Water Quality Report: 2023
Quabbin Reservoir Watershed
Ware River Watershed


Top: Rain-On-Snow Flood Event, West Branch Swift River, Quabbin Reservoir Watershed (David Gatautis, 2023)
Bottom: Aquatic Plant Monitoring, O'Loughlin Pond, Quabbin Reservoir (Tayelor Gosselin, 2023)

August 2024

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 annual hydrological and meteorological summaries, and results from special investigations. 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 for 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 incorporate regional 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 2023. Monitoring of major tributary inflows is a proactive measure aimed at identifying water quality patterns and potential problem areas that may require additional investigation or corrective action. Results from tributary monitoring were largely below state surface water quality thresholds, with exceedances attributed to higher solute loads measured during a historically wet flood year, wildlife impacts on water quality, and/or landscape attributes.

The appendices to this report include field investigation reports. 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 in the further sections.

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 unfiltered 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 using 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 and reservoirs in fulfillment of the waiver.

DWSP monitors the water quality and quantity within the watersheds and reservoirs (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 monitoring provides information regarding potential controls on observed changes in water quality over time and represents a proactive effort to identify emerging threats to water quality.

This report summarizes the water quality monitoring performed by DWSP in the Quabbin Reservoir and Ware River Watersheds during 2023.

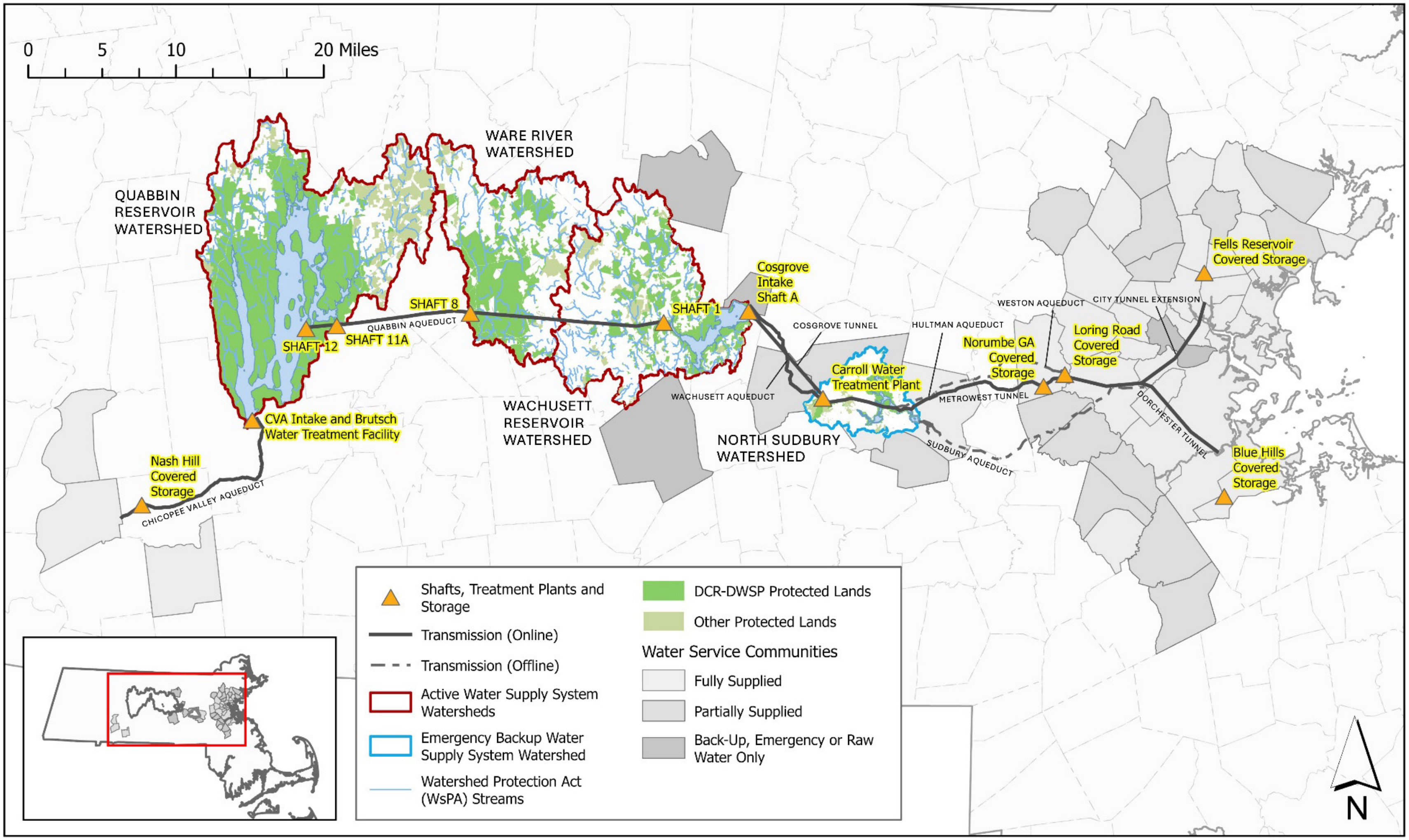


Figure 1: Quabbin Reservoir, Ware River, and Wachusett Reservoir Watershed system. Inset map in lower left depicts location of the watershed system relative to MA.

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 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. MassDEP regulations require that turbidity levels at the point of consumption for all public drinking water can only be above one NTU if it does not interfere with effective disinfection. 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 thereby is 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 (see DCR 2023a, Appendix A). Required monitoring for additional constituents at different stages in the system (e.g., after treatment, after disinfection, and at the point of consumption) is conducted by MWRA. These elements and compounds include arsenic, polychlorinated biphenyls (PCBs), haloacetic acids, and per- and polyfluoroalkyl substances (PFAS). 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. 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, 2023b). 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 and associated Watershed Protection regulations (313 CMR 11.00) give 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. The consistent 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, provide early detection of change, 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 each annual water quality report.

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

- Maintain long-term water quality statistics relative to the protection of public health.
- Document achievements of watershed control criteria applicable to the filtration avoidance requirements stipulated under the EPA's Surface Water Treatment Rule (SWTR).
- 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.
- 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 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 an 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, see also DWSP, 2023a for further context).

Water from the Quabbin Reservoir is transferred to the Wachusett Reservoir via the Quabbin Aqueduct Intake at Shaft 12 (Figure 1). Transfers at Shaft 12 typically account for more than half of the 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). 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 location 101 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. 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 diversion timing and duration annually.

Table 1: General information on a) Quabbin Reservoir, b) Quabbin Reservoir Watershed, and c) Ware River Watershed.

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)	70
Total Protected Land Area (DWSP Fee, DWSP WPR, Other protected)	Acres (excludes reservoir)	73,535
	(% Total watershed land area)	77

c) Ware River Watershed General Information

Description	Units	Quantity
Watershed Area	Acres	61,671
DWSP Controlled Area	Acres	25,756
	(% Total watershed area)	41
Total Protected Area (DWSP Fee, DWSP WPR, Other protected)	Acres	33,081
	(% Total watershed area)	54

1.4 Description of Quabbin Reservoir and Ware River Watersheds

The Quabbin Reservoir Watershed is located in the Swift River sub-basin of the Chicopee River, a major tributary of the Connecticut River, and part of the Central Uplands of north central Massachusetts (Figure 2). 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. At full capacity, the surface area of the Quabbin Reservoir spans roughly 38.2 sq. mi. (24,469 acres), or 20% 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% of the total watershed land area) for water supply protection purposes, and approximately 77% of the total land area in the watershed is protected, through 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 is the geographical drainage area to Shaft 8 Intake on the Ware River in Barre, MA. This watershed neighbors the Quabbin Reservoir Watershed to the east (Figure 3). 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 Watershed area monitored by DWSP intersects portions of the municipalities of Barre, Phillipston, Hubbardston, Oakham, Rutland, Princeton, Templeton, and Westminster, MA. 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. Further downstream, the Ware River joins the Quaboag River in Three Rivers, MA to form the Chicopee River.

Land cover in the Ware River Watershed is predominantly forest (75%), with approximately 41% of the watershed area (25,756 acres) controlled by DWSP (Table 1, Table 2). 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. Additional information regarding land use and ownership in the Quabbin Reservoir and Ware River Watersheds, as well as the calculation of statistics, is documented in the *Watershed Protection Plan FY24-FY28* (DWSP, 2023b) and the *2017 Land Management Plan* (DWSP, 2018a).

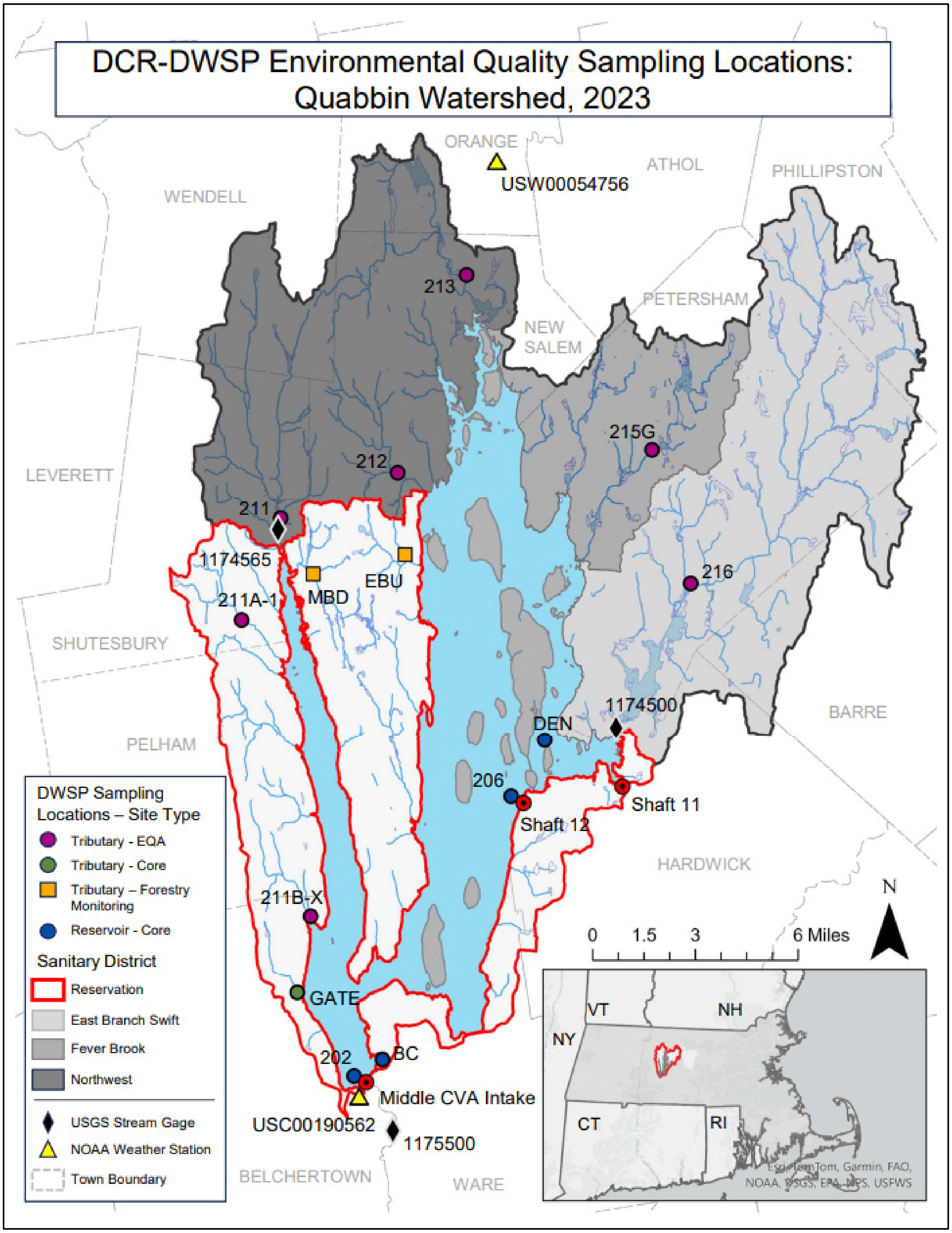


Figure 2: Map of Quabbin Reservoir Watershed showing locations of Core and EQA monitoring sites sampled in 2023. Also shown are DWSP sanitary districts. Inset map depicts the watershed relative to Massachusetts.

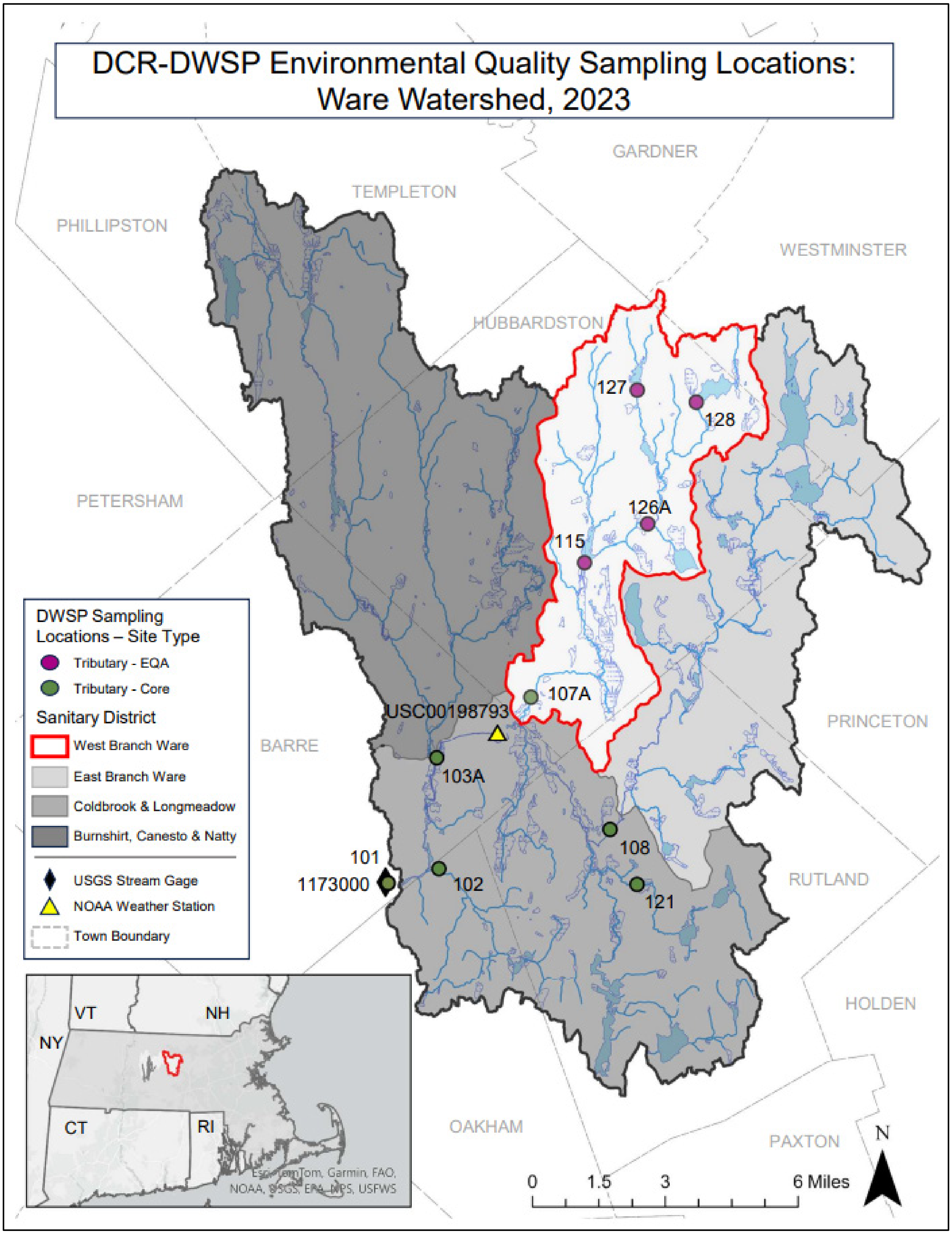


Figure 3: Map of Ware River Watershed showing locations of Core and EQA monitoring sites sampled in 2023. Also shown are DWSP sanitary districts. Inset map depicts the watershed relative to Massachusetts.

Table 2: Proportion of total land area falling under land cover/land uses classes across Quabbin Reservoir and Ware River Watershed (adapted from DWSP 2023b).

Land Cover/Land Use Class	Proportion (%) of Quabbin Reservoir Watershed Land Area	Proportion (%) of Ware River Watershed Land Area
Forest	87.62	74.77
Wetland	4.99	11.61
Agriculture	3.42	3.81
Open Water	1.25	3.22
Residential	0.24	0.87
Commercial/Industrial	0.01	0.06
Other Non-Impervious	1.82	3.19
Other Impervious	1.33	2.47

2 Methods

DWSP water quality monitoring programs in the Quabbin Reservoir and Ware River Watersheds seek to proactively assess and identify threats to water quality from biological, geological, and chemical sources. These programs include the collection and analysis of water quality samples from watershed surface waters, collection and enumeration of Quabbin Reservoir phytoplankton samples, record collection of *in situ* measurements from water quality probes, hydrological monitoring from USGS stream gages, meteorological monitoring from NOAA weather stations, monitoring for and management of aquatic invasive species within watershed water bodies, and the implementation of the Quabbin Boat Seal Program and associated Boat Decontamination Program. 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. Further documentation of parameter collection is provided in Section 6.1 of this report.

2.1 Monitoring Programs

DWSP staff monitored water quality at 21 surface water sites in the Quabbin Reservoir and Ware River Watersheds, three sites within the Quabbin Reservoir, along with numerous aquatic invasive species (AIS) monitoring ponds and hydrological and meteorological monitoring stations in 2023 (Figure 2, Figure 3). 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, a higher-resolution understanding of transport processes operating across the catchments embedded within the greater watershed, and elucidation of potential upstream impacts to Core sites. The Quabbin Reservation sanitary district within the Quabbin Reservoir Watershed and the West Branch Ware sanitary district within the Ware River Watershed were monitored in 2023. AIS investigations often follow EQA rotations, assessing long-term priority sites while incorporating regional waterbodies in line with sanitary districts of focus. Reservoir monitoring locations are long-term sampling sites located near shaft intakes and/or major stream inflows. In addition to DWSP sampling efforts, select hydrological and meteorological data from partner agencies is also routinely accessed and analyzed to better understand water quality patterns and potential drivers.

DWSP staff also conduct special investigations spanning multiple years of collection. These vary across watersheds, but include storm water sampling, monitoring of potential water quality changes following forest management activities, and evaluation of spatial and temporal trends in elevated bacteria results relative to meteorological patterns. Results of special investigative efforts are further discussed in Sections 3.3.8 and 6.2, as well as being described in previous versions of DWSP annual water quality reports (DWSP 2023a).

2.1.1 Meteorological Monitoring

Daily measurements of precipitation and air temperatures were recorded at three locations within Quabbin Reservoir and Ware River Watersheds in 2023 (Table 3). The DWSP Civil Engineer section maintains one weather station in the Quabbin Reservoir Watershed at the DCR Quabbin 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 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).

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 2023 (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 Hydrological Remote Sensing Center (NOHRSC).

Table 3: Meteorological and hydrological monitoring stations located within the Quabbin Reservoir and Ware River Watersheds.

Measurement	Site Name	Site ID	Managed by	Period of Record (POR)
Air Temperature, Precipitation	Belchertown, MA	USC00190562	DWSP	1947-2023
	Orange Municipal Airport, Orange, MA	USW00054756	NOAA	1996-2023
	Barre Falls Dam, Barre, MA	USC00190408		1959-2023
Snowpack	4NW Hardwick – Q1 (Gate 43A)	Q1	DWSP	2018-2023
	3SW Petersham – Q2 (Gate 40)	Q2		2018-2023
	2NW New Salem – Q3 (West of 202)	Q3		2018-2023
	1N Pelham – Q4 (Pelham Lookout)	Q4		2018-2023
	4E Belchertown – Q5 (Blue Meadow)	Q5		2018-2023
	3NW Petersham – Q6 (Balls Corner)	Q6		2018-2023
Mean Daily Streamflow (cfs)	Ware River, Barre	1172500	USGS	1987-2023
	Ware River, Intake Works, Barre	1173000		1987-2023
	Ware River, Gibbs Crossing	1173500		1987-2023
	Swift River, West Ware	1175500		1987-2023
	East Branch Swift River, Hardwick	1174500		1987-2023
	West Branch Swift River, Shutesbury	1174565		1995-2023
	Lower Hop Brook	-	NEON	2017-2023
	Parker's Brook	-	DFW-DER	2012-2023
Reservoir Elevation	Quabbin Reservoir, at Winsor Dam	-	DWSP	1980-2023

2.1.2 Hydrological 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 2023 (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 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 and downloaded water level data at several additional DWSP monitoring locations (sites GB, 211, 213, 215G, and 216) in 2023. DWSP Civil Engineering staff maintain long-term records of Quabbin Reservoir elevation. Paper records of daily elevation date back to the 1940s. Reservoir elevation information is currently recorded at 15-minute intervals using a Stevens-Connect continuous sensor. Historical records of reservoir elevations from 1980-2022 were used for comparison against annual reservoir elevation levels in this report.

2.1.3 Tributary Monitoring

DWSP staff monitored water quality at 19 stream sampling locations across the Quabbin Reservoir and Ware River Watersheds in 2023 (Table 4), along with two long-term study sites associated with a forest management study (Section 2.1.6.1). The tributary monitoring locations include Core sites and Environmental Quality Assessment (EQA) sites (Figure 2, Figure 3). Tributary locations vary in upstream catchment characteristics including land use and proportion wetland, as well as stream attributes (e.g., stream order, gradient, discharge, etc.). Sites are selected to characterize major inflows to the Quabbin Reservoir and Ware River, as well as to monitor areas of special interest and gather data on streams of varying upstream catchment and reach-scale attributes.

Table 4: Drainage basin characteristics of DWSP tributary monitoring sites for Quabbin Reservoir Watershed and Ware River Watershed, 2023.

					DWSP Owned Land		***Wetland***	
Watershed	**Site Type**	**Site ID**	**Site Description**	**Area (mi^2)**	**mi^2**	**%**	**mi^2**	**%**
Quabbin	Core	211	West Branch Swift River	13.6	6.36	46.8	0.47	3.46
	Core	212	Hop Brook	4.53	1.49	32.8	0.12	2.6
	EQA	213	Middle Branch Swift River	9.07	2.16	23.8	0.75	8.27
	EQA	215G	East Branch of Fever Brook	4.11	0.57	13.9	0.53	12.9
	EQA	216	East Branch Swift River	30.1	0.63	2.08	2.84	9.43
	EQA	BC	Gates Brook	0.04	0.04	100	0.00	1.04
	EQA	GATE	Boat Cove Brook	0.88	0.88	100	0.03	3.07
	EQA	211A-1	Atherton Brook	2.03	0.95	46.8	0.07	3.60
	EQA	211B-X	Cadwell Creek	2.76	2.76	100	0.07	2.60
Ware River	Core	101	Ware River, at Shaft 8 (intake)	96.5	36.5	37.8	13.4	13.9
	Core	102	Parkers Brook	5.42	4.60	84.8	0.52	9.51
	Core	103A	Burnshirt River	4.01	2.83	70.7	0.28	7.06
	Core	107A	West Branch Ware River	16	7.25	45.3	2.70	16.9
	Core	108	East Branch Ware River	22.2	2.96	13.4	3.83	17.3
	Core	121	Mill Brook	3.38	0.32	9.39	0.53	15.8
	EQA	115	Brigham Pond Outlet	11.04	4.27	38.7	1.45	13.1
	EQA	126A	Moosehorn Pond Outlet	6.23	2.46	39.5	0.89	14.3
	EQA	127	Waite Pond Outlet	0.83	0.01	0.1	0.03	4.00
	EQA	128	Lovewell Pond Outlet	1.38	0.02	1.4	0.18	13.4

Samples were collected every other week (hereafter: biweekly) at tributary sites in 2023, with sampling in Quabbin Reservoir Watershed and Ware River Watershed alternating weekly. Monitoring frequency of analytes varied across watersheds, with less frequent analysis of nutrients in Ware River EQA sites (quarterly vs. biweekly) and a quarterly sampling interval for all alkalinity analyses (Table 5). Changes to the 2023 sampling plan includes the monitoring of alkalinity at a quarterly frequency for all sites, the reduction of calcium sampling, and a shift to quarterly nutrient sampling (NO_3-N, NH_3-N, TN, and TP) in Core Ware River Watershed tributary sites (with the exception of site 101, the Ware River at Shaft 8 Intake, which retained biweekly nutrient monitoring).

Samples were analyzed by MWRA laboratories per standard methods (Table 5). Sampling plans, locations, and sample collection frequencies vary across the period of record. Further discussion on changes to analytical methods across parameters and sampling frequencies across sites are detailed in Section 2.2. Further documentation on monitoring parameters is included in Section 6.1.

Table 5: Analytes included in DWSP tributary monitoring programs, analytical methods, and monitoring frequency for 2023. Biweekly sampling denotes samples collected on an every-other-week interval.

Group	Analyte	Method (2023)	Monitoring Frequency (2023)
Bacteria	Total Coliform	SM 9223B	Biweekly
	E. coli	SM 9223B	Biweekly
Misc.	Turbidity	SM 2130 B	Biweekly
	Alkalinity	SM 2320 B	Quarterly
Nutrients	NO_3-N	EPA 353.2	Biweekly (Quabbin Sites and Ware Core Sites); Quarterly (Ware EQA Sites)
	NH_3-N	EPA 350.1	
	TKN	EPA 351.2	
	TP	EPA 365.1	
Organic Matter	TOC	SM 5310 B	Biweekly (Quabbin Sites and Ware Site 101)
Organic Matter	UV_{254}	SM 5910B 19th edition	Biweekly
Major Ions	Na	EPA 200.7	Biweekly
	Cl	EPA 300.0	Biweekly
Field Parameters	Temperature	Gibs et al. (2012)	Biweekly
	Dissolved Oxygen	Gibs et al. (2012)	Biweekly
	pH	Gibs et al. (2012)	Biweekly
	Specific Conductance	Gibs et al. (2012)	Biweekly

2.1.4 Reservoir Monitoring

2.1.4.1 Surface Water Treatment Rule Compliance Monitoring

MWRA monitors Quabbin Reservoir water prior to disinfection to ensure compliance with the Surface Water Treatment Rule. Daily monitoring is performed by MWRA at the Brutsch Water

Treatment facility in Ware, MA. MWRA provides annual turbidity and fecal coliform data from the CVA Intake, collected at the BWTF . Average and maximum daily turbidity readings and daily fecal coliform counts are summarized to account for SFWR compliance for the Quabbin Reservoir.

2.1.4.2 Reservoir Monitoring by DWSP

DWSP reservoir monitoring includes plankton monitoring, water quality sample collection, and the use of *in situ* sensors for water quality data collection. The Quabbin Reservoir was sampled regularly in 2023 to monitor phytoplankton densities, anticipate potential taste and odor problems, and recommend management actions as necessary. At site 202, phytoplankton was sampled every week from May to September, and monthly from January to April and October to December. At sites 206 and Den Hill, phytoplankton was sampled monthly year-round (ice conditions permitting). A response plan to elevated phytoplankton densities was set so that if any of the taxa of concern would exceed the established alert levels, frequency of monitoring would increase to twice a week for site 202 and twice a month for sites 206 and Den Hill (Section 3.4.10.1). Phytoplankton sampling frequency was increased to twice a month at Den Hill in response to elevated densities of *Chrysosphaerella* observed on July 12, 2023.

Water samples were collected monthly in 2023 from April to December at three depths from three stations within the reservoir for analyses of UV_{254}, turbidity, total organic carbon, and bacteria. Water samples for analyses of nutrients, silica, alkalinity, pH, sodium, and chloride were collected quarterly (May, July, October, and December), with an additional collection date in September to capture physiochemical reservoir conditions during expected elevated phytoplankton densities in the fall. Calcium monitoring was discontinued in 2023, due to low calcium levels observed in the reservoir in the past two years (e.g., 1.81 to 2.33 mg/L in 2022) demonstrating low risk of zebra mussel colonization (DWSP, 2023a).

Water-column profiles of temperature, pH, dissolved oxygen, specific conductance, chlorophyll *a*, and phycocyanin were measured via a Yellow Springs Instruments (YSI) EXO2 sonde coincident to phytoplankton and water quality sampling at each site. In addition to manual water column profiles, a remote sensing profiling buoy was deployed by MWRA and DWSP 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. Reservoir monitoring results are discussed in Section 3.4 of this report.

Table 6. Core monitoring locations in Quabbin Reservoir, 2023.

Site Name	Site ID	Location	Latitude	Longitude	Maximum 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 near Shaft 11a	42°23.386´ N	72°16.008´ W	19

2.1.5 Aquatic Invasive Species Monitoring and Management

Water bodies in the Quabbin Reservoir Watershed (n=3) and Ware River Watershed (n=5) were surveyed by DWSP for the presence of aquatic invasive species (AIS) in 2023 (Table 7). The reservoir's two regulating ponds (O'Loughlin and Pottapaug) and portions of the Reservoir shoreline and Ware River were also surveyed for AIS in 2023. Assessments conducted by GEI Consultants 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. 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 as time allows. Select water bodies in the Quabbin Reservation sanitary district and West Branch Ware sanitary district were surveyed for AIS in 2023. Pepper's Mill Pond is located outside of watersheds but is high priority for monitoring due to proximity to Quabbin Reservoir.

