, Figure 66).

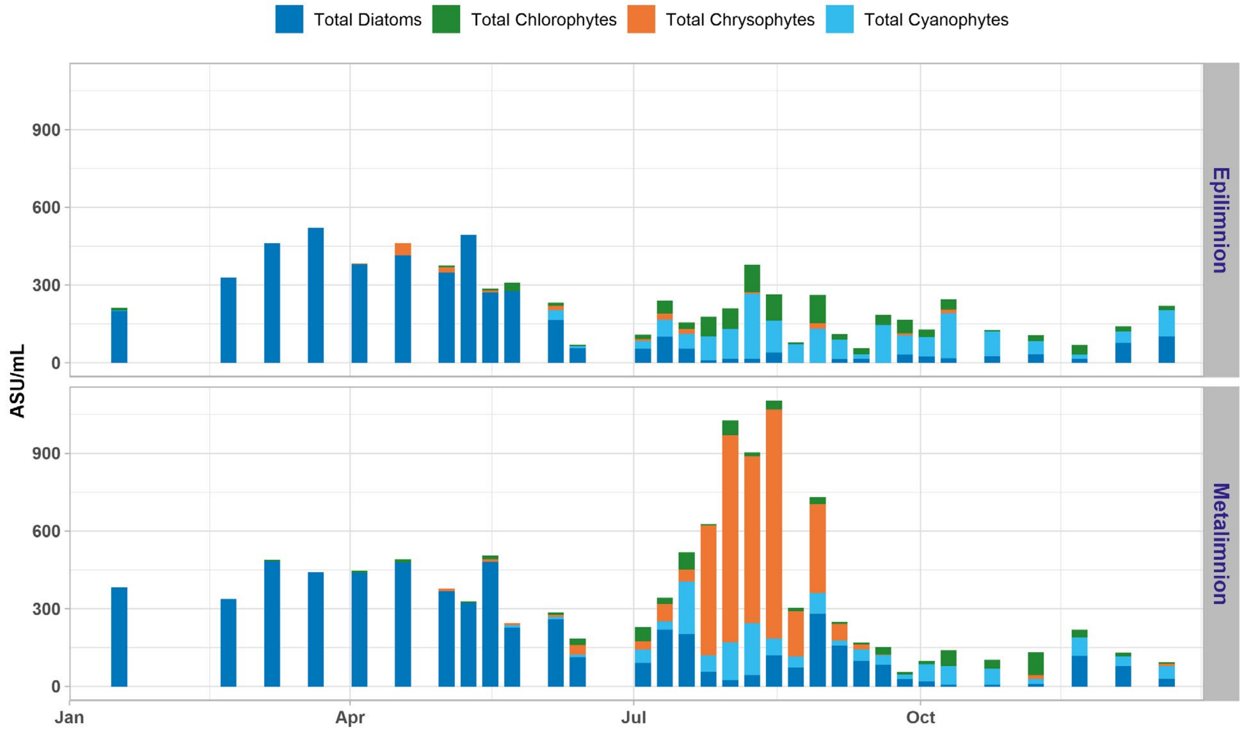
Figure 64: 2022 Wachusett Reservoir Phytoplankton Totals
Epilimnion range is 2 – 5 m, metalimnion range is 5 – 15 m.



The pattern of succession observed in 2022 followed the seasonal changes in phytoplankton community composition and density typically observed in the Wachusett Reservoir. Community composition by group is displayed in Figure 65.

Figure 65: 2022 Phytoplankton Community Composition

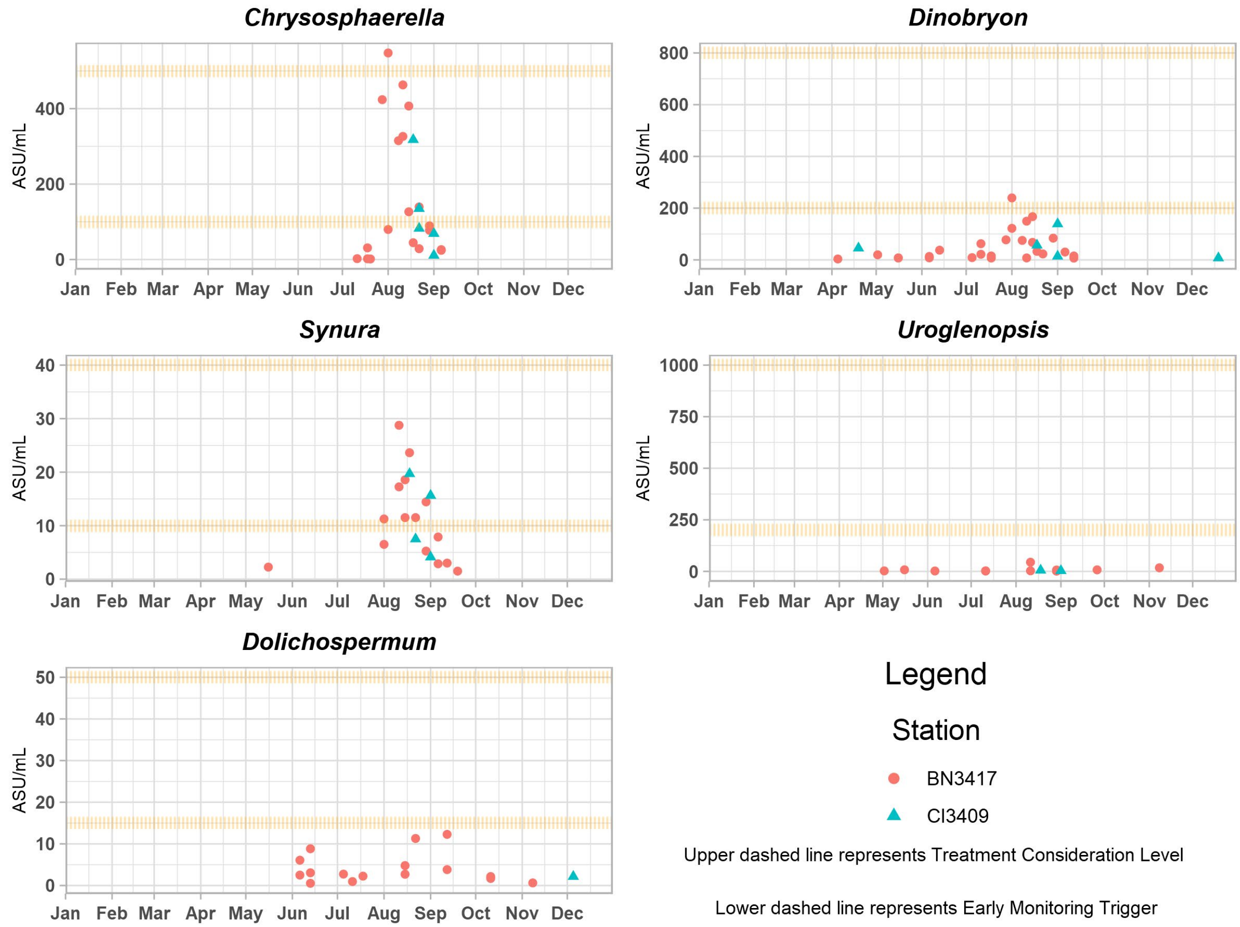
Reported as weekly maximums for Basin North and/or Cosgrove Intake.



Total densities were comprised almost entirely of diatoms from January through June. The maximum annual diatom density of 520 ASU/mL was recorded at 3 m on March 23 at Basin North. This was the fourth-lowest annual diatom maximum recorded for the period of record (1989-present). Concentrations remained above 400 ASU/mL until mid-May when waters started to warm, and stratification was initiated.

Phytoplankton densities decreased through June, then increased above 400 ASU/mL in the metalimnion as *Chrysosphaerella* densities rose and exceeded the early monitoring trigger of 100 ASU/mL for six weeks starting on July 13. Elevated concentrations of this taxa continued through late August. Elevated densities of *Synura* were also recorded during this timeframe, with a peak concentration of 28 ASU/mL observed on August 11. The early monitoring trigger of 200 ASU/mL for *Dinobryon* was exceeded once, on August 1 (Figure 66). Despite these densities, no taste and odor complaints were received from MWRA during this period. Given these results, the early monitoring triggers will be reevaluated for 2023.

Figure 66: 2022 Observed Concentrations of Nuisance Phytoplankton Taxa in Wachusett Reservoir



Dolichospermum was present in samples sporadically from June through December but remained below the 15 ASU/mL threshold (Figure 66). Areas of the Reservoir were visually surveyed for *Dolichospermum* in the fall during the cyanobacteria bloom in West Waushacum Pond which is approximately 2 miles upstream of Stillwater Basin (see Section 3.2.9.4). No surface aggregations were observed in the Reservoir at this time or throughout 2022.

Overall cyanobacteria levels were similar to those observed in recent years, increasing in late July and periodically reaching densities above 100 ASU/mL through turnover. The maximum total cyanobacteria density of 250 ASU/mL was recorded from Basin North (3 m) on August 8.

3.4.9 Zooplankton

A total of 48 zooplankton samples were collected in conjunction with the 2022 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 2022 included the *Salvelinus namaycush* (Lake Trout) mark-recapture study, the investigation for *Osmerus mordax* (Rainbow Smelt) spawning activity, the Creel Survey, and electrofishing for *Salmo salar* (Atlantic Salmon) and *Salvelinus fontinalis* (Eastern Brook Trout) in Gates and Malden Brook. Additionally, DWSP and MassWildlife cooperated in response to an introduction of *Oreochromis niloticus* (Nile Tilapia). Each of these monitoring programs involved cooperation with MassWildlife.

3.4.10.1 Salvelinus namaycush *(Lake Trout)*

The Wachusett Reservoir *S. namaycush* mark-recapture study continued in 2022. 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 (see Section 3.4.10.4). 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[66].

To date, 1,021 *S. namaycush* have been captured during fall sampling efforts between 2014 and 2022, and 832 of these individuals have been assigned a unique ID, tagged, and released (Table 31). From 2014-2022, there have been 105 recapture events and 49 individual tagged fish have been recaptured, five of which have been recaptured at least twice. In 2022, there were ten recapture events, 105 fish that had not been previously caught were tagged, and 119 fish were caught in total. Four 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 mean weight and mean length of all fish captured in 2022 were the third and second lowest on record, respectively (Table 31).

Table 31: *S. namaycush* Annual Caught and Tagged Results

Year	Caught	Tagged	Caught Mean Weight (g)	Caught Mean Length (mm)	Not Tagged
2014	110	102	2,067	582	8
2015	161	147	1,427	547	14
2016	67	60	1,312	553	7
2017	83	76	1,016	515	7
2018	71	65	1,402	541	6
2019	162	150	1,422	538	12
2020	114	NA	1,367	540	114
2021	134	127	1,172	535	7
2022	119	105	1,282	533	4
Total	**1,021**	**832**	**1,377**	**542**	233

In 2022, 87% of *S. namaycush* captured in Wachusett Reservoir were males and 13% were females. The proportions of the total catch in 2022 were consistent with the results of previous years (Figure 67). Results show that reservoir females are often larger and heavier at capture than males (Figure 68). Evidence suggests that male *S. namaycush* are caught more frequently in gill nets set during the spawn

[66] Thill, 2014

because they spend more time on the spawning grounds searching for females[67]. 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[68].

