Water Quality Report: 2022

Quabbin Reservoir Watershed

Ware River Watershed

View of Mt. Zion, Quabbin Reservoir (Brett Boisjolie 2022)

August 2023

Massachusetts Department of Conservation and Recreation
Division of Water Supply Protection
Office of Watershed Management
Quabbin/Ware Region

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Abstract

This report is a summary of water quality monitoring methods and results from 24 surface water sites located throughout the Quabbin Reservoir and Ware River Watersheds, as well as other special assessment samples and periodic hydrologic event sampling. The Department of Conservation and Recreation (DCR), Division of Water Supply Protection (DWSP), is the state agency charged with the responsibility of managing Quabbin Reservoir and its surrounding natural resources in order to protect, preserve, and enhance the environment of the Commonwealth and to assure the availability of safe drinking water to future generations. The Environmental Quality Section manages a comprehensive water quality monitoring program to ensure that Quabbin Reservoir water meets state drinking water quality standards. As part of this task, the Environmental Quality Section performs field work, collects water samples, interprets water quality data, and prepares reports of findings. This annual summary is intended to meet the needs of watershed managers, the interested public, and others whose decisions must include water quality considerations.

The Quabbin Reservoir water quality satisfied the requirements of the Filtration Avoidance Criteria established under the Environmental Protection Agency Surface Water Treatment Rule for the entirety of 2022. Monitoring of tributaries is a proactive measure aimed at identifying trends and potential problem areas that may require additional investigation or corrective action. Water quality monitoring results were compared with state surface water quality standards, with minor exceedances in the tributaries attributed to higher solute loads measured during storm events, wildlife impacts on water quality, and/or natural attributes of the landscape.

The appendices to this report include field investigation reports, water quality data summary tables, and plots of reservoir and tributary water quality results and statistics. Some of the ancillary data presented in this report has been compiled with the assistance of outside agencies (e.g., U.S. Geological Survey) and other workgroups within DWSP whose efforts are acknowledged below.

CITATION

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Abbreviations

The following abbreviations are used in this report:

AIS	Aquatic Invasive Species
BWTF	Brutsch Water Treatment Facility
Cl	Chloride
CFR	Cold water fish habitat
CVA	Chicopee Valley Aqueduct
DCR	Massachusetts Department of Conservation and Recreation
DL	Laboratory detection limit
DWSP	Division of Water Supply Protection
EPA	U.S. Environmental Protection Agency
EQA	Environmental Quality Assessment
E. coli	*Escherichia coli*
MassDEP	Massachusetts Department of Environmental Protection
MassDOT	Massachusetts Department of Transportation
MassWildlife	Massachusetts Division of Fisheries and Wildlife
MCL	Maximum Contaminant Level
MLE	Maximum likelihood estimation
MWRA	Massachusetts Water Resources Authority
NEON	National Ecological Observatory Network
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
POR	Period of Record
Si	Silica
SMCL	Secondary Maximum Contaminant Level
SOP	Standard Operating Procedure
SWE	Snow Water Equivalent
SWTR	Surface Water Treatment Rule
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
UMass	University of Massachusetts, Amherst
U.S.	United States
UV_{254}	Ultraviolet Absorbance at 254 Nanometers
USGS	U.S. Geological Survey
WDI	Winsor Dam Intake
WRF	Warm water fish habitat

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. 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
L/mg-M	Liters per milligram per meter
MG	Million gallons
MGD	Million gallons per day
μg/L	Microgram per liter
mg/L	Milligram per liter
m	Meters
MPN	Most probable number (equivalent to CFU)
nm	Nanometers
NTU	Nephelometric turbidity units
S. U.	Standard Units (pH)

1 Introduction

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management (DWSP) manages and maintains a system of watersheds and reservoirs to provide 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 communities in Massachusetts. The watershed system includes the Quabbin Reservoir, Ware River, Wachusett Reservoir, and Sudbury Reservoir Watersheds, interconnected by a series of aqueducts (Figure 1).

The U.S. EPA introduced the Federal Surface Water Treatment Rule (SWTR) in 1989, followed by the introduction of the Interim Enhanced Surface Water Treatment Rule (IESWTR) in 1998, and the Final Long Term Enhanced Surface Water Treatment Rule Term 1 (2002) and Term 2 (2006) (US EPA, 1989; 1998; 2002; 2006), to ensure that public water supply systems that use surface water or groundwater under the direct influence of surface water provide safeguards against the contamination of water by viruses and bacteria. The 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 (US EPA, 2003). The DWSP and the MWRA have maintained a joint waiver for the filtration requirement of the SWTR since 1998 and work together to manage the watersheds in fulfillment of the waiver.

DWSP monitors water quality and quantity within the watersheds (Commonwealth of MA, 2004). Water quality sampling and field inspections help identify surface waters with potential water quality issues, aid in the implementation of watershed protection plans, and ensure compliance with state and federal water quality criteria for public drinking water supply sources (e.g., the filtration avoidance requirements stipulated under the SWTR). Routine monitoring of bacteria and nutrients in the reservoirs and tributaries provides an indication of sanitary quality of water sources, ensuring security of water resources and public health. Monitoring is also conducted by DWSP staff to better understand the responses of the reservoir and tributaries to a variety of physical, chemical, and biological inputs, and to assess the ecological health of the reservoirs and watersheds. A long-term record of water quality statistics provides information regarding potential controls on observed changes and represents a proactive effort to identify emerging threats to water quality.

This report summarizes the water quality monitoring performed by DWSP in the Quabbin Reservoir and Ware River Watersheds during 2022.

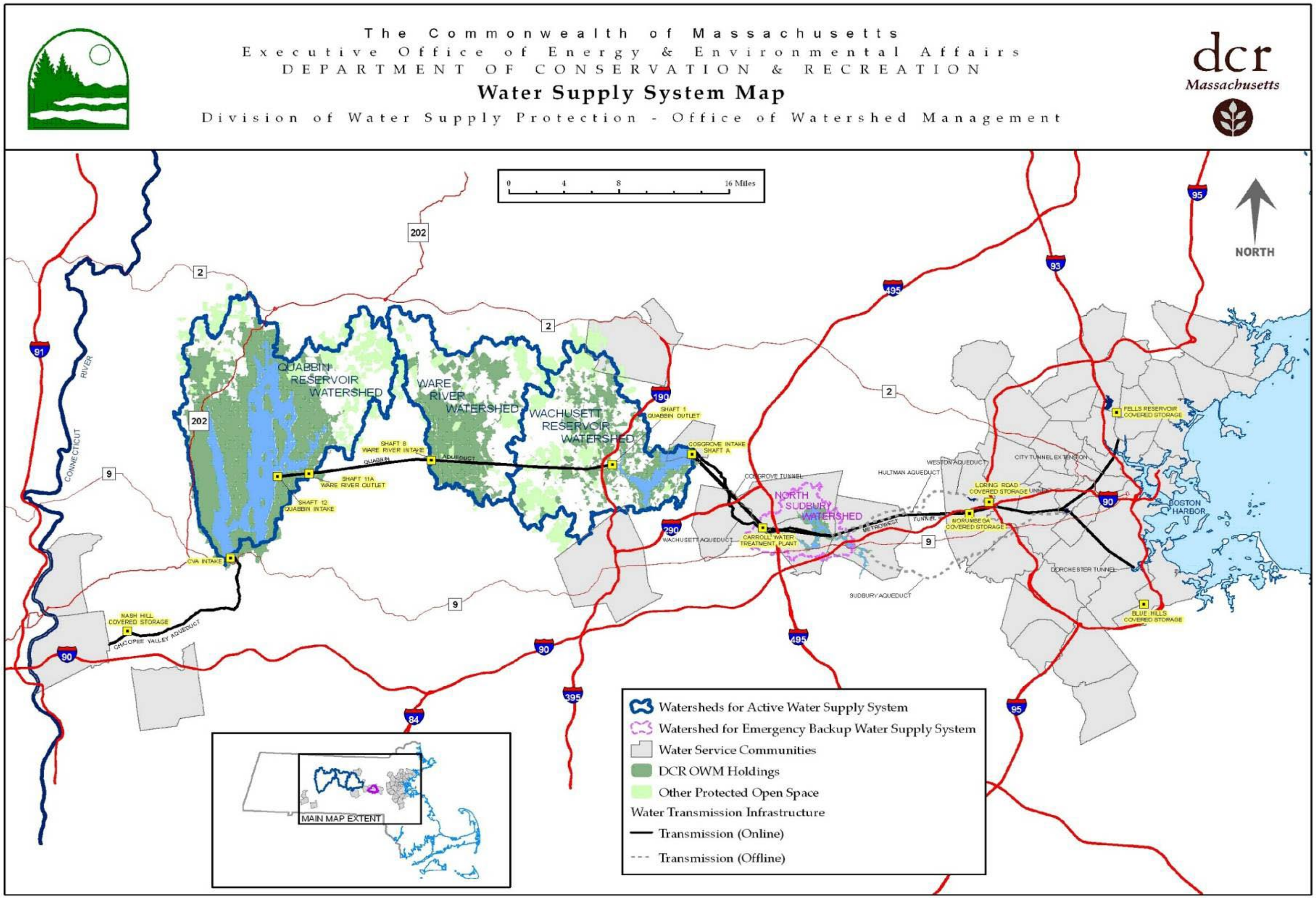

Figure 1: Quabbin Reservoir, Ware River, and Wachusett Reservoir Watershed system. Interstate highways are represented by red lines. Inset map in lower left depicts location of the watershed system relative to MA.

1.1 Public Water Supply System Regulations

Source water quality criteria 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 at least 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 remain below five NTU. Massachusetts Department of Environmental Protection (MassDEP) regulations require that turbidity levels at the point of consumption for all public drinking water remain below one NTU. Authority to enforce the SWTR has been delegated to MassDEP.

The Quabbin Reservoir is designated as Class A Public Water Supply (314 CMR 4.06(1)(d)1) and is thereby considered an Outstanding Resource Water (ORW) for the purposes of water quality protection (314 CMR 4.06). Massachusetts has developed numerical Class A water quality criteria for several parameters (Appendix A). Required monitoring for additional constituents at different stages in the distribution system (e.g., after treatment, after disinfection, and at the point of consumption) is conducted by MWRA. As MWRA produces reports that detail results of regulatory monitoring, monitoring results at each of the water system stages is not discussed as part of this report.

1.2 DWSP Monitoring Program Objectives

MWRA, as an unfiltered water supplier, is required to have a watershed protection program intended to promote and preserve high quality source water by utilizing a range of methods and strategies 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 DCR/MWRA water supply system. Watershed protection measures enacted by DWSP have been detailed in DWSP Watershed Protection Plans (WPPs) and WPP updates since 1991 (DWSP, 2023a). The goals of WPPs are to provide structured methodology to assess changes in existing threats to water quality across DWSP-managed watersheds, develop proactive strategies to prevent threats to water quality, and respond to potential threats to water quality to limit negative impacts. Environmental quality monitoring is one element of the WPPs developed by DWSP. The Watershed Protection Act of 1992 gives DWSP the authority to regulate certain land uses and activities that take place within critical areas of the watershed in order to protect drinking water quality (313 CMR 11.00). The high ambient water quality of the Quabbin Reservoir and Ware River watersheds can be attributed largely to the effectiveness of the WPPs.

DWSP staff rely on data generated by long-term monitoring programs to inform modifications to current WPPs. Data generated by long-term monitoring programs conducted by DWSP are used to assess current and historical water quality conditions, establish expected ranges of various water quality parameters, allow for routine screening of potential threats to water quality, and assess current watershed trends. Shorter-term investigations may also be conducted to evaluate specific issues. Monitoring efforts are reviewed and updated annually by DWSP to ensure that

DWSP programs remain current, appropriate, and informative for the WPP goals. Changes to annual water quality monitoring programs performed by DWSP staff are discussed in the annual water quality report for the affected watersheds (DWSP, 2019a; DWSP, 2019b).

The overarching objectives of the water quality and hydrologic monitoring programs conducted by DWSP are directly related to the WPP goals. These objectives are as follows:

1. Maintain long-term water quality statistics relative to the protection of public health.
2. Document achievements of watershed control criteria applicable to the filtration avoidance requirements stipulated under the EPA's Surface Water Treatment Rule (SWTR).
3. Identify streams and water bodies that do not meet water quality standards and where specific control measures may be initiated to eliminate or mitigate pollution sources.
4. Conduct proactive surveillance of water quality trends to identify emerging issues and support ongoing assessments of threats to water quality.

DWSP monitoring programs continuously adapt to respond to emergent and high priority threats to water quality, while utilizing current scientific information, tools, and technologies. The achievement of water supply protection goals, including specific water quality targets, can be credited to the coordinated implementation of DWSP's many programs.

1.3 Overview of DCR/MWRA Water Supply System, Quabbin Reservoir and Ware River Watersheds

The Quabbin Aqueduct connects three water sources that serve as a source of drinking water to 50 communities in Massachusetts (with additional three communities served directly from Quabbin Reservoir). The water sources connected by the Quabbin Aqueduct, from west to east, include the Quabbin Reservoir, the Ware River, and the Wachusett Reservoir (Figure 1). The Quabbin Reservoir is the largest of the sources, with a capacity of 412 billion gallons. In comparison, the Wachusett Reservoir holds 65 billion gallons at full capacity (Table 1).

Water from the Quabbin Reservoir is transferred to the Wachusett Reservoir via the Quabbin Aqueduct Intake at Shaft 12 (Figure 2). Transfers at Shaft 12 typically account for more than half of the of MWRA system supply. Water is also transferred directly to three western Massachusetts communities daily via the Chicopee Valley Aqueduct (CVA) from the Winsor Dam Intake (WDI) (Figure 2). Water from Ware River may be used to supplement Quabbin Reservoir. Ware River water is diverted into the Quabbin Aqueduct at Shaft 8 in Barre, MA, near DWSP Core tributary monitoring site 101 (Figure 3) and delivered to the Quabbin Reservoir via gravity flow. Ware River water enters the reservoir at Shaft 11A, east of the baffle dams in Hardwick, MA (Figure 2). 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. Additional information regarding land use and ownership in the Quabbin Reservoir and Ware River Watersheds is presented in the *Watershed Protection Plan FY24-FY28* (DWSP, 2023a) and the *2017 Land Management Plan* (DWSP, 2018a).

Table 1: a) General information on the Quabbin Reservoir, b) Quabbin Reservoir Watershed, and c) Ware River 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) Quabbin Reservoir General Information		
Description	**Units**	**Quantity**
Capacity	Billion gallons	412
Surface Area (at full capacity)	Acres	24,469
Length of Shoreline	Miles	118
Maximum Depth	Feet	141
Mean Depth	Feet	45
Surface Elevation, at Full Capacity	Feet, relative to Boston City Base	530
Reservoir gain (average) from 1” of precipitation	Billion gallons	1.6

b) Quabbin Reservoir Watershed General Information		
Description	**Units**	**Quantity**
Watershed Area (includes Quabbin Reservoir)	Acres	119,946
Land Area	Acres	95,364
	(% Total watershed area)	80
DWSP Controlled Area (includes Quabbin Reservoir)	Acres	88,066
	(% Total watershed area)	69.8
Total Protected Land Area (DWSP Fee, DWSP WPR, Other protected)	Acres (excludes reservoir)	73,535
	(% Total watershed land area)	77.1

c) Ware River Watershed General Information		
Description	**Units**	**Quantity**
Watershed Area	Acres	61,671
DWSP Controlled Area	Acres	25,756
	(% Total watershed area)	40.9
Total Protected Area (DWSP Fee, DWSP WPR, Other protected)	Acres	33,081
	(% Total watershed area)	53.6

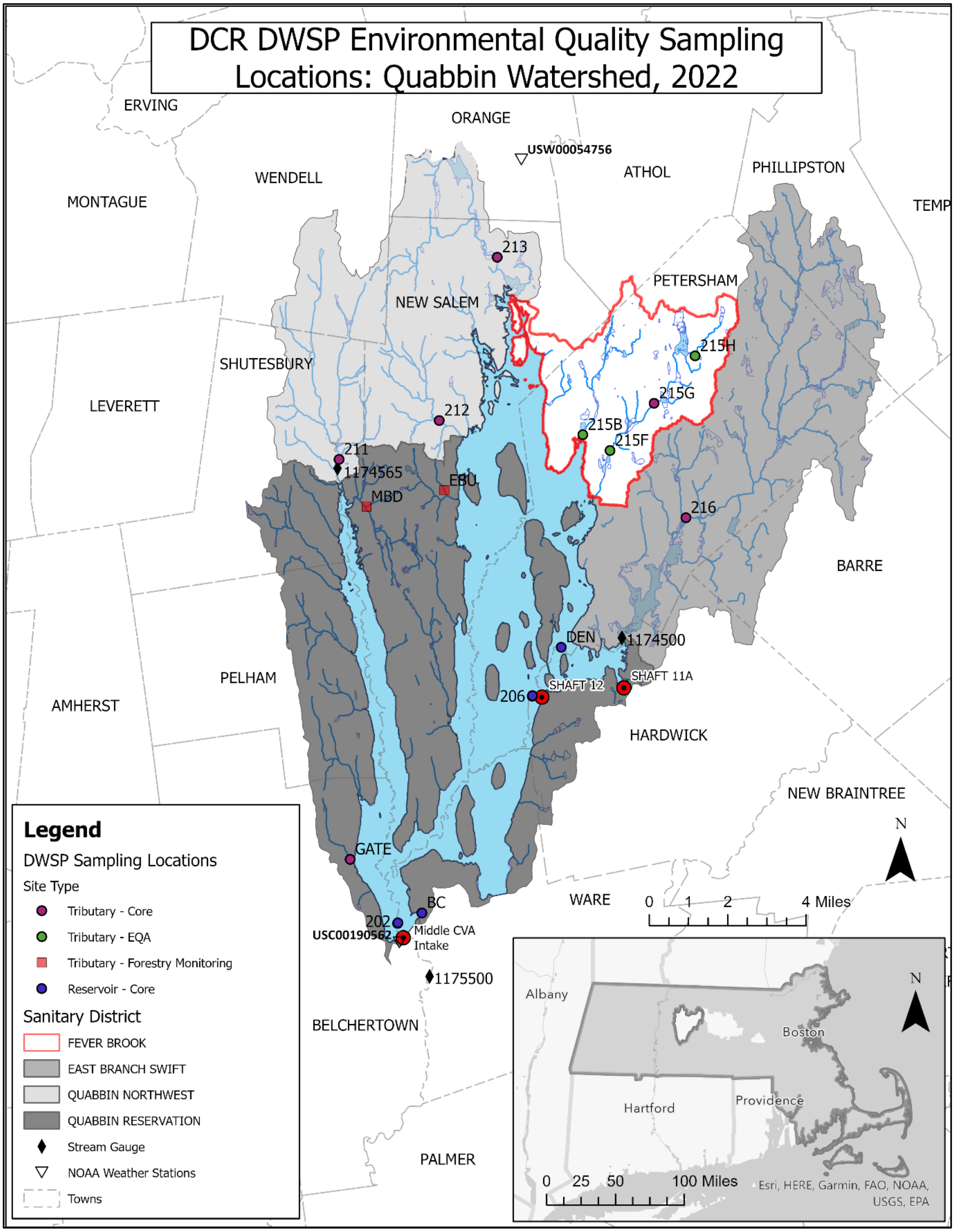

Figure 2: Map of Quabbin Reservoir Watershed showing locations of Core and EQA monitoring sites sampled in 2022. Also shown are DWSP sanitary districts. Inset map depicts the watershed relative to MA and MWRA system.

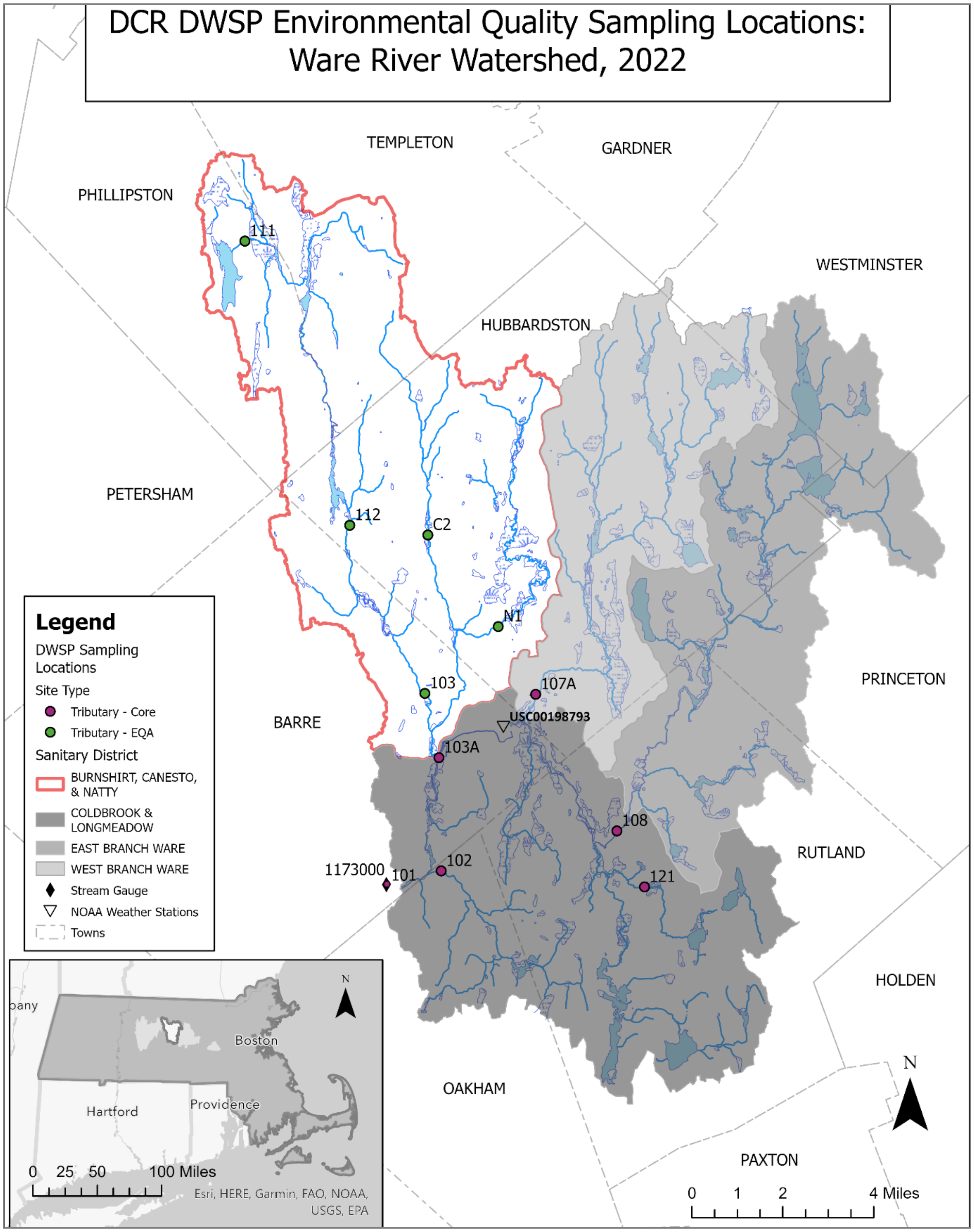

Figure 3: Map of Ware River Watershed showing locations of Core and EQA monitoring sites sampled in 2022. Also shown are DWSP sanitary districts. Inset map depicts the watershed relative to MA and MWRA system.

1.4 Description of Quabbin Reservoir and Ware River Watersheds

The Quabbin Reservoir Watershed is situated in the former Swift River sub-basin of the Chicopee River, a major tributary of the Connecticut River, and is located in the Central Uplands of north central Massachusetts. The Quabbin Reservoir Watershed encompasses approximately 187.5 sq. mi. (119,946 acres), including nearly all of the towns of New Salem and Petersham, considerable portions of Pelham, Shutesbury, and Wendell, and smaller portions of Orange, Hardwick, Phillipston, Belchertown, Ware, and Athol, MA (Figure 2). At full capacity, the surface area of the Quabbin Reservoir spans roughly 38.2 sq. mi. (24,469 acres), or 20.4% of the total watershed area, with nearly 118 miles of shoreline (Table 1). Mean and maximum depths of the Quabbin Reservoir are 45 and 141 ft, respectively.

Approximately 88% of the land surface in the Quabbin Reservoir Watershed is forested cover, with a total area comprised of less than 2% each of developed (further classified as rural-residential) or agricultural cover (Table 2). DWSP owns and controls 63,484 acres (62.0% of the total watershed land area) for water supply protection purposes, and approximately 77.1% of the total land area in the watershed is protected, including other means (Table 1). The relatively high proportion of forested, protected lands in the Quabbin Reservoir Watershed helps maintain exceptional water quality in the Quabbin Reservoir.

The Ware River Watershed neighbors the Quabbin Reservoir Watershed to the east. The Ware River begins as two branches (the East Branch and West Branch Ware River) that converge to form the Ware River in Hubbardston, MA. The Ware River forms a confluence with the Quaboag River in Three Rivers, MA to form the Chicopee River. DWSP monitors an area of 96.5 square miles (61,737 acres) of the Ware River Watershed, upstream of the Quabbin Aqueduct at Shaft 8 in Barre, MA. The Ware River Watershed area monitored by DWSP intersects portions of the municipalities of Barre, Phillipston, Hubbardston, Oakham, Rutland, Princeton, Templeton, and Westminster, MA (Figure 3).

Land cover in the Ware River Watershed is predominantly forest (74.5%), with approximately 41% of the watershed area (25,756 acres) controlled by DWSP. The Army Corps of Engineers controls approximately 600 acres (<1%) for flood control associated with the Barre Falls Dam, on the Ware River in Barre, MA. Agriculture comprises less than 3% of total watershed area for the Ware River Watershed (Table 2).

Table 2: Percentage of total area within each sanitary district accounted for by land cover class, within Quabbin Reservoir Watershed and Ware River Watershed. The land cover classes were modified from those developed with NOAA's Coastal Change Analysis Program (C-CAP) High-Resolution land cover products (NOAA, 2020) (Forest = deciduous, evergreen, and mixed forest; Developed = developed open space and impervious; Wetlands = palustrine emergent wetland, palustrine forested wetland, and palustrine scrub/shrub wetland; Agriculture = cultivated and pasture/hay; Water/Shoreline = Palustrine aquatic bed, unconsolidated shore, and water). Note: Quabbin Reservation sanitary district includes the area encompassed by the Quabbin Reservoir.

		Percentage land cover, per sanitary district			
Watershed	**Land cover class**	**East Branch Swift**	**Fever Brook**	**Quabbin Northwest**	**Quabbin Reservation**
Quabbin Reservoir	Forest	82.00	87.50	88.00	53.50
	Agriculture	3.05	0.58	1.41	0.16
	Developed	2.45	1.46	2.82	0.51
	Grassland	1.56	1.52	1.63	1.96
	Wetlands	6.74	6.07	4.29	1.54
	Barren	0.19	0.09	0.27	1.16
	Shrub	0.85	0.93	0.40	0.29
	Water / Shoreline	3.20	1.90	1.20	40.90
Watershed	**Land cover class**	**Burnshirt, Canesto, & Natty**	**Coldbrook & Longmeadow**	**East Branch Ware**	**West Branch Ware**
Ware River	Forest	81.80	71.50	70.30	71.00
	Agriculture	2.53	2.29	1.94	2.02
	Developed	4.99	4.94	6.16	4.97
	Grassland	2.00	1.15	1.50	1.54
	Wetlands	5.66	14.40	12.80	14.80
	Barren	0.17	0.21	0.25	0.38
	Shrub	1.21	1.93	0.99	1.74
	Water / Shoreline	1.64	3.59	6.12	3.54

2 Methods

DWSP monitoring of Quabbin Reservoir and Ware River Watersheds consists of collection of *in situ* measurements, collection and analysis of water samples for phytoplankton and water quality, implementation of the Quabbin Boat Seal Program and associated boat decontamination programs, and monitoring and associated management of aquatic invasive species within the reservoir and in water bodies within the Quabbin Reservoir and Ware River Watersheds. Standard operating procedures outlining specific details (e.g., make/model of equipment used) were developed by DWSP staff, and generally follow methods outlined in USGS and EPA protocols.

2.1 Monitoring Programs

DWSP staff monitored water quality at 21 surface water sites in the Quabbin Reservoir and Ware River Watersheds and three sites within the Quabbin Reservoir (Figure 2, Figure 3) in 2022. The tributary monitoring locations within each watershed include Core sites and Environmental Quality Assessment (EQA) sites. Core sites represent long-term monitoring sites throughout the watershed that are included in the monitoring plan each year. Core sites are critical for DWSP assessments, as they provide a long-term record of water quality data from primary tributaries within each watershed. Each watershed is divided into sub-watersheds, referred to as sanitary districts (Figure 2, Figure 3). EQA sites within a single sanitary district are sampled approximately once every four to five years. Data from EQA sites are used to support assessments of potential threats to water quality within each sanitary district. Monitoring of EQA sites provides a year-long assessment of water quality within a specific area of each watershed, allowing for greater spatial coverage, higher-resolution understanding of transport processes operating across the watershed, and elucidation of potential upstream impacts to Core sites. The Fever Brook sanitary district and the Burnshirt, Canesto, and Natty Brook sanitary district were monitored in 2022 for Quabbin Reservoir Watershed and Ware River Watershed, respectively.

DWSP staff also conduct several special investigations, spanning multiple years of collection. These may include stormwater sampling, monitoring of potential short-term and long-term water quality changes following forest management activities, and evaluation of spatial and temporal trends in conductivity and chloride concentrations of waters impacted by de-icing practices. Results of special investigative efforts are discussed in Section 3.2.8.1.

2.1.1 Meteorological and Hydrological Monitoring

Daily measurements of precipitation and air temperatures were recorded at three locations within Quabbin Reservoir and Ware River watersheds in 2022 (Table 3). DWSP maintains one weather station in the Quabbin Reservoir watershed at the DCR Administration Building in Belchertown, MA. The National Oceanic and Atmospheric Administration (NOAA) maintains a Climate Data Online portal through the National Center for Environmental Information, allowing access to records from weather stations within proximity of the DWSP watersheds at the Orange Municipal Airport in Orange, MA, and at the US Army Corps of Engineers Barre Falls

Dam in Barre, MA. Meteorological summaries presented in this report correspond to these DWSP (USC00190562) and NOAA weather stations (USW00054756, USC00190408). Historical records are also available from the Ware, MA NOAA weather station (USC00198793). As of 2017, this station is no longer active, and records from this station are not summarized in this report.

DWSP staff measured snow depth and snow water equivalent (SWE) weekly (during periods of snow cover) at six locations across the Quabbin Reservoir watershed in 2022 (Table 3). Reported snowpack measurements (depth and SWE) represent the mean depth and weight, respectively, of six snow cores for each sample site, for each site visit. Weekly results were reported to NOAA and the National Operational Hydrologic Remote Sensing Center (NOHRSC). Daily snowfall monitoring was recorded at the DCR Belchertown weather station.

Table 3: Meteorological and hydrologic monitoring stations located within the Quabbin Reservoir and Ware River Watersheds. Note: air temperature was not recorded at Ware, MA station (USC00198793).

Measurement	Site Name	Site ID	Managed by	Period of Record (POR)
Air Temperature, Precipitation	Belchertown, MA	USC00190562	DWSP	1947-2022
	Orange Municipal Airport, Orange, MA	USW00054756	NOAA	1996-2022
	Barre Falls Dam, MA	USC00190408		1959-2022
	Ware, MA	USC00198793		1947-2017
Snowpack	4NW Hardwick - Q1 (Gate 43A)	Q1	DWSP	2018-2022
	3SW Petersham - Q2 (Gate 40)	Q2		2018-2022
	2NW New Salem - Q3 (West of 202)	Q3		2018-2022
	1N Pelham - Q4 (Pelham Lookout)	Q4		2018-2022
	4E Belchertown - Q5 (Blue Meadow)	Q5		2018-2022
	3NW Petersham - Q6 (Balls Corner)	Q6		2018-2022
Mean Daily Streamflow (cfs)	Ware River, Barre	1172500	USGS	1987-2022
	Ware River, Intake Works, Barre	1173000		1987-2022
	Ware River, Gibbs Crossing	1173500		1987-2022
	Swift River, West Ware	1175500		1987-2022
	East Branch Swift River, Hardwick	1174500		1987-2022
	West Branch Swift River, Shutesbury	1174565		1995-2022
	Lower Hop Brook	HOPB	NEON	2017-2022
	Parker's Brook	PARB	DFW-DER	2012-2022

2.1.2 Hydrologic Monitoring

Mean daily streamflow was recorded by the U.S. Geological Survey (USGS) for six tributaries in the Quabbin and Ware River Watersheds (n=3 and n=3, respectively) in 2022 (Table 3). Mean daily streamflow at USGS stations in the Quabbin Reservoir and Ware River Watersheds has been recorded continuously since October 1987, aside from the USGS monitoring station located along the West Branch Swift River (DWSP site ID 211; USGS 01174565), where monitoring began in

1995. Massachusetts Department of Fish and Wildlife, Division of Ecological Restoration (DER) maintains a stream gage at Parkers Brook in the Ware River Watershed, generating daily streamflow data beginning in late 2012 (DWSP site ID 102). The National Ecological Observatory Network (NEON) began the development of a streamflow monitoring station along Lower Hop Brook (DWSP site 212) in 2017. Daily streamflow data generated by NEON are available beginning in late 2020 (NEON, 2020). DWSP maintained staff gages at several monitoring locations (sites GB, 211, 213, 215G, and 216) in 2022. Development of rating curves from these stream gages will continue in 2023.

2.1.3 Tributary Monitoring

DWSP staff monitored water quality at 21 surface water sites in the Quabbin Reservoir and Ware River Watersheds (Table 4) in 2022. Samples were collected at Core tributary sites every two weeks in 2022, with sampling in Quabbin Reservoir Watershed and Ware River Watershed alternating weekly. Frequency of analyses for nutrients (NO3-N, NH3-N, TN, and TP) increased from quarterly to every two weeks in 2020 and remained at this frequency through 2022. Total organic carbon was added to the sampling plan in 2021 and continued to be collected every two weeks at Core sites in the Quabbin Reservoir Watershed in 2022. Alkalinity was not monitored consistently in Core tributaries in the Quabbin Reservoir and Ware River Watersheds in 2022. Alkalinity monitoring will resume in 2023, at a quarterly frequency at these locations. The impacts of changes to sampling frequency on seasonal statistics and variability across sites are discussed in Section 3.2. Samples were analyzed by MWRA laboratories per standard methods (Table 5).

Table 4: Drainage basin characteristics of DWSP tributary monitoring sites for Quabbin Reservoir watershed and Ware River watershed, 2023. * Includes Brigham and Cunningham Pond (0.077 mi^2 and 0.043 mi^2, respectively). ** includes Stone Bridge Pond (0.144 mi^2).

Watershed	Site Type	Site ID	Site Description	Area (mi^2)	DWSP Owned Land		Wetland	
					mi^2	%	mi^2	%
Quabbin Reservoir	Core	211	West Branch Swift River, at Route 202	13.60	6.36	46.8	0.47	3.5
		212	Hop Brook, inside Gate 22	4.53	1.49	32.8	0.12	2.6
		213	Middle Branch Swift River, at Gate 30	9.07	2.16	23.8	0.75	8.3
		215G	East Branch of Fever Brook, at Camel Hump Road	4.11	0.57	13.9	0.53	12.9
		216	East Branch Swift River at Route 32A	30.10	0.63	2.1	2.84	9.4
		BC	Gates Brook, at mouth	0.04	0.04	100	0	1.0
		GATE	Boat Cove Brook, at mouth	0.88	0.88	100	0.03	3.1
	EQA	215B	West Branch Fever Brook, at mouth	4.70	1.28	27.3	0.42	8.9
		215F	Harvard Pond, at inlet	2.18	1.34	61.4	0.14	6.5
		215H	East Branch Fever Brook, at road about mouth	1.13	0	<0.1	0.08	6.9
Ware River	Core	101	Ware River, at Shaft 8 (intake)	96.50	36.50	37.8	13.40	13.9
		102	Parkers Brook, at Coldbrook Road	5.42	4.60	84.8	0.52	9.5
		103A	Burnshirt River, at Riverside Cemetery	4.01	2.83	70.7	0.28	7.1
		107A*	West Branch Ware River, at Brigham Road	16.00	7.25	45.3	2.7	16.9
		108	East Branch Ware River, at Intervale Road	22.2	2.96	13.4	3.83	17.3
		121	Mill Brook, at Charnock Hill Road	3.38	0.32	9.4	0.53	15.8
	EQA	103	Burnshirt River, at Route 62	4.37	2.91	66.7	0.35	8.0
		111	Queen Lake, at culvert below outlet	0.77	0	0	0.26	33.9
		112**	Burnshirt River	11.9	0.89	7.5	1.43	12.0
		C2	Canesto Brook, at Williamsville Road	4.55	0.27	6.0	0.21	4.7
		N1	Natty Pond Brook, at Hale Road	5.50	2.07	37.5	0.82	14.9

Analytical methods for TKN were modified in 2020. Prior to January 01, 2020, TKN concentrations were derived via EPA Method 351.2 (O'Dell, 1993a). Beginning in 2020, analysis shifted to Valderrama (1981) to facilitate monthly monitoring frequencies of N-species and TP in Core sites in Quabbin Reservoir, and an every two week monitoring frequency in Core tributary sites. Results were reported as total nitrogen (TN) in 2020 and 2022. TKN concentrations for 2020 and 2022 were derived by subtracting concentrations of NO_3-N and NO_2-N from TN concentrations. Concentrations below laboratory detection limits were substituted with the detection limit. NO_2-N has been measured previously (2010) in samples collected from Core sites and was below laboratory detection limits in all samples in the Quabbin Reservoir (n=18) and in all but four samples (n=2,005 total measurements) in Core tributaries. Thus, NO_2-N was assumed to remain below laboratory detection limits (<0.005 mg/L) in all samples collected in 2020 and 2022. DWSP did not modify sample collection methods, thus uncertainty associated with TKN concentration data is limited to assumptions made during calculations and/or sensitivity of different analytical methods. The detection limits for TN via Valderrama (1981) were 0.0034 mg/L.

Table 5: Analytes included in DWSP tributary monitoring programs, analytical methods, and monitoring frequency for 2022. TOC is monitored in Core tributaries in the Quabbin Reservoir watershed only. Alkalinity concentrations results were historically reported by titration to pH of 4.5 endpoint via Standard Method 2320B (DWSP, 2018b).

Group	Analyte	Method (2022)	Monitoring Frequency (2022)
Bacteria	Total Coliform	SM 9223B	Every two weeks
	Fecal Coliform	SM 9222D	
	E. coli	SM 9223B	
Misc.	Turbidity	SM 2130 B	
	Alkalinity	SM 2320 B	Quarterly
Nutrients & Organic Matter	NO_3-N	EPA 353.2	Every two weeks
	NH_3-N	EPA 350.1	
	TN	Valderrama (1981)	
	TP	EPA 365.1	
	TOC	SM 5310 B	
	UV_{254}	SM 5910B 19th edition	
Metals	Ca	EPA 200.7	Quarterly
	Na		
Anions	Cl	EPA 300.0	
Field Parameters	Temperature	Gibs et al. (2012)	Every two weeks
	Dissolved Oxygen		
	pH		
	Specific Conductance		

2.1.4 Reservoir Monitoring

The Quabbin Reservoir was sampled regularly in 2022 to monitor phytoplankton densities, anticipate potential taste and odor problems, and recommend management actions as necessary. At site 202, phytoplankton was sampled every two weeks from May to September, and monthly from January through April and from October through December (Appendix C). At site 206, phytoplankton was sampled monthly. Phytoplankton sampling frequency was increased to weekly at site 202 in response to elevated densities of *Chrysosphaerella* from July 6 through August 23, 2022. Water-column profiles of temperature, pH, dissolved oxygen, specific conductance, chlorophyll *a*, and phycocyanin were measured in conjunction with phytoplankton sampling. Water samples were collected monthly in 2022 from April to December at three depths from three stations within the reservoir for analyses of nutrients, UV_{254}, total organic carbon, and bacteria (in addition to collection of depth-profiles of temperature, pH, dissolved oxygen, specific conductance, chlorophyll *a*, and phycocyanin via a Yellow Springs Instruments (YSI) EXO2 sonde). Alkalinity was sampled monthly from April to December. Calcium, sodium, and chloride sampling in 2022 varied from the intended quarterly sampling frequency (May, July, October, and December), as sodium and calcium were measured in April, May, and December, and chloride was measured in April, May, July, October, and December.

Changes in sensor manufacturers, sonde configurations, and water column profile collection methods complicate direct comparisons to historical data for physiochemical parameters. Reservoir monitoring results are discussed in Section 3.3 of this report.

Table 6: Core monitoring locations in Quabbin Reservoir, 2022. Depth represents the approximate water column depth, based on surface elevation of Quabbin Reservoir at maximum capacity.

Site Name	Site ID	Location	Latitude	Longitude	Depth (m)
Winsor Dam	202	Quabbin Reservoir west arm, offshore of Winsor Dam along former Swift River riverbed	42°17.215′ N	72°20.926′ W	42
Shaft 12	206	Quabbin Reservoir at site of former Quabbin Lake, offshore of Shaft 12	42°22.292′ N	72°17.001′ W	28
Den Hill	Den Hill	Quabbin Reservoir eastern basin, north of Den Hill	42°23.386′ N	72°16.008′ W	19

In addition to manual water column profiles, a remote sensing profiling buoy was deployed by MWRA starting in 2020, located close to sampling site 202 in Winsor Basin. Profiles are collected with YSI EXO2 sondes, identical to those used by DWSP for manual profiles. The profilers automatically run every six hours (12 am, 6 am, 12 pm, and 6 pm) and collect data at 1-m increments. Results are frequently used by DWSP to augment the routine profiles and phytoplankton 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.

Oblique tows (1 min, 53-µm mesh) were performed quarterly in proximity to the Boat Launch Areas. Samples collected via oblique net tows were screened to monitor for invasive zooplankton.

2.1.5 Aquatic Macrophyte Monitoring

Water bodies in the Quabbin Reservoir Watershed (n=2) and Ware River Watershed (n=3) were surveyed by DWSP for the presence of aquatic invasive species (AIS) in 2022 (Table 7). The regulating ponds (O'Loughlin and Pottapaug) and portions of the Reservoir shoreline and Ware River were also surveyed for AIS in 2022. Assessments conducted by TRC (formerly ESS Group Inc.) were completed under a MWRA contract. MWRA and the contracted consultant assist DWSP with early detection of AIS by surveying portions of the Quabbin Reservoir and the Ware River annually.

DWSP additionally monitors for AIS in the watersheds. Several water bodies within the Quabbin Reservoir and Ware River Watersheds are monitored for AIS annually, whereas additional water bodies are evaluated every five years as a component of the current Environmental Quality Assessment. The Quabbin Reservoir consists of four sanitary districts, which comprise the area investigated for the purpose of the annual Environmental Quality Assessments, completed on a five-year basis. Thus, the water bodies in a single sanitary district, for each of the Quabbin Reservoir Watershed and the Ware River Watershed, are surveyed for AIS every five years. Select water bodies in the Quabbin Reservation sanitary district and West Branch Ware sanitary district were surveyed for AIS in 2022.

As a preventative means to further limit potential undesirable impacts to water quality resulting from AIS in Quabbin Reservoir and Ware River Watersheds, DWSP staff coordinate boat inspections, decontaminations, and perform monitoring of boat ramps, in addition to annual aquatic macrophyte surveys.

Table 7: Water bodies surveyed in 2022 for aquatic invasive macrophyte species by DWSP and TRC.

Watershed	Water Body Name	Location	Surveyed by	Date
Quabbin Reservoir	Quabbin Reservoir	New Salem, Petersham, Hardwick	TRC	8/10-8/17/2022
	O'Loughlin Pond	New Salem	TRC	8/10/2022
			DWSP	8/12/2022
	Pottapaug Pond	Hardwick	DWSP	8/15/2022
			TRC	8/16/2022
	Quabbin Reservoir, West Arm	Pelham, New Salem	TRC	8/17/2022
			DWSP	9/29/2022
	Harvard Pond	Petersham	DWSP	8/8/2022
	Peppers Mill Pond*	Ware		7/28/2022
Ware River	Ware River, upstream of Shaft 8	Barre	TRC	7/8/2022
	Long Pond	Rutland	DWSP	7/11/2022
	Whitehall Pond	Rutland		6/30/2022
	Queen Lake	Phillipston		6/23/2022

*outside of watershed, monitored because of its proximity to Quabbin Reservoir

2.1.6 Special Investigations

2.1.6.1 Forestry Monitoring

When properly executed, timber harvesting best management practices (BMPs) serve to minimize potential impacts to water quality that may occur during silvicultural activities (USFS, 2012; NASF, 2019). DWSP monitors harvest operations on DWSP lands throughout the Quabbin Reservoir and Ware River Watersheds (Section 3.2.8.1). Water quality sampling 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 timber harvesting, whereas long-term monitoring involves evaluating water quality parameters as the forest regenerates following timber harvesting operations.

2.1.6.1.1 Long-term Forestry Monitoring

DWSP conducts long-term monitoring for the potential impacts of timber harvesting on water quality at two surface water sites in the Quabbin Reservoir Watershed (Figure 2). The monitoring follows a paired-watershed study design, where data are collected at a control and treatment watershed before and after timber operations and assessed for changes that can be attributed to forest management. The paired watershed study design was selected for its robust approach for assessing long-term changes in water quality conditions as climate and hydrological differences over years is statistically controlled, allowing for attribution of water quality changes to treatment rather than climatic drivers (Hewlett and Pienaar, 1973).

Water quality sampling is conducted at two intervals to ensure that monitoring captures a full range of streamflow conditions and solute mobilization. Routine monthly grab sampling and quarterly event-based sampling occurred in 2022, meeting sampling objectives for the project. Monthly grab samples have been collected at the Middle Branch Dickey (MBD) Brook (control site) and the East Branch Underhill (EBU) Brook (treatment site) on Prescott Peninsula since April 2002. Monthly grab samples have been analyzed for nutrients (NO_3-N, NO_2-N, TKN, and TP) since 2002, and total suspended solids (TSS), UV_{254}, NH_3-N, TOC, and DOC since 2014, and continued through 2022. Periodic event-based sampling of MBD and EBU was initiated in 2014 to characterize stream response during a variety of hydrologic events (e.g., rainfall, snowmelt, rain-on-snow). Primary data generated by DWSP include measurements of precipitation, stream flow, and concentrations of solutes collected across the event hydrograph (NO_3-N, NH_3-N, NO_2-N, TKN, TP, TSS, UV_{254}, TOC, and DOC). Concentration data collected during events serve to characterize the range of nutrient and sediment concentrations observed in these watersheds and provide an estimate of event-based solute loading for MBD and EBU when coupled with event discharge data. Long-term forestry monitoring of water quality in MBD and EBU in 2022 also included installation and routine maintenance of water-level loggers and precipitation gages, downloading of field data, monitoring of weather forecasts, continued development of field procedures, sample and data collection during four events, and associated data analysis.

2.1.6.1.2 Short-term Forestry Monitoring

Short-term forestry monitoring performed by DWSP involved monitoring forestry operations through site inspections and targeted water quality sampling. Inspections and water quality sampling were conducted prior to the start of logging to establish a baseline, during operations to monitor potential short-term impacts, and following completion of harvesting activities to document potential impacts to water quality of sites adjacent to timber harvesting operations. No short-term impacts from harvesting operations on DWSP land have been detected when BMPs were properly maintained. Based on this finding, short-term forestry water quality monitoring was suspended as of January 2023, while careful planning of harvests and monitoring of BMPs will remain the primary focus of DWSP timber harvesting operations.

2.1.6.2 Environmental Quality Assessments

DWSP conducts annual Environmental Quality Assessments (EQAs) of a single sanitary district in each watershed to assess potential sources of contamination across the watershed system. Each sanitary district is comprehensively evaluated by DWSP once every five years. Water quality monitoring of select Core and EQA sites within the selected sanitary district constitutes a component of the EQA. The EQAs conducted in 2022 focused on the Fever Brook sanitary district and the Burnshirt, Canesto, and Natty sanitary district (Figure 2 and Figure 3, respectively). Concentrations of constituents measured in tributary monitoring sites in 2022 were compared to results from prior monitoring (DWSP, 2023b-c). Lastly, concentration data from 2022 were compared to regulatory thresholds/limits, when applicable.

2.2 2022 Watershed Monitoring Parameters and Historical Context

DWSP water quality monitoring was comprised of 24 unique water quality characteristics (e.g., physical, chemical, and biological) measured in the Quabbin Reservoir and Ware River Watersheds in 2022 (Appendix A). Parameters monitored by DWSP included those that may directly affect water quality (and thus, potability) and/or may indicate the presence of potential future negative impacts to water quality. An extensive discussion including relevant regulatory and guidance thresholds for the parameters monitored by DWSP is provided in Appendix A, along with analytical methods for concentration data. Results for various water quality parameters are compared to regulatory levels (e.g., maximum contaminant levels (MCLs)), thresholds for aquatic life protection, recreational contact, and the EPA Ecoregional Nutrient Criteria for Rivers and Streams, when applicable (Appendix A).

2.3 Statistical Methods and Data Management

In 2020, monitoring frequency of several parameters was increased in Core tributaries from quarterly to every two weeks (DWSP, 2021a). Select tributary monitoring sites previously established as EQA sites were converted to long-term (Core) monitoring sites in 2021 to provide better spatial coverage of either watershed (215G replaced 215 in the Quabbin Reservoir Watershed, and 121 replaced 121B in the Ware River Watershed). Parkers Brook (102) was added to the Ware River Watershed monitoring program as a Core site in 2021. Changes in the frequency of analysis of select analytes, or transitions from EQA to Core site sampling frequencies may impact seasonal statistics, long-term patterns in water quality, and comparisons to historical ranges relative to sites that have not undergone significant changes to monitoring program structure (Appendix C, Figure C35).

Monitoring frequency of select analytes in Quabbin Reservoir changed from quarterly to monthly in 2020. Total organic carbon was added to the suite of analyses for these sites in 2020, monthly. Changes in the frequency of analysis of select analytes have the potential to alter seasonal statistics, long-term patterns in water quality, and comparisons to historical ranges relative to parameters that have not undergone changes to monitoring frequency (e.g., bacteria) (Appendix C, Figure C36).

Water quality, precipitation, and streamflow data collected since 1989 are stored in a Microsoft SQL Server database, maintained by DWSP-EQ. The WAtershed system data Visualization Environment (WAVE) is a custom R/Shiny (R Core Team, 2019; Winston et al., 2019) application developed as a collaborative effort between individuals from the Department of Civil and Environmental Engineering at the University of Massachusetts Amherst and DWSP. WAVE serves as a portal to view and track data within the SQL Server database.

Field parameters (temperature, dissolved oxygen, pH, specific conductance, chlorophyll *a*, and phycocyanin) were routinely recorded and uploaded to the DWSP water quality database in 2022. Laboratory data (including concentrations of various constituents and plankton densities) were uploaded to the DWSP water quality database upon receipt via R-scripts and Shiny application tools designed for data download and database standardization (R Core Team, 2019; Winston et al., 2019). Select records with known calibration issues or ranges outside determined thresholds were flagged and removed from analysis for reporting purposes.

Concentrations below laboratory reporting limits were replaced with the detection limit for all calculations performed in this report. Concentrations above upper reporting limits were assigned a value equal to the upper detection limit. Censored data are flagged in the DWSP database. This method of handling censored data may vary from that of previous Annual Water Quality Reports for the Quabbin Reservoir and Ware River Watersheds, although it is consistent with that used in the 2022 annual water quality report for the Wachusett Reservoir Watershed (DWSP, 2023d). Due to the inherent non-normal distribution of environmental monitoring data, non-parametric measures of central tendency (median, interquartile range) were used to evaluate the variability of constituents observed in 2022 (Helsel, 2012).

Furthermore, annual statistics (mean, median, geometric mean) were calculated using methods depending on the occurrence of non-detects within each data grouping. Left-censored results were substituted with the detection limit concentration and the normal statistic was calculated using base R functions when fewer than four values are detected in a data group. Statistics were calculated using functions from the NADA package (Lee, 2020) when four or more censored values were present in a data group. A parametric method, Maximum Likelihood Estimation (MLE), was used to compute annual geometric mean *E. coli* concentrations. A non-parametric method, Regression on Order Statistics (ROS), was used with other censored data (namely nutrients) to calculate seasonal mean and median concentrations. This modification to statistical methods may produce deviations from standard methods for calculating measures of central tendency for select parameters, as reported previously (DWSP, 2021b-c). To account for this, seasonal mean and median concentration results calculated via standard methods have been incorporated into reporting tables throughout this report, in addition to those derived via either MLE or ROS methods. For some analytes where most results are below detection limits (e.g., NH_3-N and NO_3-N), minimum values are reported at detection limits while mean and median values may be lower than detection limits based on ROS methods. Methods for determining measures of central tendency remain unchanged from prior reports for constituents with no censored values. These methods of handling censored data are expected to produce more robust and unbiased results. Many of the reported calculations in this analysis did not deviate substantially from those derived via prior methods.

Summary statistics (minimum, median, mean, and maximum values) of results from 2022 monitoring are reported along with statistics from the period of record (POR) available from DCR-DWSP data records. Results from each analyte's POR provides the range of variability expected at sampling locations and allows for comparison of 2022 results against their historical context.

3 Results

3.1 Hydrology and Climate

Climate in the Quabbin Reservoir and Ware River watersheds is characterized by seasonal cycles of hot, humid summers and cold winters with mixed precipitation patterns of rain and snow (Siddique et al. 2020). The region is susceptible to extreme weather events including tropical storms, nor'easters, and recurring prolonged summer droughts. Precipitation events originate in colder regions including the Arctic, Mid/North Atlantic, and Pacific, as well as events from Continental and Gulf regions (Puntsang et al. 2016, Cole 2019). Resulting weather patterns can have variable impacts on the region in time and space based on topographic variability and position relative to storm tracks (Boutt 2016). Consistent precipitation as well as high-intensity rainfall events result in periodic high flow conditions in streams in the region throughout seasons, with a general pattern of peak streamflow from snowmelt in the spring and declining flows through growing season. Annual variations in climate (e.g., air temperature and precipitation) and hydrology can influence and explain variations in water quality patterns. Understanding annual hydrologic and meteorologic patterns in relation to historical period of record can provide important context to annual water quality patterns.