Additional programs are also established to protect against the spread of invasives in the Quabbin Reservoir. Oblique tows (1 min, 53-µm mesh) were performed quarterly in proximity to the three reservoir Boat Launch Areas. Samples collected via oblique net tows were screened to monitor for invasive zooplankton. 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, boat/motor decontaminations, and perform monitoring of boat ramps, in addition to annual aquatic macrophyte surveys.

Table 7: Water bodies surveyed in 2023 for aquatic invasive macrophyte species in Quabbin Reservoir and Ware River Watersheds

Watershed	Water Body Name	Location	Surveyed by	Date
Quabbin Reservoir	Quabbin Reservoir	New Salem, Petersham, Hardwick	GEI	8/24-8/29/2023
	Quabbin Reservoir, west arm	Pelham, New Salem	GEI	8/24/2023
	O'Loughlin Pond	New Salem	GEI and DWSP	7/11/2023
	Pottapaug Pond	Hardwick	GEI and DWSP	6/21/2023, 9/8/2023
	Bassett Pond	New Salem	DWSP	6/16/2023
	Lake Mattawa	Orange	DWSP	9/1/2023
	Pepper's Mill Pond	Ware	DWSP	5/31/2013
Ware River	Ware River, upstream of Shaft 8	Barre	GEI	9/1/2023
	Asnacomet Pond	Hubbardston	DWSP	9/22/2023
	Demond Pond	Rutland	DWSP	7/28/2023
	Long Pond	Rutland	DWSP	8/9/2023
	Lovewell Pond	Hubbardston	DWSP	8/11/2023
	Whitehall Pond	Rutland	DWSP	6/29/2023

2.1.6 Special Investigations

DWSP conducts both short-term and long-term investigations on select projects based on water quality concerns in the region. Forestry monitoring and Environmental Quality Assessments are current long-term programs to investigate water quality and landscape patterns relative to land management. Additional short-term investigations conducted in 2023 are summarized in Section 6.

2.1.6.1 Forestry Monitoring

DWSP continued to monitor water quality in association with its long-term study to assess 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 is 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, The paired watershed study design statistically controls climate and hydrological differences over years, allowing for attribution of water quality changes to treatment rather than broader climatic drivers (Hewlett and Pienaar, 1973).

Water quality sampling at paired-watershed site locations is conducted at two intervals to ensure that monitoring captures a full range of streamflow conditions and solute mobilization contexts. Routine monthly-grab sampling and quarterly event-based sampling continued in 2023, meeting annual 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 2023. Periodic event-based sampling of MBD and EBU was initiated in 2014 to characterize stream response during a variety of hydrological events (e.g., high- and low- intensity rainfall, rain-on-snow). Primary data generated by DWSP includes 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), as well as investigations into hydrograph separation using stable water isotopes (Boutt, 2021). Concentration data collected during events serves 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 2023 also included training of new DWSP staff, installation and routine maintenance of water-level loggers and precipitation gages, downloading of field data, monitoring of weather forecasts, continued development of field procedures, coordination with UMASS partners, sample and data collection during storm events, and associated data analysis.

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 2023 focused on the Quabbin Reservation sanitary district and the West Branch Ware sanitary district (Figure 2 and Figure 3, respectively).

2.2 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 2023 (Section 6.1). 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 was documented in the 2022 Quabbin/Ware Region Water Quality Report (DWSP 2023a, Appendix A). Analytical methods for concentration data are provided in Table 5. Results for various water quality parameters are compared to regulatory levels when applicable (DWSP 2023a, Appendix A).

DWSP updates sampling plans annually to align with Environmental Quality Assessments, proactively assess potential water quality concerns, and/or to focus on new regions or sites of interest. Thus, historical sampling frequency of analytes varies across time and space (Figure 4, Figure 5, Figure 6). For example, monitoring frequency of several parameters was increased in Core tributaries from quarterly to biweekly in 2020 (DWSP, 2021a). Monitoring frequency of select analytes in Quabbin Reservoir also changed from quarterly to monthly in 2020. Bacteria analyses 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. Organics includes UV_{254}, with the addition of total organic carbon at Quabbin Reservoir sites in 2020, at Quabbin Reservoir Watershed tributary sites in 2021, and Ware River site 101 in 2023. Metals and anions incorporate Ca, Na, and Cl concentrations and were added within the last 5 years due to increasing concern over specific conductance trends in waterways of the Northeastern USA (DWSP 2023a). Further documentation on changes to water quality sampling plans are available in previous versions of this annual water quality report.

Annual sampling coverage varies between Core and EQA tributary sites due to the intent of monitoring for these different sites. Core sites are monitored annually for long-term coverage and a resulting period of record that is at a relatively fine temporal scale. For many sites with long-term water quality monitoring records locations (Figure 4, Figure 5, Figure 6), this allows for a more robust discussion of changes in water quality patterns over time (20-30 years), or more near-term (e.g., 5-year or less) analysis of certain pattern for more recently added analytes (e.g., anions, TOC). Monitoring of EQA sites follows a 5-year rotation focusing on different sub-basins within each of the two water supply watersheds covered in this reporting. This monitoring is intended as a synoptic snapshot of conditions during the writing of these assessments, and thus these data have a significantly shorter period of record compared with Core monitoring locations. Period of record results from EQA sites rarely exceed three additional years of observation and are staggered in time. Due to these differences in temporal coverage, comparisons of conditions between 2023 results and historical records for EQA sites are less robust compared to the longer period of record for Core monitoring locations.

Select tributary monitoring sites previously established as EQA sites were converted to long-term (Core) monitoring sites in 2021 to provide better spatial coverage and consistent sampling of priority areas within 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. These considerations are further discussed within the water quality result narratives for the tributary and reservoir monitoring results.

There are a few notable shifts in analytical methods and detection limits over the period of record. Analytical methods for TKN returned to EPA Method 351.2 (O’Dell, 1993a) in 2023, consistent with all results prior to 2020. Beginning in 2020, analysis had shifted to Valderrama (1981) to facilitate monthly monitoring frequencies of N-species in Core sites in Quabbin Reservoir, and biweekly monitoring in Core tributary sites. Results were reported as total nitrogen (TN) in 2020-2022. During the period of 2020-2022, TKN concentrations were derived by subtracting concentrations of NO_3-N and NO_2-N from TN concentrations. 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 from this period 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. Results for TKN for tributary monitoring included in this report date from 2010 to the present.

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. Also of note is that alkalinity concentration results were historically reported by titration to pH of 4.5 endpoint via Standard Method 2320B (DWSP, 2018b).

Sensors used for collection of *in situ* parameters by DWSP vary over the period of record. Before 2021, DWSP staff used a Eureka Manta2 field sonde for data collection at Quabbin Reservoir. Starting 2021, a shift was made to the YSI EXO2 sonde to better align data collection with MWRA and DWSP-Wachusett methods. Changes in sensor manufacturers, sonde configurations, and water column profile collection methods complicate direct comparisons to historical data for physiochemical parameters. These considerations are further discussed in Section 3.4.

Figure 4: Period of record for analytes measured in 2023 tributaries monitoring sites in Quabbin Reservoir Watershed.

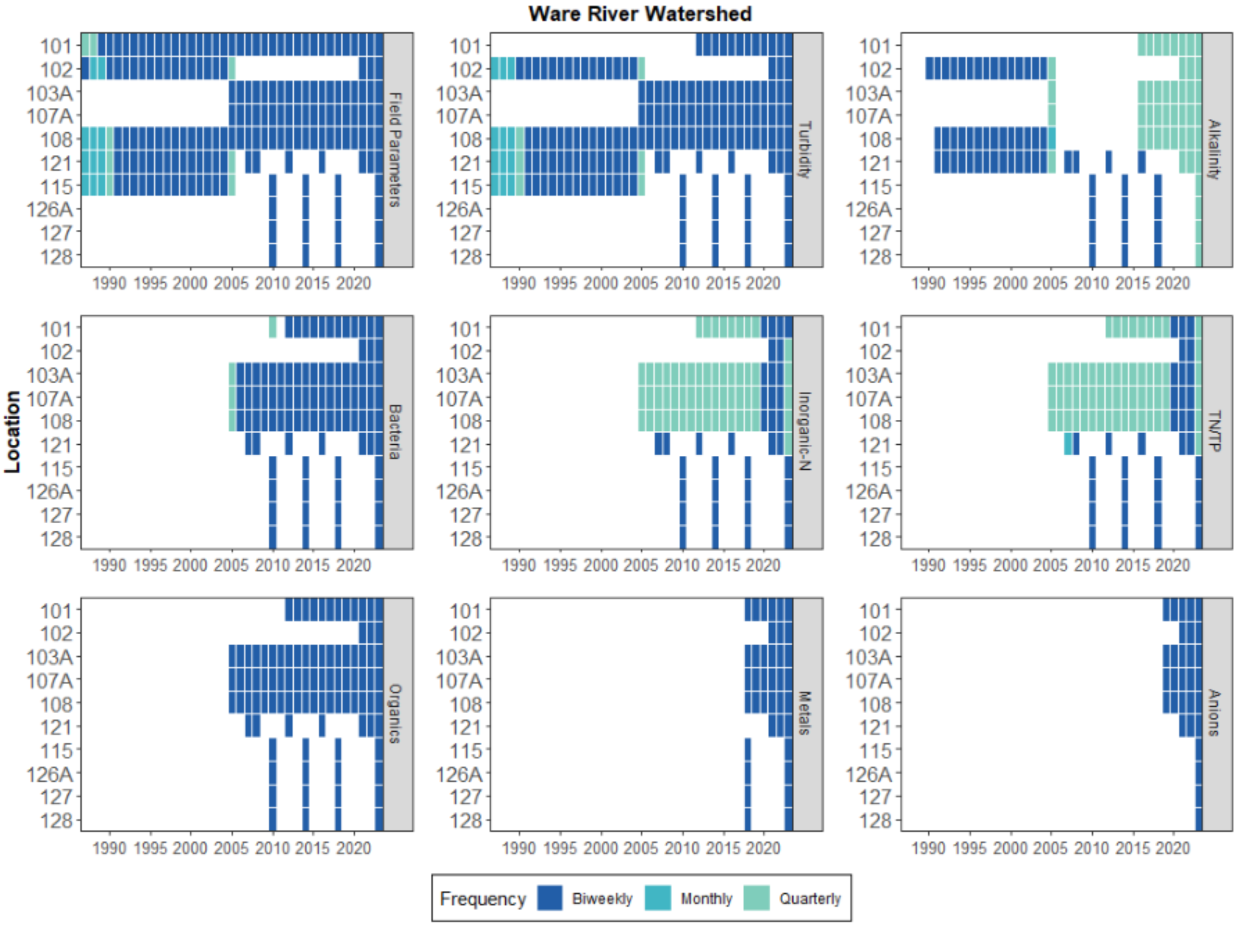


Figure 5: Period of record for analytes measured in 2023 tributaries monitoring sites in Ware River Watershed.

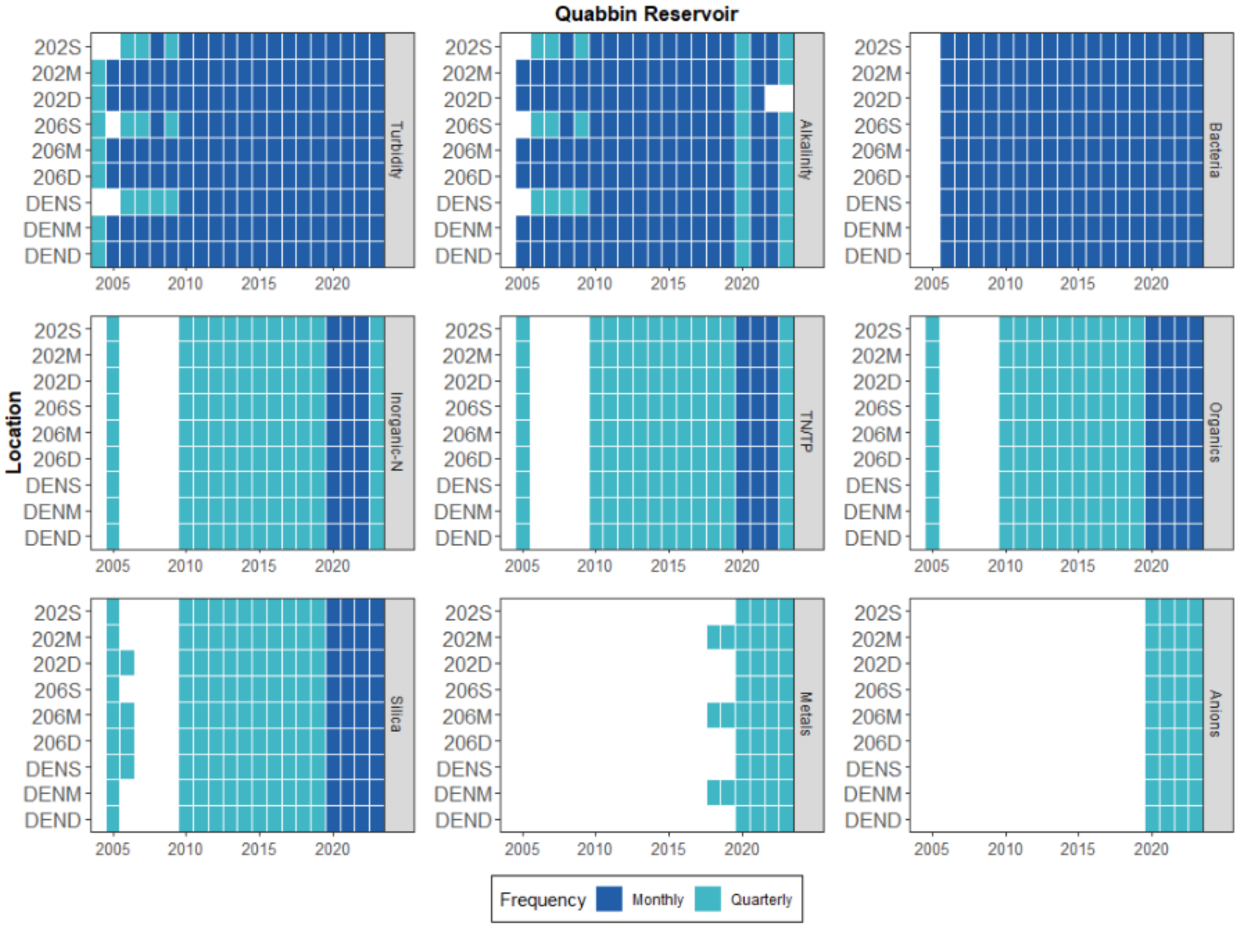


Figure 6: Period of record for analytes measured in Quabbin Reservoir monitoring sites.

2.3 Data Management and Statistical Methods

Water quality, precipitation, and streamflow data collected since 1989 are stored in a Microsoft SQL Server database, maintained by DWSP-EQ. Database development efforts continue 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, NO_3-N, NO_2-N, NH_3-N, TP, TKN, Ca, Na, Cl, Si, dissolved and total carbon, *E. coli*, total and fecal coliform, hardness, UV_{254}, and turbidity), spanning the onset of DWSP monitoring (1987) through the present. Laboratory data including concentrations of various constituents were provided by MWRA staff and then uploaded to the DWSP water quality database via R-scripts and Shiny application tools designed for data download and database standardization (R Core Team, 2019; Winston et al., 2019). Plankton density summaries were generated by DWSP-EQ staff and included in database tables for long-term record keeping. 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 1,068,937 unique data records generated by DCR and MWRA dating from 1987 through 2023 in the DWSP water-quality database for Quabbin Reservoir and Ware River Watersheds.

DWSP continued to develop its water-quality database in 2023, processing and importing data from numerous monitoring workflows and organizing historical data records. In 2023, approximately 235,562 individual records were processed and imported into the central database. 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.

Annual water quality monitoring data is reviewed before database import and periodically through the year to assess results for data accuracy, and to compare results against seasonal normal ranges (25-75%) based on the period of record. Data flags are added to records that require qualifiers for analytical use and interpretation, or for records that should be excluded from analysis due to instrumentation error, sensor calibration issues, sample collection inconsistencies, environmental factors, or other considerations. A small subset of 2023 monitoring records were flagged and removed from summary reporting following review by DWSP and MWRA staff (<1% of records). For example, ammonia results from October were excluded from reporting due to documented linearity issues with the NH_3-N calibration curve during this period (Gottshall, 2024).

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 is consistent with that used in the 2022 annual water quality report for the Quabbin Reservoir and Ware River Watershed (DWSP, 2023a). Due to the inherent non-normal distribution of environmental monitoring data, non-parametric measures of central tendency (median, interquartile range) are used to evaluate the variability of constituents observed in 2022 (Helsel, 2012).

Seasonal 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; DWSP, 2023a). 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.

Seasonal summary statistics (minimum, median, mean, and maximum values) of results from 2023 monitoring are reported along with seasonal statistics from the period of record (POR) available from DCR-DWSP data records. Results from each analyte’s POR provide the range of variability expected at sampling locations and allow for comparison of 2023 seasonal results against their historical context. Inferences into seasonal dynamics or interannual variability are limited for sites with short-duration or intermittent temporal coverage (e.g., EQA sites, more recently added Core sites, see Figures 4-6), as well as parameters with quarterly sample collection, and are provided as a point of reference to a still-emerging inquiry into ranges of seasonal variability for different parameters at different sites.

3 Results

3.1 Meteorological Monitoring

The northerly latitude and geographic location of the Northeastern United States has made it prone to the moderating and moistening effects of the Atlantic Ocean, as well as the influence of hot and cold air masses from the continent's interior (Brown et al., 2010). This has resulted in a climate with a distinct seasonality historically characterized by cold, snowy winters and warm, humid summers. Additionally, the region's proximity to the northern hemisphere polar jet stream has led to highly variable weather patterns, reflected in a broad range of daily and annual temperatures and generally abundant precipitation throughout the year (Rustad et al., 2012). These patterns have begun to shift, however, as anthropogenic influences (e.g., the burning of fossil fuels) have led to a steady climb in global temperatures with a global 3°C rise predicted by the end of the century (United Nations Environment Programme, 2023). In the contiguous United States, the fastest warming region has been identified as the Northeast where seasonal differences in temperature have decreased in recent years as winters have warmed three times faster than summers (Horton et al., 2014; Young & Young, 2021). Due to the rate of warming in the Northeast, this region is projected to warm by an additional 1°C as global warming reaches 2°C (Karmalkar & Bradley, 2017).

Massachusetts has historically been susceptible to extreme weather events such as tropical storms, nor’easters, and recurring prolonged summer droughts, and the impact of these events can vary widely across the region due to its diverse topography and locational proximity to storm tracks (Thibeault & Seth, 2014; Siddique et al., 2020). Warming temperatures as the result of climate change have led to an increase in the frequency and magnitude of these events over time which has broadly impacted freshwater systems (Demaria et al., 2016). Hydrology for the region has traditionally been characterized by spring snowmelt floods with a falling hydrograph throughout the remainder of the growing season; however, an uptick in the frequency and duration of periodic high-intensity rainfall events as a result of shifts in temperature has led to a less predictable hydrograph with high flow conditions occurring throughout the year regardless of seasonal influence (Siddique et al., 2020). Additionally, rising temperatures have been increasing the frequency of rain-on-snow events during winter months and melting snow earlier in the spring, causing winter-spring peak flows to occur approximately six days earlier in Massachusetts as compared to a century ago (Notaro et al., 2014; Demaria et al., 2016). Alterations to streamflow have been coupled with greater rates of evaporation throughout the region, causing precipitation during summer and fall months to fall on increasingly dry soils (Dudley et al., 2017). This leads to broad-scale impacts to water quality in the region as more particulates are flushed from the landscape into streams and rivers to be carried downstream (Willis & McDowell, 1982). Therefore, understanding annual meteorological patterns in relation to both historical and predicted contexts provide valuable insights into water quality patterns and emerging water quality concerns for both the Quabbin Reservoir and Ware River watersheds.

3.1.1 Air Temperature

Annual mean air temperature results (calculated from daily median temperatures) of 10.2°C, 10.2°C, and 9.8°C, were observed at the Quabbin Reservoir watershed and Ware River watershed weather stations in 2023 (Barre, Belchertown, and Orange respectively; Table 8). These values were + 0.7°C, + 0°C, and + 0.2°C as compared to observations in 2022, and were + 3°C, + 0.9°C, and + 1.2°C as compared to the annual mean values from the period of record (defined in Table 3). Minimum and maximum daily recorded temperatures ranged from -26.1°C to 38.3°C in Barre, -24°C to 33.3°C in Belchertown, and -25.6°C to 33.9°C in Orange. Five of the ten coldest daily recorded temperatures for 2023 (ranging from -26.1°C to -13.3°C) were observed in the Ware River watershed during the month of February, as well as seven of the ten warmest days for 2023 (ranging from 33.9°C to 38.3°C; April through September). Daily median temperatures recorded at the Quabbin Reservoir and Ware River weather stations generally fell within the temperature ranges observed during the period of record, though there were several outliers observed with the greatest concentration occurring during winter and spring months (December to February and March to May respectively; Figure 7). When compared to daily mean minimum and maximum temperatures for the period of record, 52% of days in 2023 exceeded historical mean daily minimums by >2°C and 55% of days in 2023 exceeded historical mean daily maximums by >2°C (Figure 8). It's worth noting that, given the variable nature of temperature patterns in the Northeast, such deviations could be deemed within normal bounds when assessed against historical temperature data spanning 5, 10, and 20 years.

Monthly mean temperatures in 2023 exhibited a wide range, from a minimum of -7.51°C (February) to a maximum of 30.81°C (July), both observed in the Ware River watershed (Barre).

This compares to the mean historical range of -12.03°C to 28.25°C across both the Quabbin Reservoir and Ware River watersheds. Mean monthly temperatures in the winter months (December, January, and February) of 2023 ranged from -7.51°C to 7.6°C across the Quabbin Reservoir and Ware River watersheds (Table 8) as compared to the average historical range of -12.03°C to 3.95°C. Mean monthly temperatures for spring (March, April, and May) ranged from -4.38°C to 23.25°C, slightly deviating from the historical range of -5.84°C to 20.76°C. Notably, the Ware River watershed experienced remarkable variations in winter and spring temperatures with December, January, February, March, and April all exceeding historical maximum temperature averages by more than 2°C, with January showing the greatest difference at +5.34°C. Summer ranges of mean monthly temperatures (June, July, and August) for both watersheds were observed between 11.41°C and 30.41°C as compared to the average historical range of 10.21°C to 28.25°C. Temperature ranges for fall (September, October, and November) were observed to range from -4.90°C to 24.60°C as compared to the average historical range which fell between -2.45°C and 23.33°C.

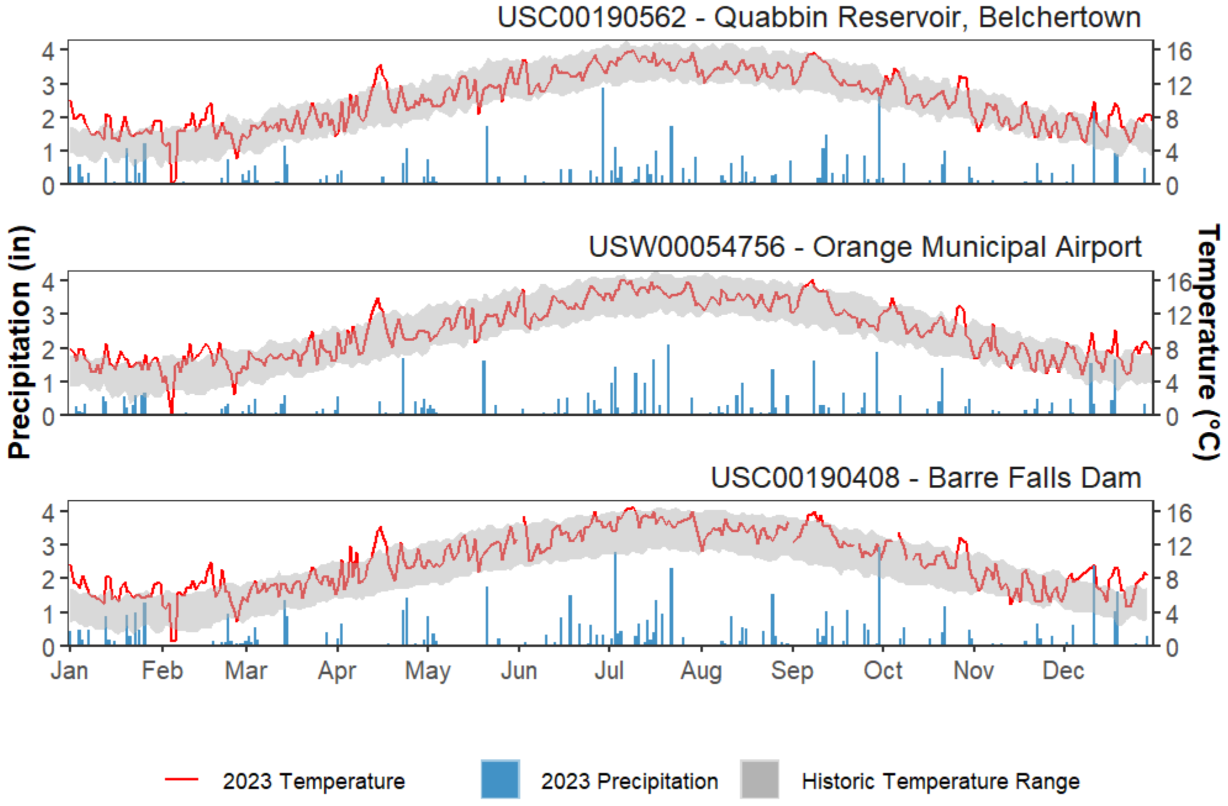


Figure 7: Climatograph of precipitation totals and daily median temperatures (in degrees Celsius) for weather stations in the Quabbin Reservoir and Ware River watersheds for 2023. The shaded band represents historical normal mean daily temperature ranges from the period of record.

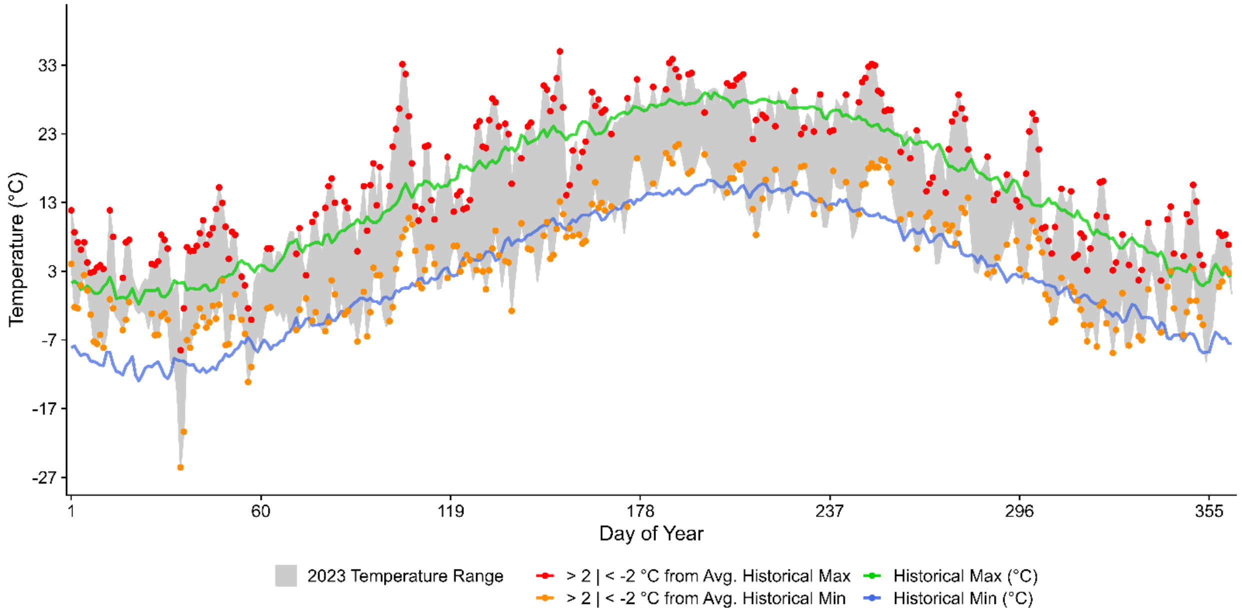


Figure 8: Temperature range showing >2|<-2°C deviations for 2023 from the average historical maximum and minimum temperatures for the POR. Temperatures displayed are an average of those recorded at all three NOAA monitoring stations (Barre, Belchertown, and Orange).

Table 8: Mean monthly minimum and maximum air temperature (in degrees Celsius) for the period of record and for 2023 at each Quabbin Reservoir and Ware River watershed weather station. Monthly means were calculated from daily records of minimum and maximum temperatures. Years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis. Delta (Δ) represents the difference between 2023 monthly mean compared to the period of record. Variations in temperature are highlighted on an orange-red gradient, with temperatures greater than 2°C and less than -2°C becoming progressively darker based on magnitude.