Figure 67: Proportion of Total *S. namaycush* Catch by Sex

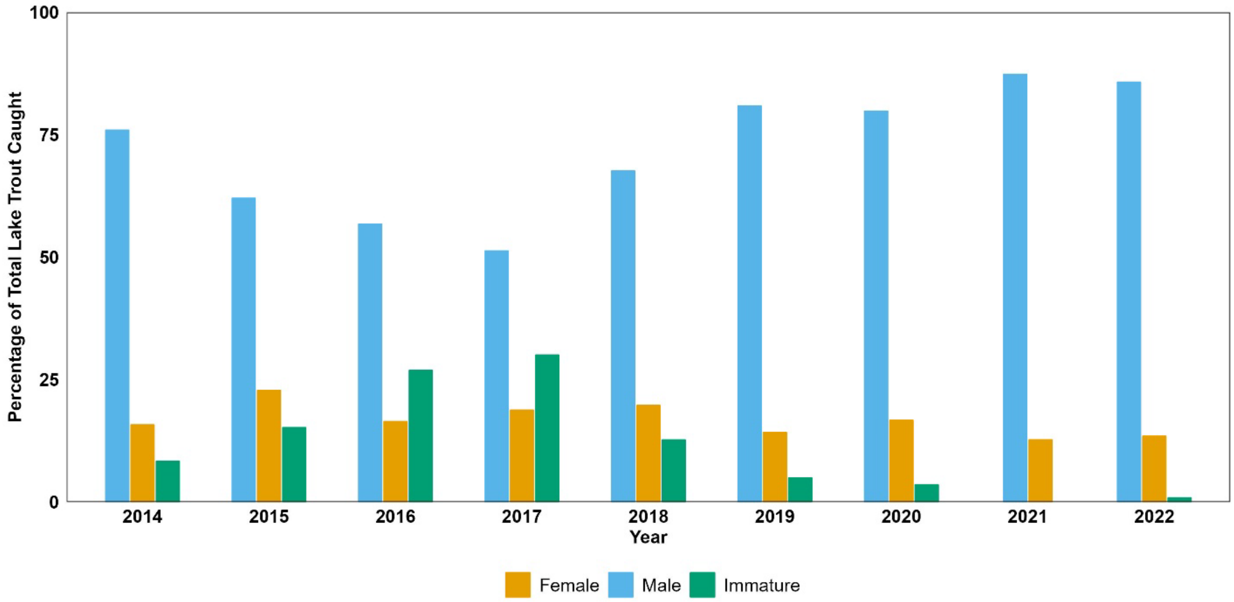
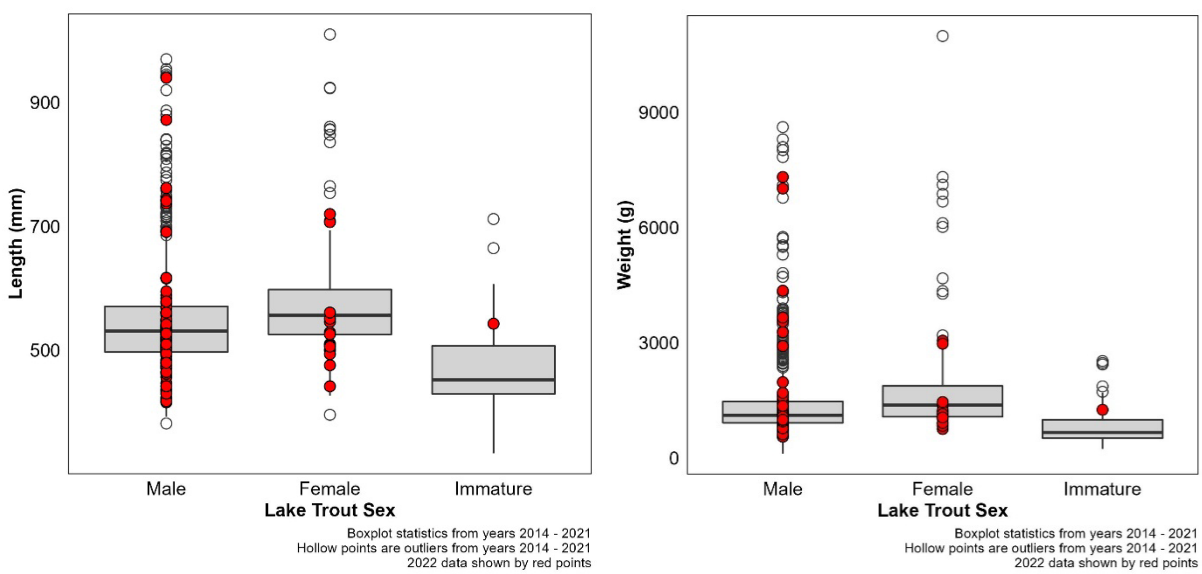


Figure 68: Wachusett *S. namaycush* Length (left) and Weight (right)



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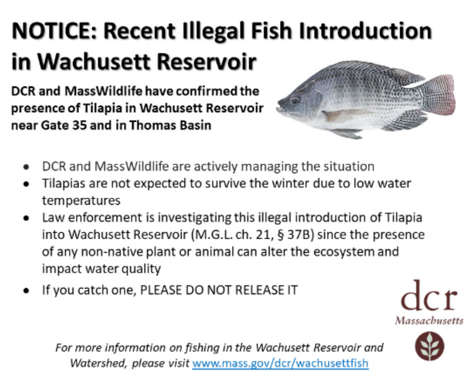
[67] Binder et al., 2016
[68] Binder et al., 2014

3.4.10.2 Illegal Introduction of Non-native Species – Oreochromis niloticus *(Nile Tilapia)*

On July 20, DWSP Ranger and DFW staff received a report that a fish believed to be *Oreochromis niloticus* (Nile Tilapia) had been caught and removed from the reservoir by an angler. A specimen was brought to DFW, and the species identity was confirmed. Based on the angler report, DWSP Aquatic Biologists surveyed Metropolitan Brook Cove on July 22 and confirmed the location of approximately nine schooling *O. niloticus*. Additional reports gathered through DWSP monitoring of social media accounts related to fishing at Wachusett Reservoir led to further surveys for *O. niloticus* in Thomas Basin. These sightings were confirmed on July 25 by DWSP staff; two small coves contained approximately 31 fish. No additional *O. niloticus* were found during a reservoir-wide survey on July 26. In total, an estimated 40 Tilapia were dispersed across three locations in the Reservoir.

In response, DWSP and DFW held a joint meeting to discuss concerns and removal options. Tilapia may have an impact on water quality by increasing turbidity during feeding and altering established food webs. However, these fish are not cold tolerant and therefore should not be able to establish a population in the reservoir. Nevertheless, DWSP and DFW determined removal of the fish should be attempted. Initial removal attempts with seine nets took place at Metropolitan Brook Cove on August 5 and four Tilapia were removed. On August 9, informational signs were posted at several kiosks near shoreline fishing access gates. These signs requested that any Tilapia caught by anglers not be released (Figure 69). DWSP and DFW staff attempted removal in Thomas Basin on August 12 with two electrofishing boats. A total of 13 Tilapia were removed during this attempt. A final removal attempt on August 18-19 using gillnets was unsuccessful. During a shoreline survey on September 29, three Tilapia were observed in Stillwater Basin. DWSP and DFW remain confident that water temperatures below 4 °C will kill any remaining *O. niloticus*[69]. DWSP will survey the shoreline in the spring of 2023 and will investigate any further reports of *O. niloticus* in the Reservoir.

Figure 69: Educational Signage for Tilapia



3.4.10.3 Other Fish Species

As a part of annual monitoring for *Osmerus mordax* (Rainbow Smelt) spawning activity, DWSP biologists investigated shoreline areas throughout the month of April. These surveys coincided with the creel survey, which occurred during the same period. No evidence of *O. mordax* schools, eggs, or specimens were found, and no reports of spawning activity were received from anglers. *O. mordax* are a coldwater fish species with preferences for deep, oligotrophic lakes, and are considered a valuable prey item for

[69] Azaza et al., 2007

salmonids[70]. This coldwater species is likely an important component of the Wachusett Reservoir food web and efforts to monitor the Wachusett Reservoir population and document spawning activity will continue annually.

On August 10, DWSP staff assisted MassWildlife with backpack electroshocking along several stretches of Malden Brook, including the areas upstream of the Thomas Street culvert, downstream of Malden Road, and upstream of the dam at Malden Road. The primary purpose of the survey was to evaluate *Salvelinus fontinalis* (Eastern Brook Trout) in Malden Brook, to support efforts to remove the Malden Brook Dam at Edwards Pond. *S. fontinalis*, *Rhinichthys atratulus* (Blacknose Dace), and *Etheostoma olmstedi* (Tessellated darter) lengths were also collected during the survey.

On September 15, DWSP staff assisted MassWildlife with backpack electroshocking along a stretch of Gates Brook, downstream of Worcester Street in West Boylston. The primary purpose of the surveys was to collect *Salmo salar* (Atlantic Salmon) and *S. fontinalis* length and weight. Species presence, total length, and weight data for *S. salar*, *S. fontinalis*, and *R. atratulus* were collected during the survey.

3.4.10.4 Creel Survey

A creel survey is a survey of anglers designed to collect information on fishing effort, species catch, and fish harvest. A creel survey was conducted on the Wachusett Reservoir for the entire duration of the 2022 fishing season, which ran from April 2 to November 30. DWSP and MassWildlife conduct an angler creel survey every five years, with the previous survey completed in 2017. During the 2022 creel survey, 2,027 anglers were interviewed over the course of 101 survey days out of a possible 242 fishing days. The total number of anglers interviewed is an increase in comparison to previous survey years. The complete results of the 2022 survey will be published in a separate report.

3.4.11 Bacteria

Reservoir bacteria samples were collected on 15 days in 2022 at 23 reservoir transect locations (Figure 3). Ice cover on Wachusett Reservoir prevented sampling for bacteria between mid-January and early March. Elevated *E. coli* concentrations were observed in January in at transects points south of the narrows and at one at point near Crescent Island (F3). Elevated bacteria were also detected during March sampling, though only at one or two transect points, and again in June, August and September at point F3, which is a popular bird loafing area with exposed rocks. 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. The highest result in 2022 at location A3 (closest to the Cosgrove Intake) was 2 MPN/100 mL on October 27 and December 2. All reservoir transect bacteria results for 2022 are provided in Table 32.

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[70] Hammers, 2018

Table 32: Reservoir Bacteria Transect Results for 2022 – *E. coli* (MPN/100 mL); Sampled at 0.1 – 0.3 m

Date	A3*	B2	B3	C1	C3	C5	D1	D2	D4	E2	E4	F2	F3	F4	G2	H2	I2	J2	J3	J4	K2	M1	N1
Jan 06	1	1	1	1	1	1	2	1	3	1	2	5	11	1	4	9	22	11	12	43	59	36	22
Mar 17	1	5	2	1	4	1	4	1	12	9	3	4	2	3	1	1	6	1	1	1	3	1	1
Mar 31	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	2	4	50	4	3	1
Apr 11	1	1	1	1	1	1	1	1	1	1	1	1	6	1	1	1	1	1	1	5	1	10	10
May 19	1	1	1	1	1	1	1	1	2	2	2	1	2	1	1	1	1	1	1	3	2	1	3
Jun 23	1	2	1	1	1	1	1	1	1	1	1	5	18	1	1	1	1	1	1	1	1	1	1
Jul 28	1	2	1	1	1	6	2	1	1	1	1	1	1	1	—	1	1	1	1	1	1	1	1
Aug 24	1	3	2	1	2	2	4	1	3	2	2	1	12	5	3	1	1	1	1	2	1	1	1
Sep 29	1	3	1	1	1	2	1	1	1	1	1	3	10	3	1	1	1	1	1	1	1	1	3
Oct 13	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	4	1	1
Oct 27	2	2	6	1	1	1	1	1	1	1	1	3	2	1	1	2	21	1	19	6	2	12	1
Nov 03	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	2	2	5	4	2	1
Nov 17	1	1	1	1	1	3	1	1	1	2	1	1	1	2	3	5	9	2	48	25	43	9	16
Dec 02	1	1	1	2	1	1	1	1	1	1	1	2	1	1	1	1	3	10	12	29	16	18	9
Dec 21	2	1	4	1	1	1	4	1	2	10	9	2	70	45	1	5	6	5	11	27	16	6	15

* Cosgrove Intake

Bacteria samples were collected seven days per week by MWRA staff from Carroll Water Treatment Plant (CWTP) at Walnut Hill in Marlborough to demonstrate regulatory compliance. The SDWA regulations for drinking water require that a minimum of ninety percent of all source water samples (in any six-month period) contain less than 20 MPN/100 mL fecal coliform. All 365 samples collected at CWTP in 2022 contained less than the standard, with a maximum concentration of 7 MPN/100 mL on July 20. Most samples (69%) did not contain any detectable bacteria. DWSP has put considerable time and effort into implementing a rigorous bird harassment program, and the results in 2022 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[71]. It is updated periodically to reflect changes in AIS composition within and in proximity to the Reservoir.

