Water Quality Report: 2021

Wachusett Reservoir Watershed

Wachusett Reservoir from Wachusett Mountain – Dan Crocker (2021)

SEPTEMBER 2022

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 2021. 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 2021, Wachusett Reservoir water quality satisfied the requirements of the Filtration Avoidance Criteria established under the United States Environmental Protection Agency Surface Water Treatment Rule.

Compliance with state surface water quality standards among the tributaries varied, with minor exceedances attributed to higher solute loads measured during storm events and during low flow conditions, wildlife impacts, and/or natural attributes of the landscape. Excessive loading of dissolved salts to the tributaries and Reservoir has continued, as evidenced by specific conductance and chloride results for 2021. Elevated concentrations of some parameters (turbidity, *E. coli*, UV absorbance, total organic carbon) occurred during 2021, likely due to the above average precipitation that occurred during the summer and early fall. 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 2 and 110 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. 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 2021 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 2021 which satisfied these requirements and continue to ensure availability of safe drinking water to present and future generations.

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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, followed by the Interim Enhanced Surface Water Treatment Rule (IESWTR) in 2002 (US EPA, 1989; US EPA, 2002), to ensure that public water supply systems that use surface water, or groundwater under direct influence of surface water, provide safeguards against the contamination of water by viruses and bacteria. These regulations require filtration by every surface water supplier unless strict source water quality criteria and watershed protection goals can be met, including the development and implementation of a detailed watershed protection plan. DWSP and MWRA have maintained a joint waiver for the filtration requirement of the SWTR since 1998 and work together to manage the water supply watersheds in fulfillment of the waiver[3].

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

This annual summary is intended to meet the needs of watershed managers, the interested public, and others whose decisions must reflect water quality considerations. The following pages summarize and discuss water quality monitoring methods, results, and major findings from all water quality and hydrological monitoring activities carried out by DWSP in the Wachusett Reservoir watershed during 2021. Additionally, some background information is included for context and programmatic status updates are provided to document changes in monitoring programs. Data generated from water quality monitoring in 2021 and prior years are available upon request.

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

The remainder of Section 1 provides an overview of the water quality regulations applicable to the water resources of the Wachusett Reservoir watershed, summarizes DWSP goals and objectives with respect to its water quality monitoring programs and includes an overview of the MWRA water supply system and Wachusett Reservoir watershed. Section 2 presents methods for water quality monitoring programs in 2021, including an overview of monitoring locations, the parameters monitored and their manner of analysis, and documentation of statistical methods and data management tools utilized. Section 3 presents results for all Wachusett Watershed monitoring programs. Conclusions and recommendations are offered in Section 4, where significant findings are discussed and any proposed changes to Wachusett Watershed water quality monitoring programs are presented. References are listed in Section 5 and additional information and data are provided in the Appendices.

1.1 Public Water Supply System Regulations

Water quality criteria in the SWTR rely on an indicator organism, fecal coliform bacteria, and a surrogate parameter, turbidity, to provide a measure of the sanitary quality of the water. The SWTR requires that fecal coliform concentrations at the intake of an unfiltered surface water supply shall not exceed 20 colony-forming units (CFU) per 100-mL in ninety percent of the samples in any six-month period. There are two standards for turbidity levels at source water intakes. The SWTR requires that turbidity levels at the intake are below 5.0 NTU at all times[5]. Massachusetts Department of Environmental Protection (MassDEP) regulations require that turbidity levels at the point of consumption for all public drinking water remains below 1.0 NTU at all times[6]. Authority to enforce the SWTR has been delegated to MassDEP.

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

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

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

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

1.2 DWSP Monitoring Program Objectives

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[12]. The broadly defined goal for water quality/quantity monitoring programs is:

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

The data obtained from water quality and hydrologic monitoring programs are used to assess current water quality conditions, establish ranges of values for parameters considered normal or typical, screen for excursions from normal ranges, alert staff to potential contamination events, and assess watershed trends. Shorter term studies may be conducted to evaluate specific issues. These programs are re-evaluated with each iteration of the WPP to ensure that they are providing the breadth and depth of information necessary to evaluate the performance of DWSP water quality control programs. Specific water quality and hydrologic monitoring activities are also reviewed and updated by 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 information, and implementing new tools and technologies. It is important to note that monitoring is just one element of a much larger watershed protection program carried out by DWSP. The achievement of water supply protection goals, including specific water quality targets, is dependent upon the coordinated implementation of each of DWSP's many watershed protection programs. The Watershed Protection Act

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

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

1.3 MWRA System and Wachusett Watershed Overview

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

Table 1: 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	Billion gallons
Surface Area at Full Capacity	4,033	Acres
Length of Shoreline	32.6	Miles
Maximum Depth	123	Feet
Mean Depth	49	Feet
Surface Elevation, at Full Capacity	395	Feet, relative to Boston City Base
Typical Operational Elevation	390.5	Feet, relative to Boston City Base

b) Wachusett Reservoir Watershed General Information[15]		
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	20,584	Acres (includes Watershed Preservation Restrictions)
	29.0	(% Total watershed land area)
Other Protected Area	12,263	Acres
	17.2	(% Total watershed land area)

Water from Quabbin Reservoir is transferred to Wachusett Reservoir via the Quabbin Aqueduct Intake at Shaft 12, which outlets into the Quinapoxet River at Shaft 1 just upstream of the Quinapoxet Basin (Figure 1). Quabbin Reservoir water is also transferred directly to three western Massachusetts communities daily

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

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

The Wachusett Reservoir watershed is in central Massachusetts, east of the Ware River and north of Worcester. With a surface area of approximately 6.5 square miles and a shoreline of 32.6 miles, Wachusett Reservoir drains 110 square miles (70,876 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”[16]. 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[17].

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 20,584 acres (29.0%) of watershed area for water supply protection purposes. Including the Reservoir, DWSP owns or controls 32.9% 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*[18] and the *2017 Land Management Plan*[19].

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

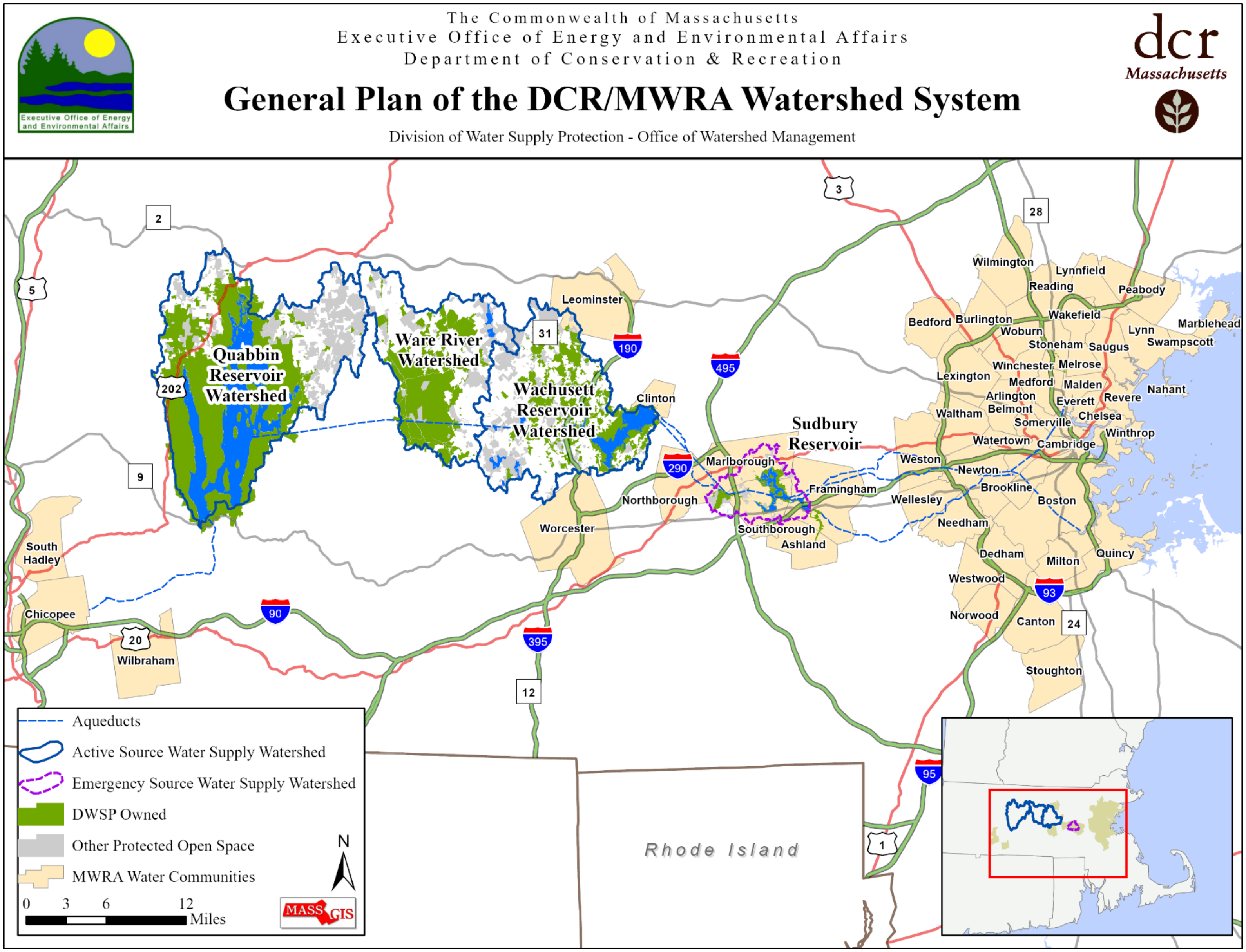

Figure 1: Quabbin Reservoir, Ware River, and Wachusett Reservoir Wastershed System

2 Methods

This section provides an overview of how each element of DWSP water quality and hydrologic monitoring was carried out during 2021, including what parameters were sampled, their monitoring frequency and locations, and methods of analysis. Additional details and information about equipment and techniques used during monitoring activities can be found in standard operating procedures (SOPs) that have been developed for each monitoring activity, which are available upon request.

2.1 Monitoring Programs

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

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

2.1.1 Wachusett Watershed Monitoring Locations

DWSP staff collected routine water quality samples from eight groundwater wells, 20 tributary monitoring stations, and 27 stations on Wachusett Reservoir in 2021. 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 the table below (Table 3). Bacteria sampling is conducted at 23 surface stations situated along transect lines covering the Wachusett Reservoir basins east of Rt. 140 (Figure 3).

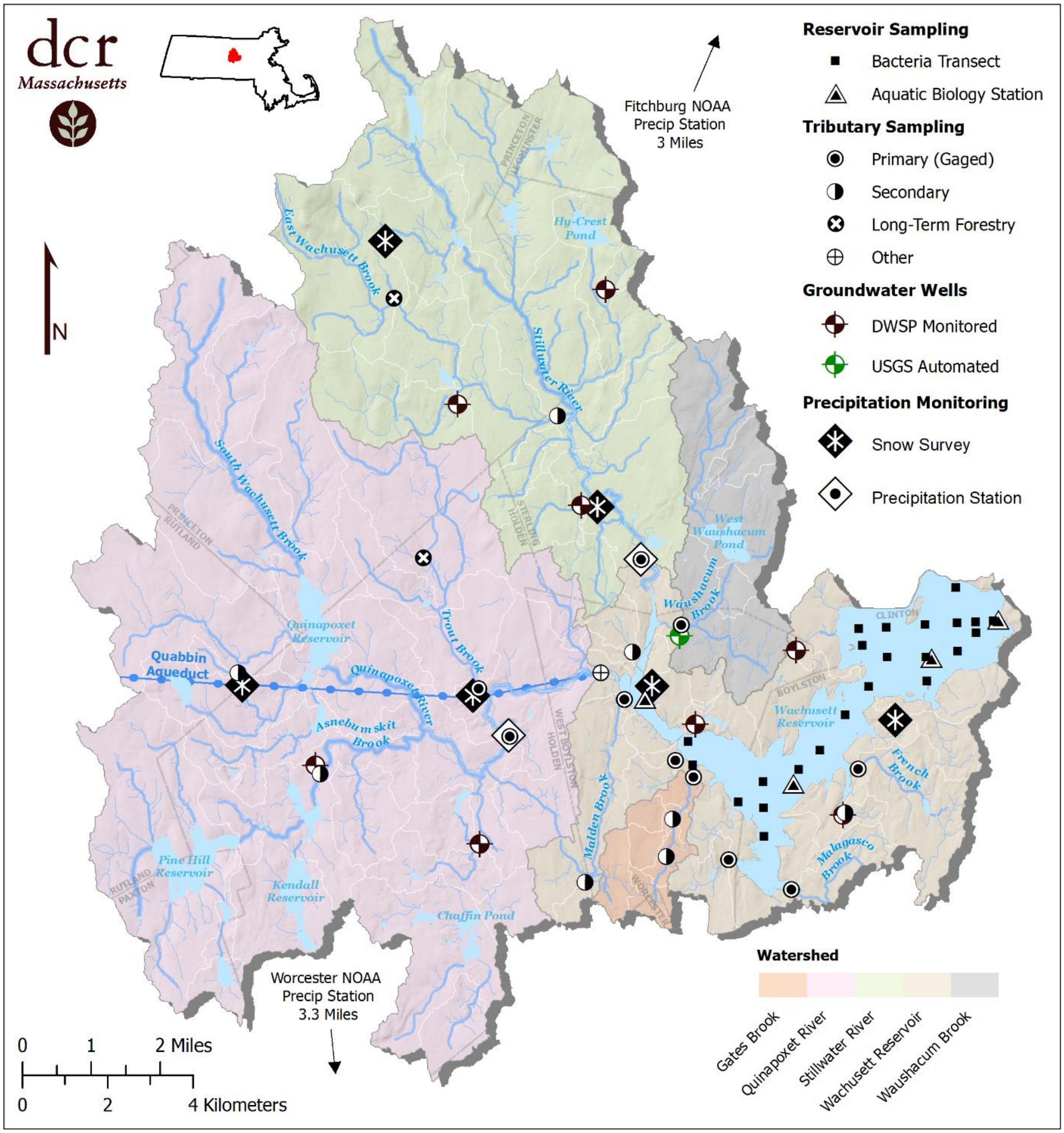

Figure 2: Hydrology, Subbasins, and Water Quality Monitoring Locations for Calendar Year 2021 in the Wachusett Reservoir Watershed

Table 2: Wachusett Tributary Sampling Locations, 2021

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

LTF = Long-term forestry

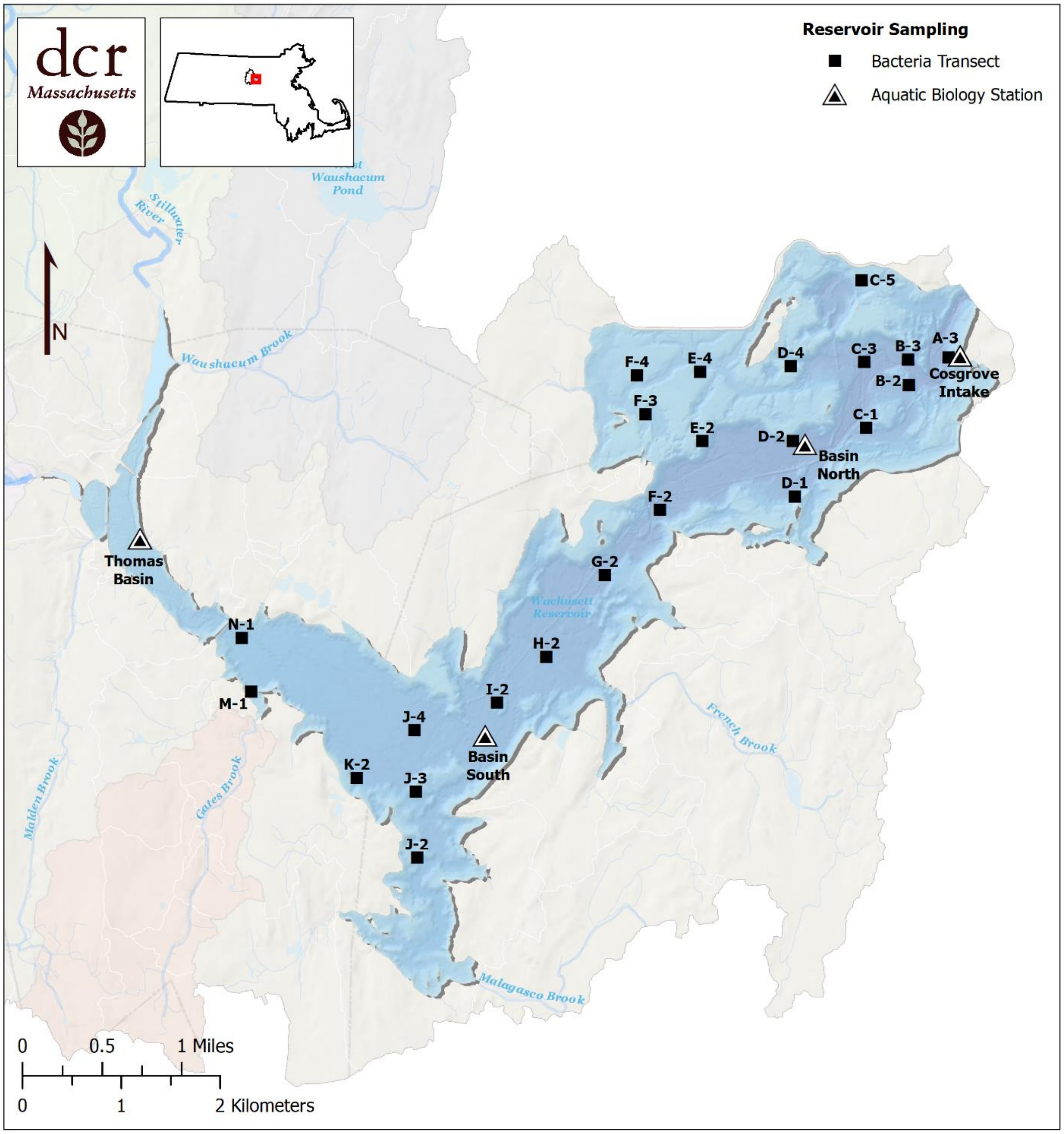

Figure 3: Wachusett Reservoir Sampling Locations

Table 3: Wachusett Reservoir Sampling Locations

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

N/A = Not applicable

2.1.2 Meteorological and Hydrological Monitoring

2.1.2.1 Precipitation and Air Temperature

DWSP monitors precipitation and uses this information to provide context for the water quality and hydrological conditions observed in the tributaries, groundwater, and Reservoir. The type, amount, intensity, frequency, and spatial distribution of precipitation (or snowmelt) across the landscape are the dominant drivers of the water quality and hydrologic dynamics. 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 46.86 inches, with a historical low of 35.36 inches (2001) and high of 61.20 (2018). Average monthly precipitation ranges from 2.97 inches (February) to 4.89 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 (e.g., Gulf of Mexico, Caribbean Sea) Ocean. 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.

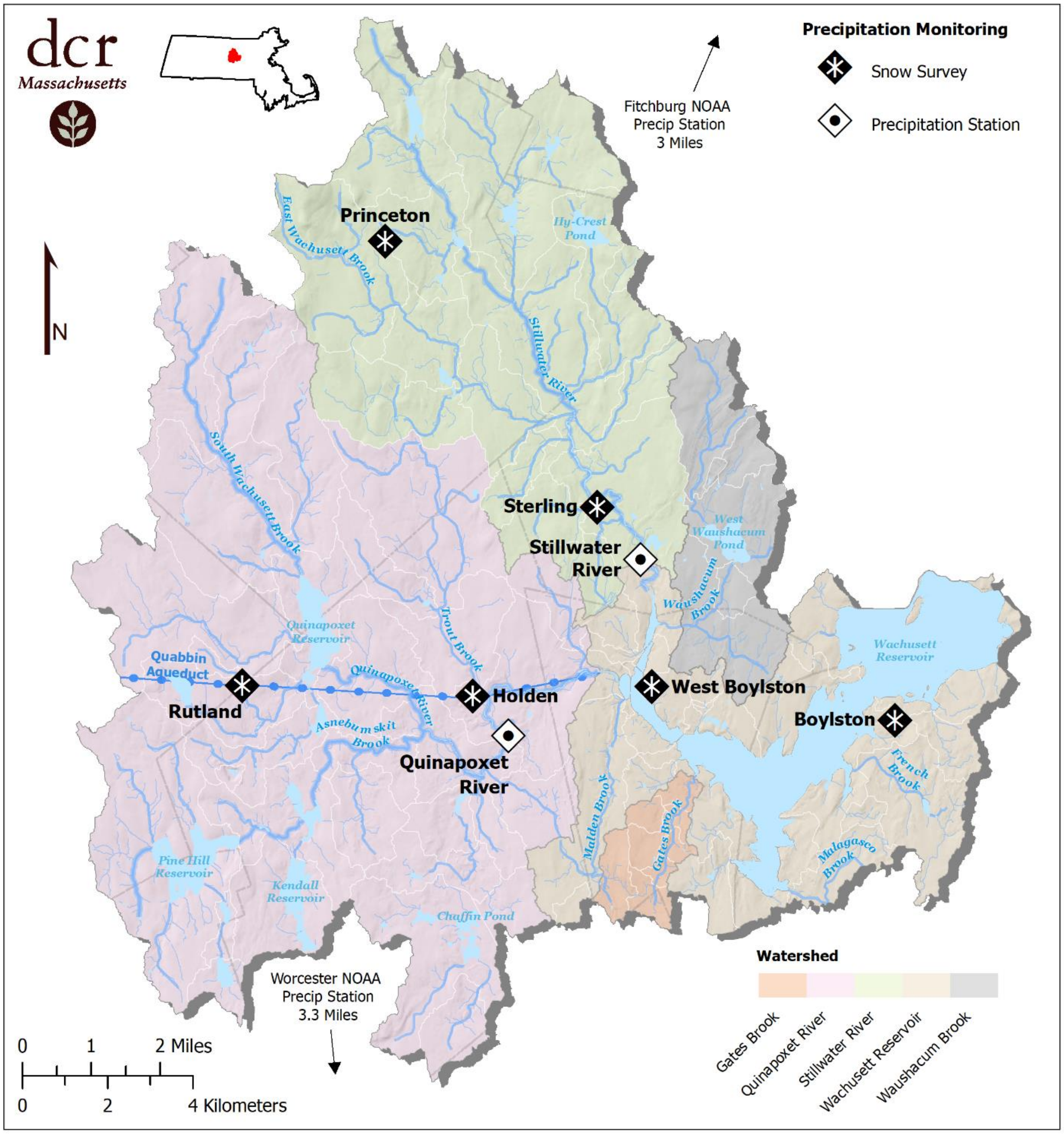

Figure 4: Active Precipitation Monitoring Stations in the Wachusett Reservoir Watershed

2.1.3 Hydrologic Monitoring

2.1.3.1 Streamflow

Streamflow monitoring of stage and discharge (flow) has been conducted at primary tributary sampling locations for more than two decades using both manual and automated methods. The USGS was responsible for the development and maintenance of stage-discharge relationships at these locations and continues to operate three stations (Quinapoxet River – 01095375, Stillwater River – 01095220, and Gates Brook – 01095434) using continuous monitoring technologies. Details about USGS monitoring methods and equipment for these stations can be found the National Water Information System (NWIS) website[20]. 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 4) 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*.

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*.

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.

In 2019 new real-time monitoring instrumentation was added to the Waushacum Brook monitoring station to pilot a viable replacement for aging Onset HOBO dataloggers. The equipment utilizes a Mayfly datalogger[21], 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[22]. 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, with one other station scheduled for installation in 2022.

[20] https://waterdata.usgs.gov/ma/nwis/current/?type=MWRA&group_key=basin_cd
[21] https://stroudcenter.org/news/digital-mayfly-swarm-is-emerging/
[22] https://monitormywatershed.org/sites/WACH-MD01/

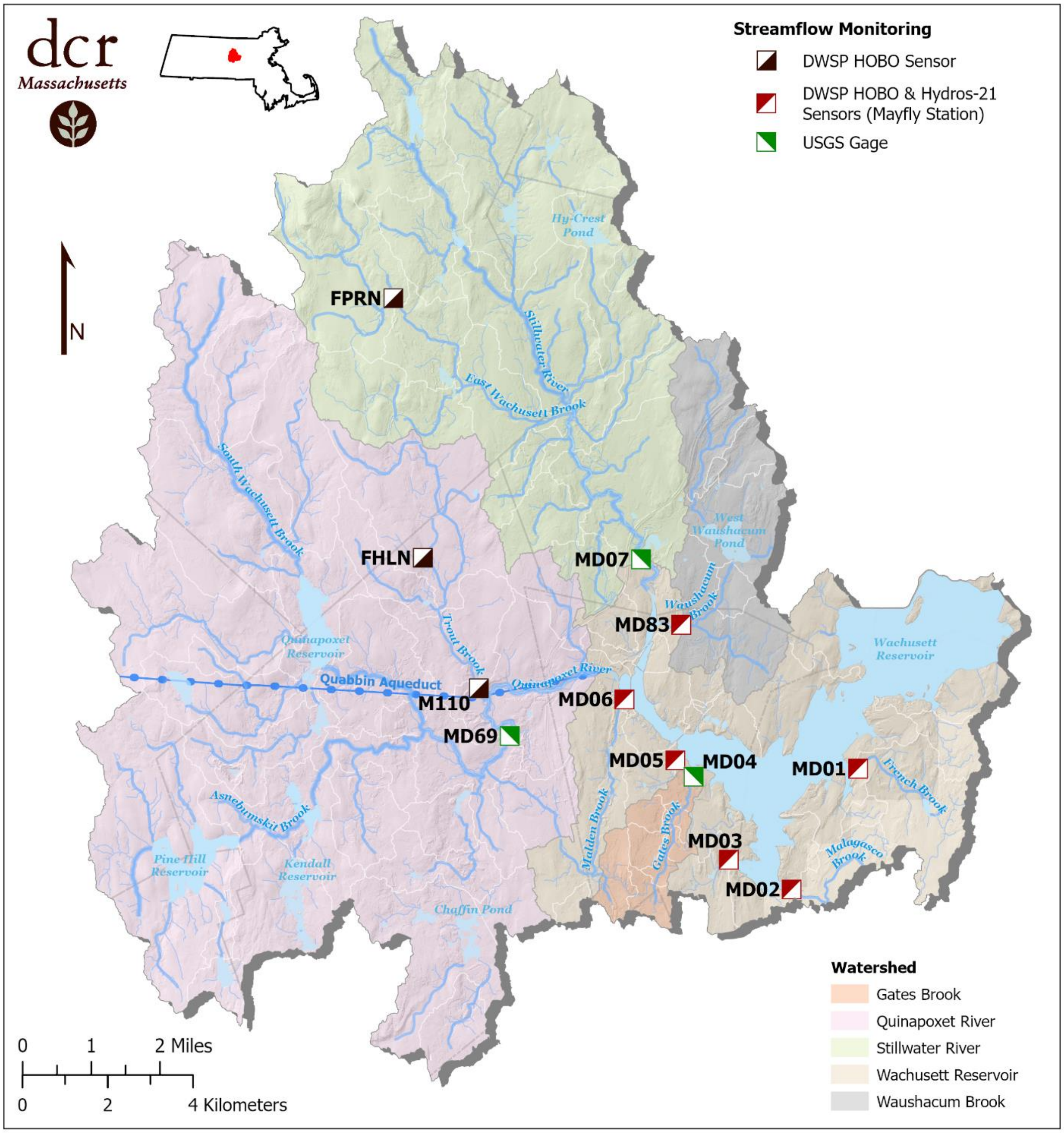

Figure 5: Streamflow Monitoring Locations in Wachusett Reservoir Watershed

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[23]. 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 2021, DWSP continued its partnership with USGS to measure monthly groundwater levels from Sterling - Rt 140 and report them to USGS for the National Water Information System and to DCR Office of Water Resources as part of the statewide hydrologic monitoring network.

An additional seven groundwater wells were sampled monthly in 2021, continuing the expanded groundwater monitoring that began in 2019, primarily due to the increased interest in collecting additional specific conductance/Cl data in the Wachusett Watershed (Figure 26). Water levels are measured as part of this expanded monitoring effort. A total of eight wells are now sampled by DWSP, seven of which were previously monitored by USGS and have historical water level data. The periods of historical data and other summary information about the wells sampled by DWSP can be found in Table 5.

Table 5: Wachusett Groundwater Well Information

DWSP Code	Well Name	USGS Code	Type	Depth (ft)	Elevation (ft)	Historical Period
MDW1	Holden - Wachusett St	422102071501401	Dug	10.5	670	1995 - 2002
MDW2	Boylston - Rt 70	422125071440101	Augered	12.2	475	1995 - 2002
MDW3	West Boylston - Gate 27	N/A	Augered	15.1	403	N/A
MDW4	West Boylston - Rt 110	422334071444201	Augered	29.4	525	1995 - 2002
MDW5	Sterling - Justice Hill Rd	422805071480801	Dug	19.5	710	1947 - 2015
MDW6	Princeton - Rt 62	422636071503601	Augered	21.9	695	1995 - 2002
MDW7	Sterling - Rt 140	422520071483001	Augered	24.4	505	1995 - 2021
MDW8	Holden - Jefferson	422201071530201	Augered	20.3	815	1995 - 2002
WSW26	West Boylston - Prescott St	422341071464901	Augered	16.8	485	2012 - 2021

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 Boylston – Prescott St), which records groundwater levels hourly. Data and information about this USGS monitoring well can be found at the NWIS website[24]. Additional details about groundwater level monitoring are provided in the DWSP *SOP for the Monitoring of Groundwater (WATWEL)*.

[23] Bent, 1999

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

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 2021 (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.

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[25] ensures the samples were representative of the surrounding groundwater. Two wells (Holden – Wachusett St and Sterling – Justice Hill Rd) are dug wells and therefore unable to be fully purged due to the large volumes of water they contain. Additionally, the Holden – Jefferson well has a narrow diameter that prevents purging with a submersible pump. As a result, specific conductance and temperature readings are collected *in situ* without purging and Cl samples were unable to be collected in this well (MDW8). Specific conductance and temperature are measured with a Yellow Springs Instrumentation (YSI) Professional Plus 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 *SOP for the Monitoring of Groundwater (WATWEL)*.

Additional groundwater samples were collected during routine well monitoring to be analyzed for stable isotopes, deuterium (^{2}H) and oxygen-18 (^{18}O). These data will allow DWSP to observe the influence of rain, which contains fewer heavy isotopes, in the samples collected from wells in the Wachusett Watershed. Wells that are better mixed with deeper groundwater show less depletion of heavy isotopes, whereas wells containing a higher proportion of recently infiltrated precipitation show more depletion of heavy isotopes. This monitoring effort is anticipated to lead to a better understanding of groundwater recharge and aquifer dynamics within the Wachusett Watershed.

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

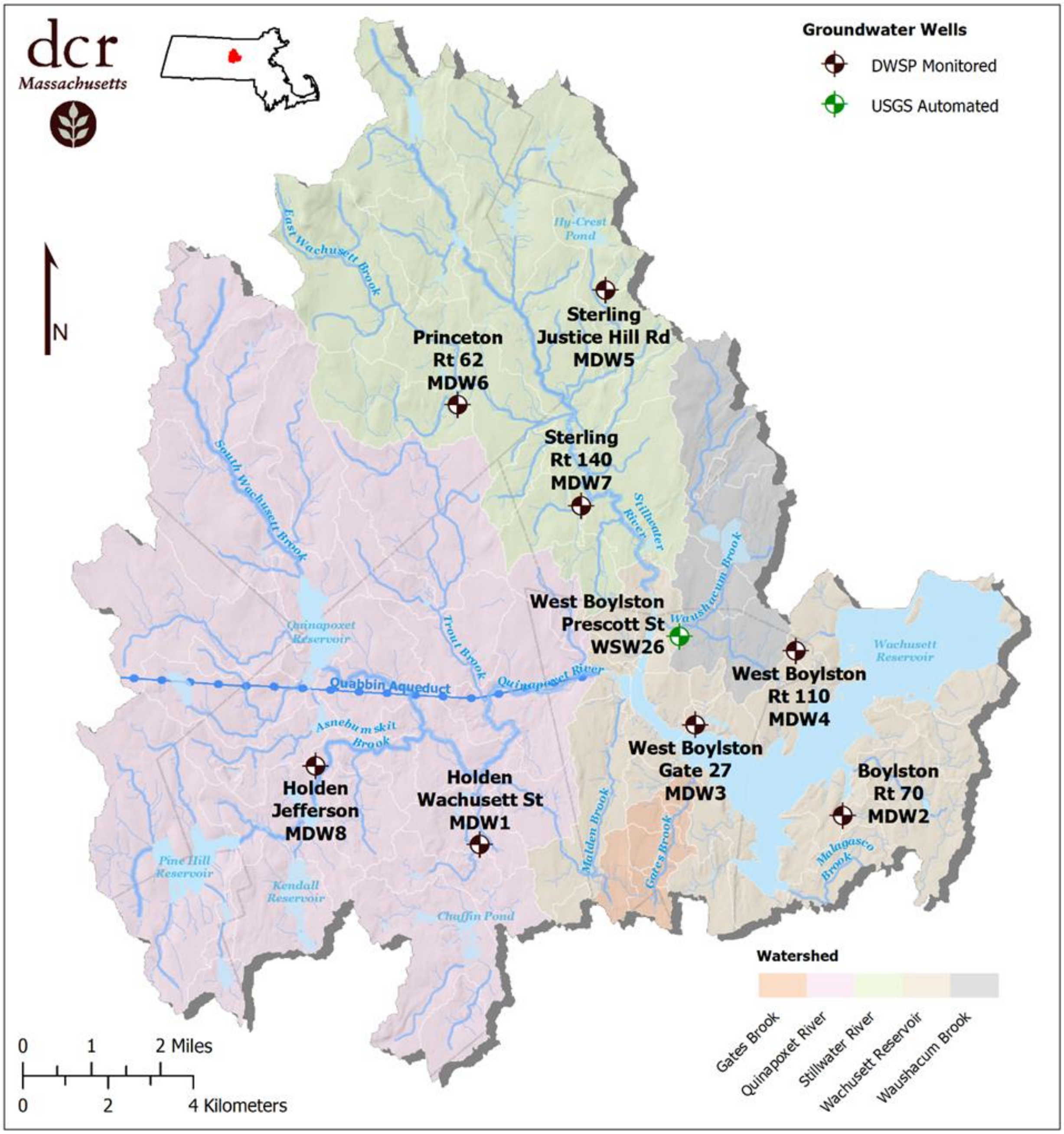

Figure 6: DWSP Groundwater Monitoring Wells in Wachusett Reservoir Watershed

2.1.5 Tributary Monitoring

The principle tributary monitoring programs are divided into two groups: 1) Routine tributary monitoring for bacteria and turbidity (MWRA project code WATTRB) and 2) Nutrient and total suspended solids (TSS) monitoring (MWRA project code WATMDC, referred to as 'nutrient monitoring'). Other tributary monitoring occurs at the two long-term forestry (LTF) project study locations (MWRA project code WATBMP) and short-term forestry (STF) monitoring locations (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 2021, routine water quality samples for bacteria, turbidity, and field parameters were collected from eighteen stations on seventeen tributaries. Each tributary station was visited every other week throughout the entire year (Table 2 – Primary and Secondary). 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)*.

2.1.5.2 Nutrient Monitoring

In 2021, 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[26], ammonia-nitrogen (NH_3-N), chloride (Cl), UV absorbance at 254 nm (UV_{254}), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), total Kjeldahl nitrogen (TKN), total organic carbon (TOC), total phosphorus (TP), and total suspended solids (TSS). All samples were analyzed at the MWRA lab on Deer Island. Nutrient measurement units are all mg/L with the exception of UV_{254}, which is reported in ABU/cm and TP which is reported in µg/L. Since the Quabbin Transfer comprises such a significant volume of water to Wachusett Reservoir, Shaft 1 is sampled for nutrients as well, usually monthly (when flowing). All primary tributaries were sampled 12 times for nutrients in 2021. The Quabbin Transfer was sampled six times in 2021. 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)*.

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

Table 6: 2021 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 2021
Nutrients	WATMDC	NH_3-N, NO_2-N, NO_3-N, TKN, TP, TSS, TOC, UV_{254}, Cl, Alkalinity	Monthly	Primary, Other	128*
Bacteria and Turbidity	WATTRB (Only for bacteria)	*E. coli*, turbidity	Twice per Month	Primary, Secondary	432 (*E. coli*) 448 (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	567
		Stage		Primary	446
Long-term Forestry	WATBMP	NH_3-N, NO_2-N, NO_3-N, TKN, TP, TSS, TOC, UV_{254} + Field Parameters	Monthly/Quarterly Storms	LTF	24* (monthly) (13* samples from 1 storm)
Short-term Forestry	N/A	Turbidity	Varied	17 timber harvest lots (not mapped)	187

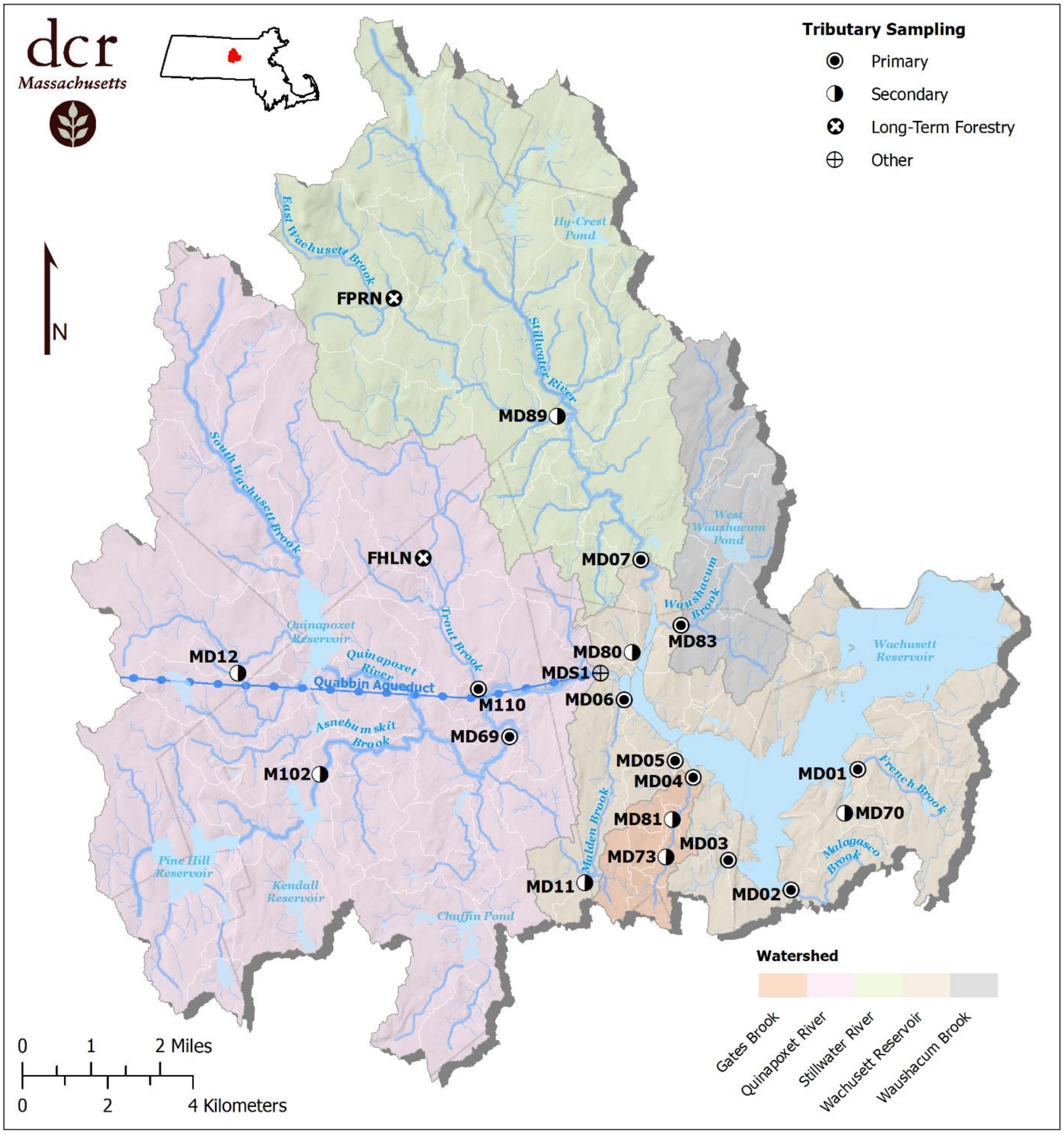

Figure 7: Tributary Sampling Locations in the Wachusett Reservoir Watershed

2.1.6 Reservoir Monitoring

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

Table 7: 2020 Reservoir Monitoring Program Components

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

Program Name	MWRA Project Code	Parameter or Analysis	Typical Sampling Frequency	Sample Locations	# Samples Collected in 2021
Profiles	N/A	Water temperature, specific conductance, chlorophyll *a*, phycocyanin, dissolved oxygen, pH	Weekly (May – Sept), semi-weekly (Oct – April)	Primary: BN3417, CI3409, Secondary: BS3412, TB3427, other	58
Phytoplankton	N/A	Phytoplankton density	Weekly (May – Sept), semi-weekly (Oct – April)	Primary: BN3417, CI3409, Secondary: BS3412, TB3427, other	114
Nutrients	WATMDC	Alkalinity, NH_3-N, NO_3-N, Silica, TKN, TP, UV_{254}	Quarterly (4x)	BN3417, BS3412, TB3427	40*
Bacteria	WATTRN	*E. coli*	Monthly (minimum)	23 transect stations	322
Macrophytes	N/A	Species present, location, density	Throughout growing season	Entire reservoir	n/a
Zooplankton	N/A	Population screening	Quarterly (4x)	BN3417, BS3412, TB3427	48
Lake Trout	N/A	Species, length, weight	Multiple sample trips during fall spawn	Entire reservoir – spawning locations	See Section 3.4.10

2.1.6.1 Water Quality Profiles

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

A total of 58 profiles were collected from four locations in 2021. These included 12 profiles collected in conjunction with reservoir nutrient monitoring.