3.1.1 Climatic Conditions

3.1.1.1 Air Temperature

The mean value of daily median temperatures of 9.5°C, 10.2°C, and 9.6°C were observed at the three Quabbin Reservoir watershed and Ware River watershed weather stations in 2022 (Barre, Belchertown, and Orange, respectively). Minimum and maximum daily recorded temperatures in 2022 ranged from -25°C to 37.8°C (Barre), -21.1°C to 34.4°C (Belchertown), and -23.8°C to 35.6°C (Orange) at the three weather stations. Daily median temperatures throughout Quabbin Reservoir watershed during 2022 typically fell within the daily temperature ranges for the period of record (Figure 4), although there were several unseasonably warm days in winter, spring, and late fall. January 2022 was a notably cold month, with numerous dates' records falling below the historical temperature range. Daily median temperatures in the Ware River watershed (at Barre Falls Dam) were on the high end of the historical range throughout the summer and included numerous dates where temperature exceeded historical maximum daily medians. The records show a hot and dry summer at both watersheds, more severe within Ware River Watershed. Seven of the fifteen highest daily maximum temperature on record at the Barre Falls Dam weather station are from 2022 observations.

Mean monthly temperatures in the winter months (December, January, February) of 2022 ranged from -13.38 to 5.29°C across the Quabbin Reservoir and Ware River watersheds (Table 8), compared to the winter mean monthly historical range of -11.99 to 3.49°C. The mean values of daily minimums were lower compared to the period of record at all sites during a cold January 2022. However, warmer temperatures throughout February led to mean monthly maximum temperatures above historical averages at all three weather stations (above historical means by 1.26-3.76°C). Spring months (March, April, May) in 2022 exhibited a mean monthly temperature range (-4.96 to 23.98°C) higher than the historical range (-5.86 to 20.68°C). The mean values of monthly maximum records were higher by 2.71-4.27°C at Barre weather station relative to the period of record. Summer months (June, July, August) were characterized by persistent hot and dry weather, with the magnitude of impacts varying across watersheds. Within the Quabbin Reservoir watershed, climate stations mean monthly temperatures during the summer ranged from 11.6-29.8°C, with the mean values of monthly maximum temperatures above historical means by 0.08-2.63°C. Summer monthly mean temperatures at the Barre weather station in Ware River Watershed ranged from 10.47-32.06°C, with the mean value of monthly maximum temperatures between 3.63-6.31°C degrees above historical monthly means. Temperatures in the fall ranged from -2.56 to 24.09°C across the watershed weather stations. The mean value of monthly maximum temperatures in the fall were above the historical means in Ware River Watershed (2.32-2.76°C above historical means at Barre weather station). In Quabbin Reservoir Watershed, the mean value of November maximum temperatures were >2°C above historical mean values, while other fall months (September, October) were closer to the historical means.

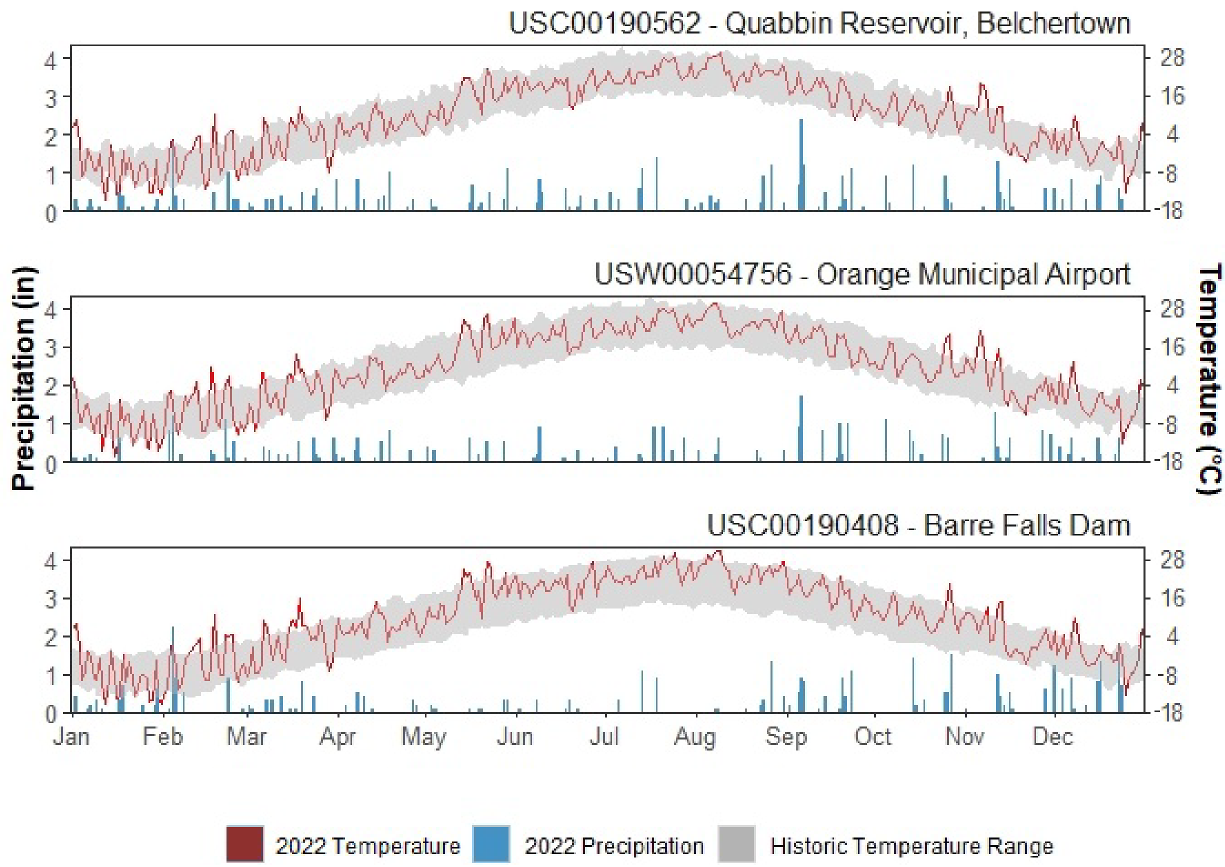

Figure 4: Climatograph of precipitation totals and daily median temperatures (in degrees Celsius) for weather stations in the Quabbin Reservoir and Ware River watersheds from January 1 through December 31, 2022. Shaded band represents historical mean daily temperature ranges (minimum to maximum temperature) for Belchertown (1990-2021), Orange (1997-2021), and Barre (1960-2021) weather stations.

Table 8: Mean values of daily minimum and maximum temperature (in degrees Celsius) summarized by month for the period of record and 2022 at each meteorological station in the Quabbin Reservoir and Ware River watersheds. Years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis. Delta (Δ) represents difference between 2022 monthly mean compared to the period of record. Variations >2°C are highlighted in red shading. Period of record (POR): 1960-2021 (Barre), 1990-2021 (Belchertown), 1997-2021 (Orange).

Weather Station	Month	Mean of Daily Min (°C)			Mean of Daily Max (°C)		
		POR	2022	Δ	POR	2022	Δ
Barre	Jan	-11.99	-13.38	-1.39	-0.59	-0.38	0.21
	Feb	-11.31	-10.16	1.15	0.79	4.55	3.76
	Mar	-5.86	-4.96	0.90	6.08	9.22	3.14
	Apr	-0.28	-0.11	0.17	12.77	15.48	2.71
	May	5.32	7.98	2.66	19.71	23.98	4.27
	Jun	10.20	10.47	0.27	24.04	27.67	3.63
	Jul	13.22	13.70	0.48	26.81	32.06	5.25
	Aug	12.11	15.12	3.01	25.75	32.06	6.31
	Sep	7.59	9.05	1.46	21.77	24.09	2.32
	Oct	1.85	3.00	1.15	15.41	17.84	2.43
	Nov	-2.44	-2.56	-0.12	8.84	11.60	2.76
	Dec	-8.26	-6.20	2.06	2.18	4.85	2.67
Belchertown	Jan	-8.80	-11.02	-2.22	0.36	0.11	-0.25
	Feb	-8.58	-8.41	0.17	1.92	4.13	2.21
	Mar	-4.11	-4.10	0.01	6.73	8.41	1.68
	Apr	1.65	1.37	-0.28	13.83	13.64	-0.19
	May	7.79	8.85	1.06	20.17	21.48	1.31
	Jun	13.05	11.93	-1.12	24.96	25.04	0.08
	Jul	16.13	15.55	-0.58	27.77	29.11	1.34
	Aug	15.23	16.77	1.54	26.94	29.57	2.63
	Sep	11.01	10.46	-0.55	22.82	22.40	-0.42
	Oct	4.96	5.14	0.18	16.03	16.86	0.83
	Nov	-0.41	0.16	0.57	9.10	11.85	2.75
	Dec	-5.14	-5.03	0.11	3.28	5.39	2.11
Orange	Jan	-10.27	-13.07	-2.80	0.41	-0.79	-1.20
	Feb	-9.34	-8.50	0.84	2.30	3.59	1.29
	Mar	-4.65	-3.79	0.86	7.05	8.49	1.44
	Apr	0.68	1.00	0.32	14.26	14.17	-0.09
	May	6.94	8.56	1.62	20.68	22.91	2.23
	Jun	12.26	11.60	-0.66	25.20	25.62	0.42
	Jul	15.28	15.26	-0.02	28.11	29.80	1.69
	Aug	14.53	16.21	1.68	27.25	29.73	2.48
	Sep	9.98	10.06	0.08	23.15	22.71	-0.44
	Oct	3.55	3.94	0.39	15.85	17.18	1.33
	Nov	-1.87	-0.66	1.21	9.44	11.73	2.29
	Dec	-6.67	-5.75	0.92	3.49	4.64	1.15

3.1.1.2 Precipitation

In 2022, total annual rainfall ranged from 38.1 (Orange Municipal Airport weather station) to 48.6 inches (Belchertown weather station) across the Quabbin Reservoir and Ware River Watersheds' weather stations (Figure 5). Annual rainfall in 2022 was below long-term median precipitation by 4.1 and 2.2 inches at Barre and Orange respectively, while annual precipitation was above the historical median at Belchertown by 3.3 inches. Monthly precipitation in Belchertown trended close to historical monthly means throughout 2022 (Table 9). Annual precipitation exceeding historical medians at Belchertown precipitation station in 2022 was in part due to rainfall in September, where monthly precipitation total (7.4 inches) was 3.3 inches higher than mean total monthly precipitation from the period of record (4.1 inches). Precipitation records from Orange Municipal Airport were also similar to monthly means, with the exception of June and August where 2022 monthly precipitation totals were below historical monthly means by 2 inches or greater. Precipitation records from Barre in 2022 included three months in a row where monthly rainfall was >2" below monthly means (April-June), with rainfall deficit extending through August. The summer drought conditions were slightly offset by above normal rainfall conditions in February and December of 2022.

Table 9: Mean total monthly precipitation (from period of record) and total monthly precipitation (for 2022) in inches from meteorological station in the Quabbin Reservoir and Ware River watersheds, summarized by month. Period of record (POR): 1951-2021 (Barre), 1947-2021 (Belchertown), 1998-2021 (Orange). Years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis. Delta (Δ) represents difference between 2022 total monthly precipitation compared to the period of record. Variations >2" are highlighted in red.

Month	Barre (in)			Belchertown (in)			Orange (in)		
	POR	2022	Δ	POR	2022	Δ	POR	2022	Δ
Jan	3.2	3.1	-0.1	3.4	2.5	-0.9	2.6	1.2	-1.4
Feb	2.7	4.7	2.0	3.0	4.7	1.7	2.7	4.4	1.7
Mar	3.3	2.7	-0.6	3.6	3.0	-0.6	3.1	3.2	0.1
Apr	3.9	1.7	-2.2	3.9	4.1	0.2	3.4	3.0	-0.4
May	3.8	1.3	-2.5	3.9	3.6	-0.3	3.3	2.5	-0.8
Jun	3.9	0.9	-3.0	4.1	3.1	-1.0	4.4	1.8	-2.6
Jul	3.9	2.3	-1.6	4.3	4.2	-0.1	3.9	3.5	-0.4
Aug	4.1	2.5	-1.6	4.5	4.0	-0.5	3.8	1.8	-2.0
Sep	3.9	5.4	1.5	4.1	7.4	3.3	4.2	5.7	1.5
Oct	4.1	4.4	0.3	4.0	3.8	-0.2	4.5	3.9	-0.6
Nov	3.7	2.9	-0.8	3.9	3.7	-0.2	3.1	4.1	1.0
Dec	3.7	7.4	3.7	3.9	4.5	0.6	3.5	3.0	-0.5

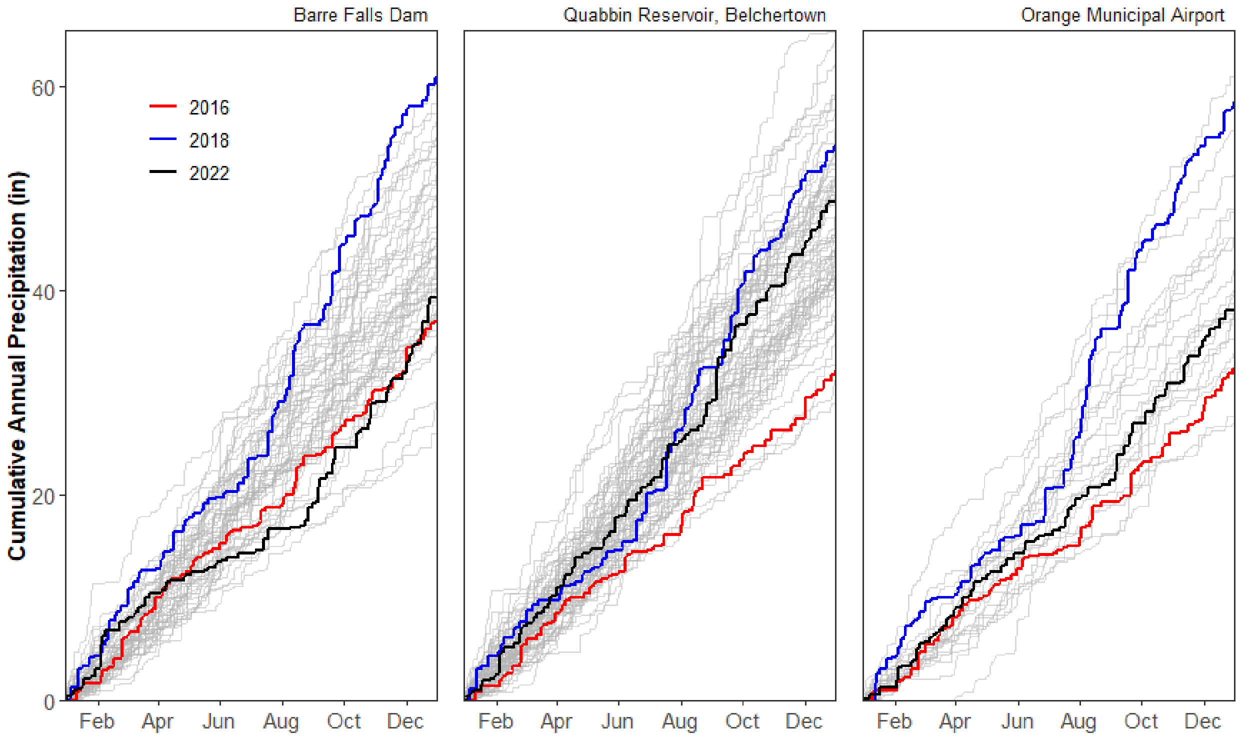

Figure 5: Annual cumulative monthly precipitation totals for Barre Falls Dam (USC00190408), Quabbin Administrative Building in Belchertown, MA (USC00190562), and Orange Municipal Airport (USW00054756) weather stations. Colored lines indicate recent years of high and low annual precipitation totals (2018, and 2016, respectively) compared to the period of record (shaded lines, see Table 3 for site-specific record ranges) and 2021 (black line) at the three weather stations. Note: years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis.

The Quabbin Reservoir-Ware River Region was under drought designations for six months in 2022, and the west region of Quabbin Reservoir Watershed for two additional months beyond that. According to the Massachusetts Drought Management Task Force, the Quabbin-Ware region entered mild drought conditions on May 1 and entered significant drought conditions on June 1. The eastern region of Quabbin Reservoir Watershed and the entirety of Ware River Watershed were designated at the “critical drought” level on July 1. By August 9, the entirety of both watersheds was under critical drought designation. This status remained in place until October 7, where regular September rain events helped lessen drought severity and resulted in a mild drought designation for the Quabbin-Ware region. Drought designation was lifted for Ware River watershed and the eastern position of the Quabbin Reservoir watershed on November 14 following fall rains. The western portion of the Quabbin Reservoir watershed remained under “mild drought” designation through the end of 2022 (MassDMTF 2023).

Results from snow monitoring in Quabbin Reservoir watershed are presented in an annual memo summarizing seasonal patterns and multi-year trends prepared by the DWSP Civil Engineering Section (DWSP 2023e). Total annual snowfall at Belchertown was 40 inches, below the 75-year historical annual mean of 51.2-in. The highest mean snow depth was 8.9 inches on Feb 1, 2022. Mean snow depth from all snow surveys was 4.9 inches (DWSP 2022b).

3.1.2 Streamflow

Daily mean streamflow records from two USGS stream gages in major tributaries to the Quabbin Reservoir (West and East Branch Swift River) correspond with seasonal drought conditions and subsequent fall and winter re-wetting in 2022 (Table 10). Periodic rainfall and rain-on-snow events generated annual peak discharge events throughout February and March at the Quabbin stream gage locations (Figure 6). Above-normal (East Branch Swift) and normal (West Branch Swift) streamflow conditions throughout the early winter and spring preceded a prolonged period of low-flow conditions below the normal range reflective of hot and dry conditions throughout the summer. The monthly mean value of daily mean flow was below historical monthly mean values from May through November 2022. The monthly minimum values of mean daily flows in August matched historical lows from the gage period of record at both gages (0.4 cfs at West Branch Swift and 0.0 cfs at East Branch Swift, respectively). Although periodic rainfall events ≥ 1 inch occurred within the Quabbin Reservoir Watershed

Table 10: Monthly mean stream discharge (calculated from daily mean discharge records, in cubic feet per second) for the period of record and 2022 from select USGS gauging stations in the Quabbin Reservoir and Ware River watersheds. Years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis. Period of record (POR): 1995-2021 (West Branch Swift), 1988-2021 (East Branch Swift), 1988-2021 (Ware River).

Month	West Branch Swift (01174565)		East Branch Swift (01174500)		Ware River (01173000)	
	POR	2022	POR	2022	POR	2022
Jan	30.49	16.90	98.98	104.07	195.94	171.65
Feb	28.46	40.54	98.84	228.92	203.03	475.57
Mar	41.45	37.23	135.69	190.19	297.99	373.16
Apr	46.04	36.42	154.43	173.73	365.52	284.13
May	25.92	19.18	94.85	79.94	208.18	99.06
Jun	19.70	5.68	61.11	26.90	128.73	41.49
Jul	13.18	1.49	40.80	7.55	75.70	23.20
Aug	9.37	0.59	35.68	0.55	63.41	7.86
Sep	10.84	3.19	33.81	25.61	64.86	38.09
Oct	17.72	4.46	58.21	34.63	112.68	70.45
Nov	22.26	11.65	76.92	76.04	164.61	97.98
Dec	30.56	30.69	104.76	160.10	215.46	284.32

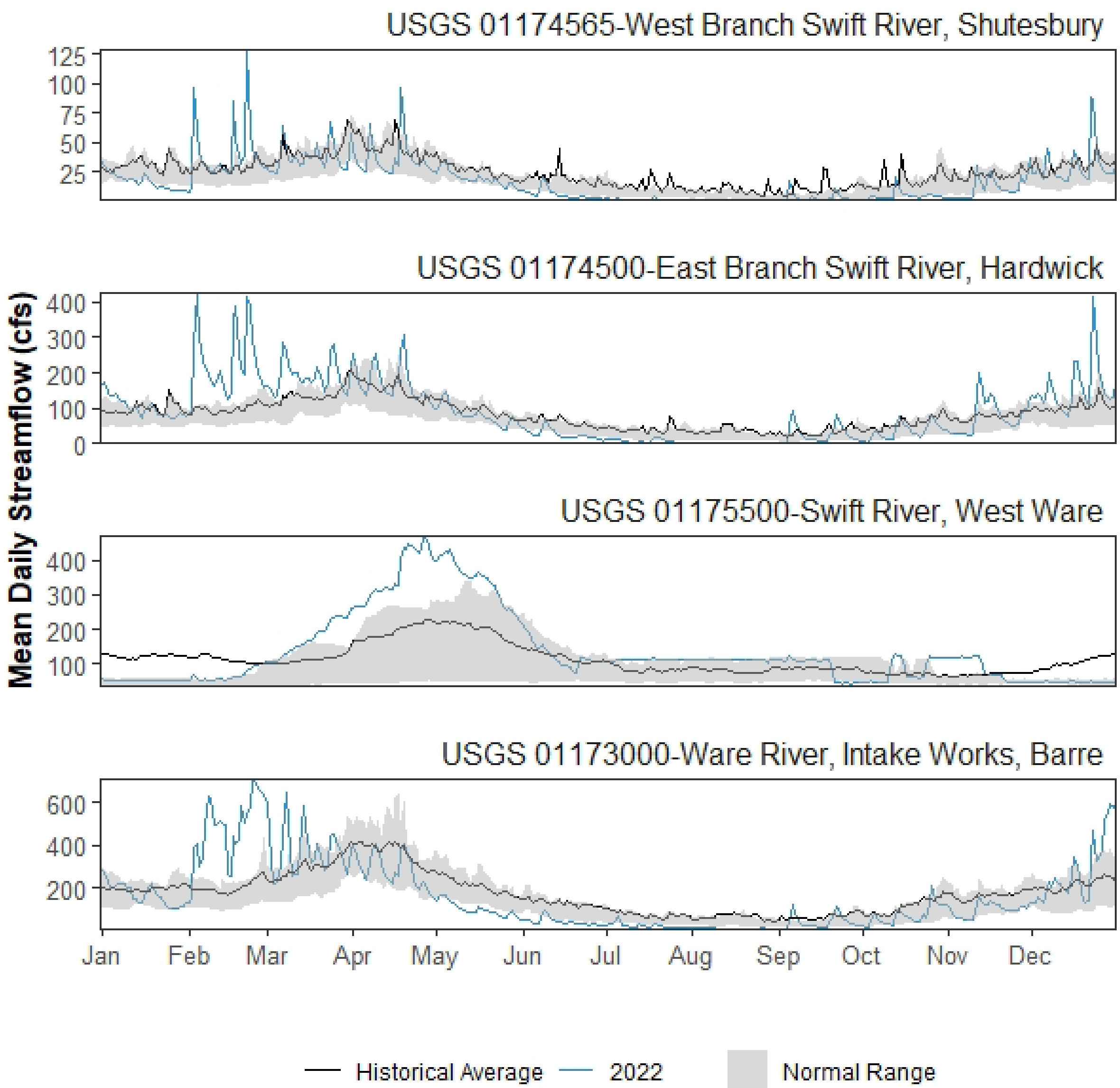

Figure 6: Hydrograph of mean daily streamflow (cfs) at four USGS stream gages in the Quabbin Reservoir and Ware River watersheds. The mean value of all mean daily flows for the period of record are represented by the solid black line. Daily mean flows in 2022 are represented by the blue line. The gray band denotes the normal (25th to 75th percentile) flow range for the period of record.

throughout September 2022, daily mean streamflow remained below historical averages until November, when late fall and early winter rains resulted in within-normal to above-normal flow events. The West Branch Swift ranged in daily mean streamflow in 2022 from a minimum of 0.39 cfs (September 2-3) to a high of 128 cfs (February 22), with an annual mean value of 17 cfs. The East Branch Swift ranged in daily mean streamflow in 2022 from a minimum of 0 cfs

(August 12-24, September 2-3) to a high of 426 cfs (February 4), with an annual mean value of 91 cfs.

Stream-discharge patterns from the Ware River (Intake Works, Barre, MA) USGS gage exhibit similar responses to prolonged drought conditions in 2022 (Figure 6). Peak streamflow was 712 cfs on February 24, with numerous high flows records throughout February and March. Overall monthly mean streamflow values were lower than historical means from late April through November (Table 10). The year's minimum daily mean streamflow of 4.91 cfs was recorded on August 15, reflective of low flow conditions through summer and fall. Streamflow conditions returned within normal range in the late fall, with December rainfall and rain-on-snow event elevating streamflow above the historical mean through the latter half of December. The annual mean of daily mean streamflow for the Ware River at Intake Works station was 162 cfs in 2022.

Downstream releases from the Quabbin Reservoir into the Swift River can be observed from the daily mean discharge records from the USGS gage in West Ware (Figure 6). Reservoir releases followed historical seasonal patterns though annual peak flows from April to May were above historical normal ranges. The maximum value for mean daily streamflow records in 2022 was 472 cfs on April 27. Flow conditions were below historical normal range periodically in the fall and throughout the winter, including a minimum daily mean streamflow of 39.2 cfs on September 27. A small number of years with very high spillover volumes (e.g.,2019, 2006, 1997) result in a winter historical streamflow mean above the normal range at this site. The annual mean of daily mean streamflow for the Swift River gage station in 2022 was 137 cfs.

Cumulative annual discharge was calculated from USGS daily mean discharge records at each of the three gage locations and reported in million gallons (MG) (Figure 7). Seasonal patterns were similar across all sites while varying in magnitude, with impacts of drought on streamflow evident from the distinct, nearly flat line of cumulative discharge from April to October at all gage locations. The West Branch Swift stream gage recorded a cumulative discharge total of 4,052 MG in 2022, a value in the lower half of annual cumulative totals from the 27-year period of record for the gage. Annual cumulative discharge in 2022 was lower than the historical mean annual discharge (5,854 MG) at the site (range 2,871 to 10,353 MG). Cumulative discharge at the East Branch Swift River gage totaled 21,564 MG in 2022, slightly higher than the mean cumulative discharge of 20,007 MG from the site's 33-year period of record (range 8,138 to 31,507 MG). The stream gage on Ware River at the Intake Works in Barre, MA recorded a cumulative total of 38,187 MG, below the historical mean (42,526 MG) based on the 35-year period of record (range 22,796 to 65,891 MG).

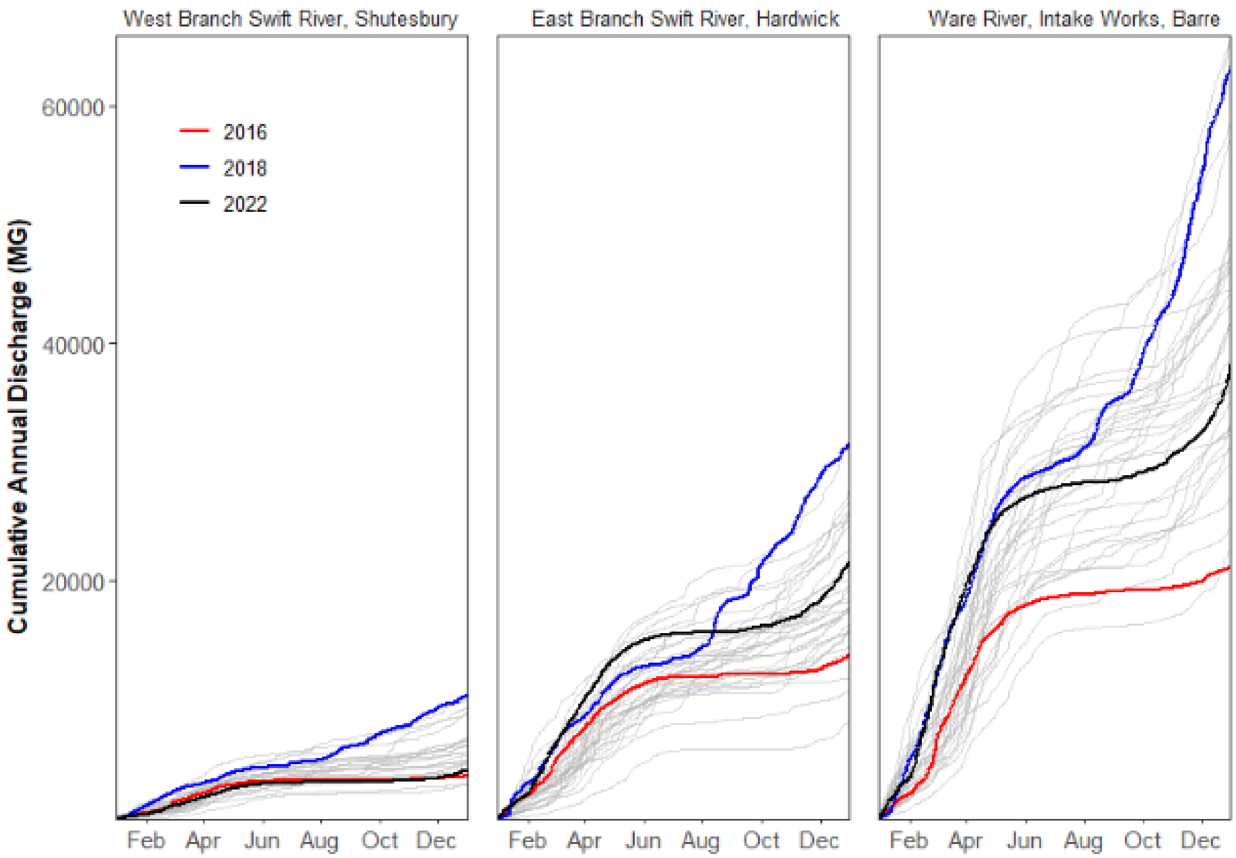

Figure 7: Cumulative annual discharge (in millions of gallons) calculated from daily mean discharge records at three USGS stream gages in the Quabbin Reservoir and Ware River watersheds. Colored lines indicate recent years of high and low cumulative annual discharge totals (2018, and 2016, respectively) compared to the period of record (shaded lines, see Table 3 for site-specific record ranges) and 2022 (black line) at three USGS stream gages. Note: years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis.

3.1.2.1 *Reservoir Elevation*

Quabbin Reservoir elevation remained within normal (25th to 75th percentile) operating range throughout select months during 2022. Elevation of the water surface of Quabbin Reservoir ranged from a minimum of 522.62 to a maximum of 530.11 ft BCB on November 30, 2022, and April 27, 2022, respectively (Figure 8).

Daily reservoir elevation was trending above seasonal normal level following excess precipitation during the latter half of 2021. Above normal elevation was maintained into the beginning of May, but rapidly fell to below normal (e.g., 25th percentile daily elevations) by early August coincident with increasing drought severity. Daily reservoir elevation exceeded the spillway watch trigger of 528 ft BCB beginning on February 12 and continuing through July 03, 2022. The reservoir was actively discharging via the spillway from during this time. Reservoir elevation began to rebound in mid-December, ending 2022 on the lower end of normal elevation ranges for the season. Annual dynamics of reservoir elevation followed that of previous years, driven predominantly by seasonal changes in precipitation/snowmelt and subsequent riverine inputs (DWSP, 2023e).

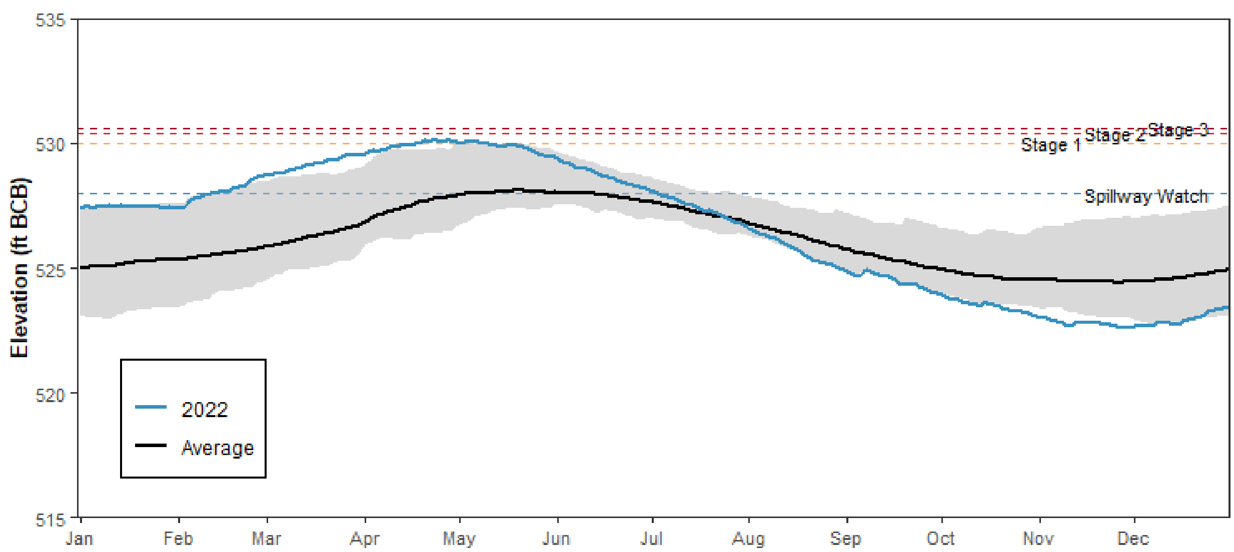

Figure 8: Daily elevation of the Quabbin Reservoir from January 1 through December 31, 2022, relative to spillway watch triggers (DWSP, 2019d) established by DWSP Civil Engineering Section. Gray band represent daily normals (defined as 25th to 75th percentiles) and the black line is the mean daily elevation for the period of record (1980 through 2022).

3.2 Tributary Monitoring

3.2.1 Water Temperature and Dissolved Oxygen

3.2.1.1 Water Temperature

Water temperature in Quabbin Reservoir watershed Core tributaries ranged from 0 to 23.9˚C in 2022 (Table 11). Water temperature exhibited a typical distinct seasonality during 2022, falling within established seasonal ranges for each site (aside from 215G). Seasonal median temperatures in 2022 were generally comparable to that of the period of record for each site, although temperature departures were most pronounced during the late spring to early fall (coincident with period of most intense drought conditions). Despite the prolonged severe to extreme drought coupled with periods of excessive heat that impacted the region during the summer of 2022, median water temperatures observed in 2022 were cooler than that of the period of record for sites 211, 216, and Boat Cove Brook in the Quabbin Reservoir watershed. Gates Brook exhibited minimal divergence from seasonal normal values during 2022. Little variation or decrease in stream temperature with drought has previously been attributed to catchment-specific characteristics such as canopy cover, catchment scale, upstream reservoir inputs, and groundwater contributions to baseflow (Mosley et al., 2012; Sprague, 2005). The limited coverage for Boat Cove Brook during the summer of 2022 likely skewed seasonal temperature statistics toward the cooler summer months. In contrast, the results for stream temperature in tributaries in the Ware River watershed during this time period demonstrated a ubiquitous increase in median summer temperatures relative to the period of record. The latter may in part be attributed to the spatiotemporal variability of the 2022 drought conditions.

MassDEP designates cold water fish habitats as rivers and streams in which mean and maximum daily temperatures over a seven-day period generally do not exceed 20˚C (314 CMR 4.06). Warm water fish habitats generally exceed 20˚C but may not surpass 28.3˚C. Water temperature data generated by DWSP represent a discrete collection time, thus these data cannot be compared directly to cold water fish habitat criteria. Rather, comparisons to these thresholds may indicate the potential for a location to become impaired. Sites 211, 212, and 216 in the Quabbin Reservoir watershed represent rivers that have been identified as suitable habitat for cold water fish by MassDEP. Instantaneous water temperatures exceeded the 20˚C threshold on four dates at site 216 in 2022 (20.1 to 23.9˚C). Sites 211 and 212 remained below 20˚C throughout 2022, as did GATE and BC. No sites in the Quabbin Reservoir watershed exceeded the temperature criteria for warm water fish habitat (28.3˚C) in 2022.

Water temperature in Ware River watershed Core tributaries ranged from 0 to 27˚C in 2022 (Table 12). Water temperature followed a distinct seasonality in 2022, largely remaining within historical ranges but exceeding seasonal normals on select dates between May and September.

Seasonal median temperatures in 2022 were comparable to that of the period of record for Ware River tributary sites, although mean and median temperatures in the summer were greater than that of the period of record for all core sites. Mean summer water temperatures at individual core sites were 0.9 to 2.5˚C warmer during the summer of 2022 relative to the period of record. Historical seasonal maximum temperatures were exceeded by one site (103A) on a single date in 2022. The maximum annual temperature at all core sites (excluding 121) occurred on August 09, 2022, coincident with below normal observed mean daily streamflow for the Ware River at intake works (USGS ID 1173000) and following two dates of the greatest maximum daily temperature measured in 2022 in Barre, MA (GHCND: USC00190408).

Sites 102, 107A, and 108 in the Ware River watershed are rivers that have been identified as suitable habitat for cold water fish by MassDEP. Instantaneous water temperatures exceeded the 20˚C threshold on five dates at site 107A and on four dates at site 108 in 2022 (20.3 to 26.1˚C). Site 102 remained below 20˚C throughout 2022. No sites in the Ware River watershed exceeded the temperature criteria for warm water fish habitat (28.3˚C) in 2022 (Figure 9).

Table 11: Descriptive statistics (minimum, median, mean, and maximum) for water temperature measured in Core tributary sites in the Quabbin Reservoir watershed during 2022.

Location	Season	Water Temperature (°C)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Fall	6	244	1.1	0.0	9.2	9.0	9.4	9.0	16.6	19.0
	Spring	7	246	0.1	-0.1	7.0	6.0	5.6	5.8	13.3	18.2
	Summer	7	249	13.9	9.0	16.2	16.2	16.4	16.2	19.9	21.0
	Winter	6	249	0.0	-0.4	0.1	0.3	0.8	0.8	3.1	5.3
212	Fall	6	229	1.1	0.0	9.7	9.6	10.0	9.5	17.9	20.0
	Spring	7	234	0.0	-0.4	7.6	6.1	5.9	6.3	13.8	19.7
	Summer	7	238	14.5	10.0	17.6	17.1	17.7	17.2	19.9	22.6
	Winter	6	230	0.0	-0.4	0.0	0.0	0.7	0.7	3.3	6.0
213	Fall	6	234	2.0	1.0	10.0	10.0	10.8	10.2	19.7	21.3
	Spring	7	243	0.1	-0.4	10.0	7.8	7.9	7.7	18.0	23.1
	Summer	7	243	17.8	5.3	21.0	20.0	20.8	19.7	22.7	24.8
	Winter	6	241	0.1	-0.2	0.4	0.2	0.6	0.6	2.2	9.0
215G	Fall	6	19	3.4	1.5	11.0	13.5	12.0	12.2	20.4	22.0
	Spring	7	18	0.3	0.9	11.4	12.3	9.1	11.0	19.5	19.9
	Summer	6	19	18.8	14.2	21.9	21.1	21.6	20.9	23.2	25.2
	Winter	6	15	0.0	0.5	0.8	1.5	1.2	1.7	3.8	3.9
216	Fall	6	240	2.4	0.3	10.2	10.5	11.2	10.5	20.1	21.7
	Spring	7	245	0.0	-0.5	10.7	8.3	8.3	8.0	17.4	22.5
	Summer	7	249	16.5	8.8	19.5	20.0	20.7	19.7	23.9	25.2
	Winter	6	246	0.0	-0.5	0.1	0.1	0.9	0.7	4.0	6.5
BC	Fall	6	157	2.1	0.1	10.9	10.1	10.9	10.6	17.9	20.9
	Spring	7	182	0.2	-0.1	9.8	8.1	7.9	8.1	14.3	20.1
	Summer	4	152	14.1	11.1	16.0	18.3	16.5	18.2	19.8	23.6
	Winter	6	176	0.0	-0.4	0.3	1.0	1.5	1.4	6.2	10.0
GATE	Fall	6	194	4.0	0.3	10.3	10.6	11.0	10.5	18.2	19.2
	Spring	7	176	0.3	0.0	6.7	6.6	5.4	6.2	11.4	15.1
	Summer	5	180	12.9	9.8	16.1	16.0	15.9	15.9	19.3	20.1
	Winter	6	175	0.2	-0.4	1.0	1.3	2.1	1.88	6.4	7.0

Table 12: Descriptive statistics (minimum, median, mean, and maximum) for water temperature measured in Core tributary sites in the Ware River Watershed during 2022.

Location	Season	Water Temperature (°C)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Fall	7	214	3.2	0.8	10.5	11.0	10.8	11.1	18.7	23.9
	Spring	7	208	1.7	-0.5	9.3	9.0	11.1	8.5	21.3	21.1
	Summer	6	215	19.6	11.5	22.1	21.0	22.0	21.0	24.4	27.0
	Winter	6	204	0.0	-0.5	0.2	0.1	0.3	0.6	0.6	8.0
102	Fall	7	112	2.7	1.0	9.4	8.0	9.2	8.5	15.8	19.0
	Spring	7	109	3.6	1.0	7.6	7.0	9.5	7.0	17.3	16.0
	Summer	6	114	16.1	10.0	16.9	15.0	17.2	14.9	19.1	20.2
	Winter	6	109	0.2	0.0	1.6	1.0	1.6	1.4	2.7	8.0
103A	Fall	7	108	2.7	0.5	9.5	10.1	9.9	9.9	17.2	21.7
	Spring	7	95	1.1	-0.4	8.8	9.0	9.9	8.5	19.6	19.0
	Summer	6	109	17.7	11.5	21.7	19.6	21.7	19.4	27.0	24.5
	Winter	6	80	0.0	-0.4	0.1	0.2	0.1	0.7	0.3	7.0
107A	Fall	7	108	2.3	0.4	10.1	10.4	9.9	10.2	17.0	23.0
	Spring	7	101	1.1	-0.1	8.1	8.9	10.3	8.5	22.1	20.4
	Summer	6	108	18.8	11.7	20.9	20.7	21.1	20.2	24.9	25.6
	Winter	6	89	0.0	-0.5	0.0	0.1	0.0	0.6	0.1	7.0
108	Fall	7	208	3.0	0.0	9.9	10.0	10.3	10.3	18.1	23.6
	Spring	7	206	2.9	-0.5	8.3	8.3	11.0	8.2	22.5	21.4
	Summer	6	209	20.9	12.2	22.5	20.2	22.8	20.3	26.1	26.3
	Winter	6	200	0.0	-0.5	0.2	0.0	0.2	0.5	0.5	7.3
121	Fall	7	133	4.0	1.0	10.2	10.0	10.7	10.4	18.7	21.0
	Spring	7	122	3.0	0.0	8.6	10.0	11.9	9.2	24.1	22.2
	Summer	6	132	20.0	12.0	23.0	20.2	22.7	20.2	23.9	28.0
	Winter	6	123	0.4	0.0	0.50	0.6	0.8	1.0	1.4	8.0

3.2.1.2 Dissolved Oxygen

Dissolved oxygen concentrations in Quabbin Reservoir watershed Core tributaries ranged from 4.2 to 17.3 mg/L in 2022 (Table 13). Dissolved oxygen concentrations demonstrated a typical seasonality during 2022, relatively depleted during warmer months and elevated in winter and fall. Concentrations of dissolved oxygen were inversely related to water temperature and fell within established ranges for each site, aside from 215G for which continuous long-term records are limited. Dissolved oxygen measured during warmer months and periods of extended low flow (e.g., June through August, 2022), trended lower than historical normal ranges for the same intra-annual period. Seasonal median dissolved oxygen concentrations in 2022 were generally comparable to that of the period of record for each site, aside from summer results.

In addition to temperature, dissolved oxygen concentrations of Class A inland waters are criteria used to determine suitability of water resources for aquatic life habitat. MassDEP designates cold water fish habitats as rivers and streams in which dissolved oxygen remains above 6 mg/L and warm water fish habitats as those with dissolved oxygen concentrations greater than 5 mg/L (314

CMR 4.06). Dissolved oxygen fell below 6 mg/L on three dates at site 216, which is identified as a cold water fish habitat. Dissolved oxygen concentrations remained above 6 mg/L in other locations in the Quabbin Reservoir watershed identified as cold water fish habitats (e.g., 211 and 212) for the entirety of 2022. Dissolved oxygen concentrations measured at GATE also remained above 6 mg/L for the entirety of 2022.

A period of relatively low dissolved oxygen (4.2 to 5.4 mg/L) observed at site 213 occurred from July 05 to August 30, 2022. Dissolved oxygen concentrations at 215G fell below 5 mg/L on one date in 2022 (August 30). These results were likely attributable to extreme low flows coupled with warm water temperatures. The minimum streamflow observed at the East Branch Swift River in 2022 occurred from August 13 to August 24, 2022, during which time the gage recorded no measurable flow. Low streamflow conditions impacted sites across the watershed throughout the months of July and August. Greater minimum water temperatures during the summer months at 213 combined with extended low flow conditions (and likely subsequent increased proportion of streamflow derived from groundwater) throughout July and August 2022 may have also contributed to the observed low dissolved oxygen concentrations, as it is atypical for 213 to remain below threshold concentrations across multiple consecutive sample dates.

Dissolved oxygen concentrations in Ware River watershed Core tributaries ranged from 3.7 to 17.3 mg/L in 2022 (Table 14). Dissolved oxygen concentrations were relatively depleted during warmer months and elevated in winter and fall, inversely related to water temperature. Like the response observed in core tributaries in the Quabbin Reservoir watershed, seasonal median dissolved oxygen concentrations in 2022 were comparable to that of the period of record for most sites, aside from summer measurements. The median dissolved oxygen concentration during the summer at 108 was 2.2 mg/L lower in 2022 relative to the period of record. This site also exhibited an increase in median spring temperature relative to the period of record.

Dissolved oxygen concentrations fell below 6 mg/L at sites 107A and 108 on one and eight dates, respectively, in 2022. Dissolved oxygen concentrations remained above 6 mg/L at site 102 for the entirety of 2022. Concentrations of dissolved oxygen fell below 5 mg/L at sites 103A and 121 on August 09, 2022. This date coincides with the minimum annual dissolved oxygen concentration observed at other Core sites in the Ware River watershed. The ubiquity of these results further suggests extreme low flows coupled with warm water temperatures may have impacted oxygen content of surface waters across the watershed.

Table 13: Descriptive statistics (minimum, median, mean, and maximum) for dissolved oxygen measured in Core tributary sites in the Quabbin Reservoir Watershed during 2022.

Location	Season	Dissolved Oxygen (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Fall	7	222	6.7	5.8	10.0	10.7	10.2	10.9	15.7	16.2
	Spring	7	216	8.8	6.5	12.1	12.2	12.4	12.3	15.2	17.6
	Summer	7	227	6.1	4.7	6.6	9.0	6.9	9.0	8.2	12.2
	Winter	6	208	13.5	10.2	14.2	13.7	14.3	13.8	15.4	17.7
212	Fall	7	205	7.7	4.9	10.3	10.7	10.6	10.9	14.5	16.3
	Spring	7	199	9.9	6.3	12.0	12.2	12.6	12.2	15.2	16.8
	Summer	7	212	7	4.5	8.3	8.9	8.3	8.8	9.7	11.8
	Winter	6	195	13.4	10.7	14.2	13.8	14.1	14.0	14.9	17.9
213	Fall	7	213	4.9	2.5	7.0	7.5	7.3	7.9	10.9	15.9
	Spring	7	213	6.5	3.6	8.9	9.9	9.9	9.9	12.9	17.9
	Summer	7	219	4.2	1.6	5.3	5.4	5.2	5.5	6.6	10.0
	Winter	6	209	10	7.2	11.3	11.6	11.1	11.8	11.8	17.1
215G	Fall	7	19	6.5	6.3	8.7	9.0	8.6	9.3	12.2	14.2
	Spring	7	17	7.1	7.2	9.6	10.0	11.0	10.6	15.4	14.2
	Summer	6	19	4.6	5.4	6.0	6.9	5.7	7.0	6.5	9.3
	Winter	6	15	11.3	11.7	12.3	13.6	12.3	13.5	13.5	14.9
216	Fall	7	218	6.4	5.7	10.2	10.6	10.0	10.9	13.8	16.7
	Spring	7	215	8.3	5.8	11.2	11.8	11.8	11.8	15.1	17.2
	Summer	7	225	4.9	4.7	6.8	8.6	6.9	8.6	9.7	11.6
	Winter	6	213	12.9	9.8	14.0	13.9	14.2	14.0	15.2	17.7
BC	Fall	7	137	5.5	5.7	8.7	10.4	8.1	10.6	12.5	16.1
	Spring	7	175	8.2	6.0	10.7	11.5	11.3	11.6	15.0	17.9
	Summer	4	146	6.6	4.6	7.2	8.5	7.1	8.5	7.5	11.5
	Winter	6	161	12.2	10.9	13.6	13.5	13.5	13.7	14.5	17.2
GATE	Fall	7	171	8.6	6.1	11.2	11.0	11.3	11.1	14.9	17.2
	Spring	7	165	11.1	6.9	12.8	12.4	13.1	12.6	15.5	17.4
	Summer	5	179	7.5	5.1	8.9	9.5	9.0	9.5	10.1	14.4
	Winter	6	154	13.1	10.5	15.1	14.0	15.1	14.2	17.3	17.9

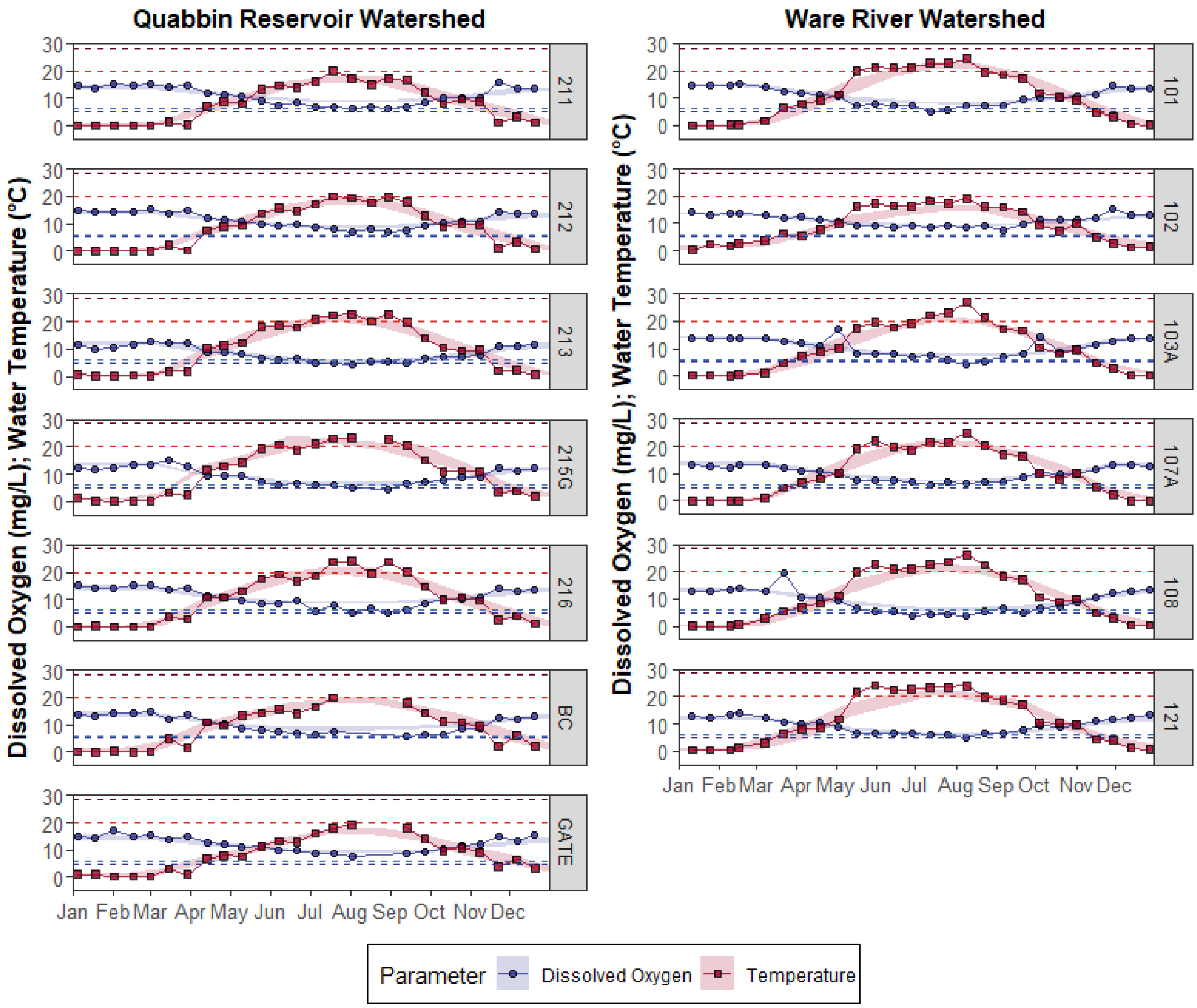

Figure 9: Time series of water temperature and dissolved oxygen measured in core tributary sites in 2022. The shaded bands represent seasonal interquartile ranges (25th to 75th percentile) for the period of record at each location. The dashed horizontal lines correspond to the lower recommended dissolved oxygen concentration for CFR (6.0 mg/L; light blue) and WFR (5.0 mg/L; dark blue), and the upper temperature limits for CFR (20˚C; red) and WFR (28.3˚C; burgundy) waters. Note: the period of record may be variable across sites, thus impacting seasonal statistics (Appendix C).

Table 14: Descriptive statistics (minimum, median, mean, and maximum) for dissolved oxygen measured in Core tributary sites in the Ware River Watershed during 2022.