Table 33. Aquatic Invasive Species in or Near Wachusett Reservoir

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

AIS were first recorded in Wachusett Reservoir in the late 1990s and have been actively managed since 2002. Early years of management focused on *Myriophyllum spicatum* (Eurasian water-milfoil) and *Cabomba caroliniana* (fanwort). In recent years, *Myriophyllum heterophyllum* (variable water-milfoil) was added as a target species. Several minute and cryptic AIS, including *Glossostigma cleistanthum* (mudmat) and *Elatine ambigua* (Asian waterwort), have also been documented in the Reservoir and are monitored on a routine basis as part of an overall AIS detection and management program.

The following sections of this report provide details of AIS management activities undertaken in the Reservoir, elsewhere in the Watershed, and near the Reservoir during 2022 as well as those planned for 2023.

3.5.1 Wachusett Reservoir – Invasive Macrophyte Control Program

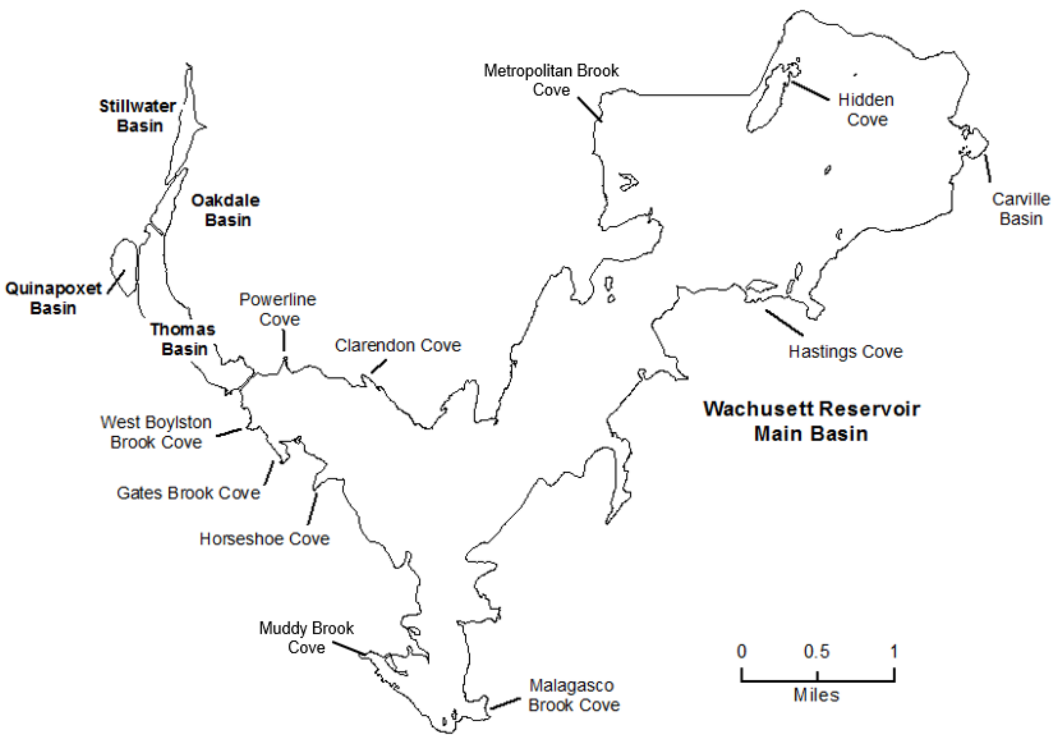
M. spicatum was first identified in the Wachusett Reservoir system in August 1999. The plants were initially isolated to Stillwater Basin; however, over the next several years, distribution extended southerly, in the direction of water flow, progressing through Oakdale Basin, into Thomas Basin and the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

Removal of *M. spicatum* and *C. caroliniana* via hand-harvesting was initiated in Oakdale Basin in 2002. Despite these efforts, *M. spicatum* and *C. caroliniana* gradually spread throughout Thomas Basin and into several coves of the main basin (Figure 70). As new infestations are identified, these areas are also targeted in annual removal efforts. Diver Assisted Suction Harvesting (DASH) was first implemented in 2012 and has continued as the primary control strategy for dense patches of plant growth. Hand-harvesting is used in areas where target species growth is less dense. An extensive DASH project in Stillwater Basin was initiated in 2013 to reduce the potential for re-infestation from dense growth in this uppermost basin of the Reservoir. Likewise, management of VLM reservoir-wide, including in Quinapoxet

[71] Trahan-Liptak & Carr, 2016

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 70: Locations of 2022 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 (ESS Group, Inc.)
- Scouting the entire littoral zone of Wachusett Reservoir every five years (completed in 2012, 2016 and 2021)

Highlights of management in 2022 include the following:

- Low density of *M. spicatum* and *C. caroliniana* continued in the upper basins (Figure 71).
- Removal of *M. heterophyllum* continued in all managed areas of the Reservoir. Target plant density in areas where *M. heterophyllum* has occurred for multiple years (e.g., Hastings Cove, Carville Basin) continues to decrease requiring less diver effort (Figure 73).

- *M. heterophyllum* historically present in Muddy Brook Cove was first managed in 2021. No plants of this species were observed during 2022 management efforts.
- In 2021, DASH was implemented to remove a pioneer infestation of *M. heterophyllum* in Metropolitan Brook Cove discovered during DCR's shoreline surveys. This rapid response appears to have been effective, as these plants were not observed during surveys in 2022.
- A total of approximately 23,300 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 72).
- Transition from reporting biomass removal in gallons to reporting number of individual plant stems removed by species continues in Stillwater Basin and is a sign of remarkable success in this program. Large beds of *M. heterophyllum* plants removed are still reported in gallons. Lower water levels in 2022 resulted in higher biomass of AIS in typically shallow areas at the north, east, and south portions of the basin. Overall, however, native vegetation continues to repopulate previously dense areas of AIS.

Figure 71: *M. spicatum*, *C. caroliniana*, and *M. heterophyllum* Removed from Wachusett Reservoir 2003 to 2022
Panel A and B: Plot includes totals removed from Oakdale, Thomas, and Powerline Coves, Panel B: Plot includes totals for M. heterophyllum *stems and gallons which are used depending on plant density.*

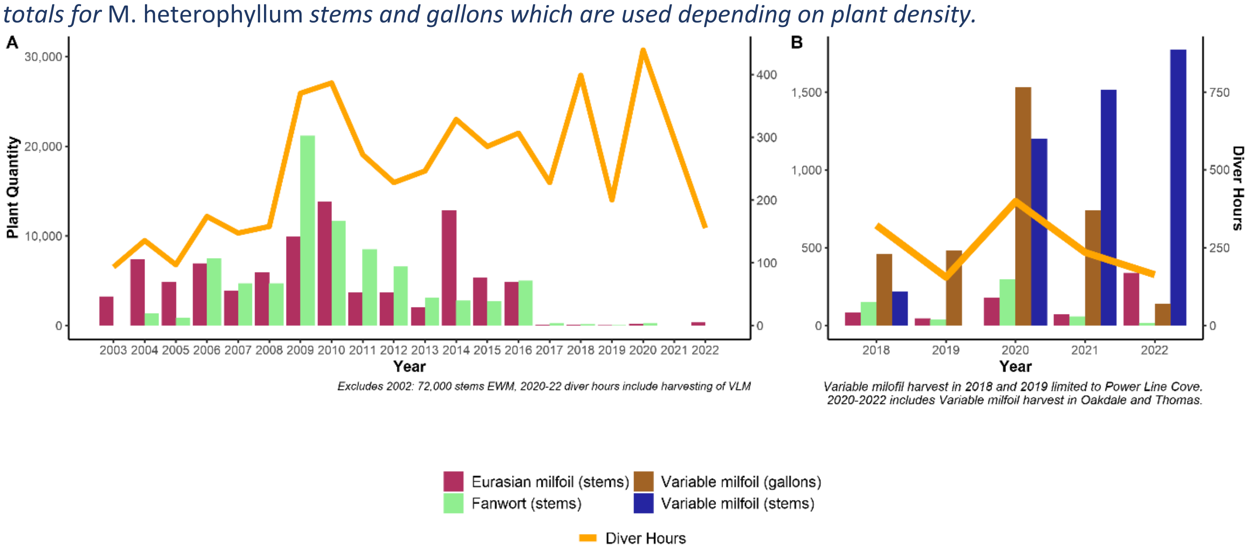


Figure 72: *M. spicatum* and *C. caroliniana* Removed from Quinapoxet Basin 2017 – 2022

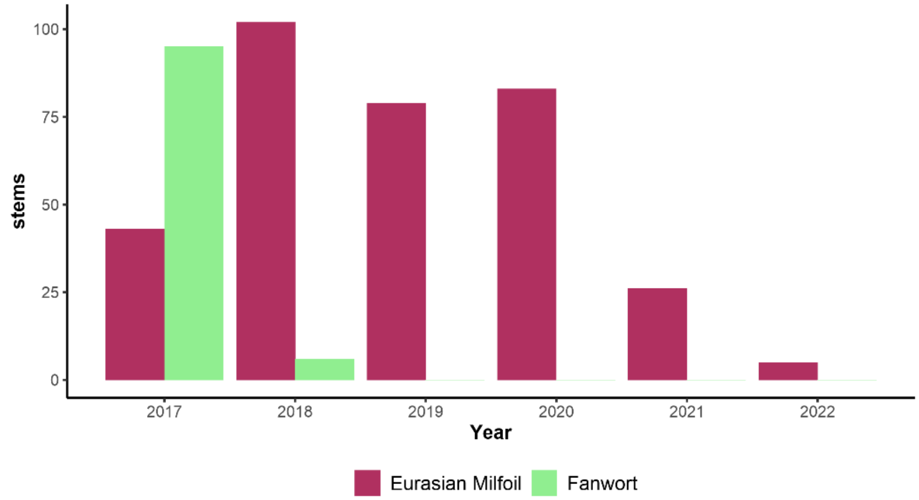
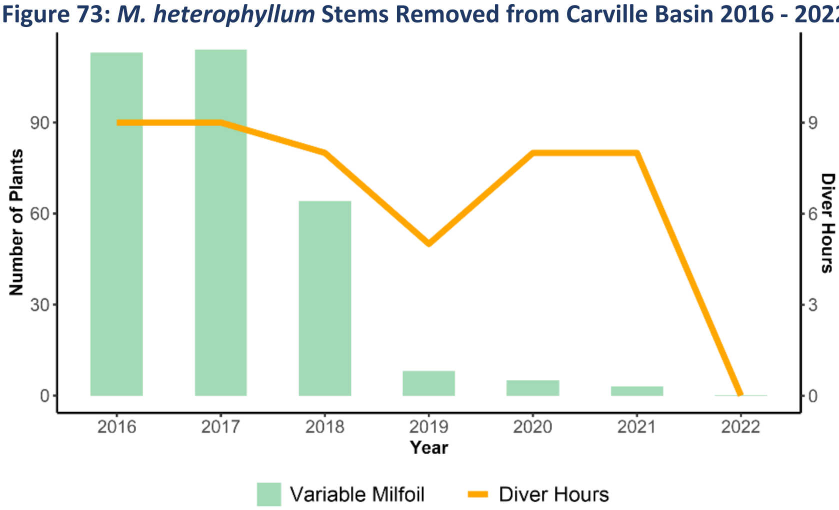