Three remote sensing profiling buoys have been deployed annually by MWRA starting in 2016. In 2021 these buoys correspond to DWSP routine sampling sites at Basin South and Basin North. An additional profiling buoy was placed outside of Cosgrove Intake. Profiles are collected with YSI EXO2 sondes identical to those used by DWSP. The profilers automatically run every 6 hours (12am, 6am, 12pm, and 6pm) and collect data at 1-m increments. The data can be viewed remotely shortly after collection via the MWRA Operations Management Monitoring System (OMMS) website. Results are frequently used by DWSP to augment the routine profile/plankton sampling program. For example, if elevated chlorophyll *a* values are observed in remote sensing data, DWSP may sample earlier than scheduled to capture associated phytoplankton data. The high frequency profile data also allows for identification and visualization of diurnal patterns and both short and long-term effects of environmental forces such as cooling temperatures during turnover and seiche effects due to wind events.

2.1.6.2 Nutrient Monitoring

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

2.1.6.3 Bacteria Monitoring

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

2.1.6.4 Phytoplankton Monitoring

Routine monitoring for phytoplankton follows a seasonal schedule with samples collected every other week from October through April and at least once per week from May through September. Sampling frequency may intensify in response to increases in density of specific phytoplankton genera (see Section A-18, Table A-2), or decrease when conditions such as ice cover physically prevent sampling. Monitoring by DWSP staff takes place at either Basin North (BN3417) or at the Cosgrove Intake Facility (CI3409) with additional locations sampled as necessary to characterize the phytoplankton community present throughout the reservoir. Grab samples are typically collected from at least two depths including an epilimnion sample at 3 m and (during stratification) a metalimnion sample. The exact depth of the latter is typically selected based on results of a water column profile collected in conjunction with phytoplankton sample collection. Chlorophyll *a* data obtained from the reservoir profile are typically used to select the discrete metalimnion sample depths, typically corresponding to depths where chlorophyll *a* values are highest. More information on sampling protocols and details of phytoplankton sample collection and enumeration may be found in the following DWSP SOPs: *SOP Collection of Reservoir Profiles*, *Phytoplankton Collection and Reporting* and *Microscopic Enumeration of Phytoplankton*. A change in enumeration method for *Microcystis aeruginosa* was made in late September: the method described in the *Microscopic Enumeration of Phytoplankton* document for counting *Dolichospermum* was implemented along with area measurements of all *Microcystis aeruginosa* colonies observed in the S-R Cell.

In 2021, phytoplankton monitoring was carried out on 47 days, resulting in 114 individual samples. The entire phytoplankton community was assessed in all samples except for four which were analyzed solely for taxa of concern (see Section A-18, Table A-2). Three increases in taste and odor producing

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[27] Worden & Pistrang, 2003

phytoplankton genera were documented through routine monitoring requiring an increase in monitoring frequency for a total of eight weeks in 2021.

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*.

2.1.6.6 Macrophyte Monitoring

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

DWSP staff conducted surveys of the entire reservoir shoreline in 2021 (see Section 3.5.2.1). Additional surveys were conducted in support of ongoing management programs including physical AIS management in the reservoir and herbicide treatment projects in three local pond systems: Clamshell Pond in Clinton, the Lily Ponds in West Boylston, and South Meadow Pond Complex in Clinton and Lancaster.

2.1.6.7 Fish Monitoring

Surveys of two important Wachusett Reservoir fish populations, Rainbow Smelt and Lake Trout, were completed in 2021. Shoreline surveys for *Osmerus mordax* (Rainbow Smelt) spawning activity were carried out in early spring. *O. mordax* are considered an important prey species in the reservoir and there is evidence that Rainbow Smelt abundance in other waterbodies is correlated with *Salvelinus namaycush* (Lake Trout) condition and length at catch[28]. *S. namaycush* are the target of an annual mark and recapture study, which DWSP conducts each year in cooperation with MassWildlife.

2.1.7 Additional Watershed Monitoring and Special Studies

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

[28] Stolarski, 2019.

2.1.7.1 Forestry Monitoring

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

Long-term Forestry Monitoring

Two locations in the Wachusett Reservoir watershed have been established for long-term monitoring of the potential impacts of timber harvesting on water quality. This project involves collection of water quality and flow data downstream of a timber lot that will be sold and harvested and downstream of a second lot (control) that will not be harvested. Monitoring for this study will span a period of at least ten years, with at least five years of sampling occurring both pre- and post-harvest. Eight 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)*.

Short-term Forestry Monitoring

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

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 2021. A separate storm sampling report will be produced providing a detailed summary and analysis of the 46 storms that were sampled at routine

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[29] DWSP, 2018b

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

2.1.7.3 Stormwater Basins

Monitoring of the stormwater basins located on either side of the Route 12/140 causeway was initiated in summer 2019. Baseline vegetation data were collected along shoreline transects of each forebay and within the constructed wetlands. Water temperature, pH, dissolved oxygen, and specific conductance were recorded with a YSI Professional Plus multi-sensor meter at inlet and outlet locations of each forebay at least monthly from July through December. Photographic documentation of vegetation and water level was also recorded using a customized ESRI Collector application. These data will be used to assess 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 2021 Watershed Monitoring Parameters

In 2021, 23 distinct physical, chemical, and biological parameters were monitored across all water quality and hydrologic monitoring programs throughout the Wachusett Reservoir watershed (Table 8)[30]. These parameters were selected because they either directly affect water quality or can indicate potential water quality issues. Criteria or regulatory standards exist for many of these parameters for aquatic life protection, drinking water supply, 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 2021 are presented and discussed in Section 3.

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[30] Additional groundwater parameters were added in May 2021, however these are not discussed in this report and will be included in the 2022 Annual Water Quality Report

Table 8: 2021 Monitoring Parameters

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

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

2.3 Statistical Methods and Data Management

All numerical calculations and related graphics were generated using the R programming language[31] and preserved in scripts, which document the exact steps that were utilized to produce the 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[32]. 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 four or more values are detected in a data group, statistics are calculated using functions from the NADA package[33]. 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 report 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[34] 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 2021 and prior years are available upon request.

[31] R Core Team, 2019
[32] Wickham, 2016
[33] Lee, 2022
[34] Chang et al., 2019

3 Results

In 2021, DWSP staff analyzed 432 turbidity samples from 17 tributaries and 114 phytoplankton samples from the reservoir. A total of 2,270 physiochemical measurements (571 each of temperature and specific conductance; 564 of dissolved oxygen and pH) were taken in the field at tributary stations and Shaft 1, with another 58 water column profiles (temperature, specific conductance, dissolved oxygen, percent oxygen saturation, chlorophyll *a*, phycocyanin, and pH) recorded from the reservoir. A total of 754 bacteria samples were collected and delivered to the MWRA Southborough laboratory for *E. coli* analysis (432 from tributaries and 322 from the reservoir), and 1,645 samples (1,393 tributary, 252 reservoir) were collected and shipped to the MWRA Deer Island laboratory for a total of 2,399 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 2021.

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 2021 ranged from -12.4 °C (January 29) to 26.7 °C (June 29) (Figure 8). The lowest daily minimum temperature (average of all stations) observed in 2021 was -19.59 °C on January 31, while the highest daily maximum temperature was 33.9 °C on June 30.

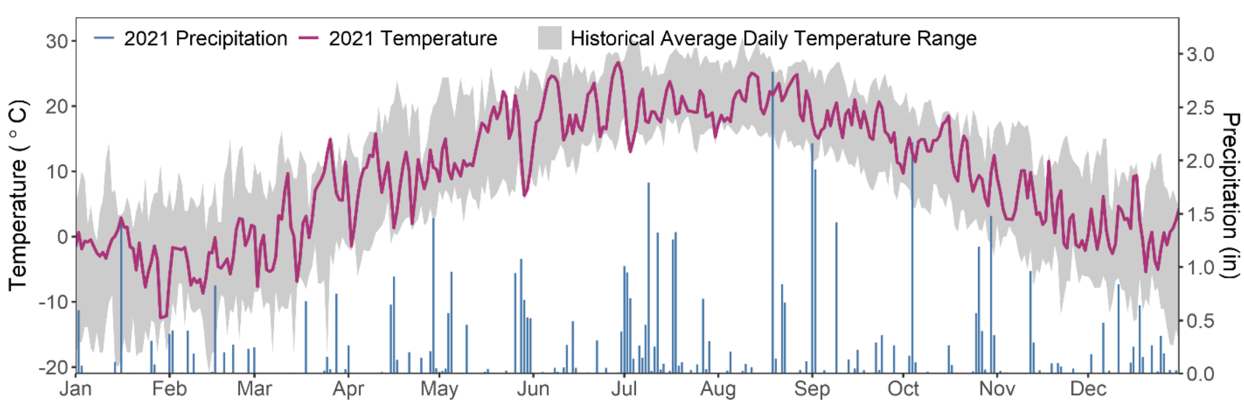

Figure 8: Climatograph of Daily Mean Temperatures and Daily Precipitation Totals for Wachusett Watershed from January 1 through December 31, 2021

Shaded band represents average daily temperature ranges from 1998 – 2021.

All monthly average temperatures were within historical ranges, except for July (19.2°C), which was nearly 2 degrees below the lowest historical monthly mean temperature for that month. Nine months in 2021 had above normal temperatures and three below (Figure 9). The mean annual temperature for 2021 was 9.65 °C, which was the same as in 2020 and 0.5 degrees above normal.

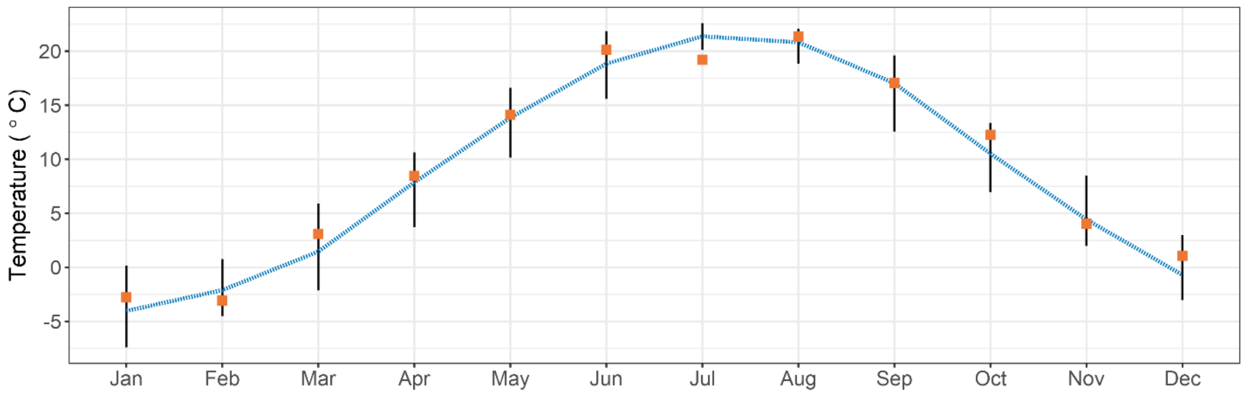

Figure 9: Wachusett Reservoir Watershed Monthly Mean Temperatures for 2021
Monthly mean temperatures for 2021 (orange squares) are shown in relation to the long-term average monthly temperatures (blue dashed line). The vertical black lines indicate the minimum and maximum monthly mean temperatures over the period of record, which began in 1998.

3.1.1.2 Precipitation

As illustrated by Figure 10, Wachusett Reservoir watershed received above average precipitation in 2021, with 54.8 inches of rainfall (7.93 inches more than average annual precipitation).

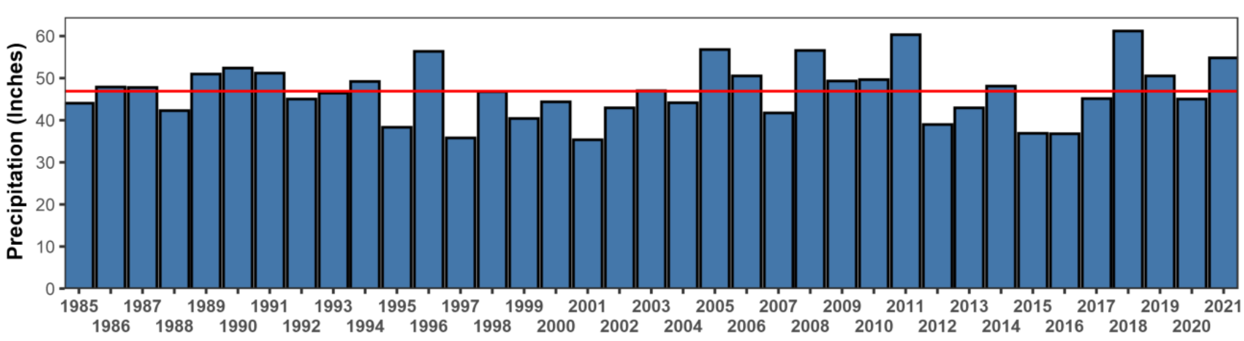

Figure 10: Annual Precipitation for Wachusett Watershed, 1985 to 2021
The red line indicates the long-term average annual total precipitation.

In late February, the calendar year cumulative precipitation dropped below normal and a mild (level 1) drought was declared for the Central Massachusetts Region in early April. The drought status was updated to normal (level 0) in early May due to surplus precipitation during April[35]. June was the driest month of the year with only 1.76 inches of precipitation. July was the wettest month of 2021 (11.16 inches), which was more than 7 inches above normal and the wettest July on record for Worcester County[36]. Additionally, August through October all received above average precipitation, which kept streamflows and groundwater levels much higher than usual for those months of the year. Noteworthy storms in 2021 occurred August 19 (2.83 inches), September 1-2 (4.08 inches), October 4 (2.17 inches). Small and medium storms were numerous throughout 2021, with 15 days receiving at least one inch of precipitation, 36 days with at least 0.5 inches, and 69 days with at least 0.2 inches. As one of the wetter years since 1985, the numerous days with rainfall directly influenced the solute concentrations observed in the tributaries throughout the year.

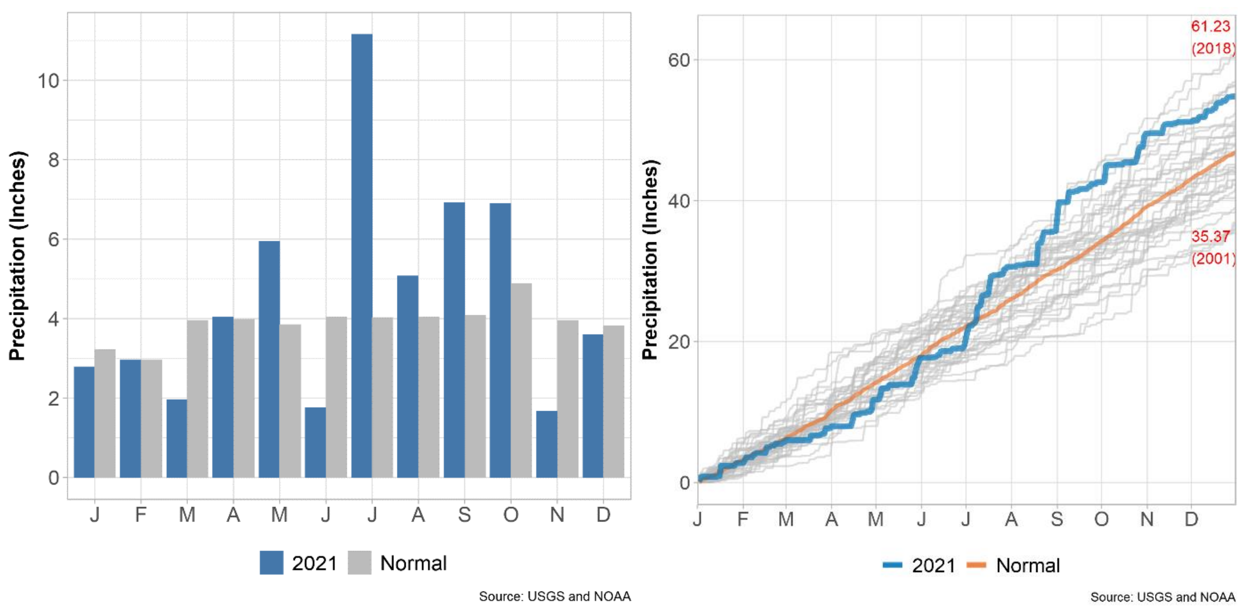

Figure 11: Wachusett Watershed Monthly Total (left) and Daily Cumulative Precipitation (right) for 2021

Table 9: Monthly Total Precipitation for 2021 and Statistics for the Period of Record 1985 to 2021

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Precipitation (in)	2.79	2.97	1.96	4.04	5.94	1.76	11.16	5.08	6.93	6.9	1.67	3.6	54.8
Normal (in)	3.22	2.97	3.95	3.99	3.85	4.04	4.03	4.05	4.09	4.89	3.96	3.83	46.87
Departure (in)	-0.43	0	-1.99	0.05	2.09	-2.28	7.13	1.03	2.84	2.01	-2.29	-0.23	7.93
Years	37	37	37	37	37	37	37	37	37	37	37	37	

Snow

Figure 12 shows the snowpack measurement results for calendar year 2021. 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.

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[35] MA Drought Management Taskforce, 2021

[36] Need NWS or NOAA citation here

The first accumulation of snowpack in 2021 occurred in late January and early February, totaling 11.5 inches (Watershed average) by the week 5 survey. Snowpack depth and SWE increased again the following week, followed by a period of compaction, without much SWE loss. Snowpack increased again by the week 8 survey before rapidly diminishing over the following two weeks leaving insufficient snowpack to measure by March 17 (week 11). Total precipitation for the winter months of 2021 was below normal and the lack of late winter snowpack contributed to the drought conditions that arose in the late spring and early summer. More detailed information was recorded in snowpack reports that were produced for the two weeks that a measurement was taken.

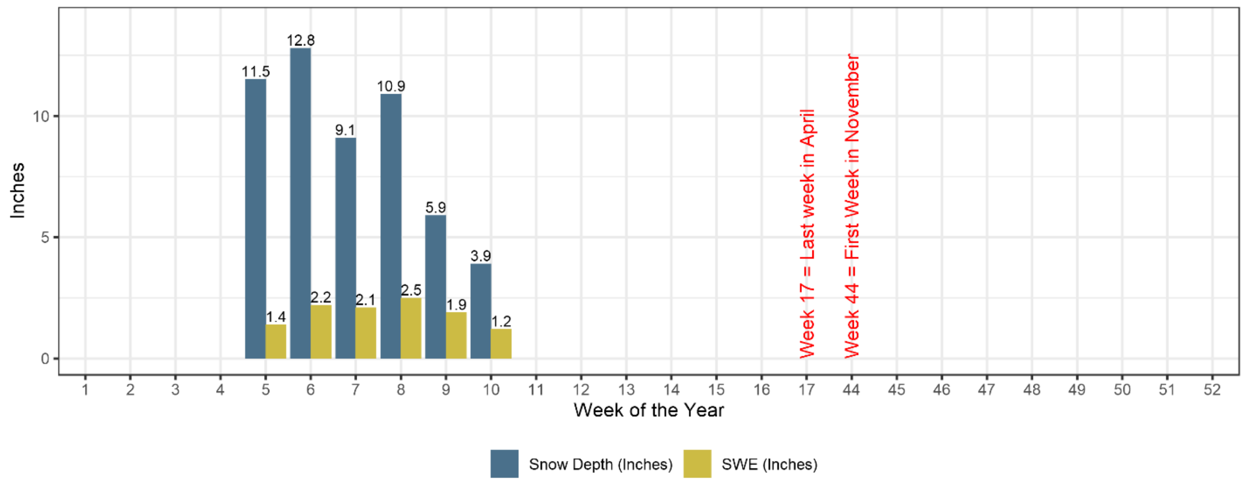


Figure 12: Snowpack Measurements in 2021
SWE = Snow-water-equivalent.

3.1.2 Groundwater Levels

Results of groundwater level monitoring are presented in Figure 13. During the 2021 sampling period all wells had measurable water levels every month. Water levels are shown in comparison with monthly historical ranges for all wells except West Boylston - Prescott St, which has daily historical ranges presented due to the availability of eight years of automated water level measurements by USGS. When compared with these historical ranges, groundwater levels can be indicative of drought or excess saturation water in the watershed. The historical ranges of groundwater levels will become more robust as groundwater levels continue to be monitored.

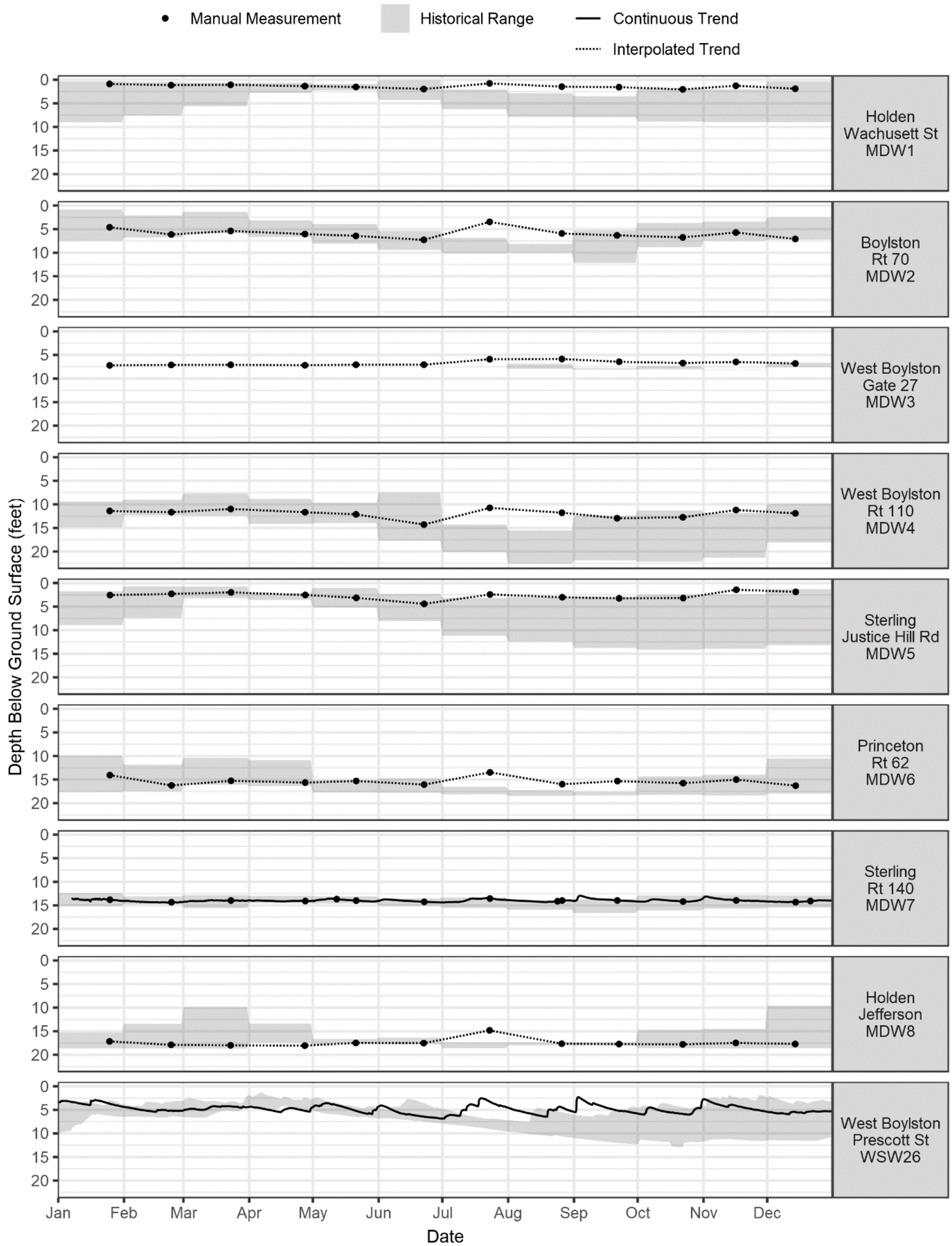


Figure 13: Wachusett Groundwater Depth Measurements in 2021 With Historical Ranges for Comparison

3.1.3 Streamflow and Quabbin Transfer

The total surface water inflow to Wachusett Reservoir in 2021 was estimated to be 101.6 billion gallons; about 30% more than in 2020. The seasonal hydrologic patterns typical of Wachusett Watershed were mostly absent in 2021, driven by a negligible late winter snowpack, excess precipitation in the months July – October, and a record cold July. The usual springtime high flows and summertime low flows did not occur in 2021 and streamflows stayed at moderate levels throughout the entire year.

Water transfers from the Quabbin Reservoir comprised 48% of the total surface water inflow in 2021, which is about 8 billion more gallons than in 2020 despite the increased inflows the Wachusett Reservoir from the watershed tributaries. Surplus water from the Quabbin Reservoir, which has lower concentrations of nutrients and chloride, was moved to Wachusett Reservoir in 2021 to displace a larger volume of local water and improve overall reservoir water quality. Figure 14 shows a breakdown of annual total flow (MG) among all the tributaries as well as ungaged areas and the Quabbin Transfer. About 33% of surface water inputs came from the Quinapoxet and Stillwater Rivers, while about 18% was contributed by the smaller tributaries and ungaged areas.

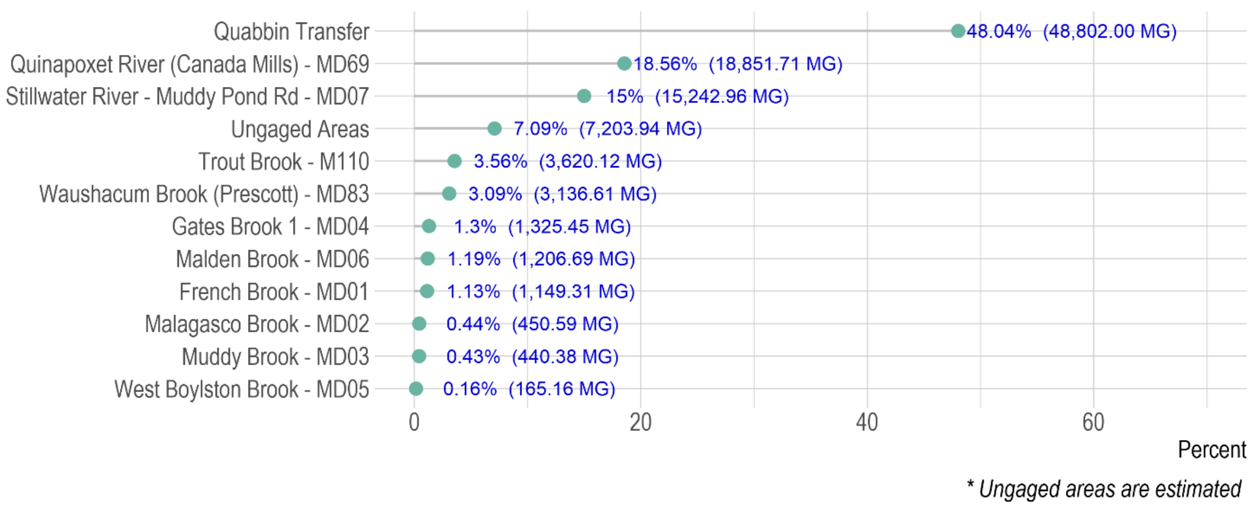


Figure 14: Wachusett Reservoir Surface Water Inflows for 2021

Total annual discharges for the Quinapoxet and Stillwater Rivers for 2021 were 16% and 10% above average, respectively (Figure 15).

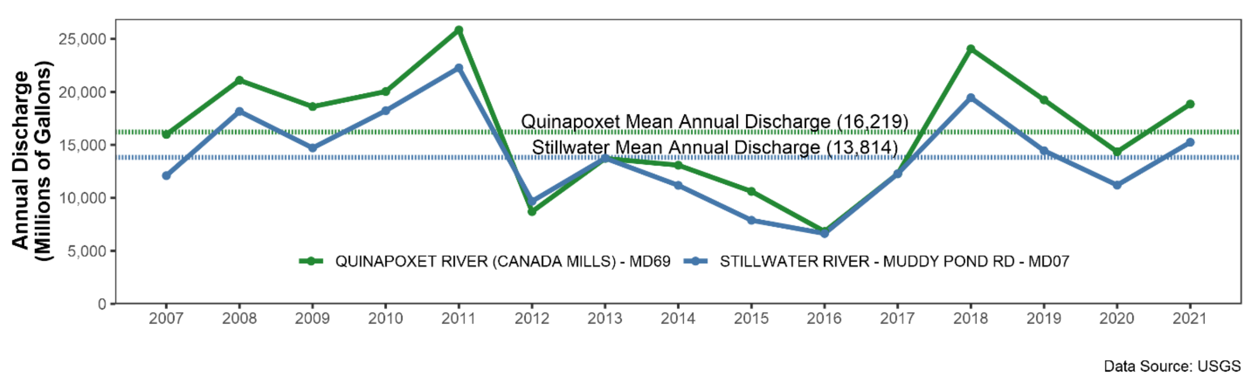


Figure 15: Annual Discharge in the Quinapoxet and Stillwater Rivers (MG) (2007 to 2021)

Table 10 provides summary statistics of surface water discharge for 2021. Daily flow rates in the smaller tributaries ranged from 0.06 cfs at West Boylston Brook to 239.1 cfs at Trout Brook. The maximum instantaneous flows at these tributaries ranged from 8.2 cfs at West Boylston Brook to 364.7 cfs at Trout Brook.

Table 10: 2021 Flow Statistics for Wachusett Reservoir Tributaries

Location	Min Daily Flow (CFS)	Ave Daily Flow (CFS)	Max Daily Flow (CFS)	2021 Peak Inst. Flow (CFS)	Min Month Vol (MG)	Ave Month Vol (MG)	Max Month Vol (MG)	2021 Total Vol (MG)
French Brook - MD01	0.09	4.85	78.3	121.6	32.4	95.8	185.9	1,149
Gates Brook 1 - MD04	1.47	5.62	56.3	122.0	65.9	110.5	210.4	1,325
Malagasco Brook - MD02	0.55	1.90	13.2	22.6	22.1	37.6	62.1	451
Malden Brook - MD06	1.47	5.10	28.9	60.1	61.1	100.6	171.1	1,207
Muddy Brook - MD03	0.27	1.86	16.8	39.7	18.8	36.7	54.3	440
Quinapoxet River - MD69	14.6	79.91	785.0	1,250.0	859.6	1,570.9	2,187.9	18,852
Stillwater River - MD07	5.88	64.61	775.0	1,130.0	544.9	1,270.2	1,737.1	15,243
Trout Brook - M110	1.45	15.3	239.1	364.7	158.1	301.7	457.0	3,620
Waushacum Brook - MD83	1.36	13.26	86.0	138.8	154.9	261.4	433.3	3,137
West Boylston Brook - MD05	0.06	0.70	8.2	54.2	5.2	13.8	30.5	165
Ungaged Areas*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7,204
Quabbin Transfer	N/A	N/A	N/A	N/A	N/A	N/A	N/A	48,802

* Estimated

The annual discharge totals for the smaller tributaries are presented in Figure 16. Trout Brook contributed the largest water volume to Wachusett Reservoir of the smaller tributaries with 3,620 MG (~3.56%), while Waushacum Brook contributed 3,137 MG (~3.09%) of the surface water inflow to the reservoir. The other gaged small tributaries combined to contribute less than 5% of the surface water inflows to Wachusett Reservoir. Non-gaged areas contributed approximately 7% of the total inflows (estimated).

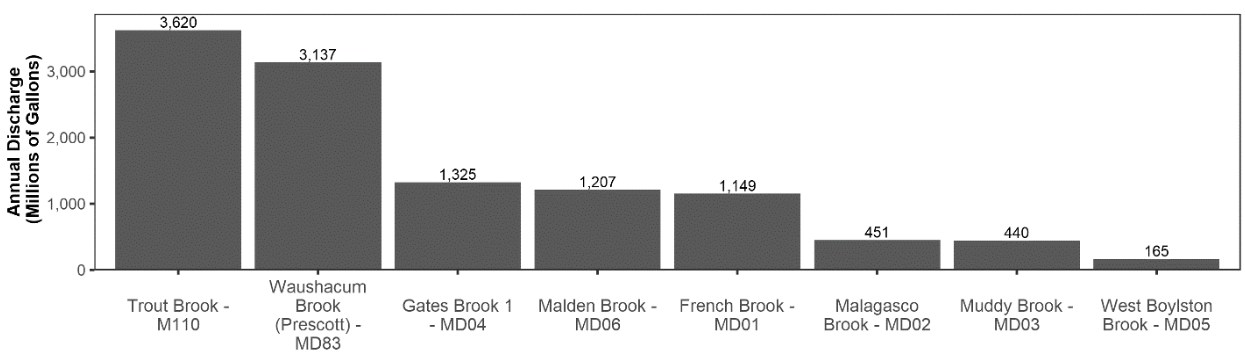


Figure 16: Annual Discharge (MG) for Smaller Gaged Wachusett Tributaries for 2021

As previously mentioned, monthly tributary flows departed from their typical seasonal patterns during 2021 (Figure 17). Flows were lower than normal in the spring months and highest in the late summer and early fall. The higher summertime flows did have an impact on water quality, as the excess precipitation caused more flushing of nutrients, sediment, bacteria and other particles from the watershed landscape.

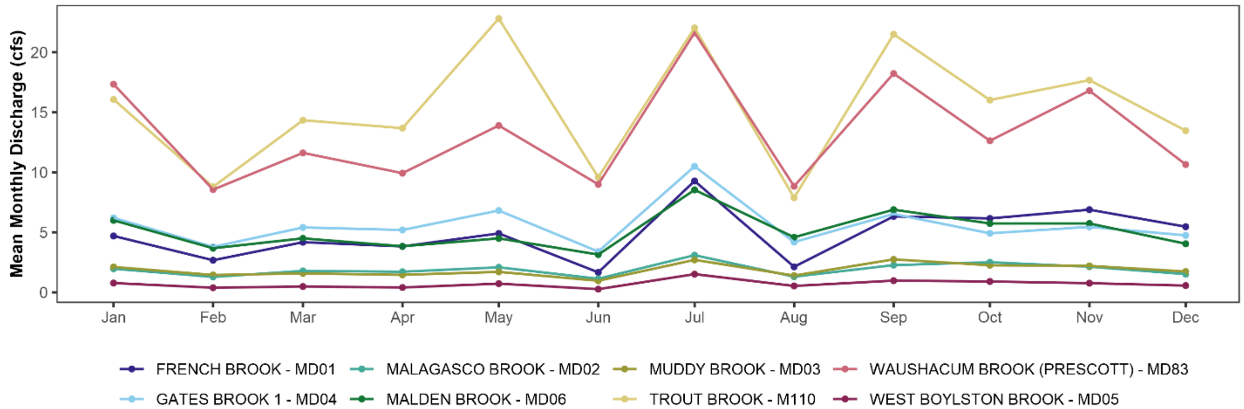


Figure 17: Mean Monthly Discharge in Smaller Wachusett Tributaries (CFS) in 2021

Monthly discharges in the Quinapoxet and Stillwater Rivers for 2021 were below normal in February, March, April and December. The Stillwater River monthly discharge was also below normal for June. Monthly flows from July – November were much higher than normal (more than double), reaching their highest levels for the year in the months that are usually the lowest.

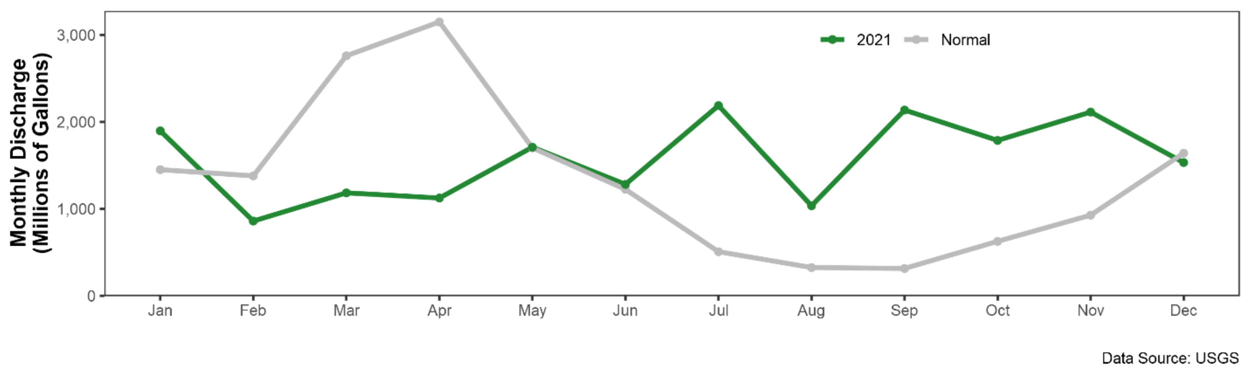


Figure 18: Monthly Discharge in the Quinapoxet River (MG) 2021

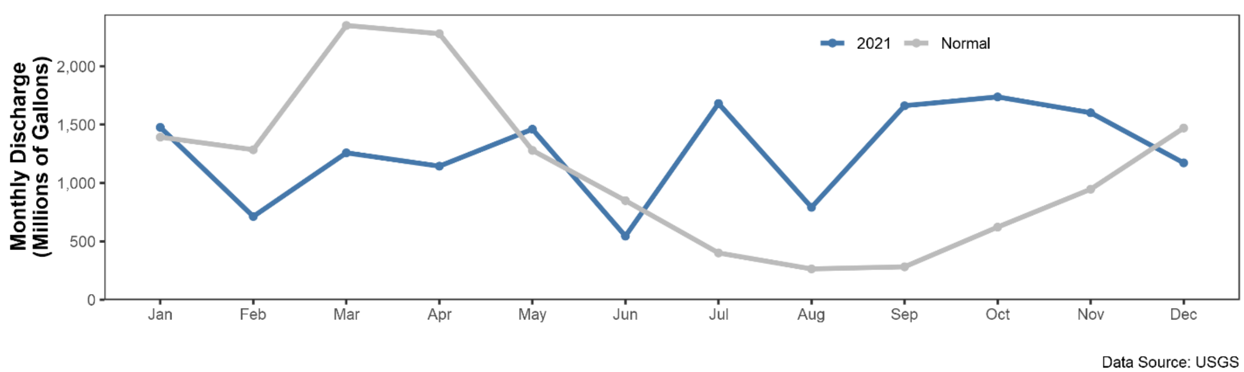


Figure 19: Monthly Discharge in the Stillwater River (MG) 2021

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

The Quabbin Transfer was initiated on March 9 and was kept on until April 26 with a 5-day pause in mid-April. The transfer resumed on May 17 and water was transferred to Wachusett Reservoir on a nearly continuous basis through the remainder of the year. In 2021, the transfer was on for a total of 265 days and delivered a total volume of 48.8 billion gallons to Wachusett Reservoir with an average transfer rate of 184 MGD (Figure 20). This is equivalent to 75% of Wachusett Reservoir capacity (65 billion gallons) and is about 4,596 MG more than the average transfer volume between 2005 and 2020 (44,203.55 MG) (Figure 21). Wachusett Reservoir elevation exceeded its standard operating band on four separate occasions (Figure 20), but these exceedances were slight and for short durations. The reservoir elevation peaked near 392 ft just after the first of the year and then proceeded to decline through the winter to its annual low point in early March, reaching just below the 388 ft winter operating band. For the next month the reservoir slowly gained elevation, reaching the non-winter operating band by early April. The reservoir remained in the operating band (390 – 391.5 ft) for the remainder of the year, except for the three brief precipitation driven peaks in June, July and September.