Location	Season	Dissolved Oxygen (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Fall	7	25	7.3	7.7	10.4	10.9	10.6	11.0	14.4	14.4
	Spring	7	28	7.4	8.2	11.5	11.3	10.9	11.7	14.3	16.3
	Summer	6	24	5.1	6.9	7.3	8.6	6.7	8.7	7.6	10.9
	Winter	6	26	13.6	11.9	14.5	14.6	14.4	14.7	15.0	16.1
102	Fall	7	103	7.6	8.4	11.3	11.0	11.2	11.0	15.4	13.5
	Spring	7	103	9.1	6.2	11.3	11.6	11.2	11.6	13.2	15.9
	Summer	6	106	8.5	7.7	8.8	9.3	8.8	9.3	9.4	11.0
	Winter	6	97	13.2	9.1	13.4	13.1	13.5	13.2	14	16.6
103A	Fall	7	105	6.9	4.1	10.1	10	10.4	10.3	14.2	17.0
	Spring	7	93	8.0	6.6	11.9	10.7	11.8	11.2	17.3	16.5
	Summer	6	109	4.2	4.2	6.5	7.6	6.3	7.5	8.0	10.0
	Winter	6	76	13.7	11.2	13.8	14.1	13.8	14.1	13.9	17.5
107A	Fall	7	105	7.2	6.5	10	10.1	10.1	10.6	13	17.4
	Spring	7	98	7.6	6.7	10.9	10.6	10.4	11.2	13.3	17.7
	Summer	6	107	5.8	4.9	7.1	7.7	6.9	7.7	7.7	10.1
	Winter	6	82	12.2	11.3	13	13.7	12.9	13.8	13.5	17.7
108	Fall	7	196	5.2	4.1	6.9	8.7	8.2	9.0	12.2	15.5
	Spring	6	191	5.5	4.6	10.0	10.6	9.3	10.7	13.0	17.2
	Summer	6	202	3.7	3.5	4.3	6.5	4.5	6.5	5.4	9.3
	Winter	6	180	12.7	4.9	13.1	13	13.1	13.1	13.7	17.7
121	Fall	7	123	6.7	6.1	9.3	8.8	9.2	8.9	11.6	14.3
	Spring	7	112	6.5	6.8	10.2	9.7	9.4	10	12.4	13.6
	Summer	6	125	4.8	4.1	6.3	6.6	6.1	6.7	6.5	10.1
	Winter	6	111	12.5	9.4	13.0	12.1	13.1	12.1	14.0	15.2

3.2.2 Specific Conductance, Sodium, and Chloride

3.2.2.1 Specific Conductance

Specific conductance ranged from 22 to 169 µS/cm in Quabbin Reservoir watershed Core monitoring tributaries and from 73 to 433 µS/cm in Core monitoring tributaries in the Ware River watershed during 2022. Chronic (904 µS/cm) and acute (3,193 µS/cm) thresholds for conductivity established by MassDEP were not exceeded at any DWSP monitoring sites in the Quabbin Reservoir or Ware River watersheds during 2022.

Specific conductance was generally elevated during low flow conditions and declined with increasing streamflow. The extended period of drought and subsequent below normal stream flow during the summer and into the fall of 2022 resulted in a prolonged interval of elevated specific conductance, relative to typical seasonal normals. Elevated specific conductance during summer months in surface waters in the northeast USA has been previously attributed to legacy contributions from deicing salts via groundwater discharge to baseflow (Kelly et al., 2008). Intra-annual patterns of elevated specific conductance have previously been most pronounced in Boat Cove Brook in the Quabbin Reservoir watershed and tributaries in the Ware River watershed – a pattern potentially driven by spatial variability in specific conductance of groundwater. During 2022 however, streamflow ceased at Boat Cove Brook beginning after July 19, and not returning until the latter half of September 2022. Specific conductance decreased with increasing drought severity at site 212, suggesting heterogeneity of upstream sources of specific conductance for the Hop Brook watershed. Deviations from historical seasonal specific conductance ranges were most pronounced in tributaries in the Ware River watershed, reflective of spatial gradients in land use/cover across watersheds and increased drought severity in the Ware River watershed relative to the Quabbin Reservoir watershed.

The median specific conductance for the period of record for each Core monitoring site was exceeded during most seasons, at each site, in 2022 (Table 15, Table 16, Figure 10). A lack of dilution from recent precipitation events during the latter half of 2022 likely served to further intensify this pattern. Annual median specific conductance has been on an upward trajectory since the onset of routine monitoring at select sites in the Quabbin Reservoir watershed, and the majority of Core sites in the Ware River watershed, a trend further exacerbated by the impacts of the 2022 drought on in stream specific conductance.

In addition to elevated annual median specific conductance in Core tributaries relative to prior years, some locations continue to exhibit an increasing pattern in annual specific conductance (e.g., 212, 213, 216, and BC). In contrast, other locations continued to exhibit no significant change (e.g., 211 in the Quabbin Reservoir watershed), or have demonstrated a notable decrease annual median specific conductance since the onset of monitoring (Gates Brook in the Quabbin Reservoir watershed). In the Ware River watershed, annual median specific conductance has increased at all Core sites that have maintained a consistent monitoring record (e.g., 101, 103A, 107A, and 108), albeit to different degrees of severity (slope).

Table 15: Descriptive statistics (minimum, median, mean, and maximum) for specific conductance measured in Core tributary sites in the Quabbin Reservoir watershed in 2022 and during the period of record.

Location	Season	Specific Conductance (µS/cm)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	6	249	43	18	48	43	48	46	54	194
	Spring	7	246	43	28	47	45	49	47	56	130
	Summer	7	249	54	25	88	57	104	60	157	153
	Fall	6	244	56	27	64	50	68	56	96	152
212	Winter	6	230	92	11	121	91	113	95	126	212
	Spring	7	234	102	35	106	92	108	95	115	190
	Summer	7	238	87	52	120	100	113	101	139	170
	Fall	6	229	147	48	160	99	159	102	168	180
213	Winter	6	241	78	42	95	78	96	78	113	136
	Spring	7	243	88	33	100	81	98	83	108	141
	Summer	7	243	126	42	145	95	143	95	169	167
	Fall	6	234	103	40	121	85	120	87	142	166
215G	Winter	6	15	67	72	80	90	80	89	94	120
	Spring	7	18	66	65	77	84	76	84	89	115
	Summer	6	19	74	52	81	73	83	72	93	95
	Fall	6	19	86	63	105	84	102	82	114	98
216	Winter	6	246	68	6	81	70	80	73	92	190
	Spring	7	245	70	40	74	67	76	69	87	115
	Summer	7	249	80	38	85	72	86	73	94	144
	Fall	6	240	84	43	90	70	90	73	94	133
BC	Winter	6	176	63	37	76	64	77	66	95	137
	Spring	7	182	64	30	68	60	75	61	101	95
	Summer	4	152	109	40	117	88	119	89	132	142
	Fall	6	157	95	30	117	90	116	89	131	141
GATE	Winter	6	175	23	17	25	26	25	26	28	49
	Spring	7	176	22	18	23	23	23	24	26	30
	Summer	5	180	28	17	31	25	30	26	31	58
	Fall	6	194	28	15	34	28	33	28	37	42

Table 16: Descriptive statistics (minimum, median, mean, and maximum) for specific conductance measured in Core tributary monitoring sites in the Ware River watershed in 2022 and during the period of record.

Location	Season	Specific Conductance (µS/cm)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	6	198	82	43	112	85	107	85	119	142
	Spring	7	203	90	43	109	77	105	78	118	126
	Summer	6	208	118	42	123	86	123	84	128	137
	Fall	7	206	101	40	118	82	116	83	125	140
102	Winter	6	109	82	58	93.8	100	96	105	112	270
	Spring	7	109	80	50	101	95	99	103	118	200
	Summer	6	114	121	55	127	111	126	121	129	200
	Fall	7	112	97	55	119	103	121	111	163	200
103A	Winter	6	80	84	54	94.5	76	93	77	101	109
	Spring	7	95	82	50	89.4	70	88	75	96	126
	Summer	6	108	89	38	99.0	69	101	73	116	163
	Fall	7	104	81	52	87.7	68	90	74	107	141
107A	Winter	6	89.0	73	57	92.4	87	90	88	110	133
	Spring	7	101	77	47	83.6	76	85	79	97	129
	Summer	6	108	98	46	111	82	110	82	118	142
	Fall	7	108	93	50	119	81	115	91	137	233
108	Winter	6	200	92	40	105	79	109	81	130	209
	Spring	7	206	94	43	110	70	113	74.8	139	250
	Summer	6	209	141	42	146	78	145	81.0	149	151
	Fall	7	208	127	38	146	80	144	82.6	157	139
121	Winter	6	123	300	108	335	210	336	217	377	401
	Spring	7	122	250	92	340	185	328	201	400	369
	Summer	6	132	365	78	408	200	404	212	433	381
	Fall	7	133	321	90	388	200	368	214	392	400

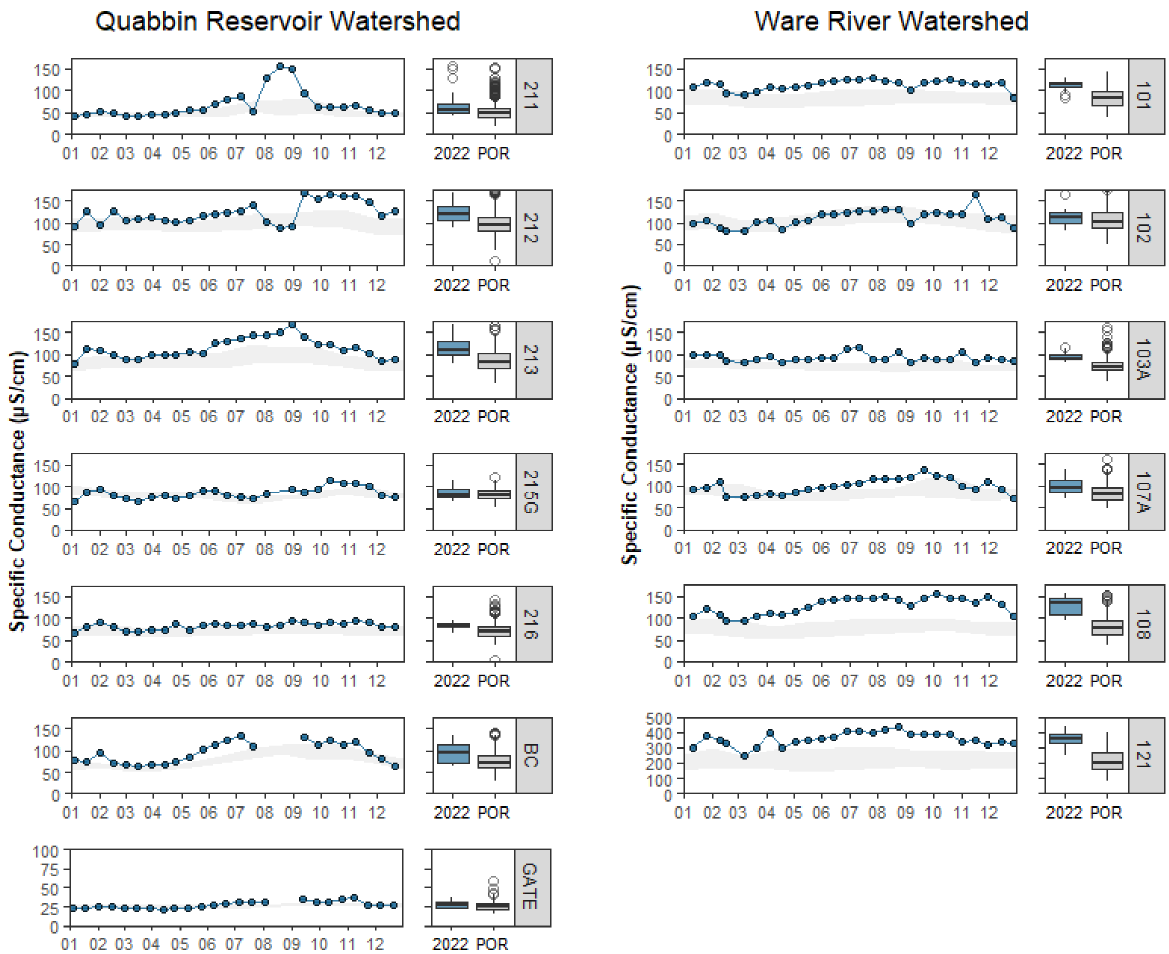

Figure 10: Time series and boxplots of specific conductance measured in core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel. Note: the period of record may be variable across sites, thus impacting long-term statistics (Appendix C).

3.2.2.2 Sodium and Chloride

Routine monitoring for sodium (Na) and chloride (Cl) began in DWSP Core monitoring sites in Quabbin Reservoir watershed in September 2018 and Ware River watershed in January 2019. Concentrations of Na and Cl observed in Core monitoring tributaries in the Ware River watershed ranged from 8.48 to 55.1 mg/L and from 12.4 to 102 mg/L, respectively, in 2022. Concentrations of these solutes in Core tributaries in the Quabbin Reservoir watershed were notably lower (1.18 to 20.9 mg/L for Na and 1.17 to 35.3 mg/L for Cl). The spatial contrast in Cl concentrations in tributaries across the two watersheds generally mirrors that of specific conductance. Thus, similar processes may contribute to the dynamics and transport of Na, Cl, and specific conductance in tributaries in the Quabbin Reservoir and Ware River watersheds. The spatial heterogeneity in concentrations of Na and Cl observed in 2022 was consistent with prior monitoring. This likely reflects differences in land cover and watershed characteristics, such as impervious surface cover, that may contribute to variable inputs of Na and Cl to individual tributaries across the two watersheds.

The secondary MCL for Cl in drinking water (250 mg/L) established by the US EPA was not exceeded in any Core tributary samples collected in 2022 from the Quabbin Reservoir or Ware River watersheds. Concentrations of Na in samples collected at 121 in the Ware River watershed exceeded the MassDEP Office of Research and Standards (ORS) guidelines for Na in drinking water for the entirety of 2022 (n = 26 samples > 20 mg/L Na). Prior to 2021, Mill Brook was sampled at DWSP Core site 121B, located upstream of 121. Concentrations of Na at 121B were also regularly above the MassDEP ORS guidelines. Contributions of road-salt laden runoff originating in the upstream reaches of the Mill Brook (e.g., potentially sourced from several high-density residential housing developments, and runoff from Route 122 and 56 in Rutland, MA) may drive the dynamics observed in downstream reaches. The remaining Core sites in the Ware River watershed exhibit less pronounced impacts from roadway deicing and development (ranges of Na and Cl were 8.48 to 23.3 mg/L and 12.4 to 37.2 mg/L in 2022, respectively), relative to Mill Brook (Site 121).

Spatial and temporal patterns in specific conductance and associated concentrations of Na and Cl observed in 2022 generally presented as repeated patterns of concentration during low flow and dilution during episodic high flow and following spring snowmelt. Contributions from groundwater during an extended period of below-normal streamflow observed during the late spring into fall of 2022 likely resulted in elevated stream Cl concentrations during this time (Figure 11). Gradients in specific conductance between monitoring sites were associated with differences in land cover, proximity to major paved surfaces (e.g., roads and parking lots), and geogenic variability. Median annual concentrations of Na, Cl, and specific conductance were generally greater in tributaries within the Ware River watershed, relative to Core monitoring sites in the Quabbin Reservoir watershed in 2022. The latter may be reflective of the high ratio of protected and forested lands, relative to developed lands, in the Quabbin Reservoir watershed, with comparatively more developed areas in Ware River watershed. Likewise, spatial variability of annual trends in specific conductance was generally reflective of differences in watershed characteristics (e.g., proximity to major transportation corridors, impervious surface cover, population, etc.) for a given tributary. The approximate 1:1 molar ratios of Na to Cl and linear relationship between Cl concentrations and specific conductance in surface waters suggests that increasing concentrations of Cl may be driving changes in annual median specific conductance for the majority of Core monitoring tributaries (Appendix C, Figure C39).

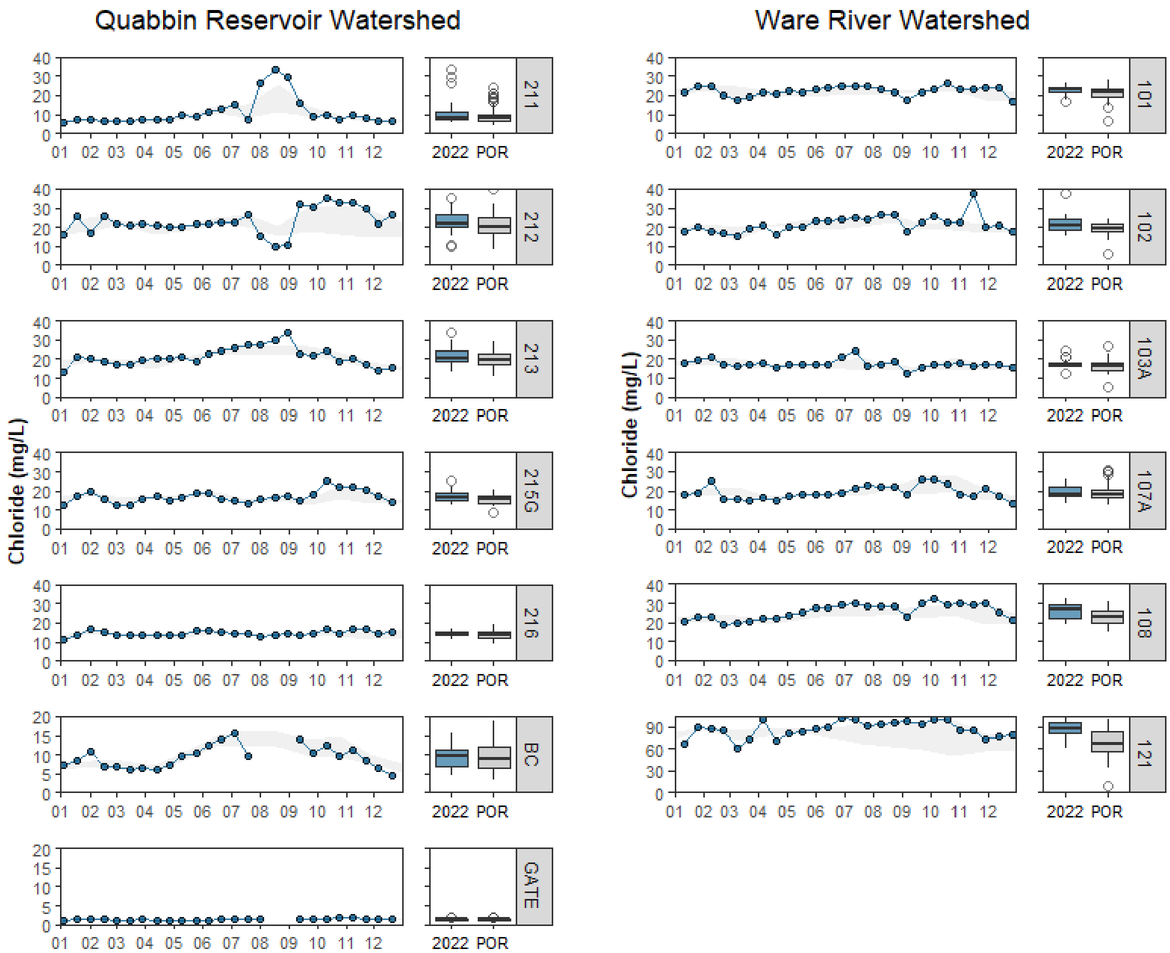

Figure 11. Time series and boxplots of chloride measured in core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel. Note: the period of record may be variable across sites, thus impacting long-term statistics (Appendix C).

3.2.3 Turbidity

Turbidity in Core tributaries in Quabbin Reservoir and Ware River Watersheds was within historical seasonal ranges for most samples collected in 2022 (Figure 12). Turbidity ranged from 0.13 to 5.1 NTU in Quabbin Reservoir Core tributaries and from 0.39 to 17.0 NTU in Ware River Watershed Core tributaries (Table 17, Table 18). Turbidity in Core sites remained below the five NTU SWTR requirement in all but six samples collected in 2022. Turbidity levels above one NTU were associated with Core tributaries in the Ware River Watershed during summer and early fall of 2022, or high flow events in either watershed.

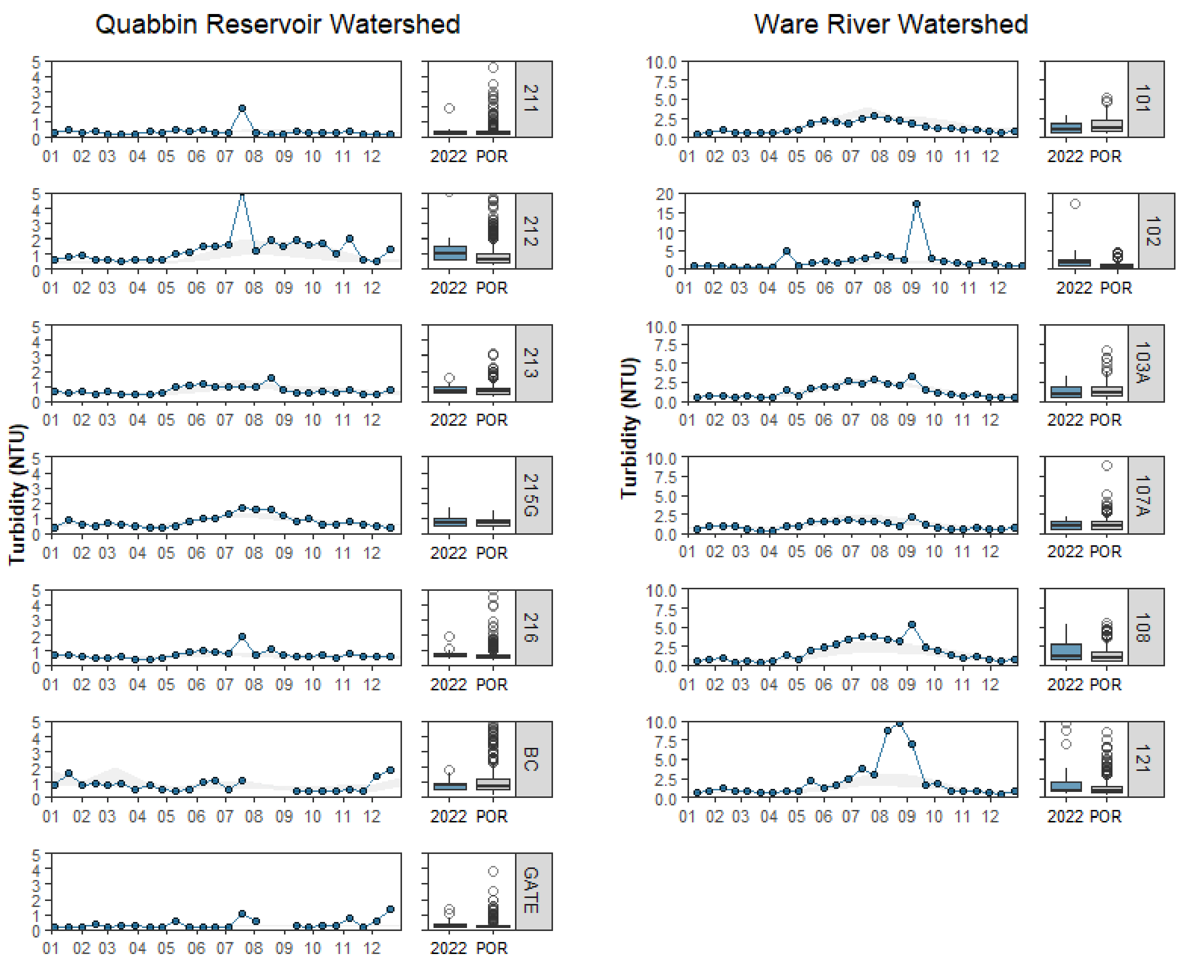

Figure 12: Time series and boxplots of turbidity measured in Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel. Note: the period of record may be variable across sites, thus impacting long-term statistics (Appendix C).

Turbidity levels in 2022 increased during the summer and declined during the winter, with peaks corresponding to precipitation events and/or sediment mobilization following high flow events. Seasonal dynamics in turbidity were comparable across tributaries in either watershed. Annual peak summer turbidity levels were greater in Ware River tributaries than in Quabbin Reservoir tributaries. Annual median turbidity in 2022 exceeded that of the period of record for all sites in the Quabbin Reservoir Watershed, excluding 211, as well as most sites in the Ware River Watershed. The elevated annual turbidity in either watershed is likely the result of prolonged above normal turbidity coincident with severe drought conditions, coupled with episodic turbidity peaks during rewetting in September (Ware River) and moderate rainfall events preceded by relative dry conditions in July in the Quabbin Reservoir Watershed. Data from 2022 highlight this potential impact of repeated short-term droughts in the NE USA on turbidity loading to Quabbin Reservoir.

Variability in turbidity across sites may be attributed to differences in land use, localized meteorological effects, and sub-catchment hydrology. Turbidity levels observed in 2022 were generally consistent with those of previous years, indicating the continued high quality of surface waters in the Quabbin Reservoir and Ware River Watersheds.

Table 17: Descriptive statistics (minimum, median, mean, and maximum) for turbidity measured in Core tributary sites in the Quabbin Reservoir Watershed during 2022.

Location	Season	Turbidity (NTU)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	6	248	0.18	0.16	0.29	0.28	0.30	0.31	0.47	2.70
	Spring	7	241	0.22	0.15	0.32	0.30	0.34	0.37	0.56	8.00
	Summer	7	247	0.20	0.20	0.32	0.36	0.54	0.47	1.90	4.58
	Fall	6	244	0.20	0.18	0.34	0.30	0.34	0.39	0.42	2.76
212	Winter	6	227	0.53	0.20	0.75	0.45	0.81	0.52	1.30	3.00
	Spring	7	229	0.52	0.20	0.64	0.42	0.73	0.63	1.10	10.0
	Summer	7	236	1.20	0.30	1.50	1.12	2.04	1.44	5.10	15.0
	Fall	6	230	0.61	0.30	1.65	0.76	1.47	1.07	2.00	8.46
213	Winter	6	240	0.46	0.29	0.64	0.49	0.61	0.52	0.80	2.14
	Spring	7	236	0.43	0.30	0.59	0.50	0.67	0.60	1.10	3.00
	Summer	7	243	0.77	0.40	0.94	1.00	1.05	1.06	1.60	3.17
	Fall	6	233	0.43	0.30	0.58	0.73	0.59	0.79	0.73	2.00
215G	Winter	6	16	0.35	0.21	0.49	0.57	0.54	0.58	0.86	0.89
	Spring	7	18	0.38	0.28	0.50	0.51	0.54	0.53	0.81	0.90
	Summer	7	20	0.94	0.56	1.30	0.95	1.33	0.98	1.70	1.46
	Fall	6	19	0.55	0.40	0.69	0.70	0.72	0.70	1.00	1.00
216	Winter	6	244	0.54	0.30	0.61	0.50	0.62	0.56	0.70	2.88
	Spring	7	239	0.44	0.30	0.55	0.52	0.58	0.64	0.90	5.00
	Summer	7	246	0.72	0.30	0.94	0.70	1.03	0.75	1.90	2.24
	Fall	6	242	0.54	0.29	0.63	0.57	0.65	0.65	0.79	5.86
BC	Winter	6	169	0.80	0.30	1.19	0.99	1.24	1.28	1.80	6.85
	Spring	7	175	0.42	0.30	0.59	0.78	0.67	1.17	0.94	6.00
	Summer	4	144	0.55	0.23	1.05	0.72	0.94	1.13	1.10	23.00
	Fall	6	134	0.43	0.16	0.45	0.53	0.46	1.01	0.51	6.59
GATE	Winter	6	169	0.15	0.08	0.29	0.20	0.47	0.23	1.40	2.00
	Spring	7	172	0.13	0.09	0.14	0.20	0.22	0.29	0.52	8.00
	Summer	5	180	0.18	0.10	0.21	0.21	0.45	0.29	1.10	1.92
	Fall	6	174	0.13	0.08	0.24	0.20	0.30	0.29	0.72	3.80

Table 18: Descriptive statistics (minimum, median, mean, and maximum) for turbidity measured in Core tributary sites in the Ware River Watershed during 2022.

Location	Season	Turbidity (NTU)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	6	65	0.50	0.47	0.63	0.77	0.68	0.79	1.00	1.60
	Spring	7	60	0.54	0.40	0.91	0.86	1.10	1.08	2.20	2.71
	Summer	6	63	1.90	1.20	2.30	2.60	2.32	2.68	2.90	5.20
	Fall	7	65	0.81	0.68	1.30	1.54	1.24	1.65	1.80	3.20
102	Winter	6	109	0.64	0.40	0.89	0.60	0.84	0.77	0.98	2.50
	Spring	7	110	0.61	0.40	1.00	0.60	1.69	0.72	5.00	2.00
	Summer	6	112	1.90	0.60	2.80	1.70	2.82	1.81	3.70	4.50
	Fall	7	112	1.30	0.50	2.20	1.00	4.13	1.27	17.0	4.00
103A	Winter	6	85	0.53	0.33	0.58	0.61	0.60	0.69	0.71	2.70
	Spring	7	100	0.42	0.19	0.74	0.74	1.03	0.93	1.80	3.83
	Summer	6	107	1.80	0.83	2.25	2.34	2.32	2.46	2.90	6.63
	Fall	7	112	0.50	0.33	0.86	1.10	1.25	1.31	3.30	5.63
107A	Winter	6	89	0.50	0.39	0.77	0.61	0.76	0.71	1.00	2.54
	Spring	7	101	0.39	0.32	0.85	0.73	0.89	0.93	1.60	8.93
	Summer	6	105	1.00	0.82	1.55	1.72	1.45	1.91	1.70	5.05
	Fall	7	112	0.51	0.42	0.81	0.92	0.93	1.02	2.10	2.89
108	Winter	6	199	0.42	0.30	0.66	0.67	0.69	0.75	1.00	3.10
	Spring	7	205	0.48	0.30	0.87	0.70	1.17	0.92	2.40	2.94
	Summer	6	206	2.80	0.60	3.40	2.20	3.40	2.32	3.80	5.50
	Fall	7	212	0.84	0.30	1.30	1.20	2.01	1.40	5.40	4.01
121	Winter	6	122	0.49	0.30	0.78	0.60	0.80	0.66	1.20	3.00
	Spring	7	123	0.60	0.30	0.86	0.60	1.03	0.69	2.20	1.83
	Summer	6	129	1.60	0.65	3.40	1.76	4.90	2.17	9.80	8.50
	Fall	7	134	0.65	0.30	0.81	1.04	1.90	1.43	6.90	7.65

3.2.4 Total Coliform and *E. coli* Bacteria

Water quality monitoring of bacteria in the Quabbin Reservoir and Ware River Watershed Core tributary sites primarily includes *E. coli* and total coliform bacteria. Analysis for fecal coliform in Core tributaries in the Quabbin Reservoir and Ware River Watersheds was not performed in 2022. Elevated bacteria results from Quabbin Reservoir and Ware River tributaries that exceed the upper bounds of seasonal normals (75th percentiles) and that cannot be attributed to a recent meteorological event are followed up with site inspection and re-sampling for *E. coli* concentrations. Historically, follow-up sampling has previously attributed elevated *E. coli* concentrations to wildlife activity, recent precipitation, or findings that were inconclusive. Follow-up samples were collected from Boat Cove Brook in 2022 (Appendix B).

3.2.4.1 Total Coliform

Variability in total coliform concentrations observed in Core tributaries in Quabbin Reservoir and Ware River Watersheds largely mirrored that of stream temperature throughout 2022 (Section 3.2.1.1). Total coliform in Quabbin Reservoir Watershed Core monitoring tributaries ranged from 97 to greater than 24,200 MPN/100 mL (Table 19) and from 10 to greater than 24,200 MPN/100 mL in Core monitoring tributaries in the Ware River Watershed in 2022 (Table 20).

Seasonal total coliform concentrations for samples collected in 2022 generally approached or intermittently exceeded seasonal normals for the period of record at sites with a consistent monitoring record (i.e., excluding the more recent additions of 215G, 102, and 121). Total coliform results for Boat Cove Brook trended below monthly normal ranges for the early half of 2022, despite a demonstrated history of elevated bacteria levels at this location. The timing of annual maximum total coliform concentrations in 2022 coincided with high-streamflow, high temperatures, and dry antecedent conditions across DWSP watersheds (Section 3.1). These meteorologically driven events represent discrete instances of contaminant transport across landscapes, as total coliform levels returned to pre-event concentrations in all subsequent samples. Select locations demonstrated a greater susceptibility to episodic peaks in bacterial counts, with instantaneous results driving seasonal descriptive statistics above that of the period of record. This phenomenon was most pronounced at site 212 in 2021 and did not occur in 2022. Historical seasonal maximum total coliform concentrations were not observed in 2022 at locations with long-term monitoring records (Appendix C).

Table 19: Descriptive statistics (minimum, median, mean, and maximum) for total coliform measured in Core tributary sites in the Quabbin Reservoir Watershed during 2022.

Location	Season	Total Coliform (MPN/100 mL)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	6	76	272	110	358	441	387	527	624	2,190
	Spring	7	75	148	108	512	676	749	916	2,760	3,450
	Summer	7	77	1,290	1,220	3,080	3,450	5,329	5,402	19,900	24,200
	Fall	6	79	520	488	1,290	1,670	2,182	3,161	6,490	24,200
212	Winter	6	75	148	110	332	399	361	519	780	2,850
	Spring	7	76	98	84	313	500	649	938	2,610	8,660
	Summer	7	79	1,250	813	4,880	5,790	6,927	8,290	24,200	24,200
	Fall	6	79	663	393	2,995	2,190	3,984	4,473	8,660	24,200
213	Winter	6	76	187	121	384	343	344	673	441	6,870
	Spring	7	77	97	98	443	1,010	1,046	2,165	4,350	24,200
	Summer	7	79	2,140	2,250	2,760	5,480	3,453	6,956	7,270	24,200
	Fall	6	79	379	359	1,115	2,010	1,628	3,713	4,350	24,200
215G	Winter	6	16	173	156	231	346	260	377	364	909
	Spring	7	18	122	135	1,270	1,420	1,522	1,713	4,110	5,480
	Summer	7	20	1,860	3,870	4,610	5,790	4,773	6,473	11,200	17,300
	Fall	6	19	609	504	1,425	1,990	3,297	2,449	11,200	7,700
216	Winter	6	76	108	86	295	357	284	614	384	6,490
	Spring	7	75	158	95	281	548	557	931	2,280	5,170
	Summer	7	77	2,010	1,070	3,780	3,450	9,084	5,538	24,200	24,200
	Fall	6	79	364	288	729	1,080	1,075	2,057	2,100	19,900
BC	Winter	6	75	199	122	397	384	387	704	624	8,660
	Spring	7	77	98	86	327	743	454	1,714	1,400	15,500
	Summer	4	77	1,110	1,170	2,650	6,870	6,578	8,600	19,900	24,200
	Fall	8	76	1,300	228	4,480	3,035	4,999	5,894	14,100	24,200
GATE	Winter	6	75	187	135	235	345	290	394	495	1,270
	Spring	7	76	201	195	410	664	708	893	2,850	7,270
	Summer	5	76	833	1,090	1,900	3,870	3,721	5,930	11,200	24,200
	Fall	6	76	355	388	2,070	2,190	1,625	3,887	2,310	24,200

Table 20: Descriptive statistics (minimum, median, mean, and maximum) for total coliform measured in Core tributary sites in the Ware River Watershed during 2022.

Location	Season	Total Coliform (MPN/100 mL)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	6	66	175	109	439	392	460	648	839	3,450
	Spring	7	61	173	73	733	852	916	1,141	2,140	7,700
	Summer	6	63	1,720	1,330	2,995	5,790	4,312	7,418	7,700	24,200
	Fall	7	67	985	331	1,500	2,380	3,018	3,261	7,700	24,200
102	Winter	6	6	145	171	334	270	331	283	556	504
	Spring	7	6	216	181	1,110	652	1,652	764	4,350	2,010
	Summer	6	7	2,380	2,760	4,130	4,350	5,090	4,794	10,500	7,700
	Fall	7	7	676	435	3,870	1,990	6,189	3,732	24,200	13,000
103A	Winter	6	66	185	173	327	478	317	691	420	6,490
	Spring	7	69	318	110	1,660	908	1,798	1,276	5,170	4,610
	Summer	6	77	1,850	1,920	5,080	6,490	8,243	8,072	24,200	24,200
	Fall	7	77	683	404	1,310	2,610	5,889	3,823	24,200	24,200
107A	Winter	6	74	292	160	457	492	462	674	620	4,350
	Spring	7	74	259	160	1,070	948	1,555	1,567	3,450	9,210
	Summer	6	77	1,580	1,170	4,725	4,110	4,600	5,937	8,660	24,200
	Fall	7	77	383	464	1,610	1,620	5,390	3,059	24,200	24,200
108	Winter	6	78	318	75	350	341	377	578	529	4,610
	Spring	7	74	238	121	880	817	1,921	1,114	5,790	4,610
	Summer	6	78	2,760	1,520	4,970	5,170	5,408	6,499	9,800	24,200
	Fall	7	77	670	504	1,260	1,840	5,227	3,158	24,200	24,200
121	Winter	6	19	146	110	241	414	262	649	388	2,490
	Spring	7	19	213	145	1,370	1,220	1,401	1,877	2,720	6,130
	Summer	6	20	1,580	1,940	4,890	4,880	4,728	5,036	6,870	9,800
	Fall	7	20	10	759	1,560	1,845	2,967	2,892	8,160	14,100

3.2.4.2 E. coli

E. coli results corresponding to Core monitoring tributaries in the Quabbin Reservoir Watershed and Ware River Watershed were compared to the Class A standards for non-intake waters, and annual geometric means were compared to those of previous years. *E. coli* concentrations ranged from less than 10 to 7,700 MPN/100 mL in Quabbin Reservoir Watershed tributaries (Table 21) and from less than 10 to 2,910 MPN/100 mL in the Ware River Watershed tributaries in 2022 (Table 22). The maximum *E. coli* result observed in 2022 occurred on July 19, 2022, at site 212 in the Quabbin Reservoir Watershed. Beaver activity upstream of the DWSP sample site on Hop Brook has been previously documented (DWSP, 2017), and field observations in 2022 confirmed that wildlife continue to impact this location. Of the 335 samples collected from Core tributaries and analyzed for *E. coli* in 2022, approximately 27% (n = 89) were below detection limits (<10 MPN/100 mL).

Twenty-seven samples exceeded the Class A Standard for single samples (*E. coli* >235 MPN/100 mL) in Core sites in the Quabbin Reservoir and Ware River Watersheds in 2022. *E. coli* concentrations in excess of 235 MPN/100 mL occurred primarily during the latter half of 2022 (Figure 13). Exceedances of the Class A single sample threshold typically followed precipitation events. Of the results in excess of 235 MPN /100 mL, five corresponded to samples collected from 103A in the Ware River Watershed and four in BC in the Quabbin Reservoir Watershed. In most cases, no potential sources of pollution were observed during sample collection, and *E. coli* concentrations decreased in subsequent samples (Figure 13). At Boat Cove Brook, investigations revealed near-stream wildlife impacts, suspected to be the source of elevated *E. coli* (Appendix B). *E. coli* concentrations in Core tributaries in 2022 continued to demonstrate a high sanitary quality.

Table 21: Descriptive statistics (minimum, median, mean, and maximum) for *E. coli* measured in Core tributary sites in the Quabbin Reservoir Watershed during 2022. Detection Limits for *E. coli* were <10 MPN/100 mL.

Location	Season	***E. coli* (MPN/100 mL)**									
		Count		**Minimum**		**Median**		**Mean**		**Maximum**	
		2022	**POR**	**2022**	**POR**	**2022**	**POR**	**2022**	**POR**	**2022**	**POR**
211	Winter	6	107	10	10	8	4	18	8	63	63
	Spring	7	99	10	10	10	7	9	17	20	156
	Summer	7	105	10	10	31	31	128	147	677	6,870
	Fall	6	105	10	10	15	10	20	37	41	644
212	Winter	6	105	10	10	26	5	28	12	63	189
	Spring	7	100	10	10	10	10	34	30	120	481
	Summer	7	107	10	10	31	63	1,145	232	7,700	5,480
	Fall	6	105	10	10	122	20	136	97	292	2,360
213	Winter	6	107	10	10	15	10	19	26	41	327
	Spring	7	101	10	10	10	31	28	49	86	426
	Summer	7	108	10	10	41	63	84	294	368	12,000
	Fall	6	105	10	10	47	31	251	122	1,310	3,260
215G	Winter	6	16	10	10	5	8	5	10	10	41
	Spring	7	18	10	10	5	9	18	14	63	31
	Summer	7	20	10	10	41	31	80	53	359	448
	Fall	6	19	10	10	26	10	47	16	158	63
216	Winter	6	107	10	10	10	10	14	16	31	292
	Spring	7	99	10	10	5	10	19	16	63	187
	Summer	7	105	10	10	31	41	148	81	504	1,010
	Fall	6	104	10	10	15	20	19	102	52	6,870
BC	Winter	6	105	10	10	31	6	35	18	63	189
	Spring	7	101	10	10	10	10	11	39	20	697
	Summer	4	104	10	10	68	104	277	666	960	19,900
	Fall	8	94	41	10	122	31	505	207	2,140	3,870
GATE	Winter	6	104	10	10	5	2	6	9	10	249
	Spring	7	100	10	10	5	1	10	16	31	529
	Summer	5	103	10	10	31	20	80	63	313	1,660
	Fall	6	102	10	10	10	10	12	105	20	5,170

Table 22: Descriptive statistics (minimum, median, mean, and maximum) for *E. coli* measured in Core tributary sites in the Ware River Watershed during 2022. Detection Limits for *E. coli* were <10 MPN/100 mL.

Location	Season	*E. coli* (MPN/100 mL)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	6	66	10	10	20	10	23	15	52	146
	Spring	7	61	10	10	20	10	32	29	121	228
	Summer	6	63	20	10	52	86	64	142	146	1,220
	Fall	7	67	10	10	31	31	90	73	345	1,550
102	Winter	6	6	10	10	10	5	12	11	31	41
	Spring	7	6	10	10	10	5	58	14	256	41
	Summer	6	7	20	41	63	52	164	87	697	206
	Fall	7	7	41	10	109	41	510	118	2,910	609
103A	Winter	6	85	10	10	8	10	9	14	20	197
	Spring	7	94	10	10	30	20	64	34	171	228
	Summer	6	101	108	10	203	121	202	183	313	1,420
	Fall	7	107	10	10	30	41	333	88	1,940	1,040
107A	Winter	6	89	10	10	5	10	7	13	10	96
	Spring	7	97	10	10	10	10	41	32	135	488
	Summer	6	99	10	10	8	52	22	107	74	1,400
	Fall	7	107	10	10	20	20	321	112	2,100	4,880
108	Winter	6	104	10	10	8	10	11	14	20	107
	Spring	7	102	10	10	10	10	100	30	355	189
	Summer	6	102	10	10	69	85	64	141	109	1,780
	Fall	7	107	10	10	41	31	227	70	1,400	1,350
121	Winter	6	27	10	10	5	3	8	14	20	148
	Spring	7	29	10	10	41	20	66	31	238	256
	Summer	6	32	31	10	41	85	69	98	218	336
	Fall	7	34	10	10	31	20	61	60	201	282

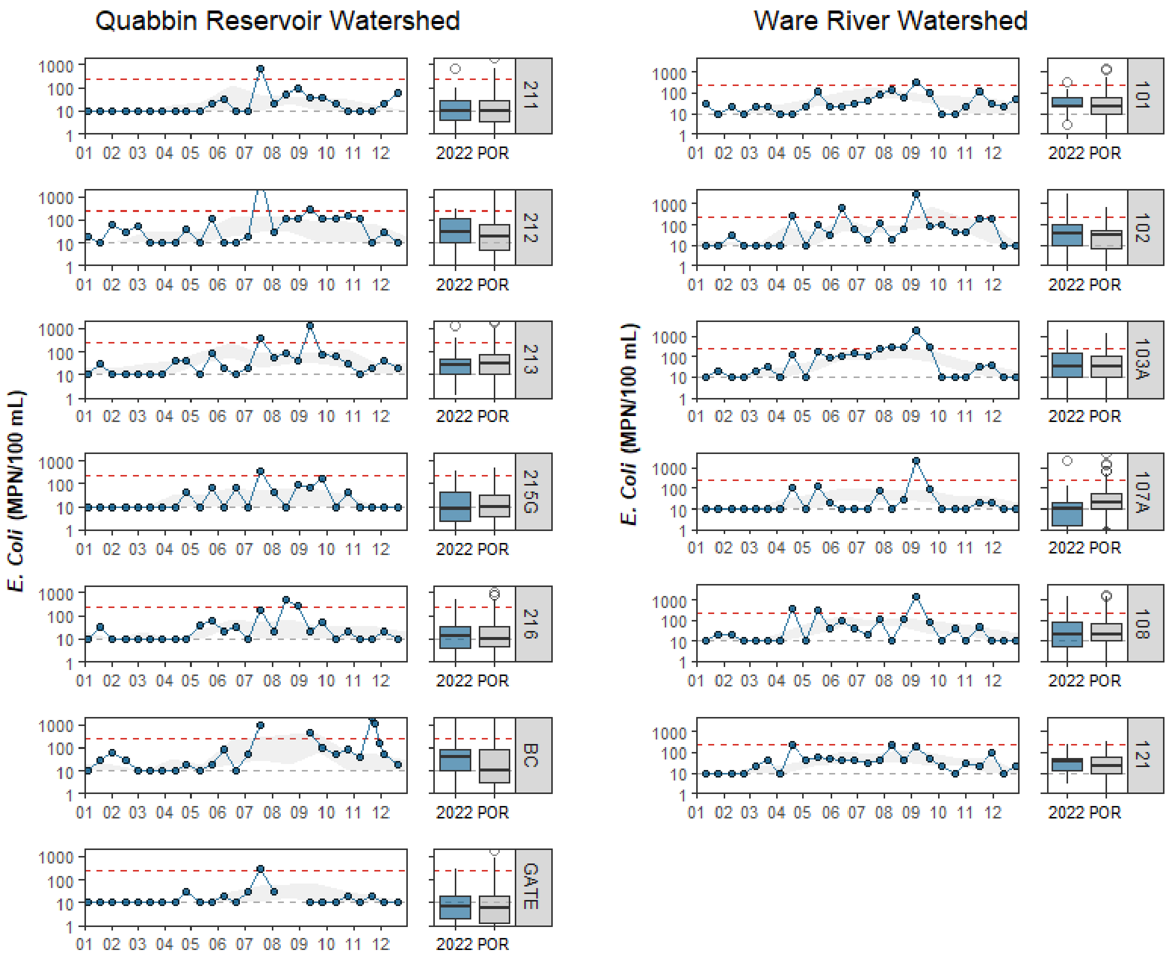

Figure 13: Time series and boxplots of *E. coli* measured in Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel. The horizontal dashed grey and red lines correspond to laboratory detection limits (10 MPN/100 mL) and the MassDEP Class A single sample maximum standard of 235 MPN/100 mL. Note that the mid-July result at Site 212 was 5,480 MPN/100 mL.

The annual geometric mean *E. coli* concentration remained below 126 MPN/100 mL and the Class A standards for all Core monitoring sites in 2022 (Table 23). Long-term records of annual geometric mean *E. coli* results do not exhibit unidirectional trends in most Core monitoring sites. Annual geometric mean *E. coli* at sites 211 and 212 in the Quabbin Reservoir Watershed has been on an upward trajectory in recent years. Results for these locations were comparable to or below 2021 results (Appendix C). Temporal variability in annual geometric mean *E. coli* concentrations exhibited a non-uniform response to climate extremes (e.g., drought in 2016 and 2020, extreme precipitation excess in summer 2021). This contrast may reflect the timing of sample collection relative to precipitation events throughout the period of record, differences in the degree to which the two watersheds may have been impacted by saturation excess overland flow, or variations in factors controlling the sources of *E. coli* to the watersheds.

Boat Cove Brook, in the Quabbin Reservoir Watershed, had demonstrated an upward trend in annual *E. coli* concentrations from 2012 to 2017, then a decline from 2018 to 2021 (DWSP, 2018b; DWSP, 2019a; DWSP, 2022). However, 2022 brought a period of *E. coli* in excess of historical normals that was attributed to nearby wildlife activity (Appendix B). Work to assess potential bacteria sources near this sample location has been described in previous reports (DWSP, 2018b).

Table 23: Annual geometric mean *E. coli* for Core tributary sites.

Year	Annual Geometric Mean E. coli (MPN/100 mL)												
	Ware River Watershed						Quabbin Reservoir Watershed						
	101	102	103A	107A	108	121	211	212	213	215G	216	BC	GATE
2005	-	-	17	10	13	-	10	28	13	-	13	36	10
2006	-	-	29	14	20	-	7	8	20	-	10	14	6
2007	-	-	34	46	22	67	15	16	26	-	19	10	10
2008	-	-	40	40	30	19	6	10	17	-	16	6	5
2009	-	-	21	18	23	-	12	13	31	-	12	9	8
2010	18	-	28	19	31	-	18	24	57	-	19	25	18
2011	-	-	21	14	32	-	11	19	44	-	26	9	9
2012	29	-	20	17	22	15	13	21	43	-	14	15	15
2013	23	-	26	22	21	-	6	13	34	8	15	5	10
2014	17	-	33	16	21	-	14	20	41	-	15	21	6
2015	16	-	35	23	24	-	13	38	37	-	11	28	11
2016	20	-	28	17	25	21	32	56	43	-	24	47	8
2017	34	-	36	26	27	-	15	22	25	15	13	66	8
2018	33	-	59	36	40	-	13	29	35	-	18	38	2
2019	21	-	35	14	25	-	9	11	25	-	11	30	10
2020	24	-	42	21	22	-	15	26	16	-	21	23	13
2021	33	20	29	20	23	26	12	44	34	11	13	19	6
2022	30	36	36	12	23	28	14	38	26	7	16	42	9

3.2.5 Nutrient Dynamics

3.2.5.1 Nitrogen Species

3.2.5.1.1 Ammonia-Nitrogen

Concentrations of ammonia (NH_3-N) in Quabbin Reservoir and Ware River Watershed tributaries have routinely been below detection limits (50% of samples from Core tributaries in 2022). Concentrations of NH_3-N in Quabbin Reservoir and Ware River Watershed Core monitoring tributaries ranged from <0.005 to 0.104 mg/L and <0.005 to 0.077 mg/L, respectively, in 2022 (Table 24, Table 25). Concentrations of NH_3-N were generally within historical ranges for most Core tributary sites in 2022, with exceedances of previous seasonal maximum concentrations observed at several sites. Concentrations of NH_3-N in Core monitoring tributaries in the Quabbin Reservoir and Ware River Watersheds were below the MA acute and chronic aquatic life criteria (17 mg/L and 1.9 mg/L, respectively) and the WHO taste and odor thresholds for drinking water (1.5 mg/L and 1.9 mg/L) for the entirety of 2022.

Concentrations of NH_3-N were most frequently above detection limits at site 215G in the Quabbin Reservoir Watershed and site 121 in the Ware River Watershed. 215G was incorporated as a long-term monitoring location in 2021 to replace the upstream site 215, where beaver activity has resulted in channel inundation and decreased channel velocity. Site 121 is located downstream of 121B on the Mill River in Rutland, MA, a location with a documented increase in beaver activity over time. For comparison, concentrations of NH_3-N measured at sites 215 and 121B in the Quabbin Reservoir Watershed in 2020 were markedly greater than median seasonal concentration observed for the period of record (DWSP, 2021a). Beaver dams may alter in-stream biogeochemical pathways, acting as sinks for NO_3-N (via denitrification) and subsequent sources for ammonium in stream settings (Lazer et al., 2015; Bason et al., 2017). The notably greater NH_3N concentrations and corresponding relative depletion in NO_3-N concentrations observed in Fever Brook and Mill Brook in 2021 and 2022 suggest that the beaver continue to impact N-cycling in the upstream reaches of these particular sub-watersheds during 2022.

2022 marked the third consecutive year of monitoring NH_3-N at a frequency of every two weeks in Core tributaries, compared with pre-2022 quarterly monitoring. The increased monitoring frequency likely impacted seasonal descriptive statistics, as well as intra-annual and site-to-site variability (Jones et al., 2012; Elwan et al., 2018). For example, the range of concentrations of NH_3-N observed at site 108 in summer 2022 was comparable to the range of concentrations across all seasons for the period of record (<0.005 to 0.034 mg/L vs. <0.005 to 0.037 mg/L, respectively) at this location. As different factors may play variable roles in terrestrial aquatic N-cycling across watersheds (e.g., 211, vs. 215G, vs. Boat Cove Brook; Quabbin Reservoir Watershed vs. Ware River Watershed), the insights on controls on riverine N-loading to Quabbin Reservoir derived from the introduction of increased (e.g., every other week) analyses of NH_3-N may also vary. Namely, NH_3-N was below laboratory detection limits in all but two samples collected from Gates Brook in 2022, and for the entirety of 2020 and 2021. In contrast, concentrations of NH_3-N varied over an order of magnitude in samples collected during the summer at site 215G, and maximum annual NH_3-N concentrations at site 103A were observed in February 2022. Site 108 and 121 in the Ware River Watershed also demonstrated distinct intra-seasonal variability in concentrations of NH_3-N for all three years of monitoring. Despite the intra-seasonal variability introduced by increased monitoring frequency, NH_3-N concentrations observed in Ware River Watershed tributaries exhibited a comparable seasonal variability to large tributaries in the Quabbin Reservoir Watershed (e.g., 211, 212, 213, 215G, and 216) in 2022. The general timing of annual increases in instream NH_3-N concentrations was consistent across watersheds (Appendix C).

Table 24: Descriptive statistics (minimum, median, mean, and maximum) for NH_3-N measured in Core tributary sites in the Quabbin Reservoir Watershed during 2022. Detection limits for NH_3-N were <0.005 mg/L.