Figure 73: *M. heterophyllum* Stems Removed from Carville Basin 2016 - 2022



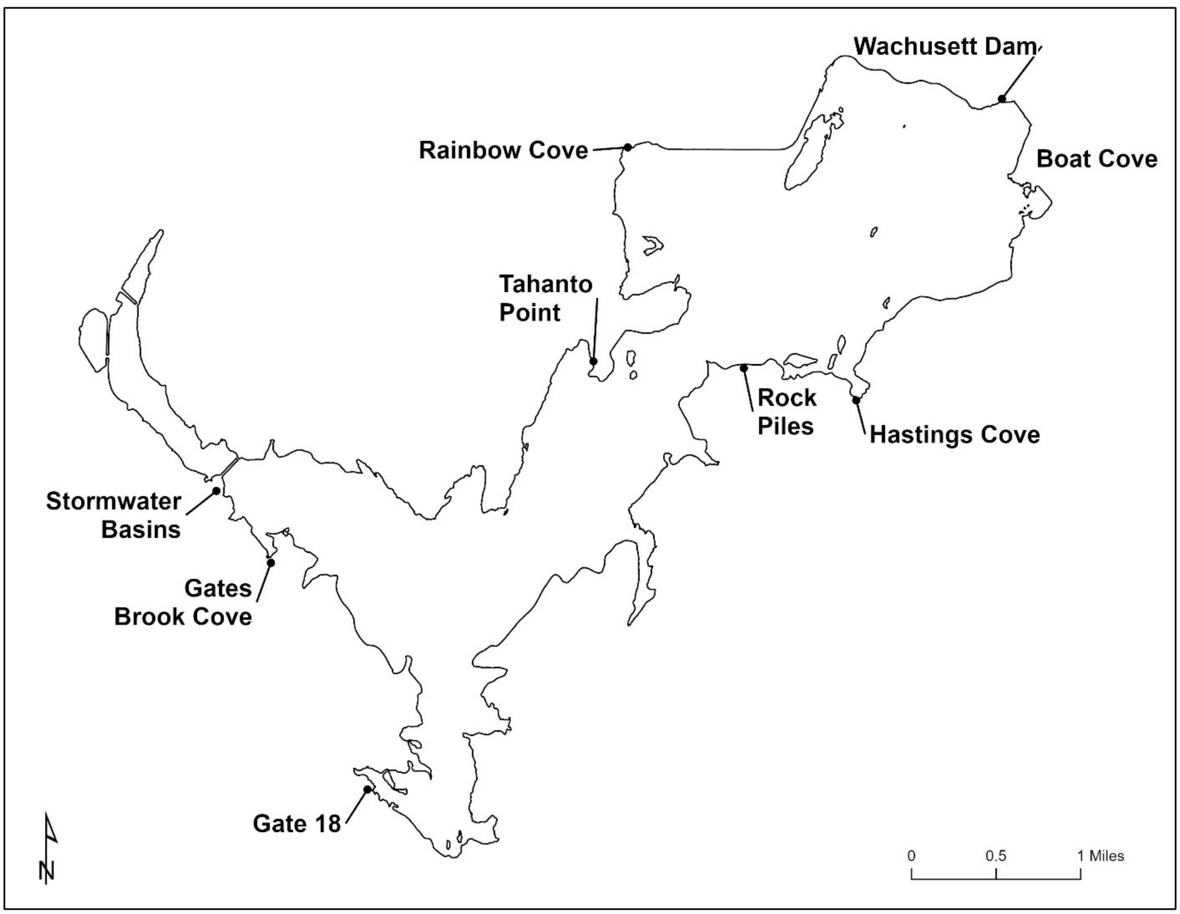
3.5.1.1 Phragmites Management

DWSP EQ staff surveyed and managed *Phragmites australis* (common reed) at 20 locations around the Wachusett Reservoir shoreline in 2022 (Table 34, Figure 74). Manual and mechanical removal were the primary 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. Active management in 2022 included one event on September 7.

Table 34: Shoreline *Phragmites australis* at Wachusett Reservoir

Stand ID	Initial Area (ft^2)	First Documented	2022 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	Hand pull
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	Absent
Storm Water Basins (x3)	19	2017	Hand pull
Rock Piles	112	2018	Absent
Dam	6	2018	Absent
Gate 18 Storm Water Basins	10	2021	Seed removal

Figure 74: *Phragmites australis* Stand Locations Around Wachusett Reservoir



This management effort and timing was the same as 2021, when management occurred once, on September 8. The reduction in management effort in 2021 and 2022 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 and stem density appeared to be reduced, and the number of seed heads remain limited. The low number of seed heads late in the growing season may be indicative of the decreasing condition of the stands, as they typically form July to September[53]. As in 2021, 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 or Point B, the Wachusett Dam, Rock Piles, and two Hastings Cove locations. The stand at Boat Cove A appears drastically reduced. A new stand was observed between the Boat Cove A stand and Carville Basin; this new stand is Boat Cove D, and it was cut during September 9 management. Management in 2023 will include monthly monitoring from June to October, with monthly management with physical and mechanical methods as needed.

3.5.2 Wachusett Reservoir – Vegetation Monitoring

3.5.2.1 Contracted Aquatic Macrophyte Surveys

MWRA contracts with TRC, formerly ESS Group, Inc., to carry out point-intercept surveys of DWSP/MWRA source and emergency reservoirs. No new AIS were discovered in Wachusett Reservoir during the 2022 survey and substantial increases in distribution and density were not observed. *Glossostigma cleistanthum* (mudmat) was observed at nine more locations in 2022 than in 2021 but well below the 63 locations observed in 2020. *G. cleistanthum* density does appear to be increasing where it occurs, with TRC reporting an increase in year-over-year density at 31 sites. Water quality impacts from this minute non-native are assumed to be limited. TRC reported a change in the most frequently encountered native aquatic species in Wachusett Reservoir; from *Potamogeton perfoliatus* to *Elodea canadensis*. Overall, TRC reports that aquatic plant cover, density, and biovolume have remained stable over the past several years[72].

3.5.3 Supplemental Invasive Macrophyte Control Activities

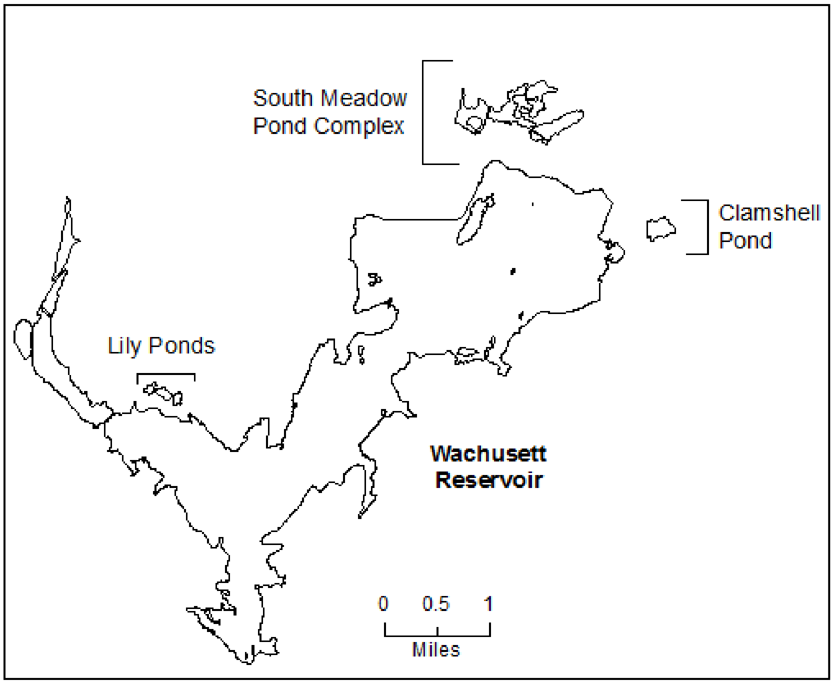
Additional activities were conducted in 2022 outside of Wachusett Reservoir in conjunction with the main components of the in-reservoir invasive control program. Details of these activities are presented below.

3.5.3.1 Management of AIS Outside of Wachusett Reservoir

AIS, including several novel species not found in Wachusett Reservoir have been identified in water bodies close to the Reservoir (Figure 75). 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 close 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.

[72] TRC, 2023

Figure 75: Locations of Local Ponds Managed for AIS



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.

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 2022, 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 26 to approximately seven 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. An additional invasive species, *Najas minor*, was observed by TRC, bringing the known submerged AIS total present in South Meadow Pond to four (*Hydrilla, M. heterophyllum, Najas minor*, and *P. crispus*). This species will be added to the ongoing management program.

Based on results of the 2022 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*, and *M. heterophyllum* anticipated. The key component of this management program will be the continued 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[73].

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 2022, approximately 30 *T. natans* plants were removed during the June survey. *T. natans* was not observed during any of the other surveys. 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 (Brittle Naiad) and *M. spicatum* were identified in the Lily Ponds in 2015. Due to the ponds' locations, approximately 600 feet (180 m) from the reservoir shoreline, a rapid response plan was initiated in fall 2015 and management has continued annually. *M. spicatum* has not been observed since the initial diquat treatment in 2015. *N. minor* remains in each pond, likely due to a seed bed which persists in sediment.

In 2022, *N. minor* in all three ponds was managed in late June via application of the systemic herbicide fluridone. Water levels in all three ponds remained low throughout the season due to drought conditions, also limiting the area where these plants could germinate. *N.* minor was not observed in subsequent surveys of the ponds in 2022.

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

4 Conclusions and Recommendations

4.1 Wachusett Tributary Water Quality

Routine tributary monitoring results for bacteria in 2022 were consistent with prior years, with several wet weather events causing elevated concentrations above the 235 MPN/ 100 mL Class A surface water standard. All monitoring locations had annual geometric means below the 126 MPN/100mL threshold, except Gates Brook 4 and West Boylston Brook. Elevated bacteria concentrations remain a problem at these two locations as well as in Asnebumskit Brook. These subbasins should be targeted for additional investigations to identify new bacteria sources or confirm the sources previously discovered. Turbidity results for 2022 were elevated compared to the prior nine years. Annual mean turbidity levels were heavily influenced by three wet weather monitoring events, responsible for 35 of the 57 turbidity results above 5.0 NTU. Extreme low flows during the prolonged drought also resulted in additional elevated turbidity results because water depths were too shallow to avoid disturbing and capturing stream bed sediments along with existing suspended bedload during sample collection. Despite the increased turbidity and occasional elevated bacteria results during 2022, Wachusett tributary sanitary quality continues to be excellent overall, providing source water that meets all drinking water standards for bacteria and turbidity.