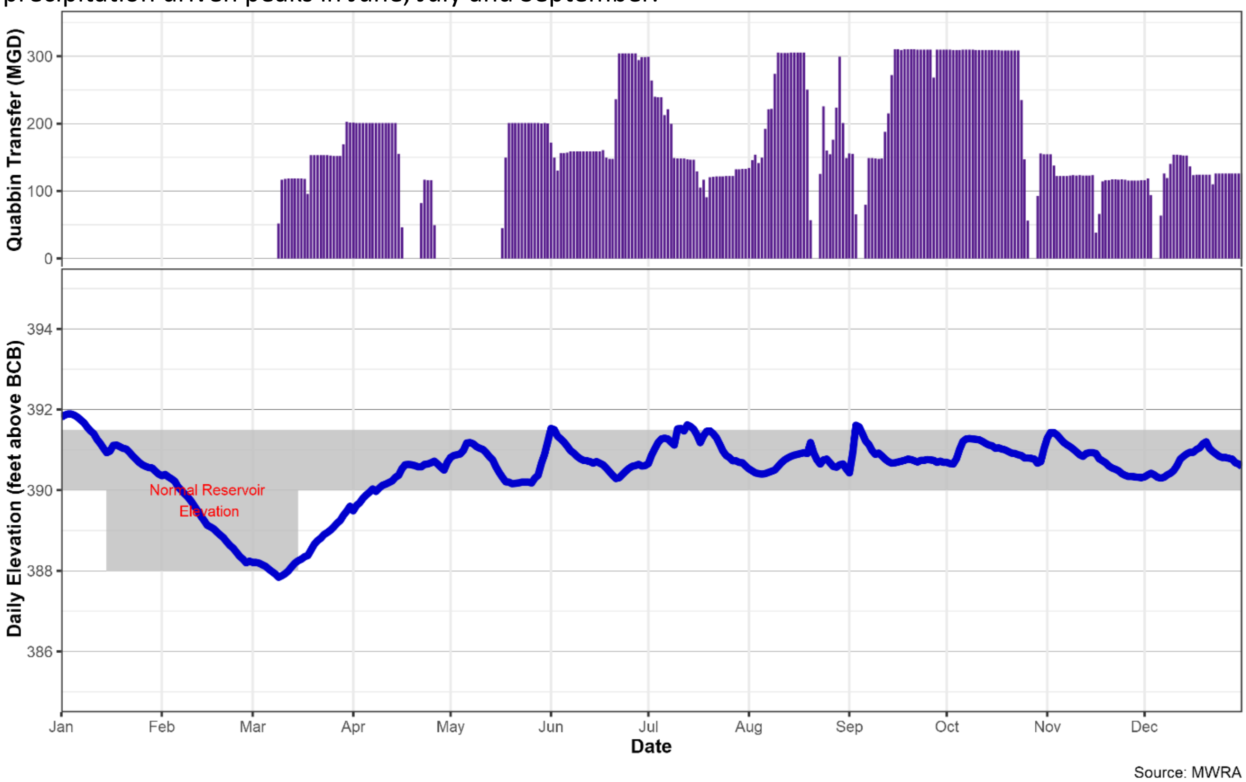


Figure 20: 2021 Daily Wachusett Reservoir Water Elevation and Daily Quabbin Transfer Rate

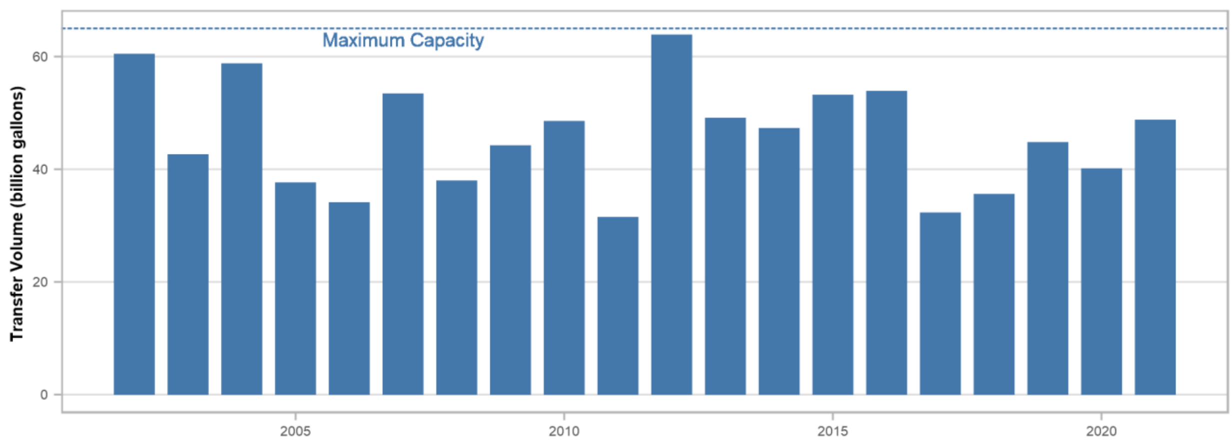


Figure 21: Annual Volume of Quabbin Transfer to Wachusett Reservoir
Maximum capacity of Wachusett Reservoir indicated by line at 65 billion gallons.

3.2 Tributary Monitoring

3.2.1 Water Temperature and Dissolved Oxygen

Tributary water temperature and dissolved oxygen results for 2021 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 2021, water temperature in Wachusett Watershed tributaries ranged from -0.5 °C at Trout Brook to 26.3 °C, at French Brook. At the 10 monitoring locations where temperature sensors were installed, the 7-day mean maximum temperature (purple line) is shown in Figure 22 and Figure 23 for comparison to the of 20 °C MassDEP coldwater fish resources (CFR) and the 28.3 °C warmwater fish resource (WFR) limit37. For the CFR tributaries with temperature sensors, all monitoring locations exceeded the 20 °C limit on at least one day over the summer (Table 11). It is likely that the other three CFR tributaries without temperature sensors also exceeded the 20 °C threshold over multiple days in 2021. Based on manual point measurements and continuous sensor data (where available) no tributaries exceeded the WFR threshold during 2021 (Figure 23). While there is no regulatory limit or guidance for drinking water supply temperatures, colder waters are preferred because many solutes (e.g., trace metals) are less soluble and biological productivity (algae, *E. coli*) is slower, which generally helps reduce the likelihood of taste, odor, and other sanitary issues.

[37] 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 2021

Monitoring Location	Days Exceeded
Gates Brook 1 - MD04	6
Malden Brook - MD06	26
Quinapoxet River (Canada Mills) - MD69	110
Stillwater River - Muddy Pond Rd - MD07	80
Trout Brook - M110	70
West Boylston Brook - MD05	2

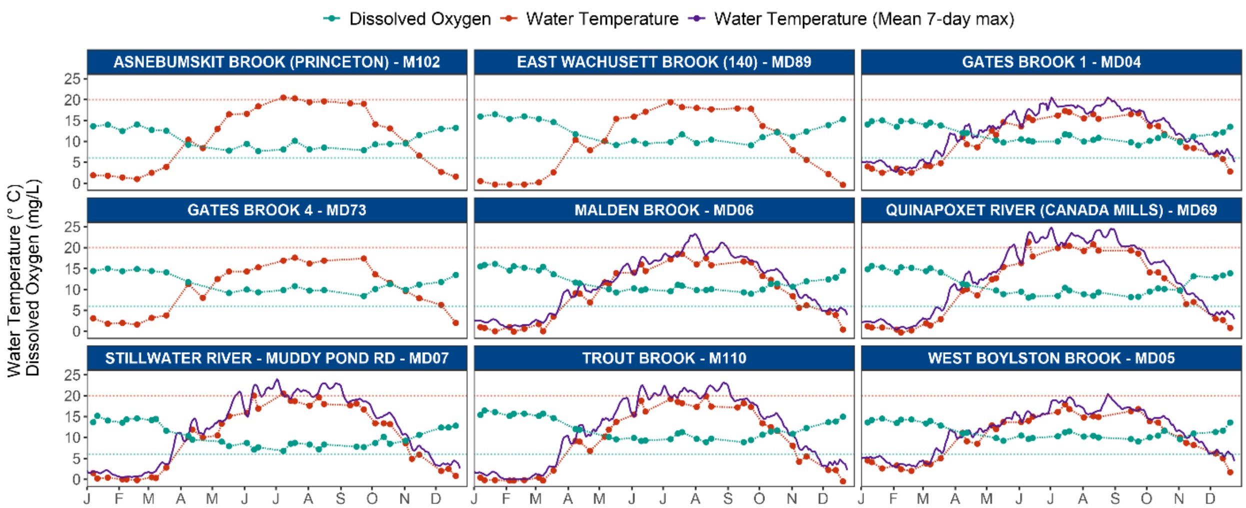


Figure 22: Water Temperature and Dissolved Oxygen for Wachusett Tributaries Designated as Coldwater Fish Resources (CFR).

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

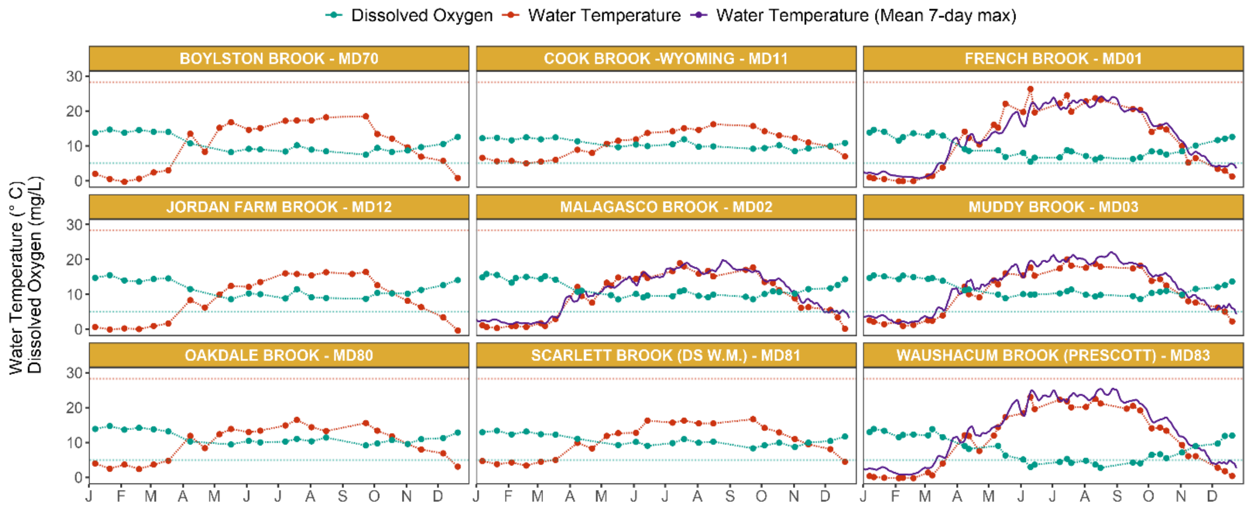


Figure 23: Water Temperature and Dissolved Oxygen for Wachusett Tributaries designated as Warmwater Fish Resources (WFR)

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

Dissolved oxygen (D.O.) concentrations in 2021 were generally inversely correlated with water temperatures, with the highest concentrations observed during the winter months when water was cold and lowest concentrations observed during the summer months when water was warm. D.O. ranged from a low of 2.77 mg/L to a high of 16.49 mg/L – both at Waushacum Brook. For CFR monitoring locations D.O. remained above the MassDEP aquatic life threshold (6.0 mg/L) at all locations at all 2021 monitoring visits (Figure 22). For WFR monitoring locations D.O. fell below the MassDEP aquatic life threshold (5.0 mg/L) only at Waushacum Brook (nine samples), which is common for this tributary during the summer months due to the large and shallow wetland area upstream of the sample 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 conducted between 2000 and 2012, however the results were not discussed in prior water quality reports. Routine sampling for alkalinity was resumed at all primary tributary monitoring locations in September of 2020 to gain insight into the observed increase in Wachusett Reservoir alkalinity in recent years.

In 2021, and in the earlier monitoring period, alkalinity concentrations in the tributaries (as $CaCO_3$) correspond well with the underlying bedrock carbonate content. A band of calcpelite, which is composed of 15 – 45% carbonate minerals[38], stretches across the Wachusett Watershed through Gates Brook, West Boylston Brook, and Waushacum Brook subbasins. These three tributaries have the highest 2020 – 2021

[38] Grady & Mullaney, 1998

mean and median alkalinity concentrations in the Wachusett Watershed. Another narrow finger of calcpelite runs under the eastern half of Wachusett Reservoir and the shoreline in Boylston, however this is situated mostly downgradient from monitoring locations on Malagasco, French and Boylston Brooks. Granite and metamorphic rocks, which have little to no carbonic content, comprise most of the bedrock throughout the rest of the watershed. Accordingly, streams draining those areas have lower alkalinity since the groundwater is largely free of carbonic minerals originating from the bedrock.

With the inclusion of the 2021 alkalinity results, the previously noted dramatic increases in alkalinity compared to the 2000 – 2012 period at French Brook and the Stillwater and Quinapoxet Rivers are now just slight increases (

Table 12). The limited number of recent measurements is insufficient to describe the normal range of interannual variability and makes it difficult to draw any conclusions about the last two years of water chemistry compared to the prior period.

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 – 2021 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 show any inter-seasonal variation.

Table 12: Wachusett Tributary Alkalinity (mg/L) 2000 – 2012 Compared to 2020 – 2021 Results

Sample Location	# Samples 2000-2012	Mean 2000-2012	Median 2000-2012	# Samples 2020-2021	Mean 2020-2021	Median 2020-2021
Cook Brook -Wyoming - MD11	61	30.85	30.80	—	—	—
French Brook - MD01	71	13.32	10.80	16	15.51	12.2
Gates Brook 1 - MD04	76	43.62	44.90	16	43.33	42.95
Jordan Farm Brook - MD12	48	16.88	15.50	—	—	—
Malagasco Brook - MD02	78	11.63	11.10	16	11.24	10.95
Malden Brook - MD06	65	20.37	22.00	16	19.81	20.55
Muddy Brook - MD03	78	21.66	22.55	16	19.08	17.65
Quinapoxet River (Canada Mills) - MD69	138	8.36	7.96	15	9.45	8.74
Rocky Brook (E Branch) - MD13	47	1.49	0.54	—	—	—
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	2	3.94	3.94
Stillwater River - Muddy Pond Rd - MD07	137	7.91	6.78	16	11.03	8.22
Trout Brook - M110	—	—	—	11	4.65	4.36
Waushacum Brook (Prescott) - MD83	—	—	—	16	30.15	27.3
West Boylston Brook - MD05	78	31.63	32.80	16	33.88	33.05

Across all tributary monitoring locations, pH values in 2021 ranged from 5.53 at Trout Brook to 8.05 at Waushacum Brook. Waushacum Brook exceeded the MassDEP recommended range for the protection of aquatic life (6.5 – 8.3)[39] on two occasions. Tributary pH values below the recommended range are common in Wachusett Watershed and were observed at roughly half of the sample locations at least once in 2021. The tributaries where pH was not detected below the recommended range include Gates, Muddy, Oakdale, Scarlett, Cook and Malagasco Brooks. In 2021 seasonal variation in pH was minimal, possibly due to the differences in precipitation patterns in 2021. Most notable was the lack of pH decline during the winter months that was observed in 2020. At many tributaries, summertime pH did not rise as high as in 2020 either, which could have been due to the excess rainfall from July through October.

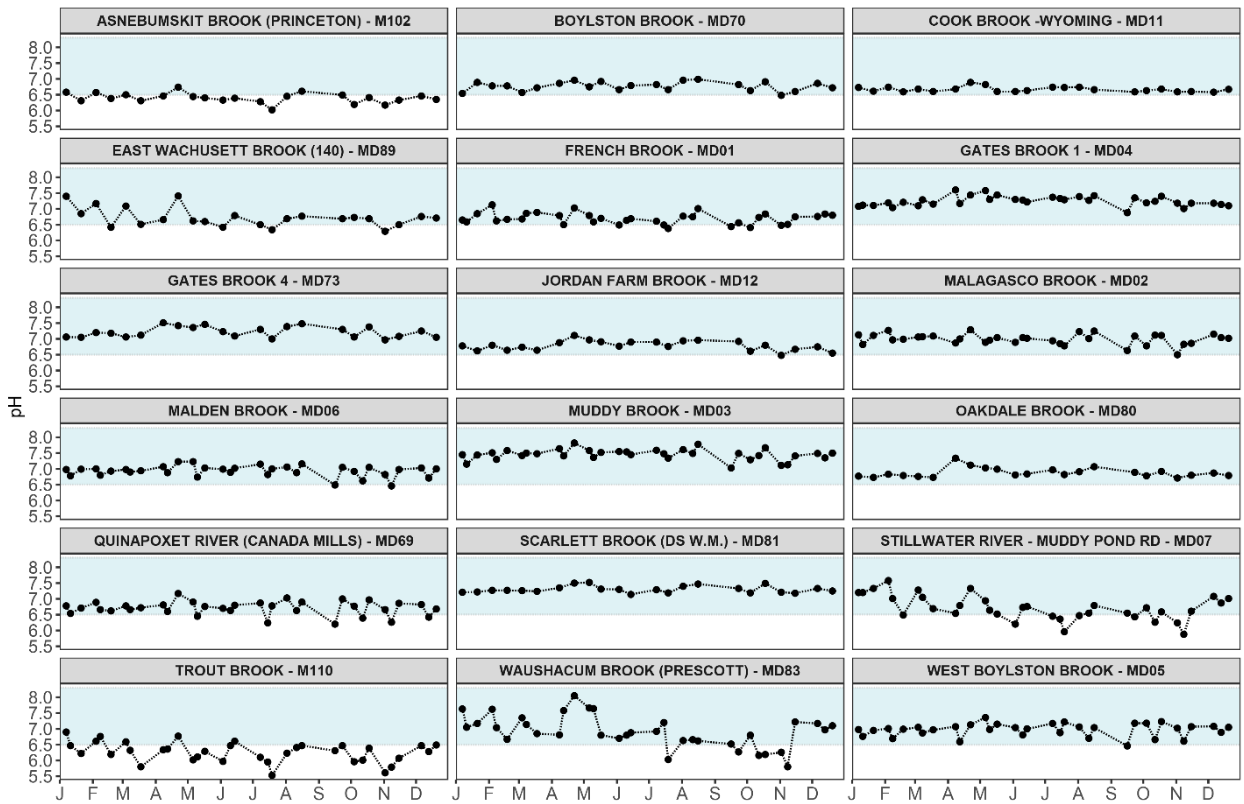


Figure 24: 2021 Results for pH in Wachusett Tributaries
The blue band represents the MassDEP Class A Surface Water standard range for pH, 6.5 – 8.3 SU.

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.

3.2.3 Specific Conductance and Chloride

In 2021, tributary specific conductance ranged from to 53.4 µS/cm at Trout Brook to 2,398 µS/cm at West Boylston Brook. Values of less than 100 µS/cm were recorded in 91% of all samples from Trout Brook (31 of 34), once at East Wachusett Brook and twice at the Stillwater River. This represents just over 6% of all specific conductance samples for the year from Wachusett tributaries. Measurements greater than 904 µS/cm, the proxy chronic Cl toxicity threshold[40], were recorded in 12.4% of all samples from 2021. For

[39] Massachusetts Surface Water Quality Standards, 2013b
[40] MassDEP, 2018

individual tributaries, this threshold was exceeded in 74% of samples from Gates Brook 4 (MD73), 60% of samples from Gates Brook 1 (MD04), 61% of samples from Oakdale Brook, and 43% of samples from West Boylston Brook. Extremely high specific conductance (>1,800 µS/cm) was observed on two dates at two different tributaries during 2021. On February 8, the day after a snow storm, West Boylston Brook specific conductance was measured at 2,398 µS/cm and on February 18, two days after a snow storm, Gates Brook 4 (MD73) specific conductance was measured at 1,891 – both below the MassDEP proxy acute Cl toxicity threshold of 3,193 µS/cm[41]. The Gates Brook USGS monitoring station recorded a maximum instantaneous specific conductance on February 16 of 8,450 µS/cm, after a snow event and subsequent temperatures above freezing, likely resulting in runoff laden with dissolved rock salt. Overall, Wachusett tributary specific conductance levels for 2021 were lower than in recent years, both for individual locations and among all locations (Table 13).

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

Location	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Asnebumskit Brook (Princeton) - M102	197	183	215	254	336	279	249	267	243	195
Boylston Brook - MD70	271	278	373	579	542	594	686	661	679	546
Cook Brook -Wyoming - MD11	378	329	493	475	526	640	624	524	489	478
East Wachusett Brook (140) - MD89	108	123	133	166	174	171	151	169	180	140
French Brook - MD01	162	207	227	321	447	364	290	318	347	250
Gates Brook 1 - MD04	616	715	759	942	1081	1272	1211	1154	1075	940
Gates Brook 4 - MD73	835	1006	1018	1276	1371	1696	1558	1451	1253	1149
Jordan Farm Brook - MD12	129	122	128	124	181	175	183	193	169	178
Malagasco Brook - MD02	292	350	313	447	473	462	451	525	558	345
Malden Brook - MD06	192	199	220	288	334	364	365	371	382	311
Muddy Brook - MD03	154	174	203	273	320	344	333	340	351	296
Oakdale Brook - MD80	534	666	686	872	982	1136	1166	989	878	954
Quinapoxet River (Canada Mills) - MD69	167	172	195	255	304	296	250	261	268	211
Scarlett Brook (DS W.M.) - MD81	372	484	514	635	620	771	747	897	632	487
Stillwater River - Muddy Pond Rd - MD07	143	144	142	182	213	170	162	174	200	152
Trout Brook - M110	61	84	74	74	86	96	92	87	86	82
Waushacum Brook (Prescott) - MD83	280	315	284	339	396	420	395	408	421	334
West Boylston Brook - MD05	512	667	739	1137	1227	1700	1274	1266	1221	901

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.

Sixteen tributary locations experienced the lowest annual mean specific conductance since at least 2016. The most likely reason for the widespread decline in specific conductance observed in 2021 is increased dilution from surplus precipitation, especially during the late summer and fall, when specific conductivity is usually the highest due to seasonal low flows. Additionally, lower than normal flows from February through April resulted in less dilution than normal during the spring, and higher than normal specific conductance for these months. Thus, as depicted in Figure 25, the typical seasonal patterns specific conductance did not occur in 2021. Specific conductance levels at three tributaries remain indicative of

[41] Ibid.

chronic elevated dissolved salt concentrations (above 904 µS/cm) which are likely having negative effects on aquatic life: Gates Brook (two stations), Oakdale Brook, and West Boylston Brook.

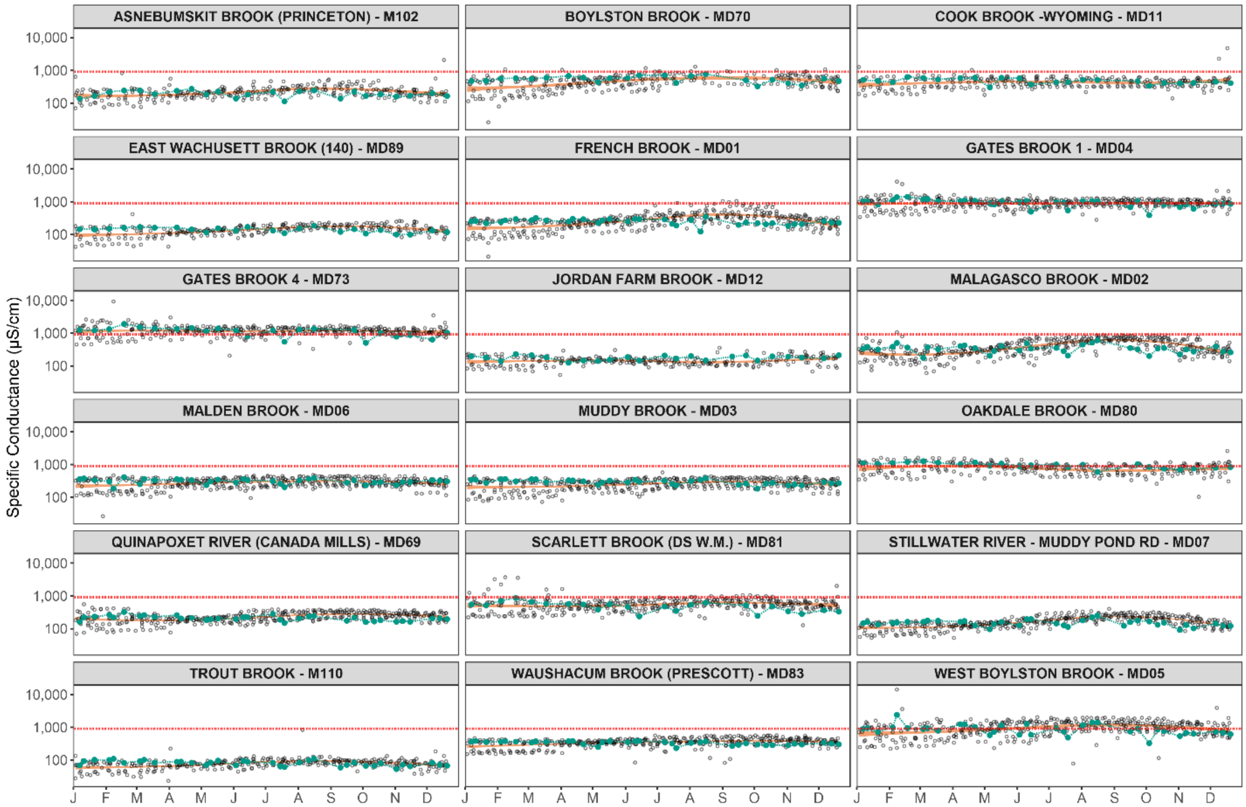


Figure 25: Specific Conductance Measurements at Wachusett Tributaries

The green points show specific conductance results for 2021, while the hollow points show results from years 2012 – 2020, 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[42].

3.2.3.1 Chloride

Chloride (Cl) concentrations in 2021 were mostly lower than 2020 concentrations across most sampling locations (Table 14). Though 22% lower than in 2020, West Boylston Brook had the highest mean annual Cl concentration (280 mg/L), followed by Gates Brook 1 (247 mg/L). As in 2020, Trout Brook and the Stillwater River had the lowest mean annual Cl concentrations at 20 and 34 mg/L, respectively.

Although Cl is not monitored at a frequency high enough to detect exceedances of the EPA aquatic life criteria, it is probable that both Gates Brook 1 and West Boylston Brook exceed the chronic threshold (230 mg/L 4-day average) most of the year, and the acute threshold (860 mg/L 1-day average) several times a

[42] Soper, 2021

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 2021

Sample Location	Count	Minimum (mg/L)	Median mg/L)	Mean (mg/L)	Maximum (mg/L)	Std. Dev (mg/L)
French Brook - MD01	12	40	60	60	79	11
Gates Brook 1 - MD04	12	170	238	247	361	55
Malagasco Brook - MD02	12	59	91	94	139	25
Malden Brook - MD06	12	60	76	75	91	11
Muddy Brook - MD03	12	50	74	71	87	13
Quinapoxet River (Canada Mills) - MD69	12	19	45	44	60	11
Shaft 1 (Quabbin Transfer) - MDS1	6	8	8	8	9	0
Stillwater River - Muddy Pond Rd - MD07	12	24	33	34	50	8
Trout Brook - M110	12	13	20	20	47	9
Waushacum Brook (Prescott) - MD83	11	62	82	76	87	10
West Boylston Brook - MD05	11	150	239	280	681	153

Contrary to previous years, seasonality in chloride concentrations in Wachusett tributaries was muted due to the surplus precipitation during the latter half of 2021 (Figure 26). The February sampling event followed a small winter storm event on the 7th where deicing products were applied to the roadways. Chloride monitoring in groundwater is discussed in Section 3.3.

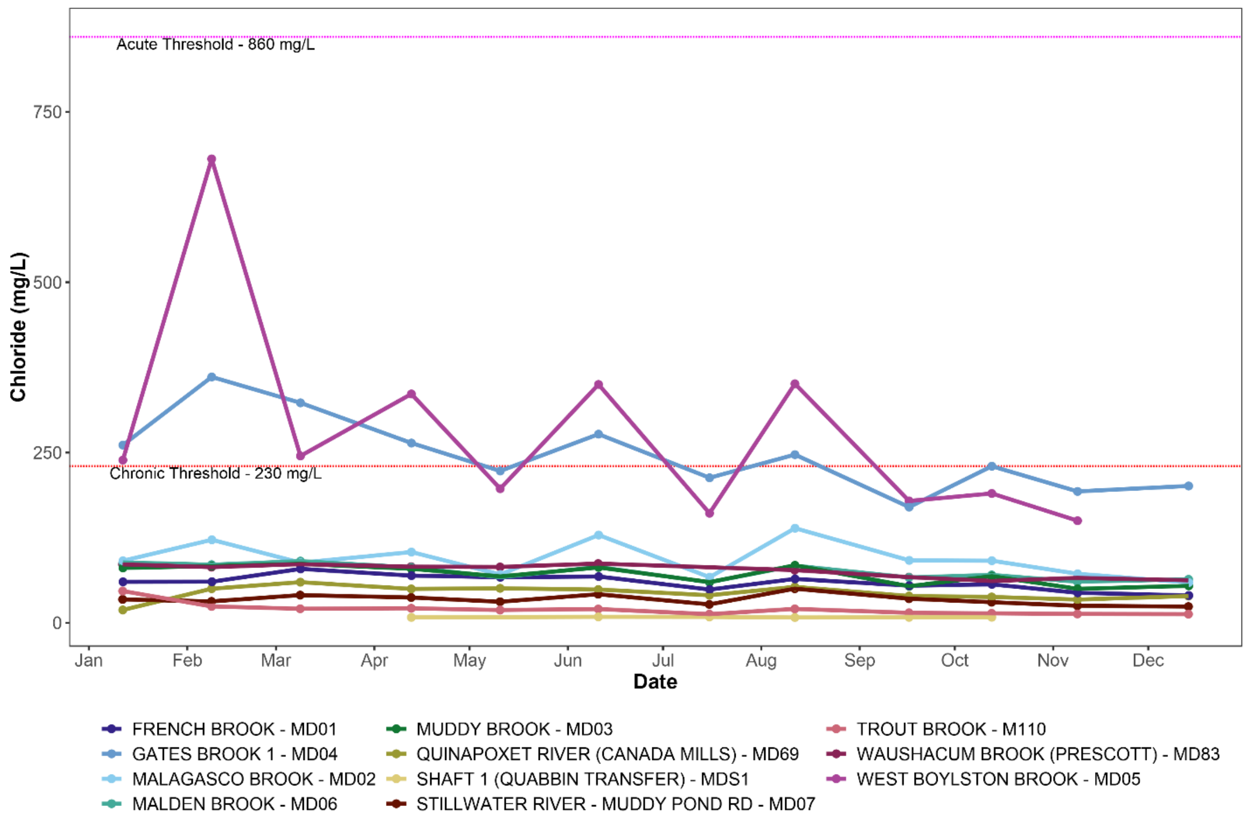


Figure 26: Chloride Concentrations in the Wachusett Tributaries During 2021

A discussion of other work completed in 2021 related to Cl and conductivity is provided in Section 3.2.9.2.

3.2.4 Turbidity

Turbidity results in Wachusett tributaries in 2021 ranged from 0.29 NTU at Cook Brook to 133 NTU at Jordan Farm Brook. There were 33 samples with turbidity levels of 5.0 NTU or higher, which were predominantly collected from Muddy Brook (11 samples), where elevated concentrations of fine particulate matter are historically persistent and naturally occurring. Wet weather sampling on June 14 and October 4 accounted for 18 of the 33 turbidity results above 5.0 NTU, with nine others coming from Muddy Brook on other dates.

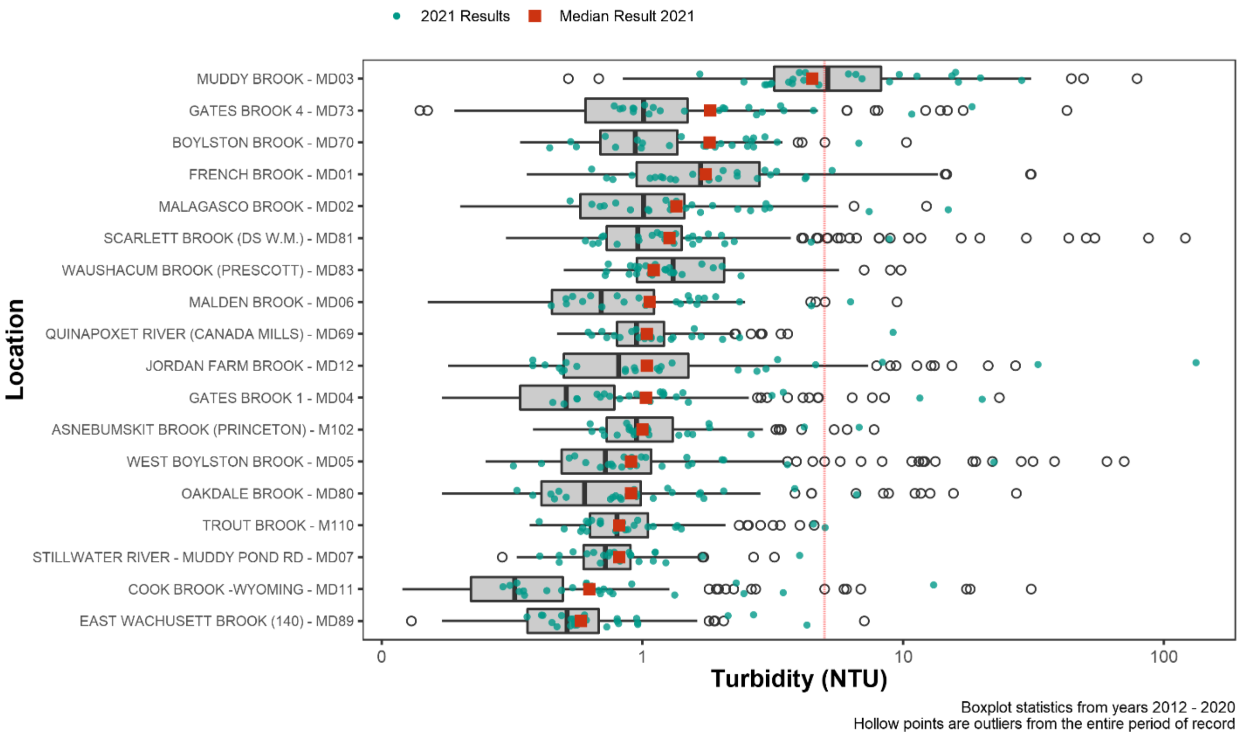
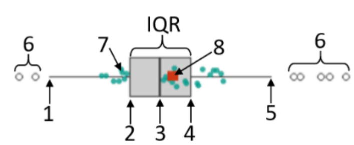


Figure 27: 2021 Turbidity Levels with 2012 – 2020 Statistics

Section 3 boxplots Explained:

1) Lower whisker = smallest observation greater than or equal to lower hinge – 1.5*IQR
2) 25% quantile (lower hinge)
3) Median, 50% quantile
4) 75% quantile (upper hinge)
5) Upper whisker = largest observation less than or equal to upper hinge + 1.5 * IQR
6) Outliers = single observations above upper whisker or below lower whisker
7) Individual sample results (green circle points)
8) Annual median result (red square point)

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



Annual mean turbidity in 2021 ranged from 0.92 NTU at East Wachusett Brook to 8.43 NTU at Jordan Farm Brook, with 10-year record high annual means occurring at several locations: Boylston, East Wachusett, Gates, Jordan Farm, Malagasco and Malden Brooks, and both the Quinapoxet and Stillwater Rivers (Table 15).

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

Sample Location	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Asnebumskit Brook (Princeton) - M102	1.14	0.94	—	1.47	1.14	1.63	1.07	1.12	1.16	1.49
Boylston Brook - MD70	1.35	1.48	0.90	0.98	0.92	1.06	1.13	1.44	1.09	1.92
Cook Brook -Wyoming - MD11	0.83	0.37	1.23	0.63	0.28	1.75	0.55	0.42	0.91	1.38
East Wachusett Brook (140) - MD89	0.56	0.55	0.56	0.60	0.47	0.86	0.65	0.57	0.54	0.92
French Brook - MD01	2.62	2.55	1.61	2.16	1.93	1.56	1.73	2.55	6.86	2.08
Gates Brook 1 - MD04	0.73	0.67	0.70	0.53	0.57	1.16	1.23	0.85	1.00	2.38
Gates Brook 4 - MD73	1.24	1.22	1.43	0.91	0.89	2.73	1.88	1.68	1.63	2.90
Jordan Farm Brook - MD12	1.67	1.39	1.21	1.61	0.51	1.68	2.22	2.44	1.65	8.43
Malagasco Brook - MD02	1.63	1.45	1.10	0.90	0.82	1.17	1.27	1.21	1.08	2.32
Malden Brook - MD06	1.09	0.99	0.79	0.84	0.52	0.75	0.95	0.96	0.96	1.48
Muddy Brook - MD03	7.07	6.90	5.87	5.46	5.48	9.12	6.86	6.83	5.36	7.92
Oakdale Brook - MD80	1.65	0.77	1.15	0.63	0.43	2.12	1.18	0.79	1.28	1.31
Quinapoxet River (Canada Mills) - MD69	1.14	0.94	0.97	1.09	1.00	1.01	1.11	1.17	1.14	1.48
Scarlett Brook (DS W.M.) - MD81	2.20	1.91	5.47	1.05	1.38	3.65	1.91	2.24	1.17	1.71
Stillwater River - Muddy Pond Rd - MD07	0.88	0.76	0.74	0.76	0.75	0.70	0.80	0.83	0.86	0.97
Trout Brook - M110	1.13	0.82	0.97	1.22	0.60	0.76	0.81	0.90	0.97	1.15
Waushacum Brook (Prescott) - MD83	1.64	1.31	1.64	1.29	2.04	1.74	1.67	1.63	2.09	1.21
West Boylston Brook - MD05	1.33	1.22	3.21	0.86	1.09	3.59	2.22	1.27	1.29	1.98

Apart from Muddy Brook, 2021 annual median turbidity was higher than the 2012 – 2020 median at all sampling locations. Annual median turbidity values ranged from 0.58 NTU at East Wachusett Brook to 4.48 NTU in Muddy Brook (Table 16). Turbidity levels were 0.90 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 2021 (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	0.63	6.78	1.00	0.91	1.49
Boylston Brook - MD70	0.44	6.76	1.81	1.27	2.53
Cook Brook -Wyoming - MD11	0.29	13.1	0.63	0.61	0.77
East Wachusett Brook (140) - MD89	0.36	4.28	0.58	0.55	0.96
French Brook - MD01	0.64	5.34	1.75	1.56	1.96
Gates Brook 1 - MD04	0.45	20.1	1.03	0.95	1.35
Gates Brook 4 - MD73	0.78	18.4	1.82	1.17	3.39
Jordan Farm Brook - MD12	0.38	133	1.04	0.86	2.75
Malagasco Brook - MD02	0.53	14.9	1.35	1.23	2.60
Malden Brook - MD06	0.45	6.29	1.06	0.85	1.64
Muddy Brook - MD03	1.66	28.5	4.48	3.78	6.96
Oakdale Brook - MD80	0.33	6.64	0.90	0.82	1.65
Quinapoxet River (Canada Mills) - MD69	0.62	9.15	1.04	1.01	1.58
Scarlett Brook (DS W. M) - MD81	0.60	8.86	1.27	1.09	1.56
Stillwater River - Muddy Pond Rd - MD07	0.40	4.01	0.81	0.74	1.12
Trout Brook - M110	0.40	5.02	0.81	0.69	1.10
Waushacum Brook (Prescott) - MD83	0.72	2.39	1.10	1.03	1.32
West Boylston Brook - MD05	0.32	22.3	0.90	0.77	1.50
All Wachusett Tributaries	**0.56**	**17.55**	**1.3**	**1.11**	**2.01**

Figure 28 shows the variability in turbidity by location for 2021 compared to the prior nine years. Several sampling locations show a historical seasonal pattern of elevated turbidity levels during the summer months (French Brook, Muddy Brook, Asnebumbskit Brook, Boylston Brook), while others exhibit less seasonality, remaining low year-round (Stillwater River, Quinapoxet River). For 2021, the high turbidity results were mostly the result of higher-than-normal flows and more days with wet weather.