Location	Season	Ammonia-N (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	6	21	0.005	0.005	0.002	0.002	0.002	0.003	0.005	0.006
	Spring	7	20	0.005	0.005	0.002	0.002	0.003	0.002	0.007	0.005
	Summer	7	20	0.005	0.005	0.010	0.002	0.008	0.009	0.012	0.082
	Fall	6	21	0.005	0.005	0.002	0.004	0.003	0.005	0.007	0.010
212	Winter	6	20	0.005	0.005	0.007	0.004	0.009	0.005	0.016	0.008
	Spring	7	20	0.005	0.005	0.002	0.003	0.005	0.007	0.009	0.034
	Summer	7	20	0.011	0.005	0.015	0.007	0.015	0.008	0.018	0.039
	Fall	6	21	0.005	0.005	0.004	0.002	0.005	0.005	0.012	0.038
213	Winter	6	21	0.005	0.005	0.009	0.006	0.012	0.007	0.033	0.016
	Spring	7	20	0.005	0.005	0.008	0.005	0.006	0.018	0.012	0.198
	Summer	7	20	0.005	0.005	0.015	0.009	0.018	0.011	0.033	0.030
	Fall	6	21	0.005	0.005	0.011	0.008	0.011	0.009	0.020	0.015
215G	Winter	6	16	0.005	0.005	0.007	0.005	0.012	0.009	0.033	0.025
	Spring	7	18	0.005	0.005	0.002	0.002	0.005	0.004	0.023	0.012
	Summer	7	20	0.016	0.005	0.027	0.010	0.033	0.014	0.056	0.032
	Fall	6	19	0.005	0.005	0.002	0.005	0.005	0.007	0.016	0.017
216	Winter	6	21	0.005	0.005	0.004	0.001	0.008	0.005	0.027	0.046
	Spring	7	20	0.005	0.005	0.002	0.001	0.004	0.007	0.008	0.054
	Summer	7	20	0.005	0.005	0.008	0.003	0.022	0.005	0.104	0.028
	Fall	6	21	0.005	0.005	0.002	0.002	0.003	0.004	0.005	0.013
BC	Winter	6	21	0.005	0.005	0.002	0.002	0.002	0.004	0.005	0.015
	Spring	7	20	0.005	0.005	0.002	0.002	0.004	0.003	0.007	0.007
	Summer	4	18	0.005	0.005	0.007	0.003	0.007	0.004	0.014	0.015
	Fall	6	18	0.005	0.005	0.002	0.002	0.002	0.003	0.005	0.012
GATE	Winter	6	21	0.005	0.005	0.002	0.002	0.002	0.002	0.005	0.005
	Spring	7	20	0.005	0.005	0.002	0.002	0.002	0.002	0.005	0.005
	Summer	5	20	0.005	0.005	0.002	0.002	0.007	0.003	0.022	0.006
	Fall	6	21	0.005	0.005	0.002	0.002	0.002	0.003	0.005	0.007

Table 25: Descriptive statistics (minimum, median, mean, and maximum) for NH_3-N measured in Core tributary sites in the Ware River Watershed during 2022. Detection limits for NH_3-N were <0.005 mg/L.

Location	Season	Ammonia-N (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	5	22	0.005	0.005	0.002	0.005	0.008	0.006	0.024	0.016
	Spring	7	18	0.005	0.005	0.002	0.004	0.007	0.006	0.018	0.031
	Summer	6	22	0.007	0.005	0.009	0.010	0.015	0.011	0.043	0.025
	Fall	7	21	0.005	0.005	0.002	0.005	0.004	0.007	0.006	0.055
102	Winter	6	6	0.005	0.005	0.002	0.007	0.005	0.007	0.012	0.012
	Spring	7	6	0.005	0.005	0.002	0.002	0.005	0.004	0.014	0.010
	Summer	6	7	0.005	0.005	0.007	0.002	0.008	0.005	0.016	0.012
	Fall	7	7	0.005	0.005	0.002	0.005	0.003	0.017	0.008	0.093
103A	Winter	6	22	0.005	0.005	0.010	0.005	0.011	0.007	0.021	0.027
	Spring	7	17	0.005	0.005	0.002	0.006	0.007	0.007	0.016	0.028
	Summer	6	22	0.005	0.005	0.011	0.006	0.011	0.009	0.015	0.027
	Fall	7	21	0.005	0.005	0.002	0.005	0.004	0.006	0.012	0.011
107A	Winter	6	22	0.005	0.005	0.005	0.006	0.006	0.007	0.011	0.018
	Spring	7	18	0.005	0.005	0.002	0.002	0.006	0.006	0.017	0.046
	Summer	6	22	0.005	0.005	0.009	0.006	0.009	0.007	0.015	0.019
	Fall	7	21	0.005	0.005	0.002	0.003	0.003	0.004	0.008	0.017
108	Winter	6	22	0.005	0.005	0.007	0.008	0.010	0.015	0.022	0.123
	Spring	7	18	0.005	0.005	0.005	0.005	0.010	0.008	0.029	0.039
	Summer	6	22	0.015	0.005	0.022	0.020	0.024	0.018	0.037	0.034
	Fall	7	21	0.005	0.005	0.008	0.006	0.009	0.008	0.017	0.017
121	Winter	6	19	0.005	0.005	0.031	0.010	0.033	0.016	0.069	0.053
	Spring	7	19	0.005	0.005	0.006	0.007	0.008	0.008	0.020	0.011
	Summer	6	20	0.012	0.005	0.034	0.016	0.041	0.028	0.077	0.136
	Fall	7	20	0.005	0.005	0.002	0.012	0.004	0.020	0.010	0.103

3.2.5.1.2 Nitrate-Nitrogen

Concentrations of nitrate (NO_3-N) ranged from <0.005 to 0.157 mg/L in Quabbin Reservoir Watershed Core sites in 2022 (Table 26). Concentrations of NO_3-N observed in Ware River Watershed during 2022 ranged from <0.005 to 0.158 mg/L (Table 27). Concentrations of NO_3-N observed in Core tributary monitoring sites in Quabbin Reservoir and Ware River Watersheds during 2022 were largely within historical seasonal ranges but revealed differences in seasonal median concentrations when compared to those for the period of record for most sites. For locations with a continuous monitoring record, median winter NO_3-N concentrations were comparable to median winter NO_3-N concentrations observed in 2021, but typically greater than the period of record. The latter may reflect differences in sampling frequency introduced in 2020 (e.g., winter NO_3-N samples were previously collected once, each December. Beginning in 2020, winter NO_3-N samples represent samples collected every other week during the months of January, February, and December).

Seasonal concentration ranges of NO_3-N were generally similar in Core tributaries in the Ware River Watershed compared to Core tributaries in the Quabbin Reservoir Watershed. Variations in concentrations of NO_3-N across Core tributaries likely reflect differences in watershed characteristics combined with land use and management across the two watersheds. Core monitoring tributaries in the Quabbin Reservoir and Ware River Watersheds were well below the EPA MCL for drinking water of 10 mg/L for the entirety of 2022 and within local ecoregional background levels (0.16 - 0.31 mg/L) throughout 2022.

Concentrations of NO_3-N in Quabbin Reservoir and Ware River Watersheds followed expected seasonal patterns for the first half of 2022, with the greatest concentrations of NO_3-N observed in samples collected from most Core tributaries in the winter months into early March, and subsequent depletion in early summer and fall, where uptake or increases in denitrification rates likely contributed to NO_3-N removal/reduction. Small Core tributaries in the Quabbin Reservoir Watershed (e.g., Gates Brook and Boat Cove Brook) did not follow these patterns, rather these locations favored greater concentrations during low flows (e.g., summer) and relative depletion of NO_3-N concentrations during spring and winter high flows (Appendix C). The latter indicates key differences in controls on biogeochemical N-cycling in small low-order tributaries compared to higher-order (larger) tributaries to the Quabbin Reservoir and those in the Ware River Watershed. Median winter NO_3-N concentrations in 2022 were greater than those for the period of record for most Core sites (excluding Gates Brook) with a consistent monitoring record in either watershed (Appendix C). Below normal streamflow present throughout the late summer and early fall may have resulted in a lack of dilution of stream NO_3-N concentrations (Section 3.1.2).

Increased analyses of NO_3-N in 2022 (e.g., every two weeks) revealed several key patterns not presented by single quarterly (seasonal) results. Temporally, within a seasonal period, in-stream NO_3-N concentrations may vary from below 25th percentile concentrations to maximum concentrations observed for the period of record (Appendix C). This is to be expected, given the dynamic controls on NO_3-N transport across terrestrial and aquatic ecosystems. Other sites offered comparatively little to no intra-seasonal variability in NO_3-N concentrations at every two week monitoring frequency. The latter typically occurred at locations where NO_3-N concentrations remained below laboratory detection limits for the entire three-month window (e.g., Gates Brook) and ultimately serves to provide meaningful information relative to N-loading in small tributary systems. Furthermore, seasonal median NO_3-N concentrations for some sites in 2022 illustrated patterns distinct from that of the period of record. Specifically, streams demonstrated a mixed response to drought relative to in stream NO_3-N concentrations. NO_3-N concentrations declined rapidly with decreasing streamflow in sites 213 and 216, and gradually increased with increasing drought severity in sites 211, 215G, and 107A (Appendix C). Higher frequency sampling of nutrients in surface waters generally results in more accurate annual load estimates (Jones et al., 2012; Elwan et al., 2018). As variations in NO_3-N concentrations may drastically impact estimates of N-loading, thoroughly understanding the processes controlling NO_3-N concentrations – including typical intra- and interannual variability – is critical for deriving accurate estimates of N-delivery to Quabbin Reservoir.

Table 26: Descriptive statistics (minimum, median, mean, and maximum) for NO_3-N measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2022. Detection limits for NO_3-N were <0.005 mg/L.

Location	Season	Nitrate-N (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	6	26	0.008	0.009	0.026	0.020	0.026	0.026	0.051	0.104
	Spring	7	28	0.007	0.005	0.014	0.022	0.015	0.025	0.024	0.071
	Summer	7	31	0.056	0.005	0.104	0.036	0.100	0.050	0.143	0.133
	Fall	6	31	0.015	0.007	0.022	0.025	0.031	0.043	0.083	0.139
212	Winter	6	25	0.033	0.038	0.060	0.060	0.061	0.063	0.085	0.173
	Spring	7	28	0.024	0.020	0.037	0.059	0.039	0.060	0.061	0.122
	Summer	7	30	0.058	0.008	0.078	0.057	0.076	0.058	0.107	0.116
	Fall	6	31	0.005	0.005	0.025	0.037	0.027	0.039	0.055	0.084
213	Winter	6	26	0.031	0.047	0.093	0.075	0.094	0.088	0.157	0.266
	Spring	7	28	0.009	0.005	0.015	0.067	0.032	0.065	0.083	0.186
	Summer	7	30	0.005	0.005	0.008	0.011	0.010	0.013	0.027	0.044
	Fall	6	31	0.006	0.005	0.009	0.014	0.015	0.020	0.039	0.058
215G	Winter	6	16	0.005	0.005	0.011	0.012	0.011	0.015	0.018	0.043
	Spring	7	18	0.005	0.005	0.002	0.003	0.005	0.005	0.013	0.021
	Summer	7	20	0.008	0.005	0.024	0.005	0.037	0.007	0.082	0.026
	Fall	6	19	0.005	0.005	0.002	0.005	0.006	0.005	0.018	0.011
216	Winter	6	26	0.018	0.017	0.063	0.045	0.061	0.057	0.105	0.194
	Spring	7	28	0.013	0.008	0.027	0.043	0.032	0.050	0.059	0.133
	Summer	7	30	0.014	0.007	0.036	0.039	0.033	0.040	0.058	0.096
	Fall	6	30	0.005	0.005	0.002	0.014	0.006	0.016	0.016	0.036
BC	Winter	6	26	0.005	0.005	0.018	0.015	0.021	0.023	0.045	0.099
	Spring	7	28	0.005	0.005	0.008	0.009	0.009	0.013	0.016	0.043
	Summer	4	25	0.035	0.005	0.039	0.025	0.042	0.034	0.054	0.108
	Fall	6	24	0.005	0.005	0.007	0.006	0.008	0.018	0.016	0.114
GATE	Winter	6	26	0.005	0.005	0.002	0.004	0.003	0.005	0.006	0.011
	Spring	7	28	0.005	0.005	0.002	0.003	0.003	0.004	0.006	0.008
	Summer	5	29	0.005	0.005	0.021	0.005	0.041	0.009	0.115	0.041
	Fall	6	29	0.005	0.005	0.002	0.005	0.008	0.010	0.034	0.055

Table 27: Descriptive statistics (minimum, median, mean, and maximum) for NO_3-N measured in Core tributary monitoring sites in the Ware River Watershed during 2022. Detection limits for NO_3-N were <0.005 mg/L.

Location	Season	Nitrate-N (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	5	22	0.005	0.012	0.054	0.039	0.044	0.037	0.068	0.058
	Spring	7	18	0.006	0.005	0.014	0.013	0.021	0.026	0.065	0.105
	Summer	6	22	0.006	0.006	0.015	0.022	0.014	0.024	0.022	0.048
	Fall	7	21	0.005	0.005	0.006	0.009	0.009	0.010	0.028	0.028
102	Winter	6	6	0.005	0.018	0.025	0.027	0.022	0.025	0.031	0.031
	Spring	7	6	0.005	0.006	0.007	0.010	0.010	0.012	0.023	0.026
	Summer	6	7	0.005	0.005	0.026	0.014	0.026	0.013	0.033	0.024
	Fall	7	7	0.005	0.007	0.012	0.013	0.013	0.014	0.020	0.021
103A	Winter	6	28	0.005	0.013	0.080	0.056	0.069	0.050	0.092	0.085
	Spring	7	25	0.025	0.005	0.029	0.036	0.040	0.041	0.097	0.115
	Summer	6	31	0.010	0.005	0.026	0.028	0.032	0.032	0.057	0.071
	Fall	7	31	0.005	0.005	0.002	0.009	0.008	0.013	0.023	0.041
107A	Winter	6	28	0.005	0.011	0.052	0.037	0.043	0.040	0.070	0.106
	Spring	7	25	0.005	0.005	0.012	0.022	0.016	0.034	0.045	0.132
	Summer	6	31	0.016	0.005	0.080	0.018	0.082	0.023	0.158	0.090
	Fall	7	31	0.005	0.005	0.002	0.011	0.011	0.017	0.052	0.109
108	Winter	6	28	0.005	0.012	0.057	0.048	0.050	0.050	0.073	0.113
	Spring	7	26	0.012	0.008	0.021	0.041	0.027	0.043	0.056	0.122
	Summer	6	31	0.012	0.005	0.019	0.034	0.021	0.032	0.034	0.082
	Fall	7	31	0.005	0.005	0.009	0.012	0.013	0.014	0.027	0.041
121	Winter	6	26	0.005	0.006	0.087	0.050	0.075	0.055	0.130	0.154
	Spring	7	27	0.010	0.005	0.016	0.009	0.026	0.017	0.081	0.120
	Summer	6	29	0.008	0.005	0.014	0.009	0.015	0.017	0.025	0.092
	Fall	7	33	0.005	0.005	0.002	0.008	0.004	0.016	0.007	0.087

3.2.5.1.3 Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) concentrations in Quabbin Reservoir Watershed Core tributary sites ranged from 0.016 to 0.470 mg/L in 2022 (Table 28). TKN concentrations in Ware River Watershed Core tributary sites ranged from 0.097 to 0.528 mg/L during 2022 (Table 29). TKN concentrations observed in Quabbin Reservoir Watershed tributaries in 2022 were within historical seasonal ranges (Figure 14). TKN concentrations in 2022 exceeded historical seasonal maximums for sites 101, 103A, and 107A in the Ware River Watershed in samples (n=3) following precipitation events that occurred in April and May. TKN concentrations measured in 2022 in most Core tributaries in the Quabbin Reservoir and Ware River Watersheds fell within established ranges for local ecoregional background concentrations (0.1 - 0.3 mg/L; Appendix A), except for sites with a greater percentage of wetland cover or immediately downstream of a wetland (e.g., 215G, 107A, and 121).

TKN dynamics in Core tributaries in the Quabbin Reservoir and Ware River Watersheds loosely mirrored that of TP and organic content (Figure 14), with relative enrichment during summer (Section 3.2.6). Similar to patterns presented by concentrations of other N-species in 2022, TKN concentrations exhibited considerable variability for select Core sites within seasons. Organic nitrogen (TKN - NH3-N) was the most abundant nitrogen form in Core tributaries in either watershed in 2022. Dominance of organic nitrogen in headwater streams in the US has been documented previously (Scott et al., 2007). Notably, the fraction of total nitrogen comprised of organic nitrogen did not increase ubiquitously with hydrologic events (Figure 15) across sites, suggesting that the increase in TN during high flows is driven predominantly by increases in inorganic N-species (namely, NO_3-N and NH_3-N), and that these relationships may be both site-specific and dependent on event characteristics. This is further corroborated by observed patterns in concentrations of in-stream inorganic N-forms during 2022. These relationships were elucidated more clearly in 2020 through 2022 relative to prior years, in part due to the increased monitoring frequency of all N-forms for both watersheds.

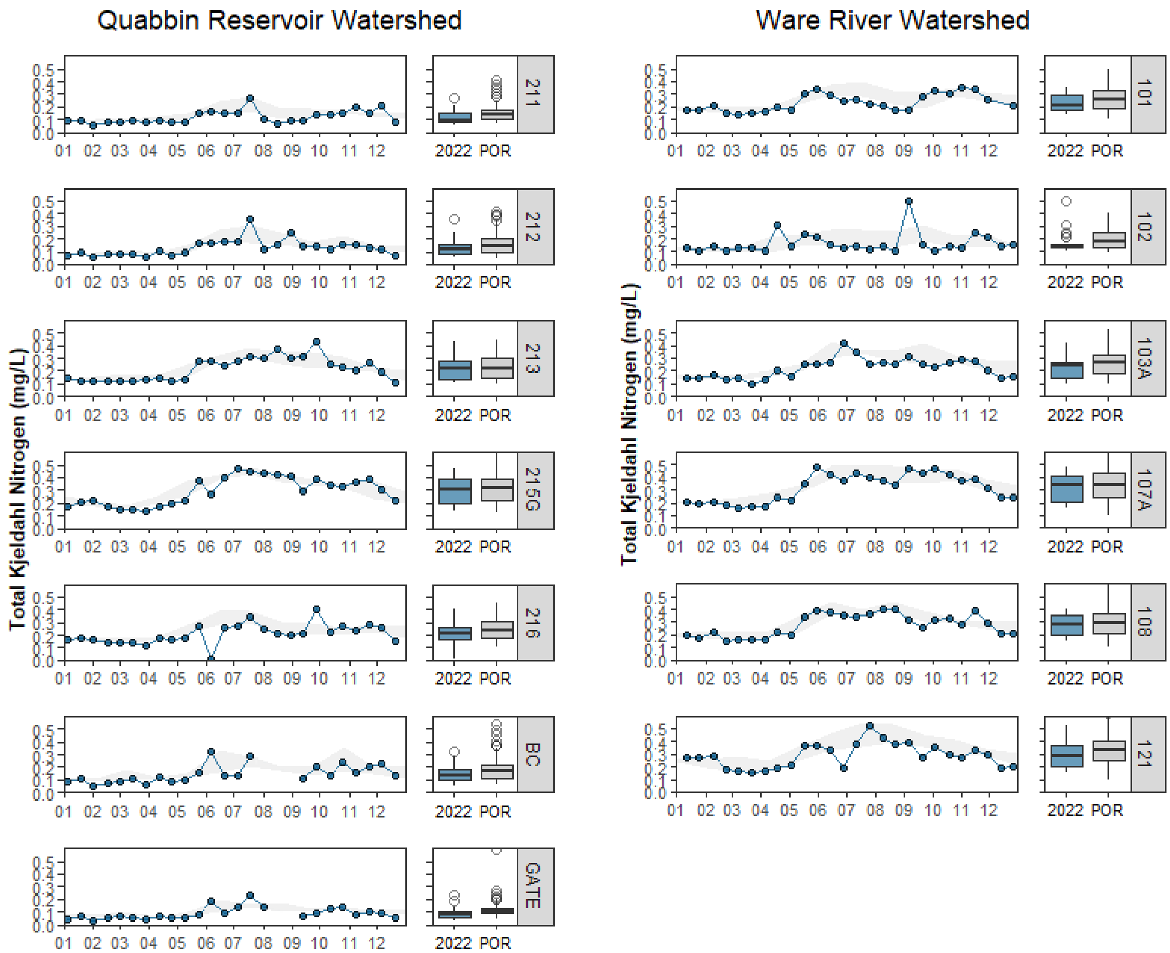

Figure 14: Time series and boxplots of TKN measured in Quabbin Reservoir Watershed Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel.

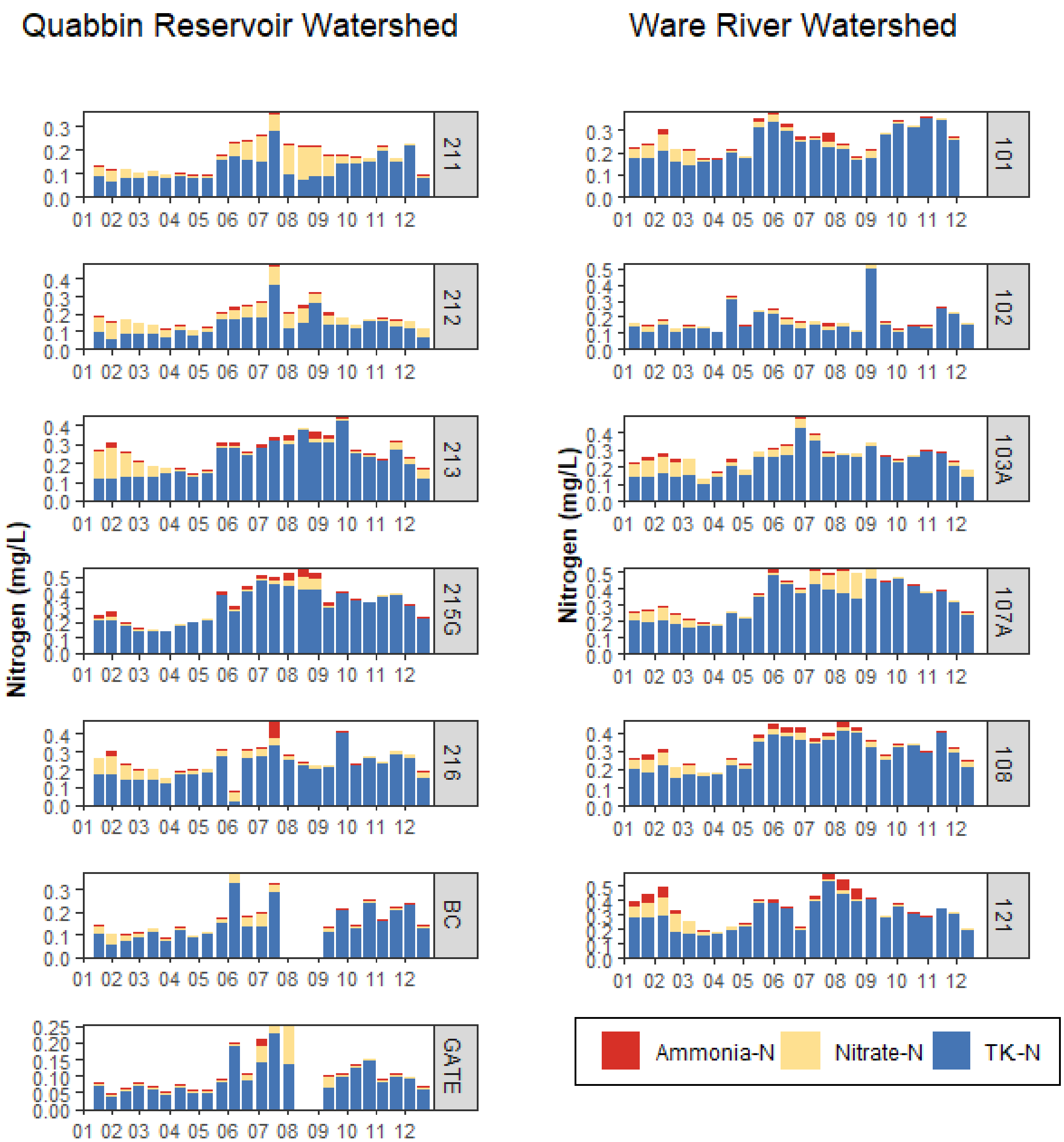

Figure 15: Bar plots depicting the temporal distributions of nitrogen species observed in Quabbin Reservoir Watershed Core tributary sites during 2022.

Table 28: Descriptive statistics (minimum, median, mean, and maximum) for TKN measured in Core tributary sites in the Quabbin Reservoir Watershed during 2022. Detection limits for TKN were 0.100 mg/L until 2020.

Location	Season	Total Kjeldahl Nitrogen (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	6	26	0.060	0.081	0.084	0.097	0.102	0.110	0.214	0.208
	Spring	7	28	0.075	0.071	0.080	0.098	0.091	0.113	0.154	0.331
	Summer	7	31	0.068	0.100	0.148	0.169	0.142	0.202	0.274	0.417
	Fall	6	31	0.086	0.088	0.142	0.148	0.141	0.149	0.194	0.215
212	Winter	6	25	0.057	0.071	0.075	0.099	0.081	0.114	0.120	0.339
	Spring	7	28	0.063	0.047	0.082	0.092	0.094	0.126	0.163	0.421
	Summer	7	30	0.112	0.117	0.173	0.221	0.198	0.226	0.362	0.396
	Fall	6	31	0.114	0.073	0.137	0.137	0.138	0.151	0.159	0.258
213	Winter	6	26	0.113	0.100	0.120	0.139	0.134	0.155	0.194	0.266
	Spring	7	28	0.122	0.100	0.139	0.166	0.154	0.173	0.281	0.283
	Summer	7	29	0.240	0.199	0.301	0.314	0.299	0.318	0.377	0.440
	Fall	6	31	0.206	0.133	0.259	0.237	0.282	0.256	0.426	0.408
215G	Winter	5	16	0.169	0.127	0.212	0.238	0.215	0.242	0.304	0.392
	Spring	7	18	0.135	0.163	0.179	0.238	0.198	0.283	0.374	0.566
	Summer	7	20	0.269	0.321	0.418	0.421	0.407	0.420	0.470	0.567
	Fall	6	19	0.293	0.191	0.354	0.339	0.349	0.350	0.386	0.713
216	Winter	6	26	0.139	0.110	0.164	0.214	0.176	0.218	0.262	0.337
	Spring	7	28	0.123	0.100	0.170	0.176	0.171	0.192	0.274	0.410
	Summer	7	29	0.016	0.169	0.253	0.313	0.223	0.328	0.338	0.448
	Fall	6	31	0.213	0.151	0.250	0.248	0.270	0.251	0.405	0.415
BC	Winter	6	26	0.054	0.093	0.098	0.147	0.113	0.153	0.229	0.259
	Spring	7	28	0.066	0.067	0.102	0.117	0.104	0.139	0.152	0.242
	Summer	4	25	0.131	0.143	0.210	0.213	0.220	0.249	0.329	0.538
	Fall	6	25	0.110	0.100	0.180	0.172	0.174	0.210	0.242	0.450
GATE	Winter	6	26	0.035	0.048	0.055	0.073	0.058	0.087	0.088	0.244
	Spring	7	28	0.044	0.044	0.056	0.070	0.058	0.082	0.080	0.188
	Summer	5	28	0.086	0.063	0.139	0.142	0.155	0.151	0.228	0.592
	Fall	6	30	0.061	0.065	0.095	0.106	0.099	0.109	0.143	0.199

Table 29: Descriptive statistics (minimum, median, mean, and maximum) for TKN measured in Core tributary sites in the Ware River Watershed during 2022. Detection limits for TKN were 0.100 mg/L until 2020.

Location	Season	Total Kjeldahl Nitrogen (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	4	22	0.155	0.139	0.172	0.223	0.177	0.226	0.208	0.391
	Spring	7	18	0.141	0.100	0.169	0.190	0.210	0.191	0.337	0.266
	Summer	6	22	0.168	0.246	0.232	0.356	0.232	0.351	0.294	0.500
	Fall	7	20	0.176	0.124	0.309	0.280	0.290	0.273	0.348	0.459
102	Winter	5	6	0.102	0.096	0.134	0.124	0.126	0.119	0.144	0.131
	Spring	7	6	0.100	0.092	0.136	0.120	0.177	0.140	0.307	0.242
	Summer	6	7	0.107	0.187	0.130	0.277	0.129	0.280	0.152	0.404
	Fall	7	7	0.102	0.107	0.151	0.183	0.211	0.213	0.499	0.343
103A	Winter	5	28	0.135	0.117	0.143	0.192	0.145	0.208	0.165	0.391
	Spring	7	25	0.097	0.100	0.153	0.171	0.177	0.185	0.254	0.386
	Summer	6	30	0.250	0.246	0.265	0.331	0.300	0.373	0.420	0.971
	Fall	7	30	0.203	0.137	0.258	0.306	0.259	0.315	0.313	0.670
107A	Winter	5	28	0.185	0.122	0.202	0.224	0.206	0.259	0.242	0.526
	Spring	7	25	0.162	0.100	0.218	0.240	0.257	0.241	0.480	0.339
	Summer	6	30	0.336	0.327	0.386	0.458	0.388	0.466	0.430	0.926
	Fall	7	30	0.314	0.185	0.416	0.379	0.407	0.382	0.464	0.519
108	Winter	5	28	0.146	0.101	0.197	0.214	0.191	0.241	0.222	0.383
	Spring	7	26	0.160	0.100	0.197	0.212	0.235	0.215	0.386	0.359
	Summer	6	30	0.340	0.281	0.368	0.401	0.372	0.415	0.403	0.590
	Fall	7	30	0.253	0.182	0.317	0.318	0.312	0.321	0.392	0.498
121	Winter	5	26	0.179	0.100	0.274	0.252	0.240	0.277	0.288	0.644
	Spring	7	27	0.150	0.120	0.195	0.260	0.233	0.266	0.371	0.398
	Summer	6	28	0.187	0.100	0.385	0.448	0.376	0.510	0.528	2.040
	Fall	7	32	0.277	0.253	0.301	0.360	0.321	0.378	0.397	0.591

3.2.5.2 Total Phosphorus

Total phosphorus (TP) concentrations measured in Core monitoring tributaries in the Quabbin Reservoir during 2022 ranged from 0.006 to 0.129 mg/L (Figure 16).

Seasonal median concentrations of TP were comparable to the period of record. Concentrations of TP in Core tributaries in the Quabbin Reservoir Watershed exhibited season dynamics typical of that observed previously (e.g., enrichment in summer/fall and relative depletion during winter/spring) (DWSP, 2020a). Relative site-to-site variability was consistent with prior monitoring periods, although variable concentration-discharge relationships existed across sites. TP concentrations in Core tributary monitoring locations in the Quabbin Reservoir Watershed exceeded EPA ecoregional background TP concentrations for Region VIII - Subregion 58 (0.005 mg/L) on all dates and Region XIV - Subregion 59 (0.024 mg/L) on select dates during 2022.

The maximum concentration of TP (0.129 mg/L) observed in Quabbin Reservoir watershed tributaries in 2022 occurred in the sample collected at Gates Brook on August 02, 2022. This date corresponded to exceptionally low streamflow conditions across the watershed, with a stage reading at Gates Brook of 0.75 ft, the lowest observation at this site for 2022. The proceeding routine sample (August 17, 2022) was not collected due to dry stream conditions. Additionally, DWSP owns the entirety of the upstream reaches of Gates Brook. Thus, the new historical maximum concentration of TP observed at Gates Brook in 2022 is likely not indicative of new sources of TP to the stream channel, but rather potentially the result of lack of recent precipitation inputs and high rates of evapotranspiration, algal inputs, or artificial introduction of stream substrate materials into sample collection containers during low flow collections.

In the Ware River Watershed, TP concentrations were between <0.005 to 0.145 mg/L in 2022 (Figure 16). Similar to patterns observed in the Quabbin Reservoir Watershed during 2022, TP concentrations were comparable to seasonal medians for the period of record at all sites with a consistent monitoring record and during all seasons in 2022. EPA ecoregional background TP concentrations for Region VIII - Subregion 58 and Region XIV - Subregion 59 (0.005 mg/L and 0.024 mg/L) were exceeded by Core tributaries in the Ware River Watershed for much of 2022.

TP concentrations exhibited distinct seasonality for select Core sites in both watersheds (Figure 16). In tributaries in the Quabbin Reservoir Watershed and Ware River Watershed, TP concentrations were greatest during the summer and early fall and comparatively lower during the spring and winter, behavior consistent with other forested headwater catchments in the NE USA (Lisboa et al., 2016). The observed gradient in TP concentrations across Quabbin Reservoir and Ware River Watersheds may be partially attributed to variations in land cover, wetland connectivity, groundwater contributions, and timing of sample collection relative to hydrometeorological events (Reddy et al., 1999; Lisboa et al., 2016). Precipitation events in September 2022 resulted in peaks in stream TP concentrations in Core tributaries (Figure 16). In contrast, the two-watersheds exhibited a mixed response of TP concentrations relative to variable antecedent wetness and temperature regimes, highlighting the complexities of process-driven loading of TP to Quabbin Reservoir (Morris et al. 2014, Lisboa et al., 2016). The prolonged period of drought that impacted the region throughout much of the latter half of 2022 likely helped to dampen observed fluctuations in TP concentrations that would have otherwise been observed following precipitation and subsequent loading events. Nevertheless, the monitoring interval of every two weeks in 2021 ultimately allowed for observation of these relationships and monitoring in 2022 highlighted the degree to which extended drought conditions may impact seasonal TP loading to Quabbin Reservoir upon the onset of rewetting.

Table 30: Descriptive statistics (minimum, median, mean, and maximum) for TP in Core tributary sites in the Quabbin Reservoir Watershed during 2022. Detection limits for TP were 0.005 mg/L.

Location	Season	Total Phosphorus (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	5	20	0.007	0.005	0.009	0.010	0.010	0.010	0.013	0.018
	Spring	7	23	0.007	0.005	0.013	0.012	0.012	0.012	0.014	0.028
	Summer	7	25	0.007	0.006	0.014	0.014	0.014	0.015	0.021	0.038
	Fall	6	25	0.007	0.005	0.009	0.010	0.010	0.012	0.015	0.022
212	Winter	5	19	0.010	0.006	0.011	0.011	0.013	0.012	0.022	0.022
	Spring	7	23	0.012	0.005	0.016	0.014	0.015	0.015	0.019	0.059
	Summer	7	24	0.016	0.011	0.021	0.020	0.023	0.023	0.040	0.056
	Fall	6	25	0.012	0.005	0.015	0.013	0.020	0.015	0.045	0.034
213	Winter	5	20	0.010	0.006	0.012	0.012	0.013	0.012	0.016	0.018
	Spring	7	23	0.012	0.005	0.014	0.014	0.016	0.014	0.025	0.024
	Summer	7	24	0.018	0.008	0.021	0.022	0.023	0.022	0.038	0.039
	Fall	6	25	0.014	0.008	0.016	0.016	0.020	0.015	0.037	0.023
215G	Winter	5	16	0.011	0.007	0.014	0.014	0.014	0.014	0.017	0.020
	Spring	7	18	0.010	0.009	0.013	0.014	0.013	0.014	0.021	0.027
	Summer	7	20	0.021	0.011	0.024	0.021	0.025	0.021	0.032	0.028
	Fall	6	19	0.015	0.009	0.018	0.017	0.018	0.016	0.022	0.020
216	Winter	5	20	0.013	0.008	0.016	0.014	0.015	0.014	0.017	0.021
	Spring	7	23	0.011	0.007	0.014	0.016	0.015	0.017	0.022	0.060
	Summer	7	24	0.013	0.009	0.020	0.025	0.019	0.026	0.027	0.045
	Fall	6	24	0.013	0.005	0.014	0.015	0.017	0.016	0.024	0.044
BC	Winter	5	20	0.011	0.007	0.013	0.013	0.014	0.015	0.018	0.031
	Spring	7	23	0.011	0.007	0.018	0.019	0.020	0.019	0.030	0.031
	Summer	4	22	0.020	0.010	0.024	0.022	0.026	0.024	0.038	0.061
	Fall	6	21	0.013	0.008	0.017	0.016	0.018	0.019	0.027	0.037
GATE	Winter	5	20	0.006	0.005	0.009	0.008	0.008	0.009	0.010	0.017
	Spring	7	23	0.006	0.005	0.012	0.011	0.011	0.011	0.015	0.023
	Summer	5	23	0.012	0.005	0.022	0.015	0.040	0.015	0.129	0.038
	Fall	6	23	0.008	0.005	0.014	0.012	0.013	0.013	0.019	0.025

Table 31: Descriptive statistics (minimum, median, mean, and maximum) for TP in Core tributary sites in the Ware River Watershed during 2022. Detection limits for TP were 0.005 mg/L.

Location	Season	Total Phosphorus (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	6	15	0.005	0.009	0.013	0.017	0.013	0.016	0.018	0.026
	Spring	7	14	0.009	0.007	0.015	0.013	0.016	0.014	0.026	0.022
	Summer	6	15	0.018	0.020	0.023	0.029	0.022	0.029	0.026	0.043
	Fall	7	14	0.014	0.009	0.018	0.026	0.018	0.024	0.022	0.035
102	Winter	6	6	0.005	0.010	0.016	0.017	0.016	0.017	0.021	0.026
	Spring	7	6	0.013	0.013	0.021	0.014	0.026	0.016	0.046	0.022
	Summer	6	7	0.024	0.022	0.028	0.028	0.028	0.029	0.032	0.038
	Fall	7	7	0.018	0.014	0.028	0.028	0.042	0.025	0.145	0.033
103A	Winter	6	21	0.005	0.008	0.012	0.014	0.012	0.015	0.014	0.029
	Spring	7	21	0.009	0.007	0.015	0.012	0.017	0.013	0.027	0.026
	Summer	6	23	0.021	0.019	0.024	0.033	0.026	0.031	0.032	0.045
	Fall	7	24	0.013	0.011	0.020	0.025	0.022	0.027	0.040	0.081
107A	Winter	6	21	0.005	0.007	0.013	0.014	0.013	0.014	0.020	0.022
	Spring	7	21	0.010	0.009	0.013	0.014	0.015	0.014	0.025	0.021
	Summer	6	23	0.017	0.018	0.027	0.030	0.025	0.031	0.031	0.057
	Fall	7	24	0.012	0.010	0.018	0.023	0.020	0.024	0.036	0.044
108	Winter	6	21	0.005	0.006	0.011	0.012	0.011	0.013	0.014	0.034
	Spring	7	22	0.008	0.008	0.011	0.012	0.014	0.012	0.024	0.020
	Summer	6	23	0.016	0.016	0.022	0.026	0.023	0.028	0.028	0.049
	Fall	7	24	0.014	0.008	0.018	0.022	0.023	0.022	0.041	0.037
121	Winter	6	26	0.005	0.007	0.013	0.012	0.012	0.012	0.015	0.020
	Spring	7	28	0.006	0.007	0.012	0.015	0.015	0.017	0.026	0.036
	Summer	6	30	0.016	0.015	0.023	0.032	0.023	0.031	0.033	0.056
	Fall	7	33	0.010	0.013	0.016	0.019	0.018	0.023	0.034	0.056

Analytical methods for TP were modified in 2020. TP concentrations for tributaries were derived via EPA Method 365.1 (O'Dell, 1993b) until January 01, 2020. Analysis was performed via Valderrama (1981) thereafter to facilitate increased monitoring frequencies of TP in Core tributaries (e.g., every two weeks). Analytical methods for TP returned to EPA methods in 2021. Uncertainty associated with TP concentration data for 2020 is limited to sensitivity of different analytical methods, as sample collection and storage were not altered in 2020. Because of the variation associated with the change in TP methods for 2020, TP concentration data corresponding to samples collected in 2020 were excluded from calculations for period of record statistics.

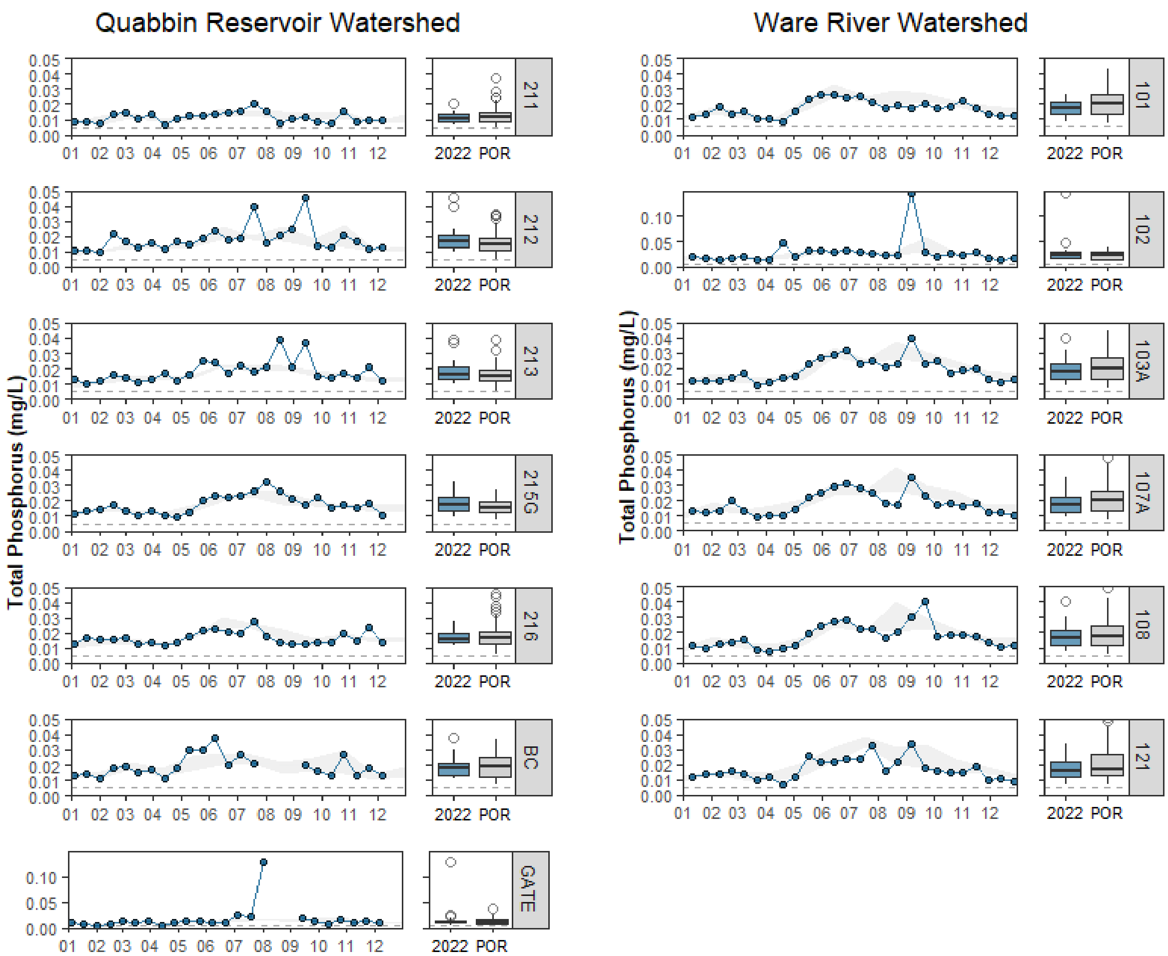

Figure 16: Time series and boxplots of TP measured in Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel. The horizontal dashed grey line corresponds to laboratory detection limits (0.005 mg/L).

3.2.6 Total Organic Carbon and UV_{254}

3.2.6.1 Total Organic Carbon

Total organic carbon (TOC) was introduced to DWSP monitoring programs in 2021 as an additional proxy for understanding disinfection-byproduct precursor potential of source waters in the Quabbin Reservoir Watershed (Golea et al., 2017). TOC was monitored every two weeks in Core tributaries in the Quabbin Reservoir Watershed beginning in January 2021. TOC was not measured in Ware River Watershed tributaries during 2022. Concentrations of TOC in Core tributaries in the Quabbin Reservoir Watershed ranged from 1.32 to 9.12 mg/L in 2022. TOC was elevated during the early summer or fall months at each site, with seasonality most pronounced at site 215G in the northeastern region of the watershed (Table 32), consistent with spatial gradients established several decades prior (Garvey and Tobiason, 2003). A large proportion of annual TOC export occurs during later summer and fall sampling, due to seasonal changes in temperature and streamflow (Clark et al., 2012), and during high flow events (Raymond and Saiers, 2010, Dhillon and Inamdar, 2013). Locations downstream of wetlands in Quabbin Reservoir Watershed (e.g., 215G and 216) generally had elevated TOC relative to locations with a lower proportion of wetland cover (e.g., GATE). Organic carbon export from catchments in the northern hemisphere has been linked to the proportion of the catchment that constitutes wetland land cover (Curtis, 1998; Raymond and Saiers, 2010). Median annual TOC concentrations in 2022 trended lower than annual medians in 2021, likely a reflection of the contrasting climatic conditions presented by the first two years of TOC monitoring (e.g., July 2021 marked the wettest July for the period of record in Belchertown, whereas a severe drought impacted the region for much of the summer and early fall of 2022).

High-resolution concentrations of TOC, in tandem with UV_{254} absorbance and streamflow data, may elucidate potential hot spots or hot moments of organic carbon loading to Quabbin Reservoir. TOC concentrations loosely mirror that of UV_{254} absorbance (typically elevated with high flow events, warmer temperatures, and associated with percentage of wetlands present in a catchment), suggesting that UV_{254} data alone may provide insights into organic matter processing and transport across the watershed. However, when considered alongside TOC concentrations, meaningful information may be generated regarding the quantity and type of organic matter, as wells as controls on its transport at the catchment scale (Section 3.2.6.2).

Continued long-term monitoring of TOC concentrations in Quabbin Reservoir Watershed may allow for a comprehensive understanding of processes controlling the transport, fate, and storage of organic matter across Quabbin Reservoir Watershed. Furthermore, TOC concentrations collected in conjunction with UV_{254} absorbance data may be used to generate a high-resolution spatial and temporal representation of DBP-precursor potential across the watershed, which may ultimately guide future management decisions. The latter is of particular interest, given increasing trends in riverine organic carbon (Worrall and Burt, 2004; Ledesma et al., 2012; Gavin et al., 2018) linked to changes in atmospheric sulfate deposition, rising temperatures, and changes in precipitation and streamflow regimes (Evans et al., 2006; Ren et al., 2016; Garvin et al., 2018).

Table 32: Descriptive statistics (minimum, median, mean, and maximum) for TOC in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2022, the second year of routine TOC monitoring in tributary sites.

Location	Season	Total Organic Carbon (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	2021	2022	2021	2022	2021	2022	2021	2022	2021
211	Winter	6	6	1.79	2.20	2.71	2.86	2.92	2.78	4.30	3.06
	Spring	7	7	2.31	2.13	2.52	2.73	2.72	2.79	3.81	3.78
	Summer	7	7	1.38	2.47	2.72	3.38	2.57	3.86	4.42	5.47
	Fall	6	6	2.70	3.25	3.64	3.71	3.76	4.20	4.96	6.15
212	Winter	6	6	1.32	1.61	2.27	2.29	2.27	2.32	3.19	2.82
	Spring	7	7	2.00	1.89	2.25	2.52	2.49	2.57	3.77	3.28
	Summer	7	7	2.41	3.12	3.23	3.54	3.50	3.99	6.73	5.88
	Fall	6	6	2.54	2.67	3.37	3.21	3.41	3.69	4.33	6.45
213	Winter	6	6	1.96	2.25	3.20	3.23	3.41	3.11	5.17	3.66
	Spring	7	7	2.71	2.65	3.08	3.40	3.42	3.66	5.61	5.00
	Summer	7	7	4.34	4.28	4.79	5.05	4.84	5.22	5.72	6.80
	Fall	6	6	4.34	3.49	6.05	4.62	5.81	4.41	6.96	5.33
215G	Winter	6	5	4.87	4.99	5.66	5.90	5.95	5.78	7.96	6.33
	Spring	7	7	3.97	3.74	4.36	5.34	4.95	5.19	7.76	6.53
	Summer	7	6	6.28	7.51	7.53	9.10	7.40	8.83	8.33	10.00
	Fall	6	6	6.28	7.77	8.11	9.63	8.00	9.38	9.12	10.80
216	Winter	6	6	3.57	3.62	4.36	4.85	4.76	4.60	6.29	5.40
	Spring	7	7	3.46	3.60	3.93	4.63	4.11	4.61	5.90	5.80
	Summer	7	7	3.69	4.74	4.59	6.62	4.58	6.45	5.37	9.40
	Fall	6	6	5.49	5.56	6.52	6.99	6.52	6.91	7.54	7.94
BC	Winter	6	6	1.61	2.44	3.13	4.19	3.47	4.02	5.31	5.26
	Spring	7	7	2.78	2.55	3.04	3.49	3.30	4.15	4.24	6.25
	Summer	4	7	2.99	2.69	3.19	3.82	4.02	4.47	6.71	7.93
	Fall	6	6	3.88	3.87	4.87	4.29	5.33	5.69	8.36	13.20
GATE	Winter	6	6	1.34	1.77	2.31	2.56	2.18	2.42	2.68	2.81
	Spring	7	7	2.11	1.82	2.29	2.35	2.39	2.48	3.04	3.49
	Summer	5	7	2.28	1.77	2.50	2.85	3.31	2.89	6.55	4.41
	Fall	6	6	2.39	2.69	2.59	2.97	2.98	3.51	4.92	6.38

3.2.6.2 UV_{254}

UV_{254} absorbance in Quabbin Reservoir Watershed Core tributary monitoring sites ranged from 0.033 to 0.422ABU/cm in 2022 (Figure 17, Table 33). UV_{254} was lower in tributaries along the west arm of the Quabbin Reservoir and on Prescott Peninsula (e.g., GB, 211, 212) than those located within the northernmost reaches of the watershed (e.g., 213, 215G) or on the east arm (216). Seasonal dynamics in UV_{254} absorbance measured in Core tributaries in the Quabbin Reservoir Watershed were comparable to that of the period of record for the majority of Core tributary monitoring sites in the watershed during 2022. The Core sites located along the east arm of the Quabbin Reservoir (215G and 216) demonstrated a greater deviation from historical seasonal medians during the summer and fall months when streamflow conditions were routinely below normal and drought conditions impacted the region (Section 3.1.1.2). Following rewetting beginning in September and into fall months, UV_{254} increased towards typical ranges values at most sites. Prior to 2020, UV_{254} was measured quarterly in Quabbin Reservoir Watershed Core tributaries (DWSP, 2019a). Thus, some of the variability in UV_{254} observed in 2022 relative to historical seasonal ranges may be attributed to differences in sample frequencies, with more frequent samples more likely to capture hydrologic-driven variability in stream UV_{254} dynamics. Furthermore, deviations from the seasonal medians for each site for the periods of record may also be attributed to the distinct hydrologic conditions presented in 2021 (e.g., low flow through spring months followed by record-breaking precipitation totals in July).

UV_{254} absorbance in Ware River Watershed Core tributary monitoring sites ranged from 0.087 to 0.573 ABU/cm in 2022 (Figure 17, Table 34). Median UV_{254} in Core monitoring tributaries in the Ware River Watershed in 2022 trended near or below seasonal medians for winter, spring, and summer samples, and exceeded seasonal medians during the fall for most Core sites with a continuous record. Monitoring frequency for UV_{254} in Core tributaries in the Ware River Watershed did not change in 2022. UV_{254} was generally greater in Core tributaries in the Ware River Watershed compared to Core tributaries in the Quabbin Reservoir Watershed. A greater percentage of wetlands comprises the upstream reaches of Core tributaries in the Ware River Watershed (Table 4). The timing of seasonal variability in absorbance values of UV_{254} was comparable between Ware River and Quabbin Reservoir Watersheds for 2022 (e.g., UV_{254} absorbance peaked during summer months for both watersheds, coincident with warmer water temperatures). Moreover, historical variations in sampling frequencies (e.g., quarterly vs. every two weeks) in Core monitoring tributaries in the Quabbin Reservoir Watershed compared to those in the Ware River Watershed may serve to mask inter-watershed differences in pre-2020 data.

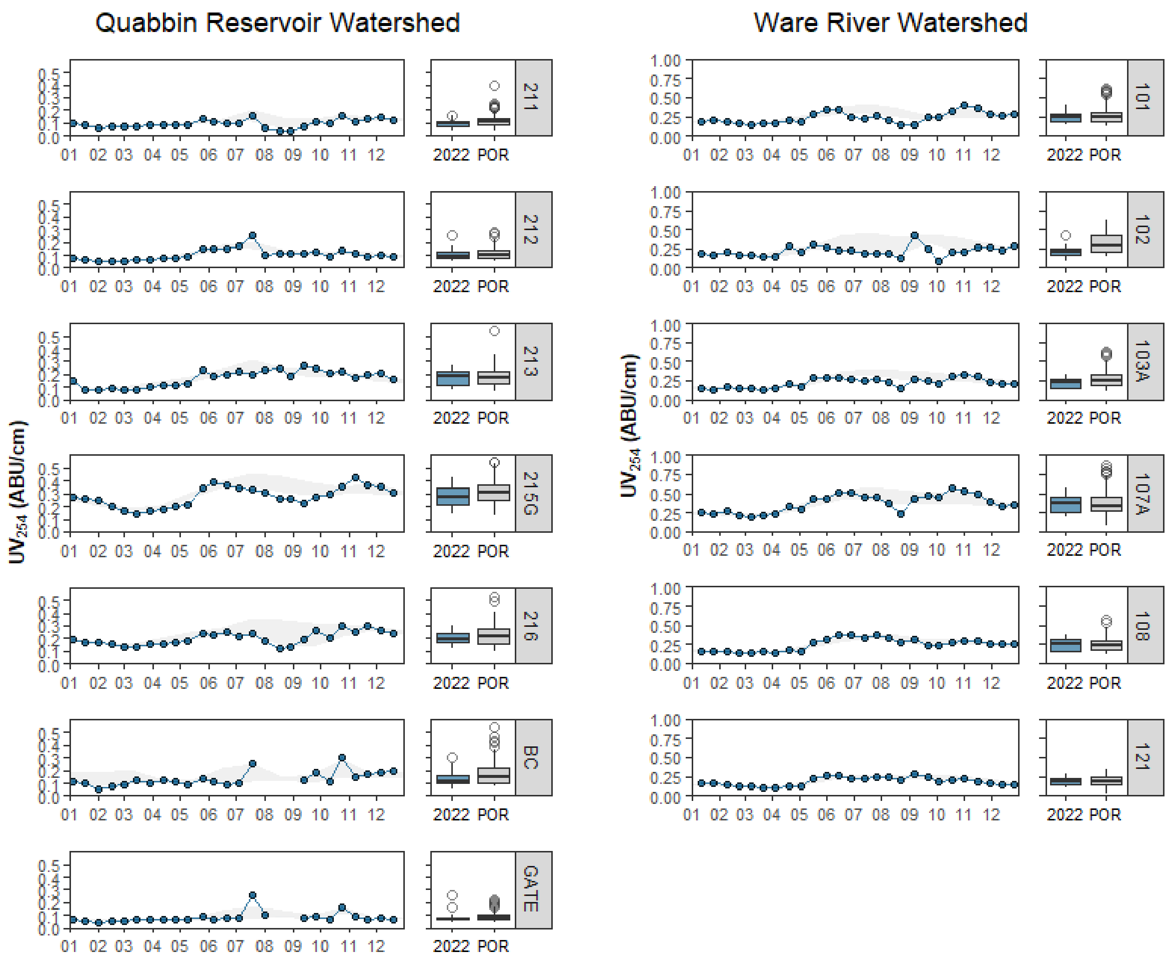

Figure 17: Time series and boxplots of UV_{254} measured in Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel.