Tributary water temperatures followed predictable seasonal patterns, with summertime high temperatures rising above the MassDEP recommended threshold for coldwater species (20 °C) in several tributaries for durations spanning 13 – 121 days (though not necessarily consecutive). 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), for a brief period at the end of September, and Waushacum Brook (WFR) on eight 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 low dissolved oxygen measured in the Stillwater River can be attributed to record low flows, with many pools becoming stagnant and warm. To help reduce stress on coldwater species and improve other aspects of tributary water quality, DWSP should continue to actively promote the pre-treatment of stormwater, most importantly through the reduction of direct discharges of stormwater collected from impervious surfaces and the promotion of forested stream buffer zones.

In the fall of 2020, monitoring for alkalinity in Wachusett tributaries resumed to determine the cause of the rising alkalinity trend observed in Wachusett Reservoir in recent years. Alkalinity was previously sampled in tributaries between 2000 and 2012. The 2020-2022 mean alkalinities for Wachusett tributaries were comparable to historical concentrations, except for French Brook and the Stillwater and Quinapoxet Rivers, which show slight increases over the prior period. It will require several more years of monitoring to establish interannual variability ranges and determine which tributaries have increased in alkalinity since the 2000 – 2012 time period. If time allows, the causes and implications of any rising alkalinity trends will also be explored in greater depth.

Wachusett tributary pH results for 2022 were below the recommended range at least once at 13 monitoring locations, which is typical for Wachusett tributaries. A notable decline in pH was observed across several tributaries coinciding with the onset of drought conditions, which may have resulted from a change in hyporheic zone biogeochemistry as aquifer levels dropped. Waushacum Brook pH was observed above the recommended range during one monitoring visit. Sensor calibration for pH was out of range during most monitoring visits for the first half of 2022, and then again in September. This adds uncertainty to the reliability of the pH measurements during these periods of 2022. New protocols and calibration reports were instituted in the latter half of 2022 to avoid these repeated calibration issues going forward. Despite the observed excursions noted above, the pH values and seasonal patterns observed in Wachusett tributaries are reflective of natural conditions and are not a water quality concern for the drinking water supply at this time.

Routine tributary and groundwater monitoring results for dissolved salts and specific conductance in 2022 continue to be elevated across several Wachusett Watershed subbasins. Chloride concentrations in Gates and West Boylston Brooks continued to be above chronic toxicity thresholds during most months in 2022. High temporal resolution specific conductivity data collected from the Mayfly monitoring stations shows continued evidence of chloride spikes above the acute toxicity threshold for aquatic life occurring after road salt applications at some water quality monitoring stations.

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. The expanded groundwater monitoring effort concluded in 2022, and a separate report was produced to summarize and interpret the data collected and offer recommendations for future groundwater monitoring and research. The conductivity blitz for surface waters was not completed in 2022 as expected due to the prolonged drought conditions which dried up many intermittent and headwater streams. This project will continue in 2023. High frequency conductivity monitoring (10–15-minute measurement intervals) at three USGS stations and five 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 80% of the watershed land area. Once Muddy Brook and Trout Brook Mayfly stations are fully operational, this percentage will increase to 87%. 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 2022 were consistent with historical data and demonstrate continued adherence to drinking water quality standards. For 2022, median nitrate concentrations were comparable to the median over the prior nine years, except for Trout Brook and West Boylston Brook, which were slightly higher. Annual mean TKN concentrations were generally similar to the 2015 – 2021 medians, however, Malden and Waushacum Brooks and the Quinapoxet and Stillwater River mean annual TKN concentrations were at their highest observed levels on record. Mean TN concentrations in 2022 were similar to prior years across respective monitoring stations, with the exception of Waushacum Brook and the Stillwater River, which had their highest mean annual TN concentration on record, though only slightly higher than in previous years. Although TKN and TN concentrations have continued to be observed above ecoregional background levels at several monitoring locations and reached record high concentrations in 2022, these concentrations are well below regulatory standards and are not sufficiently elevated to be a water quality concern. Phosphorous concentrations in Wachusett tributaries for 2022 were generally low and mostly within ecoregional background ranges. 2022 annual median TP concentrations were similar to or lower than the 2013 – 2021 medians, with the exception of French Brook, which slightly higher than the 2013 – 2021 median. If time and resources allow, additional investigations could be conducted to confirm sources of nitrogen in Malagasco and Malden Brooks and sources of phosphorous in French, Malagasco, and Trout Brooks.

Total organic carbon (TOC) concentrations and UV_{254} absorbance levels during 2022 were higher than historical values across most Wachusett tributaries, with 2022 annual median values higher than 2013 – 2021 medians at all tributaries except for Trout and Malagasco Brooks. Despite these higher levels, organic carbon concentrations observed in Wachusett tributaries are considered normal for streams and rivers. Because organic carbon in raw drinking water sources can become precursors to several disinfection byproducts that are harmful to human health and have regulatory limits, any opportunities to reduce organic carbon loads in Wachusett tributaries should be explored.

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 biologic factors such as diatom production and silica availability.

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.

Annual mean specific conductance observed in the Wachusett Reservoir decreased slightly and the annual minimum was lower than the previous five years; the annual maximum specific conductance was higher than the previous three years. Alkalinity continues to be higher when compared to the early period of record, especially over the last four years. Enhanced monitoring and mitigation programs (see Section 4.1) are being implemented to address these trends and monitoring within the Reservoir will continue to provide a reference for detection of downstream changes resulting from these modifications within the Watershed.

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 2023 at six primary tributary monitoring locations: French, Malagasco, Muddy, Malden, Waushacum and West Boylston Brooks. Trout Brook is slated for upgrade in 2023, depending on availability of parts. These stations measure conductivity, temperature, and depth at 15-minute increments with real-time raw data access via the internet. Existing HOBO U20 depth and temperature loggers will remain in place at West Boylston Brook (for water depth) and Trout Brook (until Mayfly station is complete and tested).

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. The location of the Boylston site will likely be moved closer to the access road parking area on Rt. 70.

Monitoring Element	Current Program	Proposed Changes
Real-time flow monitoring	10 tributaries (3 by USGS)	Change sensor from HOBO to Hydros-21, except for West Boylston and Trout Brooks
Precipitation	2 USGS Stations, 2 NOAA Stations	No change
Snowpack (seasonally)	Weekly, 6 locations	Boylston location moved closer to Rt. 70
Groundwater Levels	Monthly manual, 8 wells	End sampling in MDW8. MDW7 will continue to be sampled alongside the automated sampling equipment added by USGS at the end of 2022.

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 2023. One well, MDW8, will be removed from sampling due to the limited ability to sample it. No samples will be collected for lab analysis under the WATWEL project in 2023.

Monitoring Element	Current Program	Proposed Changes
Groundwater Quality	Monthly – Eight wells for specific conductance and temperature; Seven wells for dissolved oxygen and pH	End sampling in MDW8 due to the inability to purge it and inability to collect dissolved oxygen and pH data. Samples will not be collected for WATWEL parameters.

4.3.3 Tributary Monitoring

Routine tributary monitoring (WATMDC and WATTRB) and field parameters will continue at the same frequency and with the same parameters as in 2022. Real-time conductivity monitoring has been expanded to all primary tributary monitoring locations except for Trout Brook, which is scheduled for a monitoring station upgrade in the summer/fall of 2023.

Monitoring Element	Current Program	Proposed Changes
Nutrients, Cl, UV absorbance, TSS, Alkalinity (WATMDC)	Monthly, 10 primary tributaries + Quabbin Transfer (MDS1)	No change
Bacteria and Turbidity (WATTRB)	2x per month, 18 Locations	No change
Field parameters (water temperature, pH, specific conductance, pH, stage)	3x per month in conjunction with other projects	No change
Real-time conductivity monitoring (USGS or DWSP – using Mayfly)	3 USGS, Waushacum Brook	Add all remaining primary sampling locations. Equipment upgrades

4.3.4 Special Projects and Other Sampling

4.3.4.1 Short-term Forestry Monitoring

Monitoring protocols for short-term forestry monitoring in the Wachusett Watershed were revised in 2021 after a comprehensive analysis showed that there was no statistical difference between turbidity levels at stream crossings during a timber harvest and the periods before and after. Turbidity levels have only exceeded 5.0 NTU on five occasions since 2012 and most of these were due to storm events, or short-lived and localized disturbances during bridge installations. Additional data collected in 2022 were consistent with historical observations and continue to support the conclusion that timber harvest operations on DWSP property do not pose a threat to water quality. Upon further review, and in light of higher priority threats to water quality in the DWSP watersheds, it was decided that short-term forestry monitoring be suspended altogether so that staff resources can be allocated towards higher priority water quality threats, as outlined in the forthcoming Watershed Protection Plan update FY2024 – FY2029.

4.3.4.2 Long-term Forestry Study

Monitoring for long-term effects of water quality at forestry locations will remain paused until the timber harvest is completed, as 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. The experimental lot (Princeton) has been sold and harvest is expected to begin in 2023.

4.3.4.3 Quabbin Transfer (Shaft-1) Monitoring

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

4.3.4.4 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.

4.3.4.5 Flow Targeted Nutrient Samples

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

4.3.4.6 Groundwater Isotope Sampling

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

4.3.4.7 Tributary Storm Sampling

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

4.3.4.8 Surface Water Conductivity Blitz

In May of 2021, a new short-term (1-year) monitoring initiative was launched to gather more information about the geographic variability of elevated conductivity (and chloride by proxy) of surface waters in the Wachusett Watershed. Specific conductivity and other field parameters will be measured at as many surface water locations across the Watershed as possible, with emphasis on areas that have not been monitored in the past and areas that are significantly impacted by freshwater salinization. This project is behind schedule; it was expected to take until the end of the fall 2022. Unfortunately, drought conditions during the summer of 2022 dried up many intermittent streams and prevented data collection. Depending on staff availability, this effort will continue in 2023, targeting many locations that were dry during the 2022 drought. The results of this 'Conductivity Blitz' will be compiled and analyzed in FY 2024.

4.4 Reservoir Monitoring for 2023

Reservoir monitoring programs will continue as carried out in 2022. The majority of these programs have a well-established framework which provide for flexibility in response to current environmental conditions. These programs are detailed elsewhere in this report and briefly described below, but overall, no changes are proposed.

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

Monitoring and management of AIS within Wachusett Reservoir and in ponds near the Reservoir will continue on an as-needed basis in 2022.