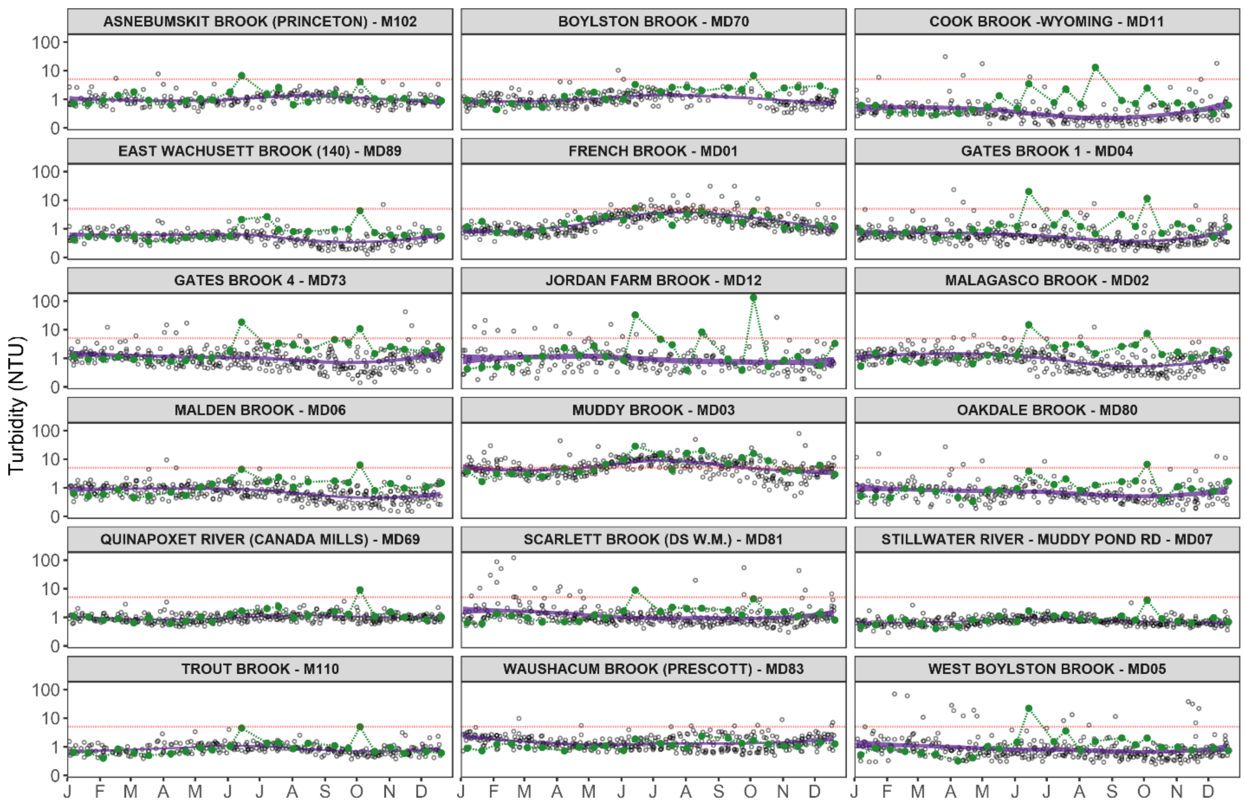


Figure 28: Turbidity Results at Wachusett Tributaries

The green points show turbidity results for 2021, while the hollow points show results from years 2012 – 2020, 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 2021 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 2021 was 2.42 NTU and the median was 1.06 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 28.5 mg/L at West Boylston Brook. Only 12 of 125 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 2021 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	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
French Brook - MD01	8.60	5.45	4.66	3.02	3.84	3.00	3.92	7.03	12.43	4.87
Gates Brook 1 - MD04	3.13	2.23	4.20	2.48	3.25	2.21	2.56	3.08	3.33	2.50
Malagasco Brook - MD02	3.25	4.40	2.83	2.80	3.10	3.58	2.93	4.25	3.48	3.13
Malden Brook - MD06	3.42	2.45	3.60	4.27	3.13	2.50	2.77	2.82	2.83	2.50
Muddy Brook - MD03	4.90	4.11	2.82	2.50	6.74	11.99	6.12	4.23	7.16	3.29
Quinapoxet River (Canada Mills) - MD69	3.60	2.77	2.33	2.49	3.13	2.50	2.75	2.50	2.50	2.50
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	1.75	2.82	2.45	2.50	2.50
Stillwater River - Muddy Pond Rd - MD07	2.62	2.38	2.33	2.50	3.88	2.43	2.49	2.50	2.71	2.50
Trout Brook - M110	—	—	—	2.91	2.94	2.50	2.92	2.75	2.50	2.50
Waushacum Brook (Prescott) - MD83	2.65	3.83	2.44	2.50	2.89	2.43	5.06	3.00	2.79	3.00
West Boylston Brook - MD05	2.92	2.84	9.98	2.49	2.77	4.33	4.88	2.96	15.96	4.88

Dash (—) = No data

3.2.6 *E. coli* Bacteria in Tributaries

Bacteria samples collected from the tributary stations during 2021 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 9,800 MPN/100 mL at Jordan Farm Brook during the storm on October 4). As in previous years, the highest concentrations were mostly recorded during or following precipitation. Twenty of the 27 samples that exceeded 1,000 MPN/100 mL were collected during the storm events on June 14 and October 4. The only dry weather samples that exceeded 1,000 MPN/100 mL were collected from Boylston Brook on June 3 and Jordan Farm Brook on December 20.

In 2021, 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 28 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. This increase was likely exacerbated by the surplus rainfall that occurred from July to October.

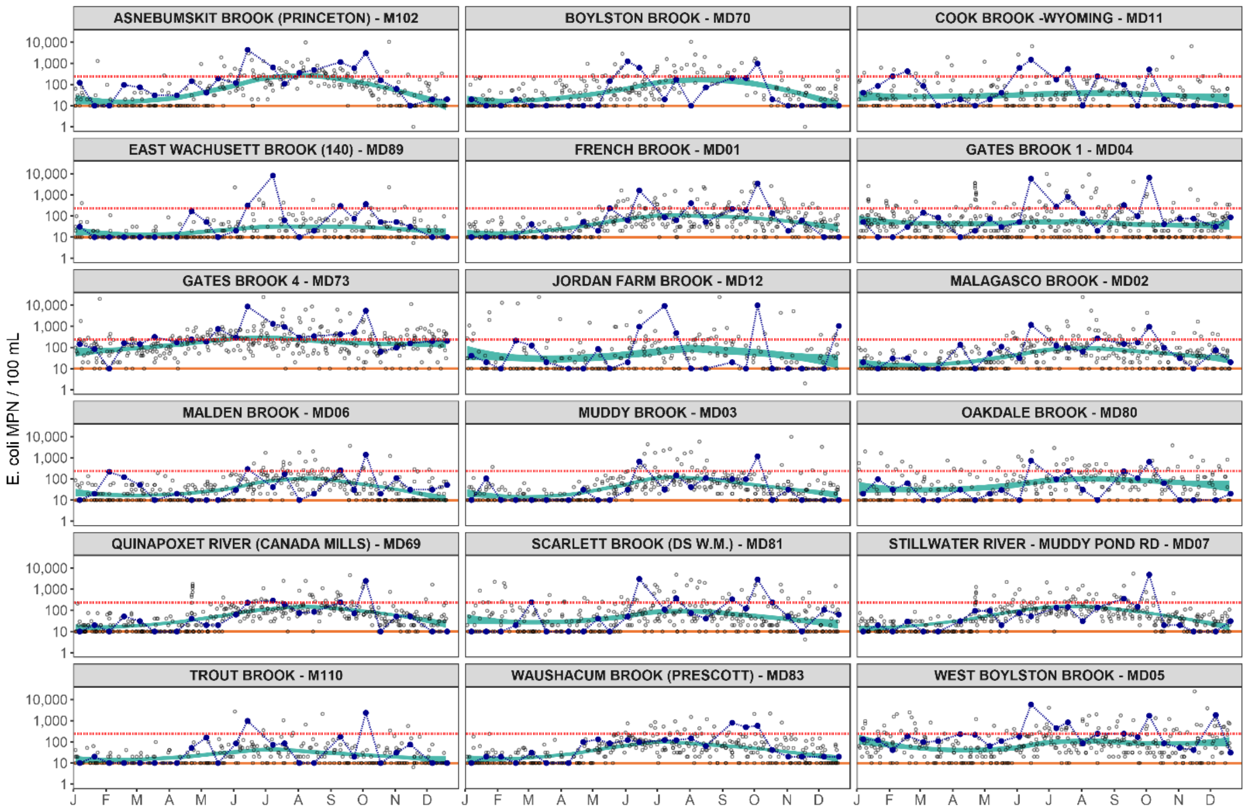


Figure 29: *E. coli* Concentrations in Wachusett Tributaries
The blue points show E. coli results for 2021, while the hollow points show results from years 2012 – 2020, with the green band representing a LOESS smooth function 95% confidence interval for the same period. The red dashed line is the MassDEP 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 2021 annual geometric means were similar to previous years across all sample locations (Figure 30). Annual geometric mean at West Boylston Brook has increased in the past two consecutive years and exceeded the longer term geometric mean standard (126 MPN/100 mL) in 2021.

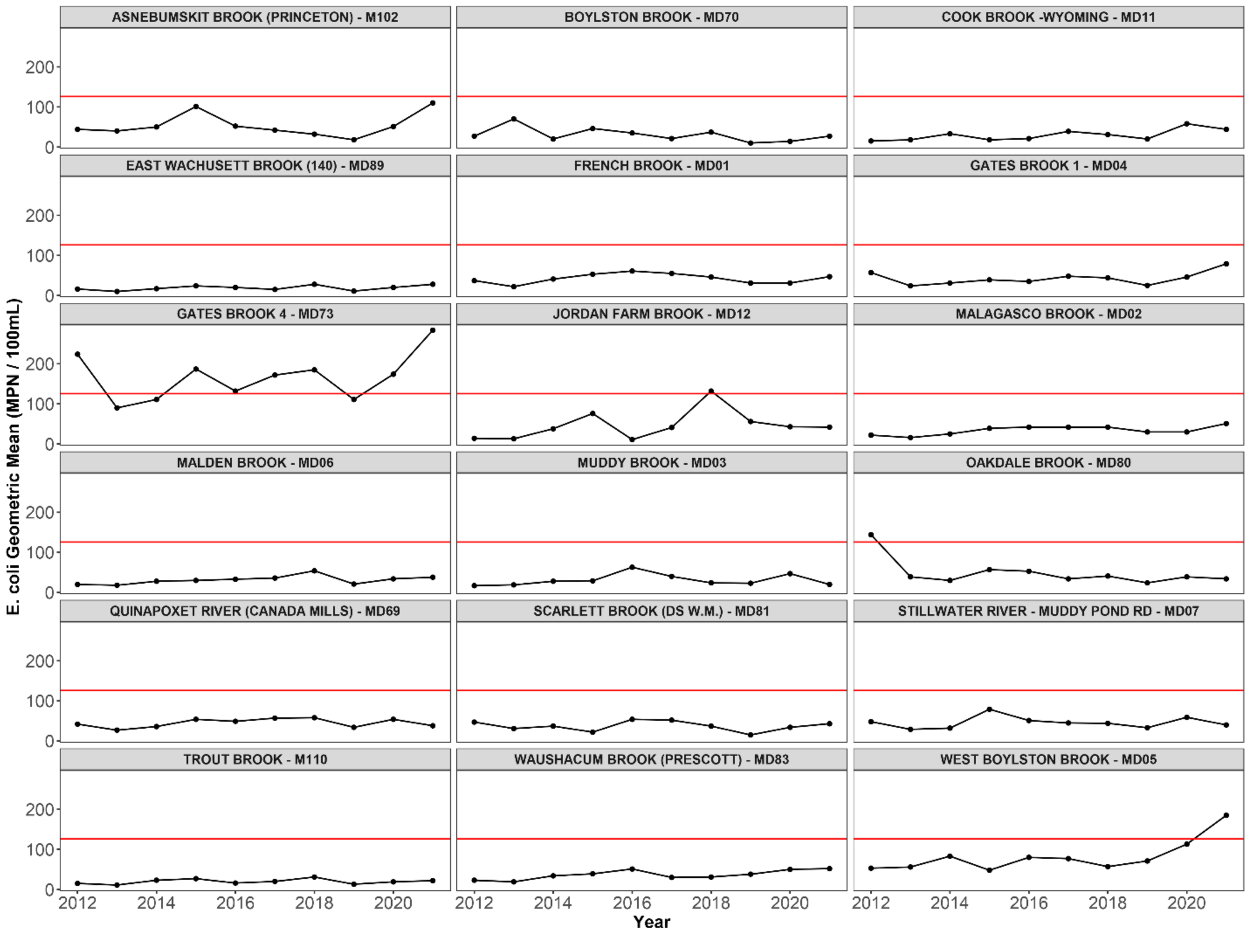


Figure 30: Annual Geometric Mean *E. coli* for Wachusett Reservoir Tributaries (MPN/100 mL).
The red line indicates the MassDEP Class A surface water quality standard: 126 MPN/100 mL (geometric mean).

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 2021 (Table 18). Muddy Brook had the lowest 2021 geometric mean (20 MPN/100 mL). As in 2020, Gates Brook 4 had the highest geometric mean (284 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[43].

[43] DWSP, 2019

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

Sample Location	GMEAN 2018	GMEAN 2019	GMEAN 2020	GMEAN 2021	%>235 2018	%>235 2019	%>235 2020	%>235 2021
Asnebumskit Brook (Princeton) - M102	32	18	51	110	29	12	30	29
Boylston Brook - MD70	37	10	14	27	5	10	8	12
Cook Brook -Wyoming - MD11	31	20	58	44	0	0	16	29
East Wachusett Brook (140) - MD89	28	11	20	28	4	0	5	17
French Brook - MD01	46	31	31	47	17	8	5	12
Gates Brook 1 - MD04	44	25	46	79	8	8	5	21
Gates Brook 4 - MD73	185	111	174	284	29	21	30	50
Jordan Farm Brook - MD12	132	56	43	42	35	25	18	21
Malagasco Brook - MD02	42	30	30	51	17	8	5	12
Malden Brook - MD06	54	21	34	38	17	4	5	12
Muddy Brook - MD03	24	23	47	20	0	8	20	8
Oakdale Brook - MD80	41	24	39	34	8	4	5	8
Quinapoxet River (Canada Mills) - MD69	58	34	54	38	4	4	10	12
Scarlett Brook (DS W. M) - MD81	37	15	34	43	4	4	10	25
Stillwater River - Muddy Pond Rd - MD07	44	33	59	40	4	4	10	8
Trout Brook - M110	31	13	19	22	4	4	5	8
Waushacum Brook (Prescott) - MD83	31	38	50	52	8	0	10	12
West Boylston Brook - MD05	57	71	113	185	12	17	25	29

2021 geometric means were higher than both the five-year average and ten-year average geometric means for 12 of 18 tributaries (Table 19). Gates Brook 4, Asnebumskit Brook, and West Boylston Brook were the only tributaries to have a 2021 geometric mean substantially higher than normal, whereas other tributaries had 2021 geometric means close to their historical averages.

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

Sample Location	2021 GEOMETRIC MEAN	5 YEAR MEAN	10 YEAR MEAN
Asnebumskit Brook (Princeton) - M102	110	51	54
Boylston Brook - MD70	27	22	31
Cook Brook -Wyoming - MD11	44	38	30
East Wachusett Brook (140) - MD89	28	20	19
French Brook - MD01	47	42	42
Gates Brook 1 - MD04	79	48	43
Gates Brook 4 - MD73	284	185	167
Jordan Farm Brook - MD12	42	63	47
Malagasco Brook - MD02	51	39	34
Malden Brook - MD06	38	37	31
Muddy Brook - MD03	20	31	31
Oakdale Brook - MD80	34	34	50
Quinapoxet River (Canada Mills) - MD69	38	48	45
Scarlett Brook (DS W. M) - MD81	43	36	37
Stillwater River - Muddy Pond Rd - MD07	40	44	46
Trout Brook - M110	22	21	20
Waushacum Brook (Prescott) - MD83	52	40	37
West Boylston Brook - MD05	185	101	82

In 2021, wet weather samples continued to have higher bacteria concentrations than dry weather samples (Table 20). For all sampling locations, exceedances of the MassDEP Class A water quality single sample regulatory limit (235 MPN/100 mL) were more likely to occur during wet conditions, and nine 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 2021 (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	62	295	20	0	13.3	55.6	15	9
Boylston Brook - MD70	17	58	60	33.3	6.7	22.2	15	9
Cook Brook -Wyoming - MD11	34	71	33.3	33.3	26.7	33.3	15	9
East Wachusett Brook (140) - MD89	15	109	53.3	22.2	0	44.4	15	9
French Brook - MD01	29	110	40	22.2	6.7	22.2	15	9
Gates Brook 1 - MD04	35	333	20	0	0	55.6	15	9
Gates Brook 4 - MD73	152	807	6.7	0	33.3	77.8	15	9
Jordan Farm Brook - MD12	19	173	60	22.2	6.7	44.4	15	9
Malagasco Brook - MD02	31	124	26.7	11.1	6.7	22.2	15	9
Malden Brook - MD06	26	74	26.7	22.2	0	33.3	15	9
Muddy Brook - MD03	14	42	60	33.3	0	22.2	15	9
Oakdale Brook - MD80	21	85	40	22.2	0	22.2	15	9
Quinapoxet River (Canada Mills) - MD69	24	91	33.3	22.2	0	33.3	15	9
Scarlett Brook (DS W. M) - MD81	20	187	46.7	11.1	13.3	44.4	15	9
Stillwater River - Muddy Pond Rd - MD07	23	111	26.7	22.2	0	22.2	15	9
Trout Brook - M110	12	87	66.7	22.2	0	22.2	15	9
Waushacum Brook (Prescott) - MD83	31	127	20	11.1	0	33.3	15	9
West Boylston Brook - MD05	102	499	0	0	6.7	66.7	15	9

It is very difficult for tributary waters to meet the single sample standard (235 MPN/100 mL), even in streams with undeveloped watersheds. There can be dramatic fluctuations in bacteria concentrations due to precipitation events and variable flow conditions, even without human-related sources of contamination. The longer term geometric mean standard has been met by most Wachusett tributaries in the last five years, and the tributaries which occasionally surpass this 126 MPN/100 mL threshold have known bacteria sources, which are either being actively monitored and managed (agricultural operations), or cannot be managed because of their location and origin (avian wildlife). West Boylston Brook has demonstrated the most dramatic rise in annual geometric mean *E. coli* in the last three years, thus investigation of possible new sources of bacteria within the subbasin drainage area is warranted. *E coli* concentrations for 2021 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 2021, Ammonia-nitrogen (NH_3-N) concentrations were below the limit of detection in 25% 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 31). 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.

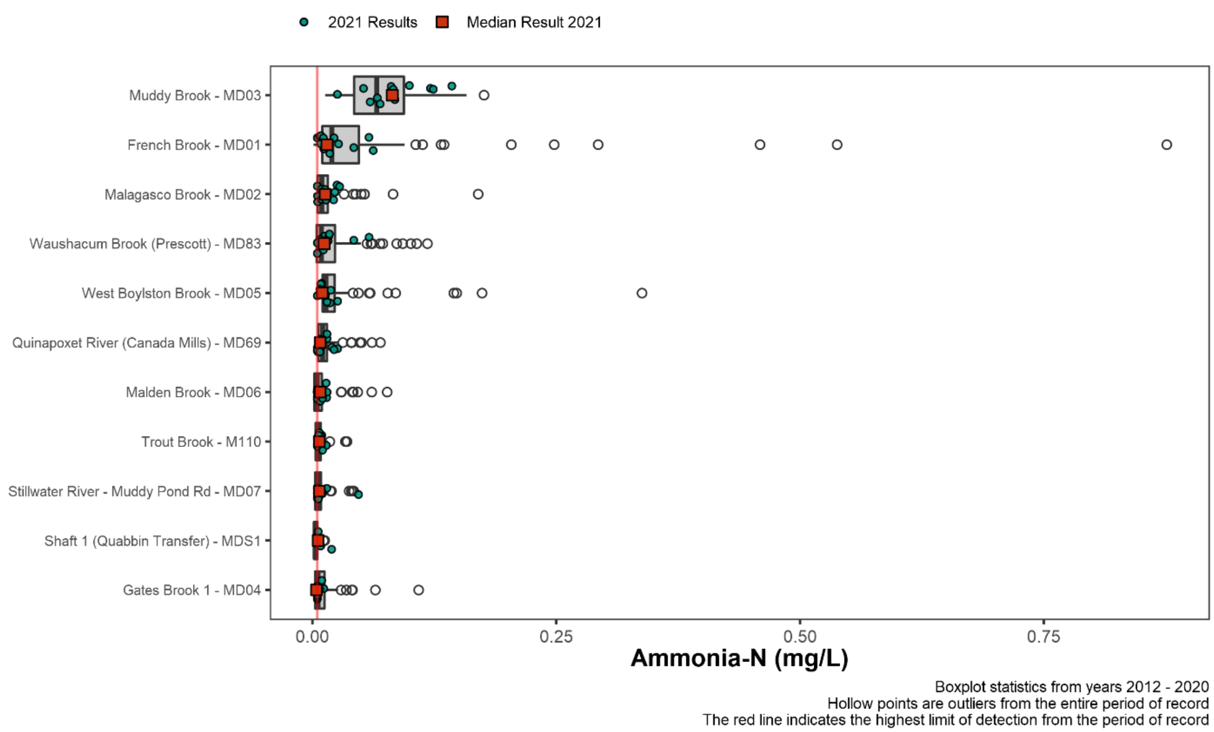


Figure 31: 2021 Ammonia-Nitrogen Concentrations with 2012 - 2020 Statistics

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. For tributaries other than Muddy Brook, the highest NH_3-N concentrations in 2021 occurred during drier spring months. Gates Brook had the lowest annual mean NH_3-N concentrations in 2021 (0.005 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	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
French Brook - MD01	0.045	0.051	0.034	0.041	0.018	0.012	0.029	0.026	0.201	0.023
Gates Brook 1 - MD04	0.008	0.010	0.014	0.012	0.013	0.008	0.008	0.012	0.006	0.005
Malagasco Brook - MD02	0.014	0.014	0.015	0.028	0.012	0.014	0.011	0.014	0.009	0.014
Malden Brook - MD06	0.011	0.007	0.009	0.016	0.004	0.005	0.012	0.006	0.009	0.008
Muddy Brook - MD03	0.069	0.065	0.067	0.076	0.060	0.078	0.086	0.094	0.055	0.084
Quinapoxet River (Canada Mills) - MD69	0.012	0.012	0.017	0.021	0.011	0.015	0.012	0.011	0.009	0.012
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	0.004	0.003	0.006	0.003	0.008
Stillwater River - Muddy Pond Rd - MD07	0.009	0.007	0.012	0.011	0.007	0.006	0.006	0.005	0.007	0.010
Trout Brook - M110	—	—	—	0.012	0.007	0.008	0.006	0.008	0.007	0.007
Waushacum Brook (Prescott) - MD83	0.019	0.014	0.024	0.023	0.010	0.013	0.011	0.029	0.028	0.017
West Boylston Brook - MD05	0.013	0.014	0.049	0.021	0.016	0.037	0.027	0.034	0.016	0.013

Nitrite-Nitrogen

Nitrite-nitrogen (NO_2-N) is rarely detected in Wachusett Reservoir tributaries, therefore results are not displayed below. In 2021, there was only a single NO_2-N sample with a concentration above the 0.005 mg/L detection limit: 0.0054 mg/L at Malagasco Brook on September 16. 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 2021 were below the EPA MCL of 1.0 mg/L.

Nitrate-Nitrogen

Annual mean nitrate-nitrogen (NO_3-N) concentrations for 2021 ranged from 0.057 mg/L at Waushacum Brook to 1.115 mg/L at West Boylston Brook (Table 22), with individual measurements from below detection (< 0.005 mg/L) to 1.46 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 2021 concentrations slightly lower than in 2020 for most tributaries. The mean annual NO_3-N concentration at Trout Brook for 2021 was the highest on record, however, this was less than 0.04 mg/L higher than the lowest mean annual concentration on record. There were no high outliers in 2021 and median NO_3-N concentrations were mostly below historical medians from the 2012 – 2020 period (Figure 32).

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

Sample Location	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
French Brook - MD01	0.13	0.16	0.17	0.09	0.15	0.11	0.13	0.12	0.10	0.07
Gates Brook 1 - MD04	0.80	0.92	0.86	0.79	0.76	0.93	0.85	0.89	0.75	0.81
Malagasco Brook - MD02	0.49	0.68	0.58	0.70	0.62	0.68	0.60	0.63	0.62	0.61
Malden Brook - MD06	0.43	0.55	0.44	0.53	0.44	0.49	0.45	0.46	0.42	0.41
Muddy Brook - MD03	0.10	0.14	0.14	0.13	0.14	0.11	0.11	0.10	0.10	0.07
Quinapoxet River (Canada Mills) - MD69	0.22	0.25	0.25	0.29	0.21	0.32	0.24	0.28	0.28	0.19
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	0.02	0.05	0.02	0.01	0.01
Stillwater River - Muddy Pond Rd - MD07	0.14	0.16	0.14	0.16	0.12	0.13	0.11	0.13	0.13	0.12
Trout Brook - M110	—	—	—	0.11	0.10	0.10	0.10	0.10	0.09	0.13
Waushacum Brook (Prescott) - MD83	0.04	0.04	0.05	0.05	0.02	0.03	0.07	0.07	0.06	0.06
West Boylston Brook - MD05	1.17	1.39	1.14	1.25	1.20	1.28	1.07	1.17	1.09	1.12

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.

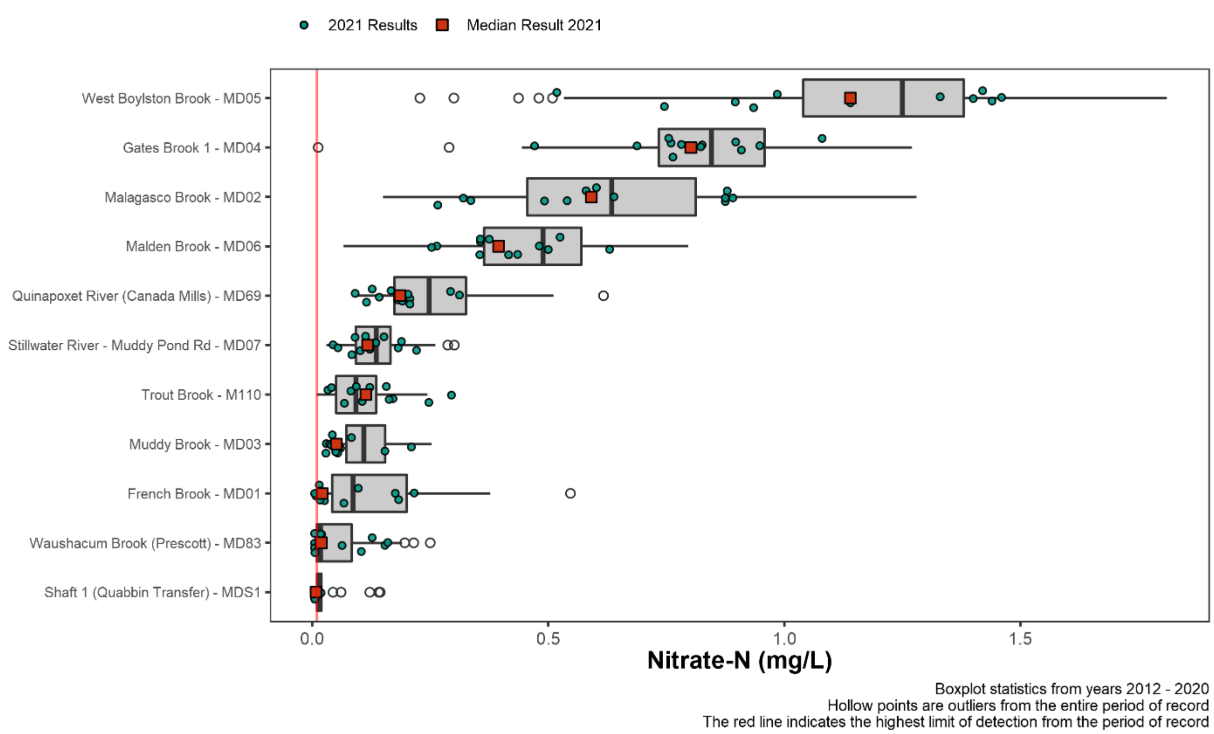


Figure 32: 2021 Nitrate-Nitrogen Concentrations with 2012 - 2020 Statistics

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. Malagasco Brook and the Quinapoxet River mean annual TKN was the highest on record, though not significantly higher than in previous years. Gates and West Boylston Brooks had the lowest mean annual TKN concentrations in 2021: 0.22 and 0.24 mg/L, respectively. Median TKN concentrations for 2021 were higher than the period of record median at all tributaries. Individual TKN sample concentrations in 2021 ranged from below detection (0.1 mg/L) at Gates Brook 1 to 0.946 mg/L at Malagasco Brook (Figure 33).

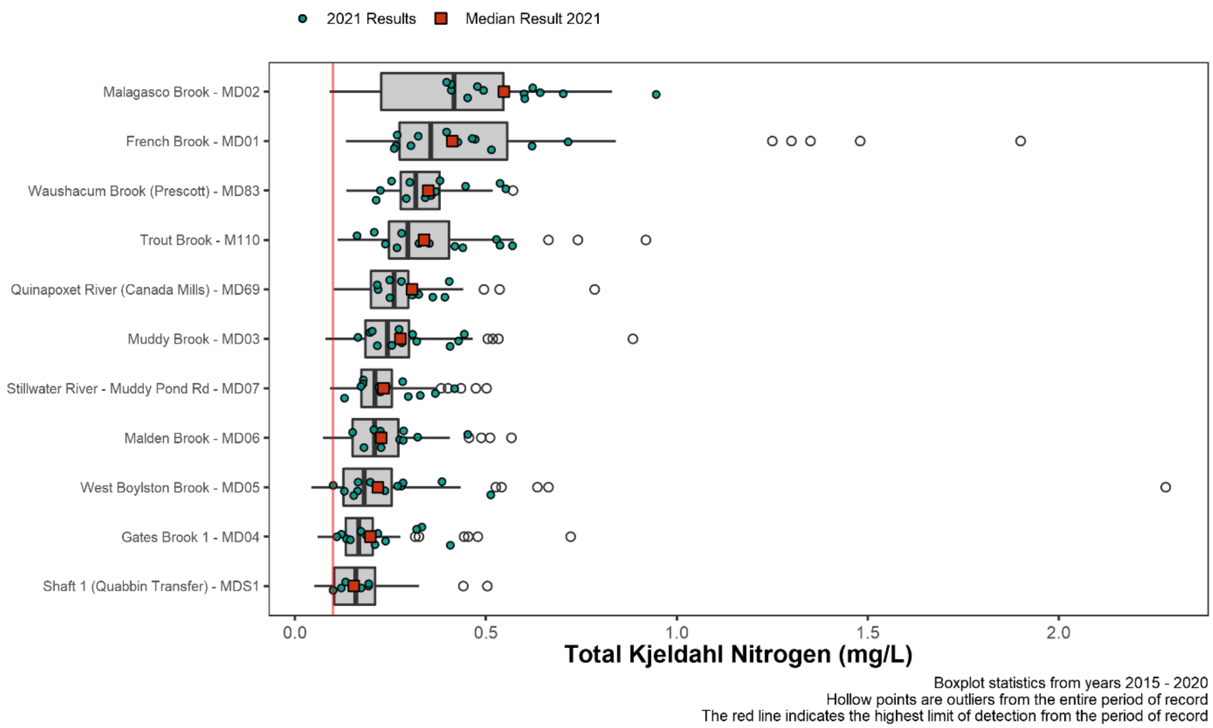


Figure 33: 2021 Total Kjeldahl Nitrogen Concentrations with 2015 - 2020 Statistics

The mean and median annual TKN concentrations observed in 2021 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 and swamps within their subbasins, which are highly productive environments where organic compounds containing nitrogen and carbon are constantly breaking down and entering surface waters. It is possible that the surplus rainfall during the productive summer and early fall months of 2021 caused higher than normal flushing of organic particles from the landscape and wetlands.

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

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

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 and not indicative of any water quality problems.

Total Nitrogen

Total Nitrogen (TN) concentrations in 2021 ranged from 0.23 mg/L at Muddy Brook to 1.71 at West Boylston Brook, with mean annual concentrations for 2021 ranging from 0.37 mg/L at Muddy Brook to 1.36 mg/L at West Boylston Brook. With the exception of French Brook in 2020, TN concentrations have been stable at each tributary since 2015. Malagasco and Trout Brooks 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
French Brook - MD01	0.49	0.51	0.47	0.62	0.55	0.91	0.49
Gates Brook 1 - MD04	0.95	0.98	1.09	1.01	1.11	0.96	1.03
Malagasco Brook - MD02	1.07	0.97	1.15	1.08	1.02	1.00	1.18
Malden Brook - MD06	0.77	0.67	0.71	0.71	0.67	0.66	0.67
Muddy Brook - MD03	0.39	0.38	0.38	0.38	0.35	0.42	0.37
Quinapoxet River (Canada Mills) - MD69	0.59	0.50	0.57	0.51	0.54	0.54	0.50
Shaft 1 (Quabbin Transfer) - MDS1	—	—	0.15	0.27	0.22	0.21	0.17
Stillwater River - Muddy Pond Rd - MD07	0.37	0.39	0.37	0.34	0.33	0.37	0.38
Trout Brook - M110	0.45	0.41	0.46	0.45	0.48	0.43	0.50
Waushacum Brook (Prescott) - MD83	0.34	0.39	0.34	0.40	0.42	0.42	0.42
West Boylston Brook - MD05	1.44	1.39	1.47	1.33	1.44	1.45	1.36

Figure 34 shows the relative proportion of all nitrogen species in the Wachusett tributaries, which differ considerably based on the landscape characteristics of each tributary subbasin. Less developed subbasins, such as Trout Brook, French Brook, and Waushacum Brook, usually have higher proportions of organic nitrogen (see discussion of TKN in the Appendix, Section A.4) while more developed subbasins, such as

West Boylston Brook and Gates Brook, have much lower proportions of organic nitrogen. This phenomenon is a function of the availability of organic nitrogen source material and inorganic nitrogen uptake by plants. On a per unit area basis, less developed subbasins have greater amounts of organic nitrogen within the landscape and more nutrient uptake by plants. The ratios of various nitrogen species play a significant role in aquatic ecology, both in the tributaries and reservoir, in terms of algal production and bacteria growth and survival.

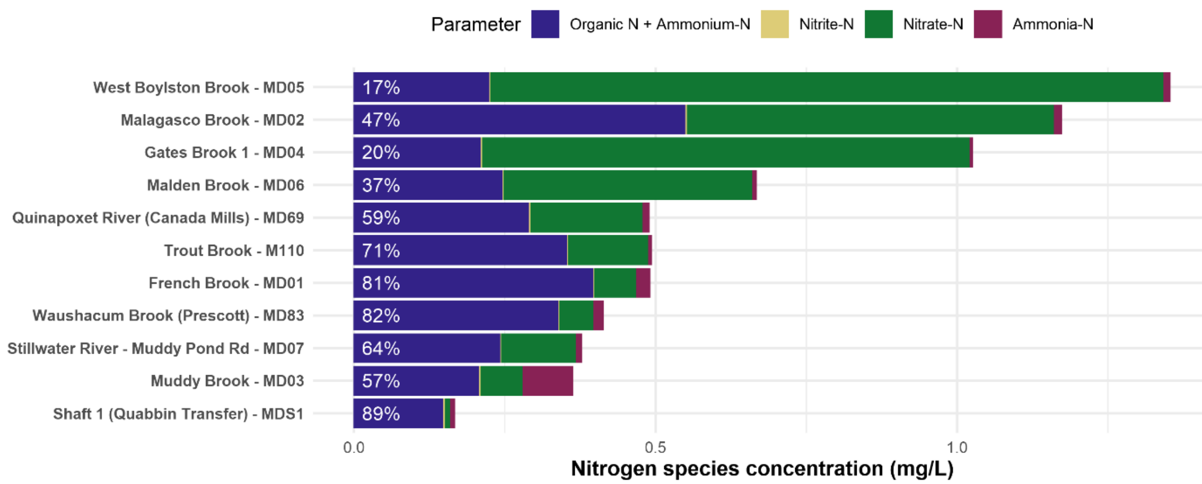


Figure 34: 2021 Mean Total **Nitrogen Concentrations at Wachusett Tributaries.**
Percentages indicate the organic nitrogen fraction of total nitrogen at each sample location.

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

3.2.7.2 Total Phosphorus in Wachusett Reservoir Watershed Tributaries

Total phosphorus (TP) concentrations measured in Wachusett tributaries during 2021 ranged from 8.2 µg/L at Waushacum Brook to 77.1 µg/L at Malagasco Brook (Figure 35). Annual mean concentrations ranged from 14.55 µg/L at the Stillwater River to 38.5 µg/L at Malagasco Brook (Table 25). Seven tributaries had mean annual TP concentrations lower than the 2012 – 2020 period mean, while three tributary means were slightly higher (Malagasco, Malden and West Boylston Brooks) (Figure 35). 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 sediment can be collected in samples.

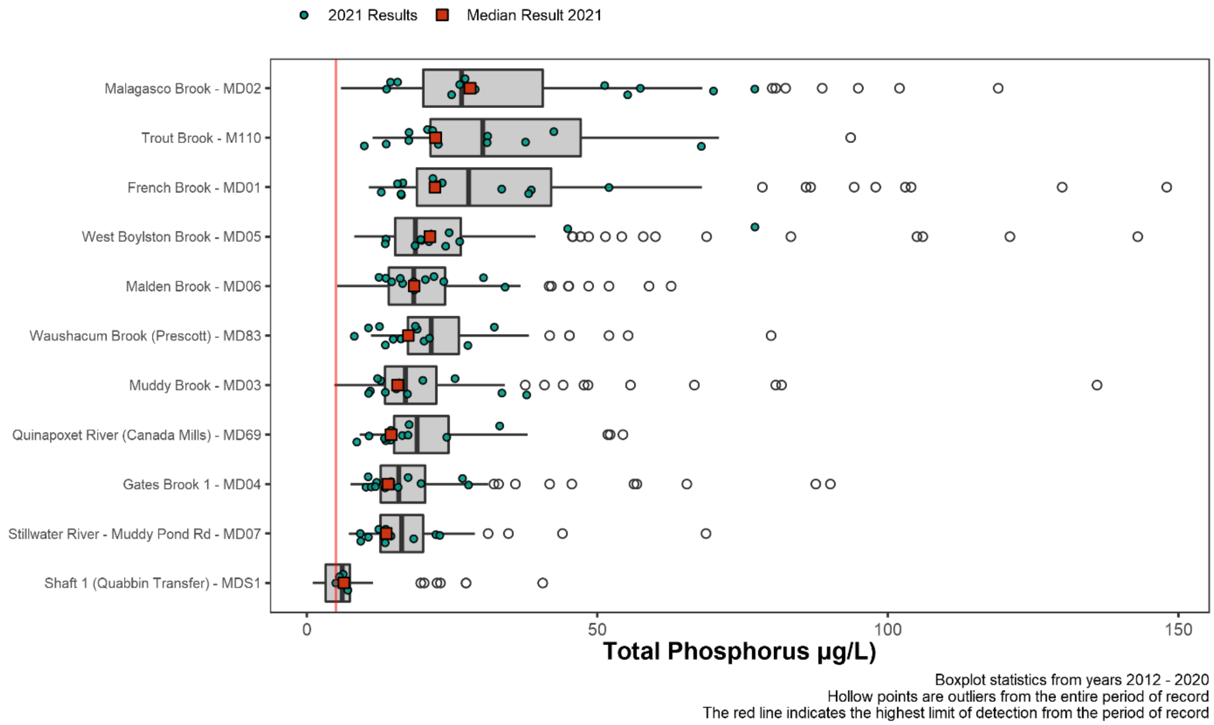


Figure 35: 2021 Total Phosphorus Concentrations with 2012 - 2020 Statistics

Mean annual TP concentrations in 2021 for most Wachusett tributaries were within typical ecoregional background concentrations (12 – 23.75 µg/L). Four tributaries (French, Trout, Malagasco and West Boylston Brooks) have long-term median TP concentrations above 23 µg/L, which could be reflective of local background conditions, or possibly the result of anthropogenic sources. Three of these subbasins have on-lot waste disposal systems (septic) on developed parcels. Furthermore, French Brook subbasin contains a golf course which covers 10% of the drainage area and Malagasco Brook contains a nursery operation which covers 8% of its drainage area. The flow weighted mean TP concentration for all tributaries for 2021 was 20.86 µg/L. However, the Quabbin Transfer contribution lowers the flow-weighted TP concentration to 10.84 µg/L for all surface water delivered to Wachusett Reservoir. The tributaries with long-term mean TP concentrations greater than 20 µg/L are not meeting DWSP water quality goals and are contributing towards nutrient enrichment within individual tributaries and the 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	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
French Brook - MD01	49	32	31	32	29	23	26	44	54	26
Gates Brook 1 - MD04	25	17	25	15	17	15	19	23	21	16
Malagasco Brook - MD02	44	26	34	38	25	37	36	30	30	39
Malden Brook - MD06	28	18	25	24	20	16	20	18	21	20
Muddy Brook - MD03	27	21	19	18	20	21	21	19	31	19
Quinapoxet River (Canada Mills) - MD69	27	19	20	24	21	17	19	18	23	17
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	8	12	7	10	6
Stillwater River - Muddy Pond Rd - MD07	23	15	18	19	19	15	16	15	18	15
Trout Brook - M110	—	—	—	50	38	31	29	29	35	28
Waushacum Brook (Prescott) - MD83	29	23	25	22	26	20	19	21	26	18
West Boylston Brook - MD05	35	19	37	21	18	20	31	25	32	27

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

In 2021, Total Organic Carbon (TOC) sample concentrations in the Wachusett tributaries ranged from 1.6 mg/L at West Boylston Brook to 20.5 mg/L at Malagasco Brook (Figure 36; Table 26). The overall mean concentration for 2021 was 5.31 mg/L, which is 15% higher than the long-term mean concentration since 2012 (4.60 mg/L). All tributaries had median TOC concentrations for 2021 higher than the 2012 – 2020 median, and for some tributaries the 2021 medians exceeded the 75th percentile value from the previous nine years (Figure 36).

The 2021 flow-weighted mean TOC concentration for all tributaries and Quabbin Transfer was 3.39 mg/L. Without the Quabbin Transfer, the flow-weighted mean concentration would have been 6.52 mg/L, or 92% higher. The highest mean annual TOC concentrations were recorded from Malagasco and Trout Brooks, with the lowest concentrations from Muddy, Gates, and Waushacum Brooks (Figure 36). The source of elevated carbon loading at Trout Brook is thought to be Poutwater Pond, a quaking bog located in Holden, yet this remains to be confirmed by TOC analysis on water collected from the bog outflow. The likely source of organic carbon in Malagasco Brook is a headwaters wetland that covers 17% of the subbasin drainage area. The large plant/tree nursery in Malagasco subbasin may be contributing to elevated carbon loads in that subbasin, however this also has not yet been investigated or confirmed.