Table 33: Descriptive statistics (minimum, median, mean, and maximum) for UV_{254} measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2022.

Location	Season	UV_{254} (ABU/cm)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	6	22	0.068	0.066	0.092	0.109	0.099	0.113	0.145	0.159
	Spring	7	24	0.071	0.060	0.085	0.086	0.089	0.094	0.138	0.221
	Summer	7	26	0.033	0.076	0.102	0.128	0.087	0.155	0.162	0.390
	Fall	6	24	0.073	0.041	0.108	0.129	0.113	0.124	0.156	0.231
212	Winter	6	22	0.049	0.053	0.072	0.079	0.072	0.083	0.102	0.142
	Spring	7	24	0.055	0.048	0.075	0.078	0.080	0.085	0.148	0.157
	Summer	7	25	0.097	0.067	0.148	0.174	0.147	0.170	0.250	0.279
	Fall	6	24	0.086	0.052	0.112	0.104	0.109	0.110	0.136	0.223
213	Winter	6	22	0.076	0.072	0.120	0.129	0.129	0.134	0.209	0.227
	Spring	7	24	0.085	0.065	0.110	0.114	0.122	0.131	0.234	0.292
	Summer	7	26	0.185	0.182	0.203	0.238	0.210	0.260	0.243	0.546
	Fall	6	24	0.169	0.135	0.219	0.196	0.220	0.195	0.272	0.327
215G	Winter	6	16	0.203	0.200	0.265	0.279	0.274	0.272	0.361	0.326
	Spring	7	18	0.146	0.132	0.175	0.214	0.203	0.223	0.342	0.320
	Summer	7	20	0.262	0.303	0.332	0.396	0.323	0.410	0.388	0.547
	Fall	6	19	0.230	0.252	0.326	0.316	0.325	0.354	0.422	0.548
216	Winter	6	22	0.159	0.130	0.184	0.222	0.201	0.220	0.268	0.308
	Spring	7	24	0.130	0.108	0.162	0.168	0.167	0.177	0.242	0.264
	Summer	7	26	0.126	0.121	0.211	0.271	0.196	0.286	0.249	0.520
	Fall	6	24	0.190	0.103	0.263	0.257	0.255	0.231	0.304	0.401
BC	Winter	6	22	0.052	0.089	0.108	0.160	0.120	0.168	0.194	0.285
	Spring	7	24	0.084	0.080	0.108	0.111	0.110	0.156	0.137	0.358
	Summer	4	23	0.093	0.092	0.105	0.141	0.138	0.189	0.249	0.467
	Fall	6	20	0.118	0.080	0.161	0.152	0.175	0.187	0.298	0.535
GATE	Winter	6	22	0.041	0.050	0.064	0.074	0.062	0.074	0.078	0.103
	Spring	7	24	0.057	0.046	0.070	0.063	0.069	0.074	0.088	0.156
	Summer	5	25	0.072	0.055	0.085	0.099	0.118	0.113	0.254	0.207
	Fall	6	23	0.065	0.062	0.084	0.088	0.093	0.097	0.169	0.225

Table 34: Descriptive statistics (minimum, median, mean, and maximum) for UV_{254} measured in Core tributary monitoring sites in the Ware River Watershed during 2022.

Location	Season	UV_{254} (ABU/cm)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	6	66	0.169	0.119	0.193	0.201	0.212	0.205	0.282	0.398
	Spring	7	62	0.143	0.114	0.184	0.198	0.208	0.207	0.334	0.337
	Summer	6	66	0.132	0.167	0.234	0.329	0.231	0.339	0.331	0.599
	Fall	7	63	0.132	0.128	0.270	0.268	0.282	0.290	0.392	0.613
102	Winter	6	6	0.158	0.151	0.190	0.197	0.203	0.198	0.288	0.239
	Spring	7	6	0.150	0.144	0.198	0.189	0.218	0.198	0.308	0.287
	Summer	6	7	0.117	0.283	0.190	0.424	0.186	0.446	0.224	0.623
	Fall	7	7	0.087	0.229	0.236	0.406	0.241	0.387	0.430	0.471
103A	Winter	6	84	0.134	0.103	0.157	0.182	0.169	0.186	0.217	0.384
	Spring	7	99	0.138	0.103	0.175	0.176	0.197	0.190	0.290	0.622
	Summer	6	108	0.150	0.208	0.261	0.345	0.241	0.349	0.278	0.587
	Fall	7	109	0.202	0.136	0.271	0.265	0.273	0.280	0.327	0.609
107A	Winter	6	88	0.219	0.172	0.255	0.271	0.274	0.276	0.352	0.550
	Spring	7	103	0.203	0.070	0.287	0.273	0.305	0.285	0.433	0.484
	Summer	6	105	0.241	0.155	0.456	0.484	0.422	0.486	0.506	0.864
	Fall	7	108	0.386	0.164	0.472	0.404	0.476	0.414	0.573	0.772
108	Winter	6	103	0.138	0.119	0.159	0.177	0.185	0.185	0.253	0.312
	Spring	7	108	0.138	0.116	0.158	0.173	0.195	0.184	0.324	0.300
	Summer	6	107	0.274	0.204	0.357	0.329	0.346	0.331	0.373	0.579
	Fall	7	108	0.235	0.189	0.281	0.262	0.274	0.278	0.315	0.481
121	Winter	6	26	0.120	0.091	0.148	0.146	0.145	0.145	0.163	0.191
	Spring	7	28	0.097	0.029	0.123	0.126	0.150	0.133	0.257	0.209
	Summer	6	30	0.205	0.180	0.231	0.243	0.229	0.244	0.257	0.338
	Fall	7	33	0.153	0.139	0.201	0.216	0.208	0.214	0.287	0.312

3.2.7 Calcium and pH

3.2.7.1 Calcium

Calcium (Ca) monitoring in Quabbin Reservoir watershed tributaries began in 2010 to assess the risk of colonization by aquatic invasive organisms (e.g., zebra mussels). Monitoring for Ca began in tributaries in the Ware River watershed in 2018. Calcium concentrations below 12 mg/L, in combination with a pH of less than 7.4, result in a low risk of zebra mussel colonization (DCR and MA Division of Fish and Game, 2009).

Ca concentrations in Quabbin Reservoir watershed Core sites in 2022 ranged from 0.65 to 12.1 mg/L and were largely within historical ranges observed for each site (Appendix C). The 12 mg/L Ca threshold was exceeded on July 05, 2022 at Boat Cove Brook, in the Quabbin Reservoir watershed, although pH at this location was routinely below 7.4, thus this site remains at low risk for colonization by zebra mussels.

The range of Ca concentrations observed in Core monitoring tributaries in the Ware River watershed was 2.08 to 21.9 mg/L Ca (Appendix C). Previously, the 12 mg/L Ca threshold was exceeded at site 121B (upstream of 121) in the Ware River watershed throughout the year. In 2022, 12 mg/L Ca was exceeded in samples collected across summer, fall, and winter months at 121. In all cases, pH remained below 7.4.

Comparable to prior monitoring, Ca concentrations were seasonally elevated during the summer and fall months at most Core tributaries in the Quabbin Reservoir and Ware River watersheds. The timing of seasonally elevated stream Ca concentrations relative to low streamflow conditions suggests that groundwater contributions may be a source of elevated calcium to some streams in the watershed (Appendix C). Continued monitoring of Ca in streams in the Quabbin Reservoir and Ware River watersheds will serve to better inform the drivers behind the seasonal dynamics and long-term trends in calcium concentrations observed in tributaries to the Quabbin Reservoir and Ware River.

3.2.7.2 pH

The pH in Core monitoring tributaries ranged from 5.41 to 7.71 in the Quabbin Reservoir watershed in 2022. pH of Core tributaries in the Ware River watershed spanned a comparable range in 2022, from a minimum of 5.50 to 6.97. MassDEP has established a recommended range of pH for the protection of aquatic life (6.5 to 8.3 SU and within 0.5 SU of the natural background range). Median pH values observed in Core monitoring tributaries in the Quabbin Reservoir watershed typically approached or fell below the minimum established standards for Class A inland waters as established by MassDEP (6.5 to 8.3) in 2022, consistent with prior observations throughout the period of record (DWSP, 2020a). The same was observed in tributaries in the Ware River watershed, although, in both watersheds, individual measurements of pH in 2022 exceeded the interquartile range for each site.

The annual precipitation-weighted mean pH of rainfall within the Quabbin Reservoir watershed has increased steadily over the past several decades (NADP, 2022). The established pattern of inter-site variability in pH was preserved in the 2022 record, relative to prior years. Spatial variability in surface water pH across the Quabbin Reservoir watershed and Ware River watershed may be attributed to variations in watershed characteristics such as geogenic variability and land use, and meteorological drivers. pH measurements of Core monitoring tributaries in 2022 were generally within established ranges for each site for the period of record (Appendix C).

Median summer pH at Core tributary monitoring sites in the Quabbin Reservoir watershed in 2022 was greater than that of the period of record across all sites with a consistent monitoring record (i.e., excluding 215G in the Quabbin Reservoir watershed, and 102 and 121 in the Ware River watershed). This may have been driven by below normal streamflow conditions present during much of the summer and fall months of 2022, and subsequent lack of low-pH rainfall inputs during this time.

3.2.8 Special Investigations

3.2.8.1 Forestry Water Quality Monitoring

3.2.8.1.1 Long-term Forestry Monitoring

Timber harvest in the treatment watershed (EBU) began on December 18, 2019, and was completed October 11, 2020, ending the calibration period of the long-term forestry monitoring study. Data from the calibration period is currently being analyzed and summarized for an upcoming report describing the pre-treatment relationship between watersheds. This reporting will serve as a basis for analyzing change during the post-treatment study period, beginning with data collected in late 2020 and into 2022.

3.2.8.1.2 Short-term Forestry Monitoring

The Environmental Quality Section reviewed forestry lot proposals, inspected sites, and updated the forestry water quality monitoring database in 2022. Field review of proposed DWSP timber lots was conducted in the Ware River and Quabbin Reservoir Watersheds. No issues were identified in 2022.

3.2.8.2 Environmental Quality Assessments

3.2.8.2.1 Fever Brook Sanitary District

Water quality in surface water in the Fever Brook sanitary district in 2022 was generally comparable to that of previous monitoring periods, with some exceptions (DWSP, 2023b). Data collected in 2022 were compared to historical data for these locations.

Surface water samples collected in 2022 throughout the Fever Brook sanitary district ultimately revealed no widespread indicators of impairment/degradation of water quality. Monitoring of EQA sites in the Quabbin Reservoir Watershed will shift to sites in the Quabbin Reservation sanitary district in 2023. Monitoring of tributaries in the Fever Brook sanitary district is anticipated to resume in 2027.

3.2.8.2.2 Burnshirt, Canesto, and Natty Sanitary District

Water quality in surface water in the Burnshirt, Canesto, and Natty sanitary district in 2022 was similar to that of previous monitoring periods, with some exceptions (DWSP, 2023c). Data collected in 2022 were compared to historical data for these locations.

No widespread impairment/degradation of water quality was observed in surface waters in the Burnshirt, Canesto, and Natty sanitary district in 2022. Monitoring of EQA sites in the Ware River Watershed will shift to sites in the West Branch Ware sanitary district in 2023. Monitoring of tributaries in the Burnshirt, Canesto, and Natty sanitary district is anticipated to resume in 2027.

3.2.8.3 Water-Quality Database

DWSP continued to develop their water-quality database in 2022, processing and importing data from numerous monitoring workflows and organizing historical data records. Work related to DWSP data management and integration of historical records (prior to 2010) remains ongoing. This includes documentation of historical detection limits, verification of results, attribution of data flags, and ensuring completeness of record. Database development efforts continued to build off the database migrated to a SQL Server platform in 2021 for cloud-based storage and easy access for filtering and analyzing historical records. The current database contains historical water quality data including field parameters (water temperature, dissolved oxygen, oxygen saturation, specific conductance, pH, secchi depth, chlorophyll *a*, and phycocyanin) and constituent concentration results (alkalinity, NO3-N, NO2-N, NH3-N, TP, TKN, Ca, Na, Cl, Si, dissolved and total carbon, E. coli, total and fecal coliform, hardness, UV254, and turbidity), spanning the onset of DWSP monitoring (1987) through present. Workflows are developed using R, RStudio, ArcGIS, and SQL Server Management software to automate QA/QC and data import processes for incoming raw data generated from field equipment (e.g., multiparameter probes), MWRA lab results, and phytoplankton identification and enumeration, as well calibration records and field notes. In total there are 498,991 unique data records generated by DCR and MWRA dating from 1987 through 2022 in the DWSP water-quality database for Quabbin Reservoir and Ware River Watersheds. This includes 37,394 individual records processed and imported from 2022 data results.

3.3 Reservoir Monitoring

Water quality of the Quabbin Reservoir in 2022 continued to meet the stringent source water quality criteria stipulated under the SWTR and associated filtration avoidance waiver. The following sections provide a detailed summary of DWSP monitoring efforts conducted in 2022 for the purpose of evaluating the physical, chemical, and biological dynamics of the Quabbin Reservoir. Unless otherwise noted, data presented in this section were collected by DWSP.

Depth profiles of physiochemical parameters reveal general patterns in water column characteristics such as the timing of seasonal turnover and stratification, the relative position of the epilimnion, metalimnion, and hypolimnion, the general degree of mixing within the water column, and the timing and location of relative increases in primary productivity. For this report, several depth profiles of various physiochemical water quality parameters (temperature, pH, dissolved oxygen, specific conductance, pH, chlorophyll *a*, and phycocyanin) from each site were selected to demonstrate changes in seasonal conditions and show periods of peak primary productivity. 2022 was the second year an EXO2 multiparameter sonde was used for manual depth profiles, in place of the Eureka Manta used from 2006 to 2020. Seasonal descriptive statistics were calculated for each site to summarize the variation of conditions throughout 2022, relative to prior monitoring conditions (Table 35, Appendix C).

3.3.1 Water Temperature

Water column temperature profiles indicate the timing of seasonal changes in stratification throughout the Quabbin Reservoir (Figure 18). Shifts in the timing and extent of the various stages of stratification may have profound implications on water quality, ecology, and primary productivity. Though there were periods of partial ice coverage, the reservoir did not fully freeze in 2022. The timing of seasonal turnover was consistent with the historical record. Winter minimum temperatures were warmer than 2020 and 2021. Temperatures measured in 2022 remained within the established historical monitoring range for site 202. Temperatures at site 206 fell below historical minimum temperatures in the spring (March 10, 2022). Mean summer temperatures for 2022 were greater than that of the period of record across all stations, with the greatest divergence from seasonal means occurring at Den Hill (2.957°C warmer than the period of record). The minimum water column temperature at site 202 was 1.88 °C on March 10, 2022 (Table 35; 2.15 °C cooler than the minimum temperature observed in 2021 at site 202). Variations in temporal coverage across years (resulting from ice coverage) may in part drive deviations in observed temperatures during the winter and spring months.

Table 35: Descriptive statistics (minimum, median, mean, and maximum) for physical water quality parameters monitored in Quabbin Reservoir during 2022 at DWSP monitoring site 202. (See Appendix C for descriptive statistics on physical water quality parameters for DWSP monitoring sites 206 and Den Hill). Statistics provided include measurements conducted in conjunction with monthly Quabbin Reservoir water quality monitoring and routine phytoplankton sampling (January through December 2022). Negative phycocyanin concentrations (n=34) were excluded from calculations for descriptive statistics, as they likely represent sensor interference.

Parameter	Season	Count	Minimum	Median	Mean	Maximum
Water Temperature (°C)	Winter	84	4.7	4.8	5.9	7.0
	Spring	168	1.9	4.5	6.2	14.6
	Summer	455	7.2	10.5	13.3	25.4
	Fall	164	8.4	13.1	13.4	22.2
Chlorophyll (µg/L)	Winter	84	0.41	0.96	0.94	1.28
	Spring	168	0.21	1.02	1.08	2.05
	Summer	447	0	0.71	1.51	30.6
	Fall	164	0.04	0.58	0.51	0.94
Phycocyanin (µg/L)	Winter	84	0.17	0.32	0.38	0.63
	Spring	168	0.17	0.33	0.33	0.51
	Summer	427	0	0.53	0.45	1.26
	Fall	164	0.03	0.37	0.35	0.56
Dissolved Oxygen (mg/L)	Winter	84	11.3	11.9	11.7	12.2
	Spring	168	10.7	13.2	12.6	13.6
	Summer	455	8.1	10.7	10.5	12.5
	Fall	164	6.1	9.2	9.1	11.1
pH	Winter	43	6.6	6.7	6.8	7.8
	Spring	168	6.4	6.6	6.7	7.6
	Summer	455	5.8	6.6	6.6	7.9
	Fall	164	5.6	6.5	6.4	7.5
Specific Conductance (µS/cm)	Winter	84	47.0	48.0	49.0	51.3
	Spring	168	46.9	47.3	47.8	49.2
	Summer	455	47.0	47.5	47.6	49.0
	Fall	164	47.5	47.9	48.0	48.9

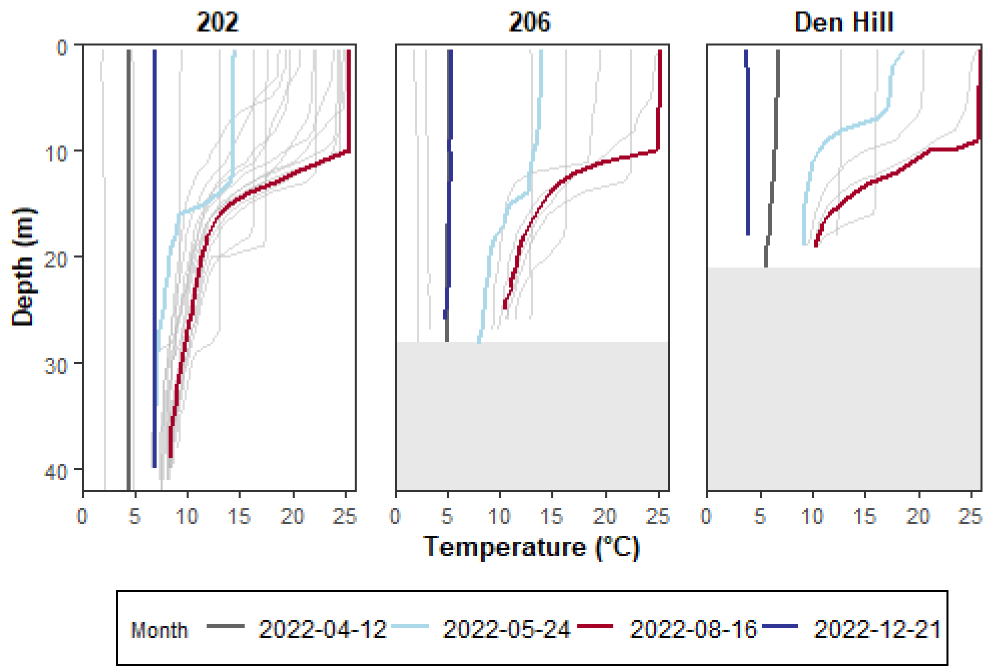

Figure 18: Profiles of temperature at Quabbin Reservoir Core sites on select dates in 2022. The April profile (gray) illustrates spring isothermy, which existed from the start of the sampling season through most of April at site 202 and was established sooner at 206 and Den Hill. The May profile (light blue) corresponds to the onset of reservoir stratification. The August profile (red) represents the maximum surface temperature observed at site 202 and continued stratification at all sites. The December profile (dark blue) shows a return to isothermy at all sites following fall turnover. Gray lines in each plot show profiles from other 2022 sample dates. Gray bands at sites 206 and Den Hill indicate the max water column depth recorded for 2022.

3.3.2 Chlorophyll *a*

Chlorophyll *a* may be used to estimate the overall biomass of the phytoplankton community. DWSP staff consult *in-situ* measurements of chlorophyll *a* (in addition to concentrations of dissolved oxygen) to determine the location in the water column where samples are collected for phytoplankton enumeration on a given date. On average, chlorophyll *a* concentrations in the reservoir are low, characteristic of low-productivity oligotrophic systems in New England.

In 2022, a temporary aggregation of *Chrysosphaerella* drove maximum chlorophyll *a* concentrations higher than is typically observed in the Quabbin Reservoir (Figure 19). The maximum chlorophyll *a* concentration observed via manual profiles collected by DWSP staff was 30.55 µg/L at 18 m depth on July 20, 2022 (Figure 20). The maximum chlorophyll *a* concentration observed for data collected by the MWRA EXO2 buoy was 103 µg/L at 20 m depth on July 27, 2022 (Figure 19). Chlorophyll *a* concentrations in excess of 15.0 µg/L were intermittently observed at site 202 within a discrete depth band (18 m to 22 m depth) during July and August via manual profile data generated by DWSP and by the MWRA EXO2 buoy (Figure 19, Figure 20). Though unusual for the Quabbin Reservoir, similar maximum values (34.63 µg/L at 18 m on September 03, 2019) were recorded in association with a *Chrysosphaerella* aggregation that occurred in 2019 (DWSP, 2022a). Despite these high maximum concentrations, chlorophyll *a* returned to baseline concentrations for the remainder of 2022 (Figure 19). In 2022, the mean summer chlorophyll *a* concentration at site 202 for the water column was 1.51 µg/L and 1.11 µg/L, for data collected by DWSP via manual profiles and by the MWRA EXO2 buoy, respectively (Table 35). Mean and median water column chlorophyll *a* concentrations at all sites in 2022 were similar to 2020. In contrast to the trends typically observed in chlorophyll *a* across sites, Den Hill had the lowest summer chlorophyll *a* maximum (15.22 µg/L) in 2022 (Appendix C).

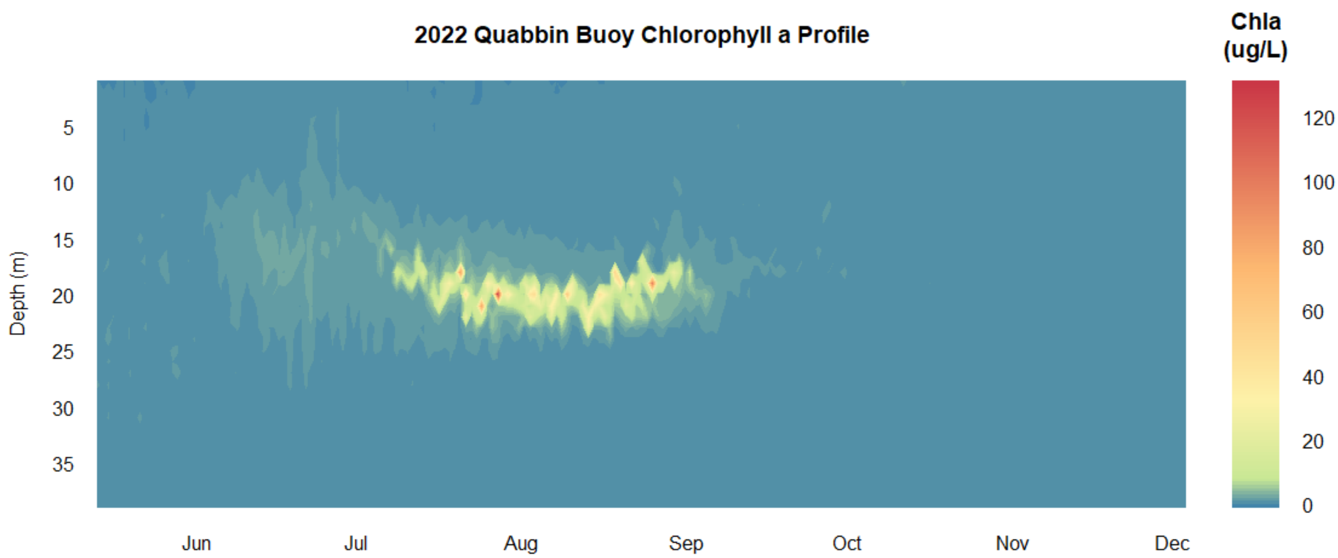

Figure 19: Chlorophyll *a* heatmap from buoy EXO2 noon profile collections from May through mid-December.

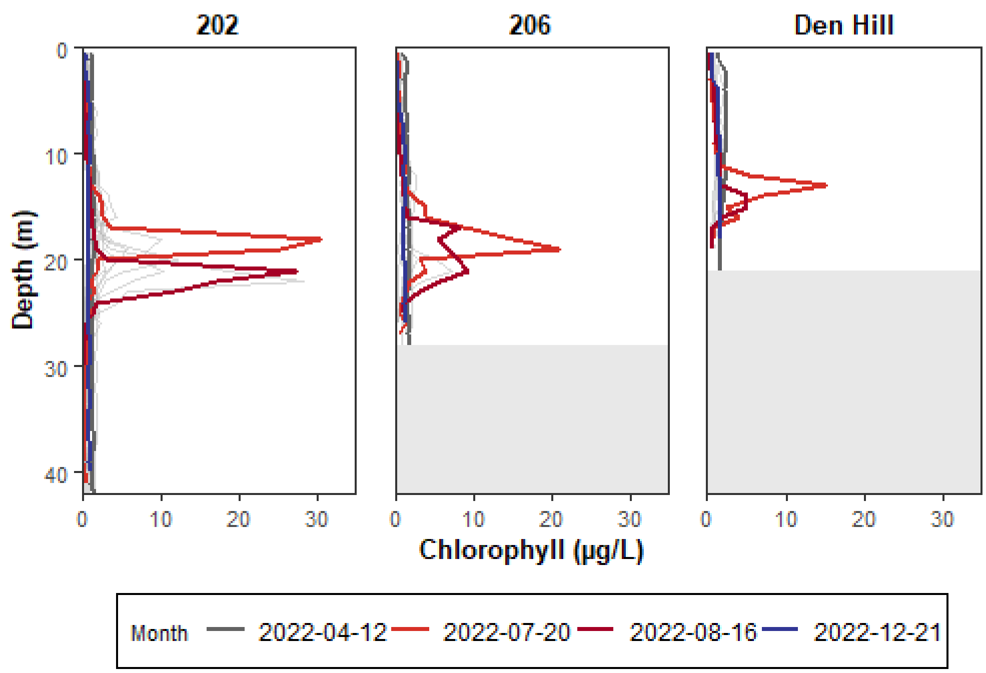

Figure 20: Profiles of chlorophyll *a* at Quabbin Reservoir Core sites on select dates in 2022. The April profile (dark gray) corresponds to a fully mixed water column and low to moderate density of diatoms in the spring, which existed from March through most of April at site 202. The July and August profiles (orange and red) correspond to documented Chrysophyte presence throughout Quabbin Reservoir. The December profile (blue) shows a return to a mixed water column following fall turnover. Gray lines in each plot show profiles from other 2022 sample dates. Gray bands at sites 206 and Den Hill indicate the max water column depth recorded for 2022.

3.3.3 Dissolved Oxygen

Concentrations of dissolved oxygen in Quabbin Reservoir followed expected seasonal patterns in 2022. Changes in dissolved oxygen concentrations in Quabbin Reservoir generally coincided with changes in water temperatures, followed stratification stages, and/or rose with relative increases in phytoplankton abundance (Figure 21). Dissolved oxygen concentrations were typically greater in the winter or spring, likely attributed to cooler water temperatures (Table 35, Appendix C). Concentrations of dissolved oxygen in surface water decreased with stratification, as the warmer water in the epilimnion became unable to hold as much oxygen as colder deep water. Once stratified, dissolved oxygen levels below the thermocline became elevated alongside an increase in phytoplankton activity in July at all sites and persisted below the epilimnion through August (Figure 21).

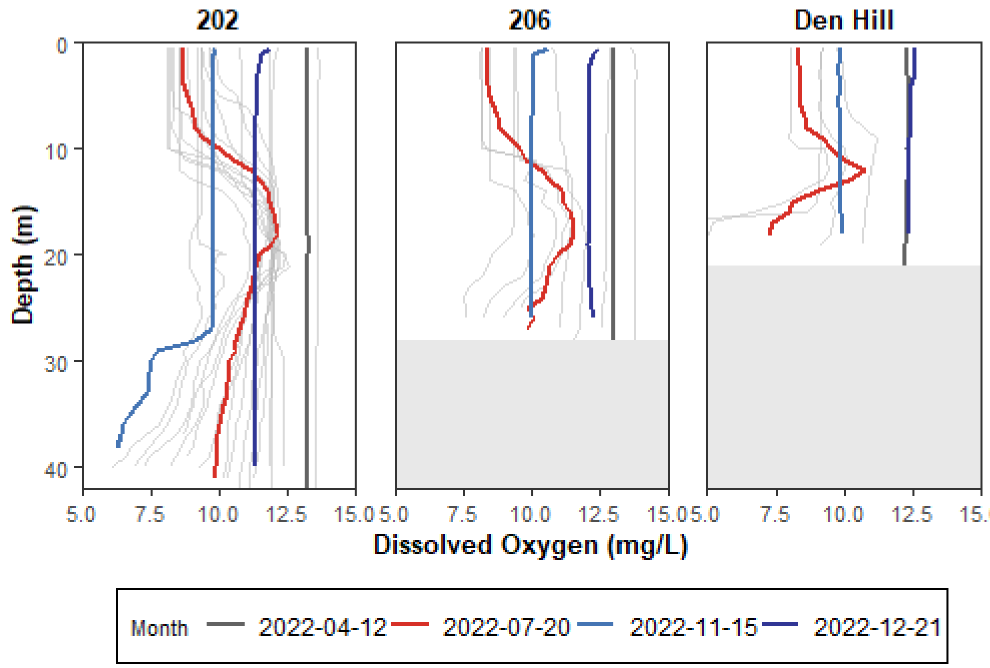

Figure 21: Profiles of dissolved oxygen at Quabbin Reservoir Core sites on select dates in 2022. The April profile (dark gray) illustrates the dissolved oxygen concentrations of a fully mixed water column in the spring, which existed from the start of the sampling season through most of April at site 202 and was established sooner at 206 and Den Hill. The July profile (red) depicts an increase in dissolved oxygen concentrations at depth, leading to stratification. The November profile (light blue) shows declining dissolved oxygen concentrations throughout the water column as productivity declined in the fall, prior to seasonal turnover. The December profile (dark blue) shows a return to a mixed water column following fall turnover. Gray lines in each plot show profiles from other 2022 sample dates. Gray bands at sites 206 and Den Hill indicate the max water column depth recorded for 2022.

Following typical seasonal patterns for Quabbin Reservoir, dissolved oxygen depletion was most pronounced during the late stages of stratification, with dissolved oxygen concentrations declining with depth. This was particularly distinct for water below the thermocline that remains isolated from atmospheric influence, and where rates of decomposition, a process that consumes oxygen, exceed photosynthesis. The minimum dissolved oxygen concentration in 2022 was 0.06 mg/L, at 19 m on October 18 at Den Hill (Appendix C). Dissolved oxygen is typically depleted at depth at Den Hill with an annual minimum between 0.87 and 2.41 mg/L in the last five years. However, the low bottom water concentrations observed at Den Hill in 2022 represent new historical minima. Dissolved oxygen concentrations were unremarkable for the entirety of the water column at sites 202 and 206 on the same date. At Den Hill, the observed bottom water hypoxia was limited to the lowermost 3 meters of the water column on October 18.

Following fall turnover in November, oxygen was recirculated throughout the water column. Dissolved oxygen was the greatest during the spring (annual maximum concentration of 13.79 mg/L at 202) (Figure 21). The median dissolved oxygen concentrations in 2022 remained above

6 mg/L at all sites (Table 35, Appendix C), sustaining concentrations required to support cold water aquatic species (314 CMR 4.06).

3.3.4 Alkalinity and pH

The dynamics of pH in Quabbin Reservoir are largely governed by the exchange of inorganic carbon between the atmosphere and water (carbon dioxide-bicarbonate-carbonate buffering). The pH of Quabbin Reservoir generally decreases with depth and may vary with changes in photosynthesis and respiration, and contributions from various weather events (e.g., freshwater inputs). Generally, pH within Quabbin Reservoir is unremarkable, ranging from 5.02 to 7.78 in 2022, and has not exhibited strong temporal trends since the onset of routine monitoring by DWSP. Quabbin Reservoir water remains slightly acidic with median pH at DWSP monitoring sites ranging from 6.51 to 6.83 in 2022 (Table 35).

Alkalinity in Quabbin Reservoir remained low (<7 mg/L as $CaCO_3$) throughout 2022 and exhibited little variability with depth, changes in stratification, or seasonality (Appendix C). Alkalinity concentrations ranged from 3.48 to 6.67 mg/L as $CaCO_3$ in 2022. Median alkalinity was generally greatest at Den Hill in 2022 (4.12 to 4.21 mg/L as $CaCO_3$), relative to other routine monitoring sites in Quabbin Reservoir. This pattern was consistent with previous years. Alkalinity measured at each site in the Quabbin Reservoir during 2022 approached or exceeded historical medians but remained within the established range of values for each site. Although an increase in alkalinity has been observed since 2015 in the Wachusett Reservoir (DWSP, 2021b), median annual alkalinity throughout the water column of the Quabbin Reservoir has remained relatively stable since 2015, following an initial increase from 2005 alkalinity concentrations (Appendix C). Increasing trends in low-alkalinity lakes and large rivers have been observed across the US and attributed to recovery from acid rain and contamination from road salt runoff (Stoddard et al., 1999; Stets et al., 2014; NH DES, 2020). Additionally, the pH (annual precipitation-weighted mean) of rainfall within the Quabbin Reservoir Watershed has been increasing steadily for decades (NADP, 2021). Temporal changes in alkalinity concentrations in lakes and reservoirs in New England may be attributed to interactions of multiple factors (e.g., natural geogenic variability, urbanization and associated chemical weathering of the built environment, acid rain inputs, or changes in or introduced during sample collection and analysis).

3.3.5 Specific Conductance, Sodium, and Chloride

Specific conductance measured in the Quabbin Reservoir has historically been quite low, relative to other water bodies in the northeastern United States, which may exceed 1,000 µS/cm in highly urbanized watersheds. The relatively low observed specific conductance in Quabbin Reservoir waters is likely a reflection of land cover (e.g., percent developed lands, total lane miles, and/or percentage of impervious surface cover), the low catchment area-to-surface area ratio of the Quabbin Reservoir, geogenic characteristics of the watershed, and land management practices across the watershed. Specific conductance in Quabbin Reservoir generally varies little with depth but does demonstrate a slight stratification at times, usually within the growing season when the water column is stratified. Typically, when specific conductance does display a slight stratification, it is greatest at the surface and declines with depth. In contrast to that, water column profiles collected in April 2022 exhibited lower specific conductance at the surface, and higher concentrations at depth at all sites (Figure 22). This vertical gradient was reversed across the reservoir throughout the summer months. Specific conductance measured in Quabbin Reservoir waters was within the historical ranges during 2022, ranging from an annual minimum across all sites of 46.9 µS/cm at site 202 in the spring, to an annual maximum across all sites of 54.5 µS/cm at Den Hill in the fall (Table 35; Appendix C).

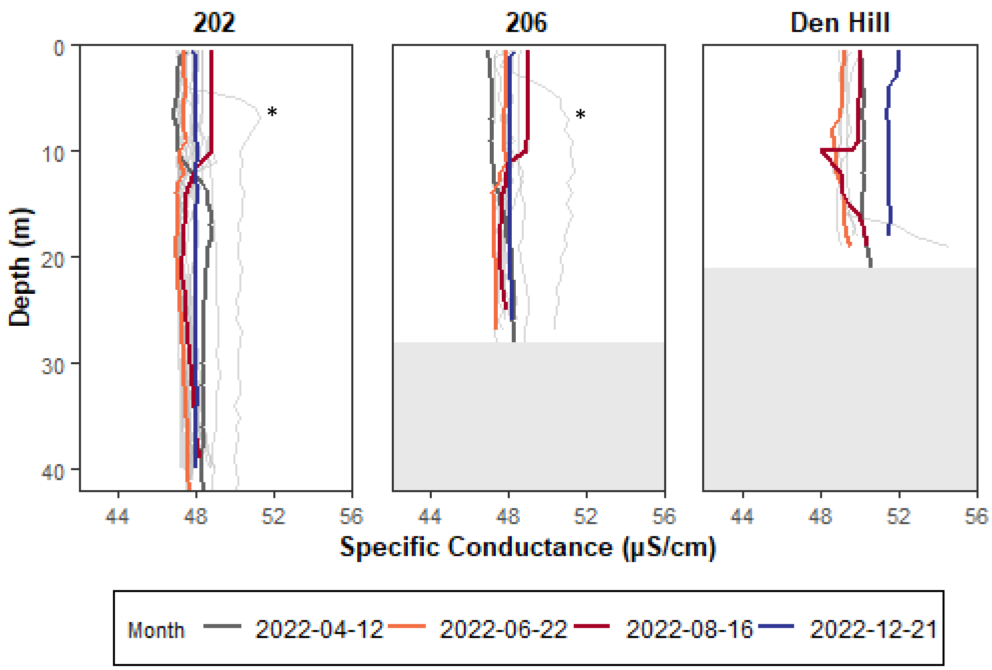

Figure 22: Profiles of specific conductance at Quabbin Reservoir Core sites in 2022. Selected colors represent the different stages of the water column in a year. The April profile (dark gray) corresponds to a mixed water column in the spring, which existed from March through most of April at site 202 and was established sooner at 206 and Den Hill. The June profile (yellow) depicts the beginning of summer stratification, and the August profile (red) represents a fully stratified water column. The December profile (blue) shows a return to a mixed water column following fall turnover. Light gray lines in each plot show profiles from other 2022 sample dates. *These two profiles show the maximum specific conductance for all of 2022, both observed on January 13, 2022.

Routine monitoring of concentrations of sodium (Na) and chloride (Cl) in Quabbin Reservoir began in 2020. In 2022, monitoring for Na and Cl in Quabbin Reservoir was conducted quarterly. Na concentrations ranged from a minimum of 5.2 mg/L at the middle of the water column of site 202, to a maximum of 5.94 in a deep sample collected at Den Hill (Table 36). Chloride concentrations ranged from a minimum of 7.74 at site 206 to a maximum of 9.39 mg/L at Den Hill. Sodium and chloride concentrations varied little with season, or with depth in the reservoir. Similar to other analytes, concentrations of both sodium and chloride were typically highest at Den Hill (Table 36). Median annual concentrations of Na and Cl measured in 2022 were comparable to prior results. Neither ORS guidelines for Na (20 mg/L) or the SMCL for Cl (250 mg/L) were exceeded in samples collected from Quabbin Reservoir in 2022.

Table 36: Concentration results for Na and Cl measured in Quabbin Reservoir during 2022 relative to the period of record (POR).

Location	Depth	Sodium (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
202	Surface	3	8	5.11	5.13	5.40	5.52	5.35	5.51	5.55	5.79
	Mid	3	8	5.38	5.35	5.47	5.55	5.47	5.54	5.55	5.74
	Deep	3	8	5.34	5.44	5.41	5.65	5.42	5.68	5.51	6.00
206	Surface	3	8	5.39	5.41	5.43	5.75	5.44	5.71	5.49	6.15
	Mid	3	8	5.22	5.20	5.44	5.43	5.40	5.54	5.53	6.11
	Deep	3	8	5.36	5.35	5.45	5.60	5.46	5.62	5.57	6.08
Den Hill	Surface	3	8	5.39	5.70	5.41	5.79	5.57	5.87	5.91	6.16
	Mid	3	8	5.53	5.45	5.56	5.78	5.63	5.76	5.81	6.00
	Deep	3	8	5.55	5.61	5.84	6.02	5.78	5.92	5.94	6.15
Location	**Depth**	**Chloride (mg/L)**									
		Count		**Minimum**		**Median**		**Mean**		**Maximum**	
		2022	**POR**	**2022**	**POR**	**2022**	**POR**	**2022**	**POR**	**2022**	**POR**
202	Surface	5	8	7.80	7.74	8.04	7.92	8.10	7.97	8.59	8.31
	Mid	5	8	7.79	7.77	7.94	7.93	8.03	8.00	8.26	8.29
	Deep	5	8	7.76	7.74	7.89	7.96	7.97	7.98	8.29	8.37
206	Surface	5	8	7.74	7.79	8.02	8.02	8.08	8.08	8.42	8.42
	Mid	5	8	7.80	7.78	8.08	8.03	8.05	8.06	8.20	8.32
	Deep	5	8	7.77	7.75	8.02	7.94	7.98	7.97	8.28	8.29
Den Hill	Surface	5	8	8.23	8.16	8.41	8.42	8.58	8.45	9.39	9.04
	Mid	5	8	8.23	8.17	8.49	8.46	8.57	8.45	9.15	8.90
	Deep	5	8	8.15	8.15	8.39	8.46	8.51	8.46	9.02	8.86

3.3.6 Turbidity

Turbidity measured in the Quabbin Reservoir was low and relatively stable throughout the year, reflective of the low productivity of the reservoir. Turbidity levels in Quabbin Reservoir ranged from 0.17 to 4.0 NTU during 2022 (Table 37), largely falling within the historical range of turbidity observed at DWSP monitoring sites (Figure 23). Turbidity remained below 1.0 NTU in Quabbin Reservoir in all but two discrete depth samples collected by DWSP in 2022.

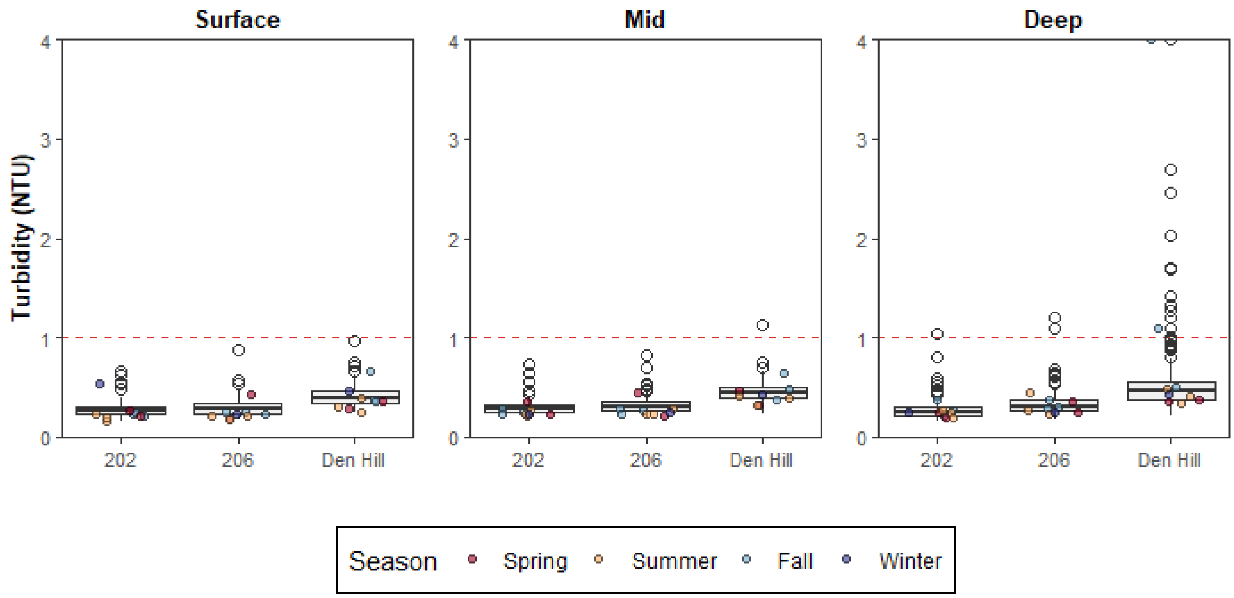

Figure 23: Boxplots depicting the seasonal and vertical distributions of turbidity in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2022 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The MassDEP 1 NTU standard, which applies to the intake, is marked by the red dashed line in each panel.

Den Hill is routinely elevated in turbidity relative to other Core monitoring locations within the Quabbin Reservoir. This well-established spatial gradient has previously been attributed to local inputs from the East Branch Swift River (DWSP, 2021a). The timing of the elevated turbidity observed at Den Hill in 2022 coincides with extreme events that impacted the region and observed bottom water hypoxia following a high-density proliferation of *Chrysosphaerella* at this location (Section 3.3.3, Section 3.3.9). Mean annual turbidity had been declining at surface and mid-depths since 2017. Mean annual turbidity increased at most station depths monitored in 2021 (DWSP, 2022), relative to the previous four years. Mean annual turbidity at depth in 2022 was less than that observed in 2021, continuing the downward trajectory observed prior to 2021 at all sites aside from Den Hill deep samples. 2022 marked the second consecutive year where mean annual turbidity measured at depth at Den Hill remained elevated. This result was largely driven by a single measurement (4.0 NTU) collected on October 18, 2022. Contributions from tributaries to the Quabbin Reservoir during high streamflow, wind-driven and hydrodynamic currents, and shoreline erosion may further contribute to instances of elevated turbidity measured in Quabbin Reservoir.

Table 37: Descriptive statistics for turbidity measured in the Quabbin Reservoir during 2022 relative to the period of record (POR).

Location	Depth	Turbidity (NTU)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
202	Surface	9	130	0.17	0.16	0.23	0.27	0.26	0.28	0.54	0.67
	Mid	9	149	0.22	0.19	0.24	0.29	0.26	0.30	0.36	0.73
	Deep	9	157	0.19	0.16	0.25	0.26	0.25	0.28	0.37	1.04
206	Surface	9	130	0.18	0.18	0.23	0.28	0.24	0.30	0.42	0.88
	Mid	9	146	0.22	0.19	0.24	0.31	0.27	0.32	0.45	0.82
	Deep	9	155	0.24	0.18	0.28	0.31	0.31	0.35	0.46	1.21
Den Hill	Surface	9	126	0.25	0.25	0.36	0.40	0.39	0.42	0.66	0.98
	Mid	9	142	0.32	0.24	0.41	0.44	0.43	0.46	0.65	1.13
	Deep	9	150	0.33	0.22	0.43	0.47	0.89	0.56	4.00	2.70

3.3.7 Secchi Disk Depth/Transparency

Simultaneous aided and unaided Secchi disk transparency were measured in the Quabbin Reservoir in 2022. Aided Secchi disk measurements were made using a standard view scope (4-inch diameter tube, 3-feet long, black on inside with Plexiglas disk on one end) to eliminate variability introduced by surface glare and waves. The aided Secchi measurements resulted in greater transparency than unaided. On average, aided transparency was approximately 1.4-m deeper than unaided measurements. The largest difference between aided and unaided measurements was 5.9-meters, taken at sampling site 202 on August 31, 2022 (Figure 24). This large difference was driven by wave height and surface glare. On one date at 202 (June 22, 2022), there was no difference between transparencies. This was likely due to low waves and overcast conditions which maximized ambient light paired with low surface glare.

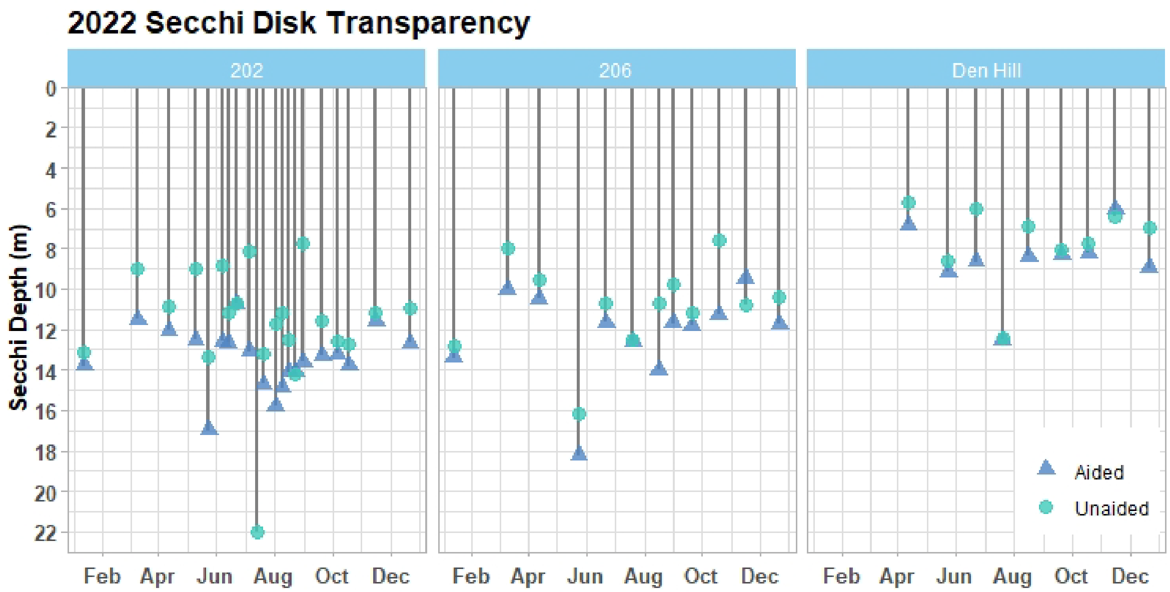

Figure 24: Secchi disk transparencies measured in 2022 in Quabbin Reservoir at DWSP monitoring sites 202 (maximum depth 42.7 m), 206 (maximum depth 28.4 m), and Den Hill (maximum depth 21.8 m). Light blue circle data points are unaided measurements, and darker blue triangle points are aided, collected using a view scope.

Water in the Quabbin Reservoir continued to demonstrate exceptional clarity in 2022, with a median aided Secchi transparency of 13.2, 11.7, and 8.4-meters, and median unaided Secchi of 11.2, 10.7, and 6.9-meters at sites 202, 206, and Den Hill respectively. Secchi disk transparency in Quabbin Reservoir was generally consistent with previous monitoring, mirroring seasonal patterns of phytoplankton dynamics (Worden, 2000; DWSP, 2019a) and turbidity. The minimum Secchi disk transparency observed in 2022 was 5.7-m unaided (April 12, 2022) and 6.0-m aided (November 15, 2022) at Den Hill monitoring site. The maximum Secchi disk transparency was 22.0-m unaided (July 13, 2022) at monitoring site 202, and 18.2-m aided (May 24, 2022) at monitoring site 206.

Transparency at Den Hill monitoring site was characteristically lower than at sites 202 and 206 (Figure 24), reflecting the nearby contribution of large riverine inputs from the East Branch Swift River and the Ware River (when diverting; Ware River diversion did occur in 2022, over three days, December 20-22). The East Branch Swift River is estimated to contribute as much as 9 to 16 percent of the annual inflow to the Quabbin Reservoir. Thus, this inflow may act as a source of color and sediment, reducing transparency and resulting in elevated levels of turbidity within the Quabbin Reservoir, most pronounced at the Den Hill monitoring site due to proximity. Reductions in Secchi disk depths from August through October at all sites may be related to decreasing reservoir elevation during drought conditions in 2022 (Section 3.1.1.2). Phytoplankton in the epilimnion peaked around June at site 202 and site 206, and at depths greater than 10 m in July and August for both sites, potentially driving corresponding temporary decreases in transparency at those sites (Section 3.3.9).

3.3.8 Nutrients

Patterns of nutrient distributions in Quabbin Reservoir in 2022 were generally consistent with those documented previously by Worden (2000) and historical ranges observed in Quabbin Reservoir. Prominent seasonal, spatial, and vertical variations were present, likely due to the interactions of demand by phytoplankton in the epilimnion and metalimnion, the decomposition of organic matter in the hypolimnion, and the timing and extent of terrestrial-derived sources of nutrients delivered via riverine loading to the Quabbin Reservoir.

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

Concentrations of nitrate (NO_3-N) and ammonia (NH_3-N) ranged from <0.005 to 0.066 mg/L and from <0.005 to 0.073 mg/L, respectively in Quabbin Reservoir in 2022. Overall, concentrations of NO_3-N and NH_3-N followed the vertical and temporal variation characteristic of historical seasonal ranges for each site (Table 38). Over half of the concentration results for NH_3-N were below laboratory detection limits (59%). Concentrations of NO_3-N and NH_3-N were generally elevated in the hypolimnion and at Den Hill relative to other sites. NH_3-N was below detection limits (<0.005 mg/L) in all samples collected from the epilimnion at sites 202 and 206. NO_3-N and NH_3-N are typically low in the spring. As is characteristically observed, NO_3-N and NH_3-N concentrations increased in the hypolimnion in the late summer and fall at all sites, likely coincident with decomposition. Monthly sampling performed throughout the fall revealed variability in seasonal concentrations of NO_3-N and NH_3-N, with concentrations generally elevated relative to historical seasonal medians. Following fall turnover in the reservoir, NO_3-N and NH_3-N concentrations decreased at each site, homogenizing across depths. Winter concentrations of NO_3-N and NH_3-N were comparable to historical medians.

Concentrations of TKN in Quabbin Reservoir Core sites ranged from 0.083 to 0.233 mg/L in 2022 (Table 38). TKN concentrations in Quabbin Reservoir exhibited little temporal variability in 2022 and were elevated in samples collected at Den Hill, relative to 202 and 206, similar to spatial patterns exhibited by other nutrients (Table 38). Concentrations of TKN in Quabbin Reservoir in spring of 2022 were largely below historical seasonal median concentrations throughout the water column. Concentrations of TKN in samples collected during the remainder of the calendar year typically remained below or approached respective seasonal medians, aside from Den Hill at depth. A proportion of the variability in concentrations of TKN observed within seasons for each site, when compared to the historical records, may be attributed to assumptions made during calculations of TKN concentrations for 2020 through 2022 data (e.g., substituting the detection limit of NO_2-N and NO_3-N), or related to differences in sensitivity of different laboratory methods (e.g., the detection limits for TN via Valderrama (1981) were lower than that of EPA 351.2 used previously). Additional variability within seasonal TKN concentrations could also be related to the increased monitoring frequency of this nutrient beginning in 2020, as demonstrated by patterns presented by other N-species, TP, and Si. Monitoring of TKN will continue monthly during calendar year 2022. Additional years of monthly data may better reveal key drivers in TKN dynamics in Quabbin Reservoir.