		Mean of Daily Min (°C)			Mean of Daily Max (°C)		
Weather Station	**Month**	**POR**	**2023**	**Δ**	**POR**	**2023**	**Δ**
Barre	Jan	-12.03	-3.64	8.39	-0.59	4.75	5.34
	Feb	-11.28	-7.51	3.76	0.88	5.32	4.44
	Mar	-5.84	-4.38	1.46	6.16	8.85	2.70
	Apr	-0.28	1.60	1.87	12.83	18.23	5.40
	May	5.38	3.92	-1.46	19.81	23.25	3.44
	Jun	10.21	11.41	1.20	24.13	25.98	1.85
	Jul	13.23	16.95	3.72	26.93	30.81	3.88
	Aug	12.18	13.35	1.17	25.89	26.69	0.79
	Sep	7.62	11.31	3.68	21.82	24.60	2.78
	Oct	1.88	5.85	3.97	15.47	18.72	3.26
	Nov	-2.45	-4.90	-2.46	8.88	8.20	-0.68
	Dec	-8.21	-2.43	5.78	2.24	7.56	5.32
Belchertown	Jan	-9.03	-2.52	6.51	0.53	4.96	4.44
	Feb	-8.51	-6.69	1.82	2.45	4.56	2.11
	Mar	-4.04	-2.99	1.06	7.13	7.82	0.69
	Apr	1.50	3.07	1.57	13.85	16.41	2.56
	May	8.06	5.72	-2.34	20.66	20.77	0.11
	Jun	12.64	12.73	0.09	24.79	24.52	-0.27
	Jul	16.36	17.65	1.30	28.25	28.86	0.61
	Aug	15.37	14.29	-1.08	27.34	25.86	-1.47
	Sep	11.45	12.39	0.94	23.33	23.46	0.13
	Oct	5.55	6.89	1.34	16.30	18.45	2.14
	Nov	-0.59	-2.29	-1.70	9.76	8.50	-1.26
	Dec	-4.75	-1.54	3.20	3.95	7.12	3.17
Orange	Jan	-10.44	-3.77	6.67	0.34	4.06	3.72
	Feb	-9.37	-7.40	1.97	2.33	4.69	2.36
	Mar	-4.67	-3.35	1.32	7.10	7.56	0.46
	Apr	0.66	2.63	1.97	14.26	16.51	2.25
	May	7.00	4.47	-2.53	20.76	21.67	0.90
	Jun	12.23	12.73	0.50	25.22	24.70	-0.52
	Jul	15.28	17.58	2.30	28.18	29.25	1.07
	Aug	14.60	14.26	-0.34	27.35	26.09	-1.25
	Sep	9.99	11.82	1.84	23.13	23.79	0.66
	Oct	3.55	6.35	2.80	15.90	18.55	2.65
	Nov	-1.87	-3.84	-1.97	9.53	8.03	-1.50
	Dec	-6.69	-2.15	4.54	3.52	6.71	3.19

3.1.2 Precipitation

Annual rainfall totals ranged from a minimum of 48.47 inches (Orange) to a maximum of 58.81 inches (Barre) across weather stations in the Quabbin Reservoir and Ware River watersheds in 2023 (Figure 9). All three monitoring sites recorded above-average annual rainfall, with Orange surpassing its historical mean by 6.04 inches (historical mean = 42.43 inches), Barre exceeding its site's historical mean by 14.49 inches (historical mean = 44.32 inches), and Belchertown receiving 6.62 inches more than its historical mean of 46.68 inches. Orange exceeded historical rainfall means by more than two inches in two months, recording +5.82 inches in July and +2.18 inches in September (Table 9). Belchertown experienced three months with more than a two-inch increase in precipitation as compared to historical means, with the greatest increase occurring in July at +4.50 inches. Barre recorded four months with more than two inches of additional rainfall as compared to historical means, with the greatest increase of +6.70 inches occurring in July, compared to a historical mean of 4.30 inches. There were very few monthly rainfall deficits greater than two inches, with Orange and Barre recording deficits of -2.07 inches and -2.31 inches respectively in November of 2023 as compared to the historical mean of 3.55 inches for November across all three weather stations (Orange, Barre, and Belchertown).

In 2023, the U.S. Drought Monitor, along with NOAA, USDA, and the National Drought Mitigation Center, reported that the Quabbin Reservoir-Ware River Region experienced abnormally dry (D0) conditions for a cumulative four months (U.S. Drought Monitor, NOAA, USDA, & National Drought Mitigation Center). In January of 2023, Franklin County (north-Quabbin Reservoir watershed) faced widespread drought with >85% of the land area designated as D0. Conditions eased to Level-0 Normal for February, March, April, and May; however, drought conditions returned in June and July with < 12% of the land area falling under a D0 designation. Hampshire County (west-Quabbin Reservoir watershed) witnessed similar patterns. In January, <85% of the land area was designated as D0. Drought conditions once again eased to Level-0 Normal conditions through May but returned to a D0 designation in June and July with D0 conditions reaching nearly 15% of the county's land area. Worcester County (east-Quabbin Reservoir watershed and Ware River watershed) recorded less elevated drought conditions in January, with <10% of the land area designated as D0. Level-0 Normal conditions were observed from February to April. Drought conditions returned in May, with <65% of land cover recorded as being under a D0 designation. No drought conditions were observed in June; however, in July, >70% of land cover fell under a D0 designation. According to the Massachusetts Drought Management Task Force (Massachusetts Drought Management Task Force, 2024), the Quabbin-Ware region was designated at Level-0 Normal conditions for the remainder of 2023. This contrasts sharply with conditions observed in 2022 where the Quabbin Reservoir-Ware River Region experienced drought designations for six months, including extended periods of "critical drought" in both watersheds (DWSP, 2023a).

Table 9: Mean total monthly precipitation (from period of record [POR]) and total monthly precipitation (for 2023) in inches from meteorological station in the Quabbin Reservoir and Ware River watersheds, summarized by month. Years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis. Delta (Δ) represents the difference between 2023 total monthly precipitation compared to the POR. Variations in precipitation are highlighted on an orange-red gradient. Precipitation greater than 2" or less than -2" become progressively darker based on magnitude.

	Barre (inches)			Belchertown (inches)			Orange (inches)		
Month	**POR**	**2023**	**Δ**	**POR**	**2023**	**Δ**	**POR**	**2023**	**Δ**
Jan	3.39	6.73	3.34	2.51	6.16	3.65	3.21	4.8	1.59
Feb	3.03	1.71	-1.32	2.78	1.49	-1.29	2.70	1.06	-1.64
Mar	3.62	3.9	0.28	3.09	3.62	0.53	3.35	2.33	-1.02
Apr	3.90	3.64	-0.26	3.41	3.01	-0.40	3.88	3.94	0.06
May	3.93	3.47	-0.46	3.24	3.2	-0.04	3.82	2.67	-1.15
Jun	4.07	4.99	0.92	4.35	4.84	0.49	3.87	3.05	-0.82
Jul	4.30	11	6.70	3.96	8.46	4.50	3.88	9.7	5.82
Aug	4.53	4.78	0.25	3.78	4.11	0.33	4.13	4.86	0.73
Sep	4.17	7.73	3.56	4.36	8.26	3.90	3.95	6.13	2.18
Oct	4.00	3.25	-0.75	4.49	3.28	-1.21	4.15	3.3	-0.85
Nov	3.85	1.48	-2.37	3.15	1.54	-1.61	3.66	1.59	-2.07
Dec	3.87	6.13	2.26	3.50	5.33	1.83	3.73	5.04	1.31

Results from snow monitoring the Quabbin Reservoir watershed are presented in an annual memo summarizing seasonal patterns and multi-year trends prepared by DWSP Civil Engineering Section (DWSP, 2024a). Total annual snowfall in Belchertown was 21 inches, below the historic annual mean of 51 inches from the 77-year POR. Mean snow depth from all snow surveys was 4.9 inches.

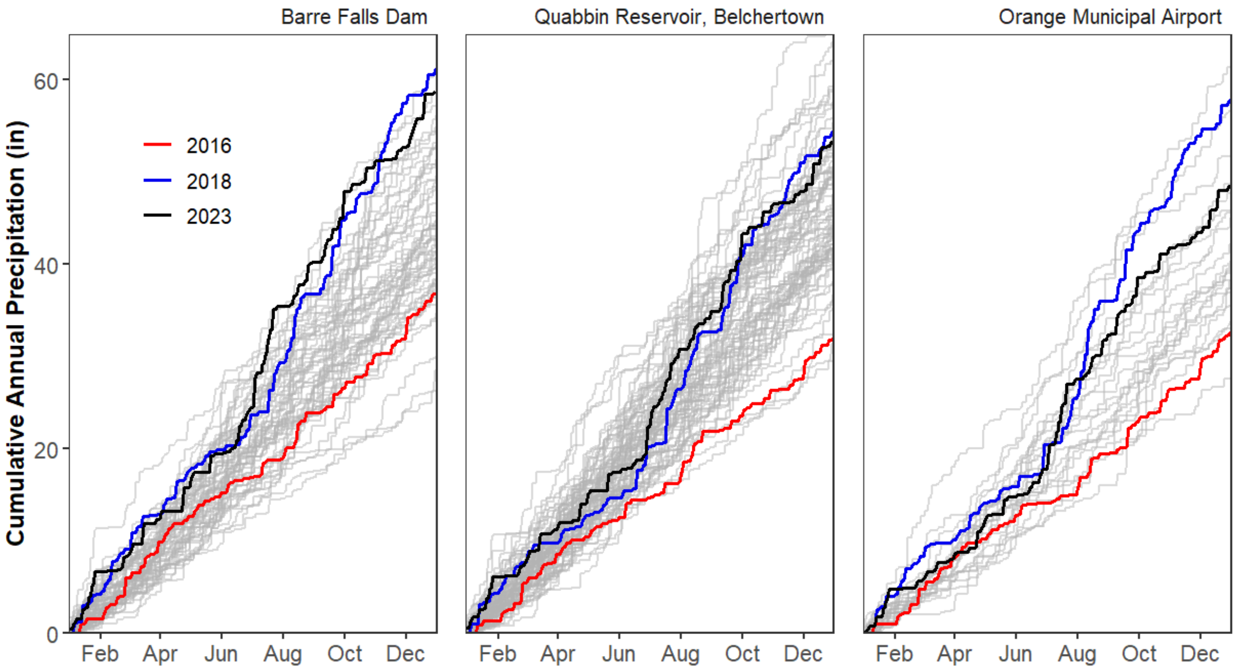


Figure 9: Annual cumulative precipitation totals for the Barre Falls Dam, Quabbin Administrative Building in Belchertown, MA, and Orange Municipal Airport (USW00054756) weather stations. Red and blue lines indicate recent years of high and low annual precipitation totals (2016 and 2018, respectively) compared to the period of record (shaded lines) and to 2023 (black line) at the three weather stations. Note that years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis.

3.2 Hydrological Monitoring

Hydrological monitoring records used for DWSP monitoring were evaluated alongside meteorological data to provide a basis for evaluating water quality patterns. Results from 2023 show a clear correlation between precipitation patterns and fluctuations in streamflow and reservoir water levels. This connection underscores the importance of meteorological and hydrological monitoring in evaluating the long-term status and trend of water resources.

3.2.1 Streamflow

Streamflow was recorded at six USGS gages throughout both the Quabbin Reservoir and Ware River watersheds. Three gages recorded streamflow rates (cfs) in two major tributaries and one outflow of the Quabbin Reservoir watershed (East Branch Swift River, Hardwick [01174500]; Swift River, West Ware [1175500]; West Branch Swift River, Shutesbury [1174565]) and three recorded streamflow in the Ware River Watershed (Ware River, Barre [1172500]; Ware River, Intake Works, Barre [1173000]; Ware River, Gibbs Crossing [1173500]; see Table 3). Typically, these systems are influenced by seasonal meteorological trends, with higher flows in the spring due to snowmelt and lower flows in the summer due to variable precipitation and higher rates of evapotranspiration. However, studies have increasingly observed that the Northeast is experiencing a trend of above-average winter temperatures, attributed to global climate changes (Siddique et al., 2020; Young & Young, 2021). This phenomenon has resulted in a notable shift in winter precipitation, with a greater proportion falling as rain rather than snow (Wuebbles et al., 2017). Consequently, these climatic alterations have had notable effects on the hydrology of rivers and streams in the region.

These trends were observed in both the Quabbin Reservoir and Ware River watersheds, where NOAA weather stations recorded rainfall at least two inches above historical averages in January and December, as well as the months of July and September (see Table 9). In January, five of six USGS gages recorded streamflow at least 10 cfs above historical average mean daily streamflow (Figure 10). For the purpose of this report, the term 'average mean daily streamflow' refers to the mean amount of water flowing through the stream on a daily basis, averaged over the entire month for a given location (Table 10). The Ware River at Gibbs Crossing registered the highest average mean daily streamflow in January of 2023 at 714.81 cfs, surpassing the historical average mean daily flow of 426.17 cfs, while the Swift River in West Ware recorded the lowest average mean daily flows for January at 49.95 cfs, compared to the historical average daily mean of 120.03 cfs. It's important to note that the Swift River at West Ware gage is positioned just downstream of Quabbin Reservoir infrastructure and is a regulated outflow from the reservoir and thus less naturally variable as compared to other monitoring locations. The East Branch Swift River, recorded peak average mean daily flows for this site during January 2023 at 222.19 cfs, which was 119.79 cfs above historical mean daily averages for the POR.

In July 2023, rainfall surpassed historical averages for the POR by an average of 5.67 inches across all three weather stations. Streamflow trends mirrored these heightened precipitation totals, with most stream gages recording average mean daily streamflow rates that exceeded historical average mean daily levels thorough July. The most notable increase occurred on the Ware River at Gibbs Crossing, where the average mean daily streamflow for July peaked at 879.74 cfs, significantly surpassing the historical average daily mean of 192.23 cfs. The East Branch Swift experienced the highest average mean daily streamflow rates of the Quabbin Reservoir tributaries for July at 248.74 cfs, exceeding historical averages by over 200 cfs. These elevated streamflow rates persisted into September and October, aligning with increased precipitation trends. Across all sites (except the West Ware gage), average mean daily streamflow remained well above historical averages for this period. The Gibb's Crossing gage continued to record the highest average mean daily flows for the Ware River, reaching 523.51 cfs (September) and 573.85 cfs (October)—far exceeding historical averages of 162.28 cfs and 240.18 cfs, respectively. For the tributaries of the Quabbin Reservoir during the same period, the East Branch Swift gage recorded the highest average mean daily streamflow at 186.53 cfs (September) and 169 cfs (October), compared to the historical averages of 38.05 cfs and 61.2 cfs. Conversely, the West Ware gage reported the lowest average mean daily flows of the watershed gages, falling 25.13 cfs below the historical mean daily average of 85.23 cfs in September and 16.85 cfs below the October historical mean daily average of 69.75 cfs.

Table 10: Monthly mean stream discharge (calculated from daily mean discharge records; cubic feet per second [cfs]) for the period of record (POR) from USGS gages in the Quabbin Reservoir and Ware River watersheds. Years with incomplete records (e.g., missing >5% of measurements) were excluded from analysis.

	West Branch Swift (01174565)		East Branch Swift (01174500)		Swift River, West Ware (1175500)	
Month	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**
Jan	30.94	43.09	102.41	222.19	120.03	49.95
Feb	28.30	24.00	99.45	121.15	109.61	48.55
Mar	41.31	37.64	137.11	187.00	109.69	50.87
Apr	45.54	31.48	154.20	145.95	190.42	50.79
May	25.81	22.83	95.12	104.47	194.60	57.18
Jun	19.35	9.53	60.90	53.41	119.53	72.31
Jul	14.14	41.08	46.57	248.74	83.02	49.03
Aug	9.57	15.13	37.48	100.58	78.66	49.20
Sep	11.48	29.52	38.05	186.53	85.23	51.76
Oct	18.21	33.54	61.20	169.00	69.75	52.96
Nov	22.16	19.10	78.00	116.88	69.06	52.13
Dec	31.61	60.89	108.55	244.94	101.76	50.94

	Ware River, Intake Works (01173000)		Ware River, Barre (1172500)		Ware River, Gibbs Crossing (1173500)	
Month	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**
Jan	199.43	321.58	113.83	183.58	426.17	714.81
Feb	204.13	243.07	115.78	155.83	415.63	425.46
Mar	298.18	304.55	167.52	194.49	588.16	574.13
Apr	362.63	261.32	212.76	134.80	664.96	474.27
May	207.30	176.53	119.75	95.75	404.09	317.40
Jun	128.57	123.12	70.91	67.24	265.45	190.53
Jul	86.78	474.42	43.84	207.48	192.29	879.74
Aug	69.00	264.55	36.62	161.93	155.76	422.10
Sep	70.05	251.55	37.74	130.01	162.27	523.51
Oct	116.86	267.42	67.31	151.99	240.18	573.84
Nov	163.76	133.11	95.92	64.27	318.95	286.70
Dec	220.45	400.16	123.05	190.65	453.73	902.10

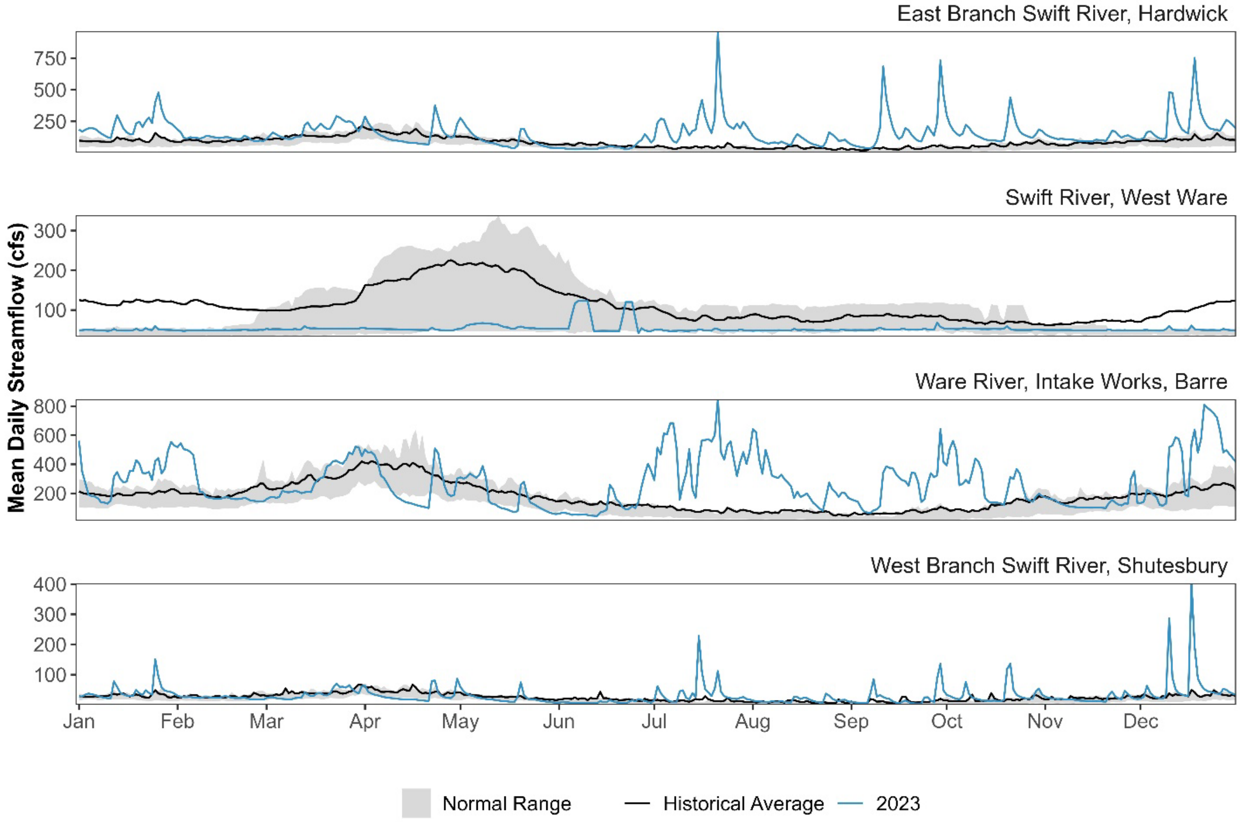


Figure 10: Hydrograph of mean daily streamflow (cfs) at four USGS stream gages in the Quabbin Reservoir and Ware River watersheds. The mean values of all mean daily flows for the period of record are represented by the solid black line. Daily mean flows for 2023 are represented by the blue line. The gray band denotes the normal (25th to 75th percentile) flow range for the period of record.

A drier-than-average November resulted in two weather stations recording precipitation levels more than two inches below historical averages. During this period, streamflow rates approached or fell below average historical mean daily streamflow. The Ware River in Barre recorded the lowest average mean daily streamflow for the month of November at 64.27 cfs—nearly 32 cfs below historical average daily means. Streamflow rates increased again in December as cumulative monthly precipitation was on average nearly two inches greater than historical averages for the POR. During this period, the Ware River, Gibb's Crossing, gage experienced the greatest average mean daily flow of all sites for 2023 at 902.10 cfs, which was 448.37 cfs greater than historical average mean daily flow. This sharp increase in streamflow is likely due to periods of heavy rainfall around mid-December where two weeks saw periods of more than two inches of rainfall within a 48-hour period, corresponding with daily peaks at the Gibb's Crossing gage on December 10 and 11 of 1620 cfs and 1460 cfs respectively, follow by daily peaks on December 18 and 19 of 2660 cfs.

A wide range of maximum and minimum daily streamflow rates were observed across all sites during 2023 for both the Quabbin Reservoir and Ware River watersheds. The USGS gage at Swift River, West Ware, ranged in mean daily streamflow from a minimum of 41.7 cfs (June 26) to a maximum of 123 cfs (June 7) with an annual mean value of 52.9 cfs. The gage at West Branch Swift ranged in streamflow from a minimum of 5.36 cfs (September 6) to a maximum of 403 cfs (December 17) with an annual mean value of 30.9 cfs. The gage at East Branch Swift observed a range in streamflow from a minimum of 32.3 cfs (June 6) to a maximum of 973 cfs (June 21) with an annual mean value of 159.06 cfs. Across Ware River gages, the Barre gage recorded streamflow ranging from 17.1 cfs (June 12) to 517 cfs (July 7), with an annual mean of 142.9 cfs. The Intake Works gage recorded streamflow ranging from a minimum of 43.1 cfs (June 13) to a maximum of 848 cfs (July 21), with an annual mean of 269.49 cfs. At Gibbs Crossing, streamflow fluctuated between a minimum of 87.3 cfs (May 31) and a maximum of 2660 cfs (December 18), with an annual mean of 526.22 cfs. All of the 25 highest daily flow rates recorded for 2023 were observed in the Ware River at the Gibbs Crossing gage.

Cumulative annual discharge was calculated from USGS daily mean discharge records at each of the gage locations and reported in million gallons (MG; Figure 11). Three sites were of focus for reporting purposes—the East Branch Swift River, Hardwick (01174500), the West Branch Swift River, Shutesbury (1174565), and the Ware River, Intake Works, Barre (1173000). Seasonal patterns varied significantly between sites, where major variations in magnitude were observed depending on location. Likewise, the high precipitation rates observed for 2023 were evident, especially when compared to earlier drought years (e.g., 2022, 2016). The West Branch Swift stream gage recorded a cumulative annual discharge of 7,466 MG for 2023, a value in the upper 50% of cumulative totals for the 27-year POR for the gage. Historical mean annual discharge for the West Branch Swift was 5,849 MG, with the POR ranging from a minimum recorded discharge of 2,860 MG (2002) to a maximum recorded discharge of 10,330 MG (2018). Cumulative annual discharge at the East Branch Swift River totaled 38,588 MG in 2023, considerably higher than the mean cumulative discharge of 19,514 MG from the site's 35-year period of record. Minimum cumulative annual discharge for East Branch Swift during the POR was recorded at 8,100 MG in 2002 and the maximum cumulative annual discharge was recorded in 1996 at 31,754 MG, making 2023 the greatest cumulative annual discharge year on record. The Ware River, Intake Works, gage recorded a cumulative annual discharge total of 65,610 MG, which was significantly greater than the historical mean cumulative discharge of 41,173. The POR ranged from a minimum of 21,164 MG (2016) to 65,686 MG (1996).

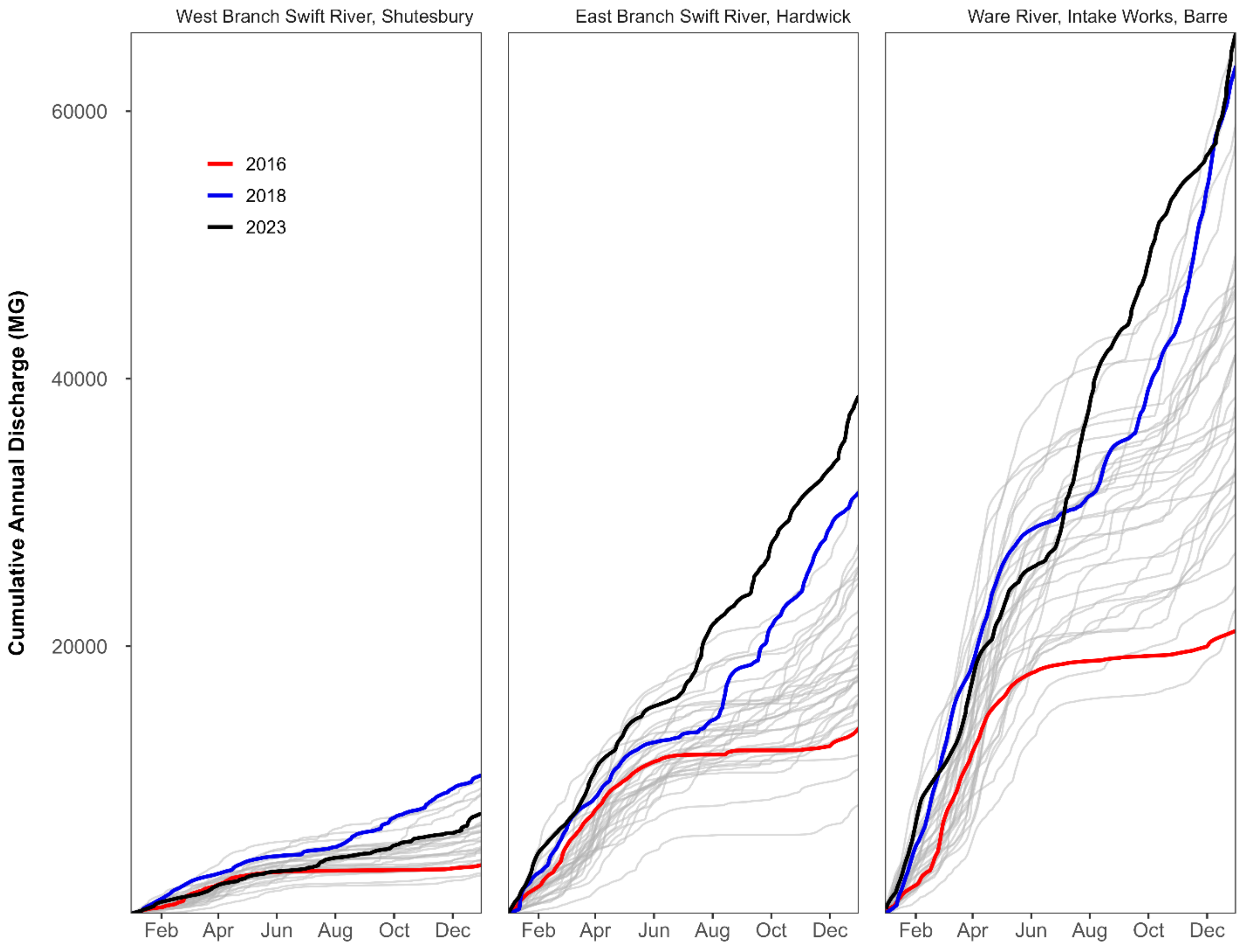


Figure 11: Cumulative annual discharge in millions of gallons (MG) calculated from daily mean discharge records at three USGS stream gages in the Quabbin Reservoir and Ware River watersheds. Colored lines indicated recent years of high and low cumulative annual discharge totals (2018 and 2016 respectively) compared to the period of record (gray lines; see Table 3 for site-specific record ranges) and 2023 (black line). Years with incomplete records (e.g., missing >5% of measurements) were excluded from analysis.

3.2.2 Reservoir Elevation

Elevation of the water surface of the Quabbin Reservoir fell within normal (25th to 75th percentile) operating range for the majority of 2023, with some deviations occurring during summer, fall, and winter months. Elevation ranged from a minimum of 523.48 ft on January 1, 2023, to a maximum of 528.32 ft Boston City Base (BCB; Figure 12) on May 9, 2023. BCB is defined as the water elevation of the Quabbin Reservoir in relation to a specific datum point in Boston, Massachusetts.

In 2022, annual rainfall fell below the long-term median precipitation levels at two out of three weather monitoring stations in the Quabbin Reservoir and Ware River Watersheds. This trend persisted throughout the year, resulting in consistent monthly rainfall deficits. As a result, the daily reservoir elevation during January and early February of 2023 remained below average seasonal levels. Elevation began to climb during the spring months (March, April, and May), rising above the historical average and exceeding the spillway watch trigger of 528 ft BCB from May 1 through 26, 2023. Elevation was below historical average in early June and continued to lower until elevation fell below normal (e.g., 25th percentile daily elevation) from June 19 through the 28. This occurred after a period of below mean rainfall was recorded in May (see Table 9). July recorded monthly rainfall totals >8" at all three weather monitoring locations, causing Quabbin Reservoir elevation to exceed normal levels (e.g., 75th percentile daily elevation) from August 6 through August 27. Following this, reservoir elevation fell within the normal range until September 14, after which it climbed again, surpassing the normal operating range from September 22 through November 6. Towards the end of November, the elevation returned to within the normal operating range, persisting through the first half of December. However, due to high-intensity rain-on-snow events towards the end of December, Quabbin Reservoir elevation approached the upper boundary of normal, eventually exceeding the normal operating range on December 30 and 31 by 0.5 and 0.7 ft, respectively.