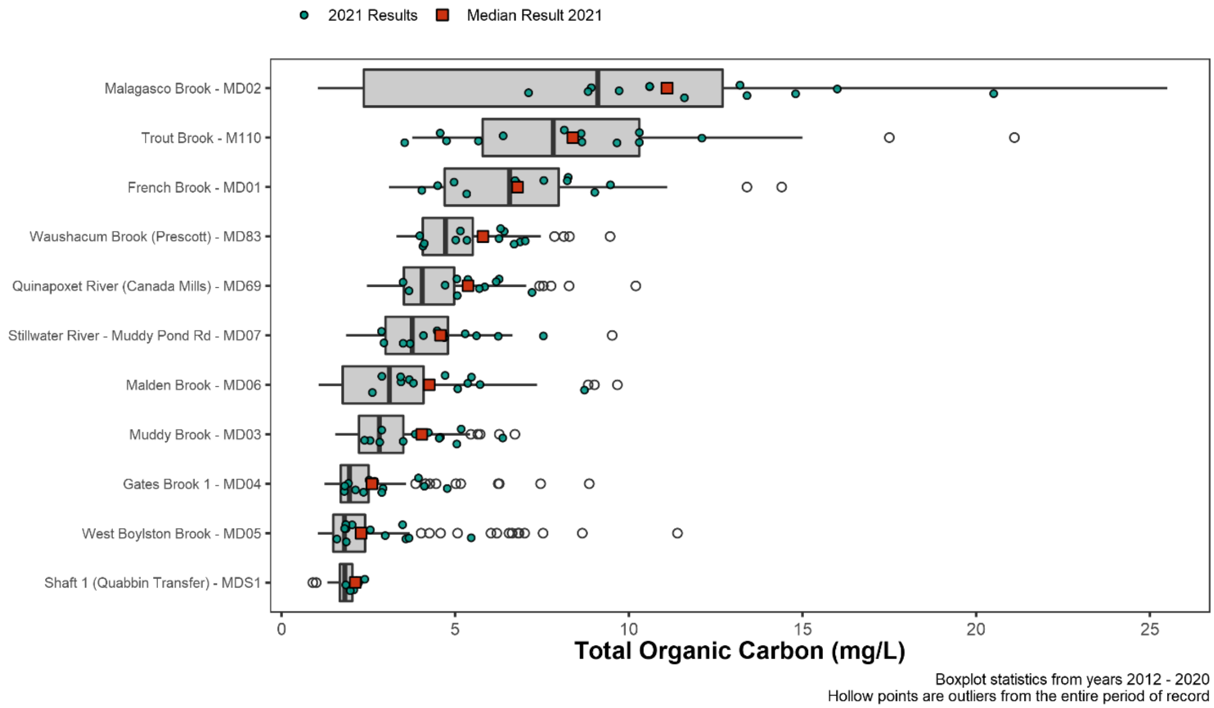


Figure 36: 2021 Total Organic **Carbon Concentrations with 2012 - 2020 Statistics**

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	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
French Brook - MD01	7.89	6.21	6.74	5.88	6.06	6.81	7.14	5.51	7.59	6.81
Gates Brook 1 - MD04	2.69	2.10	2.52	1.86	2.34	2.27	2.45	2.46	2.55	2.82
Malagasco Brook - MD02	11.70	6.40	10.80	7.79	8.83	10.82	10.81	7.20	6.80	12.11
Malden Brook - MD06	3.49	2.81	4.21	2.29	3.08	3.50	3.67	2.82	3.50	4.58
Muddy Brook - MD03	3.09	2.96	3.01	2.44	2.93	3.53	3.49	2.73	3.06	4.00
Quinapoxet River (Canada Mills) - MD69	4.56	4.28	4.76	4.11	4.92	4.53	4.73	3.61	3.92	5.33
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	1.89	1.55	1.79	2.04	2.11
Stillwater River - Muddy Pond Rd - MD07	3.79	3.55	4.58	3.89	3.84	4.54	4.79	3.34	3.65	4.64
Trout Brook - M110	—	—	—	9.54	8.50	9.43	9.31	6.51	7.06	7.73
Waushacum Brook (Prescott) - MD83	5.25	4.72	5.33	4.50	4.97	5.36	4.91	4.27	4.98	5.60
West Boylston Brook - MD05	2.50	2.11	3.20	1.76	1.88	2.26	2.71	2.80	3.07	2.73

TOC concentrations between 2 and 4 mg/L are considered low for surface waters, and the 2021 flow-weighted mean TOC concentration of 3.39 mg/L is not a concern for aquatic life. However, this concentration is higher than optimal from a drinking water treatment perspective. Although tributary TOC concentrations are within ranges that could be reflecting typical background concentrations, more research needs to be conducted to determine what portion of tributary organic carbon is of natural origin versus anthropogenic origin. Until those sources and relative quantities are better understood, recommendations for reduction cannot be made.

Measurements of UV_{254} absorbance for Wachusett tributaries in 2021 demonstrated variability comparable to TOC concentrations (Figure 36, Table 27). The highest UV_{254} absorbance levels were from

Malagasco Brook (1.25 ABU/cm) and Trout Brook, and the lowest were from Gates Brook 1 (0.037 ABU/cm). Overall, UV_{254} absorbance levels were higher in 2021 compared with the prior nine years, with mean and median absorbance levels the highest since at least 2012 observed in several tributaries (Gates Brook, Malagasco Brook, Malden Brook, Muddy Brook, Quinapoxet River, Waushacum Brook).

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

Sample Location	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
French Brook - MD01	0.315	0.229	0.251	0.226	0.199	0.248	0.313	0.237	0.311	0.309
Gates Brook 1 - MD04	0.077	0.057	0.068	0.051	0.065	0.057	0.084	0.095	0.068	0.084
Malagasco Brook - MD02	0.584	0.317	0.479	0.372	0.304	0.510	0.618	0.380	0.302	0.672
Malden Brook - MD06	0.132	0.102	0.153	0.078	0.100	0.126	0.156	0.116	0.133	0.206
Muddy Brook - MD03	0.117	0.108	0.108	0.101	0.103	0.133	0.151	0.117	0.107	0.215
Quinapoxet River (Canada Mills) - MD69	0.164	0.156	0.167	0.162	0.162	0.197	0.210	0.152	0.153	0.221
Shaft 1 (Quabbin Transfer) - MDS1	—	—	—	—	—	0.020	0.026	0.032	0.027	0.030
Stillwater River - Muddy Pond Rd - MD07	0.140	0.140	0.152	0.167	0.125	0.193	0.215	0.144	0.141	0.195
Trout Brook - M110	—	—	—	0.432	0.316	0.437	0.421	0.335	0.327	0.413
Waushacum Brook (Prescott) - MD83	0.175	0.138	0.158	0.146	0.153	0.169	0.186	0.163	0.179	0.207
West Boylston Brook - MD05	0.078	0.052	0.075	0.050	0.057	0.053	0.091	0.081	0.077	0.079

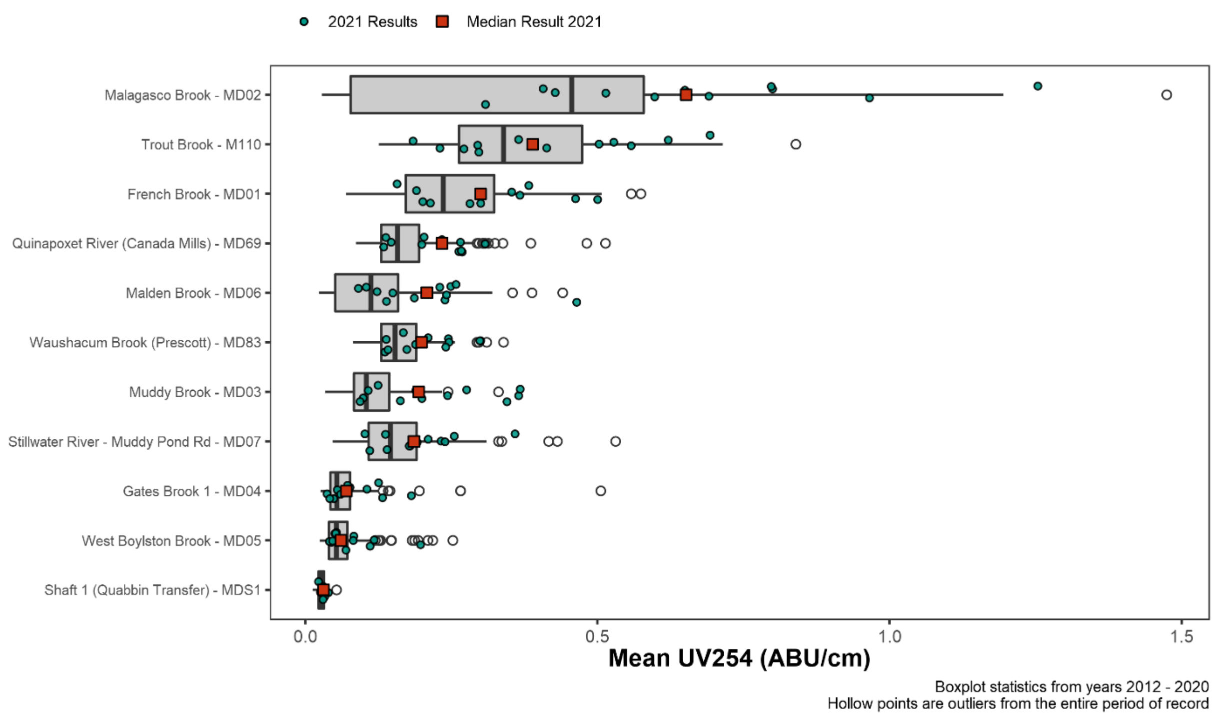


Figure 37: 2021 UV_{254} Absorbance with 2012 - 2020 Statistics

Similar to TKN, the elevated TOC concentrations and UV_{254} absorbance levels observed in 2021 is likely due to the excess precipitation during the summer and early fall months. Higher resolution TOC and UV_{254} absorbance data in comparison with streamflow would enable analyses that could better explain the loads and variability of organic matter in the tributaries on a finer time scale. 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 exaggerated by a single sample taken during anomalous hydrologic conditions, such as those observed in July of 2021.

3.2.9 Special Studies and Investigations – Tributaries

3.2.9.1 Forestry Water Quality Monitoring

Long-term forestry monitoring

In 2021, monthly monitoring at the LTF monitoring locations—Holden (FHLN) and Princeton (FPRN)—continued as part of the pre-harvest phase. A partial suspension of storm event sampling continued through 2021 because sufficient data for storm events in the pre-harvest phase has been acquired (21 events prior to 2019). One storm event was sampled on October 27 in order to test equipment and review SOPs for storm sample collection.

All necessary pre-harvest data has been collected at both study locations and the experimental lot (Princeton) was put out to bid and sold in 2021. It is expected that timber harvesting will commence at the Princeton site in 2022 and storm sampling will resume after the harvest is complete. Regular monthly sampling will continue in the harvest phase as it was conducted during the pre-harvest phase.

Short-term forestry monitoring

In 2021, 194 lot visits were made across 19 distinct forestry lots in various stages of harvest. Pre-harvest monitoring began at proposed stream crossings on two lots: WA-19-95, WA-19-328. Post-harvest monitoring was completed at nine lots, four of which were discontinued at the end of 2021 due to a change in monitoring protocols (see section 4.3.4.1). A total of 187 turbidity samples were collected from stream crossing sampling locations across all harvest phases. Dry conditions prevented sample collection only 45 times, which is a much lower percentage than normal due to the extremely wet summer (Table 28).

Table 28: Short-term Forestry Monitoring in 2021

Metric	Pre-harvest	Harvest - Active	Harvest - Suspended	Post-harvest	Total
Lot Visits	54	45	4	91	194
Crossing Observations	67	54	8	104	233
Turbidity Samples Collected	54	43	8	81	187

Turbidity results ranged from 0.10 NTU at WA-19-133 to 15.8 NTU at WA-18-211 (Figure 37). Turbidity results were less than 1.0 NTU for 92% of samples in 2021. Only two samples were above 5.0 NTU: on September 29, 2021, a bridge installation resulted in a short duration of elevated turbidity at lot WA-18-211. Immediately downstream of the bridge installation turbidity was measured at 15.8 NTU, compared to 0.53 NTU upstream of the crossing. Further downstream of the crossing turbidity was 1.27 NTU. The immediate downstream turbidity had fallen to 0.63 NTU shortly after the bridge installation was completed. Impacts from this activity were extremely localized and short-lived. The other high turbidity result (7.46 NTU) was from a sample taken during extremely low flow at lot WA-21-232 on December 17. This sample likely contained fine grained bed load material, since the sample collection bottle had to get very close to the stream bed during collection.

Mean turbidity values during harvest phases were slightly higher downstream of the crossings, but still what would be considered background levels. Overall mean turbidity values for 2021 were low and representative of background water quality conditions (Table 29). The turbidity results for 2021 indicate that sediment erosion control practices at Wachusett forestry operations continue to adequately protect water quality.

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

Sample Location	Pre-harvest	Harvest (Active and Suspended)	Post-Harvest
Upstream	—	0.54	—
Downstream	0.59	0.90	0.55

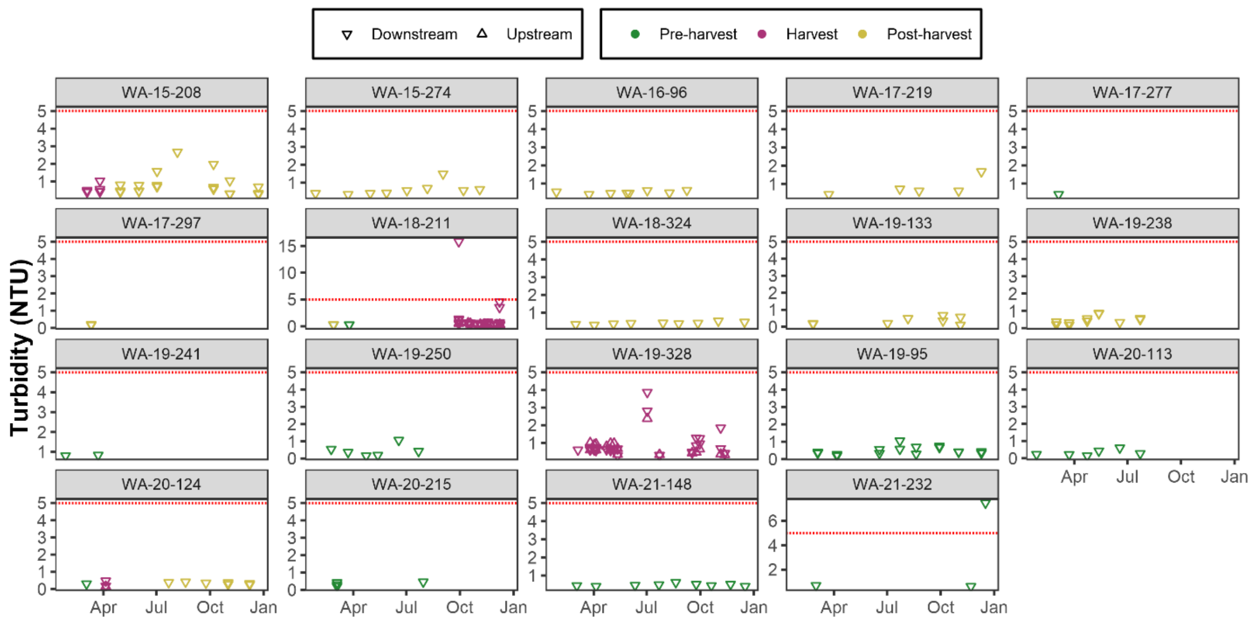


Figure 38: Turbidity Results at Short-term Forestry Monitoring Locations in 2021

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 2021, 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 more than 20 staff involved across all sections of DWSP working on 37 distinct tasks within the following categories:

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

A complete 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 will be taken in streams, wetlands, and ponds, avoiding storm runoff so that measurements reflect baseflow water chemistry as much as possible. The conductivity blitz is expected to be finished by the fall of 2022 and the results will be reported in the 2022 Annual Water Quality Report. This information will be used to help identify chloride/specific conductance hotspots within subbasins. Hotspot areas will be investigated to determine 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 is 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 full analysis of the data is pending, and the results will be presented in the 2022 Annual Water Quality Report.

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 39). 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.

Figure 39: 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 2021, 16 monitoring visits were conducted approximately monthly and during a range of weather conditions. Basins holding water were also monitored for developing mosquito larvae, visually and through collected water samples. No larvae were found through either method.

3.3 Groundwater Quality Monitoring

Expanded groundwater monitoring was continued in 2021 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. Due to above average precipitation during the summer, groundwater levels were sufficient in all wells throughout the year for sample collection. Results of well monitoring in 2021 continued to indicate a wide range in specific conductance and Cl concentrations in Wachusett Watershed groundwater (Figure 40). 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). In total, three wells — Holden - Wachusett St, Boylston - Rt 70, and West Boylston - Rt 110 — have Cl levels higher than the EPA SMCL of 250 mg/L for taste and odor in drinking water.

The ranges and medians of specific conductance and Cl results are shown in the box plots in Figure 40 and Figure 41 with logarithmic Y-axes due to the high and low skews in values. Elevated Cl levels in the Wachusett Watershed are assumed to be primarily attributable to the chronic application of deicing road salt, but due to the particularly elevated specific conductance and Cl levels in West Boylston – Rt 110, DWSP launched a supplementary investigation in 2019 to determine additional sources impacting the groundwater at that location. To date, this investigation has not created any additional insights.

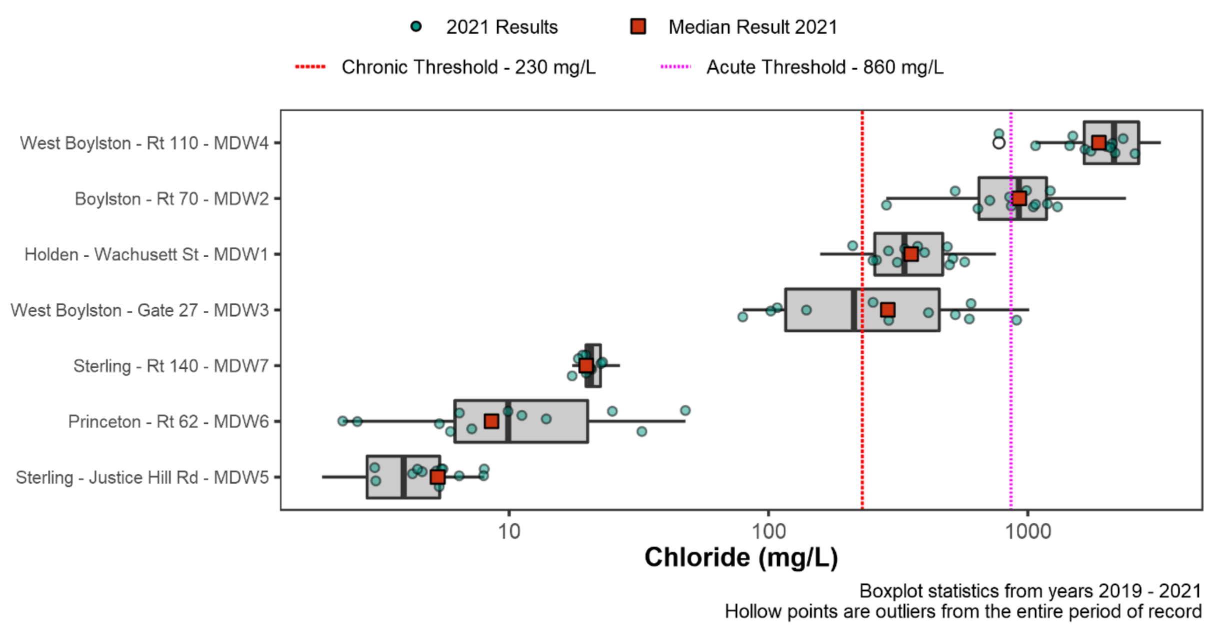


Figure 40: Chloride Results in Wachusett Watershed Wells in 2021

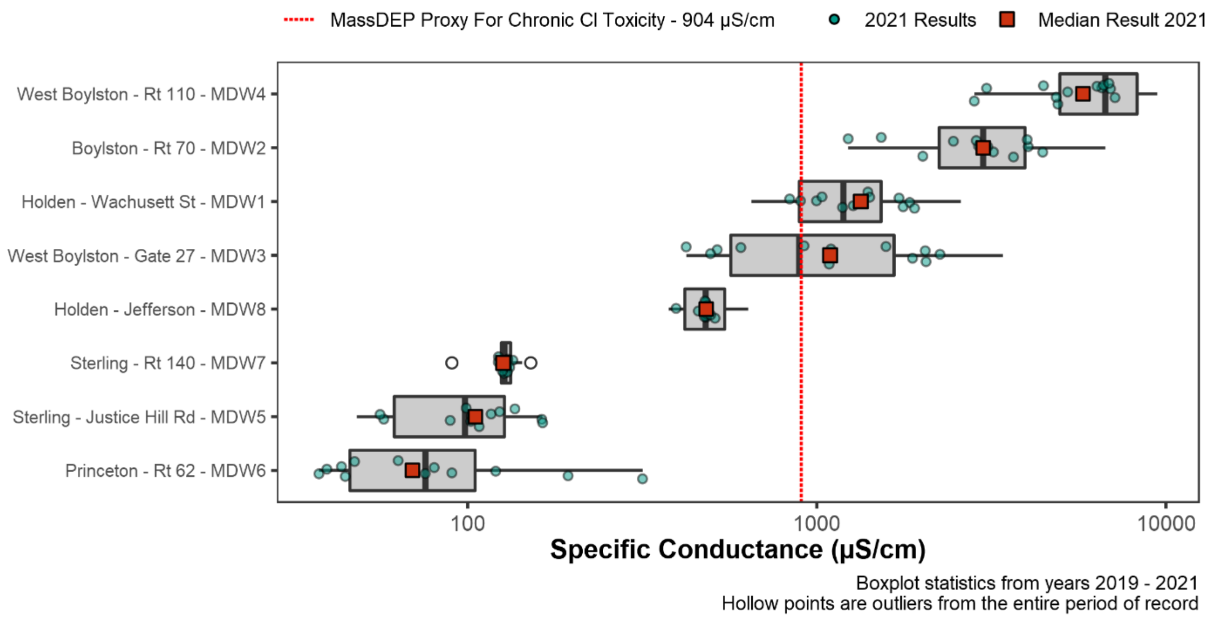


Figure 41: Specific Conductance Results in Wachusett Watershed Wells in 2021

Table 30: Groundwater Monitoring Summary for 2021

Well	Mean Water Depth Below Ground Surface (ft)	Mean Specific Conductance (µS/cm)	Mean Chloride (mg/L)
Princeton - Rt 62	15.4	96.0	14.2
Sterling - Justice Hill Rd	2.7	109.8	5.3
Sterling - Rt 140	14	127.3	20.1
Holden - Jefferson	17.4	475.8	-
West Boylston - Gate 27	6.7	1,246.4	358.6
Holden - Wachusett St	1.4	1,356.7	376.1
Boylston - Rt 70	5.9	2,952.5	891.3
West Boylston - Rt 110	11.9	5,484.3	1,791.2

Well monitoring will continue in 2022 to determine if seasonal or long-term trends are present in groundwater specific conductance and Cl concentrations. Additional data will also assist in establishing a relationship between specific conductance and Cl in each well, at which time DWSP staff may consider ending Cl sample collection as it will be possible to estimate Cl concentrations from specific conductance measurements. Groundwater contributions of Cl in Wachusett tributaries are being further explored by researchers at UMass Amherst and the final publication on this topic was released in 2021[44].

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

[44] Soper, 2021

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

3.4 Reservoir Monitoring

In general, results of reservoir monitoring programs followed expected trends and fell within or close to historical values. Notable deviations are likely related to the low volume of water transferred from Quabbin Reservoir to Wachusett Reservoir, resulting in native Wachusett Watershed water having a larger influence on water quality parameters such specific conductance, silica, and UV_{254}. Two brief periods during which chrysophyte algae exceeded early monitoring thresholds were documented in 2021 as was a prolonged period of cyanophyte presence at the surface in the fall. 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 2021 supported MassDEP aquatic life use standards for coldwater and warmwater fisheries. Recorded reservoir temperatures ranged from 1.4 °C to 25.7 °C.

Ice was present for a total of 40 days between February 2 and March 14 (Figure 42). Substantial warming started in May and the presence of a thermocline, as indicated by a 1 °C temperature decrease over one meter in depth, was first recorded on May 17 (Figure 43). Surface temperatures continued to warm, attaining a maximum recorded temperature of 25.7 °C at Basin North at 1 m on August 16. Cooling of the epilimnion started in mid-August when the combination of cooling air temperatures and wind energy pushed the thermocline deeper. However, cooling was slower than normal due to warm fall temperatures, including a 5.2 °C warmer than normal October[45]. Turnover occurred on November 14 and the water column continued to cool for the remainder of the season.

[45] Northeast Regional Climate Center, 2022

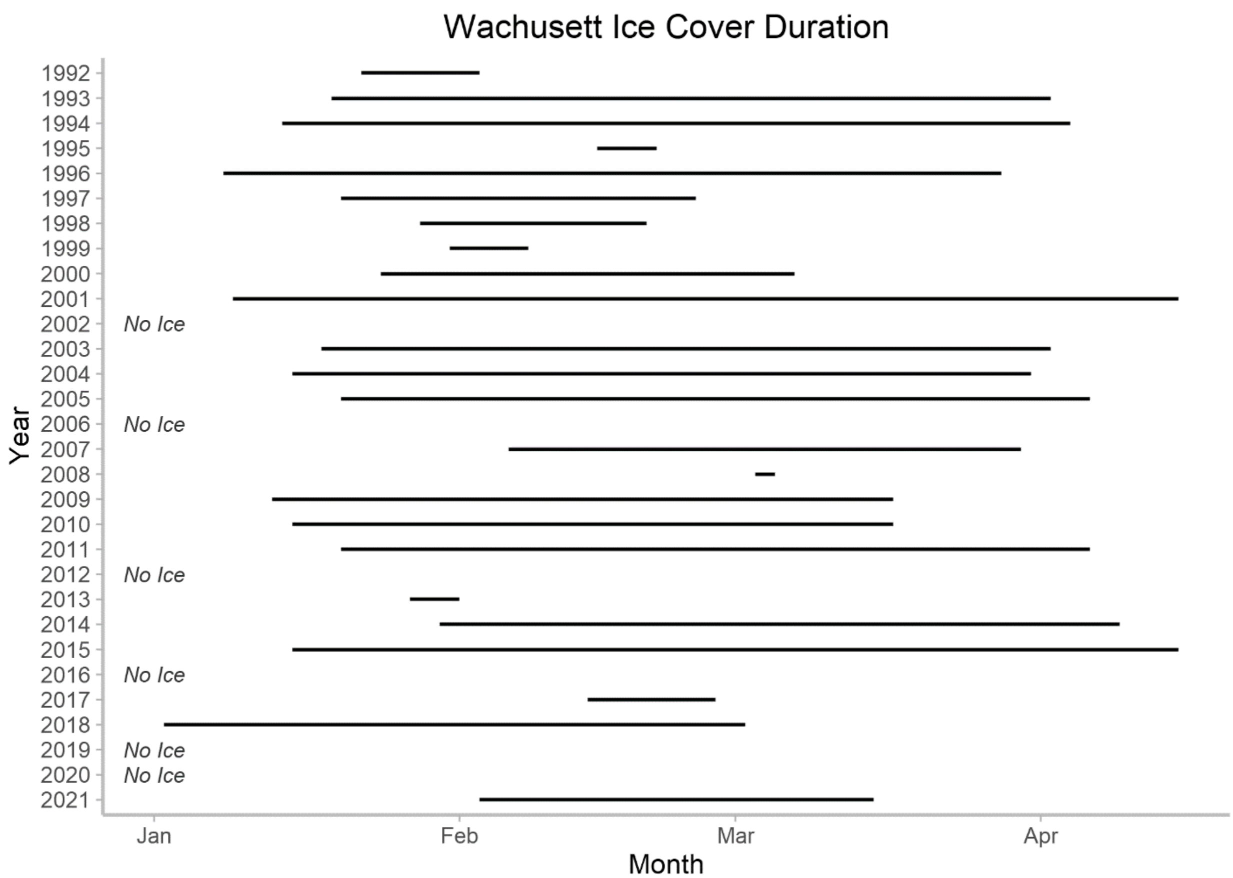


Figure 42: Ice Cover Duration for Wachusett Reservoir for the Period of Record (1992 – 2021)
Ice cover is considered complete when a majority of the north basin in frozen over. Ice may have been present during 'No Ice' years, but complete cover was not achieved.

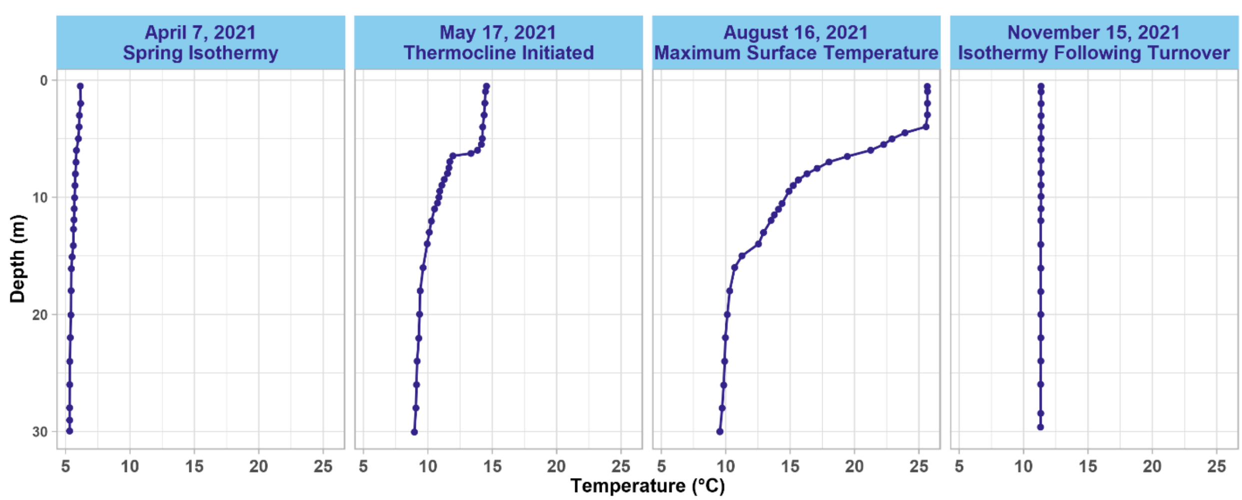


Figure 43: Profiles from Basin North Displaying Water Temperature at Critical Periods During 2021

The high temporal resolution data obtained from MWRA remote sensing buoys provide an opportunity to visualize reservoir temperature changes over the entire season (Figure 44). A brief period of stratification occurred in late May, dissipated, and then strengthened through June and the remainder of the summer.

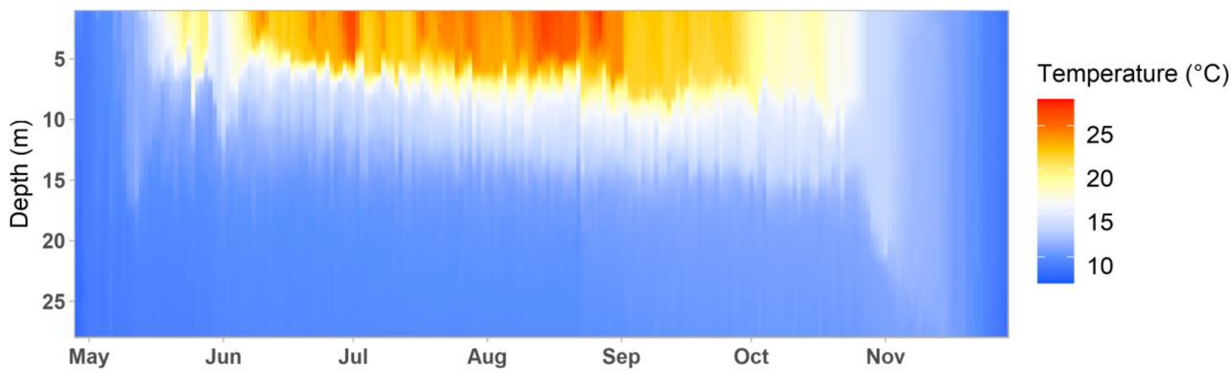


Figure 44: Water Temperature Recorded by Basin North Profiling Buoy May – November 2021
Plot based on data recorded daily at 12 pm.

3.4.2 Dissolved Oxygen

Expected patterns in dissolved oxygen were observed through the 2021 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 between October 11 and November 8 at depths below 20 m but did not fall below 4.28 mg/L based on profiles collected at Basin North (Figure 45).

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 4.28 mg/L at 30 m on November 8. 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 14 (as recorded by MWRA profile buoys), oxygen was again able to disperse through the water column and was approximately 9.3 mg/L from the surface to bottom on November 15. Elevated dissolved oxygen below the thermocline associated with increased phytoplankton activity occurred several times throughout the summer.

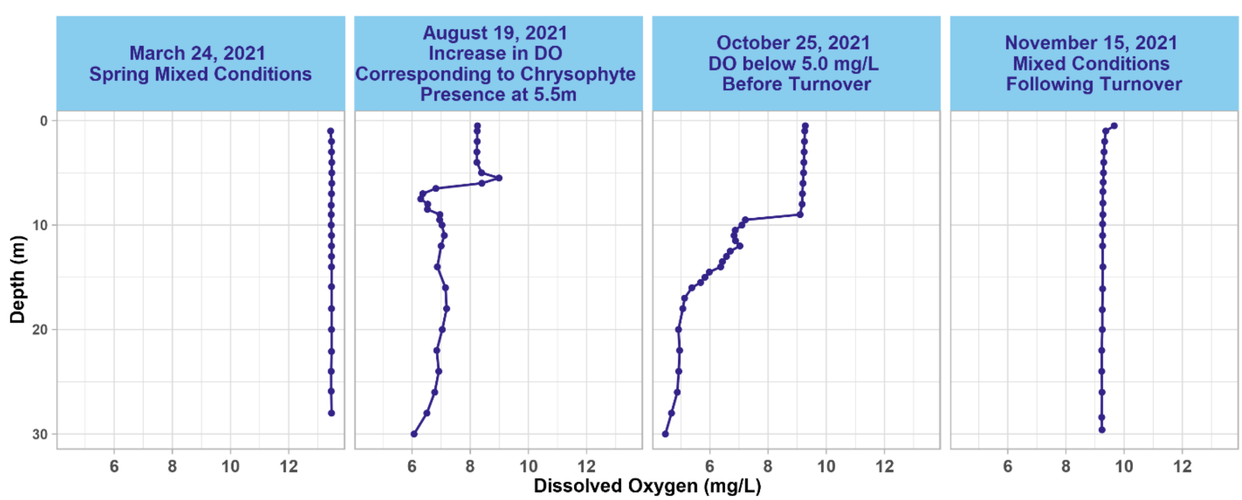


Figure 45: Profiles from Basin North Displaying Dissolved Oxygen at Critical Periods During 2021

3.4.3 Specific Conductance

Annual mean and maximum specific conductance observed in the reservoir continued to decrease slightly. The maximum value of 161.6 µS/cm was recorded at a depth of 6 m at Basin North on June 28 and the annual mean was 144 µS/cm. The annual minimum conductivity was higher than the previous two years at 106.7 µS/cm, recorded at 12 m on October 25.

Arrival of the Quabbin interflow at Basin North was first observed on June 7 with a slight decrease in specific conductance observed around 8 m. By June 21, a definitive decrease in specific conductance between 6 and 11 m indicated infiltration of the Wachusett metalimnion by the Quabbin interflow. Following this date, specific conductance within the metalimnion continued to decrease, reaching a minimum of 106.7 µS/cm at 12 m on October 25. At its maximum extent on October 5, the interflow encompassed 7 m of water between the depths of 8 and 15 m. As the reservoir epilimnion temperature decreased in mid-October, higher conductivity water found in the Wachusett epilimnion began mixing with the lower conductivity hypolimnion and Quabbin interflow, reducing the difference in specific conductance between the epilimnion and hypolimnion. By mid-November, the reservoir was again fully mixed, with a nearly uniform specific conductance of approximately 128 µS/cm on November 15 (Figure 46).

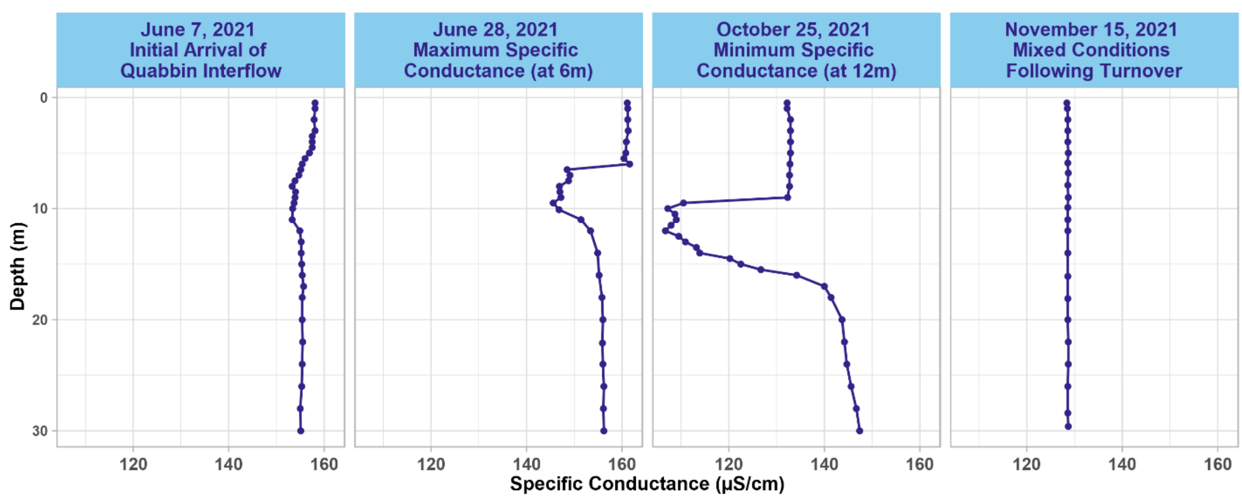


Figure 46: Profiles from Basin North Displaying Specific Conductance at Critical Periods During 2021

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 47).

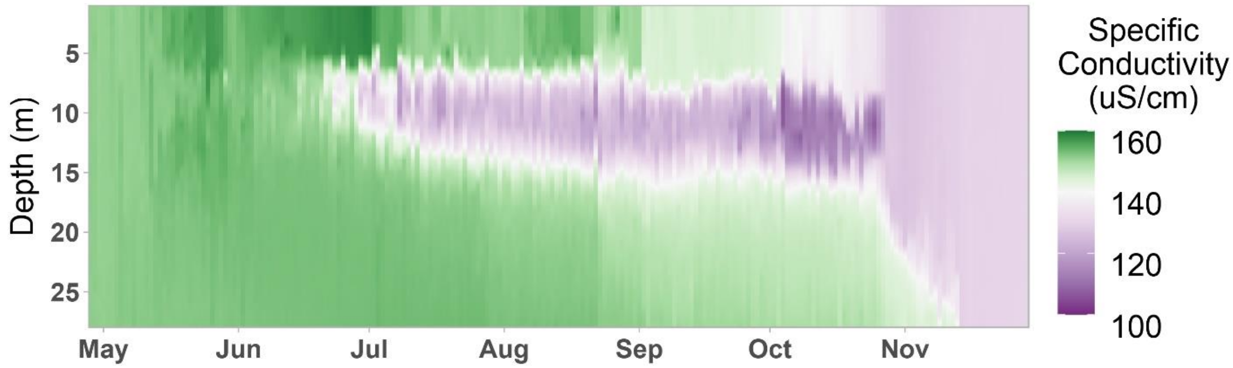


Figure 47: Specific Conductance Recorded by Basin North Profiling Buoy May – November 2021
The Quabbin interflow layer is clearly visible in the range of 107 to 130 µS/cm between mid-June and late October.

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 2021, pH ranged from neutral to slightly acidic with a maximum value of 7.6 and minimum value of 5.7. Values less than 6 were recorded below depths of 10 m in from late August through November as phytoplankton die off and release carbon at depth. pH greater than 7.4 was observed in mid-June corresponding to elevated diatom density and increased photosynthesis in the epilimnion.

3.4.6 Secchi Disk Depth/Transparency

Secchi disk depths in 2021 ranged from 5.5 m to 8.8 m. The maximum value was recorded on May 17 prior to the peak of diatom density which occurred in early June (Figure 48). Transparency increased briefly in late June and early July but decreased again in late August through October due to elevated chrysophyte and then cyanophyte densities. The annual mean Secchi disk depth of 7.0 m remained greater than the reference range of 4 m to 6.1 m for the reservoir ecoregion.