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 Biweekly Oct – April at BN3417 or CI3409 Regular phytoplankton sampling will continue; the frequency of additional monitoring for taste and odor taxa to be decided in concert with MWRA based on new alert thresholds	No change
Secchi Disk Depth		No change
Phytoplankton		Updated Phytoplankton Action Plan
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

Figure A-1: Hydrographs for Small Tributaries in Wachusett Watershed During 2022

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

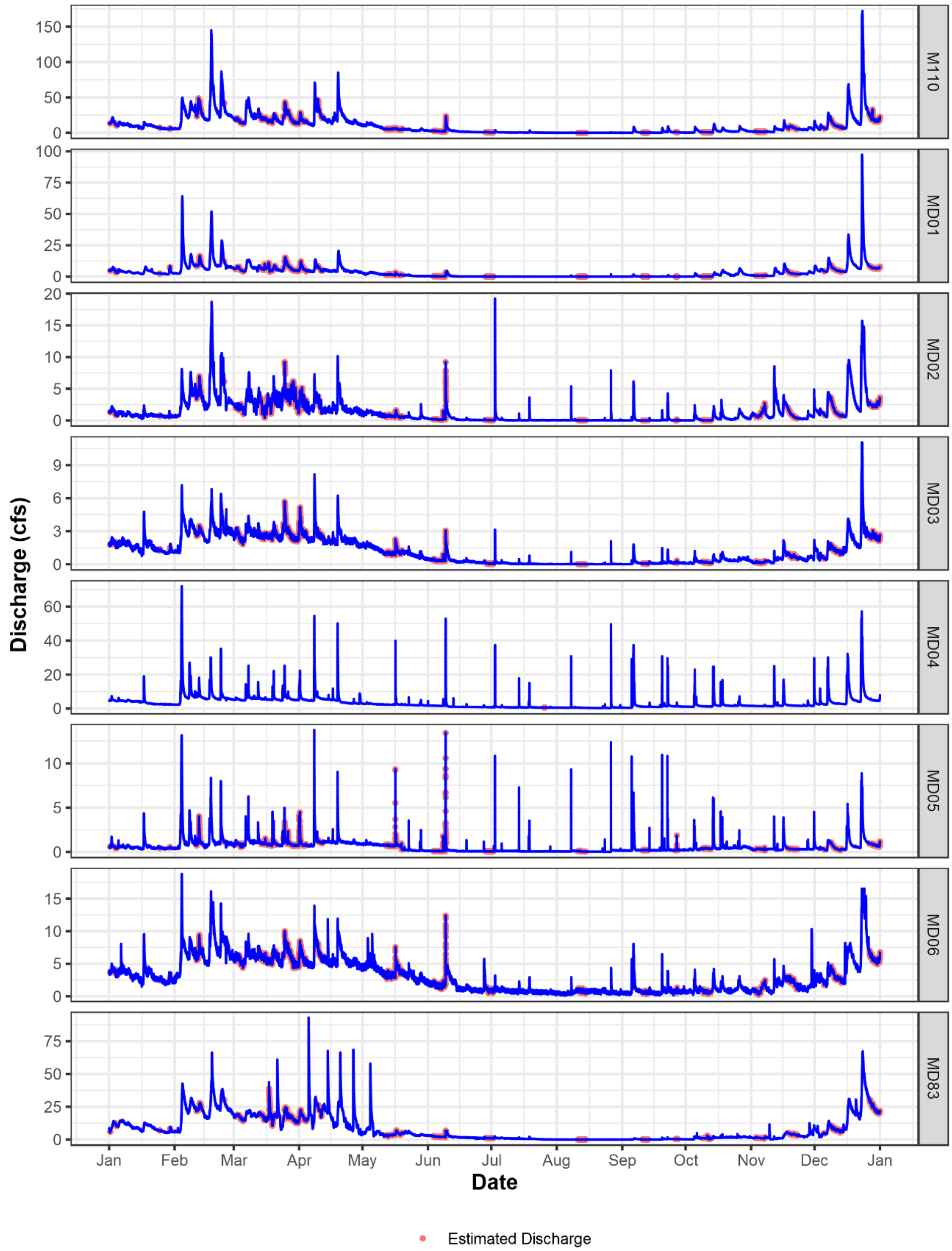

Table A-1: Water Quality Standards/Criteria Applicable to Wachusett Watershed Surface Waters

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

Parameter	Standard/Criteria	Regulatory reference	Threshold Value	Notes
Total Phosphorus	Ecoregional reference – (Streams/Rivers)	EPA recommended criteria	5.00 – 23.75 µg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA recommended criteria	7.0 – 8.0 µg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
Total Kjeldahl Nitrogen	Ecoregional reference – (Streams/Rivers)	EPA recommended criteria	0.10 – 0.30 mg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA recommended criteria	0.33 – 0.43 mg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
Total Nitrogen	Ecoregional reference – (Streams/Rivers)	EPA recommended criteria	0.42 – 0.59 mg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
	Ecoregional reference (Lakes/Reservoirs)	EPA recommended criteria	0.27 – 0.40 mg/L	25th Percentile subecoregion 58 – 25th Percentile subecoregion 59
Turbidity	Unfiltered Surface Water Supplies	EPA SWTR MCL	Maximum 5.0 NTU	May not exceed at any time
	Unfiltered Surface Water Supplies	MassDEP	Maximum of 1.0 NTU	Determined by a monthly average rounded to the nearest significant whole number. May only exceed if does not interfere with effective disinfection

2022 Watershed Monitoring Parameters and Historical Context

A-1 Ammonia-Nitrogen

Ammonia is an inorganic form of nitrogen that is usually present in surface water at low background concentrations (less than 0.1 mg/L)[74]. 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[75]. 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[76]. 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 0.184 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[77]. Possible sources of NH_3-N in the Wachusett Watershed include septic systems, landfill leachate, agriculture (from fertilizer and livestock), atmospheric deposition, and natural biological processes.

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

A-2 Nitrate-Nitrogen

Nitrate-nitrogen (NO_3-N) is an important macro-nutrient for plants and the most abundant inorganic form of nitrogen found in water[78]. Sources of nitrate include runoff from agricultural sites and fertilized lawns, failing on-site septic systems, atmospheric deposition, and some industrial discharges. Background concentrations of NO_3-N + NO_2-N (Nitrite) in rivers and streams of the Wachusett Watershed ecoregions were found to range between 0.1 mg/L and 4.12 mg/L, with the 25th percentile value (all seasons) of 0.16 mg/L (ecoregion 58)[79] and 0.31 mg/L (ecoregion 59)[80], 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),

[74] USGS, 1999
[75] Mallin et al., 2006
[76] USEPA & Tetra Tech Inc, 2013
[77] World Health Organization [WHO], 1996
[78] USGS, 1999
[79] USEPA, 2001a
[80] USEPA, 2000

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[81].

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[82]. Several other studies (mostly in Europe) have linked high levels of nitrate consumption, though in some cases below the EPA MCL, to various cancers[83]. However, more research is needed on this topic because high nitrate levels tend to be associated with other contaminants, which can confound the interpretation of study results. Fortunately, NO_3-N concentrations throughout the Wachusett Watershed have remained well below the MCL. The current water quality goal for NO_3-N is to maintain existing local background concentrations.

A-3 Nitrite-Nitrogen

Nitrite-nitrogen (NO_2-N) is a short-lived nitrogen species that is produced during nitrification/denitrification processes. Sources of nitrite are the same as for nitrate, but it is typically present in surface waters in much lower concentrations. Elevated levels of nitrite have been shown to cause methemoglobinemia in humans, which is a reduction in the ability of blood to transport oxygen to tissues[84], and is particularly lethal to infants[85]. In order to protect human health, the EPA has established the MCL for NO_2-N in drinking water at 1.0 mg/L[86]. Although nitrite concentrations are rarely above the detection limit (0.005 mg/L) in Wachusett tributaries, this parameter continues to be monitored to demonstrate compliance with the MCL and to track nutrient inputs to the Reservoir. The current water quality goal for NO_2-N is to maintain existing local background concentrations, which are well below all thresholds of concern.

A-4 Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) is the sum of organic nitrogen plus NH_3-N and ammonium-nitrogen (NH_4-N). It often constitutes a significant proportion of the total nitrogen present in a natural water body (20 – 80% in Wachusett tributaries). Background concentrations of TKN in rivers and streams of the Wachusett Watershed ecoregions were found to range between 0.05 mg/L and 1.45 mg/L, with the 25^{th} percentile value (all seasons) of 0.10 mg/L (ecoregion 58)[87] and 0.30 mg/L (ecoregion 59)[88], which are the reference conditions for streams and rivers recommended by EPA for the development of numerical TKN criteria for these ecoregions. This fraction of nitrogen is important to account for because it can be converted to other forms of nitrogen through natural processes and can contribute to unwanted plant growth in the tributaries and Reservoir. There are no water quality standards for TKN, however this metric includes NH_3-N, which is toxic at low concentrations and has specific regulatory thresholds (see 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

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81 Camargo & Alonso, 2006
82 Safe Drinking Water Act of 1974, 2019
83 Ward et al., 2018
84 Ibid
85 Walton, 1951
86 Safe Drinking Water Act of 1974, 2019
87 USEPA, 2001a
88 USEPA, 2000

sources of tributary nitrogen and allow for a better understanding of nutrient dynamics. The current water quality goal for TKN in streams, rivers, and the Reservoir is to maintain existing local background concentrations.

A-5 Total Nitrogen

Total nitrogen (TN), as measured in water, is the sum of TKN, NO_3-N and NO_2-N. This calculated parameter is important to examine in conjunction with TP because the ratio of nitrogen to phosphorus in aqueous systems controls primary production and has important implications for the ecology and drinking water quality of a water body. The dominant forms of nitrogen in surface waters are NO_3-N and organic nitrogen, with much smaller fractions of inorganic NH_3-N and NH_4-N species (See Sections A-1 – A-4).

Massachusetts has only developed numeric water quality criteria for nitrogen for specific water bodies with significant impairments from nutrient over-enrichment. Nitrogen criteria are usually created in conjunction with phosphorous criteria, as they are the two primary causal agents for eutrophication. In absence of water body specific nitrogen criteria for Wachusett Watershed water bodies, only the narrative criteria for nutrients applies – to not '*… cause or contribute to impairment of existing or designated uses.'* Thus, the internal numerical goal for TN in streams and rivers is to maintain naturally occurring local background concentrations. Background concentrations of TN in rivers and streams of the Wachusett Watershed ecoregions were found to range between 0.34 mg/L and 5.57 mg/L, with the 25^{th} percentile value (all seasons) of 0.42 mg/L (ecoregion 58)[89] and 0.59 mg/L (ecoregion 59)[90], which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TN criteria for these ecoregions. Long-term (seasonal or annual) TN concentrations above these recommended criteria likely indicate that excess nitrogen is entering waters. Any tributaries exhibiting long-term concentrations above these recommended nitrogen criteria should be examined more closely to determine if any response variables (chlorophyll, macrophytes, turbidity, macroinvertebrates) indicate that water quality impairments are occurring.

A-6 Total Phosphorus

Phosphorus is an important macronutrient and the limiting factor controlling algal productivity in Wachusett Reservoir. Phosphorous is derived from the weathering of rocks and therefore it is naturally present in soils in varying concentrations as orthophosphate (PO_4^{3-}). Plants take up orthophosphate as they grow, which is then returned to the soil in organic compounds via animal waste and the decomposition of plant and animal tissue[91]. 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.

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[89] USEPA, 2001a
[90] USEPA, 2000
[91] USGS, 2012

Lakes with TP concentrations exceeding 20-30 µg/L may experience nuisance algal growth[92]. 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)[93] and 23.75 µg/L (ecoregion 59)[94], 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.

A-7 Silica

Silica is a necessary element for the cellular function of all living organisms. It is required for protein synthesis in all phytoplankton and is essential for the formation of siliceous skeletons and scales of diatoms and chrysophytes[95]. After oxygen, silica is the most abundant element, comprising approximately 30% of the Earth's crust. It enters aquatic systems through natural weathering processes although export can be accelerated by human activities such as mining, agriculture, and disturbances of terrestrial vegetation which serve as terrestrial silica sinks. Changes in silica abundance in freshwater reservoirs can be observed on a spatial and temporal gradient as water higher in silica enters from tributaries, disperses through the Reservoir, and is subsequently taken up by phytoplankton, particularly diatoms in the spring.

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

A-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[96]. For tributaries, the water quality goal for water temperature is to remain under the

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[92] Vollenweider, 1976
[93] USEPA, 2001a
[94] USEPA, 2000
[95] Reynolds, 2006
[96] Massachusetts Surface Water Quality Standards, 2013c

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.