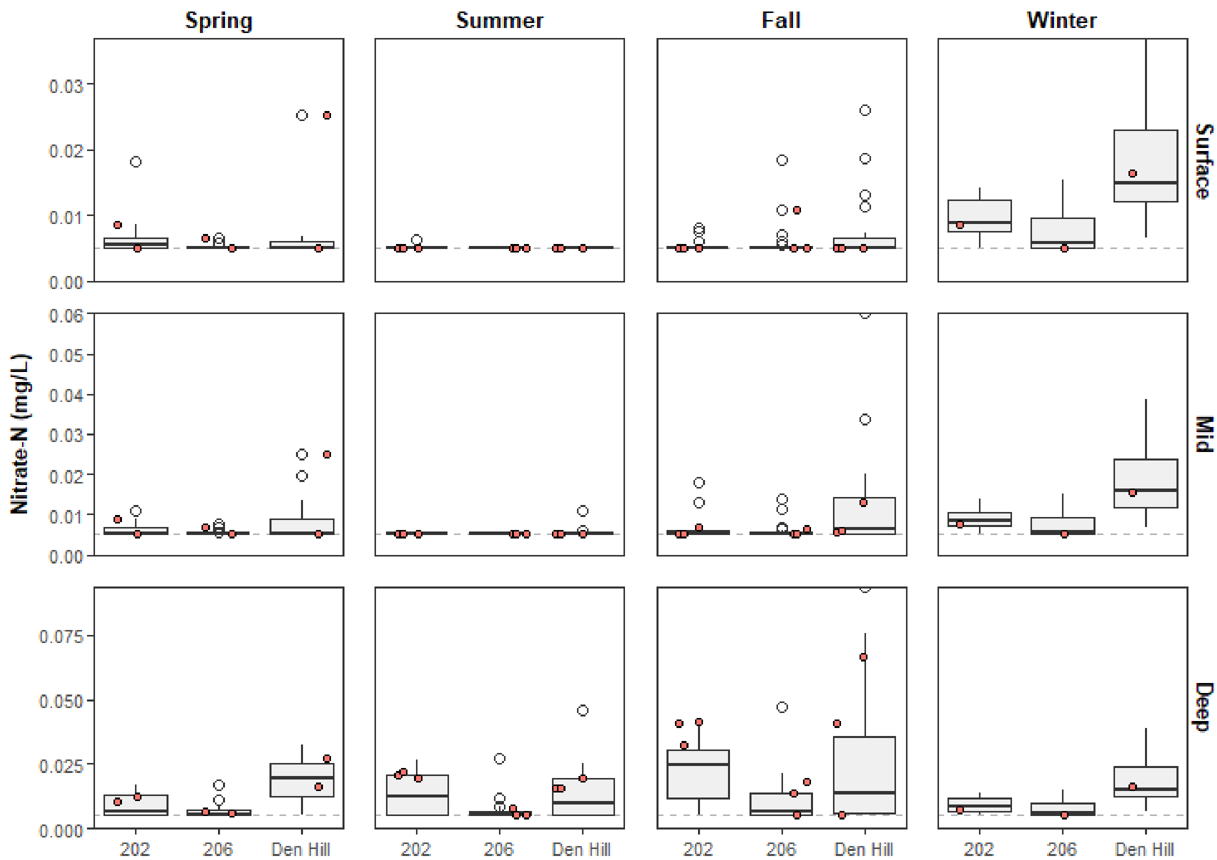

Figure 25: Boxplots depicting the seasonal and vertical distributions of NO_3-N in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2022 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

Table 38: Descriptive statistics (minimum, median, mean, and maximum) for NO_3-N, NH_3-N, and TKN in Quabbin Reservoir during 2022. Detection limits were <0.005 mg/L for NO_3-N and NH_3-N and <0.100 mg/L for TKN prior to 2020.

Location	Ammonia-N (mg/L)										
	Depth	Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
202	Surface	9	59	0.005	0.005	0.002	0.003	0.005	0.003	0.019	0.013
	Mid	9	59	0.005	0.005	0.002	0.002	0.004	0.003	0.009	0.016
	Deep	9	59	0.005	0.005	0.012	0.007	0.016	0.009	0.032	0.022
206	Surface	9	59	0.005	0.005	0.002	0.002	0.002	0.003	0.005	0.010
	Mid	9	59	0.005	0.005	0.002	0.001	0.003	0.002	0.007	0.020
	Deep	9	58	0.005	0.005	0.002	0.004	0.006	0.006	0.017	0.032
Den Hill	Surface	9	57	0.005	0.005	0.002	0.005	0.004	0.006	0.009	0.019
	Mid	9	57	0.005	0.005	0.006	0.005	0.006	0.008	0.018	0.036
	Deep	9	57	0.006	0.005	0.020	0.009	0.023	0.012	0.073	0.049
Location	Nitrate-N (mg/L)										
	Depth	Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
202	Surface	9	60	0.005	0.005	0.002	0.004	0.004	0.005	0.009	0.018
	Mid	9	60	0.005	0.005	0.002	0.004	0.004	0.005	0.009	0.018
	Deep	9	60	0.007	0.005	0.021	0.01	0.023	0.013	0.042	0.038
206	Surface	9	60	0.005	0.005	0.002	0.002	0.004	0.004	0.011	0.018
	Mid	9	60	0.005	0.005	0.002	0.003	0.003	0.004	0.007	0.015
	Deep	9	59	0.005	0.005	0.006	0.006	0.007	0.007	0.018	0.047
Den Hill	Surface	9	58	0.005	0.005	0.002	0.004	0.007	0.007	0.025	0.037
	Mid	9	58	0.005	0.005	0.005	0.005	0.008	0.009	0.025	0.060
	Deep	9	58	0.005	0.005	0.016	0.013	0.025	0.018	0.066	0.094
Location	Total Kjeldahl N (mg/L)										
	Depth	Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
202	Surface	9	61	0.083	0.090	0.116	0.128	0.118	0.147	0.156	0.560
	Mid	9	61	0.087	0.094	0.123	0.132	0.119	0.144	0.134	0.399
	Deep	9	61	0.113	0.096	0.127	0.132	0.123	0.137	0.137	0.278
206	Surface	9	61	0.087	0.094	0.117	0.133	0.115	0.144	0.130	0.342
	Mid	9	61	0.097	0.094	0.127	0.132	0.127	0.148	0.153	0.322
	Deep	9	60	0.085	0.100	0.122	0.136	0.119	0.151	0.133	0.309
Den Hill	Surface	9	59	0.104	0.100	0.153	0.165	0.143	0.178	0.176	0.457
	Mid	9	59	0.110	0.100	0.144	0.164	0.142	0.181	0.175	0.449
	Deep	9	59	0.110	0.100	0.146	0.161	0.152	0.177	0.233	0.389

3.3.8.2 Total Phosphorus

Vertical and spatial patterns in TP concentrations observed in Quabbin Reservoir remained consistent with those previously observed. Concentrations of TP ranged from <0.005 to 0.015 mg/L in 2022 (Table 39), with approximately 58% of samples (47/81) below laboratory detection limits (0.005 mg/L). Consistent with previously established spatial and temporal variation, TP was slightly elevated at depth and at Den Hill in the spring and fall compared to the other sampling depths and sites (Figure 26). Concentrations of TP increased during fall turnover. TP concentrations in all 2022 samples remained well below the 10 µg/L threshold for classification as an oligotrophic water body (Carlson, 1977). Concentrations of TP remained low throughout the water column for the entirety of 2022. Despite an increase in monitoring frequency introduced in 2020, TP concentration results did not exhibit greater intra-annual variability than quarterly concentration results collected in 2019. The latter may in part be attributed to the low concentrations of TP present in Quabbin Reservoir, relative to the sensitivity of analytical methods (e.g., detection limits).

Depletion of N-species and TP in the epilimnion during spring and summer may be attributed to seasonal uptake by phytoplankton, coupled with reduced inputs during the spring when tributary inflows were low. NH_3-N and TP depletion may serve to limit phytoplankton growth in Quabbin Reservoir, as TP may act as the limiting nutrient in lakes in temperate climates (Worden, 2000). Elevated concentrations of nutrients in the hypolimnion likely reflect natural microbial decomposition of organic matter and sedimentation from the water column (Figure 26).

Table 39: Descriptive statistics (minimum, median, mean, and maximum) for TP in Quabbin Reservoir during 2022 relative to the period of record (POR). Detection limits for TP in 2022 were <0.005 mg/L.

Location	Depth	Total Phosphorus (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
202	Surface	9	53	0.005	0.005	0.002	0.004	0.004	0.005	0.008	0.010
	Mid	9	52	0.005	0.005	0.002	0.004	0.004	0.004	0.007	0.014
	Deep	9	52	0.005	0.005	0.002	0.005	0.003	0.005	0.006	0.010
206	Surface	9	52	0.005	0.005	0.002	0.003	0.003	0.004	0.006	0.009
	Mid	9	52	0.005	0.005	0.002	0.003	0.005	0.004	0.015	0.012
	Deep	9	52	0.005	0.005	0.002	0.004	0.004	0.005	0.006	0.010
Den Hill	Surface	9	50	0.005	0.005	0.005	0.006	0.005	0.006	0.008	0.027
	Mid	9	50	0.005	0.005	0.006	0.006	0.006	0.007	0.009	0.014
	Deep	9	50	0.005	0.005	0.006	0.007	0.006	0.007	0.013	0.014

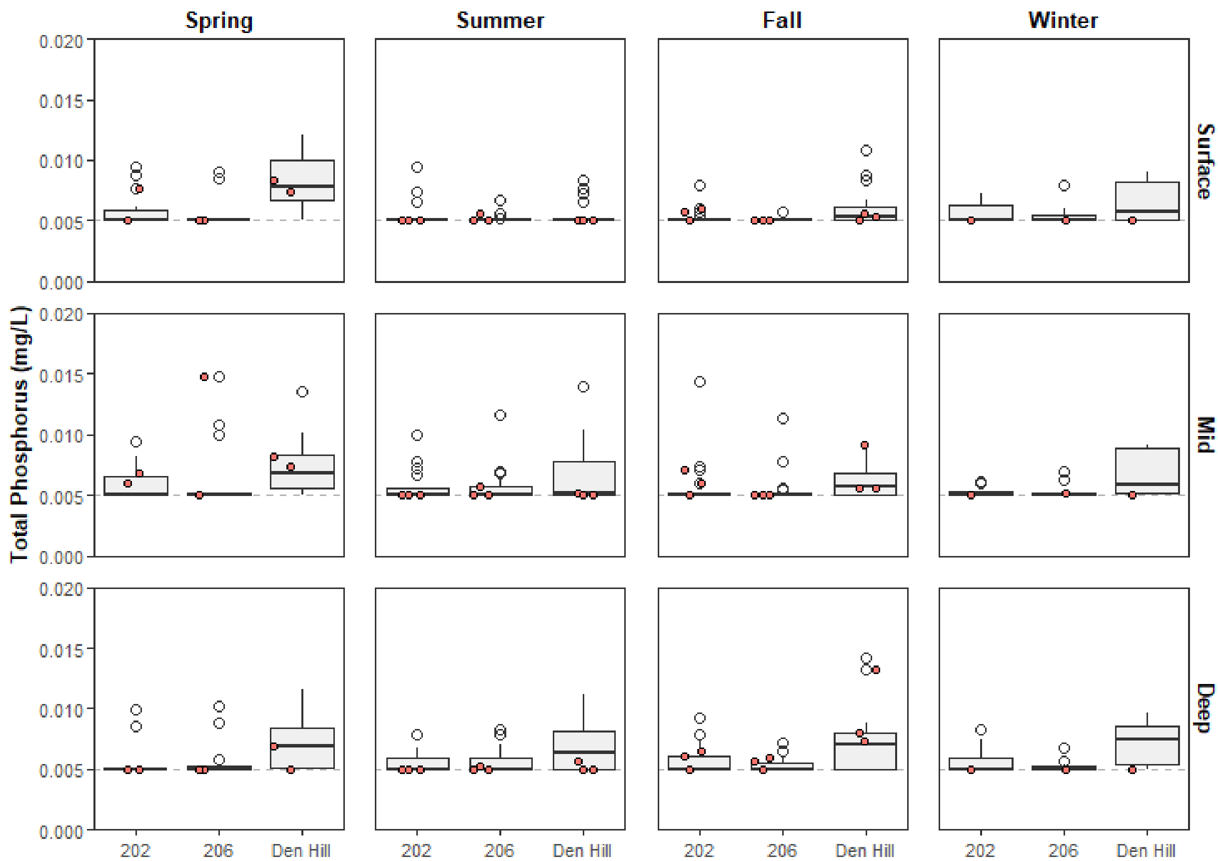

Figure 26: Boxplots depicting the seasonal and vertical distributions of total phosphorus in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2022 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

3.3.8.3 Calcium and Silica

3.3.8.3.1 Calcium

Calcium monitoring began in Quabbin Reservoir in 2010 to assess the risk of colonization by aquatic invasive organisms (e.g., zebra mussels). Water bodies with a pH <7.4 and calcium concentrations <12 mg/L, present a low risk of zebra mussel colonization (DCR and DFG, 2009). Calcium was analyzed in samples collected at three depths in 2010 and at the approximate midpoint of the metalimnion from 2011 until 2019. Zebra mussel colonization predominantly occurs in the littoral and upper sublittoral zones of freshwater lakes and ponds (Stanczykowska and Lewandowski, 1993), at depths generally less than 10 m (Marsden, 1992l Stanczykowska and Lewandowski, 1993; Wacker and Von Elert, 2003). Beginning in 2021, sample collection for calcium analyses began at three depths to better represent the portion of the water column suitable for potential habitat for zebra mussel.

Concentrations of calcium in Quabbin Reservoir exhibited little spatial or temporal variability (1.81 to 2.33 mg/L) in 2022 (Appendix C). Calcium concentrations were slightly greater in samples collected in the winter and fall (October and December, respectively) across sites (Appendix C). Additional sampling performed in the surface and deep layers of the reservoir revealed little variation in calcium throughout the water column. Calcium analyses was not performed for samples collected in May 2022. Calcium concentrations observed in 2022 in Quabbin Reservoir continue to demonstrate a low risk of zebra mussel colonization. Given the latter, in addition to the relative spatial and temporal uniformity in observed Ca concentrations in Quabbin Reservoir, quarterly sampling at the midpoint of the metalimnion at each location likely adequately captures intra-annual variability in Ca concentrations in Quabbin Reservoir.

3.3.8.3.2 Silica

Silica is utilized by phytoplankton, particularly diatoms and chrysophytes (Reynolds, 2006). Silica concentrations in Quabbin Reservoir ranged from 1.23 to 3.97 mg/L in 2022, compared to a range of 1.00 to 3.97 mg/L for the period of record. Observed ranges of monthly silica concentrations in 2022 varied relative to historical medians, but largely fell within seasonal interquartile ranges for each site/collection depth (Figure 27). Silica concentrations in 2022 typically approached or fell above seasonal median concentrations for the period of record at all sites. The increase in sampling frequency from quarterly to monthly that was introduced in 2020 may have contributed to the observed divergence from established seasonal ranges.

Concentrations of silica in Quabbin Reservoir exhibited spatial and temporal gradients consistent with seasonal productivity and subsequent riverine loading of silica to the Quabbin Reservoir. Silica concentrations in the Quabbin Reservoir were generally lower in the epilimnion and metalimnion during the summer and fall, consistent with previous results and likely attributed to uptake by phytoplankton (e.g., diatoms). The maximum silica concentration observed at each site during 2022 occurred from October through December, coincident with a period of relative low productivity across the reservoir (Section 3.3.2, Section 3.3.9) and increased riverine inputs (Section 3.1.2). Silica concentrations were greatest at Den Hill at depth (1.82 to 3.97 mg/L), similar to patterns observed in turbidity, TOC, and UV_{254} across monitoring sites and likely the result of the proximity of Den Hill to the confluence of the East Branch Swift River with the Quabbin Reservoir.

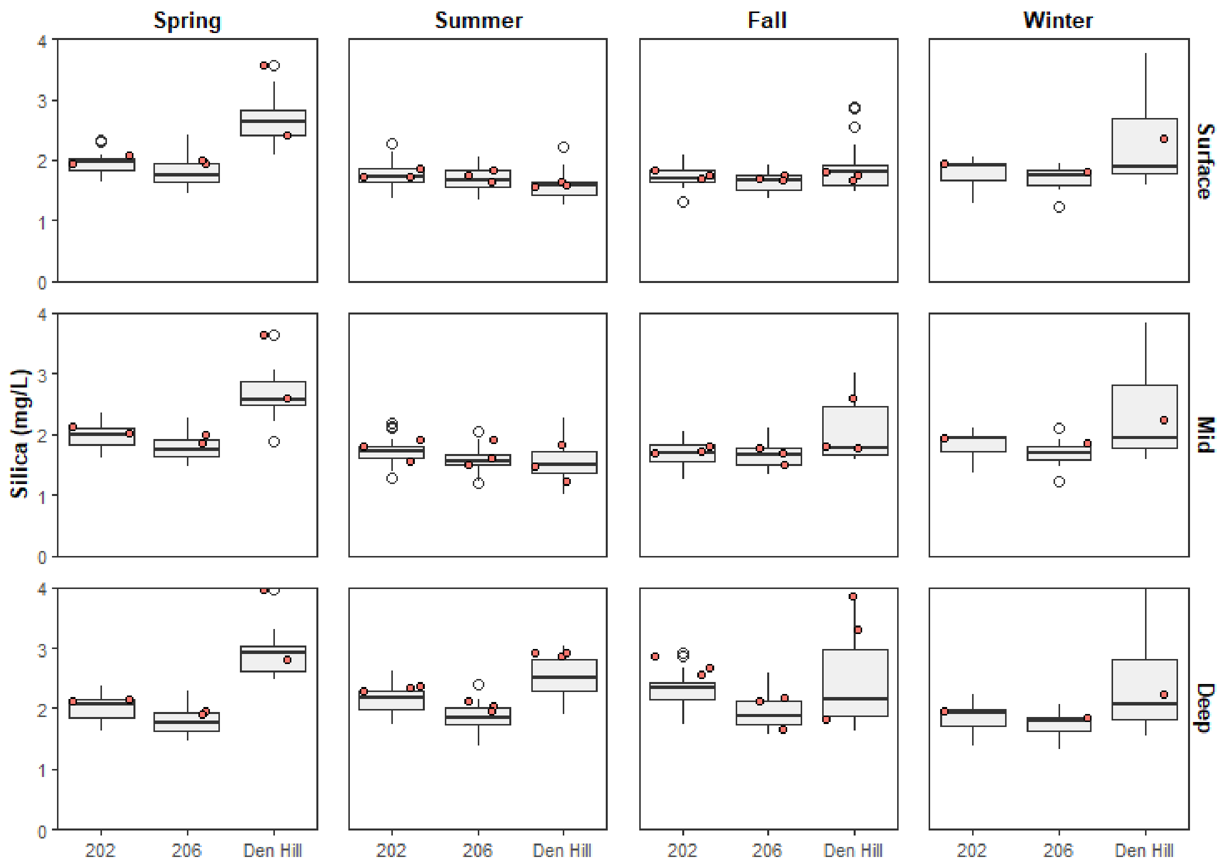

Figure 27: Boxplots depicting the seasonal and vertical distributions of silica observed in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2022 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

3.3.8.4 UV_{254} and Total Organic Carbon

3.3.8.4.1 UV_{254} Absorbance

UV_{254} absorbance in Quabbin Reservoir ranged from 0.022 to 0.028 ABU/cm at sampling site 202, from 0.021 to 0.029 ABU/cm at 206, and from 0.027 to 0.079 ABU/cm at Den Hill (Table 40). Notably, UV_{254} absorbance measured at Den Hill in 2022 trended above median absorbance results for the period of record. An increase in monitoring frequency for UV_{254} in Quabbin Reservoir was introduced in 2020. The higher resolution dataset generated in the previous two years may elucidate new insights regarding intra-annual variability in UV_{254} absorbance in Quabbin Reservoir, and also driving annual median results above historical measures.

UV_{254} absorbance in the Quabbin Reservoir is impacted by contributions from major tributaries, reservoir circulation, and mixing. Spatial gradients in UV_{254} are largely reflective of localized inputs (e.g., elevated UV_{254} at Den Hill relative to other monitoring sites). Median annual UV_{254} was greatest at Den Hill and displayed little seasonal variation in samples collected from 202 and 206 in 2022 (Figure 28). Seasonality in UV_{254} absorbance was well established for Den Hill, however. This pattern may be attributed to potential increased loading from the East Branch Swift River during the spring and winter months, when streamflow was higher, coupled with the impacts of the timing of sample collection relative to fall turnover and subsequent water column mixing. Furthermore, the higher resolution dataset generated in the previous three years may reveal previously undocumented seasonal dynamics of UV_{254} in Quabbin Reservoir.

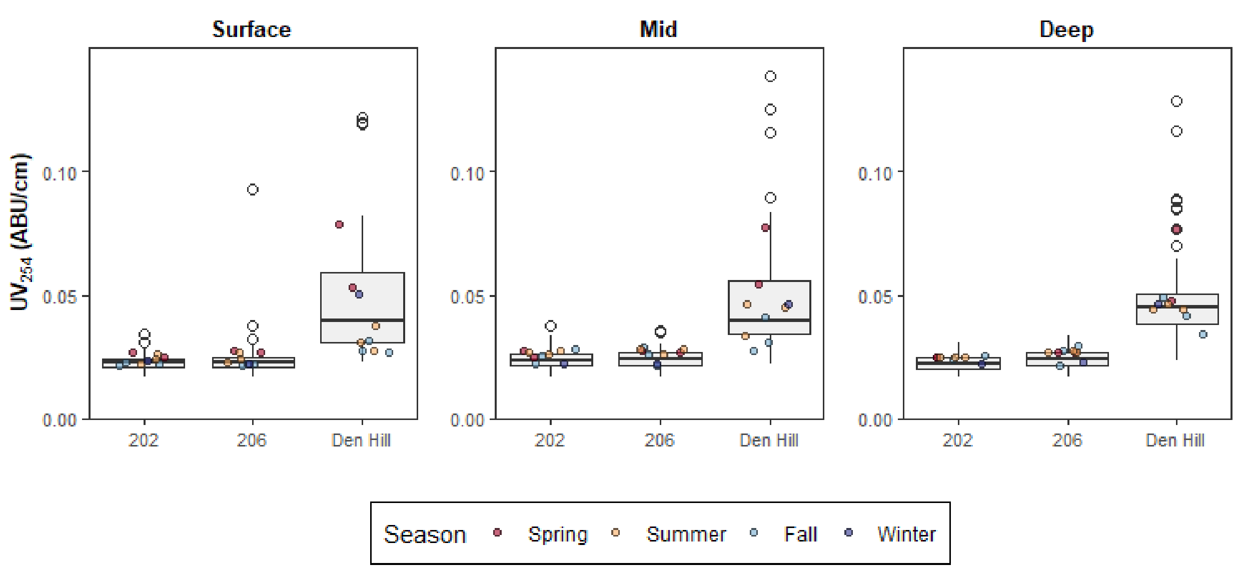

Figure 28: Boxplots depicting the seasonal and vertical distributions of UV_{254} observed in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2022 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

Table 40: Descriptive statistics (minimum, median, mean, and maximum) for UV_{254} measured in Core reservoir monitoring sites in the Quabbin Reservoir in 2022 relative to the period of record (POR).

Location	UV_{254} (ABU/cm)										
	Depth	Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
202	Surface	9	60	0.022	0.016	0.024	0.022	0.024	0.023	0.027	0.034
	Mid	9	60	0.022	0.017	0.026	0.023	0.026	0.024	0.028	0.038
	Deep	9	60	0.022	0.017	0.025	0.022	0.025	0.022	0.026	0.031
206	Surface	9	60	0.021	0.017	0.023	0.023	0.024	0.024	0.028	0.093
	Mid	9	60	0.022	0.017	0.027	0.024	0.026	0.024	0.029	0.036
	Deep	9	60	0.022	0.017	0.027	0.024	0.026	0.024	0.029	0.034
Den Hill	Surface	9	58	0.027	0.023	0.031	0.043	0.040	0.051	0.079	0.122
	Mid	9	58	0.028	0.022	0.045	0.039	0.045	0.049	0.078	0.139
	Deep	9	58	0.034	0.023	0.046	0.045	0.048	0.051	0.077	0.171

3.3.8.4.2 Total Organic Carbon

Routine monitoring for total organic carbon (TOC) in Quabbin Reservoir began in 2020. TOC concentrations ranged from a minimum of 1.72 to 3.20 mg/L in 2022 (Table 41). TOC concentrations in 2022 were comparable to those generated during monitoring in 2020 and 2021 and to results generated nearly two decades prior (2 mg/L to 2.7 mg/L; concentrations approached or exceeded 3 mg/L at Den Hill) (Garvey and Tobiason, 2003; DWSP, 2021a). Concentrations of TOC measured in Quabbin Reservoir during 2022 were less than global mean concentrations for deep and north temperate lakes (3.463 mg/L and 5.809 mg/L, respectively) (Chen et al., 2015).

Similar to results from 2020 and 2021, TOC exhibited little variability with depth or changes in stratification (Figure 29). TOC concentrations were slightly elevated in samples collected in the spring, relative to those collected during the remainder of the year when riverine inputs were reduced during drought conditions across MA (Raymond and Saiers, 2010; Yoon and Raymond 2012). Additionally, stratification conditions at the time of sample collection may have further contributed to mixing of OM-rich bottom waters with the upper water column (Figure 29).

Spatial gradients in TOC generally mirrored UV_{254} absorbance – with relative enrichment in samples collected from the Den Hill compared to 202 and 206. However, correlations among these parameters have previously been mixed, with the strongest relationships presented by Den Hill and comparatively poor relationships between UV_{254} and TOC at 202 and 206 (DWSP, 2022).

Table 41: Descriptive statistics (minimum, median, mean, and maximum) for total organic carbon measured in Core reservoir monitoring sites in the Quabbin Reservoir in 2022 relative to the period of record (POR).

Location	Total Organic Carbon (mg/L)										
	Depth	Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
202	Surface	9	17	2.09	1.89	2.32	2.06	2.30	2.11	2.44	2.39
	Mid	9	17	2.05	1.74	2.30	2.05	2.27	2.07	2.42	2.79
	Deep	9	17	1.72	1.60	2.05	1.94	2.04	1.93	2.33	2.36
206	Surface	9	16	2.03	1.82	2.34	2.16	2.31	2.15	2.49	2.53
	Mid	9	17	2.06	1.84	2.35	2.05	2.30	2.09	2.56	2.44
	Deep	9	15	1.98	1.66	2.12	1.99	2.19	2.00	2.49	2.34
Den Hill	Surface	9	17	2.28	2.03	2.48	2.50	2.57	2.50	3.12	3.32
	Mid	9	17	2.19	1.86	2.52	2.33	2.54	2.36	3.01	3.19
	Deep	9	17	2.19	1.92	2.38	2.17	2.46	2.34	3.20	3.21

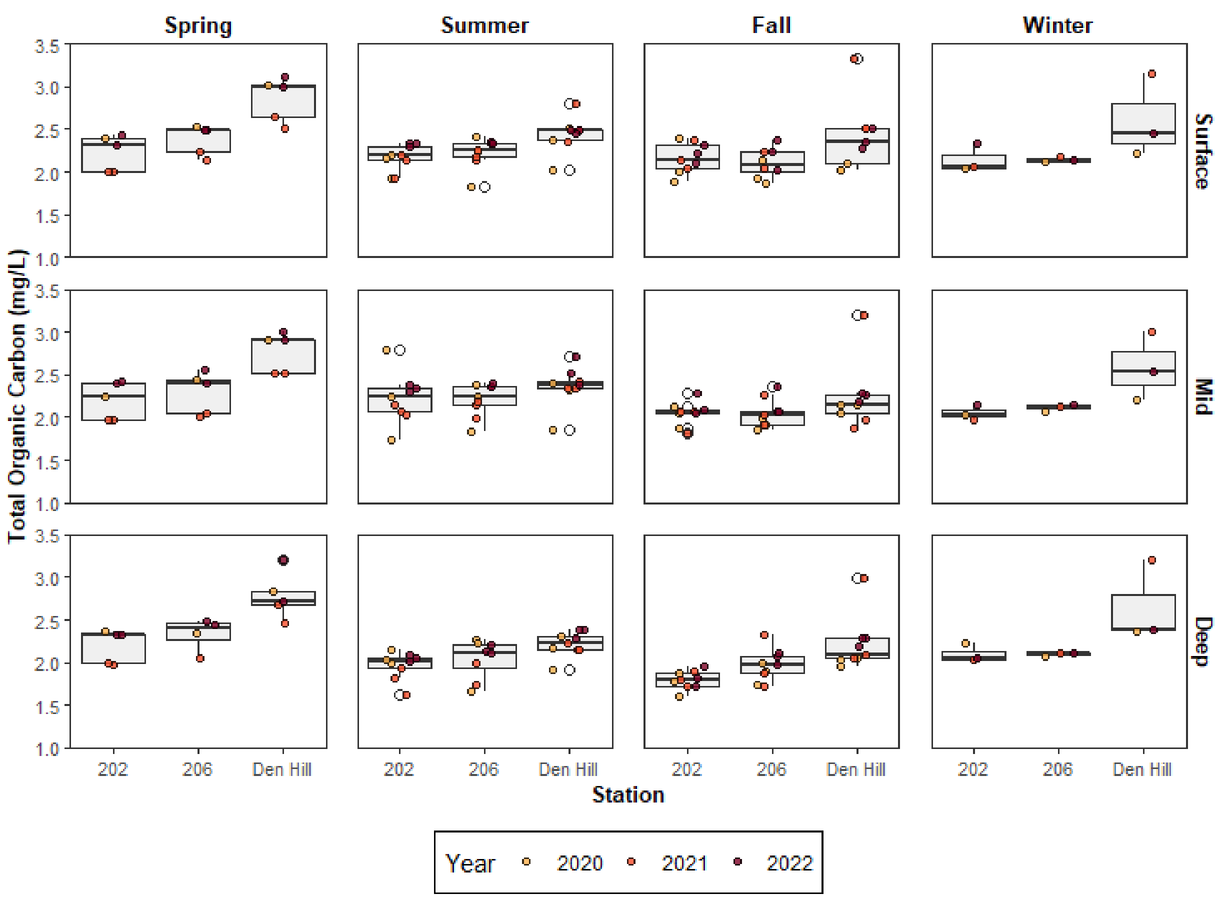

Figure 29: Boxplots depicting the seasonal and vertical distributions of TOC in Quabbin Reservoir Core sites. Individual sample results are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

3.3.9 Phytoplankton

Samples for phytoplankton enumeration were collected from Quabbin Reservoir core monitoring sites 202, 206, and Den Hill on 23, 12, and 6 days in 2022, respectively. Samples for phytoplankton enumeration were collected from two to three depths depending on the location: 1) from the epilimnion at 3 m, 2) at the chlorophyll *a* maximum (with simultaneous high dissolved oxygen), typically within the metalimnion, and 3) near intake(s) depths to closely monitor phytoplankton community composition and potential taste and odor impacts. Intake sampling was performed regularly at site 202 to maintain a regular record of phytoplankton densities that directly influence the quality of water flowing into the Chicopee Valley Aqueduct (CVA). Occasional sampling at the intake depth was performed (as needed) at site 206 to understand phytoplankton densities entering the Quabbin Aqueduct and subsequently transported to Wachusett Reservoir.

Samples were collected for routine monitoring at site 202 monthly from October through April (weather and ice conditions permitting) and every two weeks during the growing season from May through September. At site 206, samples were collected monthly (weather and ice conditions permitting) year-round. Under special circumstances (e.g., exceedance of early monitoring threshold densities, see Table 42) sampling frequency of phytoplankton was increased, and additional samples were collected based on in-situ readings of chlorophyll *a* and dissolved oxygen (Appendix C). In 2022, when time allowed, additional samples were collected from site Den Hill (DEN) to better understand the nature of the phytoplankton community feeding into the reservoir.

The first samples of the year were collected on January 13, 2022, at sites 202 and 206. The reservoir froze over on February 16 which prevented sampling until March 10, 2022. Spring total phytoplankton densities were low and remained below 300 ASU/mL at both sampling sites until mid-June (Figure 30). At site 202, stratification of the water column began building at the beginning of May and was fully achieved by May 24, 2022. As is typically observed in Quabbin Reservoir, spring samples were dominated by diatoms, with the highest densities corresponding to *Asterionella*, *Tabellaria*, and *Cyclotella*.

Following increased stability of stratification in June, phytoplankton composition became dominated by chrysophytes (mainly *Chrysosphaerella)* at both sites (Figure 31). *Chrysosphaerella* densities drove total densities in the metalimnion at 202 and 206 to the maximum total densities observed in 2022. This aggregation at depth peaked on July 20 at both sites. Compared to the 2021 peak that occurred in late June and to the historical average peak that typically occurs in Spring (March/April), the 2022 total density maximums were reached later in the year (late July).

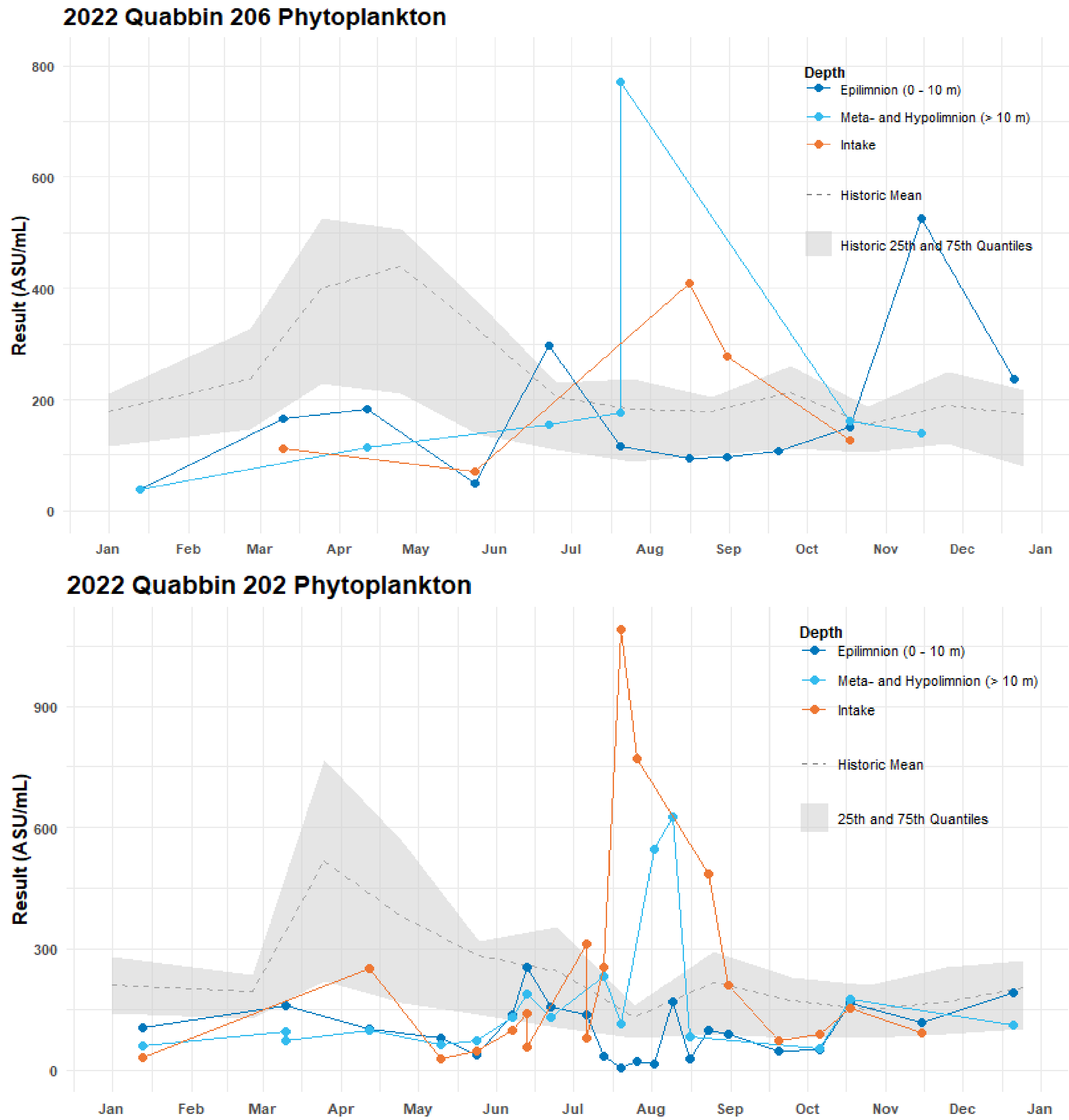

Figure 30: Total phytoplankton densities during 2022 from sampling sites 202 (top) and 206 (bottom). Sample classification (epilimnion or meta- and hypolimnion) based on depth as defined by summer temperature profiles. The average for historical data covering 2007-2022 is indicated by the dashed line, with 25th and 75th quantiles represented as gray bands, corresponding to all sample depths.

Following high levels in mid-July, phytoplankton densities at depth (meta- and hypolimnion) at both sites steadily decreased until reaching lower than 300 ASU/mL levels by August 30. Phytoplankton diversity increased following the decline in total densities (Figure 31). This is likely explained by a depletion of available nutrients limiting growth, and increasing competition, resulting in a shift in community composition (Cole and Weihe, 2016; Section 3.3.8). Community composition shifted from chrysophyte dominance driven by Chrysosphaerella, to a greater variety (albeit at lower densities) of diatoms, chlorophytes, and cyanophytes. The most common diatoms in 2022 were Asterionella and Cyclotella, the most common chlorophytes were Elakatothrix and Gloeocystis. Cyanobacteria became more dominant in fall samples and the most common cyanobacteria in 2022 was Aphanocapsa. It is typical to observe cyanobacteria dominance during the late summer and fall due to their heightened performance in warm water compared to other phytoplankton (Whitton, 2012).

Densities at different sampling depths also exhibited similar patterns across sites. The epilimnion samples typically had lower densities than samples collected from deeper in the water column. This was particularly true during the metalimnetic aggregations of Chrysosphaerella, which did not affect epilimnion total densities. Total densities in the epilimnion at both sites remained low (below 300 ASU/mL) across the entire year, with the exception of samples collected on November 15 at site 206. The community composition in the epilimnion at both sites was dominated by diatoms in the spring followed by an increase in diversity in the summer with higher levels of chrysophytes, but unlike the meta- and hypolimnion, the epilimnion was dominated by cyanophytes during the summer and not chrysophytes. Phytoplankton densities in samples collected from the intake depths at site 202 demonstrated similar seasonal shifts in phytoplankton community composition and total densities, compared with the other depths sampled for site 202. Unlike the epilimnion samples, the intake depths were affected by the metalimnetic aggregation of Chrysosphaerella, which persisted above, within, and just below the intake depths for the duration of the event.

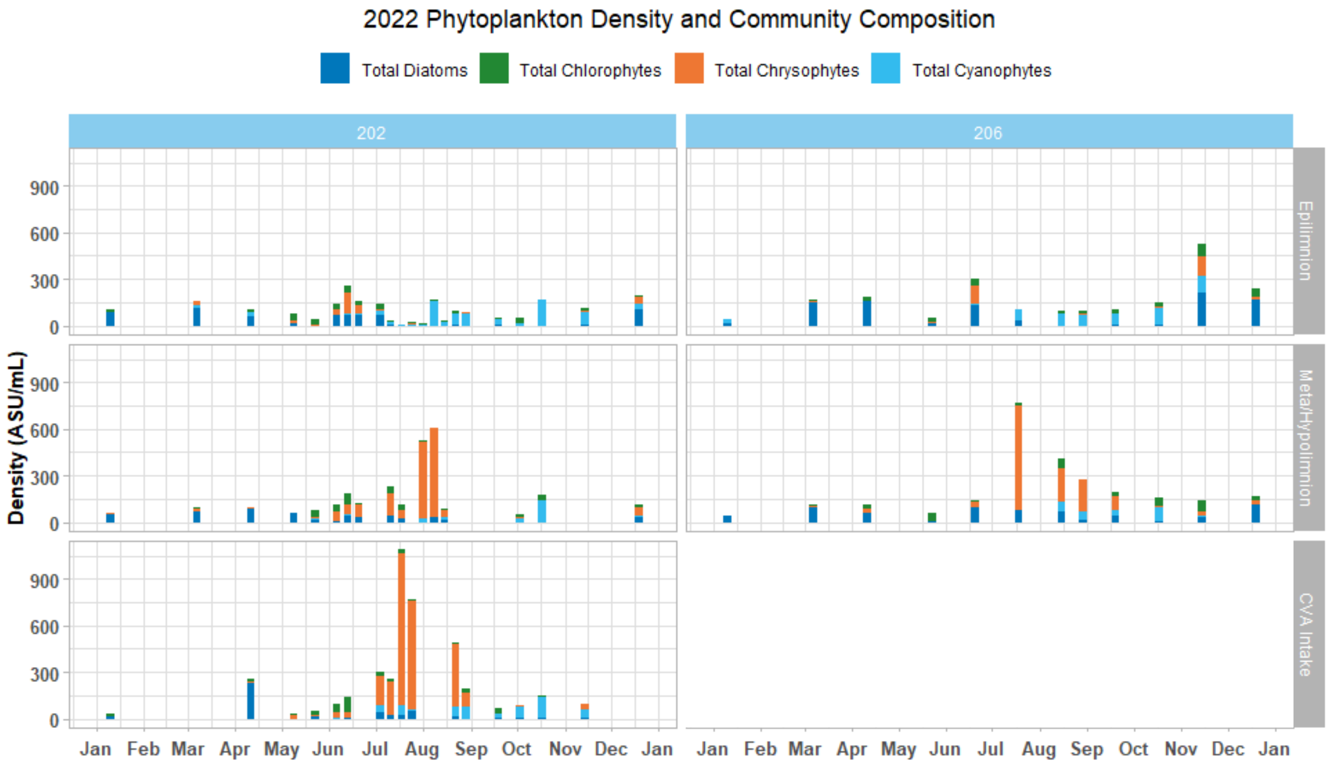

Figure 31: Phytoplankton community composition, observed in 2022 from the epilimnion and meta/hypolimnion at sampling sites 202 and 206. Additional samples were taken at the CVA intake depth at sampling site 202.

Despite the later and more intense peak in total densities than is typically observed in the Quabbin Reservoir, overall total densities and changes in community composition were consistent with trends observed in the Quabbin Reservoir over the period of record. These dynamics are also typical of oligotrophic systems. Monitoring for phytoplankton in Quabbin Reservoir will be conducted monthly (October through April) or weekly (May through September) at site 202, and monthly at site 206 and Den Hill in 2023. If an exceedance of an early monitoring trigger is observed, phytoplankton monitoring will be increased as appropriate.

Over the last seven years, monitoring methodology has been improved to better capture phytoplankton aggregations. Prior to 2016, sample depths were selected primarily based on the temperature and dissolved oxygen profiles. Routine profiling of chlorophyll *a* began in 2016, serving to better inform sample collection depths for phytoplankton enumeration than temperature and dissolved oxygen profiles. The official change in sample depth selection occurred in summer 2019, where depths with maximum chlorophyll *a* concentrations were targeted for sample collection. This change in field procedures should be considered when interpreting historical patterns of phytoplankton abundance in Quabbin Reservoir, as the sampling focus is now directly driven by chlorophyll *a* values, and thus, higher phytoplankton densities.

3.3.9.1 Taste and Odor Taxa

Chrysophyte blooms are responsible for nuisance taste and odor properties of water (Lin, 1977; Watson and Jüttner, 2019), oftentimes resulting in reports of undesirable aesthetic characteristics of finished water, such as a "fishy" or "cucumber" taste and odor (Sandgren et al., 1995; Paterson et al., 2004). Chrysophytes have been routinely detected at low densities throughout the water column in the Quabbin Reservoir (Worden, 2000; DWSP, 2019). Chrysophyte densities have been elevated over the past three years, driven by metalimnetic aggregations.

Several taxa are closely monitored by DWSP to detect potential production of undesirable tastes and odors or cyanotoxin impacts to the drinking water supply. Density thresholds for early monitoring and treatment consideration levels have been set for four chrysophytes and one cyanobacteria taxa (Table 42).

Table 42: Phytoplankton monitoring thresholds for various nuisance organisms in MWRA source waters.

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

Chrysosphaerella was the only taxa of concern to exceed the established early monitoring trigger (EMT) and treatment consideration level (TCL) in 2022 (Figure 32). Both thresholds were exceeded during the *Chrysosphaerella* aggregation that occurred between early July to late August. Most of the samples that exceeded the TCL correspond to samples from site 202. The early monitoring trigger for *Synura* was exceeded in five samples, with a majority of samples corresponding to site 206. *Dinobryon* was the second most common chrysophyte identified in samples but remained at levels below the EMT. *Uroglenopsis* was observed at countable densities (but below EMT) mainly between May and August and was not observed for the remainder of the year. *Dolichospermum* was observed at very low densities during the summer and fall, and only one sample form site Den Hill exceeded the EMT.

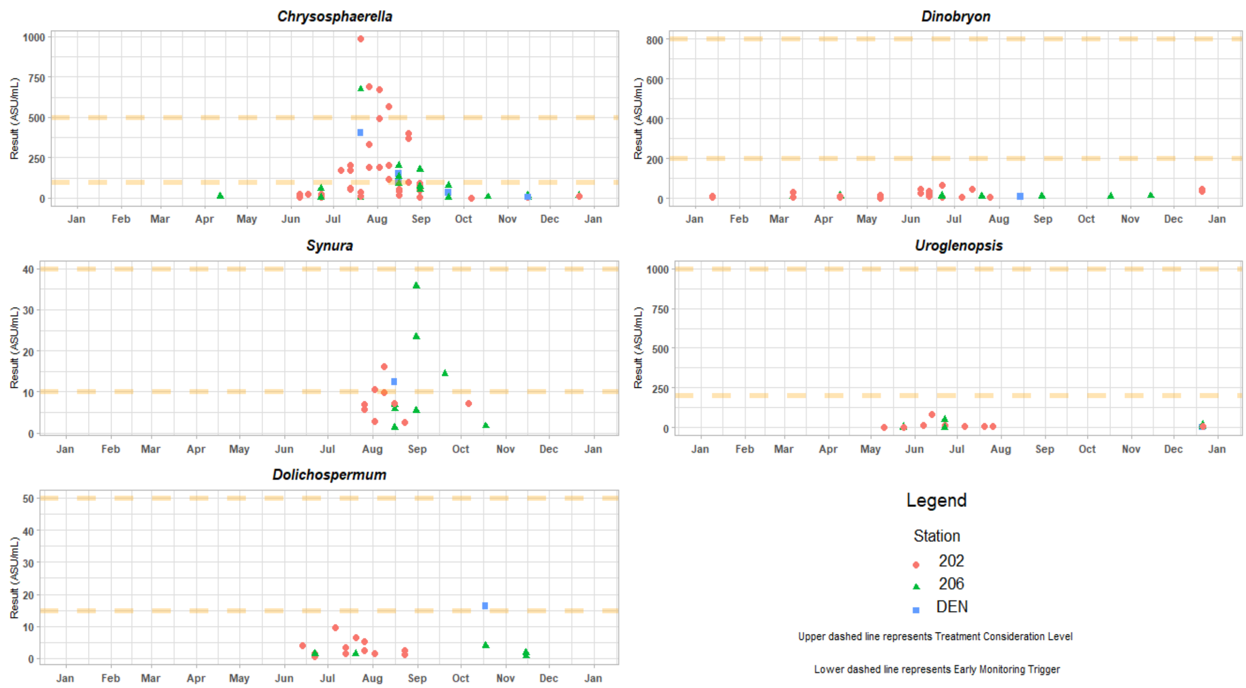

Figure 32: Occurrence of nuisance phytoplankton taxa at Quabbin sampling sites 202, 206, and Den Hill (DEN) during 2022. Upper dashed line represents the treatment consideration level, and the lower dashed line represents the early monitoring trigger specific to each taxa.

3.3.9.2 Chrysophyte Aggregations

Due to taste and odor complaints resulting from the high levels of *Chrysosphaerella* in 2019, extended discussion has been given to this taxon to understand density trends in the last four years (Figure 33). In 2019, a *Chrysosphaerella* aggregation was observed from August to November at site 202 (CVA intake/Winsor Basin) and from July to October at site 206 (Shaft 12 Intake). During these events, C*hrysosphaerella* levels remained above the early monitoring trigger of 100 ASU/mL for 11 weeks at site 202 and 12 weeks at site 206. The treatment consideration level of 500 ASU/mL was exceeded six times at site 202 between August and September and only once in August at site 206, in 2019. In 2020 there was no C*hrysosphaerella* aggregation observed, there were only two samples with *Chrysosphaerella* densities that exceeded the early monitoring trigger in 2020, both from site 206. During the summer of 2021, an aggregation of *Chrysosphaerella* occurred at sites 202 and 206. In comparison to the 2019 aggregation, the 2021 event was shorter in intensity and duration. *Chrysosphaerella* densities remained above the early monitoring trigger for four weeks at site 202, and two weeks at site 206, and the treatment consideration level of 500 ASU/mL was exceeded only once at each site (June 21 for site 202, and June 14 for site 206), in 2021.

Figure 33: *Chrysosphaerella* densities from 2019 to 2022 at site 202 and site 206. Upper dashed line represents the treatment consideration level, and the lower dashed line represents the early monitoring trigger.

In 2022, the *Chrysosphaerella* aggregation showed a similar intensity and duration pattern to the aggregation in 2019. The *Chrysosphaerella* aggregation in 2022 was observed from early July to late August. During these events, C*hrysosphaerella* densities remained above the early monitoring trigger for eight weeks at site 202, and six weeks at site 206. The treatment consideration level of 500 ASU/mL was exceeded during four sampling events at site 202 and during one sampling event at site 206. While *Chrysosphaerella* densities and threshold exceedances were similar to the 2019 aggregation, the 2022 aggregation did not result in any reported taste and odor issues.

3.3.10 Bacteria and Turbidity Monitoring for SWTR Compliance

A population of waterfowl that roost on Quabbin Reservoir in fall and winter were identified as the primary sources of fecal coliform and *E. coli* to the Quabbin Reservoir (Wolfram, 1996). Additional sources may include semi-aquatic wildlife, and inputs from major tributaries. Fecal coliform and *E. coli* in Quabbin Reservoir are historically low, reflecting microbial die-off and predation. Fecal coliform ranged from <1 to 4 CFU/100 mL in samples collected by DWSP from Quabbin Reservoir in 2022 (n=81). *E. coli* was detected at 10 MPN/100 mL in five samples collected by DWSP in 2022 (approximately 6% of samples).

The MWRA monitors Quabbin Reservoir water prior to disinfection to ensure compliance with the SWTR. Daily monitoring is performed by MWRA at the BWTF in Ware, MA. Turbidity is monitored via an in-line turbidity meter inside the BWTF. Average (mean) and maximum daily turbidity in source water measured at the BWTF ranged between 0.19 to 0.38 NTU and 0.19 to 0.78 NTU, respectively. Turbidity in Quabbin Reservoir source water remained below one NTU for the entirety of 2022 (Figure 34). Fecal coliform was not detected above 20 CFU/100-mL (Figure 34). The average and median daily fecal coliform count of Quabbin Reservoir source water in samples collected at BWTF were <1 CFU/100 mL (0.41 and <1 CFU/100 mL, respectively). *Cryptosporidium* was detected in one sample (n=24) of raw water at the BWTF in 2022, and *Giardia* was present in two samples collected in 2022, with one cyst per sample in each case. No violations of drinking water standards for these organisms occurred in 2022.

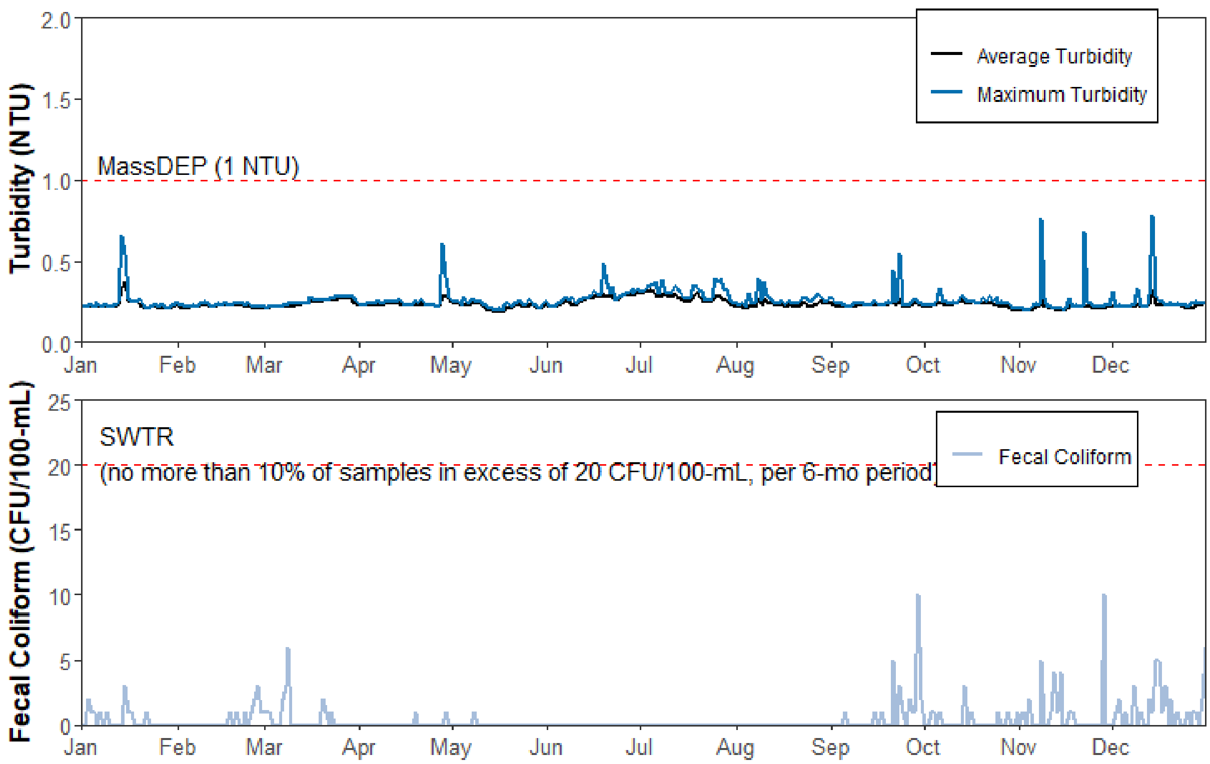

Figure 34: a) Results of daily average (mean) and maximum turbidity, and b) fecal coliform and E. coli monitoring of Quabbin Reservoir source water, Winsor Dam Intake, collected at BWTF during 2022.