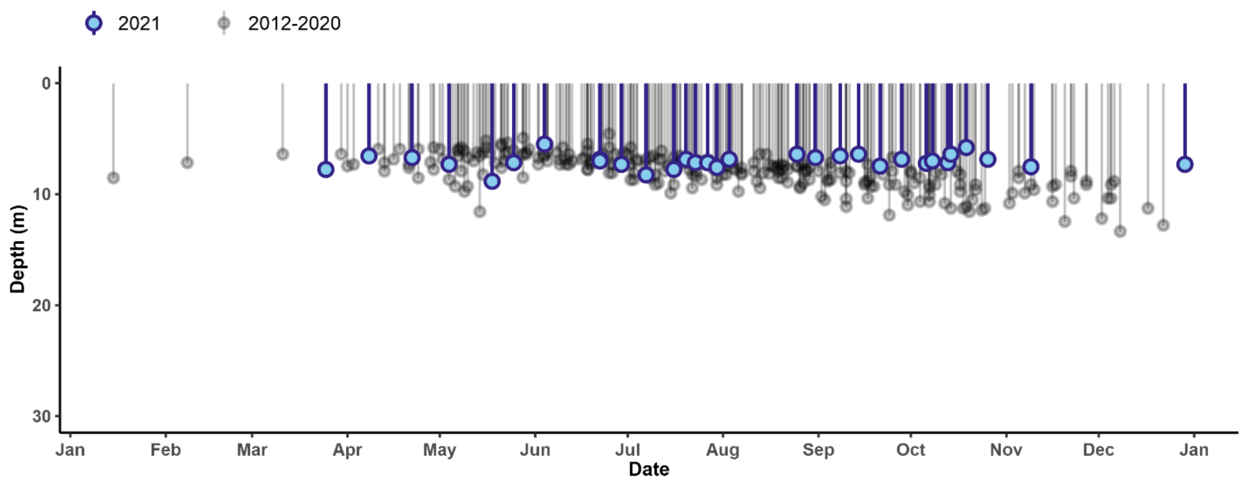


Figure 48: 2021 Secchi Disk Transparency at Basin North

3.4.7 Nutrient Dynamics

The patterns of nutrient distribution in 2021 quarterly samples generally followed those documented in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics[46]. 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 2021 was 6.90 mg/L as CaCO3 and 66% of results for individual sites were lower than annual means (Figure 49). Alkalinity continues to be elevated compared to the early period of record, especially over the last four years. The maximum alkalinity of 8.74 mg/L as CaCO3 was recorded in the summer at Thomas Basin while the minimum of 5.58 mg/L as CaCO3 was recorded at Thomas Basin in the fall during a period when water at this location was heavily influenced by the Quabbin Transfer.

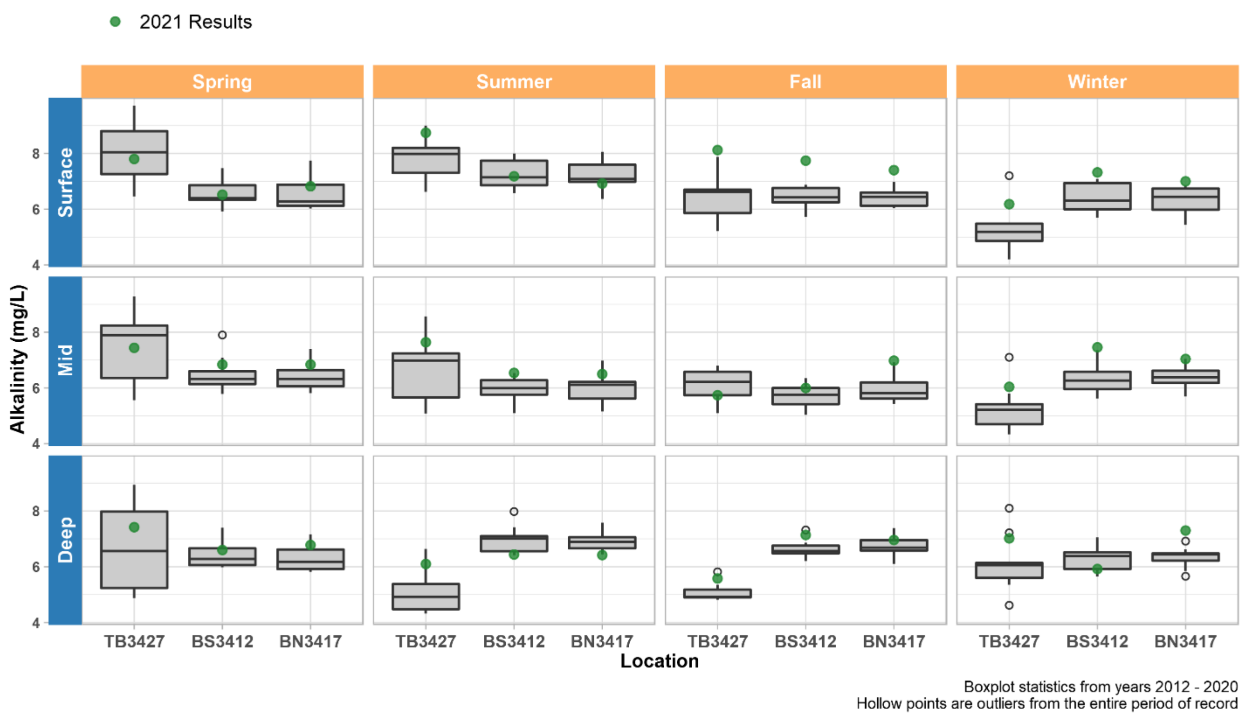


Figure 49: 2021 Alkalinity as $CaCO_3$ in Wachusett Reservoir

[46] Worden & Pistrang, 2003

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 remain low, with concentrations ranging from below the detection limit (0.005 mg/L, 20% of samples) to a maximum observed value of 0.032 mg/L (Figure 50). Highest values are present at mid and deep sample depths during the summer and fall when ammonia builds in the hypolimnion. All values are within the historical range and well below regulatory thresholds reservoir wide (Figure 50). Fifty-four percent of results since 2012 have been lower than the detection limit.

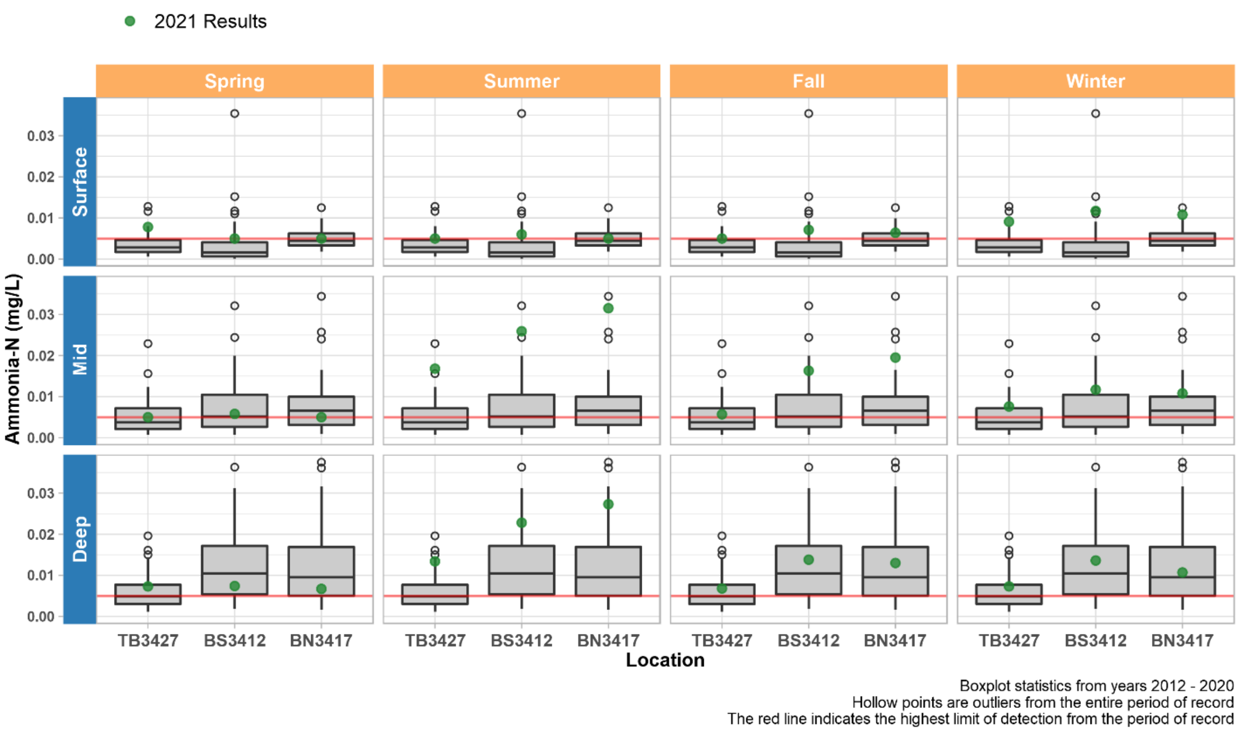


Figure 50: 2021 Ammonia-nitrogen in Wachusett Reservoir

Nitrate-nitrogen

Nitrate-nitrogen (NO_3-N) concentrations are well below the SDWA threshold of 10 mg/L, ranging from below detection (0.005 mg/L) to 0.138 mg/L (Figure 51). The highest concentrations are most often observed in the spring and in the main basin locations at depth during periods of stratification. This pattern continued in 2021, with spring values at all sites falling between 0.069 and 0.086 mg/L. Maximum concentrations for 2021 were recorded in the hypolimnion at the height of stratification at Basin South and Basin North.

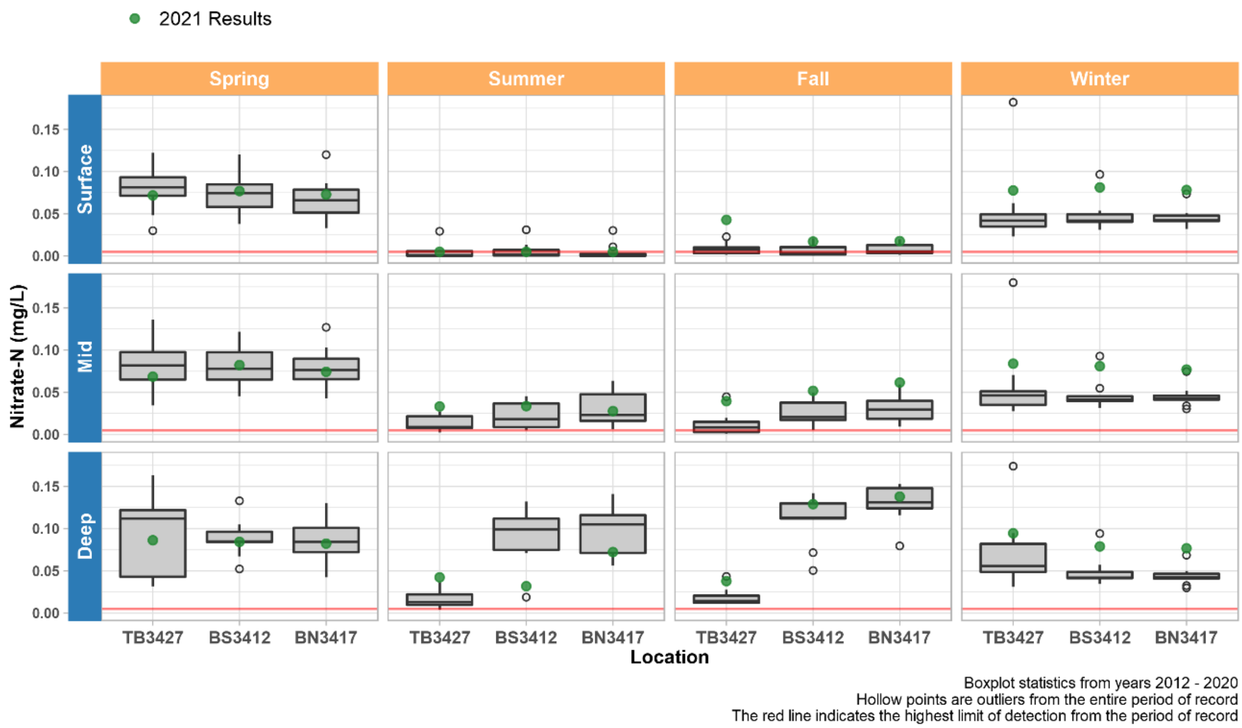


Figure 51: 2021 Nitrate-Nitrogen in Wachusett Reservoir

Total Kjeldahl Nitrogen

Concentrations for Total Kjeldahl Nitrogen (TKN) fell between the detection limit of 0.1 and 0.371 mg/L. Two spring and three summer values from Thomas Basin were slightly greater than the 50th percentile, but were within the historical range (Figure 52). Increased TKN at this location and season 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.

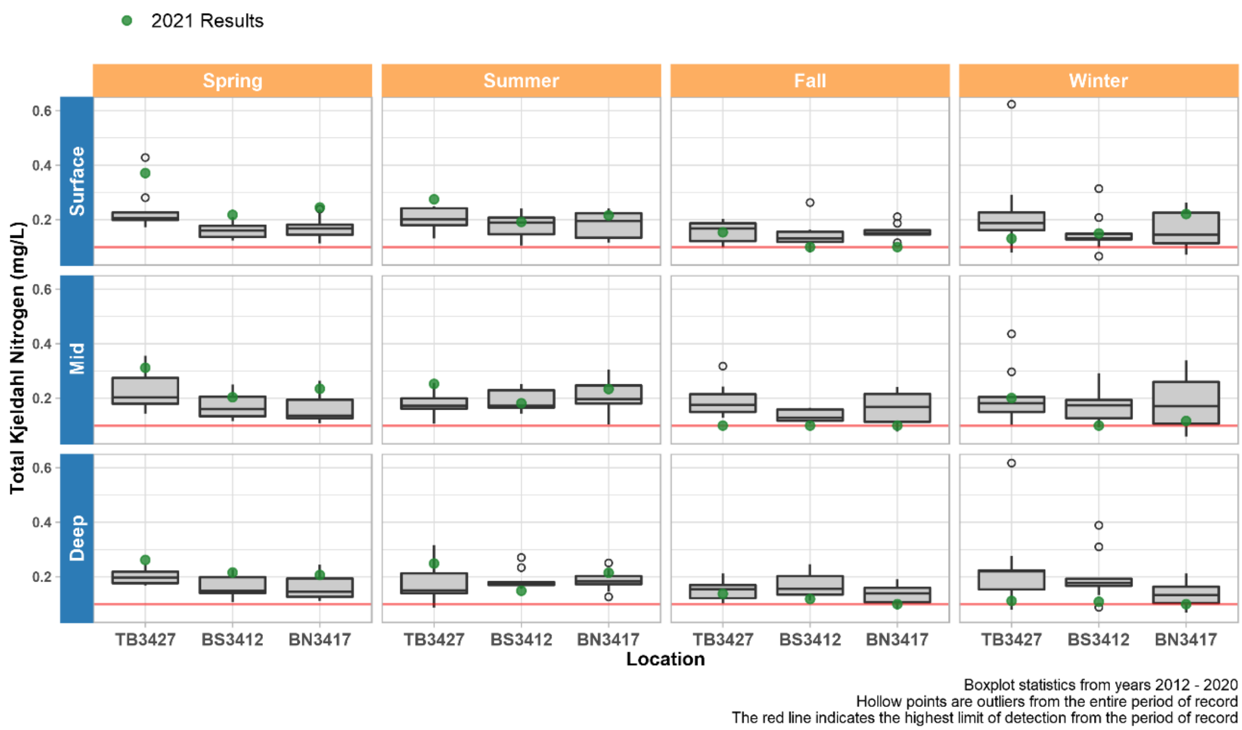


Figure 52: 2021 Total Kjeldahl Nitrogen in Wachusett Reservoir

3.4.7.3 Silica

Silica concentrations were between 1600 and 4480 ug/L in 2021 (Figure 53). The 75th percentile was exceeded in 42% of samples, mostly in the summer, fall, and winter. 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. Diatom concentrations in 2021 did not reach typical high densities in the spring, leaving silica available in the water column. Additional watershed inputs from rain events in July and September likely contributed to elevated silica through the remainder of the year.

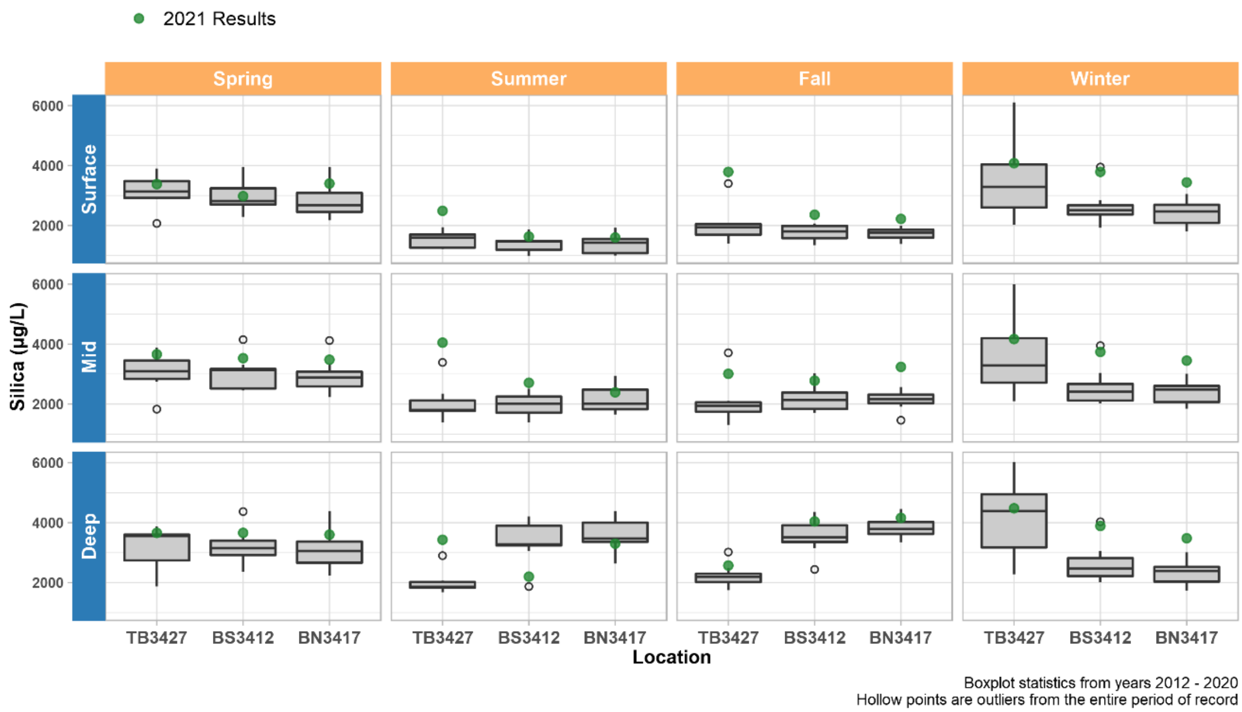


Figure 53: 2021 Silica in Wachusett Reservoir

3.4.7.4 *Total Phosphorus*

Total phosphorus (TP) results for 2021 were below the 75th percentile at all sites except for six collected from Thomas Basin (TB3427) in the summer and fall. All other results were lower than the 10 µg/L threshold for classification as an oligotrophic water body (Figure 54). Results greater than this threshold occurred in Thomas Basin (TB3427) at depths where water from Stillwater and Quinapoxet Rivers was dominant. TP at 66% of sites was lower in 2021 than in 2020 and most increases were insignificant.

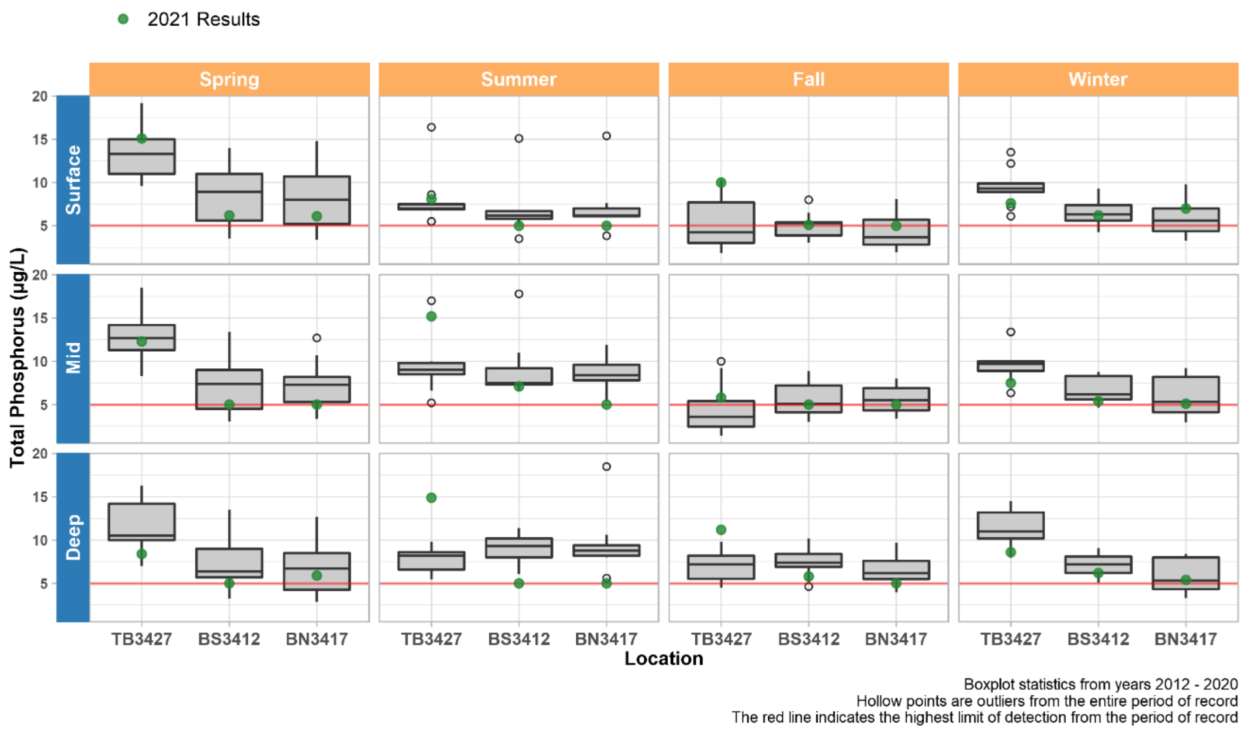


Figure 54: 2021 Total Phosphorus in Wachusett Reservoir

3.4.7.5 UV Absorbance

Measurements of UV_{254} were elevated much of the season, with 53% of individual site results exceeding the 75th percentile (Figure 55). Many of these elevated results were recorded at Thomas Basin where the influence of native water contributed from the Stillwater and Quinapoxet Rivers is typically higher. However, results were elevated at all sites in the fall when levels and variation are typically low. This change was likely due higher than normal summer rainfall and resulting increased watershed inputs. Elevated UV254 values were also observed in tributary sample results (Figure 37). UV254 ranged from 0.060 to 0.241 ABU/cm, which is 5% higher than the maximum for the previous nine years.

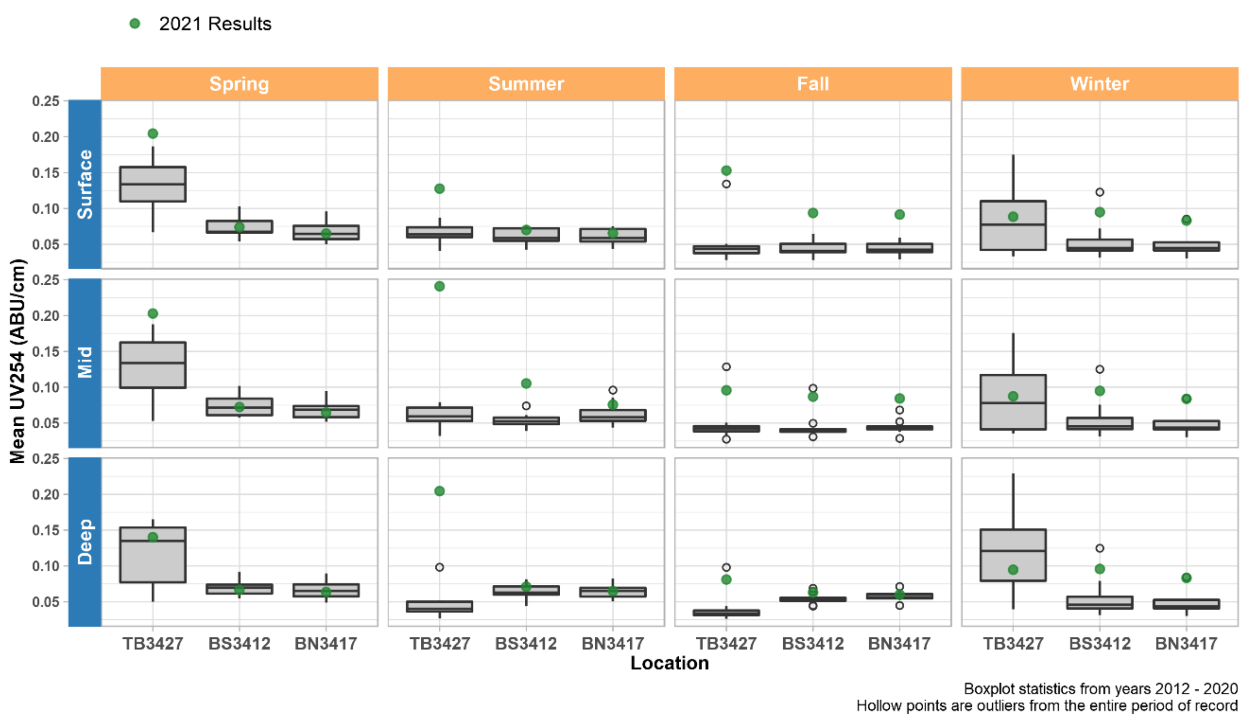


Figure 55: 2021 Wachusett Reservoir UV_{254}

3.4.8 Phytoplankton

A total of 114 algae samples were collected and analyzed on 47 days during the 2021 season. Ice-free conditions in the north basin of the reservoir allowed collection of samples from Basin North in January. Ice-in occurred on February 2 resulting in suspension of sampling until March 24. Sampling continued through the end of the year with the last sample collected on December 28. Spring diatom densities were very low compared to the period of record. Three increases in taste and odor producing phytoplankton genera occurred: elevated *Dolichospermum* was recorded on June 3, a period of elevated *Chrysosphaerella* occurred in July, and *Dinobryon* was elevated in mid-August (Figure 56). Overall chrysophyte densities were lower than in recent years. A notable increase in the cyanophyte Microcystis aeruginosa occurred in the fall. Surface scums were observed in several locations on warm, calm days in early October and colonies persisted in the water column through December.

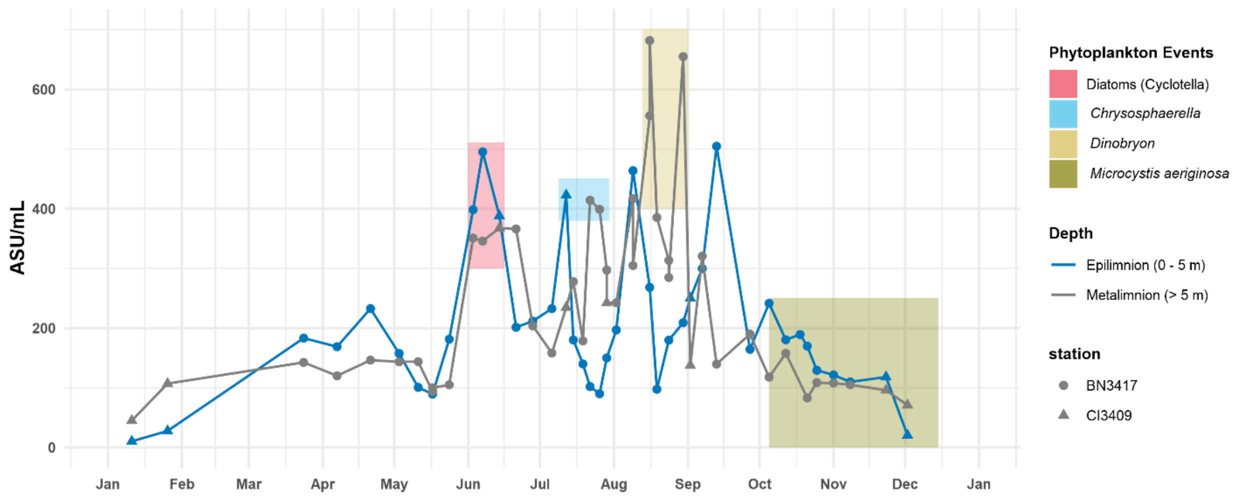


Figure 56: 2021 Wachusett Reservoir Phytoplankton Totals
Epilimnion range is 1 – 5 m, metalimnion range is 5 – 15 m.

The pattern of succession observed in 2021 followed the seasonal changes in phytoplankton community composition and density typically observed in the Wachusett Reservoir. Community composition by group is displayed in Figure 57.

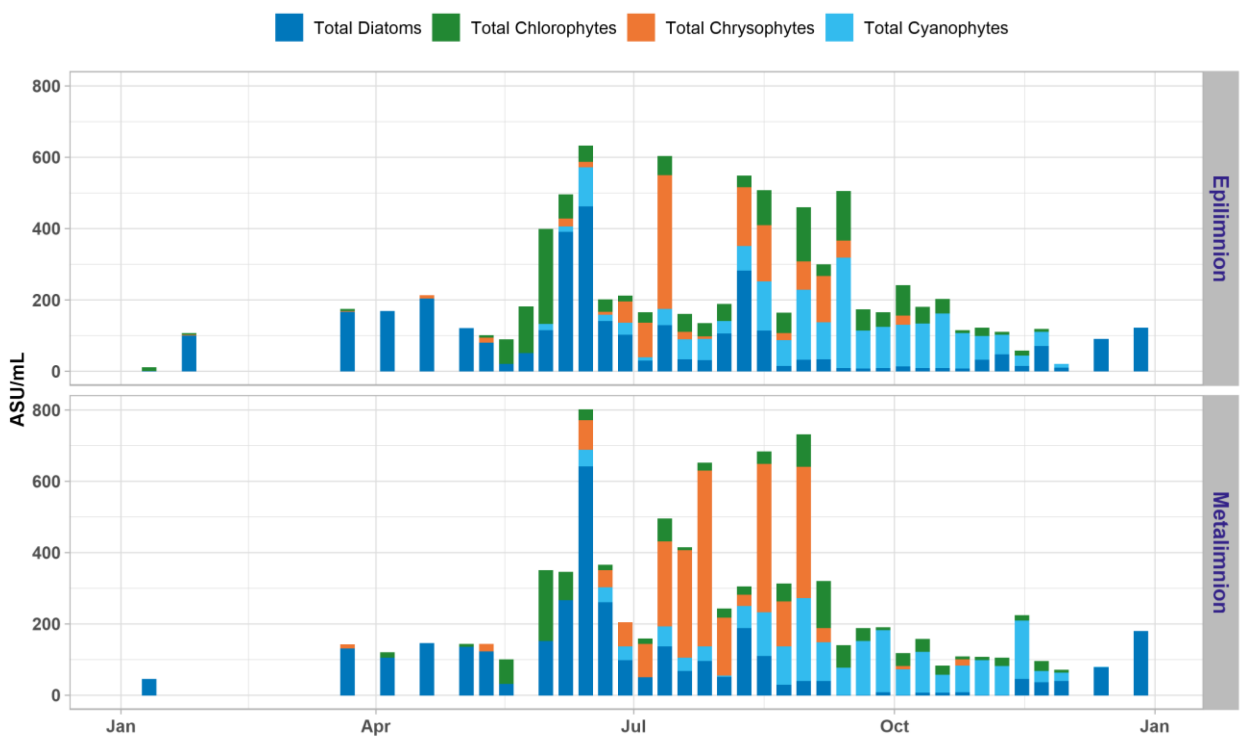


Figure 57: 2021 Phytoplankton Community Composition
Reported as weekly maximums for Basin North and Cosgrove Intake.

Total densities remained below 235 ASU/mL until June 3. Increased densities of *Asterionella* and *Cyclotella* were observed in early June with the maximum diatom density for the year recorded on June 7 with 390

ASU/mL observed at Basin North at 3 m. This was the second lowest annual diatom maximum recorded for the period of record (1989-present).

Elevated *Dolichospermum* was observed within the epilimnion in early June and the early monitoring trigger of 15 ASU/mL was exceeded once on June 3. *Dolichospermum* was observed sporadically at densities below the 15 ASU/mL threshold through the remainder of the growing season (Figure 58). Surface aggregations of this cyanophyte were not observed in 2021.

Phytoplankton densities decreased through June, then rose to just above 400 ASU/mL as *Chrysosphaerella* exceeded the early monitoring trigger of 100 ASU/mL for three weeks in July. The early monitoring trigger of 200 ASU/mL for *Dinobryon* was exceeded on July 12 and again for one week in late August. *Synura* was also present above the early monitoring trigger of 10 ASU/mL for one date in late August (Figure 58).

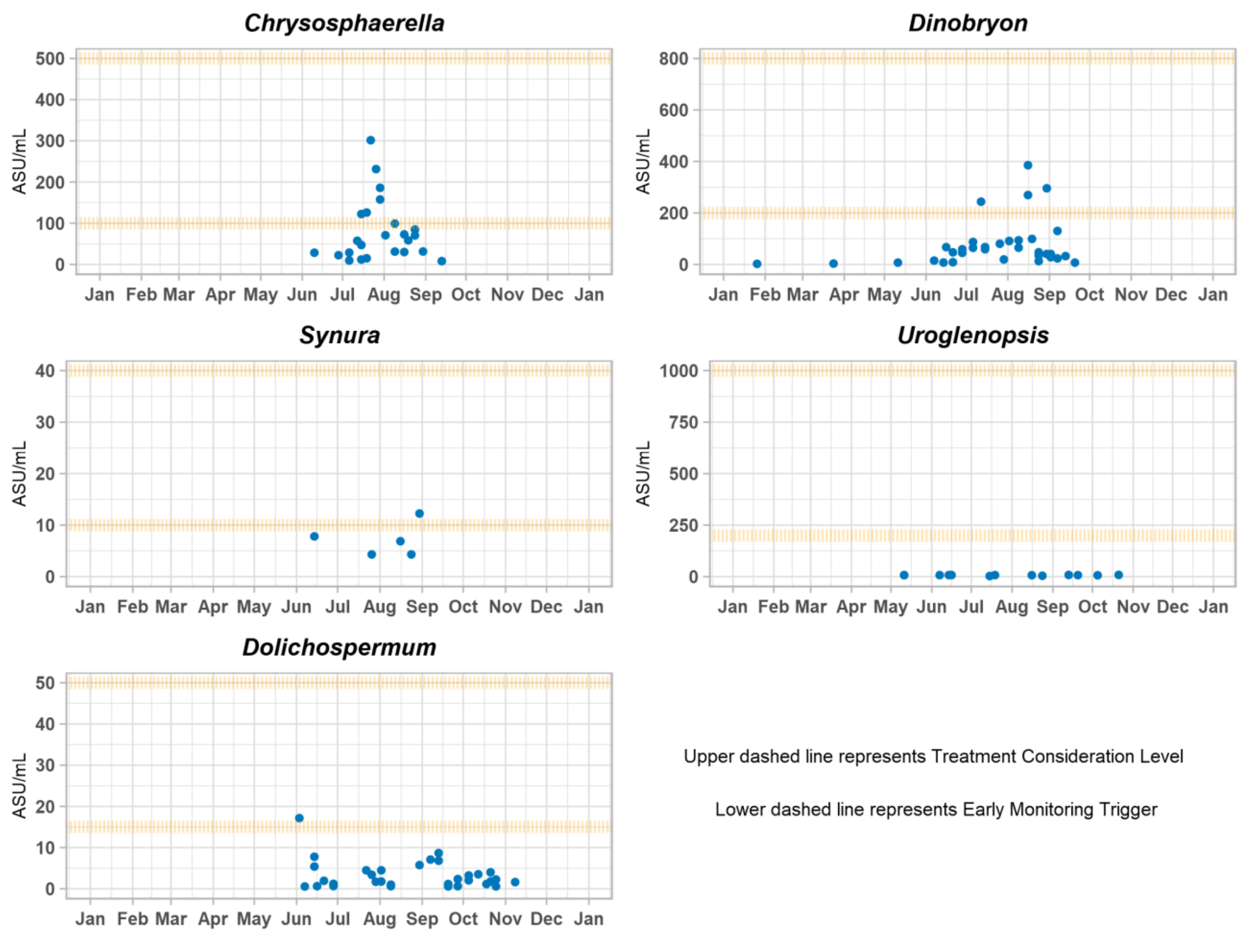


Figure 58: 2021 Occurrence of Nuisance Phytoplankton Taxa in Wachusett Reservoir

In late August, *Microcystis aeruginosa* was observed in surface samples at low density. Colonies of this cyanophyte were visible from the surface and appeared sporadically in samples through September. In late September, *M. aeruginosa* was present in samples more frequently, and the enumeration protocol for this taxa was adjusted to account for the large colonies (see section 2.1.6.4, Phytoplankton Monitoring). Warm, calm conditions the week of October 5 led to streaking and surface aggregations of *M. aeruginosa* which were observed in downwind locations throughout the reservoir, especially on October 6 and 7. Colonies remained present in the epilimnion through the break-down of stratification in

November and were last observed on December 12. Throughout this period, overall concentrations remained low and mostly isolated in the epilimnion and were therefore determined to not be a threat to water entering the intake.

Overall cyanobacteria levels were similar to those observed in 2019 and slightly higher than in 2020 (Figure 59). The maximum total cyanobacteria density of 309 ASU/mL was recorded from Basin North (3 m) on September 13 and the dominant cyanobacteria taxa was *Gomphosphaeria*.

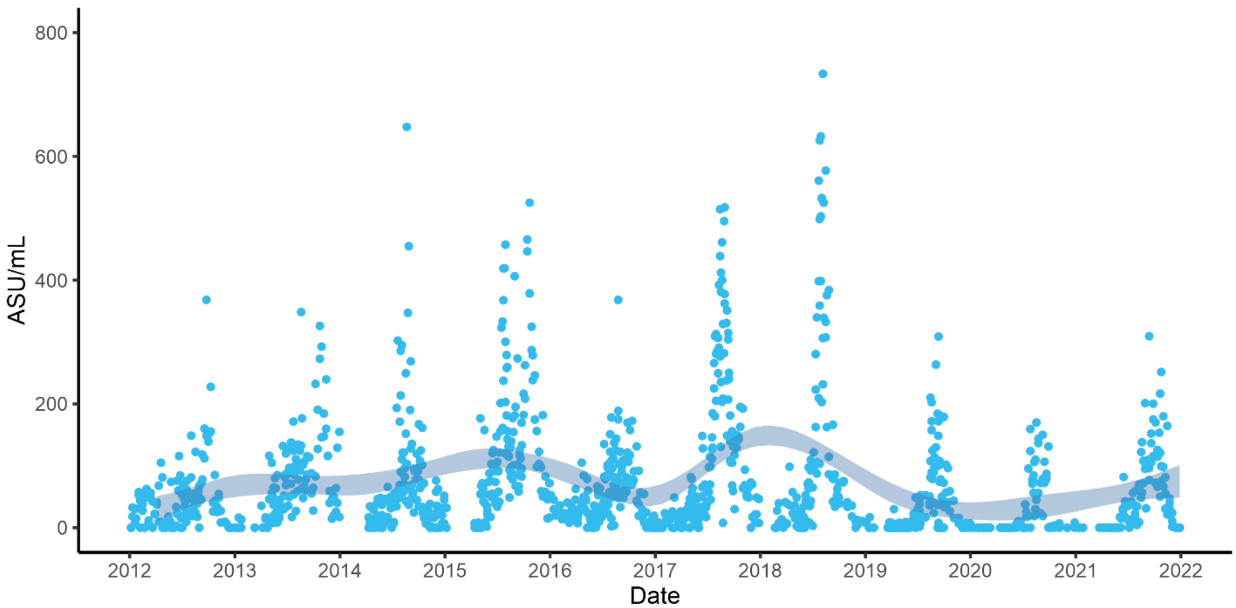


Figure 59: Total Cyanophytes at Basin North 2012 – 2021
The blue band represents a LOESS smooth function 95% confidence interval for the same period.

3.4.9 Zooplankton

A total of 48 zooplankton samples were collected in conjunction with the 2021 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.

3.4.10 Fish

Monitoring programs in 2021 included the Lake Trout mark-recapture study, the investigation for Rainbow Smelt spawning activity, and electrofishing for Landlocked Atlantic Salmon in Gates Brook and the Stillwater River. Each of these monitoring programs involved cooperation with MassWildlife.

3.4.10.1 Lake Trout (Salvelinus namaycush)

The Wachusett Reservoir Lake Trout mark-recapture study continued in 2021. The mark-recapture study began in 2014 to investigate the status, life history, and sustainable yield of the Wachusett Reservoir Lake Trout population. Lake Trout are an important coldwater predator in the Wachusett Reservoir food web and are the most popular game fish for anglers. As more information on the Lake Trout population is collected, DWSP and MassWildlife will be able to evaluate both the effects of angling pressure and the susceptibility to climate change [47].

In 2014, MassWildlife and DWSP partnered to initiate a tagging study of Lake Trout in Wachusett Reservoir similar to the ongoing effort at Quabbin Reservoir. This project involves setting gill nets to capture Lake Trout moving onto shallow spawning areas after dark in the fall, weighing and measuring each fish caught, inserting a passive integrated transponder (PIT) tag, and releasing the fish. The length and weight data collected during this study are used to develop a length-weight relationship for the Wachusett Lake Trout population (Figure 60). When a tagged Lake Trout is recaptured, the PIT tag identifies the individual fish, which is then measured, weighed, and released. The changes in weight and length collected from recaptured fish helps develop growth rates for the Wachusett population.