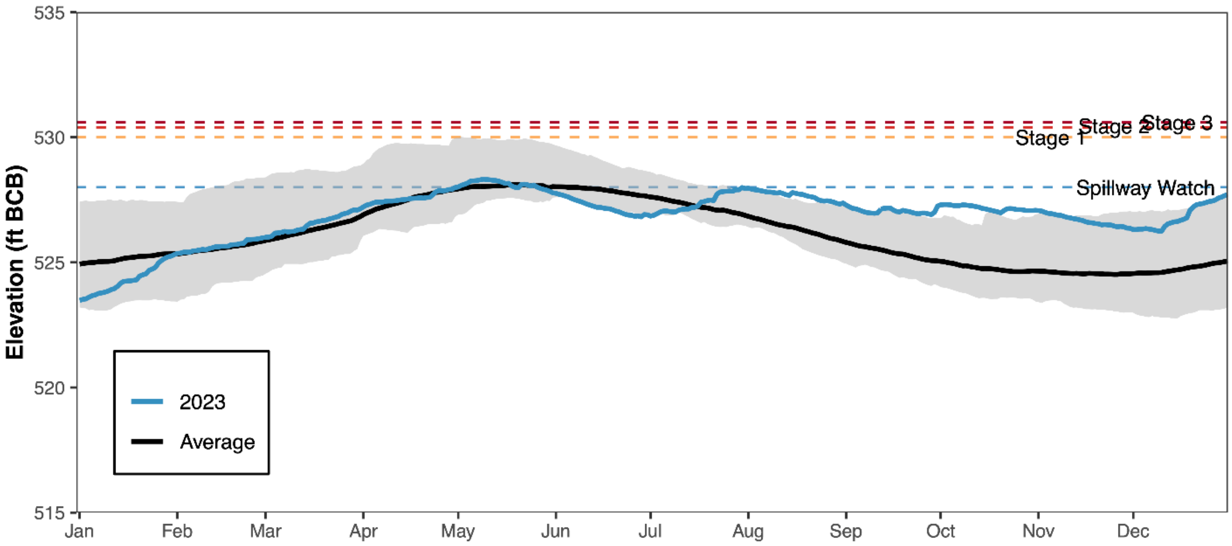


Figure 12: Daily elevation of the Quabbin Reservoir from January 1 through December 31, 2023, relative to spillway watch triggers (DWSP, 2019b) established by DWSP Civil Engineering Section. The gray band represents the normal daily elevation range (defined as the 25th to 75th percentiles) and the black line is the mean daily elevation for the period of record.

3.3 Tributary Monitoring

3.3.1 Water Temperature and Dissolved Oxygen

3.3.1.1 Water Temperature

Water temperature in Quabbin Reservoir watershed tributaries ranged from 0.4 to 25.8˚C in 2023, compared to the historical range of -0.5 to 25.2 ˚C (Figure 13, Table 11). Water temperature exhibited a typical distinct seasonality during 2023, falling within established seasonal ranges for each site, aside from certain observations at 215G. The maximum temperature records for these sites in 2023 (25.8˚C at 215G on 7/6/2023) was a new maximum temperature observed at these sites. A new winter maximum water temperature was recorded for site 215G in 2023 (6˚C on 12/19/2023), more than two degrees higher than historical winter observations (previous high of 3.9˚C on 12/5/2017). These new maximum observations in the records may be in part be due to relatively smaller period of record for observations at this site (25 summer and 25 winter observations) compared to long-established Core sites (e.g., 211, 212, 213, 216 with 240+ summer and 240+ winter observations). However, it also reflects the seasonal patterns of above-normal air temperatures recorded at nearby weather stations during these seasons in 2023 (see Section 3.1.1).

Seasonal average temperatures (mean and median) were elevated at several locations in 2023 compared to the period of record, most pronounced during the winter months. Median and mean winter temperatures at all Quabbin Reservoir watershed tributaries sampled in 2023 were

>1˚C higher than the period of record. These findings highlight the watershed-wide patterns of higher winter air temperature and historically low snowfall that occurred in 2023. Summer average temperatures in 2023 were also higher than the period of record at several sites focused on the western portion of the Quabbin Reservoir Watershed, including 211 (2.3 ˚C higher compared to historical median). Central Quabbin sites (213) and East Quabbin locations (215G, 216) exhibited only small variations in average summer temperatures. These results highlight the spatiotemporal variability in summer rainfall and climatic conditions summarized in Section 3.1. Other upstream catchment-specific characteristics (canopy cover, catchment scale, upstream inputs, groundwater contributions) also vary across these sampling locations and can affect stream temperature response to weather variability (Mosley et al., 2012; Sprague, 2005).

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. Core 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 one date at sites 211 and 212 in 2023 (20.9˚C and 21.5˚C, respectively, on 7/6/2023), and four dates at site 216 in summer and early fall 2023 (20.4 to 24˚C). No sites in the Quabbin Reservoir watershed exceeded the temperature criteria for warm water fish habitat (28.3˚C) in 2023.

Water temperature in Ware River watershed Core tributaries ranged from 0 to 25.5˚C in 2023 (Table 12). Water temperature followed a distinct seasonality in 2023, largely remaining within historical ranges. One Core site in the Fall (121) and one EQA site in the Winter (126A) had new seasonal maximum record in 2023. Several sites exhibited higher than normal temperature readings in early fall 2023. Site 102, a small tributary inflow to the Ware River just upstream of the Shaft 8 Intake (Site 101), exhibited higher-than-normal water temperatures throughout the summer months (Figure 13). Similar to the Quabbin Reservoir watershed sites, seasonal average temperatures (mean and median) were elevated at several locations in Ware River watershed monitoring sites in 2023 compared to the period of record. In the Ware River watershed sites, elevated water temperature results in 2023 were most pronounced during the winter and spring months, during which all monitored sites exhibited seasonal averages (median and mean) above those of the period of record. These water temperature results correspond with the higher daily min and daily max air temperatures recorded during the spring at the Ware River watershed weather station compared to Quabbin Reservoir watershed stations (see Table 8). Mean water temperatures at individual Core sites were 0.4 to 1.7˚C warmer during the winter of 2023 relative to the period of record, while spring mean water temperatures were 0.3 to 2.4˚C warmer.

Core 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 in the summer and early fall on four dates at site 107A, on six dates at site

108, and on one date at site 102 in 2023 (20.2 to 23.2˚C). No sites in the Ware River watershed exceeded the temperature criteria for warm water fish habitat (28.3˚C) in 2023 (Figure 13).

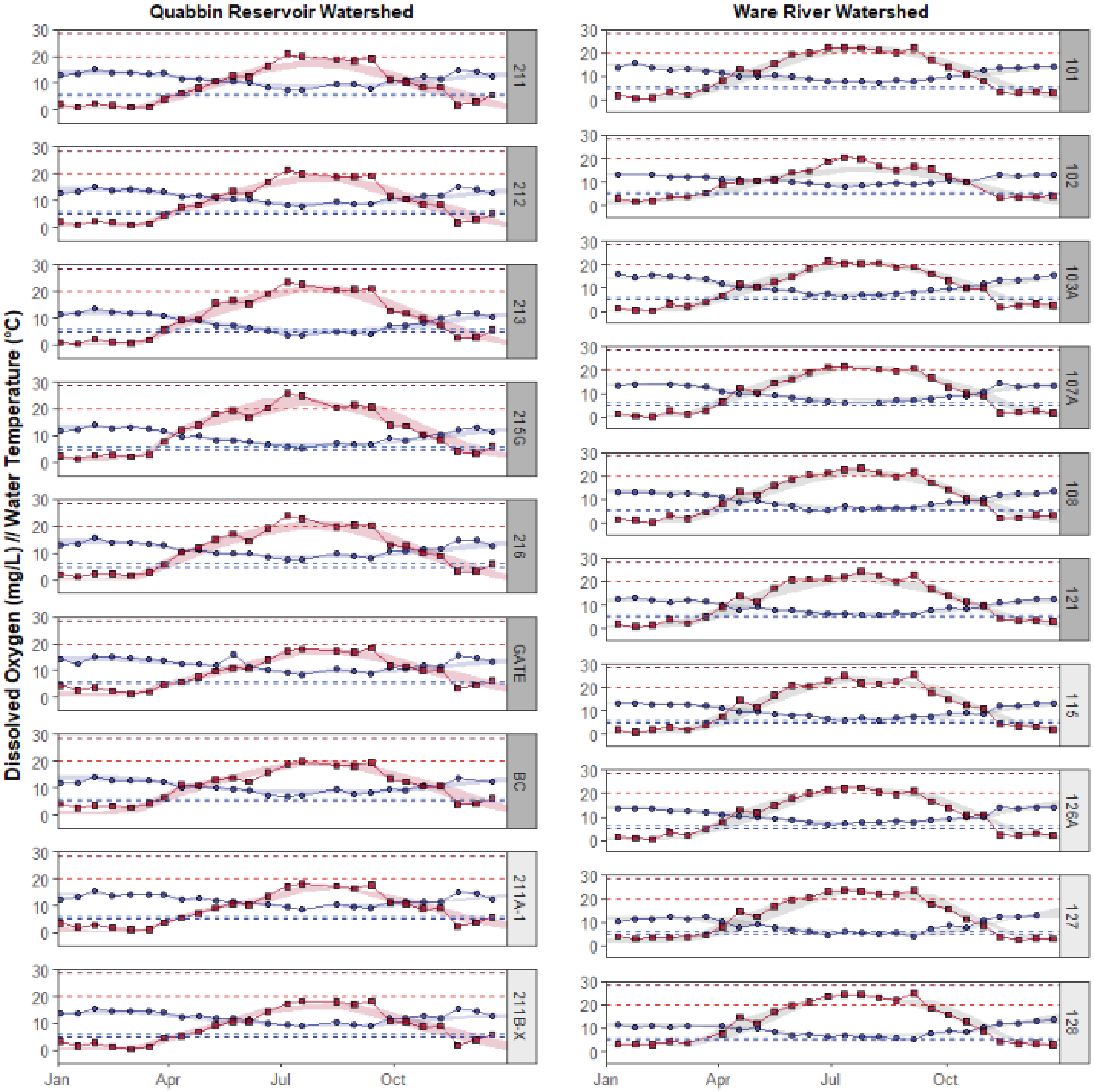


Figure 13: Time series of water temperature and dissolved oxygen measured in 2023 tributary sites. The shaded bands represent seasonal interquartile ranges (25th to 75th percentile) for the period of record at each location. Dark gray site labels correspond to Core sampling locations, light gray site labels correspond to EQA sampling locations. 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; light red) and WFR (28.3˚C; dark red) waters.

Table 11: Seasonal statistics for water temperature measured in the Quabbin Reservoir Watershed tributary sites.

		Water Temperature (°C)									
		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	255	1.1	-0.4	2.3	0.3	2.7	0.7	5.6	5.3
	Spring	7	253	1.1	-0.1	6.1	6.0	6.2	5.8	12.7	18.2
	Summer	6	256	12.3	9.0	18.5	16.2	17.8	16.2	20.9	21.0
	Fall	6	250	1.8	0.0	9.5	9.0	9.9	9.0	19.1	19.0
212	Winter	6	236	1.0	-0.4	2.3	0.0	2.6	0.7	5.2	6.0
	Spring	7	241	0.9	-0.4	7.5	6.2	6.8	6.3	13.5	19.7
	Summer	6	245	12.4	10.0	18.9	17.1	18.1	17.2	21.5	22.6
	Fall	6	235	1.7	0.0	9.6	9.6	10.0	9.5	19.2	20.0
213	Winter	6	247	0.4	-0.2	1.7	0.2	2.2	0.6	5.6	9.0
	Spring	7	250	0.7	-0.4	9.2	7.8	8.5	7.7	16.6	23.1
	Summer	6	250	15.4	5.3	20.6	20.0	20.3	19.7	23.5	24.8
	Fall	6	240	2.7	1.0	10.8	10.0	10.9	10.2	21.0	21.3
215G	Winter	6	21	1.3	0.0	2.7	1.4	3.1	1.6	6.0	3.9
	Spring	7	25	2.2	0.3	12.1	11.9	10.8	10.4	19.3	19.9
	Summer	6	25	16.6	14.2	21.0	21.1	21.6	21.0	25.8	25.2
	Fall	6	25	4.1	1.5	12.0	13.3	11.8	12.2	20.8	22.0
216	Winter	6	252	1.2	-0.5	2.3	0.1	2.8	0.7	6.0	6.5
	Spring	7	252	1.6	-0.5	10.3	8.4	9.2	8.0	17.1	22.5
	Summer	6	256	14.4	8.8	20.1	20.0	20.1	19.7	24.0	25.2
	Fall	6	246	3.2	0.3	11.5	10.5	11.4	10.5	20.4	21.7
BC	Winter	6	181	2.4	-0.4	4.2	1.3	4.1	1.9	6.3	7.0
	Spring	7	183	1.4	0.0	5.7	6.6	6.0	6.2	10.9	15.1
	Summer	6	185	10.7	9.8	17.1	16.0	15.7	15.9	18.0	20.1
	Fall	6	200	3.4	0.3	10.9	10.6	10.9	10.5	18.4	19.2
GATE	Winter	6	182	2.7	-0.4	3.8	1.0	4.0	1.4	6.1	10.0
	Spring	7	189	2.9	0.0	11.0	8.2	9.0	8.1	13.7	20.1
	Summer	6	156	12.4	11.1	18.3	18.3	17.3	18.2	19.9	23.6
	Fall	6	163	4.0	0.1	11.6	10.4	11.8	10.6	19.4	20.9
211A-1	Winter	6	15	1.9	-0.2	3.2	0.1	3.3	0.8	5.8	4.6
	Spring	7	12	1.1	0.6	5.5	5.7	5.5	5.4	10.8	10.6
	Summer	6	14	10.3	9.6	16.9	14.7	15.5	14.2	18.1	18.0
	Fall	6	12	2.2	2.8	9.9	9.9	10.0	9.3	17.7	15.2
211B-X	Winter	6	113	1.4	-0.1	3.0	0.1	3.1	1.0	5.8	7.0
	Spring	7	109	0.4	0.0	5.2	6.0	5.4	5.5	10.7	13.2
	Summer	6	119	10.6	9.0	17.1	15.5	15.9	15.4	18.1	19.2
	Fall	6	113	1.8	1.0	9.9	9.0	9.9	9.1	18.1	18.0

Table 12: Seasonal statistics for water temperature measured in Ware River Watershed tributary sites.

		Water Temperature (°C)									
		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	210	0.6	-0.5	2.4	0.1	2.2	0.6	3.5	8.0
	Spring	7	216	2.1	-0.5	11.5	9.0	10.7	8.5	19.3	21.3
	Summer	6	221	20.0	11.5	21.5	21.0	21.2	21.0	22.1	27.0
	Fall	7	221	2.8	0.8	10.8	11.0	11.1	11.0	22.2	23.9
102	Winter	6	115	1.8	0.0	3.4	1.1	3.1	1.4	4.1	8.0
	Spring	7	117	3.8	1.0	10.3	7.0	9.1	7.1	14.2	17.3
	Summer	6	120	14.7	10.0	17.7	15.0	17.6	15.0	20.6	20.2
	Fall	6	119	3.4	1.0	11.2	8.0	10.3	8.5	16.7	19.0
103A	Winter	6	86	0.2	-0.4	2.0	0.1	1.9	0.7	3.3	7.0
	Spring	7	103	2.1	-0.4	10.5	9.0	8.8	8.5	14.5	19.6
	Summer	6	115	18.4	11.5	20.4	19.6	20.0	19.5	21.4	27.0
	Fall	7	115	1.9	0.5	9.9	10.0	10.3	9.9	19.0	21.7
107A	Winter	6	95	0.0	-0.5	1.7	0.1	1.5	0.6	2.7	7.0
	Spring	7	109	1.1	-0.1	10.3	8.9	9.1	8.6	16.0	22.1
	Summer	5	114	19.1	11.7	20.2	20.7	20.3	20.2	21.5	25.6
	Fall	7	115	1.8	0.4	10.1	10.2	10.4	10.1	20.8	23.0
108	Winter	6	206	0.2	-0.5	2.3	0.0	2.1	0.5	3.3	7.3
	Spring	7	214	1.9	-0.5	12.0	8.3	10.6	8.2	18.6	22.5
	Summer	6	215	19.7	12.2	21.5	20.4	21.6	20.3	23.2	26.3
	Fall	7	215	2.0	0.0	10.4	10.0	10.9	10.3	21.7	23.6
121	Winter	6	129	0.9	0.0	2.4	0.6	2.4	1.0	3.9	8.0
	Spring	7	130	2.3	0.0	11.3	9.6	11.5	9.3	20.9	24.1
	Summer	6	138	20.0	12.0	21.7	20.8	21.9	20.3	24.3	28.0
	Fall	7	140	3.5	1.0	11.2	10.0	11.8	10.4	22.7	21.0
115	Winter	6	118	0.9	0.0	2.1	1.0	2.3	1.2	3.4	7.0
	Spring	7	116	1.8	0.0	11.6	9.0	11.0	8.4	21.0	23.8
	Summer	6	114	20.6	15.0	22.1	22.9	22.4	22.3	25.0	28.0
	Fall	7	113	3.7	1.2	12.5	10.0	12.9	11.5	25.5	26.0
126A	Winter	6	19	0.4	-0.1	1.7	0.1	1.8	0.4	3.3	2.1
	Spring	7	20	1.9	0.3	11.5	7.9	10.2	8.1	17.8	21.4
	Summer	6	20	19.5	17.4	21.1	21.4	21.0	21.4	22.3	25.7
	Fall	7	19	1.9	0.6	10.8	11.3	10.9	10.8	21.1	23.9
127	Winter	6	19	3.0	0.6	3.4	2.0	3.4	2.0	4.1	4.0
	Spring	7	20	4.0	1.5	12.4	8.2	11.5	8.7	19.7	20.4
	Summer	6	20	20.7	17.4	22.6	21.8	22.5	21.8	23.8	25.8
	Fall	7	19	2.6	3.5	11.4	11.5	12.0	11.4	23.6	24.1
128	Winter	6	19	3.0	1.6	3.3	2.8	3.4	2.9	4.4	3.9
	Spring	6	20	3.8	0.3	13.4	8.8	12.5	9.2	19.7	22.2
	Summer	6	20	21.3	18.7	23.4	22.5	23.1	22.7	24.3	26.7
	Fall	7	19	3.5	2.3	12.8	12.3	12.6	11.7	24.8	24.9

3.3.1.2 Dissolved Oxygen

Dissolved oxygen concentrations in Quabbin Reservoir watershed tributaries ranged from 3.6 to 15.9 mg/L in 2023 (Table 13). Dissolved oxygen concentrations demonstrated a typical seasonality during 2023, relatively depleted during warmer months and elevated in winter and fall (Figure 13). Concentrations of dissolved oxygen were inversely related to water temperature and fell within established ranges for each site, aside from EQA sites 211A-1 and 211B-X for which continuous long-term records are limited. Western Quabbin sites (GATE, 211, 212, and EQA sites 211A-1 and 211B-X) exhibit higher DO concentrations on average compared to the more wetland-dominated stream systems of Central and Eastern Quabbin (213, 215G), most pronounced in the summer and fall months. Despite numerous sites having higher average winter water temperatures in 2023, average stream DO in Quabbin Reservoir watershed tributaries varied little from historical seasonal averages in a majority of sites. This may be in part due to the consistently high flow rate recorded by USGS stream gages in the watershed in 2023. High streamflow years can increase turbulence and mixing of water, which can help oxygenate the water and lead to increased DO (Ice, 1978).

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 concentrations remained above 6 mg/L at locations in the Quabbin Reservoir watershed identified as cold-water fish habitats (e.g., 211, 212, 216) for the entirety of 2023.

Dissolved oxygen concentrations in Ware River watershed tributaries ranged from 4.1 to 16.1 mg/L in 2023 (Table 14), following typical seasonal elevated patterns in winter and fall as well as relatively depleted concentrations in the warmer months. Like the response observed in tributaries in the Quabbin Reservoir watershed, seasonal median dissolved oxygen concentrations in 2023 were comparable to that of the period of record for most sites across all seasons. Median spring DO was slightly lower (<2 mg/L) compared to the period of record for the EQA sites (115, 126A, 127, 128) as well as site 101, possibly due to elevated spring air temperature and subsequent slightly elevated stream water temperatures for streams in this watershed.

Relevant to the class A inland water criteria of DEP fisheries habitat designations, dissolved oxygen concentrations fell below 6 mg/L at site 108 on three dates in June and July of 2023. Dissolved oxygen concentrations remained above 6 mg/L at site 102 and 107A for the entirety of 2023. Concentrations of dissolved oxygen did not fall below 5 mg/L at these sites in 2023.

Table 13: Seasonal statistics for dissolved oxygen measured in the Quabbin Reservoir Watershed tributary sites.

Dissolved Oxygen (mg/L)

		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	255	12.3	10.2	13.5	13.8	13.6	14.1	15.0	23.1
	Spring	7	253	10.6	6.5	11.7	12.3	12.2	12.5	13.7	21.6
	Summer	6	256	7.5	4.7	9.0	9.0	8.9	8.9	10.3	12.2
	Fall	6	250	8.1	5.8	11.3	10.7	11.5	10.9	14.8	19.6
212	Winter	6	236	12.7	10.7	13.5	13.8	13.7	14.2	15.1	23.1
	Spring	7	241	10.6	6.3	12.2	12.2	12.4	12.4	14.2	21.2
	Summer	6	245	8.0	4.5	9.1	8.9	9.1	8.8	10.4	11.8
	Fall	6	235	8.6	4.9	11.5	10.7	11.6	10.9	15.2	19.1
213	Winter	6	247	10.3	7.2	11.9	11.6	11.9	11.8	13.5	19.4
	Spring	7	250	7.1	3.6	9.3	9.8	9.7	9.9	12.0	18.0
	Summer	6	250	3.6	1.6	4.9	5.4	4.9	5.5	6.6	21.4
	Fall	6	240	4.0	2.5	7.7	7.5	8.0	7.9	11.8	15.9
215G	Winter	6	21	11.3	11.3	12.5	13.1	12.5	13.1	13.9	14.9
	Spring	7	25	8.3	7.1	9.7	10.0	10.5	10.7	13.0	15.4
	Summer	6	25	5.1	4.6	6.8	6.6	6.5	6.7	7.7	9.3
	Fall	6	25	6.7	6.3	9.3	8.8	9.3	9.1	12.3	14.2
216	Winter	6	252	12.4	9.8	13.6	13.9	13.8	14.1	15.6	20.5
	Spring	7	252	9.8	5.8	11.1	11.8	11.7	11.9	14.1	19.8
	Summer	6	256	7.6	4.7	8.7	8.6	8.7	8.6	9.8	21.2
	Fall	6	246	8.2	5.7	11.4	10.6	11.4	10.8	14.8	16.7
BC	Winter	6	181	12.7	10.5	14.6	14.3	14.2	14.7	15.2	23.5
	Spring	7	183	11.9	6.9	14.0	12.4	13.7	13.0	15.9	25.2
	Summer	6	185	8.6	5.1	10.0	9.5	10.0	9.5	11.5	14.4
	Fall	6	200	8.9	6.1	11.5	11.0	11.7	11.2	15.7	21.1
GATE	Winter	5	182	12.0	10.9	12.2	13.5	12.8	13.8	14.4	19.7
	Spring	7	189	9.6	6.0	10.4	11.5	11.2	11.7	13.0	20.0
	Summer	6	156	7.2	4.6	7.5	8.5	8.1	8.5	9.7	11.5
	Fall	6	163	8.1	5.5	10.3	10.3	10.4	10.5	13.8	16.1
211A-1	Winter	6	15	12.4	12.7	13.4	14.2	13.6	14.3	15.3	15.2
	Spring	7	12	11.6	10.9	12.7	12.0	13.0	12.5	14.3	14.5
	Summer	5	14	8.7	9.3	9.7	9.9	9.8	10.1	10.7	11.9
	Fall	6	12	9.0	9.1	11.4	11.1	11.6	11.2	14.9	13.2
211B-X	Winter	6	113	12.9	9.5	14.0	13.6	14.1	13.6	15.5	16.6
	Spring	7	109	11.8	9.0	12.9	12.3	13.1	12.3	14.6	15.6
	Summer	6	119	8.9	8.0	9.8	9.3	10.0	9.4	11.5	11.9
	Fall	6	113	8.9	7.9	11.9	10.8	12.1	11.0	15.5	14.5

Table 14: Seasonal statistics for dissolved oxygen measured in Ware River Watershed tributary sites.

Dissolved Oxygen (mg/L)

		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	31	12.6	11.9	13.9	14.6	13.9	14.6	15.7	16.1
	Spring	7	31	9.8	7.4	10.5	11.5	11.0	11.7	13.1	16.3
	Summer	6	30	7.2	5.1	7.8	8.4	8.0	8.3	8.9	10.9
	Fall	7	32	8.1	7.3	11.1	10.8	11.1	10.9	13.8	14.4
102	Winter	5	115	12.4	9.1	13.0	13.2	13.0	13.2	13.5	16.6
	Spring	7	117	9.9	6.2	11.1	11.6	11.1	11.6	12.3	15.9
	Summer	6	120	7.9	7.7	8.6	9.3	8.7	9.3	9.6	11.0
	Fall	6	119	9.0	7.6	10.4	11.1	10.8	11.0	13.1	15.4
103A	Winter	6	86	14.4	11.2	14.9	14.1	15.0	14.5	16.1	24.5
	Spring	7	103	8.9	6.6	10.4	11.1	11.3	11.5	14.3	19.1
	Summer	6	115	6.3	4.2	7.1	7.5	7.2	7.4	7.8	10.0
	Fall	7	114	7.9	4.1	10.4	10.1	10.6	10.4	13.2	19.6
107A	Winter	5	95	13.2	11.3	13.7	13.7	13.6	14.0	14.0	23.4
	Spring	7	109	8.4	6.7	10.1	10.8	10.7	11.3	13.5	20.2
	Summer	5	114	6.3	4.9	6.6	7.7	6.7	7.6	7.1	10.1
	Fall	7	115	7.1	6.5	9.0	10.1	10.1	10.7	14.3	21.3
108	Winter	6	206	12.1	4.9	13.2	13.0	13.0	13.3	13.6	21.0
	Spring	7	214	7.1	4.6	9.3	10.7	9.8	10.8	12.4	20.6
	Summer	6	215	5.2	3.5	6.1	6.5	6.0	6.5	7.2	9.3
	Fall	7	215	6.2	4.1	9.1	8.7	9.6	9.1	12.7	20.0
121	Winter	6	129	11.3	9.4	12.7	12.2	12.5	12.2	13.1	15.2
	Spring	7	130	7.7	6.5	9.4	9.8	9.4	10.0	11.9	13.6
	Summer	6	138	5.9	4.1	6.5	6.5	6.5	6.6	7.1	10.1
	Fall	7	140	6.1	6.1	8.9	8.8	9.1	8.9	11.6	14.3
115	Winter	6	118	12.7	7.5	13.1	12.9	13.1	13.1	13.5	18.7
	Spring	7	116	8.2	7.6	9.7	11.2	10.4	11.1	12.9	17.2
	Summer	6	114	6.0	5.0	6.6	7.2	6.8	7.2	8.2	12.2
	Fall	7	113	7.4	2.9	8.9	9.0	9.4	9.3	12.4	18.6
126A	Winter	6	19	12.6	11.8	13.6	14.0	13.5	14.6	13.9	21.7
	Spring	7	20	8.7	8.1	10.1	11.3	10.5	11.2	12.5	14.9
	Summer	6	20	6.9	6.8	7.4	7.6	7.5	7.9	8.0	9.2
	Fall	7	19	7.8	5.5	9.5	10.2	10.3	10.7	13.7	20.9
127	Winter	5	19	10.4	9.7	11.6	11.9	11.8	13.0	13.1	19.7
	Spring	7	20	6.8	4.9	9.4	10.9	9.4	10.0	12.3	13.2
	Summer	6	20	4.8	2.8	5.7	5.9	5.7	5.7	6.3	8.1
	Fall	7	19	4.1	2.6	8.7	8.4	9.0	8.9	12.3	20.8
128	Winter	6	19	10.4	9.8	11.2	11.8	11.8	12.6	13.6	20.2
	Spring	6	20	6.9	7.6	9.5	10.8	9.4	10.4	11.1	13.6
	Summer	6	20	5.7	6.1	6.5	7.3	6.5	7.3	7.3	8.6
	Fall	7	19	5.2	5.8	9.0	9.2	9.3	10.2	12.0	19.4

3.3.2 Specific Conductance, Sodium, and Chloride

3.3.2.1 Specific Conductance

Specific conductance ranged from 1.7 to 165.6 µS/cm across Quabbin Reservoir watershed monitoring tributaries and from 36 to 431 µS/cm across monitoring tributaries in the Ware River watershed during 2023 (Table 15). Seasonal patterns of specific conductance were generally elevated during brief periods of low and moderate streamflow conditions in the first half 2023, while concentrations generally declined with the record high flows throughout the second half of 2023. These dynamics were particularly pronounced in the Ware River Watershed, where specific conductance concentrations were above the normal historical range at a majority of sites until historical July rainfalls and subsequent record high streamflow. This dilution effect was sustained at most sites throughout the summer and fall months, as consistent >1” rainfall events maintained high flows across the watersheds. The result is a defined period of dilution evident from the timeseries figure of results, most clearly seen in sites from Ware River watershed (Figure 14). Seasonal specific conductance averages for select Quabbin Reservoir Watershed sites were slightly elevated in 2023 compared to the period of record. This was particularly true of specific conductance concentration results from spring 2023, when streamflow conditions were often within normal ranges. However, the differences in elevated 2023 seasonal mean specific conductance values compared with the period of record were small (range: 3-19 µS/cm) relative to the range of elevated 2023 seasonal mean values across Ware River Watershed sites (range: 10-161 µS/cm).