3.4 Aquatic Invasive Species Monitoring and Management

Non-native aquatic invasive species (AIS) include macrophytes, phytoplankton, zooplankton and larger fauna (primarily from the Mollusca phylum). Introduction of AIS may have adverse impacts on water quality including changes in water color and increases in turbidity, phytoplankton growth, and concentrations of trihalomethane (THM) precursors (Gettys *et al.*, 2009). These increases result from the function of these plants as nutrient "pumps," extracting nutrients from sediment and releasing them into the water column, primarily as dissolved and particulate organic matter (Gettys et al., 2009). Non-native, invasive species of macrophytes are known to aggressively displace native vegetation and grow to nuisance densities. Invasive zooplankton and fauna can outcompete native species and disrupt aquatic food webs, thus altering water quality. AIS can be introduced and transported within watersheds via human or wildlife pathways including, but not limited to, aquarium releases, recreational activity (e.g., fishing and boating equipment), waterfowl movement, and downstream flow.

Portions of Quabbin Reservoir and select ponds within the Quabbin Reservoir and Ware River Watersheds are periodically assessed for the presence of AIS by DWSP staff and by TRC (formerly ESS Group, Inc.) under MWRA contract. Several AIS have been documented through these efforts, in some cases initiating a management response (DWSP, 2020a). Early detection of AIS, education, and participation from the public is critical for successful prevention of new or increased AIS infestations. Management of AIS in Quabbin Reservoir Watershed and Ware River Watershed is primarily based on prevention programs. The following sections of this report provide details of AIS presence in the reservoir and watersheds and document the prevention and management programs currently in place within the watersheds.

3.4.1 Invasive Aquatic Macrophyte Monitoring and Distribution

Macrophyte surveys are conducted during the growing season and have been performed periodically since 1998, and on a regular basis since 2006 and 2010 in the Quabbin Reservoir and Ware River Watersheds, respectively. Shoreline assessments entail visual observations of the littoral zone via kayak, small boat, or on foot depending on water level. Some water bodies are surveyed annually, while others are surveyed every five years, on a rotating schedule based on the Sanitary District that the water body is located within. Routine monitoring prioritizes water bodies with ramps suitable for launching trailered boats, as this type of activity increases the risk of AIS spread (Rothlisberger et al., 2011). In total, 50 watershed ponds (including the Reservoir holding ponds, Prescott Peninsula ponds, and the Ware River itself) across the two watersheds are surveyed either annually or on a rotating schedule.

The following sections summarize the distribution of invasive aquatic macrophytes in the reservoir, the Quabbin Reservoir Watershed, and Ware River Watershed (Table 43). In 2022, two waterbodies were surveyed for aquatic macrophytes in the Quabbin Reservoir Watershed. In addition to these ponds, the reservoir's Boat Launch Areas 1 and 3, the west arm, and the two holding ponds (O'Loughlin and Pottapaug Ponds) were also surveyed. A total of four water bodies were surveyed in the Ware River Watershed in 2022. Waterbodies surveyed in the Quabbin

Reservoir Watershed were associated with the Fever Brook, East Branch Swift River, Quabbin Northwest, or Quabbin Reservation Sanitary Districts. Ponds surveyed in the Ware River watershed were associated with the Burnshirt, Canesto, and Natty Sanitary District or the Coldbrook & Longmeadow Sanitary District. Pepper's Mill Pond and Shaft 8 were outside of these districts, but included due to proximity.

Table 43: Aquatic invasive species in the Quabbin Reservoir, Quabbin Reservoir Watershed, and Ware River Watershed. * Includes O'Loughlin and Pottapaug holding ponds. ** No evidence of brittle naiad found since 2014, one row yellowcress since 2013, or swollen bladderwort since 2017.

Scientific Name	Common Name	Documented Presence		
		Quabbin Reservoir*	Quabbin Reservoir Watershed	Ware River Watershed
Cabomba caroliniana	Fanwort			x
Iris pseudacorus	Yellow Flag	x	x	x
Lythrum salicaria	Purple Loosetrife	x	x	x
Myosotis scorpioides	True Forget-me-not	x	x	x
Myriophyllum heterophyllum	Variable Leaf Milfoil	x	x	x
Najas minor	Brittle Naiad	x**		
Potamogeton crispus	Curly-leaf Pond Weed			x
Phragmites australis	Common Reed	x	x	x
Rorrippa microphyllum	One Row Yellowcress	x**	x	x
Utricularia inflata	Swollen Bladderwort	x	x**	x
Cipangopaludina chinensis	Chinese Mystery Snail	x	x	x

3.4.1.1 Contracted Aquatic Macrophyte Surveys

Since 2013, MWRA has contracted annually with TRC (formerly ESS Group, Inc.) to carry out point-intercept surveys of DWSP/MWRA source and emergency reservoirs. No new AIS were discovered in Quabbin Reservoir during the 2022 survey. *Myriophyllum heterophyllum* (variable leaf milfoil) was the only documented submersed AIS found in both the Quabbin Reservoir and Ware River Watersheds. Emergent invasives are not specifically included in the TRC point-intercept surveys, but the continued presence of *Phragmites australis* and *Lythrum salicaria* in the Quabbin Reservoir was noted. The extent and density of the *M. heterophyllum* in Quabbin Reservoir decreased slightly compared to 2021 (observed at 12% of surveyed points) (TRC, 2023). In the Ware River *M. heterophyllum* covered 3.45 acres above Shaft 8, reflecting a minor increase in plant growth (TRC, 2023).

3.4.1.2 Myriophyllum heterophyllum

Myriophyllum heterophyllum (variable leaf milfoil) is the most frequently encountered submersed AIS in the watersheds and is well distributed in portions of Quabbin Reservoir. In the reservoir itself, *M. heterophyllum* is well established at all three Boat Launch Areas. Of the 50 actively monitored ponds, including nine ponds on Prescott Peninsula and holding ponds, 22 have *M. heterophyllum* present. Due to the aggressive nature of this species, it is abundant and widely distributed in the waterbodies where it has become established. No new infestations were detected in the 2022 surveys.

A pioneer infestation of *M. heterophyllum* was found in Comet Pond (Ware River Watershed, Hubbardston, MA) in 2018. Plants were removed via hand-harvesting late in the 2018 season by pond residents, with DWSP assistance. AE Commercial Diving Services, Inc., removed plants in August of 2019 using diver assisted suction harvesting (DASH). Several weeks later, DCR Lakes and Ponds divers revisited the site to remove a small number of plants that were missed due to visibility issues and/or regrowth. DCR Lakes and Ponds returned in 2020 and removed several plants by hand. No management actions were taken in 2021, but in 2022 the pond association obtained a DCR grant for another DASH removal. No bids were received for the project.

3.4.1.3 Phragmites australis

Phragmites australis (common reed) is the most widely distributed emergent AIS in the Reservoir and the watersheds. It is well established in parts of the reservoir, forming dense patches along the shoreline. *Phragmites* islands are formed in some shallow locations of the reservoir where this AIS completely dominates. *Phragmites* stands are present at all three Boat Launch Areas, in the western arm of the reservoir, and in the ponds on Prescott Peninsula. Within the 50 actively monitored ponds, 22 have *Phragmites* present. No new infestations were detected in the 2022 surveys.

This species spreads using three different methods: seeds, stolons, and rhizomes. As more plants mature to reproductive age, seed production and dispersal increases. Stolons (runners that grow on the top of soil) and rhizomes (stem growth beneath the soil surface) enable small patches to rapidly spread out, becoming larger with each successive year. A single seed that successfully germinates can form a large patch, eventually displacing native species. Once established, *Phragmites* aggressively colonizes shorelines. Although labor intensive, pioneer or small infestations may be eradicated using physical methods such as cutting below the surface of the water, hand pulling, or covering with black plastic. Herbicide use is the least labor intensive and most effective means of reducing plant numbers but is currently not under consideration by DWSP. Ideally, small, isolated populations should be targeted for management before they become established. Early removal is far more effective, requires fewer resources and results in a lower environmental impact.

3.4.1.4 Cabomba caroliniana

Cabomba caroliniana (fanwort) has not been observed in the reservoir, or in the Quabbin Reservoir Watershed. It has been found in four ponds within the Ware River Watershed: Demond Pond (Rutland, MA), Long Pond (Rutland, MA), Moulton Pond (Rutland, MA), and Queen Lake (Phillipson, MA). This species was first identified in the watershed in 2010 when it was documented in Queen Lake.

The Queen Lake Association contracted a lake and pond management firm to manage the population with herbicides in 2020. The DWSP 2021 survey noted the presence of *C. caroliniana*, but the population appeared to be greatly reduced following herbicide application. The 2022 survey did not detect *C. caroliniana* presence.

C. caroliniana was first documented in Demond Pond in 2017. The Demond Pond Association was formed in 2014 and has organized almost annual herbicide treatment of the pond since 2015. This treatment creates annual drops in overall plant growth, with the initial aim of reducing *M. heterophyllum*. Both native and invasive plants (notably the two target species, *M. heterophyllum* and *C. caroliniana*) have regularly rebounded following treatment, creating the need to continue annual action. Cyanobacteria blooms (typically *Microcystis*) have been noted in Demond Pond during DWSP macrophyte surveys from 2017 through 2021 (no survey was completed in 2020 due to staffing constraints).

Long Pond's first recorded *C. caroliniana* presence was in 2021 near the boat launch and in a cove between the boat launch and Route 122. The 2022 survey found the *C. caroliniana* population had grown in density.

C. caroliniana was identified in Moulton Pond in 2012 but has not been actively managed. It is now the dominant plant in this waterbody, growing in dense and widespread beds throughout the entire pond. Hardwick Pond (Hardwick, MA), and Lake Rohunta (Orange, MA) are also infested with *C. caroliniana*. These waterbodies are outside the Quabbin and Ware River Watersheds, but are geographically close to the reservoir, thus contributing to the risk of potential introduction into the reservoir. These waterbodies are surveyed when possible to stay informed about the present *C. caroliniana* populations and other potential AIS infestations that could be a threat to the Reservoir.

3.4.1.5 Utricularia inflata

Utricularia inflata (swollen bladderwort) has been found in two ponds in the Ware River Watershed, and in the Quabbin Reservoir itself. It was found in Whitehall Pond (Rutland, MA), and Long Pond (Rutland, MA) in 2017. This AIS has not been documented in Long Pond in the two most recent surveys (performed in 2021 and 2022). *U. inflata* was found in Whitehall Pond from 2017 to 2019 but was not found during the 2021 or 2022 surveys. A single *U. inflata* was also found in a cove west of Boat Launch Area 2 in 2017. This one plant was removed, and no additional plants have been found in the reservoir since. When not blooming, *U. inflata* is difficult to distinguish from a native bladderwort species. As its blooming period occurs late spring/early summer, it is possible the seasonality of surveys (mid-summer to fall) is affecting the understanding of the presence and distribution of this species.

3.4.1.6 Iris pseudacorus

Iris pseudacorus (yellow flag iris) is an invasive species that closely resembles the native blue flag iris when not flowering. It has been documented in the reservoir and in both watersheds. *I. pseudacorus* was first documented in Connor Pond (Petersham, MA) in 2013 where it now colonizes large stretches of the western shoreline and has become densely distributed in many small coves. It is hypothesized this population of invasive irises in Connor Pond is contributing to the plants observed in Pottapaug Pond and at Boat Launch Area 3 via seed pods floating down stream. In 2019, the fragment barrier at Area 3 was repositioned to catch floating seed pods more effectively. Seedpods were observed in the fragment barrier in 2022.

I. pseudacorus plants were also found in Lovewell Pond (Hubbardston, MA), and Demond Pond (Rutland, MA), both in 2017. Members of the Demond Pond Association were notified of the locations of these plants, and hand harvesting was recommended, but several plants were found during the 2021 survey. Demond Pond was not surveyed in 2022 due to staffing constraints and the presence of an active pond association.

3.4.1.7 Lythrum salicaria

Lythrum salicaria (purple loosestrife) has been documented in 20 of the 50 surveyed watershed ponds (including the holding ponds). It has also been found in the Quabbin Reservoir, as individual plants or in small clusters along the shoreline (ESS Group Inc., 2021). It is most extensively established in Pottapaug and O'Loughlin Ponds, compared to the main reservoir. *L. salicaria* was recorded for the first time in four watershed ponds during the 2021 surveys (Edson Pond, Moulton Pond, South Spectacle Pond, and Thayer Pond). Each of these ponds had not been surveyed for five years, indicating the likely slow spread of this invasive.

L. salicaria was recorded in six areas in the 2022 survey season: Long Pond and Queen Lake in the Ware River Watershed, and Pottapaug Pond, Pepper's Mill Pond, Harvard Pond, and Boat Launch Area 3 within the Quabbin Reservoir Watershed. Despite previous observation of extensive stands, *L. salicaria* was not documented at O'Loughlin Pond in the 2022 survey. No new infestations were recorded. This plant is difficult to identify when not in bloom, making accurate estimates of the extent through the watersheds difficult to attain. Despite this, populations of *L. salicaria* do not appear to be changing rapidly year to year in watershed ponds, demonstrating a relatively low threat to water quality.

3.4.1.8 Rorippa microphylla

Rorippa microphylla, (one row yellowcress) is widely distributed in Massachusetts (USDA, 2020) and in both the Quabbin Reservoir and Ware River Watersheds. *R. microphylla* was found on the shoreline of Boat Launch Area 2 in 2012 but was not observed in the 2022 survey. In 2013 a single plant was found in O'Loughlin Pond. This plant was hand-pulled and has not been found in O'Loughlin since. *R. microphylla* was documented in the Ware River by Shaft 8 in 2016 but has never been documented there again. Pepper's Mill Pond (Ware, MA) and Muddy Pond (Oakham, MA) also have populations of *R. microphylla*. No populations were recorded at Pepper's Mill Pond in the 2022 survey. In all locations where it has been observed for multiple years, there appear to be fluctuations in population sizes. It is common to see low densities one year, and no presence the follow year. It is possible herbivores are preventing excessive growth where *R. microphylla* becomes established. To date, impacts from infestations of *R. microphylla* appear to be minor in surveyed waterbodies.

3.4.1.9 Najas minor

Najas minor (brittle naiad) was documented by ESS Group Inc. in 2014 at O'Loughlin Pond. DWSP hypothesize that *N. minor* seeds were introduced into the pond via avian passage, as birds are known to feed on the indistinguishable native *Najas gracillima* seeds (Martin and Uhler 1939; Reynolds et al., 2015). The *N. minor* infestation in O'Loughlin Pond documented in 2014 was quickly harvested using DASH. *N. minor* plants were not observed in O'Loughlin Pond for the eighth year in a row in 2022. This invasive has not been found elsewhere in the Quabbin Reservoir Watershed, or in the Ware River Watershed.

3.4.1.10 Potamogeton crispus

Potamogeton crispus (curly-leaf pondweed) has only been found in one waterbody across the two watersheds. It was first identified in 2013 at Whitehall Pond (Rutland, MA), which is managed by Lakes and Ponds due to a DCR-owned beach. This initiated several years of management (2013 through 2017, annually), including mechanical and hand-harvesting plants as well as chemical control. These treatment actions reduced densities of *P. crispus*, and in the 2022 survey no *P. crispus* plants were detected.

3.4.1.11 Myosotis scorpioides

Myosotis scorpioides (true forget-me-not) is not truly an aquatic plant but inhabits wet, disturbed shorelines and is found throughout New England. *M. scorpioides* are another very commonly found AIS around the reservoir and in the Quabbin Reservoir and Ware River Watersheds. It has been found in 16 of the regularly surveyed watershed ponds. It was first documented in the Quabbin Reservoir in 2012, along the shoreline of Boat Launch Area 2 and at Gaston Pond in Barre. In 2013 it was found in Pottapaug Pond, then found in the ponds on Prescott Peninsula in 2014. The 2022 survey found *M. scorpioides* present at Long Pond, along the eastern and northeastern shoreline. Although still a minor infestation, it does seem to be spreading.

M. scorpioides is difficult to identify when not blooming, and this may account for variation of population presence year to year. When identified, *M. scorpioides* is removed via hand pulling. As this plant can multiply by seed production and spreads by an extensive and shallow underground root system, complete eradication of this invasive species is difficult. Known impacts associated with this plant are minimal at this time.

3.4.2 Invasive Aquatic Fauna Monitoring and Distribution

Visual surveys for *Cipangopaludina chinensis* (Chinese mystery snail) and adult *Dreissena polymorpha* (zebra mussels) are performed alongside aquatic macrophyte surveys. Net tows for invasive zooplankton and the larval stages of *D. polymorpha* in the reservoir began in 2009. The following sections summarize the presence and absence of potential invasive aquatic fauna threats in the Quabbin and Ware River Watersheds.

3.4.2.1 Dreissena polymorpha

Dreissena polymorpha (zebra mussels) were discovered in Massachusetts in 2009, leading to the development and adoption of the Quabbin Boat Decontamination Program (Section 3.4.3.2). Since then, it has been determined that the low pH and calcium levels found in the Quabbin Reservoir (Section 3.3.4) make it unsuitable for *D. polymorpha* reproduction and growth. As a result, it is unlikely to find fully mature *D. polymorpha* in the reservoir. Despite this, plankton net tows are scanned for the immature larval stages of *D. polymorpha*. To date, no immature larval stages have been found in the reservoir.

3.4.2.2 Invasive Zooplankton

The potential invasive zooplankton of concern are *Bythotrephes longimanus* (spiny waterflea) and *Cercopagis pengoi* (fishhook waterflea). Oblique tows are collected quarterly near the Boat Launch Areas (BLAs) and scanned for their presence. As of 2022, neither species has been documented in the Quabbin Reservoir.

3.4.2.3 Cipangopaludina chinensis

Cipangopaludina chinensis (Chinese mystery snail) have been documented in the Quabbin Reservoir, and in one pond in each watershed. They were first documented in the reservoir in 2014, when they were found near Boat Launch Area 1, and have since been found near the hangar at the Quabbin Administration Building (Belchertown, MA). These invasive snails were first documented in the Quabbin Reservoir Watershed in Lake Mattawa (Orange, MA) in 2013, and a moderate infestation was confirmed there in 2022. They were first found in the Ware River Watershed in Long Pond (Rutland, MA) in 2016. *C. chinensis* displace native snail species by outcompeting them for resources. Despite this, few studies have been conducted to adequately determine their impacts (Solomon et al., 2010). Snails may serve as an intermediate host for fish parasites.

3.4.3 AIS Management and Boat Decontamination Programs

Aquatic invasive species (AIS) management within the Quabbin Reservoir and Ware River Watersheds is currently limited to one *Myriophyllum heterophyllum* removal project funded by MWRA and several others funded and conducted by private lake/pond associations.

The DWSP Quabbin Reservoir/Ware River Region runs several prevention programs designed to limit the spread of AIS throughout the watersheds. These programs include the Quabbin Boat Seal Program for anglers on the Quabbin Reservoir and two self-certification programs within the Ware River Watershed. The Quabbin Boat Decontamination program was initiated in 2009. The Self-Certification programs began in 2010.

3.4.3.1 Ware River Management of Myriophyllum heterophyllum

Annual management of *M. heterophyllum* has occurred since 2016 in the basin above the Shaft 8 intake along the Ware River and in sections above the railroad and Route 122 bridges along the

Ware River. Despite these efforts, *M. heterophyllum* remains an issue for water operations due to plant fragmentation. Control methods are currently restricted to physical removal of plants and drawdowns. Winter drawdowns may lessen the labor necessary to reduce *M. heterophyllum* in this area; however, the hard freezes required for this to be effective are not consistent or predictable. In addition to this, the presence of *M. heterophyllum* upstream of the Shaft 8 intake continue to repopulate the area.

M. heterophyllum upstream of Route 122 covered 3.45 acres of the total distribution (3.64 acres), demonstrating the seventh consecutive year of expansion in this area (TRC, 2023). Density of *M. heterophyllum* downstream of the Route 122 bridge decreased slightly in 2022 compared to 2021 (TRC, 2023). Davey Resource Group was contracted by MWRA to physically remove plants for the fifth consecutive year. The 2022 harvest yielded a 35% reduction in total gallons removed compared to the previous year (Davey Resource Group Inc., 2022). Downstream of Route 122 saw a decrease of 46% in gallons removed, where most of *M. heterophyllum* was dead and uprooted, likely washed down from upstream (Davey Resource Group Inc., 2022). Upstream of Route 122 saw an increase of 96% in gallons removed, advancing approximately 900 feet upstream compared to 1,090 feet the previous year (Davey Resource Group Inc., 2022). An aquatic rake was successfully used to remove plants from deeper sections. Depopulating the entire river above Route 122 would be impractical, daunting, and extremely expensive. This is an ongoing issue with no foreseeable permanent solution. For this reason, the focus is to keep the basin above the intake as free of *M. heterophyllum* as is feasible.

3.4.3.2 Quabbin Boat Decontamination Program

The Quabbin Boat Decontamination program was initiated in 2009 to mitigate the risk of AIS introduction into the reservoir through recreational fishing. The Quabbin Reservoir is a popular destination for anglers as the system hosts both cold and warm water fish species. DCR provides rental boats for anglers to use on the Quabbin Reservoir, however many people prefer to use their own boats. Though some anglers exclusively fish at the Quabbin Reservoir, many others fish at a variety of locations across New England within a season. This provides a potential pathway for the interchange of AIS between bodies of water.

The Quabbin Boat Decontamination Program was developed to prevent the spread of AIS including plants (variable-leaf milfoil, Eurasian milfoil, hydrilla, etc.), zooplankton (spiny and fish-hook water flea), and invertebrates (zebra mussels and Chinese mystery snails). Many invasive species are very well adapted to endure harsh conditions, such as periods of desiccation. Plants can spread via small seeds and small plant fragments. Zooplankton and zebra mussels are microscopic during certain life stages and can persist inside boat motors for long periods of time. The boat inspection and decontamination programs offered through DWSP serve to limit the introduction of these invasive species into the Quabbin Reservoir.

The Quabbin Boat Decontamination Program consists of two options for recreational boaters to clean their boats: warm-weather decontamination (WWD) and cold-weather quarantine (CWQ). WWD events occurred over 17 dates in 2022 throughout the fishing season. During

WWD boaters are asked what bodies of water their boats were in last, then boats are inspected for any plant material and washed. Samples of biological substances collected off boats inspected during either the WWD or CWQ programs are identified whenever possible. All parts of the boat (including hulls, all through-hull fittings, live wells, bilge, downriggers, anchors, lines, and trolling motors) in addition to the boat trailers (including rollers and bunks) are washed with warm water (140 °F) at a high pressure. Warm water is then run through the boat motor until 140 °F water runs out of the motor for 10 seconds to kill any organisms that may be present in the motor. While this program requires payment from anglers, it enables them to fish outside of the Quabbin Reservoir, then return following the completion of a decontamination event. This significantly reduces the risk of AIS introduction from other waterbodies without restricting anglers to exclusively fish at the Quabbin Reservoir. The cold-weather quarantine program occurred over five dates in 2022. The CWQ requires no fee. Boats are tagged at the beginning of the winter season, making sure boats remain on trailers for around four months. At least three consecutive days below 32 °F, or 46 days with an average low temperature of 30 °F is required to cause desiccation or cold thermal death for any potential AIS (McMahon et al., 1993).

In 2022, 160 boats were inspected and decontaminated through the WWD program. This is below the average number of decontaminations from the previous eight years (175 WWDs from 2014-2021). Seventy-two boats were inspected and sealed through the CWQ program in 2022. This is lower than the average for the previous eight years (119 CWQs from 2014-2021). In 2022, around 37% of boaters used the WWD for the first time, and around 25% of boaters used the CWQ for the first time.

Public perception of the boat decontamination programs has improved since their inception. While the programs initially met some resistance, many anglers are now grateful for the opportunity to safely recreate between the Quabbin Reservoir and other water bodies. This is likely due to a region-wide effort from state and local officials as well as pond associations, to educate anglers on the risks of AIS. Participation in boat inspections and cleaning programs is now standard practice at many recreational water bodies. Though the public is becoming more aware of AIS, continued education is crucial. Many boaters remain unaware of the span of AIS beyond zebra mussels and common invasive plant species. This demonstrates the importance of continued education efforts to keep anglers engaged to ensure the Quabbin Reservoir remains free of new AIS infestations.

3.4.3.3 Boat Ramp Monitoring and Self-Certification Programs

The Boat Ramp Monitoring/Self-Certification Program was established in 2010 and 2011 to reduce the spread of AIS in ponds that allow boaters in the Ware River Watershed. The program was implemented in 2010 utilizing two full-time seasonal positions to educate boaters and inspect watercraft. Since then, a self-certification boat inspection process has been in place to streamline the program while reducing DWSP staff resources. Efforts are focused on Comet

Pond in Hubbardston and Long Pond in Rutland because of the high volume of boaters to these water bodies.

Self-certification forms are prominently displayed at Comet and Long Ponds in boxes on the kiosks near each boat ramp, along with signage directing boaters to self-certify their watercraft as free of AIS before launching. Kiosks, signs, and forms were updated in 2021 to make the program clear and information accessible. Forms include questions about where the boat was last used, how long it has been out of the water, how they cleaned their boats and with what, and if they are aware of any AIS in the location they previously boated. These questions provide information for management purposes, in addition to encouraging boaters to take responsibility for understanding the risk of AIS in their recreational water bodies.

Boaters are asked to display the completed forms on their car dashboard. Parking areas at both ponds are periodically checked through the boating season to monitor for compliance with the program. Vehicles/boaters not displaying a completed form are given instructions, and a blank form.

A new infestation of Cabomba caroliniana (fanwort) was identified at Long Pond during the annual macrophyte survey in 2021. Fragments of *C. caroliniana* were found near the boat launch, and a dense patch had formed in the cove between the boat launch and road. Plants were topping out and flowering at the time of the survey. The size of individual plants, and the spread of the patch indicate this invasive plant had been present in Long Pond for over a year. Due to the location of the infestation in the water body, it is very likely it was introduced by boaters. This new AIS introduction highlights the importance of the self-certification process and presents an example of the consequences that follow noncompliance.

4 Conclusions and Recommendations

Data generated by DWSP in 2022 documented the continued high quality of water in the Quabbin Reservoir and Ware River Watersheds. The requirements of the filtration avoidance criteria under the SWTR were satisfied for the entirety of 2022. Water quality monitoring remains ongoing to assess and document water quality in the Quabbin Reservoir and Ware River Watersheds and ensure continued fulfillment of the requirements stipulated by the SWTR.

4.1 Quabbin Reservoir Watershed and Ware River Watershed Tributary Water Quality

Results generated from routine monitoring of Core tributaries in Quabbin Reservoir and Ware River Watersheds in 2022 were largely consistent with historical data and demonstrate continued adherence to drinking water quality standards. Infrequent individual *E. coli* concentrations above single-sample regulatory limits, attributed to flushing from storm water runoff events, returned to pre-event levels upon resampling. Results for specific conductance in Core tributaries in the Quabbin Reservoir and Ware River Watersheds collected every two weeks suggest a subtle increasing baseline in specific conductance measured in some tributaries to the Quabbin

Reservoir and Ware River Watersheds – a pattern ubiquitous with surface waters in the snowbelt region of the US. Routine nutrient monitoring results for Core tributary monitoring sites in 2022 revealed more detailed dynamics of terrestrial aquatic N-cycling than previously documented, largely attributed to increasing the monitoring frequency for nutrients (previously quarterly) in Core tributary sites. TP analysis in Core and EQA sites in Quabbin Reservoir and Ware River Watersheds returned to EPA methods in 2021. TP concentrations remained within established background ranges at all Core sites.

Results of monitoring of select water quality parameters in Quabbin Reservoir Watershed and Ware River Watershed in 2022 were consistent with historical data, did not suggest the presence of any new substantial point-source contributions, and ultimately demonstrated continued adherence to drinking water quality standards.

4.2 Quabbin Reservoir Water Quality

Results of routine water quality profiles collected in Quabbin Reservoir in 2022 were comparable to historical data and indicated that the timing of turnover and stratification occurred in line with prior seasons. Profile data additionally served to guide phytoplankton sampling. Phytoplankton density and composition changes observed through 2022 were consistent with prior years. Climatic and hydrologic drivers contributed to seasonal and vertical shifts in phytoplankton assemblages and nutrient dynamics. Although *Chrysosphaerella* were present at similar densities of those observed in 2019, there were no reported taste and odor issues in 2022. The frequency of nutrient monitoring in Quabbin Reservoir also remained monthly in 2022. Monthly results for concentrations of Si, N-species and TP highlighted unique spatial (lateral and vertical) and temporal dynamics of these solutes in the Reservoir, largely driven by hydrodynamics (e.g., seasonal turnover) and primary productivity. 2022 marked the third consecutive year that TOC was monitored routinely at Quabbin Reservoir Core sites. TOC concentrations in Quabbin Reservoir largely mirrored patterns in UV_{254}, highlighting the influence of the East Branch Swift River on water quality at Den Hill.

Monthly monitoring of select water quality parameters in the Quabbin Reservoir during 2022 was consistent with historical data and demonstrated continued adherence to drinking water quality standards.

4.3 Proposed Quabbin Reservoir and Ware River Watershed Monitoring Programs for 2022

The water quality sampling plan for the Quabbin Reservoir and Ware River Watersheds is reviewed and modified annually to direct focus to different sub-basins within the watersheds and adapt to changing conditions (including but not limited to changes in land use/land cover and/or climate-driven hydrometeorological changes). The 2023 sampling plan retains the long-term Core sites in both watersheds and replaces the sites used to support Environmental Quality Assessment (EQA) efforts.

4.3.1 Quabbin Reservoir and Ware River Watershed Tributary Monitoring

The Quabbin Reservoir Watershed tributary monitoring program includes seven Core sites and up to seven EQA sites. DCR will continue to sample every two weeks at Core sites (Table 4), discontinue the EQA sites (215B, 215F, and 215H) monitored in 2022, and begin monitoring of two different EQA sites (211A-X and 211B-1) in the Quabbin Reservation sanitary district in 2023. Monitoring of nutrients (NO_3-N, NH_3-N, TKN, and TP), UV_{254}, and TOC (in Core sites) will continue for tributaries in the Quabbin Reservoir Watershed at a frequency of every two weeks through 2023.

The Ware River Watershed tributary monitoring program includes six Core sites and up to six EQA sites. DCR will continue to sample every two weeks at Core sites, discontinue monitoring at the EQA sites monitored in 2022 (103, 111, 112, C2, and N1) and begin monitoring at four EQA sites (115, 126A, 127, and 128) located in the West Branch Ware sanitary district in 2023. Monitoring of UV_{254} will continue for tributaries in the Ware River Watershed through 2023. Monitoring at site 101 will remain consistent with that of tributaries in the Quabbin Reservoir Watershed. Nutrient (NO_3-N, NH_3-N, TKN, and TP) monitoring will return to quarterly in the remaining Core tributaries in the Ware River Watershed in 2023. All other analyses, including DWSP hydrologic and meteorological monitoring will remain unchanged from 2022.

4.3.2 Quabbin Reservoir Monitoring

Monthly Quabbin Reservoir monitoring at Core sites (202, 206, and Den Hill) will continue to be conducted by DWSP from April through December 2023, weather and reservoir conditions permitting. This monitoring will include analyses for turbidity, total and fecal coliform, and *E. coli*. Quarterly Quabbin Reservoir monitoring will be conducted in May, July, October, and December. In addition to the monthly analytes, quarterly monitoring will include alkalinity, Na, Cl, and extracted chlorophyll *a* concentrations. DWSP monitoring of nutrients (NO_3-N, NH_3-N, TKN, TP, and Si) and UV_{254} in Quabbin Reservoir Core monitoring sites will return to a quarterly frequency in 2023. Monthly analyses of TOC at three depths at Core sites within the Quabbin Reservoir will continue in 2023. Routine monitoring for phytoplankton will be performed by DWSP weekly at site 202 during the growing season (May 01 through September 30, 2023), monthly at site 202 outside of the growing season, and monthly at sites 206 and Den Hill. *In situ* profiles of temperature, pH, specific conductance, dissolved oxygen, turbidity, chlorophyll *a*, and phycocyanin will be collected at each monitoring site within the Quabbin Reservoir and used to determine appropriate sample collection depth and inform controls on phytoplankton dynamics in Quabbin Reservoir.

No other modifications to DWSP monitoring efforts in Quabbin Reservoir Watershed or Ware River Watershed are anticipated for 2023. Changes to the DWSP water quality monitoring program introduced in 2023 may aid in future management decisions and help to better elucidate potential controls on productivity and algal dynamics in Quabbin Reservoir.

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6 Appendices

6.1 Appendix A. 2022 Watershed Monitoring Parameters and Historical Context

The following text was modified from the 2019 Annual Water Quality Report prepared for the Wachusett Reservoir (DWSP, 2020b).

Table A1: Water quality parameters, and associated analytical methods, monitored by DWSP in surface water in the Quabbin Reservoir Watershed and Ware River Watershed in 2019. Monitoring for select parameters in Quabbin Reservoir or tributary monitoring locations is indicated by an "X" in columns R and T, respectively. Precipitation and air temperature measurements were recorded from meteorological stations maintained by DWSP and NOAA (Section 2.1.2). Adapted from DWSP, 2020.

Parameter Name	Units	Sampling Group	Analysis Location(s)	Analysis Method	R	T
Air Temperature	Deg-F	Meteorological	Field-Sensor			
Ammonia-nitrogen	mg/L	Nutrients	MWRA Lab	EPA 350.1, 353.2	X	X
Alkalinity	mg/L $CaCO_3$	Nutrients	MWRA Lab	SM 2320 B	X	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		
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		
Chlorophyll volts	volts	Field parameter	Field-Sensor	*In situ* Fluorometry		
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	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	N/A	X	
Specific Conductance	µS/cm	Field parameter	Field-Sensor	SM 2510 B-1997	X	X
Staff Gage Height	ft	Field parameter	Field-Sensor	Pressure Transducer/ Visual staff plate reading		X
Total Coliform	MPN/100 mL	Bacteria	MWRA Lab	9223B 20th Edition	X	X
Total Kjeldahl Nitrogen	mg/L	Nutrients	MWRA Lab	EPA 351.2	X	X
Total Nitrogen	mg/L	Nutrients	MWRA Lab	Calculated		

Parameter Name	Units	Sampling Group	Analysis Location(s)	Analysis Method	R	T
Total Organic Carbon	mg/L	Nutrients	MWRA Lab	SM 5310 B		
Total Phosphorus	µg/mL	Nutrients	MWRA Lab	EPA 365.1	X	X
Total Suspended Solids	mg/L	Nutrients	MWRA Lab	SM2540		
Turbidity FNU	FNU	Field parameter	Field-Sensor	ISO7027		
Turbidity NTU	NTU	Bacteria	DWSP Lab, USGS	EPA 180.1	X	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

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) (USGS, 1999). Ammonia is 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 (Mallin et al., 2006). In 2013 the US 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 (US EPA, 2013). There are no drinking water specific action levels or maximum contaminant levels (MCLs) designated by any US 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 (WHO, 1996). Potential sources of NH_3-N in the Quabbin Reservoir and Ware River Watersheds 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 tributaries in the Quabbin Reservoir and Ware River Watersheds are well below regulatory thresholds, 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.

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 (USGS, 1999). Sources of nitrate include runoff from agricultural sites and fertilized lawns, failing on-site septic systems, atmospheric deposition, and some industrial discharges. Background concentrations of NO_3-N + NO_2-N in rivers and streams of the Quabbin Reservoir and Ware River 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) and 0.31 mg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical NO_3-N + NO_2-N criteria for these ecoregions (US, EPA 2001a; US EPA, 2001b). NO_2-N is generally below laboratory reporting limits for surface waters in the Quabbin Reservoir and Ware River Watersheds (see Section 2.2.3), thus, background concentrations are primarily composed of NO_3-N. At elevated concentrations, nitrates can result in 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 (Camargo and Alsonso, 2006).

Consumption of nitrates can become toxic to warm-blooded animals at very high concentrations (10 mg N/L or higher), due to conversion to nitrite through reduction (see Section 2.2.3). The EPA MCL for NO_3-N is 10 mg/L (Safe Drinking Water Act of 1974). NO_3-N concentrations measured in surface waters throughout the Quabbin Reservoir and Ware River Watersheds have remained well below the MCL. The current water quality goal for NO_3-N is to maintain existing local background concentrations.

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. Background concentrations of TKN in rivers and streams of the Quabbin Reservoir and Ware River Watersheds ecoregions were found to range between 0.05 mg/L and 1.45 mg/L, with the 25th percentile value (all seasons) of 0.10 mg/L (ecoregion 58) and 0.30 mg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by EPA for the development of numerical TKN criteria for these ecoregions (US EPA, 2000; US EPA 2001a). 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 lakes. 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. The current water quality goal for TKN in streams, rivers, and the Reservoir is to maintain existing local background concentrations.

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.

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 contributing agents for eutrophication. In absence of water body specific nitrogen criteria for Quabbin Reservoir and Ware River 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 Quabbin Reservoir and Ware River 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) and 0.59 mg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TN criteria for these ecoregions (US EPA, 2000; US EPA 2001a). 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.

Total Phosphorus

Phosphorus is an important macronutrient, and the limiting factor controlling algal productivity in Quabbin Reservoir. Phosphorus 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 (USGS 2012). Through various human activities, additional phosphorus 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 phosphorus 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 phosphorus. Furthermore, human activities that accelerate erosion processes on the land surface and within streams can increase the release of phosphorus from soils and sediment into water bodies.

Lakes with TP concentrations exceeding 20-30 µg/L may experience nuisance algal growth (Vollenweider, 1976). Background concentrations of TP in rivers and streams of the Quabbin Reservoir and Ware River Watersheds ecoregions were found to range between 2.5 µg/L and 907.5 µg/L, with the 25th percentile value (all seasons) of 5 µg/L (ecoregion 58) and 23.75 µg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TP criteria for these ecoregions (US EPA 2000; US EPA 2001b). Like nitrogen, there are no Massachusetts numerical water quality standards for phosphorus for any Quabbin Reservoir Watershed or Ware River Watershed water bodies. However, the narrative water quality criteria do apply as previously described.

While elevated TP concentrations pose no direct threat to drinking water quality, they can promote algal blooms, 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 Quabbin Reservoir is to maintain naturally occurring local background concentrations.

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 (Reynolds, 2006). 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.

Water Temperature

Temperature is a critical parameter in controlling the amount of dissolved oxygen that is available in aquatic environments. As water temperatures increase, the amount of oxygen that can be dissolved in water decreases. Moreover, higher stream temperatures increase the solubility of nutrients and may correlate well with an increase in the growth of filamentous algae and may threaten sensitive aquatic habitats. Due to these aquatic life concerns, MassDEP has set regulatory thresholds for warm and coldwater fisheries. Unless naturally occurring, coldwater fisheries may not exceed 20 °C (68 °F) as a mean of 7-day maximum temperature. Warmwater fisheries may not exceed 28.3 °C (83 °F) as a mean of 7-day maximum temperature (314 CMR 4.05(3)(a)2 (2013)). 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. As is typical of most deep lakes and reservoirs in the temperate region, Quabbin 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.

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 Quabbin 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.

Alkalinity and pH

The Hydrogen ion activity (pH) of a stream is largely a function of the groundwater hydrogeology of the basins and the effectiveness of the stream water in buffering the effects of acid precipitation. The Class A water quality standard is a range between 6.5 – 8.3 (or no change from background levels). The pH in Quabbin Reservoir is determined ultimately by the exchange of inorganic carbon between the atmosphere and water (carbon dioxide-bicarbonate-carbonate buffering). Generally, pH values in Quabbin 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 Quabbin Reservoir.

Buffering capacity, or the ability of a water body to resist changes in pH from acidic or basic inputs, is quantified by alkalinity as calcium carbonate ($CaCO_3$). Waters in the northeastern U.S. typically have low alkalinity due to the region's lack of carbonate-rich bedrock. Alkalinity may also be influenced by land use within the watershed including agriculture and landscaping which may involve application of lime, weathering of concrete, and use of road deicers. Within a water body, alkalinity can affect photosynthetic activity of algae and other plants. The minimum alkalinity for aquatic life published by EPA is 20 mg/L or if lower values are naturally occurring, results cannot be lower than 25% of the natural level (US EPA, 2013). Alkalinity in Quabbin Reservoir is much lower than this threshold. Increases observed over the past 30 years are likely linked to the observed increases in specific conductance caused by regional salinization (Kaushal et al., 2005).

Bacteria

Water bodies naturally contain many microorganisms, most of which are benign. However, there are several harmful intestinal microorganisms (viruses, bacteria, and protozoa) that are sometimes present in water (e.g., *Cryptosporidium*, *Giardia, Salmonella*). Many of these are fecal microorganisms and are known to cause a host of illnesses such as intestinal and urinary tract infections, meningitis, and septicemia, dysentery, typhoid fever, and cholera (Myers et al., 2014; USGA, n.d.a). *Escherichia coli* (*E. coli*) is a species in the fecal coliform group, which originates from fecal material of humans and other warm-blooded animals (US EPA, 1986). Some strains of *E. coli* can be deadly, especially for small children or people with weakened immune systems (USEPA & Tetra Tech Inc., 2013). The presence of *E. coli* in water is often correlated with the presence of many other pathogenetic microorganisms (Myers et al., 2014), 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 (Myers et al., 2014). The only two common *E. coli* sources not applicable to the Quabbin Reservoir 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 (314 CMR 4.05(3)(a)4.c (2013)) 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. DWSP prohibits wading and swimming in Quabbin Reservoir and its tributary waters, however fishing is allowed and remains an avenue for public exposure to pathogens from the water supply prior to treatment. Despite there being low risk for pathogen exposure via recreation, DWSP uses these regulatory thresholds to evaluate the sanitary quality of waters within the Quabbin Reservoir and Ware River Watersheds. As a major public water supply, regulatory requirements for pathogens at drinking water intakes are much more stringent.

MWRA is required to measure fecal coliform concentrations in raw water prior to treatment. State and federal regulations (314 CMR 4.05(3)(a)4.c (2013)) specify that fecal coliform concentrations shall not exceed 20 organisms per mL in 90% of the samples taken in any six-month period. Results for pathogen testing at the intake are discussed in separate reports published by MWRA (MWRA, 2020b).

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 (Rhodes et al., 2001; Granato et al., 2015). Freshwater systems in Massachusetts naturally contain low levels of mineral salts in solution (Granato et al., 2015). Elevated levels of specific conductance and associated dissolved solutes (e.g., Na, Cl) may stress sensitive biota, threaten ecosystems (Jackson & Jobbágy, 2005; Corsi et al., 2010), and degrade drinking water quality (Kaushal et al., 2005; Daley et al., 2009; Kelly et al., 2010). Contamination of drinking water supplies with excess Cl may increase the corrosivity of affected waters (Stets et al., 2018), 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 (Kaushal et al., 2017), 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 (US EPA, 1988). 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" (MassDEP-DWM, 2018). 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 (310 CMR 22.07D (2016)). MassDEP does not enforce regulatory standards for specific conductance in drinking water.

Elevated levels of specific conductance and associated ions in surface water and groundwater may indicate contamination from anthropogenically-derived sources of salts to natural water systems such as septic system effluent, stormwater discharges, agricultural runoff, or road salt runoff from deicing activities (Panno et al., 2006; Lautz et al., 2014). In the snowbelt region of the U.S., road salt is the dominant source of salinity to many natural water systems (Kaushal et al., 2005; Kelly et al, 2008; Mullaney et al., 2009).

Turbidity

Turbidity is another term for water clarity, which is determined by measuring the scatter of light in the water (USGS) and reported by DWSP in Nephelometric Turbidity Units (NTU). Any dissolved or suspended particle in water will cause light scatter and increase turbidity. In streams, high turbidity is often associated with storm events which increase suspended solid concentrations (see TSS), as well as concentrations of smaller particles like clay. Reservoir turbidity may be influenced by plankton production, pollen deposits, and shoreline disturbances of organic deposits. Clay particles can also remain suspended in the water column for extended periods as a result of eroding shorelines or clay laden tributary waters delivered by storm events. For drinking water supplies, the concern over turbidity relates to aesthetics, pathogens, and 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 (310 CMR 22.08(1) (2016)) mandates that raw water turbidity levels (at the intake) always remain below 5 NTU. MassDEP regulations specify that turbidity levels may exceed 1 NTU only if it does not interfere with effective disinfection. Background concentrations of turbidity in rivers and streams of the Quabbin Reservoir and Ware River Watersheds 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) and 1.68 NTU (ecoregion 59), which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical turbidity criteria for these ecoregions (US EPA, 2000; US EPA 2001b). The current water quality goal for turbidity in streams and rivers is to maintain existing local background concentrations.

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. 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.

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. 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 (DWSP 2018).

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 subecoregions 58 and 59 are 2.1 – 6 µg/L and 1.38 – 2.7 µg/L, respectively (US EPA, 2001b).

Chlorophyll *a* and phycocyanin data are only collected from reservoir locations at this time. On average, measurements for these pigments are low (<3 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.

Phytoplankton

Algae are a large, diverse group of organisms present in nearly every ecosystem from sandy deserts to artic permafrost to freshwater reservoirs (Reynolds, 2006). 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. For Quabbin Reservoir, these management options include potential treatment of the algae present in the Reservoir with copper sulfate and adjustments within the treatment system such as increasing the ozone dose (ozone is used as the primary disinfectant at John J. Carroll Water Treatment Plant). The MWRA is responsible for in-reservoir treatment of algae and disinfection of waters prior to delivery to local distributors (Commonwealth of MA, 2004).

Phytoplankton undergo seasonal succession, with varying genera becoming dominant at different times throughout the year. In Quabbin Reservoir, phytoplankton follow the typical pattern of a freshwater temperate water body. Diatoms are 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, and a relative increase in cyanophytes during the late summer and fall is occasionally observed as these organisms take advantage of warm temperatures and nutrient influxes in the fall. Following reservoir turnover, diatom densities often increase slightly 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 42, main text). These four chrysophyte genera and one cyanobacteria genus have previously attained problematic densities in Quabbin Reservoir and can cause undesirable tastes and odors in the water supply. Once these thresholds are exceeded, monitoring frequency is increased (typically to weekly) and action is considered.

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 (Hintz et al., 2019 and Richardson, 2008). 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 (Richardson, 2008). 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 (Havel & Shurin, 2004).

As of 2019, the potential invasive zooplankton of most concern to DWSP are *Bythotrephes longimanus* (spiny waterflea) and *Cercopagis pengoi* (fishhook waterflea). Their native range is Europe and northeast Asia, and Southwest Asia, respectively (Benson et al., 2021; Liebig, et al., 2021).

The primary goal of current zooplankton monitoring in the Quabbin 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 (Dodson, 2005). 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 2009.

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 (Dodson, 2005). In Quabbin Reservoir, Secchi disk transparency is most often affected by phytoplankton dynamics and contributions from the major tributaries to the Quabbin Reservoir. Weather patterns also affect visibility. The reference condition ranges listed for subecoregions 58 and 59 are 4.0 – 6.1 m and 1.2 – 4.9 m, respectively (US EPA, 2001b).

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6.2 Appendix B. DWSP Investigations Reports

Investigations into bacterial sources at Boat Cove Brook, November 2022

E. coli was elevated above normal background levels (25th to 75th percentile) in routine samples collected from Boat Cove Brook on November 22, 2022 (2,143 MPN/100-mL). This represents the annual maximum *E. coli* level observed at this location in 2022 (Figure 1). Elevated *E. coli* in surface waters following precipitation events may be attributed to episodic flushing from upland sources, as concentrations typically return to baseline levels with decreasing streamflow. Persistent elevated levels of *E. coli* in the absence of hydrologic events, particularly during cold months, may indicate a potential wildlife presence in the near stream contributing areas.

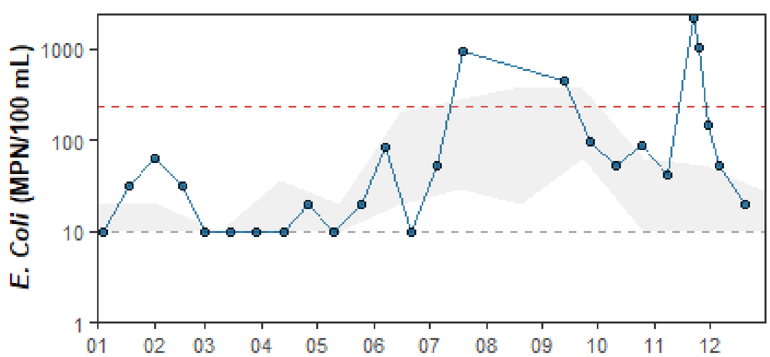

Figure 1. Time series of *E. coli* measured in Boat Cove Brook tributary during 2022. Gray line indicates the laboratory detection limit (10 MPN/100-mL). Red line indicates MassDEP Class A standards (235 MPN/100-mL). Shaded band signifies monthly 25th to 75th percentile values.

The *E. coli* results observed with November 22 routine monitoring triggered follow-up sampling to confirm the persistence of a potential threat, followed by an investigation of the upstream contributing areas to the Core site along Boat Cove Brook. The initial follow-up sample was collected on November 25, with subsequent sampling and investigation conducted on November 30, 2022. *E. coli* concentrations decreased from initial routine results with each subsequent sampling, from 1,043 MPN/100-mL to 145 MPN/100-mL, on November 25 and 30, respectively. Routine monitoring resumed, and samples collected from Boat Cove Brook on December 06, 2022, confirmed that *E. coli* had returned to baseline concentrations (52 MPN/100-mL).

DWSP staff inspected the near stream reaches of Boat Cove Brook on November 30, 2022. The surveyed reach extended from the DWSP Core sample site to approximately 0.25-mi upstream, until the reach became impassable due to thickening vegetation, primarily downed pines and multiflora rose. Beaver markings were not confirmed. Beaver activity in the nearby Boat Cove of Quabbin Reservoir was deemed inactive in September 2022. Several signs of wildlife were documented, however. Dominating these observations were deer sign, such as tracks, pellets, scrapes rubs, and fur. A large section of matted leaves was also observed approximately 6 feet from the stream bank, an estimated 150 yards upstream of the DWSP Core site (Figure 2). Other animal signs were also noted – including coyote scat, rabbit pellets and small carnivore (mink) pellets on a log. Chewings observed on autumn olive likely can be attributed to a porcupine or beaver, but the latter was indeterminant at the time of observation (Whitney, 2022). Ultimately, the results of this survey coupled with decreasing *E. coli* concentrations following the November 22 result suggest that intermittent wildlife activity may have contributed to the initial elevated result, and that subsequent results reflect dilution of initial inputs. Previous occurrences of elevated *E. coli* in Boat Cove Brook have been attributed to wildlife impacts (DWSP, 2018).

Figure 2. Clockwise, from top left: a) matted and stained leaves observed within 6 ft of the stream channel approximately 150 yards upstream of DWSP Core site along Boat Cove Brook, b) fur observed in matted leaves, c) red pines fallen across Boat Cove Brook, upstream of DWSP Core site, d) scat on a log overlaying the stream channel, and e) potential porcupine chews on autumn olive branches. Photos taken on November 30, 2022.

References

DWSP. 2018. 2017 Annual Water Quality Report: Quabbin Reservoir Watershed Ware River Watershed. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

Whitney, Jillian. “Re: beaver boat cove?.” Message to [Gary Moulton, Yuehlin Lee, Kristina Gutchess]. December 12, 2022. E-mail.

6.3 Appendix C. Figures and Tables

Tables

Table C44: Descriptive statistics (minimum, median, mean, and maximum) for Ca in Core tributary sites in the Quabbin Reservoir Watershed during 2022.

Location	Season	Calcium (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	6	43	1.69	1.15	1.90	1.76	1.91	1.83	2.19	2.80
	Spring	7	44	1.65	1.23	1.84	1.84	1.84	1.85	2.03	2.45
	Summer	7	46	2.46	1.42	3.37	2.54	3.59	2.58	4.57	4.05
	Fall	6	46	2.25	1.17	2.69	2.17	2.77	2.36	3.70	4.26
212	Winter	6	42	3.41	2.31	3.85	3.48	3.81	3.56	4.08	5.34
	Spring	7	44	3.12	0.02	3.44	3.53	3.52	3.45	4.47	4.30
	Summer	7	46	4.63	2.56	5.24	5.01	5.22	4.85	5.58	6.65
	Fall	6	46	5.07	1.35	6.34	4.70	6.20	4.54	6.81	6.51
213	Winter	6	43	2.91	1.72	3.53	3.36	3.59	3.46	4.13	5.96
	Spring	7	44	2.90	2.05	3.46	3.69	3.47	3.69	4.33	5.15
	Summer	7	46	5.32	2.17	5.87	5.29	5.88	5.11	6.44	6.90
	Fall	6	46	4.09	2.24	5.12	4.47	5.17	4.53	6.34	6.67
215G	Winter	6	5	1.73	1.78	2.11	1.94	2.08	2.03	2.44	2.54
	Spring	7	7	1.62	1.94	1.78	2.02	1.78	2.07	2.12	2.27
	Summer	7	7	2.15	1.57	2.45	2.24	2.53	2.11	3.00	2.34
	Fall	6	6	2.51	1.64	2.87	1.97	2.84	1.96	3.21	2.20
216	Winter	6	43	2.57	1.98	2.89	2.89	2.92	3.04	3.40	8.01
	Spring	7	44	2.23	1.85	2.51	2.53	2.53	2.58	3.17	3.23
	Summer	7	46	3.42	2.39	3.60	3.21	3.64	3.25	3.97	4.14
	Fall	6	46	3.45	2.08	3.76	3.41	3.75	3.27	4.04	4.62
BC	Winter	6	42	5.27	3.10	6.55	5.68	6.39	5.69	7.69	7.93
	Spring	7	44	5.01	2.70	5.74	6.00	6.11	5.92	8.53	8.77
	Summer	4	44	9.68	6.07	10.6	10.4	10.7	10.1	12.1	14.6
	Fall	6	41	8.11	3.36	10.4	8.58	10.1	8.7	11.4	14.0
GATE	Winter	6	43	1.06	0.02	1.13	1.07	1.15	1.14	1.25	2.00
	Spring	7	44	0.97	0.80	1.05	1.06	1.05	1.07	1.19	1.45
	Summer	5	46	1.29	0.90	1.40	1.23	1.45	1.23	1.73	1.91
	Fall	6	43	0.65	0.85	1.56	1.36	1.39	1.32	1.66	1.92

Table C45: Descriptive statistics (minimum, median, mean, and maximum) for Ca in Core tributary sites in the Ware River Watershed during 2022.