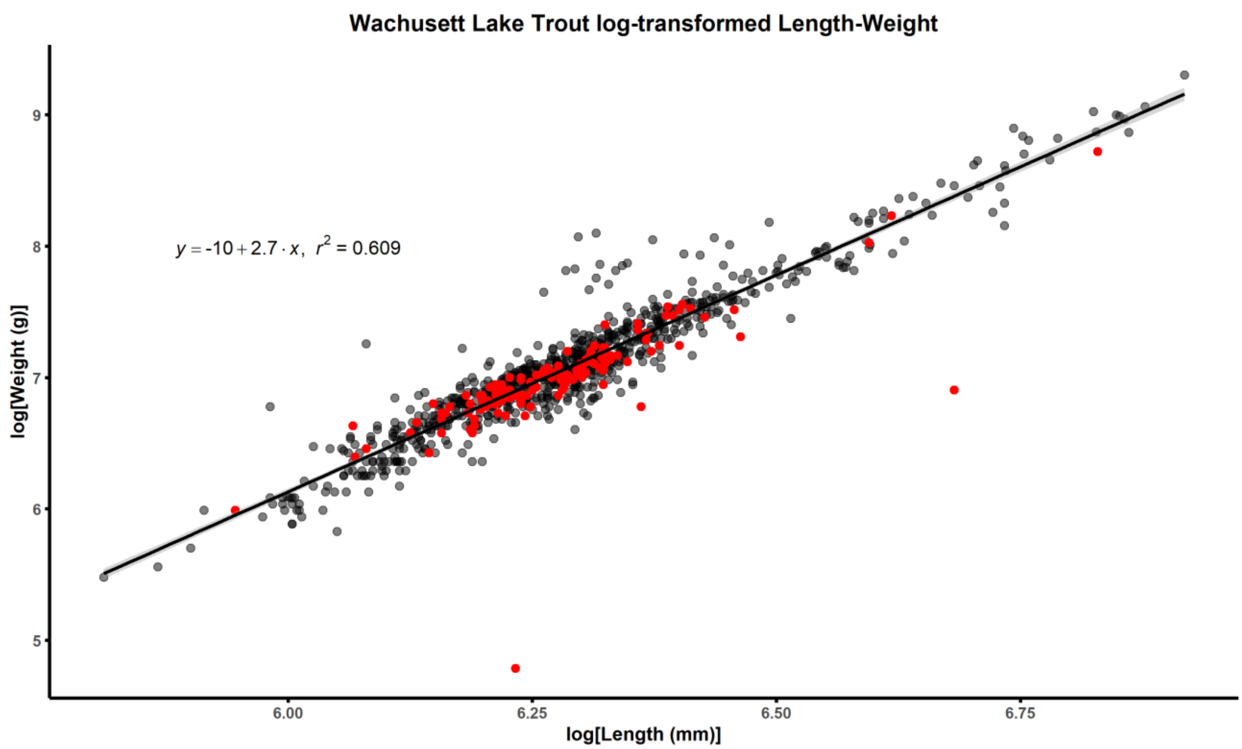


Figure 60: Wachusett Lake Trout Length-Weight Relationship, 2014 to 2021. 2021 data displayed in red.

To date, 902 Lake Trout have been captured during fall sampling efforts between 2014 and 2021, and 683 of these individuals have been assigned a unique ID and released (Table 31). Forty individual tagged fish have been recaptured, five of which have been recaptured at least twice. In total, there have been 87 recapture events from 2014-2021. In 2021, there were seven recapture events, and 127 new fish were tagged. The goal of catching 100 Lake Trout was met in three nights, as 134 fish were caught. The data collected contribute to the development of the length-weight relationship for the Wachusett Lake Trout population. The mean weight and mean length of all fish captured in 2021 were lower than the previous three years, and the second lowest on record.

[47] Thill, 2014

Table 31: Lake Trout Annual Caught and Tagged Results

Year	Caught	Tagged	Caught Mean Weight (g)	Caught Mean Length (mm)	Not Tagged
2014	110	102	2,067	582	8
2015	161	147	1,427	547	14
2016	67	60	1,312	553	7
2017	83	76	1,016	515	7
2018	71	65	1,402	541	6
2019	162	150	1,422	538	12
2020	114	NA	1,367	540	114
2021	134	127	1,172	535	7
Total	**902**	**683**	**1,389**	**544**	**219**

In 2021, 87% of Lake Trout captured in Wachusett Reservoir were males and 13% were females. The proportions of the total catch in 2021 were consistent with the results of previous years (Figure 61). Evidence suggests that male Lake Trout are caught more frequently in gill nets set during the spawn because they spend more time on the spawning grounds searching for females[48]. 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[49].

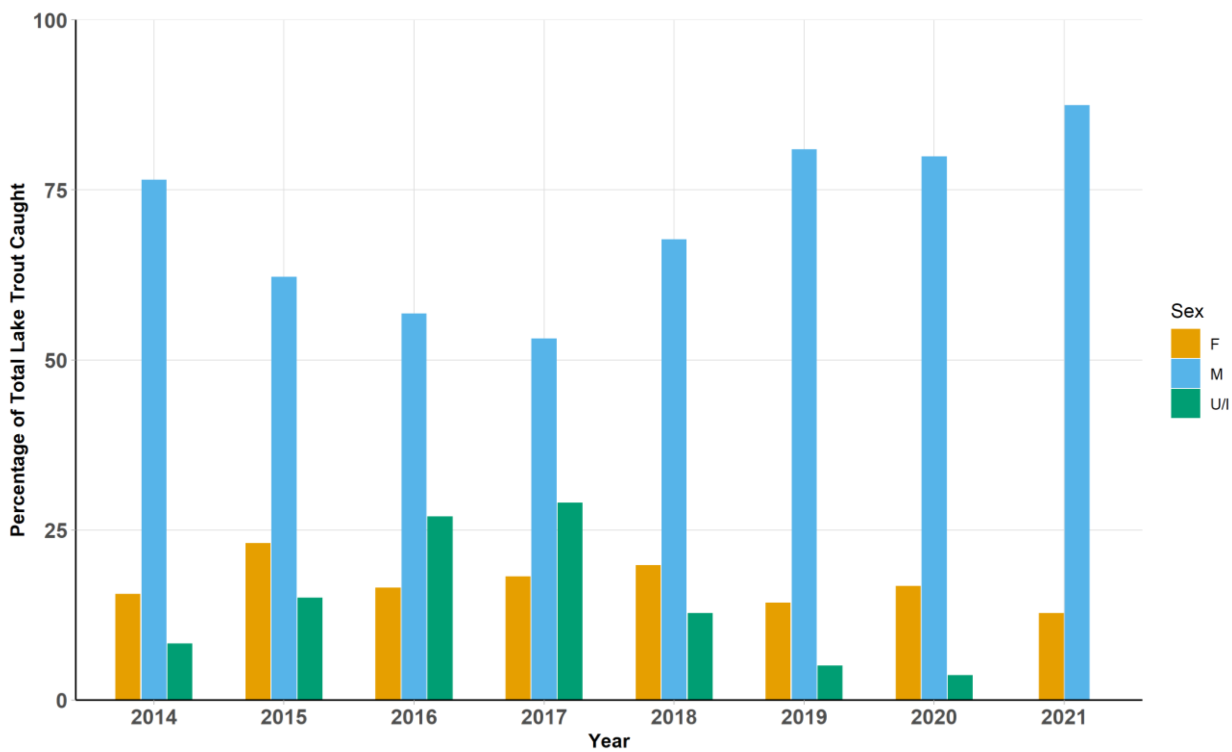


Figure 61: Proportion of Total Lake Trout Catch by Sex

3.4.10.2 Other Fish Species

As a part of annual monitoring for Rainbow Smelt spawning activity, DWSP biologists investigated shoreline areas near Gates Brook and Dover Point on March 24, 2021. No evidence of Rainbow Smelt schools, eggs, or specimens were found, and no reports of spawning activity were received from anglers.

[48] Binder et al., 2016
[49] Binder et al., 2014

Rainbow Smelt are a coldwater fish species with preferences for deep, oligotrophic lakes, and are considered a valuable prey item for salmonids[50]. This coldwater species is likely an important component of the Wachusett Reservoir food web and efforts to monitor the Wachusett Reservoir population will continue annually.

On September 29 and October 1, DWSP staff assisted MassWildlife with backpack electroshocking at five sites on the Stillwater River and one site at Gates Brook, respectively. The primary purpose of the surveys was to collect Landlocked Atlantic Salmon (*Salmo salar*) length and weight. The Gates Brook survey began just upstream of the USGS sampling station, and the Stillwater surveys were completed at five locations upstream of Stillwater Basin. Both surveys were a part of an ongoing study on Landlocked Atlantic Salmon. Species identity, total length, and weight data were collected during both surveys. Landlocked Atlantic Salmon, Eastern Brook Trout, Longnose Dace, and Blacknose Dace, were collected in the Gates Brook survey. Common Shiner, Fallfish, White Sucker, Longnose Dace, Blacknose Dace, Pumpkinseed, Eastern Brook Trout, Largemouth Bass, Chain Pickerel, Brown Trout, Brown Bullhead, Landlocked Salmon, Tessellated Darter, Bluegill, and Yellow Perch were collected in the Stillwater River surveys.

3.4.11 Bacteria

Reservoir bacteria samples were collected on 14 days in 2021 at 23 reservoir transect locations (Figure 3). Ice cover on Wachusett Reservoir prevented sampling for bacteria until late March. Elevated E. coli concentrations were observed once in March at point D2 and then not until late November, when waterfowl returned to the reservoir to roost in larger numbers. Harassment was able to confine the roosting bird populations to the southern parts of the reservoir, as evidenced by the lower bacteria results observed in Basin North (transects A - E). The highest result in 2021 at location A3 (closest to the Cosgrove Intake) was 4 MPN/100 mL on March 24. All reservoir transect bacteria results for 2021 are provided in Table 32.

[50] Hammers, 2018

Table 32: Reservoir Bacteria Transect Results for 2021 – *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
Mar 24	4	2	3	1	2	1	3	22	5	3	1	4	1	1	1	1	1	1	3	3	1	1	1
Apr 7	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	2	2	1	2	4
Apr 29	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May 14	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1
Jun 17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3
Jul 13	1	1	1	1	1	1	3	1	1	2	3	3	1	1	2	2	3	2	2	3	3	5	4
Aug 9	1	6	1	1	1	1	1	1	1	1	1	6	3	2	1	1	1	1	1	1	1	5	1
Sep 13	2	3	3	1	2	1	1	1	1	4	2	1	3	1	1	1	1	4	1	1	1	1	1
Oct 8	2	2	1	1	1	1	5	3	1	3	4	3	9	1	2	5	4	1	1	2	1	2	3
Oct 21	1	1	1	1	3	4	4	1	2	2	1	4	1	3	4	1	1	1	1	2	1	2	1
Nov 3	1	1	1	2	2	1	1	2	1	1	1	1	2	1	3	3	2	2	4	3	2	8	5
Nov 18	2	1	2	2	1	1	2	1	5	3	3	2	1	1	3	3	8	4	4	4	2	2	10
Dec 9	1	1	1	1	1	3	1	1	1	1	1	1	1	1	3	2	4	5	8	11	8	11	15
Dec 21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	9	21	4	6	6

* Cosgrove Intake

Bacteria samples were collected seven days per week by MWRA staff from Carroll Water Treatment Plant (CWTP) at Walnut Hill in Marlborough to demonstrate regulatory compliance. The SDWA regulations for drinking water require that a minimum of ninety percent of all source water samples contain less than 20 MPN/100 mL fecal coliform. All 365 samples collected at CWTP in 2021 contained less than the standard, with a maximum concentration of 9 MPN/100 mL on March 27. Most samples (66%) did not contain any detectable bacteria. DWSP has put considerable time and effort into implementing a rigorous bird harassment program, and the results in 2021 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 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.[51] It is updated periodically to reflect changes in AIS composition within and in proximity to the reservoir.

[51] Trahan-Liptak & Carr, 2016

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 water-milfoil (VWM)	x	x
Myriophyllum spicatum	Eurasian water-milfoil (EWM)	x	x
Najas minor	Brittle naiad		x
Phragmites australis	Common reed	x	x
Trapa natans	Water chestnut		x
Utricularia inflata	Inflated bladderwort		x
Pistia stratiotes	Water lettuce		x

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

The following sections of this report provide details of AIS management activities undertaken in the reservoir, elsewhere in the watershed, and near the reservoir during 2021 and those planned for 2022.

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 62). As new infestations are identified, these areas are also targeted in annual removal efforts. Diver Assisted Suction Harvesting (DASH) was first implemented in 2012 and has continued as the primary control strategy for dense patches of plant growth. Hand-harvesting is used in areas where target species growth is less dense. An extensive DASH project in Stillwater Basin was initiated in 2013 to reduce the potential for re-infestation from dense growth in this uppermost basin of the reservoir. Likewise, management of VLM reservoir-wide, including in Quinapoxet Basin, was initiated in 2020 following successful management of this historically present species. Physical control efforts are carried out by MWRA contractors and are supervised, and at times supplemented, by DWSP aquatic biologists. Details of control efforts in past years are provided in previous annual reports.

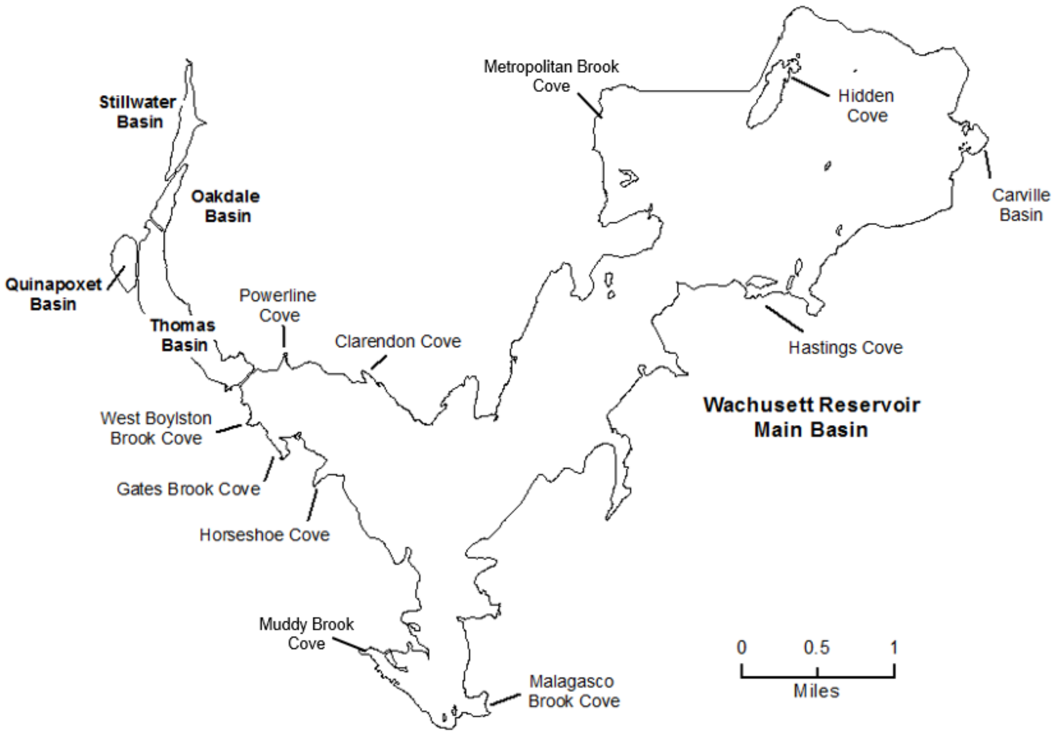


Figure 62: Locations of 2021 AIS Management in the Wachusett Reservoir System

The main components of this program are as follows:

- Deployment and maintenance of floating fragment barriers
- Hand-harvesting and Diver Assisted Suction Harvesting (DASH)
- Quality assurance checks of select areas harvested with DASH
- Routine scouting within the reservoir and watershed by the DWSP aquatic biologists to ensure early detection of pioneering infestations
- Immediate removal of pioneer infestations upon detection
- Point-intercept vegetation surveys by independent contractors (ESS Group, Inc.).
- Scouting the entire littoral zone of Wachusett Reservoir every five years (completed in 2012, 2016 and 2021**).**

Highlights of management in 2021 include:

- Low density of *M. spicatum* and *C. caroliniana* continued in the upper basins (Figure 63).
- Removal of *M. heterophyllum* continued in all managed areas of the reservoir (Figure 62). This milfoil species was previously thought to be too well-established for successful management; however, significant biovolume reductions in test areas (e.g., Hastings Cove (Figure 62)) demonstrate this plant can be managed with DASH. As shown in Figure 63, diver effort (Diver Hours) increased due to inclusion of M. heterophyllum and the increased effort required to search for single stems of invasive plants among native vegetation.
- *M. heterophyllum* historically present in Muddy Brook Cove was removed.
- DASH was implemented to remove a pioneer infestation of *M. heterophyllum* in Metropolitan Brook Cove discovered during DCR's shoreline surveys.

- A total of 73,478 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 64).
- Transition from reporting biomass removal in gallons to reporting number of individual plant stems removed by species continues in Stillwater Basin. Large beds of plants are reported in gallons, but the majority of the season's biomass removed can be enumerated as individual stems.

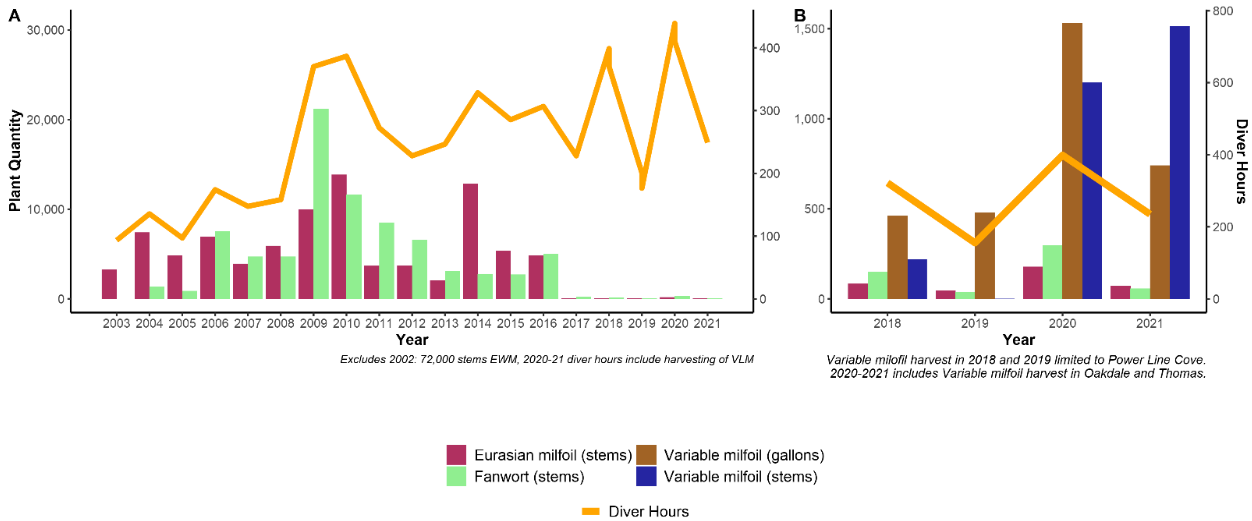


Figure 63: *M. spicatum, C. caroliniana,* and *M. heterophyllum* Removed from Wachusett Reservoir 2003 to 2021
Panel A and B: Plot includes totals removed from Oakdale, Thomas, and Powerline Coves, Panel B: Plot includes totals for M. heterophyllum stems and gallons which are used depending on plant density.

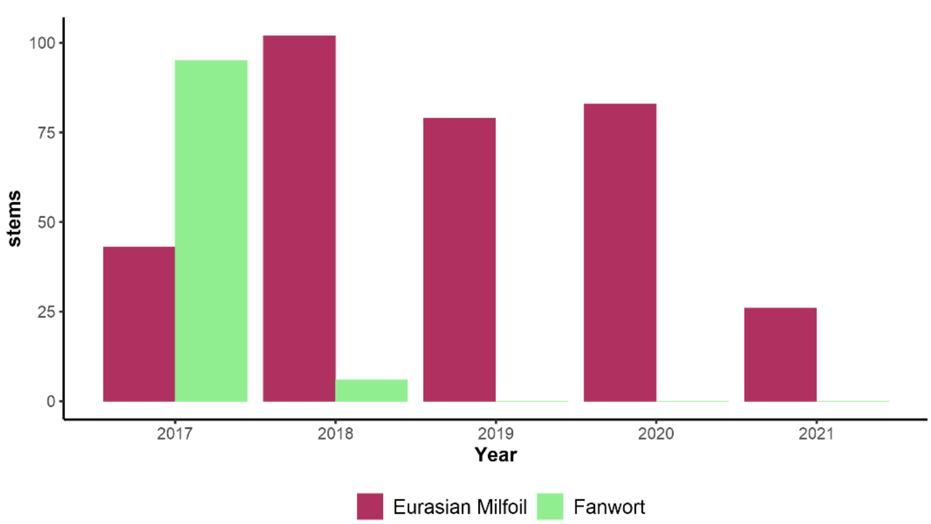


Figure 64: *M. spicatum* and *C. caroliniana* Removed from Quinapoxet Basin 2017 – 2021

Phragmites Management

DWSP EQ staff surveyed and managed *Phragmites australis* (common reed) at 19 locations around the Wachusett Reservoir shoreline in 2021 (Table 34, Figure 65). 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. A full directory of *P. australis* photographs from previous years is stored on DWSP shared network drives and additional background on *P. australis* management at Wachusett Reservoir can be found in previous Annual Water Quality Reports. *P. australis* management typically occurs monthly from June to October; the goal of monthly management is to prevent *P. australis* from going to seed and to reduce the above and below ground biomass of all stands. However, management in 2021 included one event on September 8.

Table 34: Shoreline *Phragmites australis* at Wachusett Reservoir

Stand ID	Initial Area (ft^2)	First Documented	2021 Management Method
Boat Cove A	1071	2013	Cutting, Hand pull
Boat Cove B	1640	2013	Cutting
Boat Cove C	316	2013	Cutting, Hand pull
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

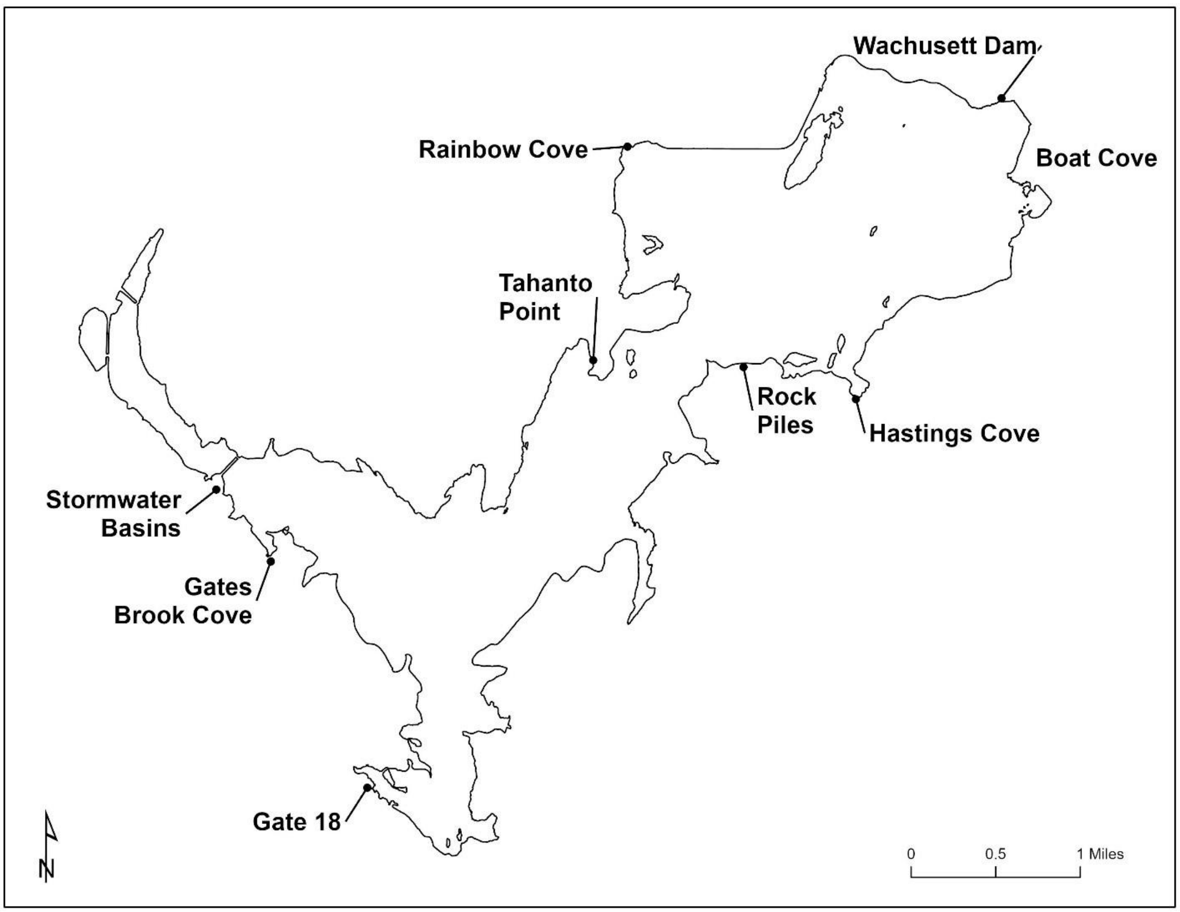


Figure 65: *Phragmites australis* Stand Locations Around Wachusett Reservoir

This management effort and timing was the same as 2020, when management occurred once, on September 3. The reduction in management effort in 2020 and 2021 is indicative of the progress made in reducing apparent above ground biomass. Overall, the reservoir stands continued to show reduced 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 2020, Hastings Cove holds a significant thatch of cut *P. australis* and a higher incidence of individual stems within the terrestrial areas along the shoreline. It is not possible to determine if these stems grew from rhizomes or from seed. *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 of *P. australis* was observed in the stormwater basins near Gate 18 on Route 140, bringing the total number of stands up to 19. The seed heads were removed and taken off site on December 30. This new location will be added to the management effort.

General management method for *Phragmites*

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

2021 Program highlights

- No *P. australis* found at Tahanto Point, the Dam, Rock Piles, Hastings Cove A, Hastings Cove F.
- Cuts completed in 2021 for established stands: Hastings Cove, Boat Cove, Rainbow Cove.
- Hand pulling effort at small expansion locations and edges of stands: Hastings Cove D, Hastings Cove E, Gates Cove.
- No new *P. australis* stands were located during 2021 Reservoir Shoreline Surveys.
- A single new stand was observed in the Gate 18 stormwater basin.

Future plans

- Management in 2022 will include monthly monitoring from June to October, with monthly management during the growing season as needed.
- Physical barrier methods may be employed at smaller stands or to divide large stands, such as Hastings Cove.
- Design and utilize Survey123 and Field Maps to track management progress.

3.5.2 Wachusett Reservoir – Vegetation Monitoring

3.5.2.1 Complete Shoreline Survey and Biovolume Assessment

A reservoir shoreline survey for aquatic macrophytes was completed in 2021. The last complete shoreline survey was in 2016. This survey goal was to identify new areas of AIS, characterize the native reservoir plant community, and collect macrophyte/vegetation biovolume data. The survey was designed to cover the entire shoreline and littoral zone in a single pass while making visual observations from aboard the boat and passively collecting biovolume data. Biologists utilized a view scope, rake tosses, and specimen collection when plant identification was difficult; however, most of the common, native reservoir macrophyte species were readily identified from the boat. Survey data, including macrophyte location, species, and density, were recorded using the ESRI Field Maps and Quick Capture applications. Biovolume data were passively collected by recording sonar logs during a survey trip using the sonar/transducer on the boat.

Surveys were completed during the primary macrophyte growing season from June to August. In 2011, the reservoir shoreline was divided into 13 survey zones to track changes over time in macrophyte presence, density, biovolume, and community composition. These reservoir zones were utilized in 2016 and 2021. A results summary of each survey zone described the dominant native plant community, and the Field Map and Quick Capture results provide georeferenced locations of native macrophytes and AIS. Biovolume data for each survey zone were processed and mapped for comparison to 2016 biovolume.

Macrophyte community composition has not changed dramatically from 2016. *Potamogeton perfoliatus* and *Elodea* species were the most common native plants observed throughout most of the littoral zone. *Nitella* is a macroalgae that was observed in many of the survey zones. Less common native species found in the main reservoir body include *Vallisneria americana* and *Potamogeton epihydrus*. As has been the case in previous years, the highest biovolume of macrophytes was found in the upper basins of the reservoir: Stillwater, Quinapoxet, and Thomas Basins. However, in comparison to the previous whole reservoir survey and biobase collection, biovolume in the upper basins has decreased after consistent AIS management. Biovolume in the main body of the reservoir has not changed dramatically from 2016.

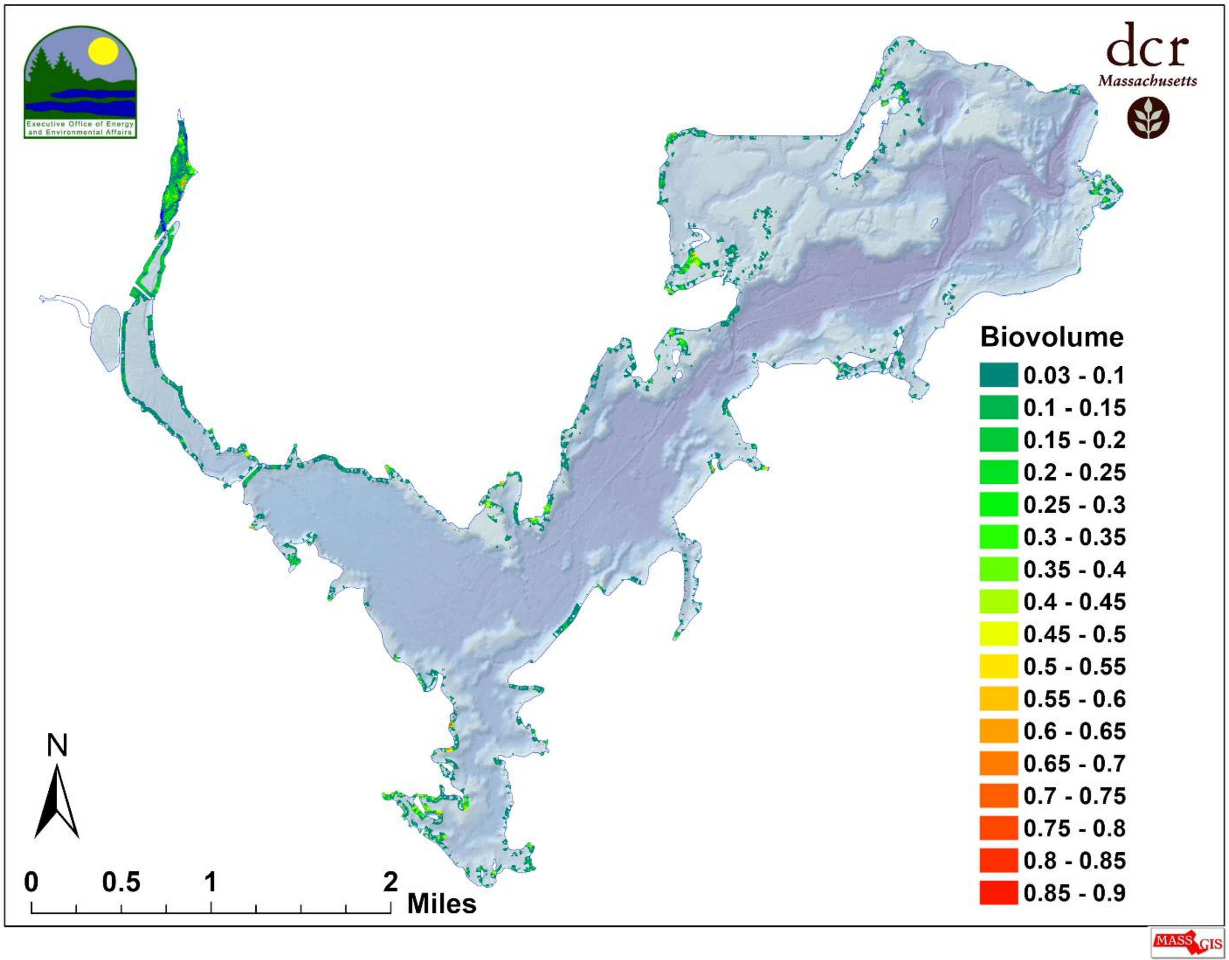


Figure 66: 2021 Wachusett Reservoir Aquatic Vegetation Biovolume.
The biovolume scale is percent biovolume in relation to Reservoir bottom depth.

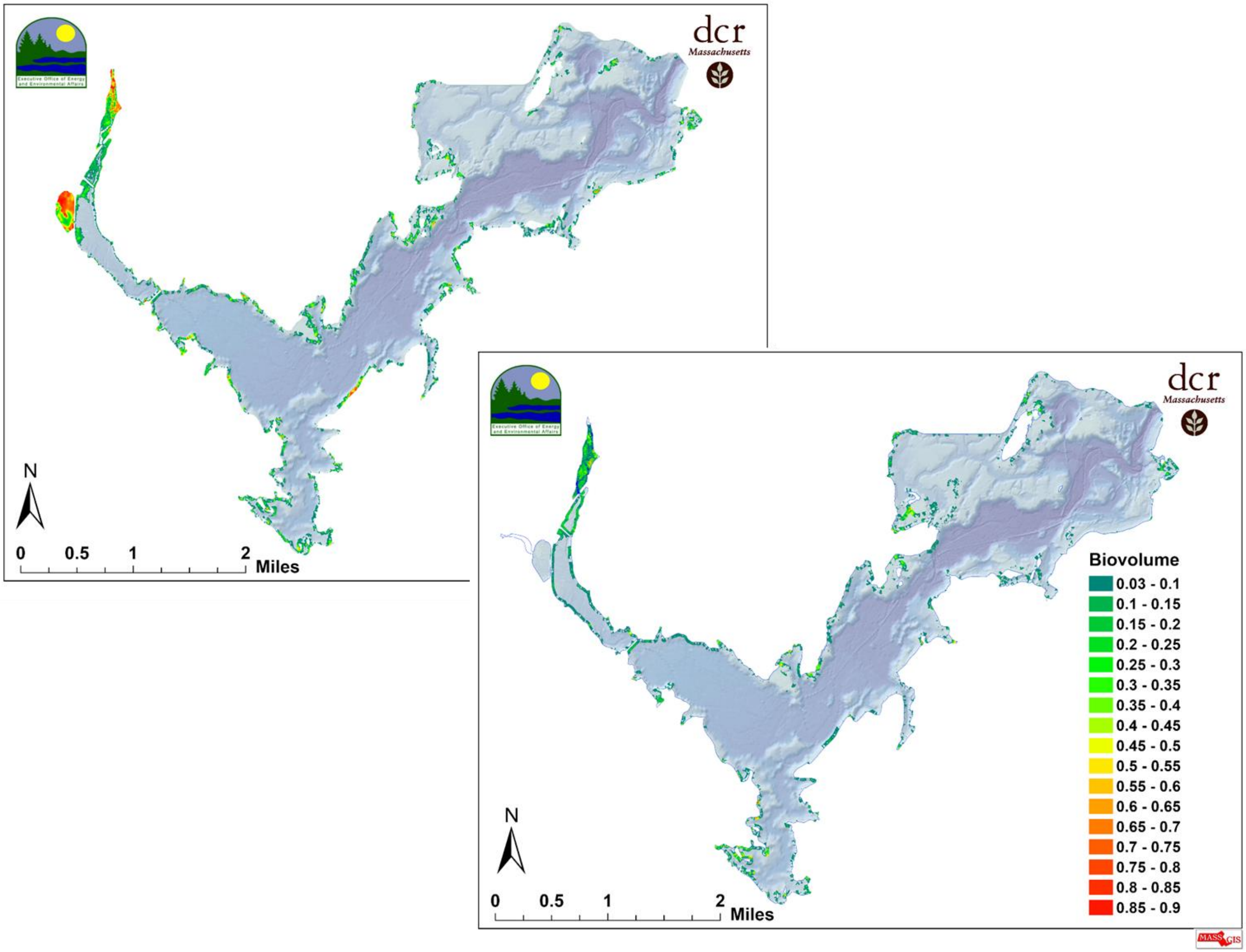


Figure 67: Wachusett Reservoir Aquatic Vegetation Biovolume Comparison: 2016 (left) to 2021 (right).
The biovolume scale is percent biovolume in relation to Reservoir bottom depth. Biovolume scale is equivalent in both maps.

3.5.2.2 Contracted Aquatic Macrophyte Surveys

MWRA contracts with ESS Group, Inc. (ESS) to carry out point-intercept surveys of DWSP/MWRA source and emergency reservoirs. No new AIS were discovered in Wachusett Reservoir during the 2021 survey and substantial increases in distribution and density were not observed. For the first year since discovery there was a year-over-year decrease in *Glossostigma cleistanthum* (mudmat) and density of this minute non-native species decreased at 18 sites while increasing or being newly detected at only 12 sites. ESS reported a decrease in aquatic plant cover compared to 2020 while biovolume remained stable, with 99% of sample locations at or below 50% biovolume [52].

3.5.3 Supplemental Invasive Macrophyte Control Activities

Additional activities were conducted in 2021 outside of Wachusett Reservoir in conjunction with the main components of the in-reservoir invasive control program. Details of these activities are presented below.

3.5.3.1 Management of AIS Outside of Wachusett Reservoir

In recent years AIS have been discovered in several local ponds (Figure 68). Although Clamshell Pond and the South Meadow Pond Complex are outside of the Wachusett Reservoir watershed, each of these waterways have been identified as potential sources of invasive species due to their proximity to the reservoir. The potential for transfer of invasive species present in these water bodies to the reservoir by waterfowl or bait buckets necessitates special management and monitoring efforts. Management of these ponds is ongoing.

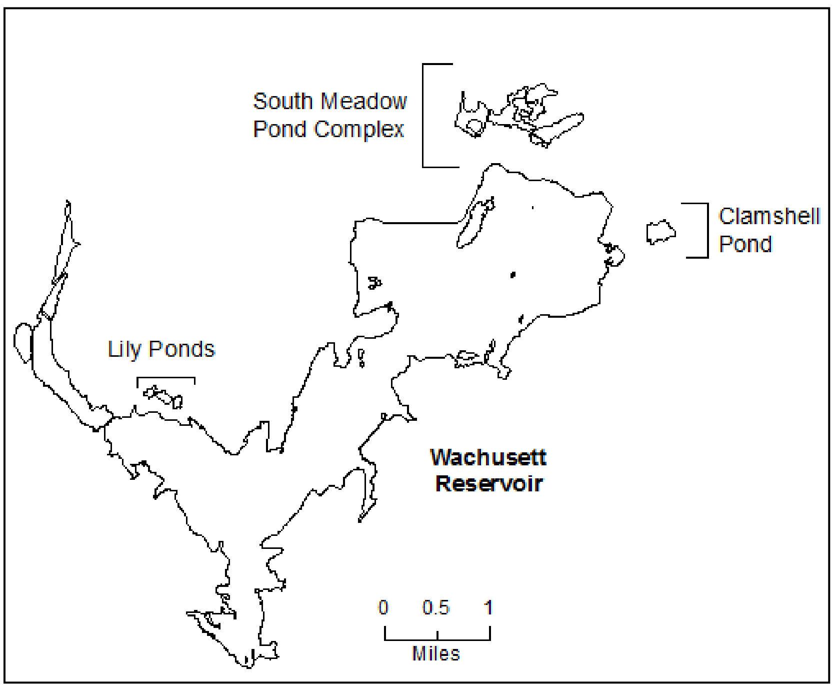


Figure 68: Locations of Local Ponds Managed for AIS

[52] ESS Group, 2022

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 on an annual basis with management of *P. crispus* added to the treatment program upon its discovery in 2015.

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

In 2021 *P. crispus* was managed with an application of diquat on June 2 to approximately 25 acres of South Meadow Pond. Three treatments with fluridone herbicide were conducted to manage *Hydrilla* on June 18, August 17, and September 29. Tuber density continues to be low. Intensive surveys of these ponds are planned for 2022 to assist DCR with refinement of management activities at these ponds.

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[53].

E. densa was treated with the contact herbicide diquat in June 2018 and *E. densa* 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 2021, 18 *T. natans* plants were removed during the June survey and five plants were removed during the August survey. As in previous years, the native macrophyte community consisted of dense patches of *Potamogeton robinsii* (Fern-leaf Pondweed), *P. ampifolius* (Big-leaf Pondweed), *Brasenia schreberi* (watershield), *Nymphaea odorata* (white water lily), *Nuphar variegata* (yellow water lily), and *Schoenoplectus subterminalis* (water bulrush), all of which were found throughout the littoral zone. *P. robbinsii* was the primary species collected by a rake toss. *Utricularia vulgaris* (common bladderwort) was also distributed throughout the pond.