Ware River sites saw elevated median specific conductance in 2023 relative to the period of record for most sites (see boxplots, Figure 14). Core site 121 and EQA site 115 exhibited higher average specific conductance across all seasons compared to their periods of record, with Core site 121 recording new maximum winter and spring specific conductance values in 2023 (423 and 431 µS/cm, respectively). Winter and spring mean specific conductance values at Mill Brook (site 121) were particularly higher compared to the period of record (77 µS/cm and 161 µS/cm higher, respectively). 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). Site 121 is a hot spot of specific conductance in the Ware River watershed, representing the drainage area of a large portion of Rutland, which contains areas of high road density in residential developments. 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 site has elevated specific conductance values relative to the other monitoring locations, requiring a separate axis on the timeseries figure to show the annual range of values at this location (Figure 14).

While 2023 specific conductance results were mostly within historical range from the period of record, annual median specific conductance has been documented to be 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 (DWSP 2023a). The record high streamflow of 2023 and subsequent dilution effects likely offset these increasing specific conductance concentration patterns at many sites in 2023. However, the new maximum spring and winter values, and higher average values for site 121 in 2023 highlights the persistence of specific conductance trends in the Ware River watershed. Further, the record high streamflow year likely resulted in a high annual loading of salt relative to other years (see also DWSP, 2024b).

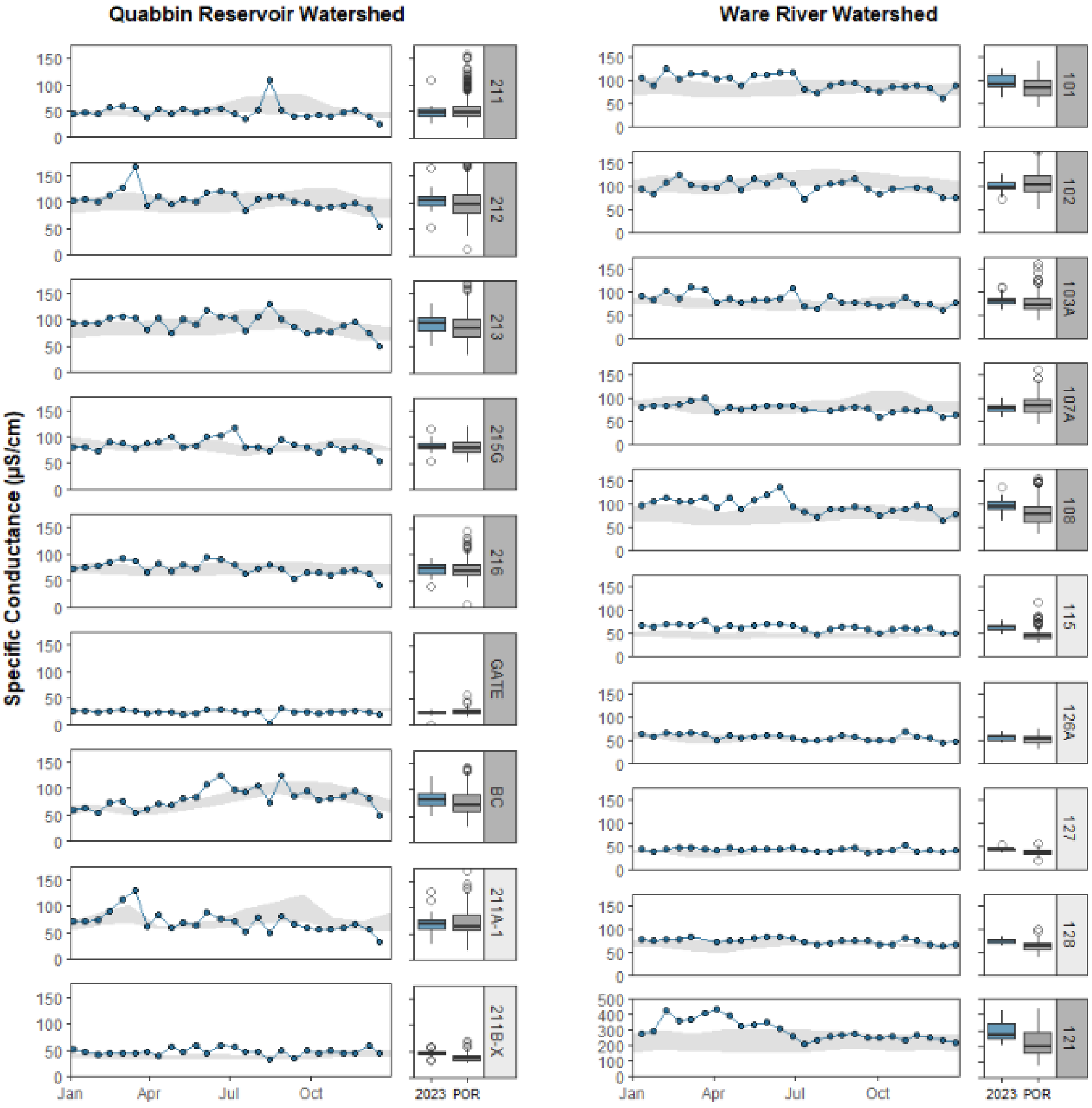


Figure 14: Time series and boxplots of 2023 specific conductance results (blue) from tributary monitoring sites compared against each site's period of record (gray).

Table 15: Seasonal statistics for specific conductance measured in the Quabbin Reservoir Watershed tributary sites.

Specific Conductance (µS/cm)

		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	255	26	18	46	43	44	46	57	194
	Spring	7	253	38	28	54	45	51	47	61	130
	Summer	7	256	35	25	53	57	58	62	110	157
	Fall	6	250	40	27	42	50	44	56	52	152
212	Winter	6	236	54	11	103	92	95	96	113	212
	Spring	7	241	93	35	106	93	114	95	166	190
	Summer	7	245	83	52	110	101	109	102	121	170
	Fall	6	235	89	48	95	100	95	104	102	180
213	Winter	6	247	50	42	92	79	84	79	103	136
	Spring	7	250	73	33	101	82	94	83	105	141
	Summer	7	250	78	42	105	96	106	96	131	169
	Fall	6	240	74	40	82	85	83	88	95	166
215G	Winter	6	21	55	67	77	81	75	86	90	120
	Spring	7	25	79	65	87	81	87	82	100	115
	Summer	7	25	74	52	95	74	93	75	116	95
	Fall	6	25	70	63	80	86	79	86	85	114
216	Winter	6	252	40	6	75	70	69	73	86	190
	Spring	7	252	66	40	81	68	79	69	92	115
	Summer	7	256	62	38	80	72	79	74	94	144
	Fall	6	246	53	43	66	70	64	73	71	133
BC	Winter	6	181	19	17	25	26	24	26	26	49
	Spring	7	183	19	18	23	23	22	24	27	30
	Summer	7	185	2	17	26	26	23	26	30	58
	Fall	6	200	22	15	24	28	24	28	26	42
GATE	Winter	6	182	51	37	62	65	64	67	82	137
	Spring	7	189	55	30	73	60	72	61	84	101
	Summer	7	156	73	40	106	89	105	90	126	142
	Fall	6	163	80	30	87	90	88	91	97	141
211A-1	Winter	6	15	31	19	71	63	66	69	92	168
	Spring	7	12	59	47	70	61	83	65	130	95
	Summer	7	14	50	45	75	72	71	83	88	139
	Fall	6	12	57	49	59	85	61	87	67	146
211B-X	Winter	6	113	41	28	46	38	47	40	58	70
	Spring	7	109	39	28	46	38	48	39	60	60
	Summer	7	119	32	28	48	37	48	37	59	60
	Fall	6	113	34	30	45	38	44	41	49	70

Table 16: Seasonal statistics for specific conductance measured in Ware River Watershed tributary sites.

Specific Conductance (µS/cm)

		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	204	60	43	96	85	95	85	124	142
	Spring	7	211	89	43	111	79	107	79	114	126
	Summer	6	214	72	42	92	88	94	85	117	137
	Fall	7	213	73	40	86	83	84	84	95	140
102	Winter	6	115	75	58	89	99	94	105	126	270
	Spring	7	117	92	50	103	97	103	103	116	200
	Summer	6	120	72	55	106	112	102	121	121	200
	Fall	6	119	82	55	96	105	97	112	117	200
103A	Winter	6	86	61	54	86	78	84	78	103	109
	Spring	7	103	79	50	85	72	90	76	111	126
	Summer	6	114	63	38	83	70	83	75	108	163
	Fall	7	111	69	52	75	70	76	75	88	141
107A	Winter	6	95	59	57	84	87	77	88	85	133
	Spring	7	109	71	47	82	78	84	79	100	129
	Summer	5	114	73	46	78	84	79	84	84	142
	Fall	7	115	60	50	76	83	74	92	80	233
108	Winter	6	206	66	40	102	80	95	81	115	209
	Spring	7	214	91	43	111	70	107	76	121	250
	Summer	6	215	74	42	90	79	95	83	137	151
	Fall	7	215	76	38	89	80	89	85	97	157
121	Winter	6	129	221	108	282	210	300	223	423	401
	Spring	7	130	324	92	365	190	372	211	431	401
	Summer	6	138	210	78	259	208	257	221	310	433
	Fall	7	140	232	90	252	212	255	222	279	400
115	Winter	6	118	51	30	66	48	62	49	70	83
	Spring	7	116	59	32	68	42	68	47	79	87
	Summer	6	114	49	32	63	42	62	48	71	117
	Fall	7	113	52	32	60	48	60	47	66	69
126A	Winter	6	19	43	42	60	50	56	53	65	74
	Spring	7	20	49	29	60	48	59	49	66	68
	Summer	6	20	48	35	53	50	54	51	61	74
	Fall	7	19	48	39	53	51	55	50	69	65
127	Winter	6	19	38	30	42	34	42	36	45	49
	Spring	7	20	40	19	43	33	43	33	47	47
	Summer	6	20	38	25	42	40	42	39	47	54
	Fall	7	19	36	32	40	37	42	38	53	52
128	Winter	6	19	63	53	75	61	72	63	77	93
	Spring	6	20	71	39	77	60	77	62	82	100
	Summer	6	20	67	44	73	69	74	67	83	85
	Fall	7	19	66	50	74	64	72	62	80	68

3.3.2.2 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 monitoring tributaries in the Ware River watershed ranged from 2.85 to 58.2 mg/L and from 3.88 to 111 mg/L, respectively, in 2023. Concentrations of these solutes in tributaries in the Quabbin Reservoir watershed were notably lower (1.28 to 21.4 mg/L for Na and 1.0 to 38.7 mg/L for Cl). The spatial heterogeneity in concentrations of Na and Cl observed in 2023 was consistent with prior monitoring. This reflects differences in land cover and watershed characteristics, such as impervious surface cover, that contribute to variable inputs of Na and Cl to individual tributaries across the two watersheds. Timeseries patterns for these major ions are also consistent with patterns observed from specific conductance observations, with lower-than-normal concentrations observed in the summer and fall of 2023 due to a sustained dilution from long-duration high streamflow conditions in both watersheds (Figure 10, Figure 15, Figure 16).

The secondary MCL for Cl in drinking water (250 mg/L) established by the US EPA was not exceeded in any tributary samples collected in 2023 from the Quabbin Reservoir or Ware River watersheds. The MassDEP Office of Research and Standards (ORS) guidelines for Na in drinking water (threshold of 20 mg/L Na) was exceeded at two sites in 2023. Once at site 212 (Hop Brook) in the Quabbin Reservoir watershed (3/16/2023, 21.4 mg/L), and for the entirety of samples collected at site 121 (Mill Brook) in the Ware River watershed (n=25 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.

Median annual concentrations of Na, Cl, and specific conductance were generally greater in Core tributaries within the Ware River watershed, relative to Core monitoring sites in the Quabbin Reservoir watershed in 2023. The latter may be reflective of the high ratio of protected, forested lands relative to developed lands in the Quabbin Reservoir watershed, with comparatively more developed areas in Ware River watershed (see Table 2). Previously documented analyses of Na, Cl, and specific conductance found approximate 1:1 molar ratios of Na to Cl and linear relationship between Cl concentrations and specific conductance in surface waters (DWSP 2023a). This suggests that increasing concentrations of Cl, likely from road salt contributions, may be driving increasing trends in annual median specific conductance for the certain Core monitoring tributaries (see also Soper et al., 2021).

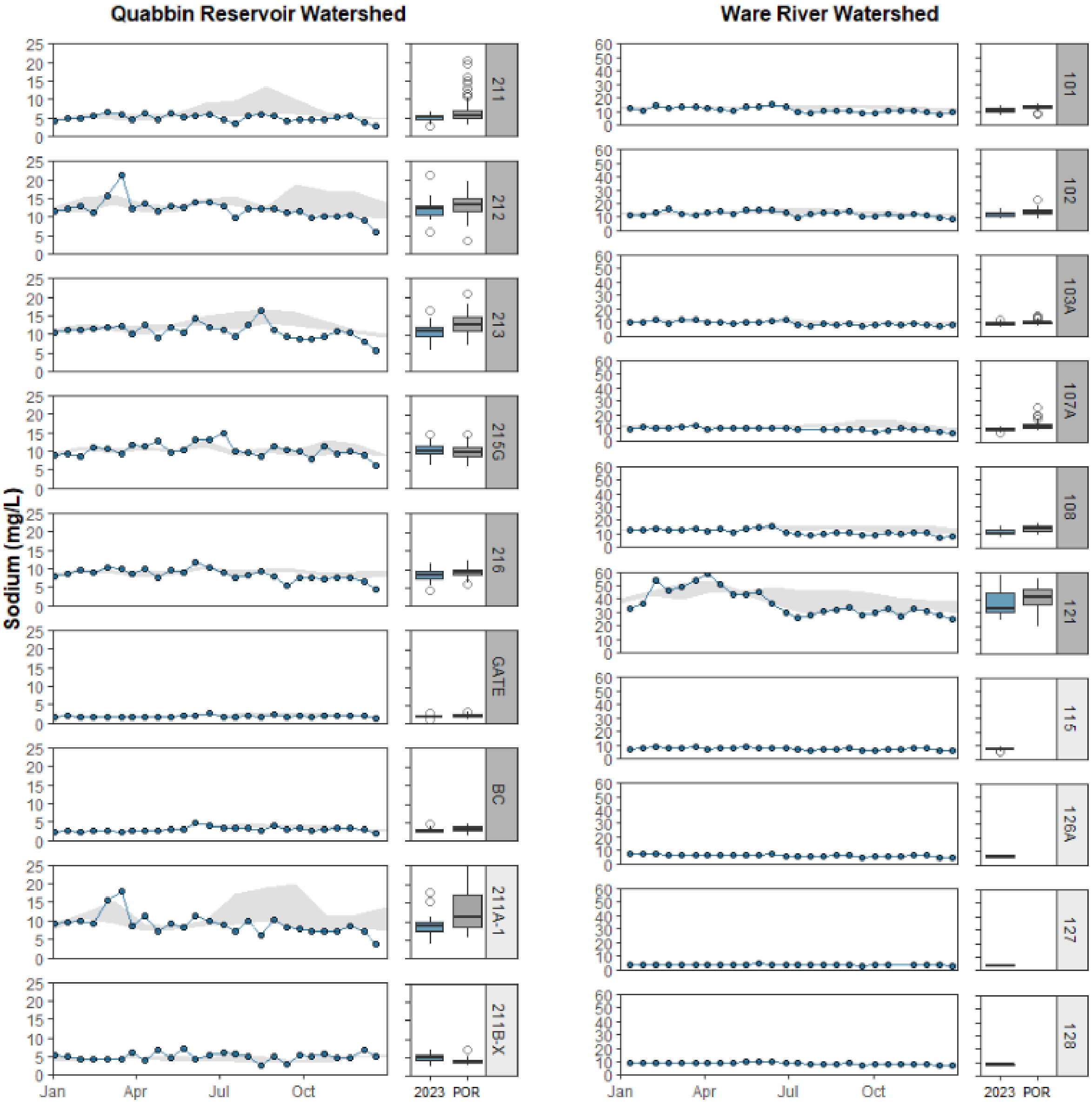


Figure 15: Time series and boxplots of 2023 sodium results (blue) from tributary monitoring sites compared against each site's period of record (gray).

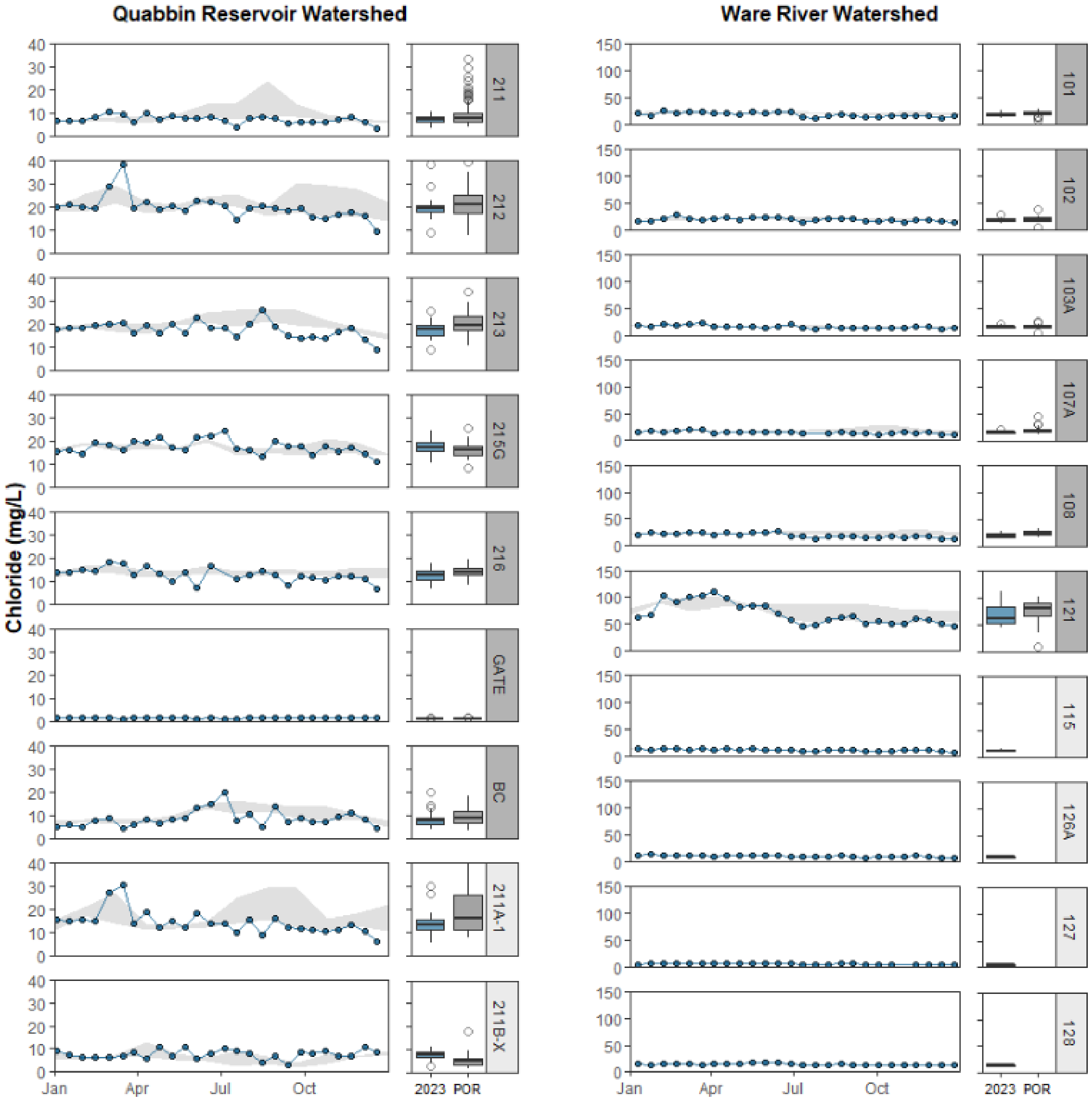


Figure 16. Time series and boxplots of 2023 chloride results (blue) from tributary monitoring sites compared against each site's period of record (gray).

3.3.3 Turbidity

Turbidity results in the Quabbin Reservoir and Ware River watershed reflected spatial and temporal variability of rainfall and subsequent runoff, following the year's seasonal patterns of high rainfall and record high stream flows (Figure 17). This resulted in some isolated periods of elevated turbidity at select sites compared to the period of record. Turbidity ranged from 0.13 to 14 NTU in Quabbin Reservoir tributaries and from 0.3 to 3.3 NTU in Ware River Watershed Core tributaries during 2023 (Table 17, Table 18).

Turbidity in Core sites remained below the five NTU SWTR requirement in all but four samples collected in 2023. These four samples were all collected during an active, high-intensity precipitation event on August 15, 2023 which resulted in variable rainfall totals across the Quabbin Reservoir and Ware River Watersheds (0.85" of rainfall recorded at Belchertown, 0.95" at Orange, and 0.55" of rainfall at Barre). The variability in rainfall rates and intensity, as well as considerations of sample collection relative to precipitation and subsequent streamflow response timing, is reflected in patterns across Quabbin Reservoir Watershed sampling locations (Figure 17). Eastern Quabbin sites (213, 215G and 216) exhibited a smaller increase in turbidity results relative to the period of record and relative to other sites during this sample collection date. Western Quabbin sites (211, 212, GATE, 211A-1, 211B-X) had elevated turbidity representing outlier points compared to annual normal ranges, with results greater than the Eastern Quabbin sites. Although these elevated results are noticeable outliers, results were within historical ranges for most sites, indicating that this type of discrete sediment loading event represents the upper range of sediment concentrations at these locations and provides insights into the range of variability of turbidity concentrations under different hydrological contexts at these sites. These rainfall-driven events represent discrete instances of sediment transport within catchments, as turbidity levels returned to pre-event concentrations in all subsequent samples. New summer maximum turbidity results were documented at site with relatively shorter period of record compared to long-established core sites (e.g., 215G, 211A-1, and 211B-X compared to 211, 212, 213, and 216), apart from Gates Brook which recorded a new maximum turbidity during the August 15 event (11 NTU).

Overall seasonal median turbidity results were similar between 2023 records and period of record averages across most monitoring locations. Some exceptions include sites 102, 127, and 128, which may be due to shorter period of records for comparison at EQA sites (127, 128) and recently added Core sites (102). Several Ware River monitoring locations exhibited lower-than-normal seasonal turbidity results in late summer and fall (101, 108, 121), potentially reflecting dilution effects following long-duration high streamflow conditions throughout the summer and fall season (see also section 2.1.3), saturated groundwater conditions, and/or attributed to sample timing relative to storm events. Variability in turbidity across sites may be attributed to differences in land use, localized meteorological effects, and sub-catchment hydrology. Turbidity levels observed in 2023 were generally consistent with those of previous years, indicating the continued high quality of surface waters in the Quabbin Reservoir and Ware River Watersheds.

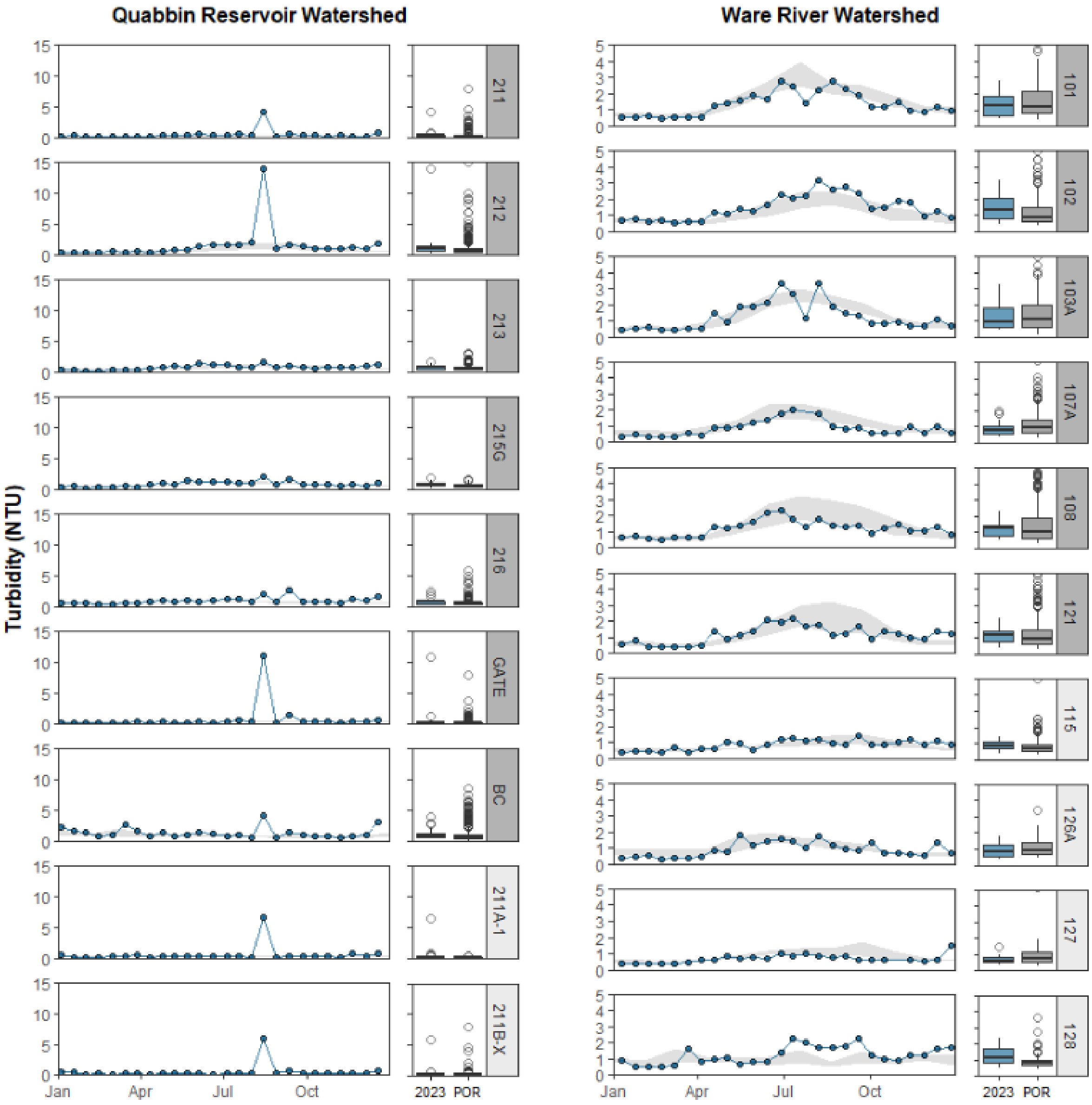


Figure 17: Time series and boxplots of 2023 turbidity results (blue) from tributary monitoring sites compared against each site’s period of record (gray).

Table 17: Seasonal statistics for turbidity measured in the Quabbin Reservoir Watershed tributary sites.

		Turbidity (NTU)									
		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	254	0.17	0.16	0.28	0.28	0.38	0.31	0.95	2.70
	Spring	7	248	0.24	0.15	0.32	0.30	0.34	0.37	0.46	8.00
	Summer	7	254	0.28	0.20	0.52	0.36	1.03	0.47	4.20	4.58
	Fall	6	250	0.31	0.18	0.36	0.30	0.39	0.39	0.57	2.76
212	Winter	6	233	0.34	0.20	0.39	0.45	0.72	0.52	1.90	3.00
	Spring	7	236	0.49	0.20	0.61	0.43	0.67	0.63	0.94	10.00
	Summer	7	243	1.10	0.30	1.70	1.18	3.36	1.46	14.00	15.00
	Fall	6	236	1.00	0.30	1.20	0.78	1.27	1.08	1.70	8.46
213	Winter	6	246	0.29	0.29	0.36	0.49	0.62	0.53	1.30	2.14
	Spring	7	243	0.40	0.30	0.70	0.50	0.66	0.60	1.00	3.00
	Summer	7	250	0.82	0.40	1.30	1.00	1.20	1.06	1.70	3.17
	Fall	6	239	0.71	0.30	0.85	0.73	0.84	0.78	1.00	2.00
215G	Winter	6	22	0.26	0.21	0.49	0.55	0.54	0.57	1.00	0.89
	Spring	7	25	0.33	0.28	0.82	0.50	0.76	0.54	1.50	0.90
	Summer	7	27	0.81	0.56	1.20	1.00	1.23	1.07	2.00	1.70
	Fall	6	25	0.64	0.40	0.76	0.70	0.88	0.70	1.60	1.00
216	Winter	6	250	0.42	0.30	0.53	0.50	0.77	0.56	1.70	2.88
	Spring	7	246	0.43	0.30	0.71	0.52	0.71	0.64	1.00	5.00
	Summer	7	253	0.71	0.30	0.95	0.70	1.09	0.76	2.10	2.24
	Fall	6	248	0.63	0.29	0.78	0.58	1.12	0.65	2.60	5.86
BC	Winter	6	175	0.13	0.08	0.19	0.20	0.28	0.24	0.64	2.00
	Spring	7	179	0.13	0.09	0.18	0.20	0.20	0.29	0.29	8.00
	Summer	7	185	0.16	0.10	0.37	0.21	1.85	0.30	11.00	1.92
	Fall	6	180	0.21	0.08	0.30	0.20	0.48	0.29	1.40	3.80
GATE	Winter	6	175	0.79	0.30	1.45	0.99	1.64	1.28	3.00	6.85
	Spring	7	182	0.78	0.30	0.89	0.77	1.27	1.15	2.70	6.00
	Summer	7	148	0.53	0.23	0.88	0.72	1.31	1.13	4.00	23.00
	Fall	6	140	0.62	0.16	0.69	0.51	0.84	0.99	1.40	6.59
211A-1	Winter	6	15	0.12	0.09	0.20	0.19	0.33	0.19	0.81	0.32
	Spring	7	12	0.12	0.11	0.25	0.21	0.26	0.22	0.47	0.41
	Summer	7	14	0.16	0.14	0.25	0.25	1.14	0.26	6.60	0.43
	Fall	6	12	0.21	0.14	0.27	0.22	0.34	0.28	0.65	0.54
211B-X	Winter	6	112	0.18	0.14	0.36	0.30	0.40	0.31	0.73	2.20
	Spring	7	109	0.16	0.19	0.28	0.30	0.26	0.41	0.35	8.00
	Summer	7	119	0.18	0.10	0.27	0.30	1.08	0.35	6.00	4.70
	Fall	6	113	0.20	0.12	0.27	0.20	0.34	0.26	0.68	0.90

Table 18: Seasonal statistics for turbidity measured in Ware River Watershed tributary sites.