A-9 Dissolved Oxygen

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

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

A-10 Alkalinity and pH

The Hydrogen ion activity (pH) of a stream is largely a function of the groundwater hydrogeology of the basins and the effectiveness of the stream water in buffering the effects of acid precipitation. pH is an 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[97]. Aquatic life can

[97] USEPA, 2021

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[98]. 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[99]. 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[100]. 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[101]. 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 application of road salt for deicing[102], 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

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[98] Godfrey et al., 1996
[99] Turk, 1983
[100] National Atmospheric Deposition Program, 2021
[101] Hornbeck et al., 1977
[102] Kaushal et al., 2020

if lower values are naturally occurring, results cannot be lower than 25% of the natural level[103]. 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[104].

A-11 Bacteria

Water bodies naturally contain many microorganisms, most of which are benign. However, there are several harmful intestinal microorganisms (viruses, bacteria, and protozoa) that are sometimes present in water (e.g., *Cryptosporidium*, *Giardia, Salmonella*). Many of these are fecal microorganisms and are known to cause a host of illnesses such as intestinal and urinary tract infections, meningitis, septicemia[105], dysentery, typhoid fever, and cholera[106]. *Escherichia coli* (*E. coli*) is a species in the fecal coliform group, which originates from fecal material of humans and other warm-blooded animals[107]. Some strains of *E. coli* can be deadly, especially for small children or people with weakened immune systems[108]. Studies have found that the presence of *E. coli* is often correlated with the presence of many other pathogenetic microorganisms[109], thus it has been selected as a useful indicator of pathogen contamination in waters. Human exposure to pathogens usually occurs through recreational contact or direct consumption of drinking water that was not adequately disinfected.

Sources of *E. coli* all stem from human or animal wastes: agricultural operations with livestock or that use manure to fertilize crops, treated wastewater, septic systems, urban runoff, land application of biosolids (sludge), pet waste, and wildlife[110]. 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[111]. DWSP prohibits boating, wading, and swimming in Wachusett Reservoir and its tributary waters, however fishing is allowed, and that is probably the only (legal) avenue for public exposure to pathogens from the water supply prior to treatment. Despite there being low risk for pathogen exposure due to recreation, DWSP uses these regulatory thresholds to evaluate the sanitary quality of waters within the Wachusett Watershed. As a major public water supply, regulatory requirements for pathogens at drinking water intakes are much more stringent.

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

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[103] USEPA, 2013
[104] Kaushal et al., 2005
[105] USGS, n.d.-a
[106] Myers et al., 2014
[107] USEPA, 1986
[108] USEPA & Tetra Tech Inc., 2013
[109] Myers et al., 2014
[110] Ibid
[111] Massachusetts Surface Water Quality Standards, 2013d

of the samples taken in any six-month period[112]. Results for pathogen testing at the intake are briefly discussed Section 3.4.11 and in greater detail in separate reports published by MWRA[113].

A-12 Specific Conductance and Dissolved Salts

Specific conductance is a measure of the ability of water to conduct an electrical current at 25 °C, dependent on the concentrations of various ions in solution[114, 115]. Freshwater systems in Massachusetts naturally contain low levels of mineral salts in solution[116]. Elevated levels of specific conductance and associated dissolved solutes (e.g., sodium, chloride) may stress sensitive biota, threaten ecosystems[117, 118], and degrade drinking water quality[119, 120, 121]. Contamination of drinking water supplies with excess chloride (Cl) may increase the corrosivity of affected waters[122], which can increase the mobilization of lead and copper from older infrastructure.

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[123], resulting in the mobilization of base cations (e.g., calcium, potassium, magnesium) to streams thereby altering natural biogeochemical cycles. The EPA established aquatic life criteria for Cl in 1988 at chronic (4-day average) and acute (1-hour average) concentrations of 230 and 830 mg/L, respectively[124]. 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"[125]. MassDEP also established an Office of Research and Standards Guideline (ORSG) of 20 mg/L sodium in drinking water and a secondary maximum contaminant level (SMCL) for Cl of 250 mg/L[126]. MassDEP does not currently enforce regulatory standards for specific conductance in drinking water.

Elevated levels of specific conductance and associated ions in surface water and groundwater may indicate contamination from anthropogenically-derived sources of salts to natural water systems such as septic system effluent, stormwater discharges, agricultural runoff, or road salt runoff from deicing

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112 Massachusetts Surface Water Quality Standards, 2013e
113 MWRA, 2021b
114 Granato et al., 2015
115 Rhodes et al., 2001
116 Granato et al., 2015
117 Jackson & Jobbágy, 2005
118 Corsi et al., 2010
119 Kaushal et al., 2005
120 Daley et al., 2009
121 Kelly et al., 2010
122 Stets et al., 2018
123 Kaushal et al., 2017
124 USEPA, 1988
125 MassDEP, 2018
126 Massachusetts Drinking Water Regulations, 2020b

activities[127,128]. In the snowbelt region of the U.S., road salt is the dominant source of chloride to many natural water systems[129, 130, 131].

Increases in specific conductance have been documented in the Wachusett Watershed and within Wachusett Reservoir, where the highest maximum specific conductance values have been recorded over the past several years. Since many aquatic organisms are sensitive to increases in Cl, community composition is likely to shift in response[132]. 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*[133].

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

Within the Reservoir, horizontal and vertical differences in specific conductance are reflective of interactions between native water contributed from the Wachusett Watershed and water transferred from Quabbin Reservoir. 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.

A-13 Total Suspended Solids

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

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[127] Panno et al., 2006
[128] Lautz et al., 2014
[129] Kaushal et al., 2005
[130] Kelly et al., 2008
[131] Mullaney et al., 2009
[132] Van Meter & Swan, 2014
[133] June-Wells et al., 2013

Depending on particle density, suspended solids may settle out of suspension at different rates and locations as a function of the changing hydraulic and geomorphological conditions between the headwaters and the Reservoir. The concentration and composition of TSS can vary widely across subbasins depending on soils, stream channel geomorphology, subbasin land cover type, and conditions (e.g., disturbances). These solids provide benthic structure (bed material) and a stock of minerals and nutrients to support aquatic life. Local stream ecology evolved under a "normal" sediment regime, which underpins much of the aquatic habitat and nutrient dynamics at the reach scale[134,135]. 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[136]. Furthermore, high TSS concentrations can harm fish by clogging gills, reducing visibility so that it is more difficult for fish to find food, and smothering eggs. Suspended solids that settle on the streambed can form thick deposits, reducing fish spawning areas and eliminating habitat for benthic macroinvertebrates. As suspended solids enter Wachusett Reservoir they begin to settle out in coves or along the shoreline, which can negatively affect aquatic life in those places as well as promote invasive or nuisance plant growth by providing nutrient rich substrate.

Fortunately, Wachusett Reservoir is a large enough system that suspended solids rarely reach the intake except in rare instances of soil/debris washing off the shoreline immediately adjacent to the Cosgrove Intake. Nearly all runoff from roadways surrounding Wachusett Reservoir is treated to remove TSS prior to being discharged into the Reservoir. Aggregations of phytoplankton which may contribute to elevated TSS are likewise rare in the area of the Cosgrove Intake. For water supplies it is desirable to have low TSS 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[137]. 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 in Wachusett tributaries are too low to be detected most of the time. Higher TSS concentrations were most often detected during targeted storm sampling, both during and after precipitation and high streamflows. Stormflow TSS in Wachusett tributaries can typically range from 5 – 50 mg/L and can occasionally exceed 100 mg/L during large storm events. The water quality goal for TSS in Wachusett Watershed tributaries is for mean concentrations during dry conditions to remain below detection (< 5 mg/L) and for concentrations during wet conditions to remain below 50 mg/L for any single sample.

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[134] Southwood, 1977
[135] Wohl et al., 2015
[136] Murphey, 2007
[137] Wetlands Protection, 2017; Water Quality Certification, 2017

A-14 Turbidity

Turbidity is another term for water clarity, which is determined by measuring the scatter of light in the water and reported by DWSP in Nephelometric Turbidity Units (NTU)[138]. 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 A-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 as a result of eroding shorelines or clay laden tributary waters delivered by storm events. For drinking water supplies, the concern over turbidity relates to aesthetics, pathogens, and treatment considerations. The particles that cause turbidity can make water cloudy or have displeasing taste or odor. These particles also promote regrowth of microbes by inhibiting disinfection and providing nutrients and minerals for their reproduction. For these reasons, and its relative ease of measurement, turbidity is a good general water quality indicator.

There are two standards for turbidity levels at drinking water intakes. The SWTR mandates that raw water turbidity levels (at the intake) always remain below 5.0 NTU. MassDEP regulations specify that turbidity levels may exceed 1.0 NTU only if it does not interfere with effective disinfection[139]. 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)[140] and 1.68 NTU (ecoregion 59)[141], 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.

A-15 Total Organic Carbon

Total organic carbon (TOC) is the sum of all organic carbon in water, both dissolved and particulate (suspended). Organic carbon sources fall into three categories: 1) Terrestrial carbon such as decaying organic matter, proteins, organic acids, and animal waste; 2) Autochthonous sources produced in-stream/reservoir, such as algae; and 3) Anthropogenic sources such as industrial and wastewater discharges, petroleum related pollution, agricultural chemicals, and the accelerated release of natural organic carbon through landscape disturbance. Background TOC concentrations in rivers are typically 1 to 10 mg/L, though waters emanating from wetlands or bogs often have much higher natural concentrations of organic carbon[142].

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

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[138] Swenson & Baldwin, 1965
[139] Massachusetts Drinking Water Regulations, 2020c
[140] USEPA, 2001a
[141] USEPA, 2000
[142] Mulholland & Kuenzler, 1979

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.

A-16 UV Absorbance

Ultraviolet light absorbance at 254 nm (UV_{254}) is used as a surrogate for the amount and reactivity of natural organic material in source water that is easier to measure than TOC. Measurements of UV_{254} are reported as the amount of ultraviolet light at a 254 nm wavelength that is able to transmit through a water sample in absorbance units per centimeter of path length (ABU/cm). Higher UV_{254} levels indicate higher organic carbon concentrations, which require increased ozone and chlorine demand for disinfection, which can subsequently increase disinfection byproduct formation. Tributary levels of UV_{254} are influenced by the same variables that are responsible for organic carbon discussed above (A-15).

As with TOC, there are no regulatory limits for UV_{254}, however measurements are used to calculate the amount of carbon reduction required in the treatment process to meet the two DBP regulatory standards. After statistical relationships are developed to correlate TOC with UV_{254} for each tributary it is then possible to discontinue TOC sampling and use UV_{254} as a proxy for organic content. Water quality goals for UV_{254} would have to be specific to each tributary based on a statistically significant correlation to TOC concentration. The targeted UV_{254} values would be analogous to local 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[143].

A-17 Chlorophyll *a* and Phycocyanin

Plants, algae, and cyanobacteria use pigments to derive light energy for photosynthesis. Chlorophyll *a* is found in all photosynthetic organisms while small amounts of accessory pigments, which transfer energy to chlorophyll *a,* are associated with specific groups of organisms. One such pigment is phycocyanin, a 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[144].

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

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143 DWSP, 2018b
144 USEPA, 2001b

as a routinely measured parameter. On average, measurements for these pigments are low (< 2.7 µg/L); however, periodic increases are observed in association with increases in algal growth. Like the algae increases, increased values are often limited to specific strata rather than spread through the entire water column.