Lily Ponds

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

DWSP biologists observed *N. minor* in each of the three ponds in early September 2021 and an herbicide treatment was conducted on September 17. Approximately eight acres were treated across all three water bodies.

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

4 Conclusions and Recommendations

4.1 Wachusett Tributary Water Quality

Routine tributary monitoring results for bacteria and turbidity in 2021 were slightly elevated due to the surplus precipitation between July and October. Despite these increases, tributary water quality continues to support drinking water quality standards. In 2021, and in prior years, bacteria levels at individual tributaries were occasionally elevated above Class A surface water standards, either due to stormwater runoff events or from known bacterial sources, for which management actions have been ongoing (agricultural operations) or are otherwise not feasible (avian wildlife). The increased concentrations of bacteria at West Boylston Brook observed in the last two years were much higher than in other tributaries and should be investigated for potential new contamination sources. Fortunately, elevated bacteria in the tributaries did not result in any elevated fecal coliform concentrations at Cosgrove Intake and SDWA standards were easily met for 2021.

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 2 – 110 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 Waushacum Brook. The summertime low D.O. in Waushacum Brook was also observed in 2021, and likely due to the large and often stagnant wetland area just upstream of the sample location. 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 2021 alkalinity results for Wachusett tributaries were more comparable to historical concentrations rather than the higher concentrations observed in 2020. 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 rising alkalinity will also be explored in greater depth.

Wachusett tributary pH results for 2021 did not show as much inter-seasonal variation as in 2020. The previously observed rise in pH during the summer months may have been tempered by the surplus rainfall during this time period. Lower than normal runoff between February and April may have prevented the seasonal decline in pH during the late winter and spring that was observed in 2020. 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 2021 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 2021, despite being at their lowest levels in more than five years. Initial data collected from the new real-time conductivity, depth, and temperature sensors in December 2021 has already provided evidence that chloride spikes above the acute toxicity threshold for aquatic life are 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 and ongoing planning efforts at DWSP and UMass. Three new initiatives began in 2021, which will provide more information about the extent, magnitude and causes of chloride impairment in Wachusett Watershed aquifers and surface waters. Expanded groundwater monitoring began in May 2021 and the conductivity blitz for surface waters began in April 2021. Real-time conductivity monitoring was added to five more primary tributary monitoring stations. Results from those initiatives will be presented in the 2022 Annual Water Quality Report.

Routine tributary nutrient monitoring results for 2021 were consistent with historical data and demonstrate continued adherence to drinking water quality standards. For 2021, median nitrate concentrations were predominantly lower than the median for the prior nine years, whereas TKN concentrations were mostly higher than the 2015 – 2020 medians. Mean TN concentrations in 2021 were similar to prior years across respective monitoring stations. Nitrogen concentrations above ecoregional background levels have continued to be observed at several monitoring locations, although they are well below regulatory standards and are not sufficiently elevated to be a water quality concern. Phosphorous concentrations in Wachusett tributaries for 2021 were generally low and mostly within ecoregional background ranges. Aside from Malagasco and West Boylston Brooks, 2021 annual median TP concentrations were lower than the 2012 – 2020 medians. If time and resources allow, additional investigations could be conducted to confirm sources of excess nitrogen in Malagasco and Malden Brooks and sources of excess phosphorous in French, Malagasco, and Trout Brooks.

Total organic carbon (TOC) concentrations and UV_{254} absorbance levels during 2021 were elevated across all Wachusett tributaries, with 2021 annul median values higher than 2012 – 2020 medians. 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 75th percentile, were isolated events, or can be tied to specific biologic factors such as diatom production and silica availability.

Results of routine water quality profiles were 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 and maximum specific conductance observed in the reservoir decreased slightly; however, the annual minimum continued to increase. Alkalinity continues to be elevated 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.

Microcystis aeruginosa was present throughout the reservoir for a prolonged period in fall 2021. This cyanophyte is known to be present in the reservoir but surface aggregations had not been previously reported. Phytoplankton sampling was increased during this period and DWSP biologists recorded photographic documentation of aggregations. DWSP biologists continue to work with rangers and other DWSP staff to monitor for and document cyanobacteria events when possible. New monitoring techniques, including remote sensing with wildlife cameras, are also being tested to enhance understanding of these events and their potential effects on water quality.

4.3 Proposed Wachusett Watershed Monitoring Programs

4.3.1 Hydrological and Climate Monitoring

Continuous monitoring station upgrades with Mayfly dataloggers and Hydros-21 CTD sensors were completed at five additional tributaries in 2021: French, Malagasco, Muddy, Malden, West Boylston Brooks. Waushacum Brook was upgraded as a pilot station previously and Trout Brook is slated for upgrade in 2022. These stations will measure conductivity, temperature, and depth at 15-minute increments with real-time raw data access via the internet. Existing HOBO U20 depth and temperatures will remain in place until the new stations are tested and are recording accurate data.

Groundwater levels will continue to be measured monthly at eight wells, however the HOBO measuring water level at 4-hour increments in the Sterling Well (Rt 140) has been removed and replaced with a USGS pressure transducer 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
Precipitation	2 USGS Stations, 2 NOAA Stations	No change
Snowpack (seasonally)	Weekly, 6 locations	Boylston location to be moved
Groundwater Levels	Monthly manual + Automated (4-hr intervals @ Rt 140 Well	DWSP HOBO datalogger removed, USGS datalogger installed

4.3.2 Groundwater Quality Monitoring

Groundwater will continue to be monitored for specific conductance, temperature, chloride, alkalinity, sulfate, fluoride, bromide, calcium, magnesium, sodium, and nitrate. Collection and analysis of laboratory samples will continue through April 2022 to complete a full year of sampling those parameters. With the purchase of a new flow cell, pH and dissolved oxygen sampling will be initiated in 2022.

Monitoring Element	Current Program	Proposed Changes
Groundwater Quality (WATWEL)	Monthly – Eight wells for specific conductance and temperature; Seven wells for chloride, alkalinity, sulfate, fluoride, bromide, calcium, magnesium, sodium, and nitrate.	End sampling for chloride, alkalinity, sulfate, fluoride, bromide, calcium, magnesium, sodium, and nitrate after one year in April 2022. Add pH and dissolved oxygen sampling in 2022.

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 2021. 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 2022.

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 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 harvests and the periods before and after. Turbidity levels have only exceeded 5.0 NTU on five occasions since 2012 and most of these are due to storm events, or short-lived and localized disturbances during bridge installations. The relative low threat to water quality posed by timber harvest operations supported the decision to scale back monitoring at these stream crossings. Beginning in 2022, monitoring will be limited to intermittent and perennial stream crossings within 2,000 meters of the reservoir (See map in Appendix B.1- Priority Monitoring Zone) and any perennial stream crossings outside of this zone. Intermittent streams outside the Priority Monitoring Zone will no longer be monitored. Additional stream crossings on timber harvest lots anywhere within the Watershed may be monitored when Environmental Quality or Forestry staff find that site conditions or nearby sensitive resources increase potential consequences from logging activities.

Furthermore, monitoring during pre-harvest and post-harvest periods will be reduced to the least number of samples needed to establish baseline water quality (turbidity) and to confirm that post-harvest turbidity has returned to baseline. Finally, monitoring at lots during active harvest operations will occur weekly, as before, however visits will be targeted when stream crossings are being actively used and wet weather events. Monitoring may be skipped if active harvest is paused for more than one week. These changes have been incorporated into the DWSP *SOP for Short-term Forestry Monitoring.*

4.3.4.2 Long-term Forestry Study

Monitoring for long-term effects of water quality at forestry locations will continue with routine monthly samples during dry weather and targeted storm sampling for large events, if feasible. The completion of a preliminary summary report for the first six years of monitoring is still pending, however sufficient flow data at the Princeton weir has been collected to allow for analysis to proceed. The experimental lot (Princeton) has been sold and harvest is expected to begin in 2022. Quarterly storm sampling is scheduled to resume in 2022 as soon as the timber harvest begins.

4.3.4.3 Quabbin Transfer (Shaft-1) Monitoring

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

4.3.4.4 Follow-up Bacteria Monitoring and DNA Fingerprinting

Follow-up samples for bacteria (*E. coli*) at routine sampling locations will be conducted within 48 – 72 hours when a result is higher than a predetermined metric based on historical observations and overall watershed conditions at the time of the sample. Additional locations may be sampled if elevated bacteria levels persist for extended periods of time for unknown reasons. 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 will be 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.

4.3.4.8 Surface Water Conductivity Blitz

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

4.4 Reservoir Monitoring for 2022

Reservoir monitoring programs will continue as carried out in 2021. 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.

A survey of Wachusett Reservoir anglers will take place during the fishing season, April – November. This survey is conducted every five years and serves to quantify recreational angling pressure placed on the reservoir's fish populations. The effects of angling, specifically harvest rates of certain apex predators in the reservoir, can have cascading effects on the reservoir food web and overall water quality. The Lake Trout mark-recapture study is also anticipated to continue for an eighth year in conjunction with MassWidlife during the fall spawning season.

Movement of water and contaminants through the reservoir remains of significant interest. Sampling of the reservoir surface will continue regularly. Monthly, biweekly, or weekly bacterial transect sampling will be completed during ice-free periods to help further understand the effect of avian populations and water movement on fecal bacteria (*E. coli*) levels throughout the reservoir and fecal coliform levels at Cosgrove Intake.

<table>
<tr><th>Monitoring Element</th><th>Current Program</th><th>Proposed Changes</th></tr>
<tr><td>Reservoir Profiles</td><td rowspan="3">Weekly May – Sept. at BN3417 or CI3409
Biweekly Oct – April at BN3417 or CI3409
Increased frequency and/or locations as needed in response to thresholds for specific genera.</td><td>No change</td></tr>
<tr><td>Secchi Disk Depth</td><td>No change</td></tr>
<tr><td>Phytoplankton</td><td>No change</td></tr>
<tr><td>Nutrients</td><td>Quarterly</td><td>No change</td></tr>
<tr><td>Zooplankton</td><td>Quarterly</td><td>No change</td></tr>
<tr><td rowspan="2">Fish</td><td>Fall Lake Trout spawn and other seasonal observations as appropriate</td><td>No change</td></tr>
<tr><td>Angler creel survey</td><td>Conducted every 5 years</td></tr>
<tr><td>Macrophytes</td><td>Surveys and contractor monitoring throughout the growing season</td><td>No change</td></tr>
<tr><td>Bacteria</td><td>At least monthly at 23 locations</td><td>No change</td></tr>
<tr><td>Stormwater Basins</td><td>Monthly</td><td>No change</td></tr>
</table>

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Appendix A

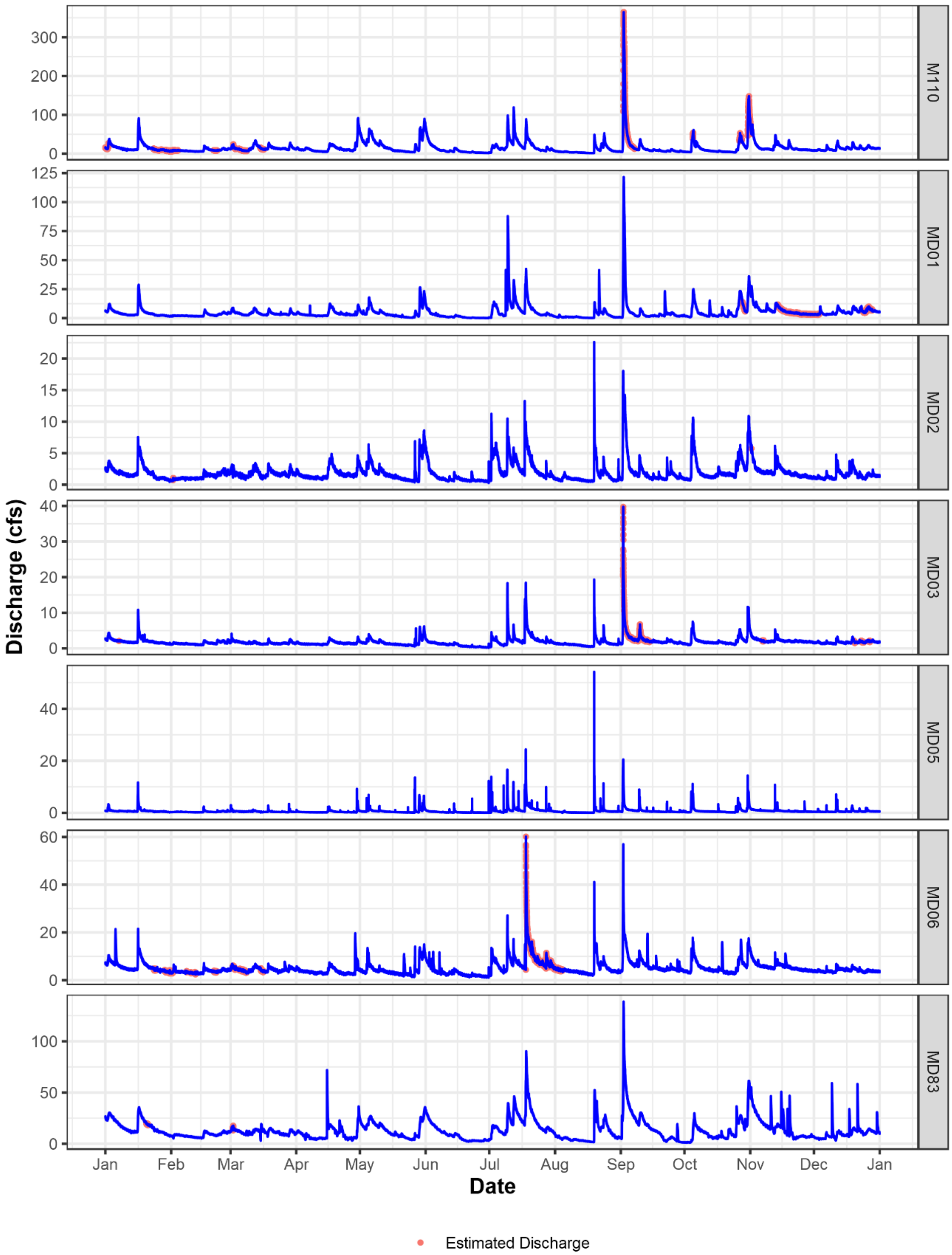

Figure A-1: Hydrographs for Small Tributaries in Wachusett Watershed During 2021
Discharge data are interpolated from measurements collected at 15-minute intervals.

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

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

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

2021 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)[54]. 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[55]. 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[56]. 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[57]. 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[58]. 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)[59] and 0.31 mg/L (ecoregion 59)[60], 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

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[54] USGS, 1999
[55] Mallin et al., 2006
[56] USEPA & Tetra Tech Inc, 2013
[57] World Health Organization [WHO], 1996
[58] USGS, 1999
[59] USEPA, 2001a
[60] USEPA, 2000

ecoregions. NO_2-N is usually present in very low concentrations (see Sections 3.2.7.1 and 3.4.7.2), therefore it can be assumed that these background concentrations are primarily composed of NO_3-N. At elevated concentrations, nitrates can cause significant water quality problems including increases in aquatic plant growth, reductions in dissolved oxygen concentrations, changes in plant and animal species composition, and loss of biodiversity[61].

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[62]. Several other studies (mostly in Europe) have linked high levels of nitrate consumption, though in some cases below the EPA MCL, to various cancers[63]. 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[64], and is particularly lethal to infants[65]. In order to protect human health, the EPA has established the MCL for NO_2-N in drinking water at 1.0 mg/L[66]. 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)[67] and 0.30 mg/L (ecoregion 59)[68], 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

[61] Camargo & Alonso, 2006
[62] Safe Drinking Water Act of 1974, 2019
[63] Ward et al., 2018
[64] Ibid
[65] Walton, 1951
[66] Safe Drinking Water Act of 1974, 2019
[67] USEPA, 2001a
[68] USEPA, 2000

3.4.7.2). Sampling for TKN in the Wachusett Reservoir watershed began in 2015 to account for organic sources of tributary nitrogen and allow for a better understanding of nutrient dynamics. The current water quality goal for TKN in streams, rivers, and the reservoir is to maintain existing local background concentrations.

A-5 Total Nitrogen

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

Massachusetts has only developed numeric water quality criteria for nitrogen for specific water bodies with significant impairments from nutrient over-enrichment. Nitrogen criteria are usually created in conjunction with phosphorous criteria, as they are the two primary causal agents for eutrophication. In absence of water body specific nitrogen criteria for Wachusett Watershed water bodies, only the narrative criteria for nutrients applies – to not '… *cause or contribute to impairment of existing or designated uses.'* Thus, the internal numerical goal for TN in streams and rivers is to maintain naturally occurring local background concentrations. Background concentrations of TN in rivers and streams of the Wachusett Watershed ecoregions were found to range between 0.34 mg/L and 5.57 mg/L, with the 25th percentile value (all seasons) of 0.42 mg/L (ecoregion 58)[69] and 0.59 mg/L (ecoregion 59)[70], 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[71]. 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

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[69] USEPA, 2001a
[70] USEPA, 2000
[71] USGS, 2012

land surface and within streams can increase the release of phosphorous from soils and sediment into water bodies.

Lakes with TP concentrations exceeding 20-30 µg/L may experience nuisance algal growth[72]. Background concentrations of TP in rivers and streams of the Wachusett Watershed ecoregions were found to range between 2.5 µg/L and 907.5 µg/L, with the 25th percentile value (all seasons) of 12 µg/L (ecoregion 58)[73] and 23.75 µg/L (ecoregion 59)[74], which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TP criteria for these ecoregions. Similar to nitrogen, there are no Massachusetts numerical water quality standards for phosphorus for any Wachusett Reservoir watershed water bodies. However, the narrative water quality criteria do apply as previously described.

In Wachusett tributaries annual mean TP concentrations are historically below 30 µg/L, but occasionally are higher for some tributaries. Reservoir concentrations are typically less than 10 µg/L. While elevated TP concentrations pose no direct threat to drinking water quality, they can promote algal blooms in the reservoir, which can cause taste and odor issues when concentration thresholds for certain species are exceeded or become toxic in the case of specific cyanobacteria. With these concerns in mind, the DWSP goal for TP in streams, rivers, and Wachusett Reservoir are to maintain naturally occurring local background concentrations, preferably below 20 µg/L in tributaries and below 10 µg/L in the reservoir.

A-7 Silica

Silica is a necessary element for the cellular function of all living organisms. It is required for protein synthesis in all phytoplankton and is essential for the formation of siliceous skeletons and scales of diatoms and chrysophytes[75]. After oxygen, silica is the most abundant element, comprising approximately 30% of the Earth's crust. It enters aquatic systems through natural weathering processes although export can be accelerated by human activities such as mining, agriculture, and disturbances of terrestrial vegetation which serve as terrestrial silica sinks. Changes in silica abundance in freshwater reservoirs can be observed on a spatial and temporal gradient as water higher in silica enters from tributaries, disperses through the reservoir, and is subsequently taken up by phytoplankton, particularly diatoms in the spring.

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

A-8 Water Temperature

Temperature is a critical 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

[72] Vollenweider, 1976
[73] USEPA, 2001a
[74] USEPA, 2000
[75] Reynolds, 2006

temperature[76]. For tributaries, the water quality goal for water temperature is to remain under the threshold temperatures for cold and warmwater fisheries, depending on their respective fishery designations.

Water temperature regulatory thresholds within the reservoir are also based on MassDEP aquatic life use standards. Although there is no guidance describing how this standard applies to lakes and reservoirs, the presumed goal for coldwater fisheries is to maintain sufficient thermal habitat and refuge for naturally reproducing coldwater communities. Water temperature data collected from discrete water quality profiles are used to monitor thermal habitat at specific locations within the reservoir. Tracking changes in thermal structure is also an important component of reservoir monitoring as these dynamics affect both biological processes and hydrologic patterns including establishment of the Quabbin Interflow. As is typical of most deep lakes and reservoirs in the temperate region, Wachusett Reservoir becomes thermally stratified in summer. The development of stratification structure usually begins in late April or early May when increasing solar radiation and atmospheric warming cause a progressive gain of heat in surficial waters. Stratification is most pronounced during summer when the water column is characterized by three distinct strata: a layer of warm, less dense water occupying the top of the water column (epilimnion), a middle stratum characterized by a thermal gradient or thermocline (metalimnion), and a stratum of cold, dense water at the bottom (hypolimnion). This thermal structure is weakened in fall as heat from the upper portion of the water column is lost to the increasingly cold atmosphere. In late October or early November, the last vestiges of stratification structure are dispersed by wind-driven turbulence and the entire water column is mixed and homogenized in an event known as fall turnover.

A-9 Dissolved Oxygen

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

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

A-10 Alkalinity and pH

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

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[76] Massachusetts Surface Water Quality Standards, 2013c

important driver of many chemical and biological processes in aquatic environments and can influence the solubility, transport and bioavailability of other substances found in the water[77]. Aquatic life can become stressed or killed when pH deviates from historical ranges. Low pH can increase corrosion rates of metal drinking water pipes, leaching high concentrations of metals into drinking water and degrading infrastructure.

The Massachusetts Acid Rain Monitoring Project has collected more than 1,610 statewide pH samples across Massachusetts over many years and has found that average surface water pH values increase in the summer and decrease in the winter[78]. 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[79]. 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[80]. 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[81]. 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[82], 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

[77] USEPA, 2021
[78] Godfrey et al., 1996
[79] Turk, 1983
[80] National Atmospheric Deposition Program, 2021
[81] Hornbeck et al., 1977
[82] Kaushal et al., 2020

within the watershed including agriculture and landscaping which may involve application of lime, weathering of concrete, and use of road deicers. Within a water body, alkalinity can affect photosynthetic activity of algae and other plants. The minimum alkalinity for aquatic life published by EPA is 20 mg/L or if lower values are naturally occurring, results cannot be lower than 25% of the natural level[83]. Alkalinity in Wachusett Reservoir is much lower than this threshold. Increases in alkalinity observed over the past 30 years, especially in the last five years, are likely linked to the observed increases in specific conductance caused by regional salinization[84].

A-11 Bacteria

Water bodies naturally contain many microorganisms, most of which are benign. However, there are several harmful intestinal microorganisms (viruses, bacteria, and protozoa) that are sometimes present in water (e.g., *Cryptosporidium*, *Giardia, Salmonella*). Many of these are fecal microorganisms and are known to cause a host of illnesses such as intestinal and urinary tract infections, meningitis, septicemia[85], dysentery, typhoid fever, and cholera[86]. *Escherichia coli* (*E. coli*) is a species in the fecal coliform group, which originates from fecal material of humans and other warm-blooded animals[87]. Some strains of *E. coli* can be deadly, especially for small children or people with weakened immune systems[88]. Studies have found that the presence of *E. coli* is often correlated with the presence of many other pathogenetic microorganisms[89], thus it has been selected as a useful indicator of pathogen contamination in waters. Human exposure to pathogens usually occurs through recreational contact or direct consumption of drinking water that was not adequately disinfected.

Sources of *E. coli* all stem from human or animal wastes: agricultural operations with livestock or that use manure to fertilize crops, treated wastewater, septic systems, urban runoff, land application of biosolids (sludge), pet waste, and wildlife[90]. The only two common *E. coli* sources not applicable to the Wachusett Watershed are biosolids, which are prohibited, and treated wastewater discharges, of which there are none.

Massachusetts Class A surface water quality standards differentiate between bacteria standards for water supply intakes and other Class A waters, which rely on *E. coli* bacteria as the indicator of sanitary quality. The Massachusetts Class A standard for non-intake waters states that the geometric mean of all *E. coli* within the most recent six months must remain below 126 MPN/100 mL (based on a minimum of five samples) and that no single sample shall exceed 235 MPN/100 mL[91]. DWSP prohibits boating, wading, and swimming in Wachusett Reservoir and its tributary waters, however fishing is allowed, and that is probably the only (legal) avenue for public exposure to pathogens from the water supply prior to treatment. Despite there being low risk for pathogen exposure due to recreation, DWSP uses these regulatory thresholds to evaluate the sanitary quality of waters within the Wachusett Watershed. As a major public water supply, regulatory requirements for pathogens at drinking water intakes are much more stringent.

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83 USEPA, 2013
84 Kaushal et al., 2005
85 USGS, n.d.-a
86 Myers et al., 2014
87 USEPA, 1986
88 USEPA & Tetra Tech Inc., 2013
89 Myers et al., 2014
90 Ibid
91 Massachusetts Surface Water Quality Standards, 2013d

MWRA is required to measure fecal coliform concentrations in raw water prior to treatment. State and federal regulations specify that fecal coliform concentrations shall not exceed 20 organisms per mL in 90% of the samples taken in any six-month period[92]. Results for pathogen testing at the intake are briefly discussed Section 3.4.11 and in greater detail in separate reports published by MWRA[93].

A-12 Specific Conductance and Dissolved Salts

Specific conductance is a measure of the ability of water to conduct an electrical current at 25 °C, dependent on the concentrations of various ions in solution[94, 95]. Freshwater systems in Massachusetts naturally contain low levels of mineral salts in solution[96]. Elevated levels of specific conductance and associated dissolved solutes (e.g., sodium, chloride) may stress sensitive biota, threaten ecosystems[97, 98], and degrade drinking water quality[99, 100, 101]. Contamination of drinking water supplies with excess chloride (Cl) may increase the corrosivity of affected waters[102], posing a risk to communities with infrastructure containing lead fixtures.

Excess sodium in drinking water may compromise the health of individuals on sodium-restricted diets, such as those with hypertension, and increase the cation-exchange capacity of nearby soils[103], resulting in the mobilization of base cations (e.g., calcium, potassium, magnesium) to streams thereby altering natural biogeochemical cycles. The EPA established aquatic life criteria for Cl in 1988 at chronic (4-day average) and acute (1-hour average) concentrations of 230 and 830 mg/L, respectively[104]. Neither threshold is to be exceeded more than once every three years. MassDEP has established a linear regression model to derive Cl concentrations from specific conductance values: "Instantaneous exceedances of the acute and chronic Cl criteria are estimated to occur at [specific conductance] readings greater than 3,193 and 904 µS/cm, respectively"[105]. MassDEP also established an Office of Research and Standards Guideline (ORSG) of 20 mg/L sodium in drinking water and a secondary maximum contaminant level (SMCL) for Cl of 250 mg/L[106]. MassDEP does not currently enforce regulatory standards for specific conductance in drinking water.

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

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[92] Massachusetts Surface Water Quality Standards, 2013e
[93] MWRA, 2021b
[94] Granato et al., 2015
[95] Rhodes et al., 2001
[96] Granato et al., 2015
[97] Jackson & Jobbágy, 2005
[98] Corsi et al., 2010
[99] Kaushal et al., 2005
[100] Daley et al., 2009
[101] Kelly et al., 2010
[102] Stets et al., 2018
[103] Kaushal et al., 2017
[104] USEPA, 1988
[105] MassDEP, 2018
[106] Massachusetts Drinking Water Regulations, 2020b

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

Increases in specific conductance have been documented in the Wachusett Watershed and within Wachusett Reservoir, where record high specific conductance values have been recorded over the past several years. Since many aquatic organisms are sensitive to increases in Cl, community composition is likely to shift in response[112]. For example, increases in Cl may negatively impact native *Potamogeton* species while facilitating growth of non-native species such as *Phragmites australis* and *Myriophyllum. spicatum*[113].

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

Within the reservoir, horizontal and vertical differences in specific conductance are reflective of interactions between native water contributed from the Wachusett Watershed and water transferred from Quabbin Reservoir. Average specific conductance values from the largest tributaries to Wachusett 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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[107] Panno et al., 2006
[108] Lautz et al., 2014
[109] Kaushal et al., 2005
[110] Kelly et al., 2008
[111] Mullaney et al., 2009
[112] Van Meter & Swan, 2014
[113] June-Wells et al., 2013

Depending on particle density, suspended solids may settle out of suspension at different rates and locations as a function of the changing hydraulic and geomorphological conditions between the headwaters and the reservoir. The concentration and composition of TSS can vary widely across subbasins depending on soils, stream channel geomorphology, subbasin land cover type, and conditions (e.g., disturbances). These solids provide benthic structure (bed material) and a stock of minerals and nutrients to support aquatic life. Local stream ecology evolved under a “normal” sediment regime, which underpins much of the aquatic habitat and nutrient dynamics at the reach scale[114,115]. When the TSS concentration and composition deviates from “normal” over a sustained period it can be detrimental to aquatic life and cause other water problems. Chronically high TSS concentrations can block light passage in water and absorb solar radiation, which can reduce dissolved oxygen concentrations by inhibiting photosynthesis in plants and by reducing oxygen saturation concentrations due to higher water temperatures[116]. Furthermore, high TSS concentrations can harm fish by clogging gills, reducing visibility so that it is more difficult for fish to find food, and smothering eggs. Suspended solids that settle on the streambed can form thick deposits, reducing fish spawning areas and eliminating habitat for benthic macroinvertebrates. As suspended solids enter Wachusett Reservoir they begin to settle out in coves or along the shoreline, which can negatively affect aquatic life in those places as well as promote invasive or nuisance plant growth by providing nutrient rich substrate.

Fortunately, Wachusett Reservoir is a large enough system that suspended solids rarely reach the intake except in rare instances of soil/debris washing off the shoreline immediately adjacent to the Cosgrove Intake. Nearly all runoff from roadways surrounding Wachusett Reservoir is treated to remove TSS prior to being discharged into the reservoir. Aggregations of phytoplankton which may contribute to elevated TSS are likewise rare in the area of the Cosgrove Intake. For water supplies it is desirable to have low TSS concentrations, as high TSS levels often lead to aesthetic issues (taste/odor), mostly due to organic suspended solids. Although TSS is often cited as the reason for water quality impairments, there are no state or federal standards for TSS in streams since other standards (turbidity, bacteria) are more useful predictors of drinking water quality. However, MassDEP does enforce specific stormwater management standards, which address both water volume and TSS loads from development projects exceeding certain size thresholds[117]. While these regulations have been helpful in mitigating stormwater runoff in recent years, there are many legacy stormwater issues that persist on properties that were developed before the standards were adopted.

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

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[114] Southwood, 1977
[115] Wohl et al., 2015
[116] Murphey, 2007
[117] 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)[118]. Any dissolved or suspended particle in water will cause light scatter and increase turbidity. In streams, high turbidity is often associated with storm events, which increase suspended solid concentrations (see TSS), as well as concentrations of smaller particles like clay. Reservoir turbidity may be influenced by plankton production, pollen deposits, and shoreline disturbances of organic deposits. Clay particles can also remain suspended in the water column for extended periods as a result of eroding shorelines or clay laden tributary waters delivered by storm events. For drinking water supplies, the concern over turbidity relates to aesthetics, pathogens, and treatment considerations. The particles that cause turbidity can make water cloudy or have displeasing taste or odor. These particles also promote regrowth of microbes by inhibiting disinfection and providing nutrients and minerals for their reproduction. For these reasons, and its relative ease of measurement, turbidity is a good general water quality indicator.

There are two standards for turbidity levels at drinking water intakes. The SWTR mandates that raw water turbidity levels (at the intake) always remain below 5.0 NTU. MassDEP regulations specify that turbidity levels may exceed 1.0 NTU only if it does not interfere with effective disinfection[119]. Background concentrations of turbidity in rivers and streams of the Wachusett Watershed ecoregions were found to range between 0.28 NTU and 4.33 NTU, with the 25th percentile value (all seasons) of 0.8 NTU (ecoregion 58)[120] and 1.68 NTU (ecoregion 59)[121], which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical turbidity criteria for these ecoregions. The current water quality goal for turbidity in streams and rivers is to maintain existing local background concentrations.

A-15 Total Organic Carbon

Total organic carbon (TOC) is the sum of all organic carbon in water, both dissolved and particulate (suspended). Organic carbon sources fall into three categories: 1) Terrestrial carbon such as decaying organic matter, proteins, organic acids, and animal waste; 2) Autochthonous sources produced in-stream/reservoir, such as algae; and 3) Anthropogenic sources such as industrial and wastewater discharges, petroleum related pollution, agricultural chemicals, and the accelerated release of natural organic carbon through landscape disturbance. Background TOC concentrations in rivers are typically 1 to 10 mg/L, though waters emanating from wetlands or bogs often have much higher natural concentrations of organic carbon[122].

While organic carbon is not a directly regulated drinking water quality parameter, carbon sources are precursors to disinfection byproducts (DBP) called trihalomethanes (THMs) and haloacetic acids, which are regulated at 60 µg/L and 80 µg/L, respectively. If TOC concentrations are above certain reactive thresholds which will cause DBP exceedances, then TOC removal is added to the water treatment process. To meet THM MCLs, water treatment guidelines typically suggest TOC removal when concentrations

[118] Swenson & Baldwin, 1965
[119] Massachusetts Drinking Water Regulations, 2020c
[120] USEPA, 2001a
[121] USEPA, 2000
[122] Mulholland & Kuenzler, 1979

exceed 2 mg/L in the source water. The water quality goal for TOC in Wachusett Watershed waters is to maintain background natural concentrations of TOC, preferably below 2 mg/L.

A-16 UV Absorbance

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

As with TOC, there are no regulatory limits for UV_{254}, however measurements are used to calculate the amount of carbon reduction required in the treatment process to meet the two DBP regulatory standards. After statistical relationships are developed to correlate TOC with UV_{254} for each tributary it is then possible to discontinue TOC sampling and use UV_{254} as a proxy for organic content. Water quality goals for UV_{254} would have to be specific to each tributary based on a statistically significant correlation to TOC concentration. The targeted UV_{254} values would be analogous to local their correlative background TOC concentrations, preferably below 2 mg/L. Although there are few management options to address organic carbon loading in streams, DWSP does proactively manage riparian vegetation along the reservoir shoreline specifically to reduce carbon inputs from leaf litter[123].

A-17 Chlorophyll *a* and Phycocyanin

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

There are currently no MA statutory action levels for algal pigments in surface waters, including drinking water sources. The EPA Office of Water does include chlorophyll *a* in its Ambient Water Quality Criteria Recommendations which are specific to the fourteen U.S. nutrient Ecoregions. The reference condition ranges listed for Wachusett Watershed's subecoregions 58 and 59 are 2.1 – 6 µg/L and 1.38 – 2.7 µg/L, respectively[124].

Chlorophyll *a* and phycocyanin data are only collected from reservoir locations at this time. Chlorophyll *a* has been measured in Wachusett Reservoir since 2011 when a fluorometer was added to the HydroLab multiprobe in use at that time. Upon upgrade to the YSI EXO2 probe in 2016, phycocyanin was also added

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[123] DWSP, 2018b
[124] 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[125]. In fresh water they can be planktonic (free-floating) or attached to structures including plants and rocks. Growth of freshwater algae is largely dependent on abiotic factors such as sunlight, temperature, and nutrients present in the water column. Changes in the algae community composition and density can therefore provide early indication of changes in water quality. In drinking water supplies, especially unfiltered systems, monitoring for these organisms can be extremely important, as certain taxa can produce compounds causing undesirable tastes, odors, and in limited cases, toxins. Phytoplankton can proliferate rapidly when ideal conditions are available and routine monitoring is essential for detecting density increases early in the growth phase so that appropriate management actions can be taken. These management options for Wachusett Reservoir include treatment of the algae present in the reservoir with copper sulfate (the last treatment was in 2014) and adjustments within the treatment system such as increasing the ozone dose.

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

[125] 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[126, 127]. They are also considered indicators of climate change as they are highly sensitive to changes in temperature and have a life span of less than one year, which means the zooplankton community can rapidly reflect environmental signals as populations change. The distribution of zooplankton, composed mostly of free-floating organisms, is largely affected by local factors of a water body, such as lake area, chemical composition, and predator abundance[128].

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

The primary goal of current zooplankton monitoring at Wachusett Reservoir is to identify new occurrences of invasive species as soon as possible. No invasive zooplankton have been found in the reservoir to date, but these species have colonized all the Great Lakes, the Finger Lakes of New York, and Lake Champlain of Vermont[129]. During these invasive species assessments, observations of native zooplankton are also made, establishing baseline data that may be used in the future to detect impacts from potential invaders and other environmental changes. Sample collection and scanning for presence of invasive species began in 2014. Samples from 2014 to present are maintained at DWSP offices and may also be assessed for community structure in the future.

A-20 Secchi Disk Depth/Transparency

A Secchi disk is a tool used to estimate water clarity and the amount of light penetration in a waterbody. The Secchi disk transparency is the water depth at which a Secchi disk, a round, alternately painted, black and white disk, is barely visible from the surface. This value can be used to estimate the depth of the euphotic zone; this area in which photosynthesis occurs is approximately three times the Secchi disk transparency[130]. In Wachusett Reservoir, Secchi disk transparency is most often affected by phytoplankton dynamics and contributions from the Wachusett Watershed and Quabbin Transfer. Weather patterns and percentage of native Wachusett Watershed water also affect visibility. Secchi disk transparency is recorded in association with Basin North (BN3417) samples and at reservoir nutrient sample locations, following the *SOP for Secchi Measurement*. The reference condition ranges listed for Wachusett Watershed's subecoregions 58 and 59 are 4.0 – 6.1 m and 1.2 – 4.9 m, respectively[131].

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[126] Hintz et al., 2019
[127] Richardson, 2008
[128] Havel & Shurin, 2004
[129] USGS, n.d.-b
[130] Dodson, 2005
[131] USEPA, 2001b

Appendix B: Short-term Forestry Monitoring Priority Zone

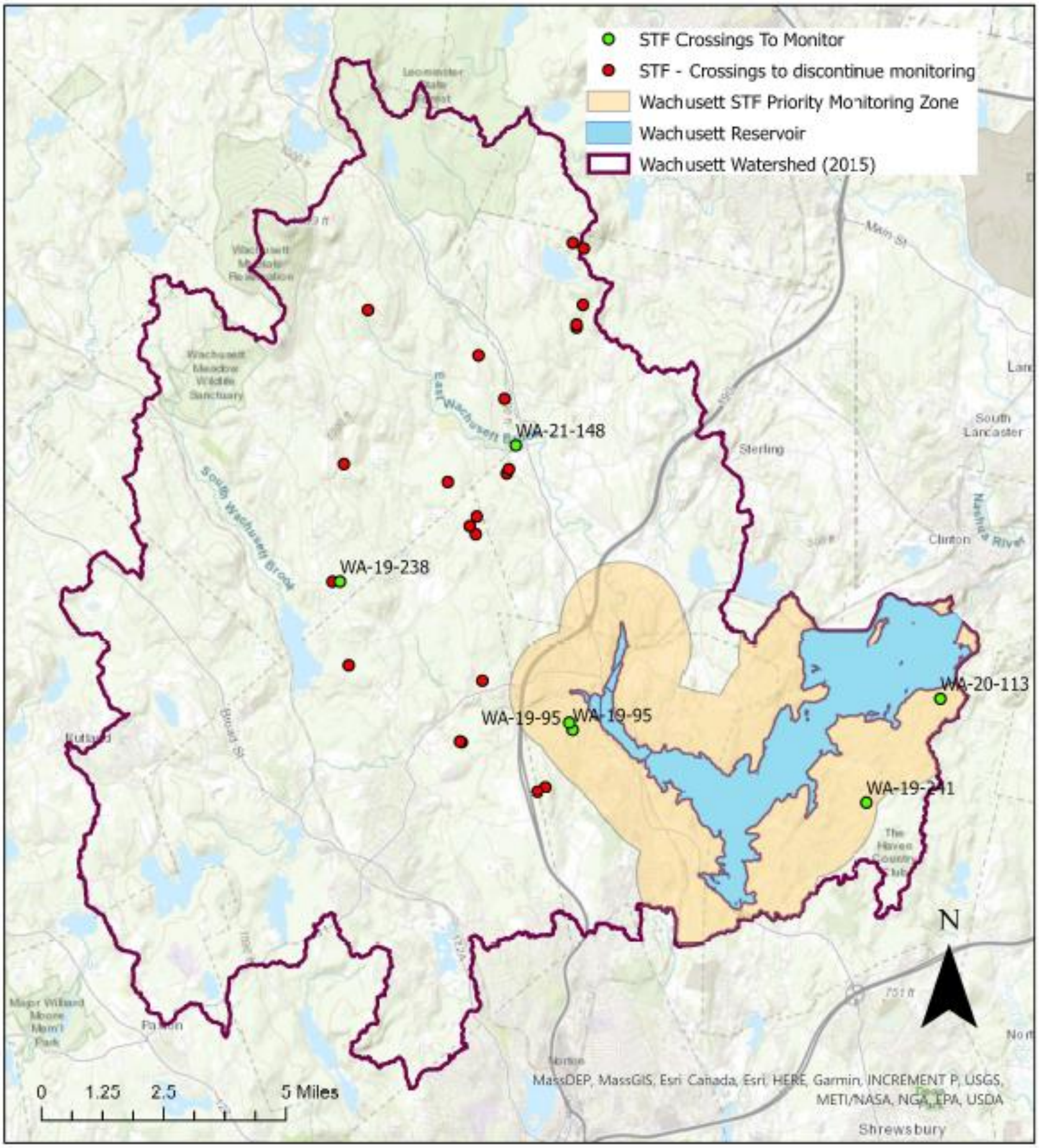

Figure B-1: Short-term Forestry Monitoring Priority Zone

The Short-term forestry monitoring protocol was revised in 2021. All stream crossings in the priority monitoring zone will be monitored, but only crossings on perennial streams will be monitored outside of this zone.