		Turbidity (NTU)									
		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	71	0.51	0.47	0.59	0.75	0.73	0.78	1.20	1.60
	Spring	7	67	0.53	0.40	1.30	0.86	1.12	1.08	1.90	2.71
	Summer	6	69	1.40	1.20	2.35	2.50	2.23	2.65	2.80	5.20
	Fall	7	72	0.91	0.68	1.20	1.50	1.43	1.61	2.30	3.20
102	Winter	6	115	0.64	0.40	0.74	0.64	0.83	0.78	1.30	2.50
	Spring	7	117	0.51	0.40	1.10	0.60	0.97	0.78	1.40	5.00
	Summer	6	118	1.70	0.60	2.25	1.70	2.35	1.86	3.20	4.50
	Fall	7	119	0.98	0.50	1.80	1.20	1.83	1.43	2.80	17.00
103A	Winter	6	91	0.45	0.33	0.59	0.61	0.64	0.69	1.10	2.70
	Spring	7	107	0.48	0.19	0.96	0.74	1.11	0.93	1.90	3.83
	Summer	6	113	1.20	0.83	2.40	2.34	2.42	2.45	3.30	6.63
	Fall	7	119	0.71	0.33	0.85	1.10	0.98	1.30	1.50	5.63
107A	Winter	6	95	0.35	0.39	0.45	0.62	0.53	0.71	1.00	2.54
	Spring	7	108	0.37	0.32	0.88	0.74	0.77	0.93	1.20	8.93
	Summer	5	111	1.00	0.82	1.80	1.70	1.60	1.89	2.00	5.05
	Fall	7	119	0.59	0.42	0.62	0.90	0.73	1.01	0.97	2.89
108	Winter	6	205	0.54	0.30	0.71	0.67	0.78	0.75	1.30	3.10
	Spring	7	212	0.66	0.30	1.20	0.70	1.07	0.93	1.60	2.94
	Summer	6	212	1.30	0.60	1.80	2.20	1.80	2.36	2.30	5.50
	Fall	7	219	0.91	0.30	1.20	1.20	1.22	1.41	1.50	5.40
121	Winter	6	128	0.38	0.30	0.67	0.60	0.79	0.67	1.40	3.00
	Spring	7	130	0.39	0.30	0.91	0.60	0.87	0.71	1.40	2.20
	Summer	6	135	1.10	0.65	1.85	1.80	1.80	2.29	2.20	9.80
	Fall	7	141	0.86	0.30	1.20	1.03	1.18	1.45	1.70	7.65
115	Winter	6	117	0.40	0.30	0.48	0.50	0.62	0.56	1.10	1.20
	Spring	7	116	0.41	0.30	0.66	0.60	0.70	0.63	1.00	5.00
	Summer	6	113	0.89	0.50	1.15	0.90	1.11	1.02	1.30	2.50
	Fall	7	113	0.84	0.40	0.89	0.80	1.00	1.01	1.40	2.50
126A	Winter	6	19	0.32	0.43	0.51	0.75	0.62	0.81	1.30	2.14
	Spring	7	20	0.36	0.44	0.77	0.89	0.84	1.09	1.80	3.38
	Summer	6	20	0.98	0.70	1.40	1.45	1.38	1.45	1.70	2.44
	Fall	7	19	0.57	0.51	0.74	0.73	0.83	0.87	1.30	1.80
127	Winter	6	19	0.35	0.31	0.40	0.55	0.60	0.57	1.50	0.92
	Spring	7	20	0.34	0.31	0.57	0.60	0.61	0.73	0.85	1.32
	Summer	6	20	0.65	0.70	0.82	1.20	0.83	1.39	0.99	5.16
	Fall	6	19	0.50	0.38	0.60	0.92	0.63	1.00	0.88	1.93
128	Winter	6	19	0.48	0.51	0.69	0.87	0.94	0.89	1.70	1.50
	Spring	7	20	0.58	0.70	0.82	0.89	0.94	1.20	1.60	3.60
	Summer	6	20	0.85	0.44	1.70	0.74	1.66	0.81	2.30	1.55
	Fall	7	19	0.95	0.56	1.20	0.84	1.38	0.93	2.30	2.00

3.3.4 Total Coliform and *E. coli* Bacteria

Water quality monitoring of bacteria in the Quabbin Reservoir and Ware River Watershed tributary sites focused on *E. coli* and total coliform bacteria in 2023. 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, and/or rising stream stage or high flow conditions. Follow-up *E. coli* samples were collected from Boat Cove Brook in 2023 (see Section 6.2.1).

3.3.4.1 Total Coliform

Total coliform concentrations observed in tributaries in Quabbin Reservoir and Ware River Watersheds are characterized by distinct seasonality (Figure 18) consistent with stream temperature throughout 2023 (Section 3.3.1.1). Intra-annual variability is high for observed concentrations of this parameter across DWSP monitoring sites. Total coliform in Quabbin Reservoir Watershed monitoring tributaries ranged from 98 to greater than 24,200 MPN/100 mL (Table 19) and from 74 to greater than 24,200 MPN/100 mL in monitoring tributaries in the Ware River Watershed in 2023 (Table 20). Seasonal total coliform concentrations for samples collected in 2023 were generally within or below seasonal normal ranges for the period of record. Annual maximum values above seasonal norms were attributed to samples collected during and following high-streamflow events. Winter mean concentrations were slightly elevated compared to historical means in several Quabbin Reservoir locations. In the Ware River Watershed, summer mean concentrations were elevated compared to historical seasonal averages, particularly at sites 103A, 107A, and 108. Differences in elevated results relative to seasonal patterns across the two watersheds may be attributed to several factors including timing of sample collection relative to rainfall events, variation in streamflow magnitude and timing across watersheds, and differences in hydrological patterns and controls between the two watersheds.

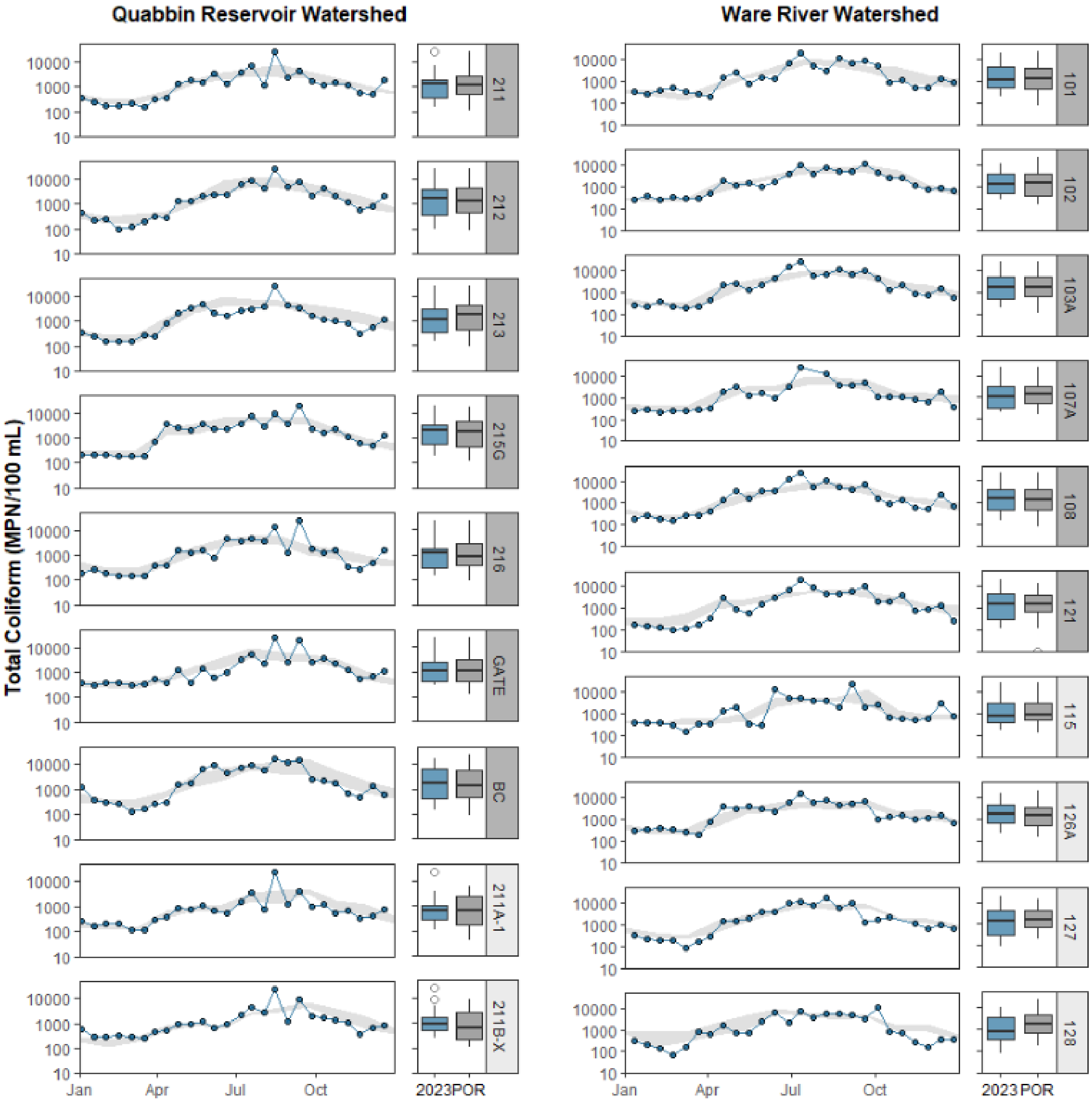


Figure 18: Time series and boxplots of 2023 total coliform results (blue) from tributary monitoring sites compared against each site's period of record (gray).

Table 19: Seasonal statistics for total coliform measured in the Quabbin Reservoir Watershed tributary sites.

		Total Coliform (MPN/100 mL)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	82	175	110	308	430	555	517	1860	2190
	Spring	7	82	161	108	341	673	802	902	1870	3450
	Summer	7	84	1230	1220	3260	3450	6146	5396	24200	24200
	Fall	6	85	556	488	1295	1550	1718	3092	4350	24200
212	Winter	6	81	98	110	333	368	637	507	2050	2850
	Spring	7	83	120	84	305	495	791	913	2050	8660
	Summer	7	86	2250	813	4610	5790	7450	8179	24200	24200
	Fall	6	85	546	393	2120	2250	3008	4439	7700	24200
213	Winter	6	82	160	121	290	343	439	649	1190	6870
	Spring	7	84	158	97	794	760	1650	2072	4610	24200
	Summer	8	86	1720	2140	3475	4880	5755	6671	24200	24200
	Fall	6	85	327	359	1075	1920	1353	3566	3260	24200
215G	Winter	6	22	199	156	213	341	442	345	1320	909
	Spring	7	25	185	122	1960	1420	1908	1660	3870	5480
	Summer	7	27	2220	1860	3650	5480	4491	6032	9140	17300
	Fall	6	25	657	504	1905	1780	4626	2653	19900	11200
216	Winter	6	82	146	86	223	355	484	590	1620	6490
	Spring	7	82	142	95	393	525	776	899	1560	5170
	Summer	7	84	759	1070	3650	3550	4497	5833	13000	24200
	Fall	6	85	285	288	1410	1050	4918	1988	24200	19900
BC	Winter	6	81	301	135	389	345	536	386	1110	1270
	Spring	7	83	298	195	402	609	667	878	1470	7270
	Summer	7	81	631	833	2480	3870	5532	5793	24200	24200
	Fall	6	82	537	355	2495	2190	5103	3721	19900	24200
GATE	Winter	6	81	259	122	509	389	694	681	1330	8660
	Spring	7	84	134	86	285	710	1518	1609	6490	15500
	Summer	7	81	4350	1110	9210	6870	9323	8500	17300	24200
	Fall	6	84	504	228	1930	3170	3862	5809	15500	24200
211A-1	Winter	6	8	173	96	241	141	330	171	728	259
	Spring	7	6	109	41	368	436	517	488	1110	1210
	Summer	7	7	554	1080	1170	2190	4635	2404	24200	4610
	Fall	6	6	336	464	812	3365	1310	3224	4110	6490
211B-X	Winter	6	7	288	109	465	185	501	217	836	402
	Spring	7	6	253	146	557	419	672	483	1170	906
	Summer	7	7	663	448	2280	2600	5236	2355	24200	4610
	Fall	6	6	369	657	1530	5045	2602	4696	9210	8660

Table 20: Seasonal statistics for total coliform measured in Ware River Watershed tributary sites.

		Total Coliform (MPN/100 mL)									
		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	72	279	109	442	392	630	632	1370	3450
	Spring	7	68	195	73	780	847	1055	1118	2720	7700
	Summer	6	69	1300	1330	6175	5790	7972	7148	19900	24200
	Fall	7	74	529	331	1110	2195	3525	3238	9210	24200
102	Winter	6	12	256	145	370	305	469	307	884	556
	Spring	7	13	292	181	959	816	931	1242	1850	4350
	Summer	6	13	1720	2380	4520	4350	5432	4931	9800	10500
	Fall	7	14	759	435	2490	2720	4058	4961	12000	24200
103A	Winter	6	72	226	173	306	428	504	660	1400	6490
	Spring	7	76	199	110	1350	959	1301	1324	2480	5170
	Summer	6	83	4610	1850	9245	6490	11147	8084	24200	24200
	Fall	7	84	708	404	2100	2605	3523	3995	9210	24200
107A	Winter	6	80	213	160	268	488	547	658	1920	4350
	Spring	7	81	233	160	1190	988	1260	1566	3260	9210
	Summer	5	83	959	1170	3870	4350	9058	5840	24200	24200
	Fall	7	84	598	383	1070	1615	1882	3253	4880	24200
108	Winter	6	84	160	75	223	341	643	564	2360	4610
	Spring	7	81	262	121	1420	857	1585	1183	3650	5790
	Summer	6	84	3450	1520	8145	5170	10288	6421	24200	24200
	Fall	7	84	565	504	1370	1815	2397	3330	7270	24200
121	Winter	6	25	109	110	165	384	372	556	1400	2490
	Spring	7	26	121	145	591	1295	987	1749	3260	6130
	Summer	6	26	3130	1580	6075	4880	8075	4965	19900	9800
	Fall	7	27	789	10	2190	1720	3896	2901	11200	14100
115	Winter	6	19	295	122	414	487	867	561	2910	1560
	Spring	7	20	161	265	331	613	670	622	1920	1330
	Summer	6	20	2060	203	4640	4230	5760	4671	14100	10500
	Fall	7	19	488	393	691	1220	4415	3389	24200	24200
126A	Winter	6	19	295	185	368	426	590	481	1560	911
	Spring	7	20	201	135	3080	677	2122	1224	3870	3650
	Summer	6	20	2250	1400	5480	3445	6488	4133	14100	7700
	Fall	7	19	933	798	1270	2990	2513	4152	6490	19900
127	Winter	6	19	187	246	265	583	419	646	933	1050
	Spring	7	20	86	216	1440	1015	1289	1349	3580	6130
	Summer	6	20	3870	2850	8535	5505	9153	6163	17300	14100
	Fall	6	19	609	1120	1410	2060	2627	3598	9210	11200
128	Winter	6	19	74	166	273	723	245	749	369	1550
	Spring	7	20	171	256	733	885	1039	2357	2610	9210
	Summer	6	20	2190	1970	5480	5170	5060	6255	7270	24200
	Fall	7	19	161	504	794	1780	2877	2417	10500	7270

3.3.4.2 E. coli

E. coli results corresponding to 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 greater than 24,200 MPN/100 mL in Quabbin Reservoir Watershed tributaries (Table 21) and from less than 10 to 521 MPN/100 mL in the Ware River Watershed tributaries in 2023 (Table 22). The maximum *E. coli* result observed in 2023 occurred during the active August 15, 2023, high intensity rainfall coincident with sample collection at site 213 (Middle Branch Swift River) in the Quabbin Reservoir Watershed. The 213 sampling location is directly downstream of a wetland complex on the Middle Branch Swift (see Table 4) with field observations of wildlife presence in the region. A follow up sample on August 22, 2023 (result of 52 MPN/100 mL) as well as subsequent routine sampling on August 29, 2023 (result of 41 MPN/100 mL), suggest this was a discrete occurrence in time and not indicative of persistent water quality issues in the upstream catchment (Figure 19).

Of the 495 samples collected from tributaries and analyzed for *E. coli* in 2023, approximately 36% (n = 177) were below detection limits (<10 MPN/100 mL). Twenty-six samples exceeded the Class A Standard for single samples (*E. coli* >235 MPN/100 mL) from tributary sites in the Quabbin Reservoir and Ware River Watersheds in 2023 (5% of samples). These occurrences were associated with high streamflow events in the summer and early fall of 2023, with nine results from the August 15, 2023 storm event (see Figure 19). In most cases, no potential sources of pollution were observed during sample collection, and *E. coli* concentrations decreased in subsequent samples. At Boat Cove Brook, follow-up investigations revealed that high *E. coli* results often followed precipitation events and returned to historical normal ranges during relatively dry periods (see Section 6.2.1). Across all sites, annual median 2023 results were within normal historical ranges (Figure 19). Thus *E. coli* concentrations in Core tributaries in 2023 continued to demonstrate a high sanitary quality.

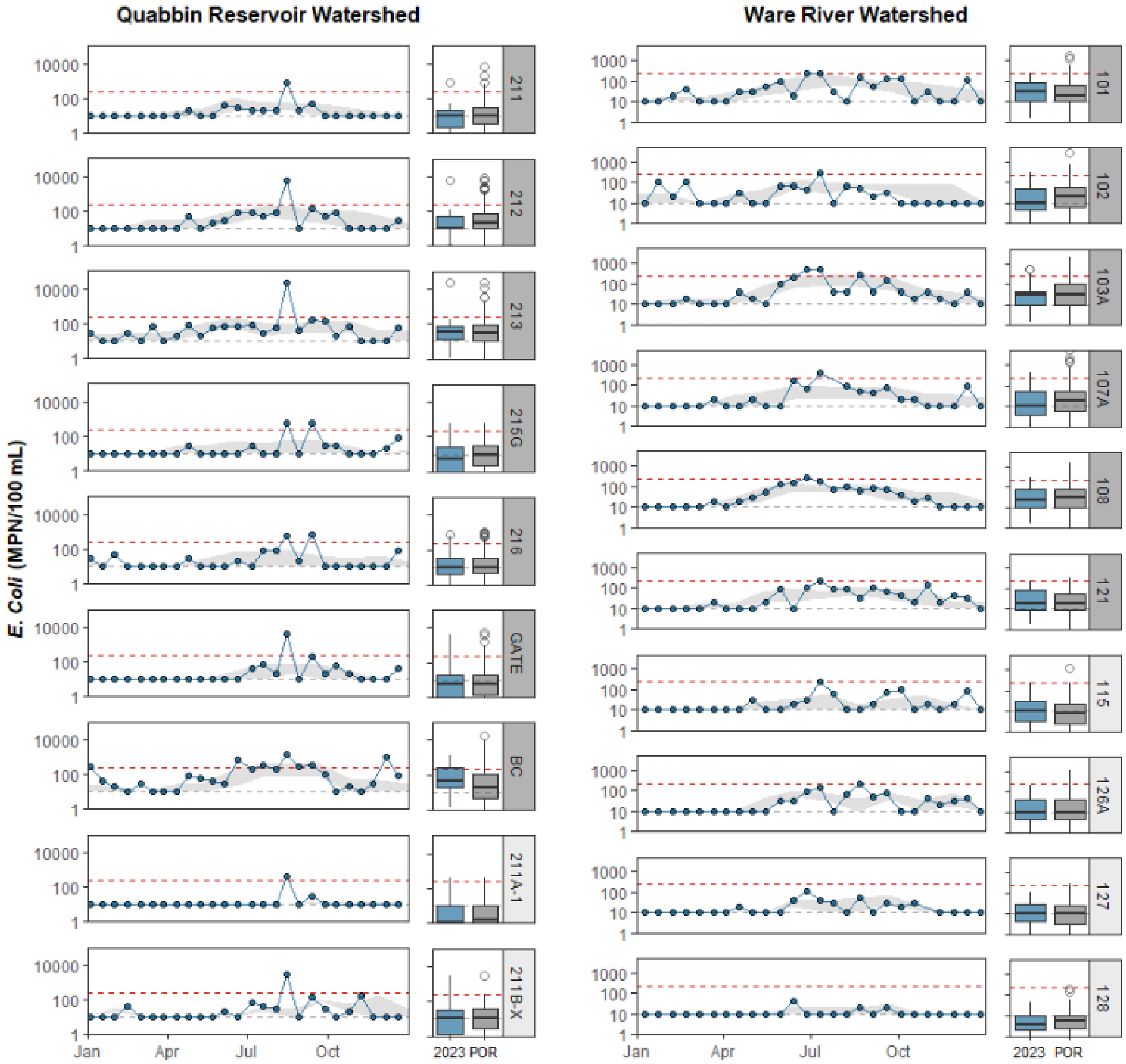


Figure 19: Time series and boxplots of 2023 *E. coli* results (blue) from tributary monitoring sites compared against each site's period of record (gray). The horizontal dashed grey and red lines correspond to laboratory detection limits (10 MPN/100 mL) and the MassDEP Class A single sample maximum standard of 235 MPN/100 mL.

Table 21: Seasonal statistics for *E. coli* measured in the Quabbin Reservoir Watershed tributary sites.

		***E. coli* (MPN/100 mL)**									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	113	10	10	10	10	10	13	10	63
	Spring	7	106	10	10	10	10	11	22	20	156
	Summer	7	112	20	10	20	31	145	177	865	6870
	Fall	6	111	10	10	10	20	17	44	52	644
212	Winter	6	111	10	10	10	10	14	19	31	189
	Spring	7	107	10	10	10	10	17	38	52	481
	Summer	7	114	10	10	86	75	833	356	5480	7700
	Fall	6	111	10	10	31	41	50	122	132	2360
213	Winter	6	113	10	10	20	10	26	32	63	327
	Spring	7	108	10	10	20	31	40	52	85	426
	Summer	8	115	31	10	69	63	3078	337	24200	12000
	Fall	6	111	10	10	47	41	70	157	173	3260
215G	Winter	6	22	10	10	10	10	24	12	84	41
	Spring	7	25	10	10	10	10	13	18	31	63
	Summer	7	27	10	10	10	31	93	62	573	448
	Fall	6	25	10	10	20	10	106	26	546	158
216	Winter	6	113	10	10	21	10	33	21	86	292
	Spring	7	106	10	10	10	10	13	20	31	187
	Summer	7	112	10	10	20	36	120	95	609	1010
	Fall	6	110	10	10	10	20	130	38	727	487
BC	Winter	6	110	10	10	10	10	15	16	41	249
	Spring	7	107	10	10	10	10	10	25	10	529
	Summer	7	108	10	10	20	31	545	77	3650	1660
	Fall	6	108	10	10	20	10	54	126	201	5170
GATE	Winter	6	111	10	10	64	10	240	25	990	189
	Spring	7	108	10	10	30	10	36	45	85	697
	Summer	7	108	31	10	292	135	452	835	1450	19900
	Fall	6	102	10	10	26	52	90	270	373	3870
211A-1	Winter	6	15	10	10	10	10	10	10	10	10
	Spring	7	12	10	10	10	10	10	10	10	10
	Summer	7	14	10	10	10	10	64	10	389	10
	Fall	6	12	10	10	10	10	14	14	31	31
211B-X	Winter	6	14	10	10	10	10	15	28	41	86
	Spring	7	13	10	10	10	10	10	12	10	20
	Summer	7	14	10	10	31	10	400	17	2610	31
	Fall	6	12	10	10	26	96	63	101	171	253

Table 22: Seasonal statistics for *E. coli* measured in Ware River Watershed tributary sites.

		***E. coli* (MPN/100 mL)**									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	72	10	10	15	10	34	18	110	146
	Spring	7	68	10	10	30	20	34	31	98	228
	Summer	6	69	10	10	87	75	113	135	238	1220
	Fall	7	74	10	10	31	31	51	76	121	1550
102	Winter	6	12	10	10	15	10	43	14	110	41
	Spring	7	13	10	10	10	10	21	40	63	256
	Summer	6	13	10	20	58	63	86	123	288	697
	Fall	7	14	10	10	10	69	14	314	31	2910
103A	Winter	6	91	10	10	10	10	17	17	41	197
	Spring	7	101	10	10	10	20	28	38	98	228
	Summer	6	107	41	30	240	132	260	202	521	1420
	Fall	7	114	10	10	41	41	48	117	161	1940
107A	Winter	6	95	10	10	10	10	23	16	85	96
	Spring	7	104	10	10	10	10	13	29	20	332
	Summer	5	105	52	10	86	52	158	87	414	1400
	Fall	7	114	10	10	20	20	26	153	74	4880
108	Winter	6	110	10	10	10	10	10	15	10	107
	Spring	7	109	10	10	20	10	40	38	135	355
	Summer	6	108	62	10	128	86	143	131	295	1470
	Fall	7	114	10	10	31	41	39	94	85	1400
121	Winter	6	33	10	10	10	10	14	20	31	148
	Spring	7	36	10	10	10	20	24	35	86	238
	Summer	6	38	10	10	86	41	92	74	228	309
	Fall	7	41	20	10	41	20	61	55	145	282
115	Winter	6	19	10	10	10	10	22	10	84	10
	Spring	7	20	10	10	10	10	13	16	30	52
	Summer	6	20	10	10	26	15	63	30	246	131
	Fall	7	19	10	10	20	10	36	81	96	1170
126A	Winter	6	19	10	10	10	10	15	11	41	20
	Spring	7	20	10	10	10	10	13	33	31	313
	Summer	6	20	10	10	81	36	96	56	226	285
	Fall	7	19	10	10	31	31	34	96	75	1100
127	Winter	6	19	10	10	10	10	10	10	10	10
	Spring	7	20	10	10	10	10	11	24	20	269
	Summer	6	20	10	10	41	25	47	33	108	110
	Fall	6	19	10	10	15	20	19	32	31	108
128	Winter	6	19	10	10	10	10	10	12	10	41
	Spring	7	20	10	10	10	10	10	12	10	20
	Summer	6	20	10	10	10	10	17	17	41	41
	Fall	7	19	10	10	10	10	11	31	20	201

The annual geometric mean *E. coli* concentration remained below 126 MPN/100 mL and the Class A standards for all Core monitoring sites in 2023 (Table 23). Annual geometric mean results from 2023 were within established historical ranges (Figure 20). EQA sites across Quabbin Reservoir (211B-X and 211A-1) and Ware River Watershed (115, 126A, 127, 128) all exhibit a decline in annual geometric mean *E. coli* for 2023 results compared to the last year of sampling, indicating a lack of persistent bacterial issues at these sites. 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 and 2023). 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.

Overall, long-term records of annual geometric mean *E. coli* results do not exhibit unidirectional trends in the monitoring sites sampled in 2023. 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, 2023a). However, 2022 brought a period of *E. coli* above the seasonal normal range, attributed to nearby wildlife activity (DWSP 2023a). Work to assess potential bacteria sources near this sample location has further been described in previous reports (DWSP, 2018b). Investigations and follow-up sampling were also taken in 2023 following several persistent high counts during the wet summer and fall seasons (Section 6.2.1). Further assessment of Boat Cove Brook's water quality conditions will be summarized in upcoming EQA reporting for the Quabbin Reservation District, anticipated in 2025.

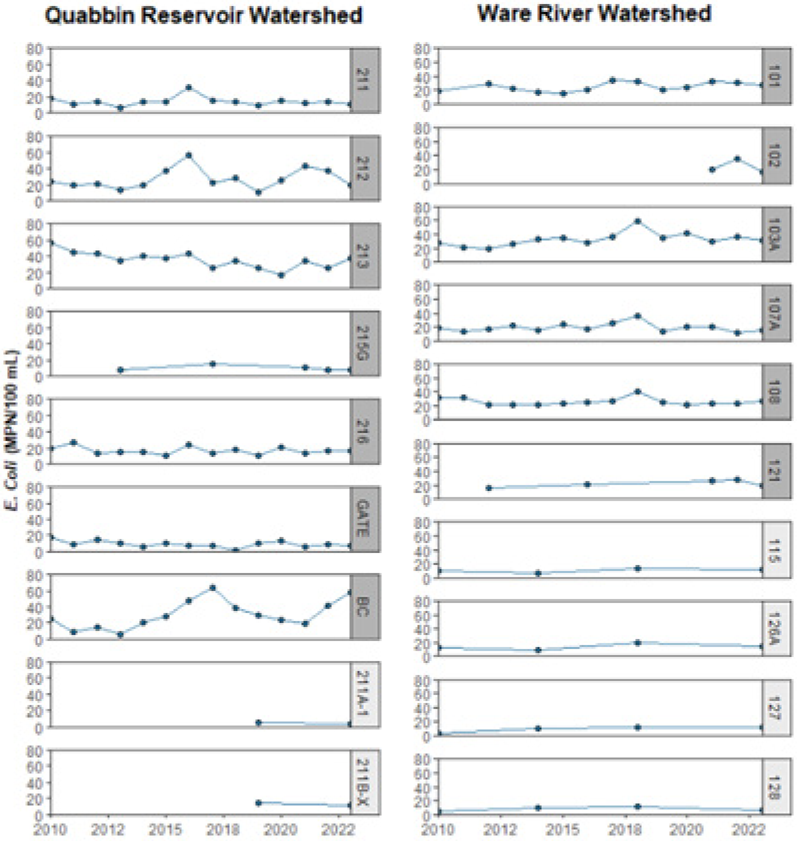


Figure 20: Time series of annual geometric mean *E. coli* in tributary sites from 2010 to 2023.