Location	Season	Calcium (mg/L)									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	6	24	2.54	2.28	3.46	3.43	3.41	3.48	4.16	4.46
	Spring	7	24	2.48	2.20	3.17	3.36	3.30	3.29	4.15	4.13
	Summer	6	26	4.36	2.84	4.58	4.16	4.56	4.12	4.71	4.94
	Fall	7	27	3.25	1.97	4.27	3.85	4.10	3.66	4.69	5.06
102	Winter	6	6	2.31	2.81	2.95	3.31	2.94	3.20	3.58	3.57
	Spring	7	6	2.25	2.79	2.74	3.11	2.84	3.11	3.67	3.47
	Summer	6	7	3.81	2.38	4.22	3.31	4.19	3.36	4.48	4.03
	Fall	7	7	3.22	2.45	3.92	3.01	3.84	2.98	4.17	3.59
103A	Winter	6	21	2.29	2.14	2.64	2.80	2.69	2.79	3.16	3.77
	Spring	7	23	2.16	1.84	2.55	2.50	2.53	2.51	3.04	3.36
	Summer	6	26	3.02	2.40	3.64	2.98	3.70	3.07	4.57	4.44
	Fall	7	27	2.44	1.91	3.04	2.73	3.05	2.75	3.68	4.31
107A	Winter	6	23	2.15	2.29	2.73	2.79	2.62	2.75	2.97	3.47
	Spring	7	24	2.08	2.05	2.41	2.80	2.56	2.69	3.31	3.34
	Summer	6	26	3.71	2.37	4.45	3.35	4.39	3.44	4.89	4.12
	Fall	7	27	3.11	2.04	3.91	3.08	3.98	3.15	5.14	5.28
108	Winter	6	24	3.03	2.94	3.58	3.74	3.75	3.82	4.72	4.81
	Spring	7	24	2.94	2.63	3.43	3.52	3.78	3.49	5.22	4.91
	Summer	6	26	5.73	3.18	5.81	5.55	5.93	5.21	6.39	6.56
	Fall	7	27	5.12	2.51	5.57	4.33	5.60	4.33	5.90	6.38
121	Winter	6	6	8.93	9.38	10.90	11.60	10.90	11.30	12.80	12.80
	Spring	7	6	7.66	10.90	10.00	11.40	9.76	11.80	11.40	14.40
	Summer	6	7	11.60	8.80	14.80	10.30	16.00	10.50	21.90	12.50
	Fall	7	7	10.80	6.55	12.60	9.91	12.50	9.43	14.30	10.50

Table C46: Descriptive statistics (minimum, median, mean, and maximum) for pH in Core tributary sites in the Quabbin Reservoir Watershed during 2022.

Location	Season	pH									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
211	Winter	6	248	5.56	4.10	6.31	6.10	6.11	6.07	6.43	7.23
	Spring	7	246	6.26	4.85	6.32	6.01	6.34	6.01	6.46	7.09
	Summer	7	249	6.10	4.40	6.48	6.29	6.42	6.19	6.53	6.93
	Fall	6	244	5.85	4.90	6.24	6.12	6.19	6.11	6.41	6.93
212	Winter	6	229	6.09	4.86	6.69	6.50	6.57	6.46	6.72	7.38
	Spring	7	234	6.64	4.65	6.74	6.56	6.77	6.51	7.01	7.64
	Summer	7	238	6.72	5.10	6.91	6.78	6.90	6.69	7.01	7.43
	Fall	6	229	6.54	5.56	6.59	6.68	6.64	6.62	6.84	7.13
213	Winter	6	240	5.62	5.01	6.24	6.10	6.10	6.11	6.28	7.07
	Spring	7	243	6.26	5.02	6.31	6.18	6.31	6.13	6.37	7.07
	Summer	7	243	6.16	4.95	6.31	6.20	6.31	6.16	6.44	7.20
	Fall	6	234	5.74	5.04	6.04	6.17	6.09	6.11	6.39	6.60
215G	Winter	6	15	5.58	4.80	5.80	5.36	5.78	5.49	5.94	6.58
	Spring	7	18	5.81	4.81	5.98	5.43	6.01	5.54	6.19	6.37
	Summer	6	19	6.08	4.77	6.20	5.27	6.20	5.38	6.37	6.18
	Fall	6	19	5.62	4.73	5.74	5.77	5.77	5.61	5.98	6.05
216	Winter	6	245	6.20	4.77	6.62	6.40	6.50	6.33	6.65	7.17
	Spring	7	245	6.53	5.31	6.60	6.40	6.68	6.34	7.01	7.56
	Summer	7	249	6.87	5.37	7.00	6.70	7.00	6.64	7.17	7.63
	Fall	6	240	6.28	5.53	6.57	6.58	6.51	6.54	6.79	7.13
BC	Winter	6	175	6.80	4.23	7.06	6.80	7.12	6.71	7.71	7.50
	Spring	7	182	7.02	5.59	7.09	6.90	7.14	6.84	7.33	7.97
	Summer	4	152	7.22	5.69	7.25	7.10	7.26	7.03	7.31	7.84
	Fall	6	157	6.55	5.15	6.96	6.94	6.91	6.90	7.09	7.50
GATE	Winter	6	174	5.41	4.09	5.99	5.62	5.89	5.69	6.17	7.75
	Spring	7	176	5.79	4.32	5.91	5.40	5.92	5.47	6.14	6.62
	Summer	5	180	6.06	4.39	6.17	5.95	6.18	5.92	6.36	7.21
	Fall	6	194	5.71	4.72	6.06	6.17	6.14	6.03	6.60	7.20

Table C47: Descriptive statistics (minimum, median, mean, and maximum) for pH in Core tributary sites in the Ware River Watershed during 2022.

Location	Season	pH									
		Count		Minimum		Median		Mean		Maximum	
		2022	POR	2022	POR	2022	POR	2022	POR	2022	POR
101	Winter	6	206	5.52	5.22	6.25	6.20	6.21	6.22	6.61	7.44
	Spring	7	215	6.31	5.11	6.53	6.20	6.54	6.18	6.87	7.04
	Summer	6	213	6.70	5.03	6.84	6.45	6.85	6.40	6.97	7.21
	Fall	7	211	5.85	4.51	6.38	6.40	6.36	6.34	6.90	7.18
102	Winter	6	109	6.18	5.70	6.49	6.40	6.51	6.36	6.78	6.80
	Spring	7	109	6.08	5.80	6.41	6.40	6.38	6.32	6.59	6.81
	Summer	6	114	6.17	5.80	6.37	6.50	6.47	6.50	6.89	6.90
	Fall	7	112	6.05	5.60	6.53	6.50	6.48	6.47	6.72	6.90
103A	Winter	6	82	5.56	5.16	6.01	6.09	6.02	6.01	6.39	6.81
	Spring	7	100	5.91	4.65	6.20	6.00	6.16	6.01	6.32	7.17
	Summer	6	106	5.95	4.43	6.26	6.11	6.26	6.02	6.51	7.02
	Fall	7	104	5.90	4.56	6.08	6.10	6.08	6.03	6.28	6.90
107A	Winter	6	89	5.50	1.11	5.84	5.80	5.83	5.74	6.21	7.06
	Spring	7	101	6.00	4.48	6.25	6.00	6.23	5.95	6.43	6.91
	Summer	6	108	6.28	4.77	6.48	6.19	6.46	6.11	6.58	6.85
	Fall	7	108	5.83	3.93	6.07	6.05	6.12	5.99	6.53	7.01
108	Winter	6	200	5.73	5.21	6.21	6.10	6.15	6.07	6.36	6.92
	Spring	7	206	6.21	5.04	6.44	6.16	6.40	6.11	6.52	7.13
	Summer	6	209	6.43	5.06	6.49	6.30	6.50	6.23	6.58	7.03
	Fall	7	208	6.24	4.43	6.33	6.20	6.35	6.13	6.48	6.72
121	Winter	6	123	6.27	2.63	6.63	6.40	6.55	6.41	6.72	6.85
	Spring	7	122	6.51	6.02	6.58	6.48	6.63	6.47	6.78	6.88
	Summer	6	132	6.66	6.04	6.72	6.60	6.75	6.63	6.88	7.40
	Fall	7	133	6.44	5.61	6.52	6.50	6.54	6.51	6.74	7.10

Table C48: Descriptive statistics (minimum, median, mean, and maximum) for alkalinity in Quabbin Reservoir Core sites during 2022.

Location	**Depth**	**Alkalinity (mg/L $CaCO_3$)**									
		Count		**Minimum**		**Median**		**Mean**		**Maximim**	
		2022	**POR**	**2022**	**POR**	**2022**	**POR**	**2022**	**POR**	**2022**	**POR**
202	Surface	9	124	3.62	2.66	3.97	3.62	4.20	3.52	6.37	4.27
	Mid	9	139	3.52	2.47	3.89	3.61	3.90	3.46	4.41	4.50
	Deep	9	146	3.48	2.51	3.88	3.55	3.82	3.43	4.06	4.51
206	Surface	9	123	3.69	2.44	3.93	3.73	3.93	3.58	4.27	4.27
	Mid	9	137	3.53	2.44	3.97	3.61	3.91	3.52	4.08	4.33
	Deep	9	144	3.58	2.63	3.88	3.57	3.86	3.51	4.02	5.51
Den Hill	Surface	9	120	3.88	2.54	4.12	3.91	4.11	3.80	4.44	5.10
	Mid	9	133	3.95	2.76	4.21	3.79	4.19	3.73	4.51	4.62
	Deep	9	140	3.55	2.60	4.14	3.82	4.30	3.77	5.66	7.50

Figures

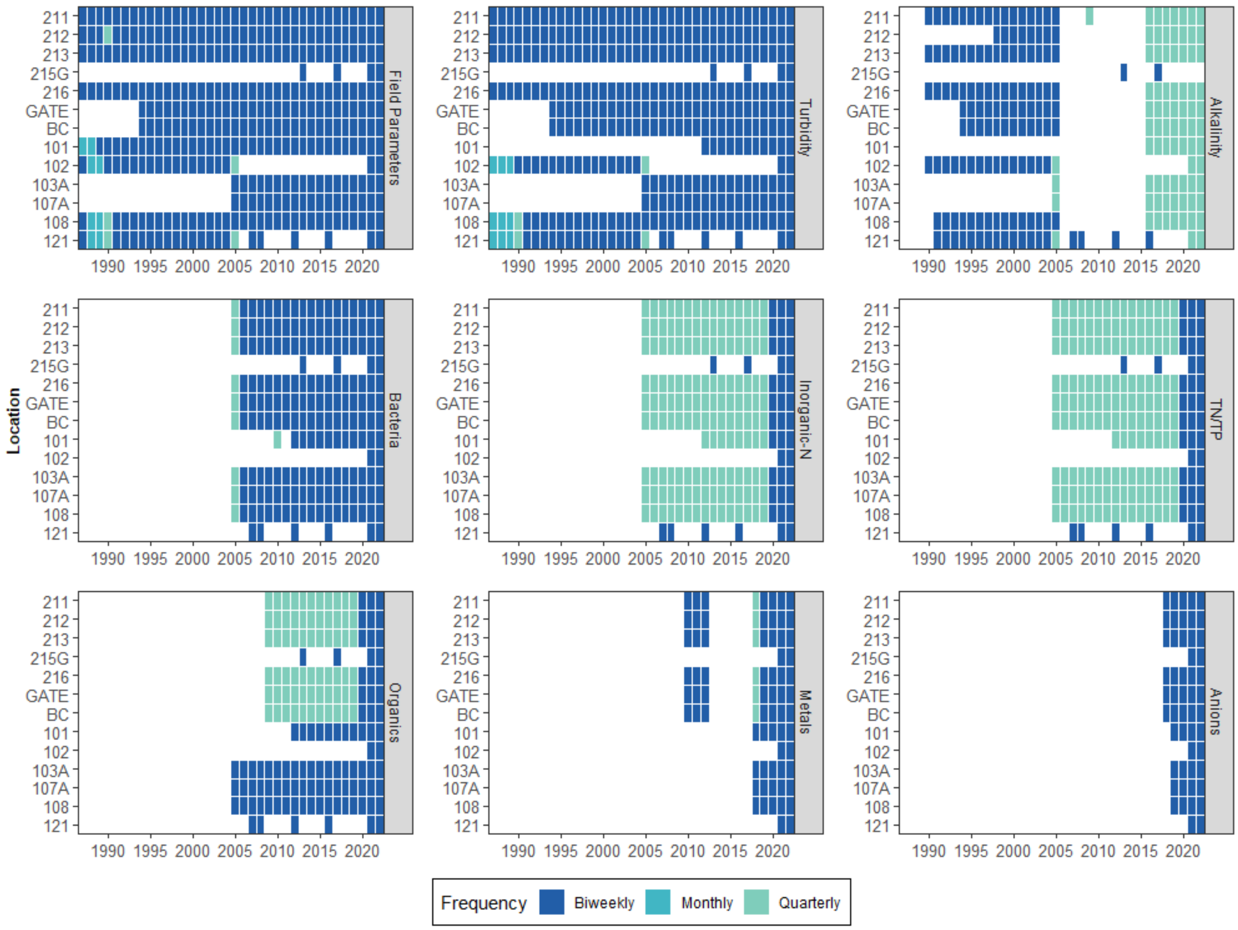

Figure C35: Period of record for analytes measured in Core tributaries in Quabbin Reservoir and Ware River Watersheds. Field parameters include specific conductance, water temperature, pH, and dissolved oxygen. Bacteria includes total coliform and *E. coli*, the latter of which was added to DWSP monitoring programs in 2005. Inorganic N represents NO_3-N and NH_3-N, with the addition of NH_3-N in 2011. TN/TP encompasses data for concentrations of TKN, total nitrogen, and total phosphorus. Organics includes UV_{254}, with the addition of total organic carbon at Core sites in the Quabbin Reservoir Watershed in 2021. Metals and anions incorporate Ca, Na, and Cl concentrations.

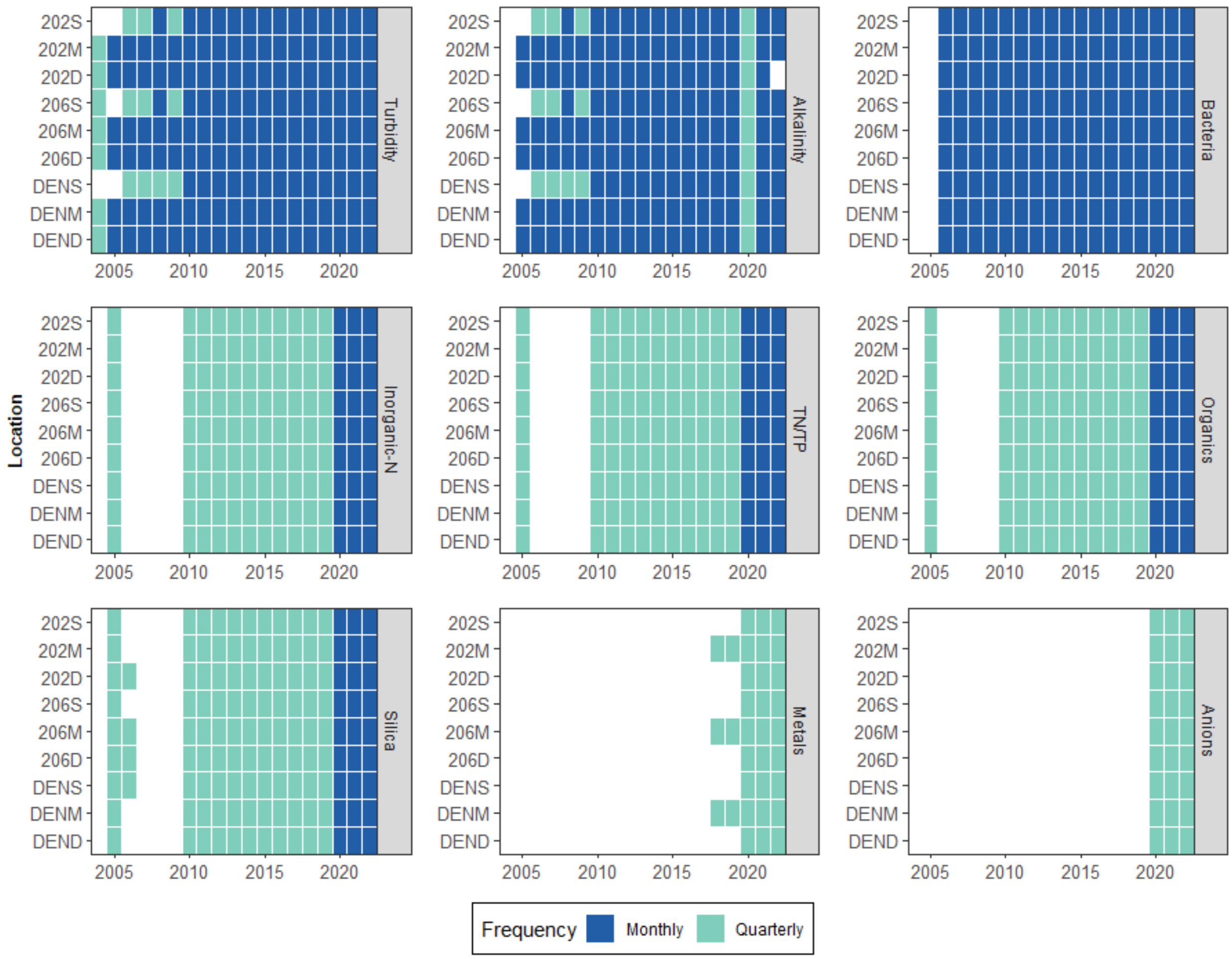

Figure C36: Period of record for analytes measured in Quabbin Reservoir monitoring sites. Field parameters including specific conductance, water temperature, pH, and dissolved oxygen were collected in conjunction with phytoplankton sampling. Bacteria includes total coliform and *E. coli*, the latter of which was added to DWSP monitoring programs in 2005. Inorganic-N represents NO_3-N and NH_3-N, with the addition of NH3-N proceeding NO_3-N in 2011. TN/TP encompasses data for concentrations of total Kjeldahl nitrogen, total nitrogen, and total phosphorus. Organics includes UV_{254} data, with the addition of total organic carbon at Core sites in the Quabbin Reservoir Watershed in 2020. Metals and anions incorporate calcium and sodium, and chloride concentrations, respectively. Silica was reported as dissolved and total silica in 2005, and as total silica thereafter.

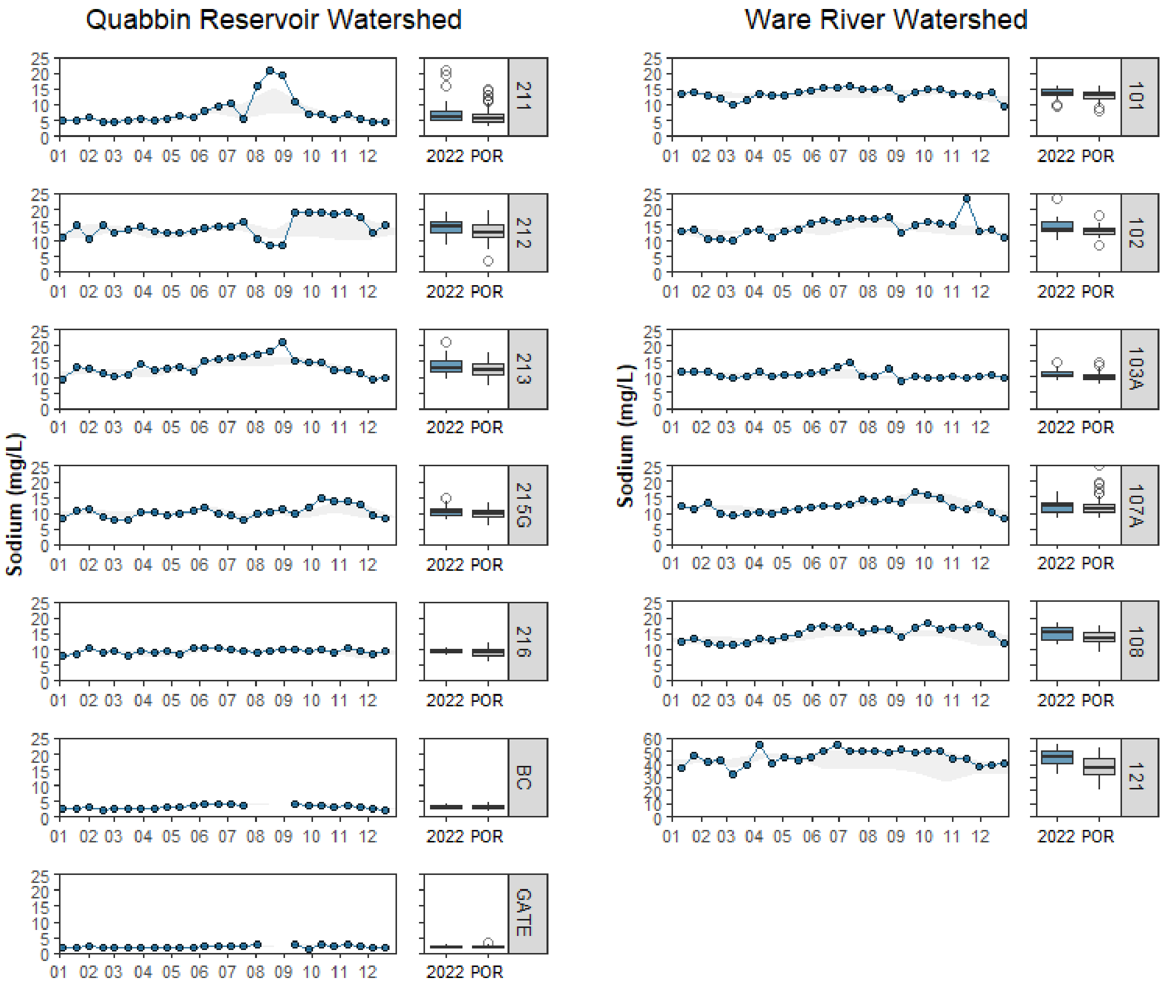

Figure C37: Time series of Na measured in Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel.

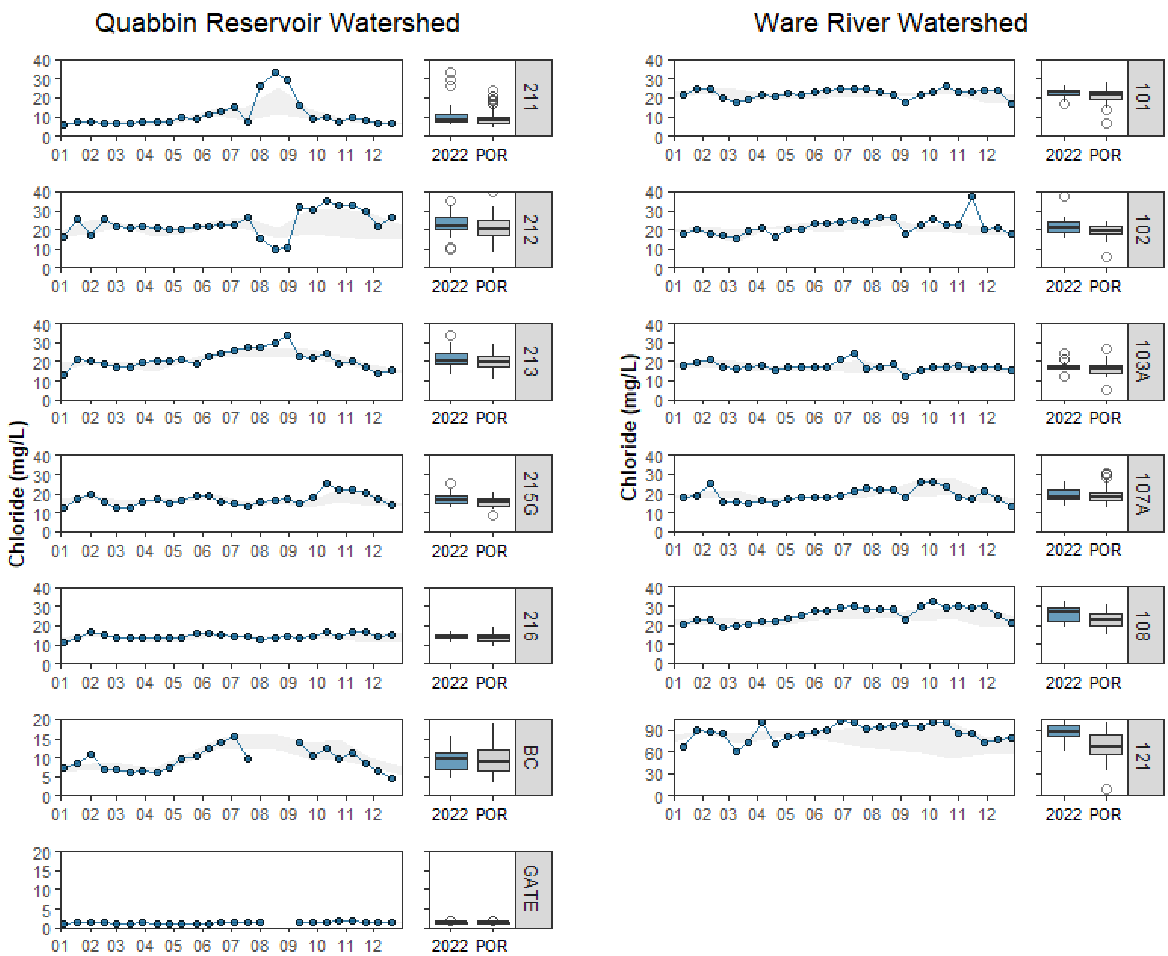

Figure C38: Time series of Cl measured in Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel.

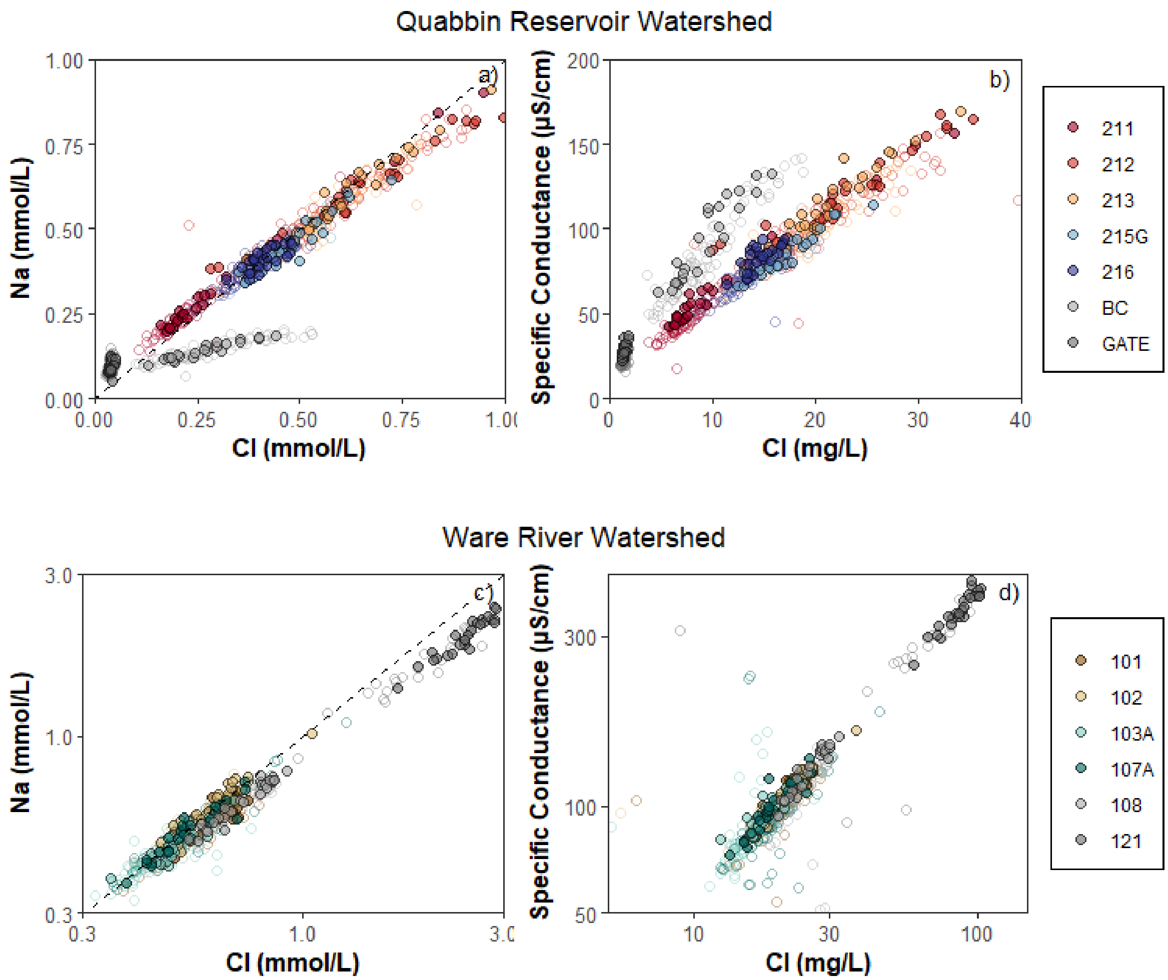

Figure C39: a) molar ratios of sodium and chloride and b) specific conductance and concentrations of chloride and in Core tributaries in the Quabbin Reservoir Watershed in 2022. c) Molar ratios of sodium and chloride and c) specific conductance and concentrations of chloride and in Core tributaries in the Ware River Watershed in 2022. The dashed line denotes a 1:1 molar ratio of sodium to chloride. The clustering of results around the 1:1 line suggests that concentrations of sodium and chloride in most tributaries to the Quabbin Reservoir likely originate from halite sources (e.g., road salt). The linear relationship among variables reveals that specific conductance in most Core tributaries is predominantly controlled by concentrations of dissolved chloride.

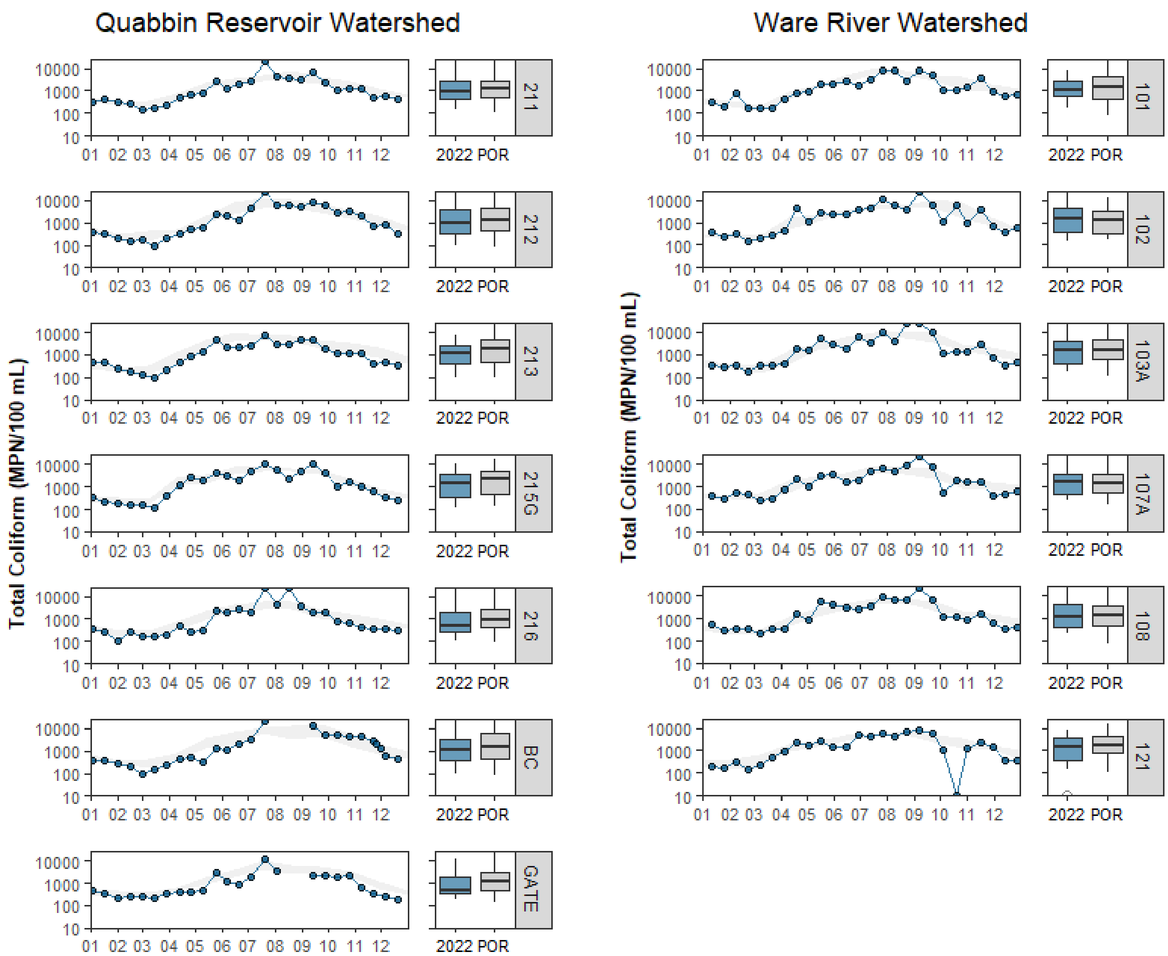

Figure C40: Time series and boxplots of total coliform measured Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel.

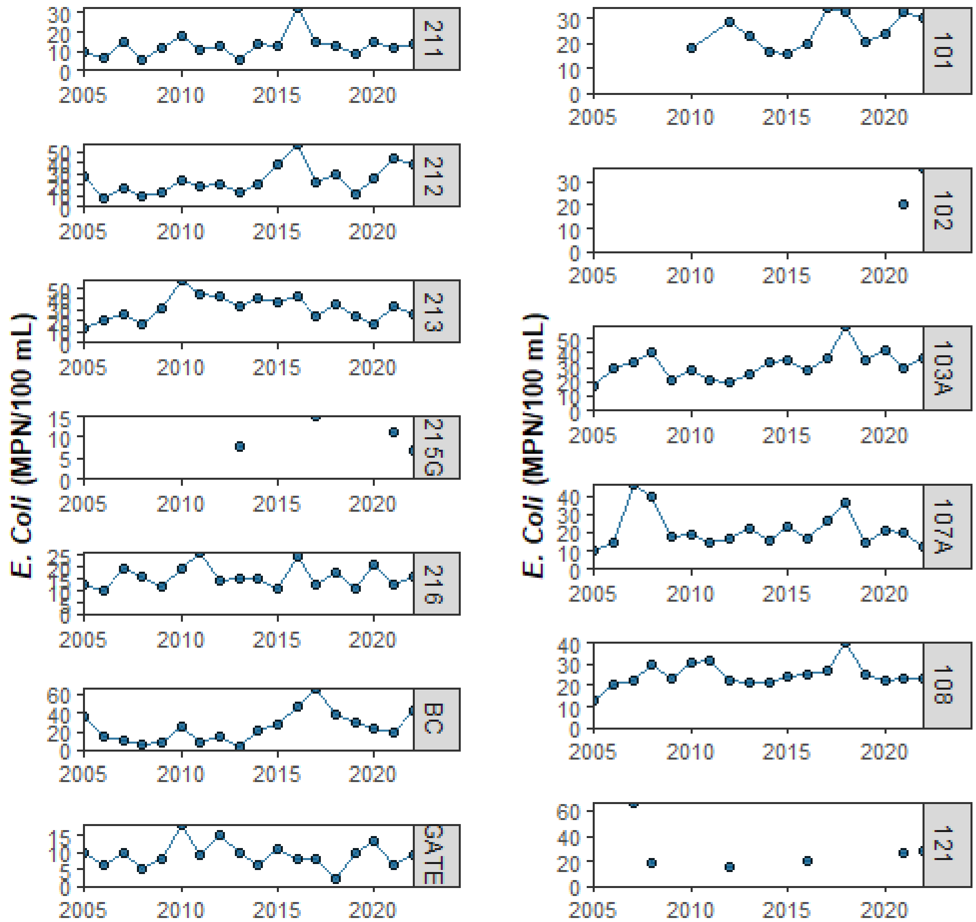

Figure C41: Time series of annual geometric mean *E. coli* in Core tributary sites from 2005 to 2022.

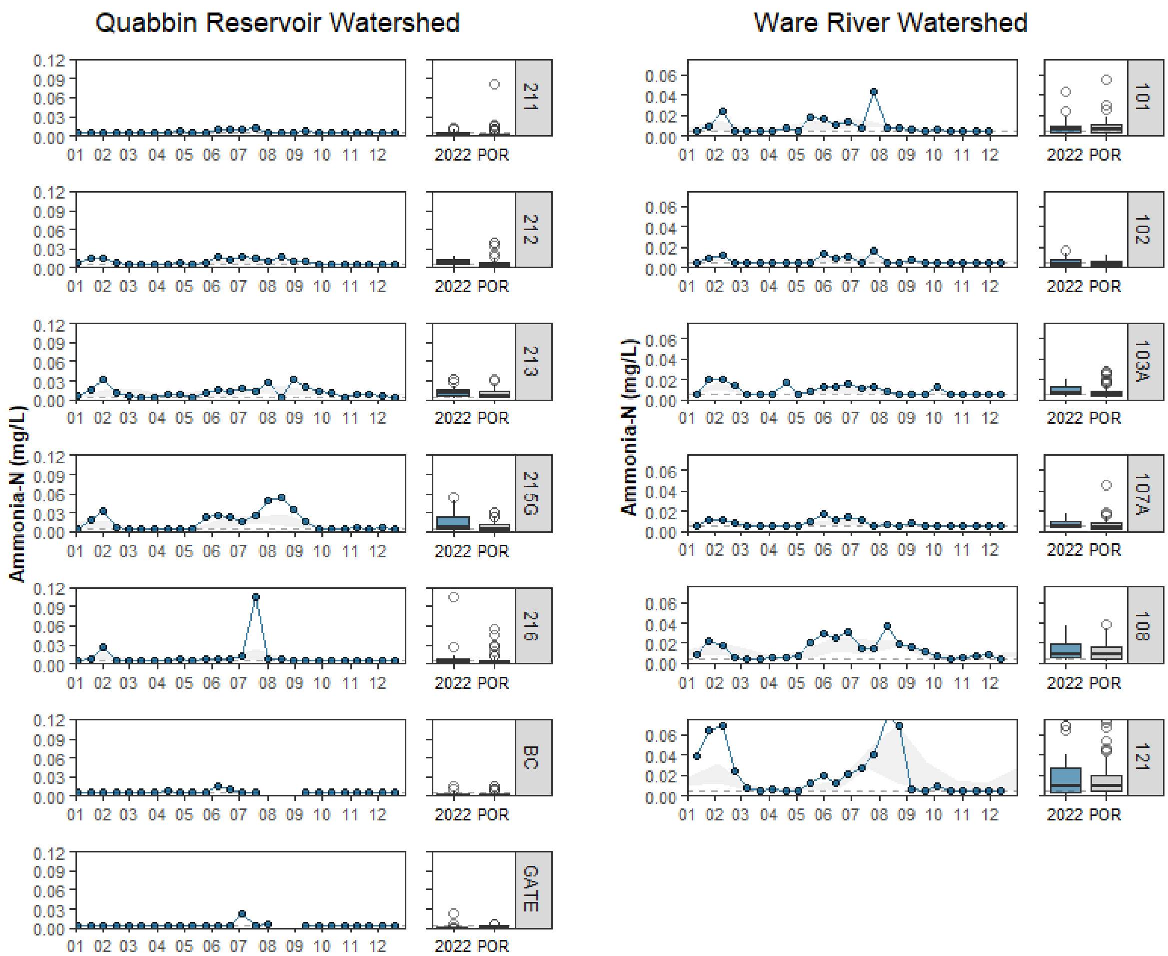

Figure C42: Time series and boxplots of NH_3-N measured in Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel. The horizontal dashed grey lines correspond to laboratory detection limits (0.005 mg/L).

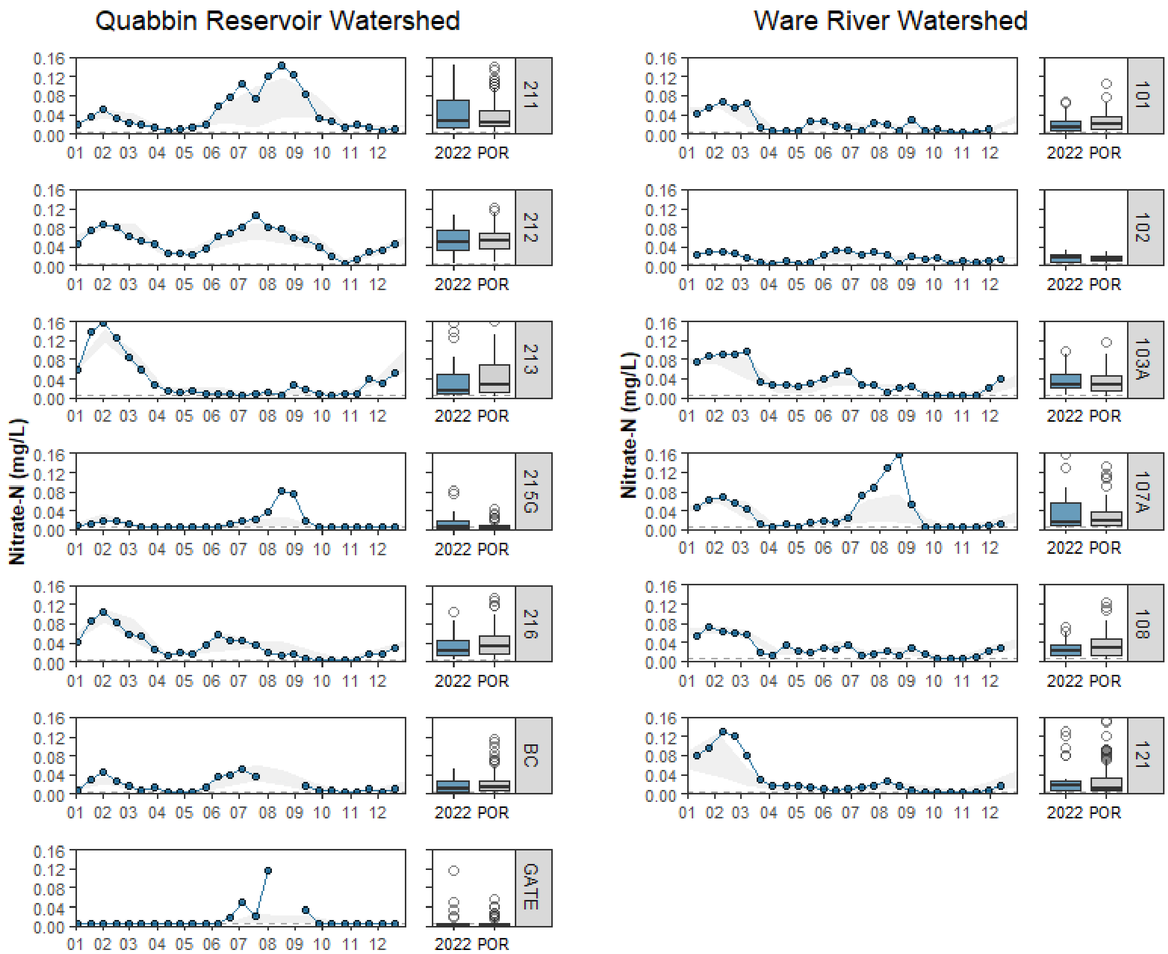

Figure C43: Time series and boxplots of NO_3-N measured Core tributary sites in 2022. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2022 are signified by the colored points in each panel. The horizontal dashed grey lines correspond to laboratory detection limits (0.005 mg/L).

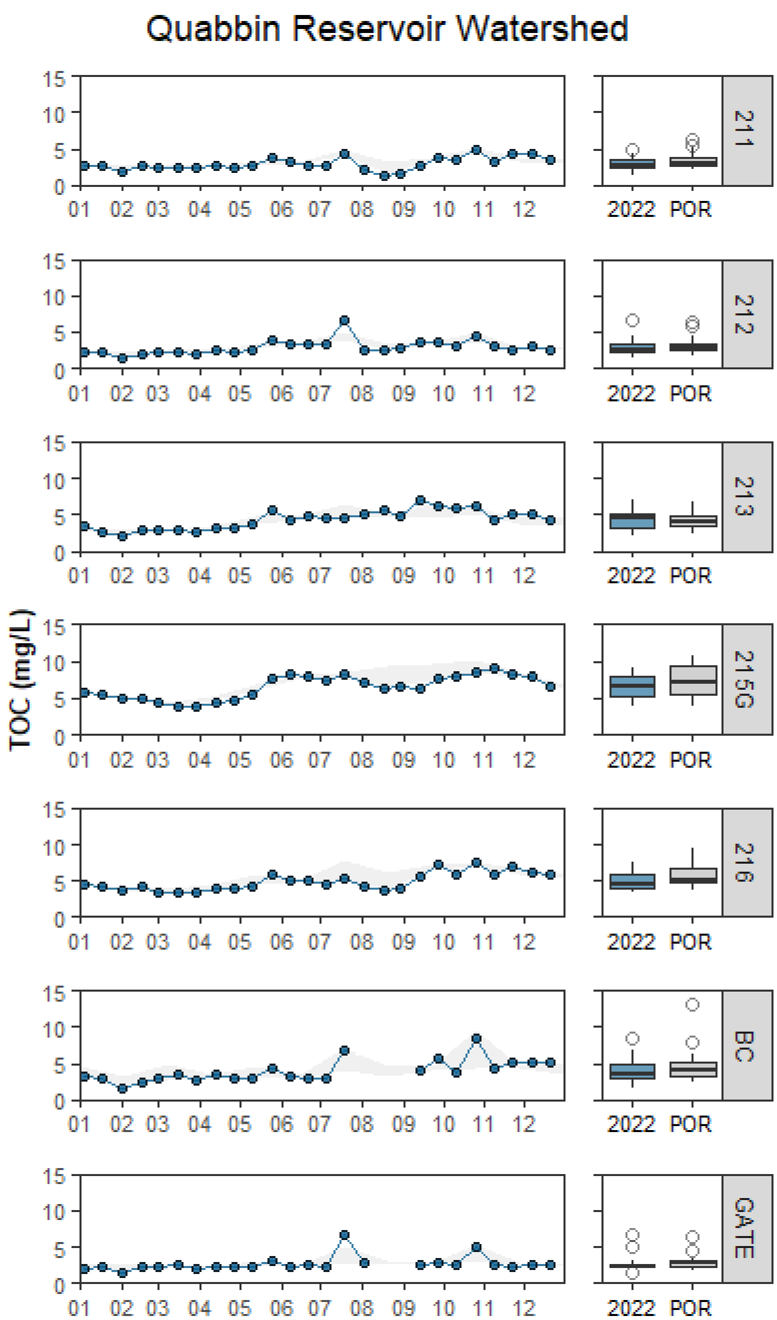

Figure C44: Time series of TOC measured in Quabbin Reservoir Watershed Core tributary sites in 2022.

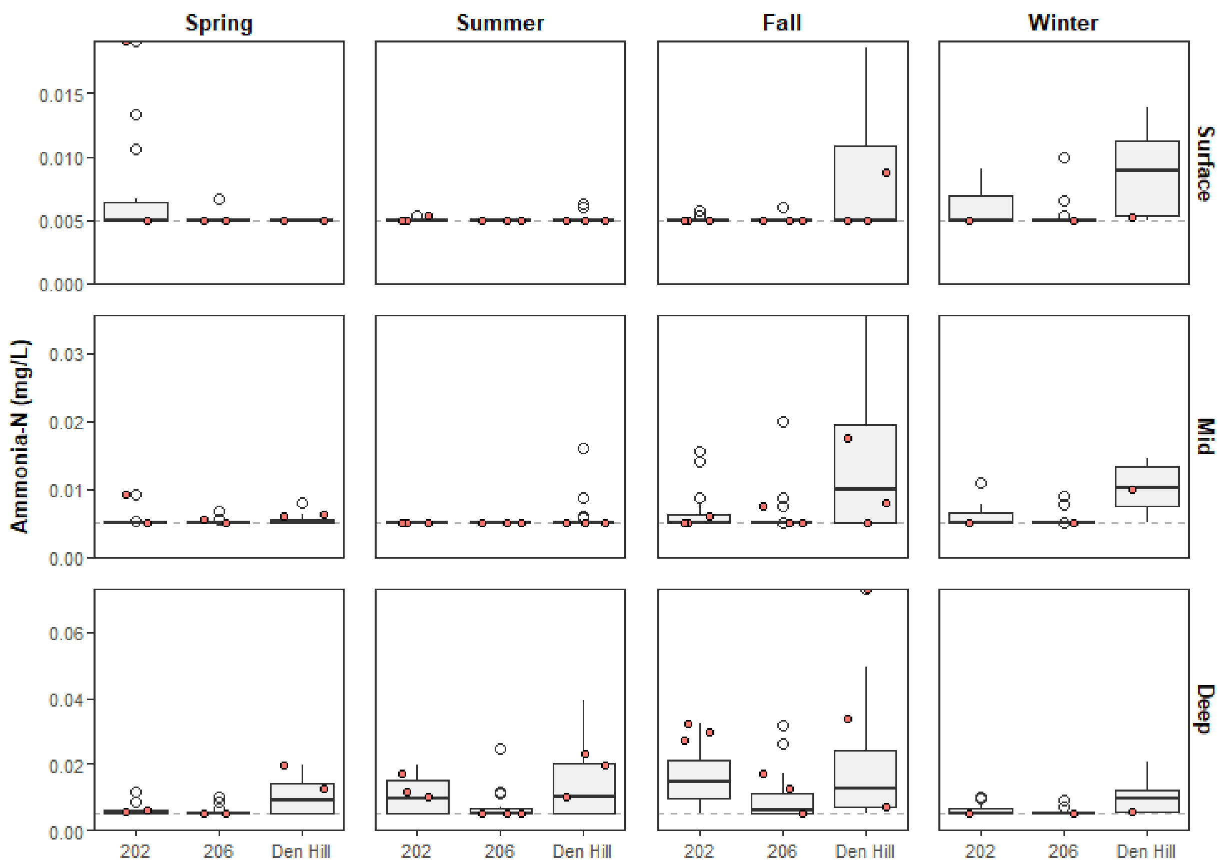

Figure C45: Boxplots depicting the seasonal and vertical distributions of NH_3-N in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2022 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

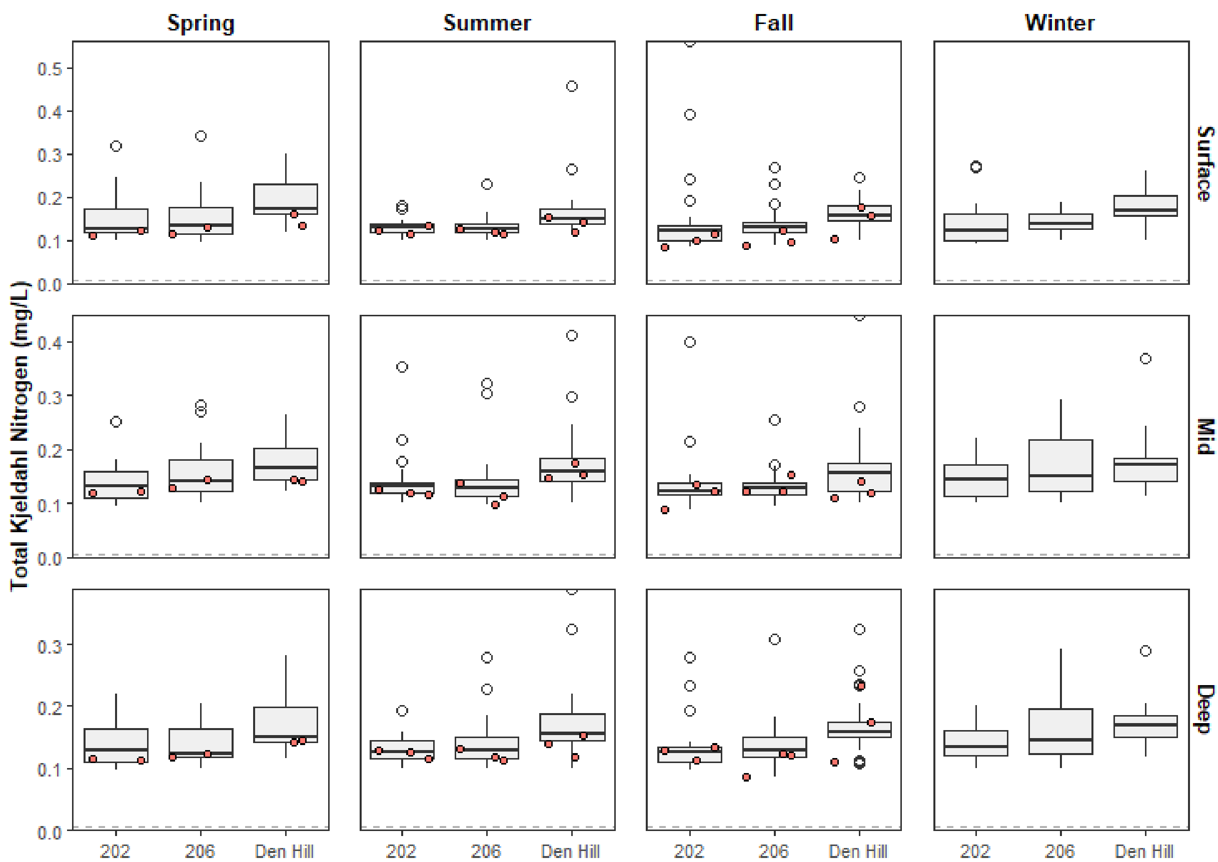

Figure C46: Boxplots depicting the seasonal and vertical distributions of TKN in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2022 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.