A-18 Phytoplankton

Algae are a large, diverse group of organisms present in nearly every ecosystem from sandy deserts to artic permafrost to freshwater reservoirs[145]. In fresh water they can be planktonic (free-floating) or attached to structures including plants and rocks. Growth of freshwater algae is largely dependent on abiotic factors such as sunlight, temperature, and nutrients present in the water column. Changes in the algae community composition and density can therefore provide early indication of changes in water quality. In drinking water supplies, especially unfiltered systems, monitoring for these organisms can be extremely important, as certain taxa can produce compounds causing undesirable tastes, odors, and in limited cases, toxins. Phytoplankton can proliferate rapidly when ideal conditions are available and routine monitoring is essential for detecting density increases early in the growth phase so that appropriate management actions can be taken. These management options for Wachusett Reservoir include treatment of the algae present in the Reservoir with copper sulfate (the last treatment was in 2014) and adjustments within the treatment system such as increasing the ozone dose.

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

While the entire phytoplankton community is assessed by DWSP biologists, MWRA and DWSP have established thresholds for five organisms (Table A-2). These four chrysophyte genera and one cyanobacteria genus have previously attained problematic densities in Wachusett Reservoir and could cause undesirable tastes and odors in the water supply. Once these thresholds are exceeded, monitoring frequency is increased (typically to twice weekly) and action is considered.

Table A-2: Early Monitoring and Treatment Consideration Thresholds for Select Phytoplankton Genera

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

145 Reynolds, 2006

A-19 Zooplankton

Zooplankton are small organisms found in nearly all surface waters and are the most abundant multicellular animal on earth. They maintain a vital role in the ecosystem as grazers, providing a pathway of energy from producers to consumers at higher trophic levels[146, 147]. 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[148].

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

The primary goal of current zooplankton monitoring at Wachusett Reservoir is to identify new occurrences of invasive species as soon as possible. No invasive zooplankton have been found in the Reservoir to date, but these species have colonized all the Great Lakes, the Finger Lakes of New York, and Lake Champlain of Vermont[149]. 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.

A-20 Secchi Disk Depth/Transparency

A Secchi disk is a tool used to estimate water clarity and the amount of light penetration in a waterbody. The Secchi disk transparency is the water depth at which a Secchi disk, a round, alternately painted, black and white disk, is barely visible from the surface. This value can be used to estimate the depth of the euphotic zone; this area in which photosynthesis occurs is approximately three times the Secchi disk transparency [150]. 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*[151]. 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[152].

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

Appendix B: Quality Assurance

Sample Completeness

As detailed in the Quality Assurance Project Plan (QAPP) for Wachusett Watershed Water Quality Monitoring (Draft), sample completeness is an indicator of data quality. This metric is used to evaluate whether or not 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 in order to meet DWSP objectives for routine tributary monitoring. The tables below show the number of samples collected and expected by Parameter (Table B.1) and by monitoring location (Table B.2).

Table B.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	539	552	98
E. coli	419	432	97
Mean UV254	120	120	100
Nitrate-N	120	120	100
Nitrite-N	120	120	100
pH	539	552	98
Specific Conductance	540	552	98
Staff Gauge Height	357	360	99
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	420	432	97
Water Temperature	540	552	98

Table B.2: Sample Completeness by Monitoring Location

Location	Collected	Expected	Percent Complete
M102	143	144	99
M110	347	348	100
MD01	341	348	98
MD02	348	348	100
MD03	348	348	100
MD04	348	348	100
MD05	348	348	100
MD06	347	348	100
MD07	348	348	100
MD11	138	144	96
MD12	114	144	79
MD69	348	348	100
MD70	120	144	83
MD73	144	144	100
MD80	144	144	100
MD81	144	144	100
MD83	348	348	100
MD89	136	144	94

Sample completeness was achieved for all parameters and at all locations, except for Jordan Farm Brook (MD12), which could not be sampled for an extended period of time due to the prolonged drought during summer 2022. Other reasons for failing to collect 100% of samples include: field personnel errors; laboratory mishaps; samples becoming damaged, contaminated, or lost during transit; equipment malfunction; and data management mistakes. For 2022, cases where percent complete was below 100 are explained below, by location (Table B.3).

Table B.3 Missing Samples for 2022

Monitoring Location	Reason for missing sample(s) (number of samples)
Asnebumskit Brook (Princeton) - M102	One E. coli sample was lost in transport (8/18) (n = 1)
Boylston Brook - MD70	Dry on four sampling visits between 7/11 and 8/18 (n = 24)
Cook Brook - Wyoming - MD11	Dry on 8/18 (n=6)
East Wachusett Brook (140) - MD89	Dry on 8/18 (n=6); Field parameters not logged on 3/14 (2 were recorded by hand on field sheet) (n=2)
French Brook - MD01	Dry on 8/18 – missing E. coli, Turbidity, and all Field Parameters (n=7)
Jordan Farm Brook - MD12	Dry on five sampling visits between 7/11 and 9/8 (n=30)
Malden Brook – MD06	Missing Staff Gauge Height from 1/18 (too much ice to chip away)
Trout Brook - M110	Missing Staff Gauge Height from 1/18 (too much ice to chip away)

Extra Samples

In 2022 EQ staff collected 10 extra *E. coli* samples in West Boylston Brook subbasin as part of an investigation into prolonged elevated bacteria levels documented at the routine West Boylston Brook monitoring station MD05 (Table B.4). Some of these samples were taken in conjunction with routine monitoring visits, the results of which are provided in the column labeled " *E. coli* Result at MD05". Each sample location in the table corresponds to a number in the map below (Figure B 1).

Table B.4 Extra Samples Collected During 2022

Location Description (Map location number)	Date-Time (ET)	*E. coli* Result (MPN/100 mL)	*E. coli* Result at MD05	Latitude (DD)	Longitude (DD)
West Boylston Brook Downstream of Central St. (2)	09-22-2022 11:52	9,210	4,610	42.3648	-71.7826
West Boylston Brook downstream of Prospect St (4)	09-29-2022 09:10	122		42.363	-71.788
West Boylston Brook upstream of Rt. 12 (1)	10-06-2022 11:42	435		42.368	-71.782
West Boylston Brook Downstream of Central St. (2)	10-06-2022 11:45	909	448	42.3648	-71.7826
West Boylston Brook downstream of Prospect St (4)	10-06-2022 11:48	120		42.363	-71.788
Unnamed Tributary to West Boylston Brook, upstream of Prospect St. (3)	10-13-2022 09:01	52		42.364	-71.786
West Boylston Brook downstream of Prospect St (4)	10-13-2022 09:05	315		42.363	-71.788
West Boylston Brook downstream of Prospect St (4)	10-19-2022 11:10	< 10		42.363	-71.788
Unnamed Tributary to West Boylston Brook, upstream of Prospect St. (3)	10-19-2022 11:14	31	95	42.364	-71.786
West Boylston Brook Downstream of Central St. (2)	10-19-2022 12:00	630		42.3648	-71.7826

These follow-up samples were used to track the source location of elevated bacteria by bracketing distinct segments of West Boylston Brook and its tributaries and identifying the reaches where excessive bacteria loading is occurring. The three additional samples taken on October 19 provide evidence that bacteria were entering West Boylston Brook between Central St. and Prospect St in West Boylston. Field reconnaissance in this area did not result in the identification of a bacterial source during 2022. Field investigations and additional bacteria sampling will continue in West Boylston Brook subbasin until the bacteria source can be identified and/or the excessive bacteria loading is mitigated.

Figure B-1: West Boylston Brook Subbasin and Follow-up Bacteria Sampling Locations, 2022

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 a result appears to be erroneous or inaccurate due to a documented issue, then the result will also be given Flag 123 (remove from analysis) in addition to the specific flag that describes the underlying factor or condition. Table B.5 lists the data records from 2022 that were flagged. The last column (Flag 123) indicates whether or not the record was removed from analyses.

Table B.5 Flagged data for 2022

The last column "Flag 123" indicates whether or not the sample was also removed from analysis (Flag 123).

Sample ID	Location	Date Time (ET)	Parameter	Units	Result	Flag	Comment	Probe ID	Flag123
100322	M110	2/7/2022 11:30	Discharge	Cfs	134.78	111 - Above rating curve	Flag automatically added at import	NA	Yes
100321	M110	2/7/2022 11:30	Staff Gauge Height	Ft	2.32	108 - Ice build up at staff plate	Artificially high stage due to ice buildup on control	NA	Yes
100322	M110	2/7/2022 11:30	Discharge	Cfs	134.78	108 - Ice build up at staff plate	Artificially high stage due to ice buildup on control	NA	Yes
101196	MD70	3/14/2022 12:43	Dissolved Oxygen	mg/L	20.8	103 - Questionable Data	Impossible DO concentration and saturation %, likely a sensor malfunction	YSI Pro Quatro - 1	Yes
101197	MD70	3/14/2022 12:43	Oxygen Saturation	%	156	103 - Questionable Data	Impossible DO concentration and saturation %, likely a sensor malfunction	YSI Pro Quatro - 1	Yes
102614	HLNW	7/22/2022 9:45	Discharge	Cfs	0	113 - Below rating curve	Flag automatically added at import	NA	No
102962	MD03	8/18/2022 11:45	Discharge	Cfs	0	113 - Below rating curve	Flag automatically added at import	NA	No
103339	MD83	9/8/2022 9:15	pH	pH	4.14	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103344	MD07	9/8/2022 9:30	pH	pH	4.03	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103349	MD89	9/8/2022 9:35	pH	pH	3.73	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103354	M110	9/8/2022 9:45	pH	pH	3.49	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103359	M102	9/8/2022 10:05	pH	pH	3.84	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103364	MD69	9/8/2022 10:30	pH	pH	3.73	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103369	MD11	9/8/2022 10:47	pH	pH	4.02	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103374	MD06	9/8/2022 11:00	pH	pH	3.75	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103379	MD80	9/8/2022 11:09	pH	pH	3.91	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103384	MD04	9/8/2022 11:30	pH	pH	4.16	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103389	MD05	9/8/2022 11:30	pH	pH	4.16	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103394	MD81	9/8/2022 11:49	pH	pH	4.1	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103399	MD73	9/8/2022 11:56	pH	pH	4.17	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103404	MD03	9/8/2022 12:15	pH	pH	3.93	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103409	MD02	9/8/2022 12:30	pH	pH	4.37	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103414	MD70	9/8/2022 12:34	pH	pH	4.17	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
103419	MD01	9/8/2022 12:45	pH	pH	3.98	125 - Sensor calibration issues	pH 4 calibration out of range, results not accurate	YSI Pro Quatro - 2	Yes
89844	MISC	9/22/2022 11:52	E. coli	MPN/100 mL	9210	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes
89851	MISC	9/29/2022 9:10	E. coli	MPN/100 mL	122	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes
90043	MISC	10/6/2022 11:42	E. coli	MPN/100 mL	435	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes
90044	MISC	10/6/2022 11:45	E. coli	MPN/100 mL	909	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes
90045	MISC	10/6/2022 11:48	E. coli	MPN/100 mL	120	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes
90156	MISC	10/13/2022 9:01	E. coli	MPN/100 mL	52	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes
90158	MISC	10/13/2022 9:05	E. coli	MPN/100 mL	315	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes
90185	MISC	10/19/2022 11:10	E. coli	MPN/100 mL	10	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes
90186	MISC	10/19/2022 11:14	E. coli	MPN/100 mL	31	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes
90191	MISC	10/19/2022 12:00	E. coli	MPN/100 mL	630	107 - Follow up sample	West Boylston Brook Bacteria investigations - Fall 2022	NA	Yes