Table 23: Annual geometric mean *E. coli* for Quabbin Reservoir Watershed tributary sites from period of record.

Annual Geometric Mean *E. coli* (MPN/100 mL)

Site

Year	211	212	213	215G	216	BC	GATE	211A-1	211B-X
2005	10	28	13	-	13	36	10	-	-
2006	7	8	20	-	10	14	6	-	-
2007	15	16	26	-	19	10	10	-	-
2008	6	10	17	-	16	6	5	-	-
2009	12	13	31	-	12	9	8	-	-
2010	18	24	57	-	19	25	18	-	-
2011	11	19	44	-	26	9	9	-	-
2012	13	21	43	-	14	15	15	-	-
2013	6	13	34	8	15	5	10	-	-
2014	14	20	41	-	15	21	6	-	-
2015	13	38	37	-	11	28	11	-	-
2016	32	56	43	-	24	47	8	-	-
2017	15	22	25	15	13	66	8	-	-
2018	13	29	35	-	18	38	2	-	-
2019	9	11	25	-	11	30	10	6	14
2020	15	26	16	-	21	23	13	-	-
2021	12	44	34	11	13	19	6	-	-
2022	14	38	26	7	16	42	9	-	-
2023	10	20	37	8	16	58	8	4	11

Table 24: Annual geometric mean *E. coli* for Ware River Watershed tributary sites from period of record.

Annual Geometric Mean *E. coli* (MPN/100 mL)

Site

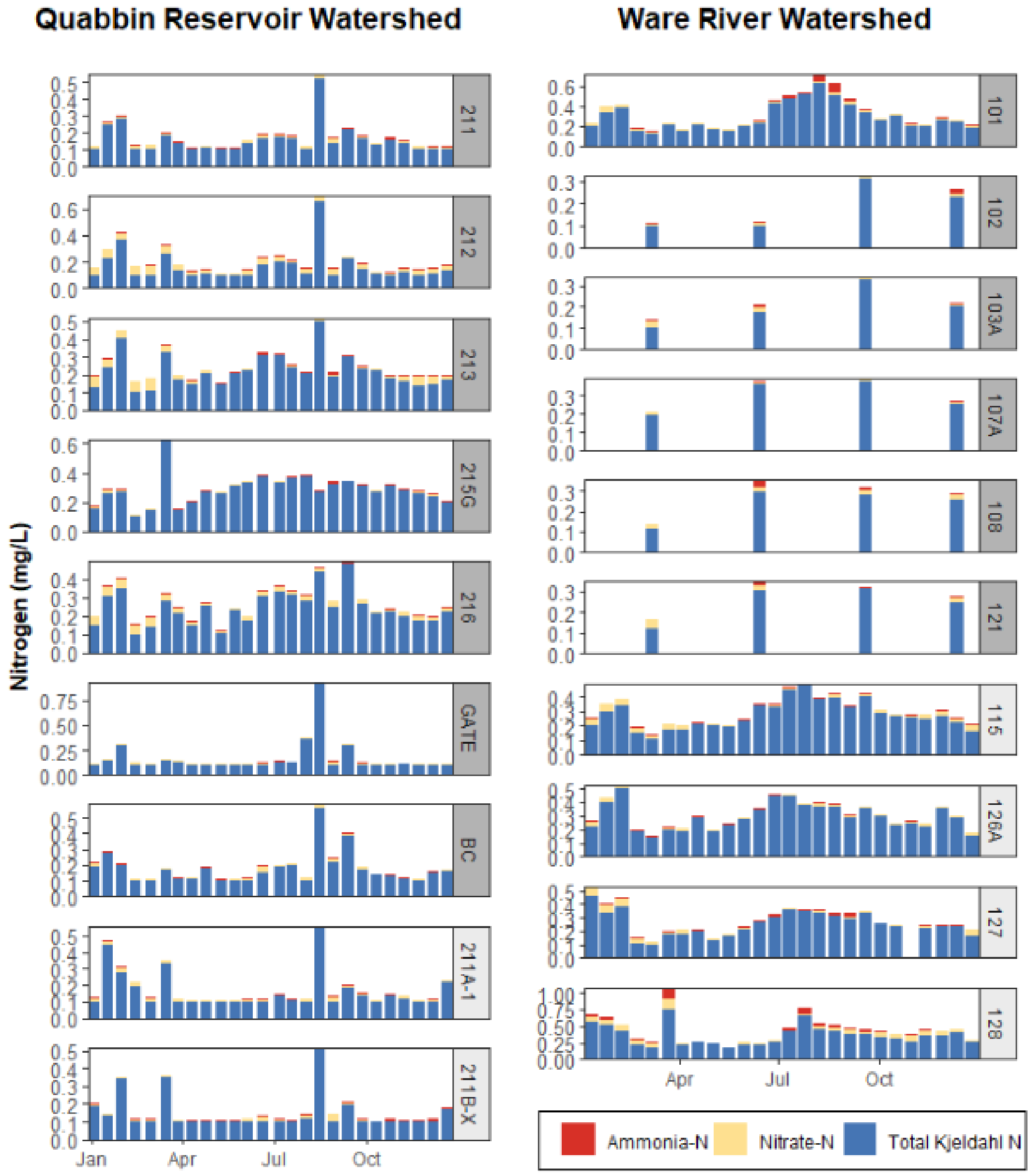
Year	101	102	103A	107A	108	121	115	126A	127	128
2005	-	-	17	10	13	-	-	-	-	-
2006	-	-	29	14	20	-	-	-	-	-
2007	-	-	34	46	22	67	-	-	-	-
2008	-	-	40	40	30	19	-	-	-	-
2009	-	-	21	18	23	-	-	-	-	-
2010	18	-	28	19	31	-	10	12	3	5
2011	-	-	21	14	32	-	-	-	-	-
2012	29	-	20	17	22	15	-	-	-	-
2013	23	-	26	22	21	-	-	-	-	-
2014	17	-	33	16	21	-	6	10	10	14
2015	16	-	35	23	24	-	-	-	-	-
2016	20	-	28	17	25	21	-	-	-	-
2017	34	-	36	26	27	-	-	-	-	-
2018	33	-	59	36	40	-	13	20	13	11
2019	21	-	35	14	25	-	-	-	-	-
2020	24	-	42	21	22	-	-	-	-	-
2021	33	20	29	20	23	26	-	-	-	-
2022	30	36	36	12	23	28	-	-	-	-
2023	27	17	31	16	27	20	11	14	12	7

3.3.5 Nutrients

DWSP monitored concentrations of nitrogen and phosphorus at tributary monitoring locations in the Quabbin Reservoir and Ware River Watersheds. Samples were analyzed for concentrations of nitrogen species (Ammonia-Nitrogen, Nitrate-Nitrogen, and Total Kjeldahl Nitrogen) and Total Phosphorus. Information on changes in analytical methods relative to the interpretation of 2023 results compared to the period of record are detailed in Section 2.2.

3.3.5.1 Total Nitrogen

Organic nitrogen (TKN - NH_3-N) was the most abundant nitrogen form in tributaries in either watershed in 2023 (Figure 21). Dominance of organic nitrogen in headwater streams in the US has been documented previously (Scott et al., 2007). Among stream monitored in Quabbin Reservoir Watershed, organic nitrogen was higher and more consistently high in streams with a higher proportion of upstream wetland area (e.g., 215G, 216, and 213 compared to other sites, see also Table 4). The August rainfall event coincident with sample collection resulted in high organic nitrogen export across sites of the Quabbin Reservoir Watershed. Nitrate (NO_3-N) was elevated during winter months across sites in both watersheds, attributed to atmospheric deposition, snowmelt, and freeze-thaw patterns (Piaktek et al., 2005). Streams of the Ware River Watershed exhibited a clear ramp up of nitrogen export in the late spring and summer months, as well as significant export of nitrogen in the early winter months of 2023 in EQA sites and site 101 (Ware River at Shaft 8 Intake). Seasonal patterns and site-specific variations in contributions of N-species are more limited at numerous Ware River sites due to variations in sampling frequency (quarterly vs. biweekly, Table 5). Further, the majority of historical nutrient sampling at the site 101 was on a quarterly basis, affecting the timescale of comparison and limiting observations of water quality patterns relative to parameters more consistently monitored at finer temporal intervals (e.g., turbidity, bacteria analyses, see Figure 5).


Quabbin Reservoir Watershed

Ware River Watershed

Figure 21: Bar plots depicting the temporal distributions of nitrogen observed in Quabbin Reservoir Watershed tributary sites during 2023.

3.3.5.1.1 Ammonia-Nitrogen

Concentrations of ammonia (NH_3-N) in Quabbin Reservoir and Ware River Watershed tributaries have routinely been below detection limits (48% of samples from tributaries in 2023). Concentrations of NH_3-N in Quabbin Reservoir and Ware River Watershed Core monitoring tributaries ranged from <0.005 to 0.016 mg/L and <0.005 to 0.171 mg/L, respectively, in 2023 (Table 25, Table 26). 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 2023.

Seasonal average concentrations of NH_3-N observed in 2023 varied little from those of the period of record across all Quabbin Reservoir monitoring streams. Streams in the Ware River watershed exhibited greater seasonal variability from historical patterns in NH_3-N concentration relative to the Quabbin Reservoir streams (Figure 22). In particularly, a series of above-normal Ammonia results were observed in the summer at site 101 (Ware River at Shaft 8 Intake), resulting in a summer NH_3-N mean 0.025 mg/L higher than historical summer mean concentrations. These coincided with persistent high streamflow at the USGS gage located at this sampling location (see Figure 10).

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 2023 suggest that the beaver continue to impact N-cycling in the upstream reaches of these particular catchments during 2023.

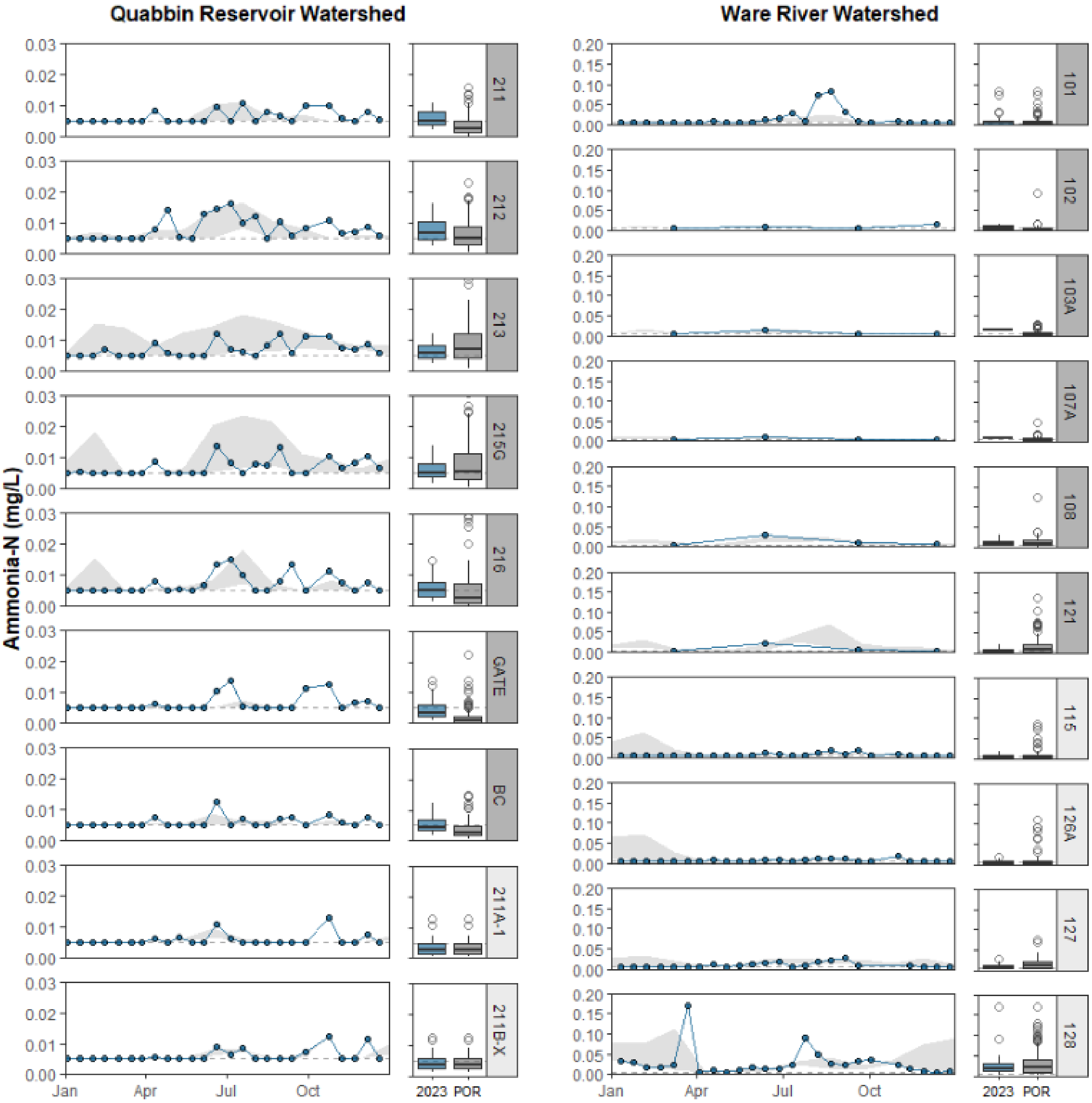


Figure 22: Time series and boxplots of 2023 ammonia results (blue) from tributary monitoring sites compared against each site's period of record (gray).

Table 25: Seasonal statistics for ammonia measured in the Quabbin Reservoir Watershed tributary sites. Detection limits for NH_3-N were <0.005 mg/L.

		Ammonia (mg/L)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	27	0.005	0.005	0.005	0.005	0.006	0.005	0.008	0.006
	Spring	7	27	0.005	0.005	0.005	0.005	0.005	0.005	0.008	0.007
	Summer	7	27	0.005	0.005	0.007	0.005	0.007	0.01	0.011	0.082
	Fall	5	27	0.005	0.005	0.006	0.005	0.007	0.006	0.01	0.01
212	Winter	6	26	0.005	0.005	0.005	0.005	0.006	0.006	0.009	0.016
	Spring	7	27	0.005	0.005	0.005	0.005	0.007	0.008	0.014	0.034
	Summer	7	27	0.005	0.005	0.012	0.008	0.012	0.011	0.016	0.039
	Fall	5	27	0.006	0.005	0.007	0.005	0.008	0.007	0.011	0.038
213	Winter	6	27	0.005	0.005	0.005	0.006	0.006	0.009	0.009	0.033
	Spring	7	27	0.005	0.005	0.005	0.006	0.006	0.016	0.009	0.198
	Summer	7	27	0.005	0.005	0.007	0.013	0.008	0.013	0.012	0.033
	Fall	5	27	0.006	0.005	0.007	0.008	0.009	0.01	0.011	0.02
215G	Winter	6	22	0.005	0.005	0.005	0.005	0.006	0.011	0.011	0.033
	Spring	7	25	0.005	0.005	0.005	0.005	0.006	0.006	0.009	0.023
	Summer	7	27	0.005	0.005	0.008	0.017	0.009	0.019	0.014	0.056
	Fall	5	25	0.005	0.005	0.007	0.005	0.007	0.007	0.01	0.017
216	Winter	6	27	0.005	0.005	0.005	0.005	0.005	0.008	0.007	0.046
	Spring	7	27	0.005	0.005	0.005	0.005	0.005	0.009	0.008	0.054
	Summer	7	27	0.005	0.005	0.008	0.005	0.009	0.011	0.015	0.104
	Fall	5	27	0.005	0.005	0.007	0.005	0.008	0.006	0.013	0.013
BC	Winter	6	27	0.005	0.005	0.005	0.005	0.005	0.005	0.007	0.005
	Spring	7	27	0.005	0.005	0.005	0.005	0.005	0.005	0.006	0.005
	Summer	7	25	0.005	0.005	0.005	0.005	0.007	0.006	0.014	0.022
	Fall	5	27	0.005	0.005	0.006	0.005	0.008	0.005	0.012	0.007
GATE	Winter	6	27	0.005	0.005	0.005	0.005	0.005	0.006	0.007	0.015
	Spring	7	27	0.005	0.005	0.005	0.005	0.005	0.005	0.007	0.007
	Summer	7	22	0.005	0.005	0.005	0.005	0.007	0.007	0.012	0.015
	Fall	5	24	0.005	0.005	0.005	0.005	0.006	0.005	0.008	0.012
211A-1	Winter	6	-	0.005	-	0.005	-	0.005	-	0.007	-
	Spring	7	-	0.005	-	0.005	-	0.005	-	0.006	-
	Summer	7	-	0.005	-	0.005	-	0.006	-	0.011	-
	Fall	5	-	0.005	-	0.005	-	0.007	-	0.013	-
211B-X	Winter	6	-	0.005	-	0.005	-	0.006	-	0.012	-
	Spring	7	-	0.005	-	0.005	-	0.005	-	0.006	-
	Summer	7	-	0.005	-	0.005	-	0.006	-	0.009	-
	Fall	5	-	0.005	-	0.005	-	0.007	-	0.012	-

Table 26: Seasonal statistics for ammonia measured in Ware River Watershed tributary sites. Detection limits for NH_3-N were <0.005 mg/L.

		Ammonia (mg/L)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	27	0.005	0.005	0.005	0.005	0.005	0.008	0.005	0.024
	Spring	7	25	0.005	0.005	0.005	0.005	0.006	0.008	0.008	0.031
	Summer	6	28	0.009	0.005	0.021	0.01	0.037	0.012	0.082	0.043
	Fall	6	28	0.005	0.005	0.008	0.005	0.011	0.008	0.032	0.055
102	Winter	1	12	0.017	0.005	0.017	0.006	0.017	0.007	0.017	0.012
	Spring	1	13	0.005	0.005	0.005	0.005	0.005	0.006	0.005	0.014
	Summer	1	13	0.01	0.005	0.01	0.005	0.01	0.007	0.01	0.016
	Fall	1	14	0.006	0.005	0.006	0.005	0.006	0.012	0.006	0.093
103A	Winter	1	28	0.005	0.005	0.005	0.005	0.005	0.009	0.005	0.027
	Spring	1	24	0.005	0.005	0.005	0.005	0.005	0.008	0.005	0.028
	Summer	1	28	0.015	0.005	0.015	0.007	0.015	0.01	0.015	0.027
	Fall	1	28	0.005	0.005	0.005	0.005	0.005	0.006	0.005	0.012
107A	Winter	1	28	0.005	0.005	0.005	0.006	0.005	0.008	0.005	0.018
	Spring	1	25	0.005	0.005	0.005	0.005	0.005	0.008	0.005	0.046
	Summer	1	28	0.01	0.005	0.01	0.006	0.01	0.008	0.01	0.019
	Fall	1	28	0.005	0.005	0.005	0.005	0.005	0.006	0.005	0.017
108	Winter	1	28	0.007	0.005	0.007	0.008	0.007	0.014	0.007	0.123
	Spring	1	25	0.005	0.005	0.005	0.005	0.005	0.01	0.005	0.039
	Summer	1	28	0.031	0.005	0.031	0.02	0.031	0.019	0.031	0.037
	Fall	1	28	0.012	0.005	0.012	0.007	0.012	0.009	0.012	0.017
121	Winter	1	25	0.005	0.005	0.005	0.011	0.005	0.02	0.005	0.069
	Spring	1	26	0.005	0.005	0.005	0.006	0.005	0.008	0.005	0.02
	Summer	1	26	0.022	0.005	0.022	0.02	0.022	0.032	0.022	0.136
	Fall	1	27	0.006	0.005	0.006	0.006	0.006	0.017	0.006	0.103
115	Winter	6	13	0.005	0.005	0.005	0.01	0.005	0.028	0.005	0.086
	Spring	7	13	0.005	0.005	0.005	0.005	0.005	0.012	0.008	0.072
	Summer	6	13	0.005	0.005	0.011	0.006	0.011	0.007	0.018	0.017
	Fall	6	13	0.005	0.005	0.008	0.006	0.009	0.008	0.018	0.015
126A	Winter	6	13	0.005	0.005	0.005	0.017	0.005	0.039	0.005	0.112
	Spring	7	13	0.005	0.005	0.005	0.005	0.005	0.015	0.008	0.092
	Summer	6	13	0.005	0.005	0.008	0.008	0.009	0.009	0.013	0.016
	Fall	6	13	0.005	0.005	0.006	0.005	0.008	0.006	0.017	0.014
127	Winter	6	13	0.005	0.005	0.005	0.015	0.005	0.022	0.005	0.076
	Spring	7	13	0.005	0.005	0.006	0.005	0.007	0.014	0.012	0.068
	Summer	6	13	0.005	0.01	0.016	0.021	0.014	0.021	0.021	0.041
	Fall	4	13	0.006	0.005	0.009	0.016	0.012	0.016	0.026	0.032
128	Winter	6	13	0.006	0.009	0.018	0.084	0.019	0.069	0.032	0.122
	Spring	7	13	0.005	0.005	0.012	0.005	0.035	0.022	0.171	0.123
	Summer	6	13	0.014	0.005	0.026	0.018	0.037	0.027	0.09	0.117
	Fall	6	13	0.008	0.008	0.024	0.019	0.023	0.037	0.036	0.129

3.3.5.1.2 Nitrate-Nitrogen

Concentrations of nitrate (NO_3-N) ranged from <0.005 to 0.068 mg/L in Quabbin Reservoir Watershed Core sites in 2023 (Table 27). Concentrations of NO_3-N observed in Ware River Watershed during 2023 ranged from <0.005 to 0.153 mg/L (Table 28). Concentrations of NO_3-N observed in tributary monitoring sites in Quabbin Reservoir and Ware River Watersheds during 2023 were largely within or below historical seasonal ranges (Figure 23). Seasonal average (mean and median) nitrate concentrations were lower in 2023 compared to the period of record at a majority of sites for a majority of seasons. Overall streams exhibited very minimal variability in nitrate concentration in 2023. 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 2023 and within local ecoregional background levels (0.16 - 0.31 mg/L) throughout 2023.

Comparison of variations in seasonal patterns across sites as well as differences between 2023 results and normal ranges from the period of record reveal insights into nitrate-transport during high stream flow seasons (Figure 23). Historically, a number of sites exhibited distinct increase in NO_3-N during the first half of 2023 (e.g., 213, 216, 101, 103A, 121) 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. Other sites (e.g., 211, GATE, BC, 211A-1, 211B-X, 102, 107A) exhibit elevated seasonal patterns of nitrate concentrations during low summer flows and relative depletion during spring and fall months. These variable patterns indicate key differences in controls on biogeochemical N-cycling that could include variations in land cover, hydrological differences in groundwater recharge, and soil characteristics. The concentrations below seasonal normal ranges at many sites in summer months coincident to high streamflow conditions lends evidence to the hypothesis that variations in hydrology is likely a major control on nitrate-loading, particularly in the summer months.

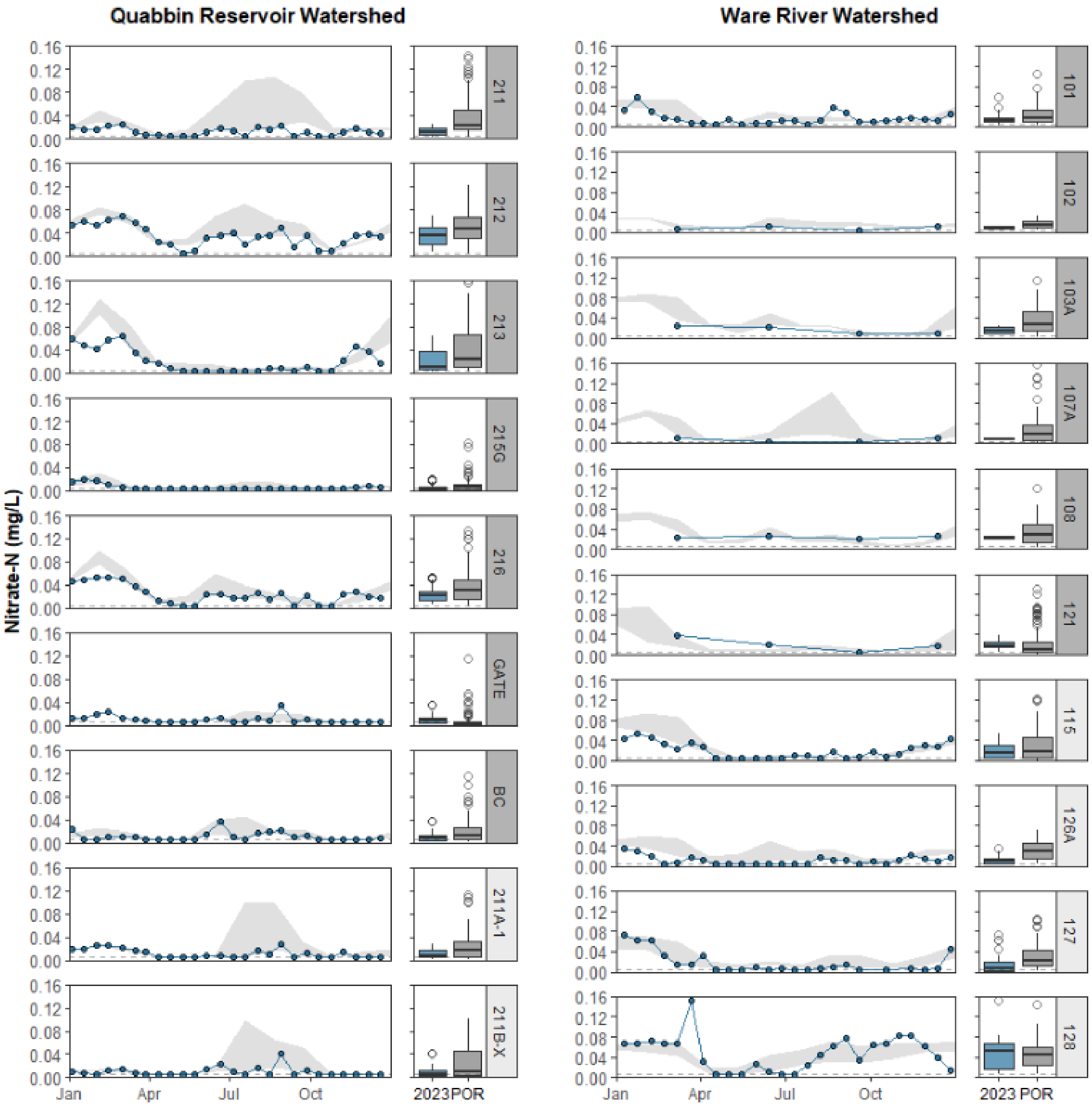


Figure 23: Time series and boxplots of 2023 NO_3-N results (blue) from tributary monitoring sites compared against each site's period of record (gray). The horizontal dashed grey lines correspond to laboratory detection limits (0.005 mg/L).

Table 27: Seasonal statistics for nitrate measured in the Quabbin Reservoir Watershed tributary sites. Detection limits for NO_3-N were <0.005 mg/L.

						Nitrate (mg/L)					
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	32	0.008	0.008	0.015	0.02	0.015	0.023	0.022	0.052
	Spring	7	35	0.005	0.005	0.006	0.019	0.009	0.022	0.025	0.071
	Summer	7	38	0.005	0.005	0.016	0.048	0.015	0.058	0.023	0.143
	Fall	6	37	0.005	0.008	0.008	0.026	0.009	0.044	0.018	0.139
212	Winter	6	31	0.034	0.033	0.054	0.056	0.05	0.059	0.064	0.088
	Spring	7	35	0.005	0.02	0.025	0.046	0.033	0.052	0.068	0.122
	Summer	7	37	0.019	0.008	0.036	0.058	0.035	0.059	0.049	0.116
	Fall	6	37	0.009	0.005	0.019	0.032	0.021	0.033	0.036	0.078
213	Winter	6	32	0.018	0.031	0.045	0.075	0.044	0.086	0.059	0.157
	Spring	7	35	0.005	0.005	0.018	0.042	0.023	0.057	0.066	0.186
	Summer	7	37	0.005	0.005	0.005	0.008	0.006	0.013	0.009	0.044
	Fall	6	37	0.005	0.005	0.008	0.012	0.016	0.018	0.046	0.058
215G	Winter	6	22	0.005	0.005	0.012	0.012	0.012	0.014	0.019	0.043
	Spring	7	25	0.005	0.005	0.005	0.005	0.005	0.007	0.007	0.021
	Summer	7	27	0.005	0.005	0.005	0.007	0.005	0.016	0.005	0.082
	Fall	6	25	0.005	0.005	0.005	0.005	0.005	0.006	0.007	0.018
216	Winter	6	32	0.017	0.017	0.047	0.046	0.039	0.054	0.053	0.119
	Spring	7	35	0.005	0.008	0.014	0.034	0.021	0.044	0.051	0.133
	Summer	7	37	0.016	0.007	0.024	0.033	0.022	0.036	0.026	0.096
	Fall	6	36	0.005	0.005	0.013	0.009	0.015	0.012	0.028	0.030
BC	Winter	6	32	0.005	0.005	0.013	0.005	0.013	0.006	0.024	0.011
	Spring	7	35	0.005	0.005	0.005	0.005	0.008	0.005	0.014	0.006
	Summer	7	34	0.005	0.005	0.011	0.005	0.013	0.015	0.034	0.115
	Fall	6	35	0.005	0.005	0.005	0.005	0.006	0.012	0.01	0.055
GATE	Winter	6	32	0.005	0.005	0.007	0.013	0.009	0.02	0.023	0.099
	Spring	7	35	0.005	0.005	0.006	0.009	0.007	0.013	0.009	0.043
	Summer	7	29	0.005	0.005	0.017	0.028	0.018	0.031	0.036	0.072
	Fall	6	30	0.005	0.005	0.005	0.006	0.007	0.018	0.013	0.114
211A-1	Winter	6	15	0.005	0.005	0.019	0.020	0.017	0.017	0.026	0.026
	Spring	7	12	0.005	0.005	0.005	0.007	0.01	0.013	0.021	0.037
	Summer	7	14	0.005	0.005	0.008	0.099	0.012	0.070	0.029	0.113
	Fall	6	12	0.005	0.005	0.006	0.011	0.008	0.020	0.015	0.070
211B-X	Winter	6	14	0.005	0.005	0.006	0.013	0.007	0.011	0.013	0.017
	Spring	7	12	0.005	0.005	0.005	0.005	0.007	0.010	0.014	0.030
	Summer	7	14	0.005	0.005	0.015	0.066	0.017	0.062	0.041	0.102
	Fall	6	12	0.005	0.005	0.005	0.008	0.006	0.023	0.012	0.060

Table 28: Seasonal statistics for nitrate measured in Ware River Watershed tributary sites. Detection limits for NO_3-N were <0.005 mg/L.

		Nitrate (mg/L)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	27	0.014	0.012	0.029	0.042	0.030	0.040	0.058	0.068
	Spring	7	25	0.005	0.005	0.007	0.014	0.009	0.025	0.017	0.105
	Summer	6	28	0.006	0.006	0.012	0.021	0.015	0.022	0.039	0.048
	Fall	7	28	0.01	0.005	0.015	0.009	0.016	0.010	0.028	0.028
102	Winter	1	12	0.013	0.013	0.013	0.026	0.013	0.025	0.013	0.031
	Spring	1	13	0.007	0.005	0.007	0.009	0.007	0.012	0.007	0.026
	Summer	1	13	0.011	0.005	0.011	0.018	0.011	0.018	0.011	0.033
	Fall	1	14	0.005	0.005	0.005	0.013	0.005	0.014	0.005	0.021
103A	Winter	1	34	0.01	0.013	0.010	0.066	0.010	0.056	0.01	0.092
	Spring	1	32	0.025	0.005	0.025	0.032	0.025	0.041	0.025	0.115
	Summer	1	37	0.021	0.005	0.021	0.027	0.021	0.033	0.021	0.071
	Fall	1	38	0.009	0.005	0.009	0.008	0.009	0.011	0.009	0.041
107A	Winter	1	34	0.011	0.011	0.011	0.036	0.011	0.038	0.011	0.070
	Spring	1	32	0.011	0.005	0.011	0.016	0.011	0.029	0.011	0.132
	Summer	1	37	0.005	0.005	0.005	0.019	0.005	0.031	0.005	0.158
	Fall	1	38	0.005	0.005	0.005	0.006	0.005	0.013	0.005	0.052
108	Winter	1	34	0.026	0.012	0.026	0.051	0.026	0.049	0.026	0.078
	Spring	1	33	0.023	0.008	0.023	0.029	0.023	0.038	0.023	0.122
	Summer	1	37	0.026	0.005	0.026	0.034	0.026	0.031	0.026	0.082
	Fall	1	38	0.022	0.005	0.022	0.01	0.022	0.012	0.022	0.034
121	Winter	1	32	0.018	0.006	0.018	0.059	0.018	0.055	0.018	0.130
	Spring	1	34	0.04	0.005	0.040	0.010	0.040	0.015	0.040	0.081
	Summer	1	35	0.02	0.005	0.020	0.009	0.020	0.015	0.020	0.092
	Fall	1	40	0.005	0.005	0.005	0.007	0.005	0.016	0.005	0.087
115	Winter	6	19	0.027	0.029	0.044	0.074	0.041	0.069	0.055	0.117
	Spring	7	20	0.005	0.005	0.005	0.023	0.015	0.034	0.035	0.122
	Summer	6	20	0.005	0.005	0.008	0.006	0.009	0.007	0.018	0.016
	Fall	7	19	0.005	0.005	0.012	0.018	0.015	0.016	0.03	0.047
126A	Winter	6	19	0.005	0.026	0.019	0.049	0.019	0.046	0.035	0.066
	Spring	7	20	0.005	0.005	0.005	0.02	0.008	0.026	0.016	0.067
	Summer	6	20	0.005	0.009	0.005	0.031	0.008	0.031	0.018	0.072
	Fall	7	19	0.005	0.005	0.012	0.017	0.011	0.02	0.023	0.051
127	Winter	6	19	0.007	0.021	0.054	0.050	0.047	0.054	0.073	0.103
	Spring	7	20	0.005	0.006	0.010	0.017	0.012	0.024	0.032	0.091
	Summer	6	20	0.005	0.005	0.006	0.018	0.006	0.02	0.009	0.055
	Fall	5	19	0.005	0.005	0.005	0.018	0.007	0.026	0.014	0.101
128	Winter	6	19	0.014	0.024	0.068	0.059	0.055	0.058	0.073	0.092
	Spring	7	20	0.005	0.005	0.028	0.02	0.042	0.029	0.153	0.144
	Summer	6	20	0.005	0.008	0.019	0.038	0.026	0.049	0.064	0.106
	Fall	7	19	0.035	0.014	0.068	0.047	0.068	0.046	0.082	0.074

3.3.5.1.3 Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) concentrations in Quabbin Reservoir Watershed Core tributary sites ranged from 0.1 to 0.916 mg/L in 2023 (Table 29). TKN concentrations in Ware River Watershed Core tributary sites ranged from 0.1 to 0.758 mg/L during 2023 (Table 30). TKN dynamics in Core tributaries in the Quabbin Reservoir and Ware River Watersheds loosely mirrored that of TP and organic content, with relative enrichment during summer (Figure 24). Seasonal averages (median and mean) were within normal ranges in 2023 relative to the period of record across streams in the Quabbin Reservoir watershed. However, summer averages among Quabbin sites were generally lower in 2023 compared to historical averages, although a few high results were observed coincident with high discharge events in August and September 2023. New seasonal maximums were observed at numerous Quabbin Reservoir watershed sites for samples collected during the August 15, 2023 storm event. The increased turbulence and mixing of water during high flow events can resuspend sediment and organic matter from the streambed, releasing stored nutrients like TKN into the water column. In contrast, persistent high flow throughout the summer can lead to more dilution of nutrients in the stream, as the volume of water passing through the system increases and spreads out the existing nutrient load.

Seasonal averages (median and mean) were slightly lower in 2023 compared to the period of record in Ware River Watershed sites, with the exception of winter and summer elevated TKN concentrations at site 101 (Ware River at Shaft 8 Intake). A new summer maximum TKN concentration was observed at 101 in 2023 (0.626 mg/L on August 8, 2023). Persistent elevated summer TKN concentrations at 101 relative to other sites may be attributed to variations in upstream catchment land cover, influences from hydrological regulation in the watershed, and/or differences in stream morphology. Further watershed-wide patterns of organic-N transport are obscured due to the limited temporal coverage at numerous Core water quality sites (quarterly vs. biweekly).

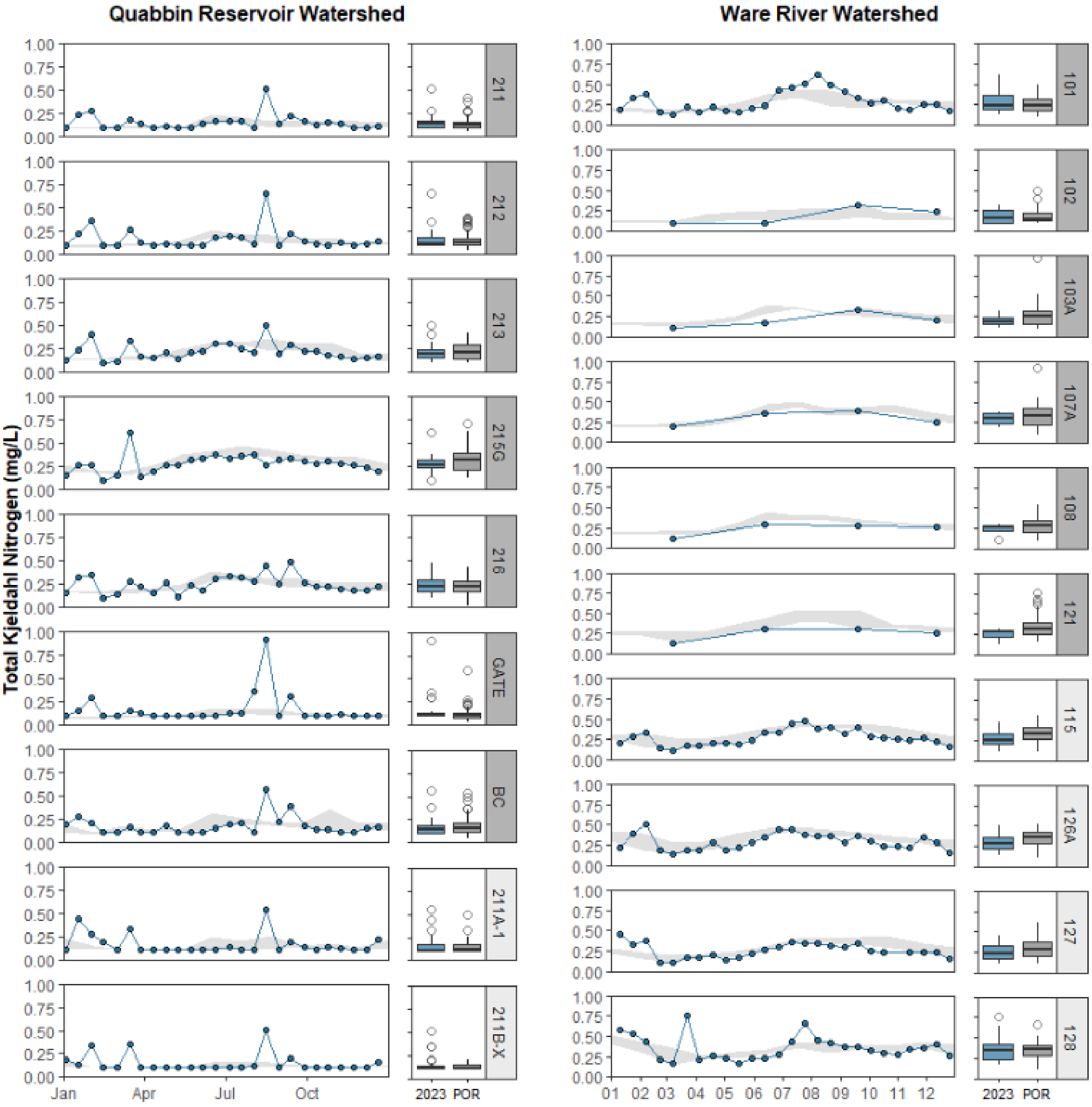


Figure 24: Time series and boxplots of 2023 TKN results (blue) from tributary monitoring sites compared against each site's period of record (gray).

Table 29: Seasonal statistics for Total Kjeldahl Nitrogen measured in the Quabbin Reservoir Watershed tributary sites. Detection limits for TKN were <0.100 mg/L.

Total Kjeldahl Nitrogen (mg/L)

		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	32	0.100	0.060	0.103	0.100	0.155	0.111	0.281	0.214
	Spring	7	35	0.100	0.071	0.100	0.100	0.119	0.105	0.185	0.187
	Summer	7	38	0.100	0.068	0.162	0.158	0.201	0.184	0.520	0.417
	Fall	6	37	0.100	0.086	0.146	0.146	0.151	0.147	0.219	0.213
212	Winter	6	31	0.100	0.057	0.122	0.098	0.172	0.109	0.358	0.339
	Spring	7	35	0.100	0.047	0.100	0.100	0.129	0.121	0.265	0.387
	Summer	7	37	0.100	0.112	0.184	0.193	0.218	0.215	0.653	0.396
	Fall	6	37	0.100	0.073	0.117	0.133	0.132	0.145	0.220	0.257
213	Winter	6	32	0.100	0.100	0.160	0.135	0.198	0.151	0.402	0.266
	Spring	7	35	0.110	0.100	0.170	0.151	0.187	0.165	0.330	0.281
	Summer	7	36	0.190	0.199	0.243	0.303	0.282	0.307	0.504	0.428
	Fall	6	37	0.139	0.133	0.202	0.238	0.205	0.257	0.296	0.426
215G	Winter	6	22	0.100	0.127	0.217	0.219	0.203	0.235	0.267	0.392
	Spring	7	25	0.143	0.135	0.261	0.219	0.277	0.259	0.617	0.566
	Summer	7	27	0.268	0.269	0.336	0.421	0.338	0.416	0.374	0.567
	Fall	6	25	0.262	0.191	0.292	0.340	0.294	0.350	0.338	0.713
216	Winter	6	32	0.100	0.110	0.199	0.176	0.218	0.204	0.348	0.337
	Spring	7	35	0.111	0.100	0.215	0.171	0.199	0.179	0.281	0.311
	Summer	7	36	0.172	0.016	0.305	0.303	0.301	0.305	0.441	0.440
	Fall	6	37	0.173	0.151	0.221	0.257	0.260	0.249	0.480	0.405
BC	Winter	6	32	0.100	0.035	0.100	0.076	0.140	0.088	0.295	0.244
	Spring	7	35	0.100	0.044	0.100	0.076	0.110	0.084	0.146	0.140
	Summer	7	33	0.100	0.063	0.119	0.137	0.260	0.154	0.916	0.592
	Fall	6	36	0.100	0.061	0.100	0.103	0.135	0.110	0.302	0.199
GATE	Winter	6	32	0.100	0.054	0.174	0.128	0.178	0.148	0.275	0.259
	Spring	7	35	0.100	0.066	0.109	0.113	0.123	0.133	0.175	0.242
	Summer	7	29	0.100	0.131	0.187	0.213	0.216	0.243	0.562	0.538
	Fall	6	31	0.105	0.100	0.134	0.176	0.173	0.209	0.383	0.450
211A-1	Winter	6	15	0.100	0.100	0.204	0.100	0.221	0.150	0.441	0.498
	Spring	7	12	0.100	0.100	0.100	0.100	0.133	0.100	0.331	0.101
	Summer	7	13	0.100	0.152	0.100	0.246	0.168	0.228	0.543	0.328
	Fall	6	12	0.100	0.119	0.124	0.140	0.128	0.149	0.186	0.219
211B-X	Winter	6	14	0.100	0.100	0.151	0.100	0.172	0.112	0.342	0.165
	Spring	7	12	0.100	0.100	0.100	0.100	0.135	0.100	0.348	0.102
	Summer	7	13	0.100	0.100	0.100	0.164	0.160	0.161	0.505	0.200
	Fall	6	12	0.100	0.100	0.100	0.100	0.116	0.105	0.199	0.128

Table 30: Seasonal statistics for Total Kjeldahl Nitrogen measured in the Quabbin Reservoir Watershed tributary sites. Detection limits for TKN were <0.100 mg/L.

		Total Kjeldahl Nitrogen (mg/L)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	27	0.154	0.139	0.222	0.210	0.249	0.218	0.378	0.391
	Spring	7	25	0.128	0.100	0.170	0.188	0.180	0.194	0.220	0.337
	Summer	6	28	0.234	0.168	0.483	0.328	0.462	0.326	0.626	0.500
	Fall	7	27	0.195	0.124	0.266	0.281	0.284	0.277	0.408	0.459
102	Winter	1	12	0.232	0.096	0.232	0.127	0.232	0.124	0.232	0.152
	Spring	1	13	0.100	0.092	0.100	0.136	0.100	0.160	0.100	0.307
	Summer	1	13	0.100	0.107	0.100	0.187	0.100	0.211	0.100	0.404
	Fall	1	14	0.314	0.102	0.314	0.181	0.314	0.212	0.314	0.499
103A	Winter	1	34	0.201	0.117	0.201	0.175	0.201	0.192	0.201	0.391
	Spring	1	32	0.106	0.097	0.106	0.170	0.106	0.178	0.106	0.271
	Summer	1	36	0.175	0.246	0.175	0.326	0.175	0.357	0.175	0.971
	Fall	1	37	0.324	0.137	0.324	0.265	0.324	0.288	0.324	0.513
107A	Winter	1	34	0.252	0.122	0.252	0.218	0.252	0.248	0.252	0.526
	Spring	1	32	0.198	0.100	0.198	0.219	0.198	0.237	0.198	0.480
	Summer	1	36	0.366	0.327	0.366	0.426	0.366	0.442	0.366	0.926
	Fall	1	37	0.383	0.185	0.383	0.380	0.383	0.379	0.383	0.511
108	Winter	1	34	0.256	0.101	0.256	0.208	0.256	0.223	0.256	0.381
	Spring	1	33	0.113	0.100	0.113	0.206	0.113	0.215	0.113	0.386
	Summer	1	36	0.296	0.281	0.296	0.383	0.296	0.392	0.296	0.541
	Fall	1	37	0.283	0.182	0.283	0.312	0.283	0.314	0.283	0.478
121	Winter	1	32	0.250	0.179	0.250	0.264	0.250	0.288	0.250	0.644
	Spring	1	34	0.122	0.149	0.122	0.254	0.122	0.258	0.122	0.398
	Summer	1	34	0.305	0.187	0.305	0.416	0.305	0.441	0.305	0.766
	Fall	1	39	0.310	0.263	0.310	0.352	0.310	0.371	0.310	0.591
115	Winter	6	19	0.148	0.100	0.210	0.271	0.226	0.254	0.334	0.368
	Spring	7	20	0.106	0.103	0.194	0.276	0.185	0.244	0.231	0.338
	Summer	6	20	0.332	0.272	0.384	0.405	0.392	0.400	0.475	0.517
	Fall	7	18	0.246	0.100	0.267	0.390	0.292	0.375	0.399	0.556
126A	Winter	6	19	0.155	0.100	0.252	0.317	0.291	0.310	0.504	0.497
	Spring	7	20	0.134	0.101	0.194	0.298	0.213	0.286	0.284	0.522
	Summer	6	20	0.340	0.320	0.374	0.438	0.389	0.432	0.445	0.486
	Fall	7	18	0.218	0.132	0.281	0.347	0.282	0.343	0.358	0.470
127	Winter	6	19	0.113	0.100	0.280	0.217	0.278	0.219	0.457	0.378
	Spring	7	20	0.100	0.100	0.175	0.218	0.166	0.203	0.216	0.307
	Summer	6	20	0.262	0.257	0.324	0.364	0.319	0.372	0.360	0.514
	Fall	6	18	0.227	0.103	0.247	0.388	0.263	0.374	0.338	0.613
128	Winter	6	19	0.216	0.163	0.418	0.396	0.404	0.377	0.575	0.511
	Spring	7	20	0.162	0.100	0.226	0.272	0.288	0.289	0.758	0.670
	Summer	6	20	0.225	0.259	0.426	0.346	0.410	0.350	0.654	0.506
	Fall	7	18	0.272	0.242	0.348	0.388	0.337	0.381	0.379	0.509

3.3.5.2 Total Phosphorus

Total phosphorus (TP) concentrations measured in monitoring tributaries of the Quabbin Reservoir during 2023 ranged from <0.005 to 0.093 mg/L (Table 31). In the Ware River Watershed, TP concentrations were between <0.005 to 0.62 mg/L in 2023 (Table 32). Seasonal median concentrations of TP were comparable to the period of record, with spring mean TP concentrations lower than average in tributaries of the Ware River Watershed. In tributaries in the Quabbin Reservoir Watershed and Ware River Watershed, TP concentrations exhibited distinct seasonality, with generally higher results during the summer and early fall and comparatively lower during the spring and winter (Figure 25). These patterns are consistent with other forested headwater catchments in the NE USA (Lisboa et al., 2020). Elevated total phosphorous coincident with high discharge events from summer thunderstorms (August 16, 2023) and rain-on-snow events (December 19, 2023) resulted in new seasonal maximums in the summer (at 211, 212) and winter (at 212, 213, 216) for certain Quabbin Reservoir Watershed tributaries.

New summer and fall maximum TP concentration were observed at site 101 (Ware River at Shaft 8 Intake) in 2023 (0.059 mg/L on August 8, 2023 and 0.044 on September 5, 2023, respectively). Nutrient sampling at this location was changed from quarterly to every two weeks in 2021. Observation of TP patterns at 101 in 2023 highlighted the degree to which extended wet periods may impact seasonal TP loading at this site, while these dynamics are partially obscured in other Ware River Core sites due to a quarterly sampling interval (Figure 25). Variations in TP concentrations across Quabbin Reservoir and Ware River Watersheds sites 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).

Table 31: Seasonal statistics for total phosphorus measured in the Quabbin Reservoir Watershed tributary sites. Detection limits for TP were 0.005 mg/L.

Total Phosphorus (mg/L)

		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	22	0.005	0.005	0.008	0.01	0.008	0.01	0.014	0.018
	Spring	7	24	0.005	0.005	0.007	0.012	0.007	0.012	0.009	0.024
	Summer	7	24	0.006	0.006	0.013	0.014	0.016	0.015	0.044	0.038
	Fall	6	23	0.005	0.006	0.007	0.01	0.008	0.012	0.016	0.022
212	Winter	6	21	0.005	0.006	0.011	0.011	0.014	0.012	0.028	0.022
	Spring	7	24	0.006	0.005	0.009	0.014	0.009	0.014	0.013	0.023
	Summer	7	24	0.012	0.011	0.019	0.019	0.029	0.022	0.093	0.056
	Fall	6	23	0.007	0.009	0.01	0.014	0.013	0.018	0.025	0.045
213	Winter	6	22	0.005	0.006	0.009	0.012	0.014	0.012	0.032	0.018
	Spring	7	24	0.005	0.005	0.009	0.014	0.01	0.014	0.013	0.025
	Summer	7	24	0.009	0.008	0.02	0.021	0.019	0.022	0.029	0.039
	Fall	6	23	0.008	0.008	0.011	0.016	0.013	0.017	0.022	0.037
215G	Winter	6	21	0.007	0.007	0.01	0.014	0.011	0.014	0.018	0.02
	Spring	7	25	0.007	0.009	0.009	0.013	0.011	0.014	0.018	0.027
	Summer	7	27	0.009	0.011	0.022	0.023	0.02	0.022	0.028	0.032
	Fall	6	25	0.014	0.009	0.015	0.018	0.017	0.017	0.024	0.022
216	Winter	6	22	0.005	0.008	0.01	0.015	0.017	0.014	0.054	0.02
	Spring	7	24	0.008	0.007	0.01	0.016	0.013	0.015	0.021	0.022
	Summer	7	24	0.01	0.009	0.026	0.024	0.023	0.024	0.032	0.045
	Fall	6	23	0.011	0.01	0.015	0.015	0.018	0.017	0.037	0.044
BC	Winter	6	22	0.005	0.005	0.008	0.009	0.008	0.009	0.014	0.017
	Spring	7	24	0.005	0.005	0.007	0.012	0.008	0.011	0.013	0.017
	Summer	7	22	0.005	0.005	0.013	0.014	0.019	0.02	0.077	0.129
	Fall	6	22	0.006	0.005	0.006	0.014	0.01	0.014	0.019	0.025
GATE	Winter	6	22	0.007	0.007	0.014	0.014	0.014	0.016	0.02	0.031
	Spring	7	24	0.007	0.008	0.014	0.019	0.013	0.02	0.018	0.031
	Summer	7	21	0.008	0.010	0.020	0.021	0.021	0.024	0.033	0.061
	Fall	6	22	0.009	0.008	0.013	0.019	0.014	0.02	0.022	0.037
211A-1	Winter	4	8	0.005	0.005	0.007	0.008	0.007	0.008	0.009	0.012
	Spring	2	6	0.005	0.005	0.006	0.008	0.006	0.008	0.006	0.011
	Summer	1	4	0.008	0.009	0.008	0.013	0.008	0.014	0.008	0.021
	Fall	1	6	0.014	0.012	0.014	0.019	0.014	0.018	0.014	0.023
211B-X	Winter	4	7	0.006	0.006	0.009	0.007	0.009	0.007	0.011	0.01
	Spring	2	6	0.005	0.005	0.006	0.009	0.006	0.008	0.007	0.011
	Summer	1	4	0.008	0.008	0.008	0.011	0.008	0.012	0.008	0.017
	Fall	1	6	0.013	0.011	0.013	0.014	0.013	0.014	0.013	0.019

Table 32: Seasonal statistics for total phosphorus measured in Ware River Watershed tributary sites. Detection limits for TP were 0.005 mg/L.

		Total Phosphorus (mg/L)									
		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	21	0.007	0.009	0.011	0.014	0.011	0.015	0.016	0.026
	Spring	7	21	0.007	0.007	0.015	0.014	0.013	0.014	0.020	0.026
	Summer	6	21	0.021	0.018	0.038	0.027	0.038	0.027	0.059	0.043
	Fall	7	21	0.012	0.009	0.016	0.021	0.022	0.022	0.044	0.035
102	Winter	1	12	0.019	0.010	0.019	0.017	0.019	0.017	0.019	0.026
	Spring	1	13	0.011	0.013	0.011	0.019	0.011	0.021	0.011	0.046
	Summer	1	13	0.024	0.022	0.024	0.028	0.024	0.028	0.024	0.038
	Fall	1	14	0.033	0.014	0.033	0.028	0.033	0.033	0.033	0.145
103A	Winter	1	23	0.014	0.008	0.014	0.013	0.014	0.014	0.014	0.029
	Spring	1	22	0.009	0.007	0.009	0.013	0.009	0.014	0.009	0.027
	Summer	1	23	0.023	0.019	0.023	0.027	0.023	0.028	0.023	0.045
	Fall	1	23	0.020	0.011	0.020	0.024	0.020	0.024	0.020	0.040
107A	Winter	1	23	0.014	0.007	0.014	0.013	0.014	0.014	0.014	0.020
	Spring	1	23	0.009	0.009	0.009	0.013	0.009	0.014	0.009	0.025
	Summer	1	23	0.023	0.017	0.023	0.027	0.023	0.027	0.023	0.043
	Fall	1	23	0.025	0.010	0.025	0.021	0.025	0.021	0.025	0.036
108	Winter	1	23	0.015	0.006	0.015	0.012	0.015	0.013	0.015	0.034
	Spring	1	23	0.009	0.008	0.009	0.011	0.009	0.012	0.009	0.024
	Summer	1	23	0.021	0.016	0.021	0.023	0.021	0.024	0.021	0.043
	Fall	1	23	0.017	0.008	0.017	0.020	0.017	0.022	0.017	0.041
121	Winter	1	25	0.014	0.008	0.014	0.013	0.014	0.013	0.014	0.020
	Spring	1	26	0.005	0.006	0.005	0.013	0.005	0.016	0.005	0.036
	Summer	1	26	0.027	0.015	0.027	0.025	0.027	0.028	0.027	0.056
	Fall	1	27	0.016	0.010	0.016	0.017	0.016	0.022	0.016	0.056
115	Winter	6	19	0.008	0.008	0.009	0.016	0.010	0.016	0.013	0.025
	Spring	7	20	0.008	0.011	0.012	0.017	0.012	0.017	0.019	0.026
	Summer	6	20	0.017	0.015	0.022	0.024	0.021	0.024	0.026	0.032
	Fall	7	18	0.012	0.009	0.015	0.020	0.016	0.021	0.021	0.031
126A	Winter	6	19	0.006	0.007	0.010	0.018	0.010	0.017	0.016	0.024
	Spring	7	20	0.008	0.010	0.016	0.019	0.014	0.021	0.018	0.049
	Summer	6	20	0.014	0.021	0.024	0.033	0.022	0.034	0.028	0.046
	Fall	7	18	0.011	0.010	0.013	0.018	0.015	0.019	0.021	0.041
127	Winter	6	19	0.005	0.005	0.009	0.013	0.009	0.013	0.013	0.018
	Spring	7	20	0.005	0.005	0.008	0.013	0.012	0.018	0.034	0.117
	Summer	6	20	0.008	0.006	0.014	0.015	0.014	0.016	0.020	0.027
	Fall	6	18	0.008	0.007	0.010	0.014	0.011	0.015	0.014	0.025
128	Winter	6	19	0.008	0.010	0.012	0.019	0.012	0.019	0.017	0.029
	Spring	7	20	0.009	0.013	0.012	0.019	0.020	0.021	0.062	0.057
	Summer	6	20	0.016	0.017	0.021	0.021	0.022	0.024	0.032	0.042
	Fall	7	18	0.012	0.010	0.017	0.016	0.018	0.016	0.023	0.021

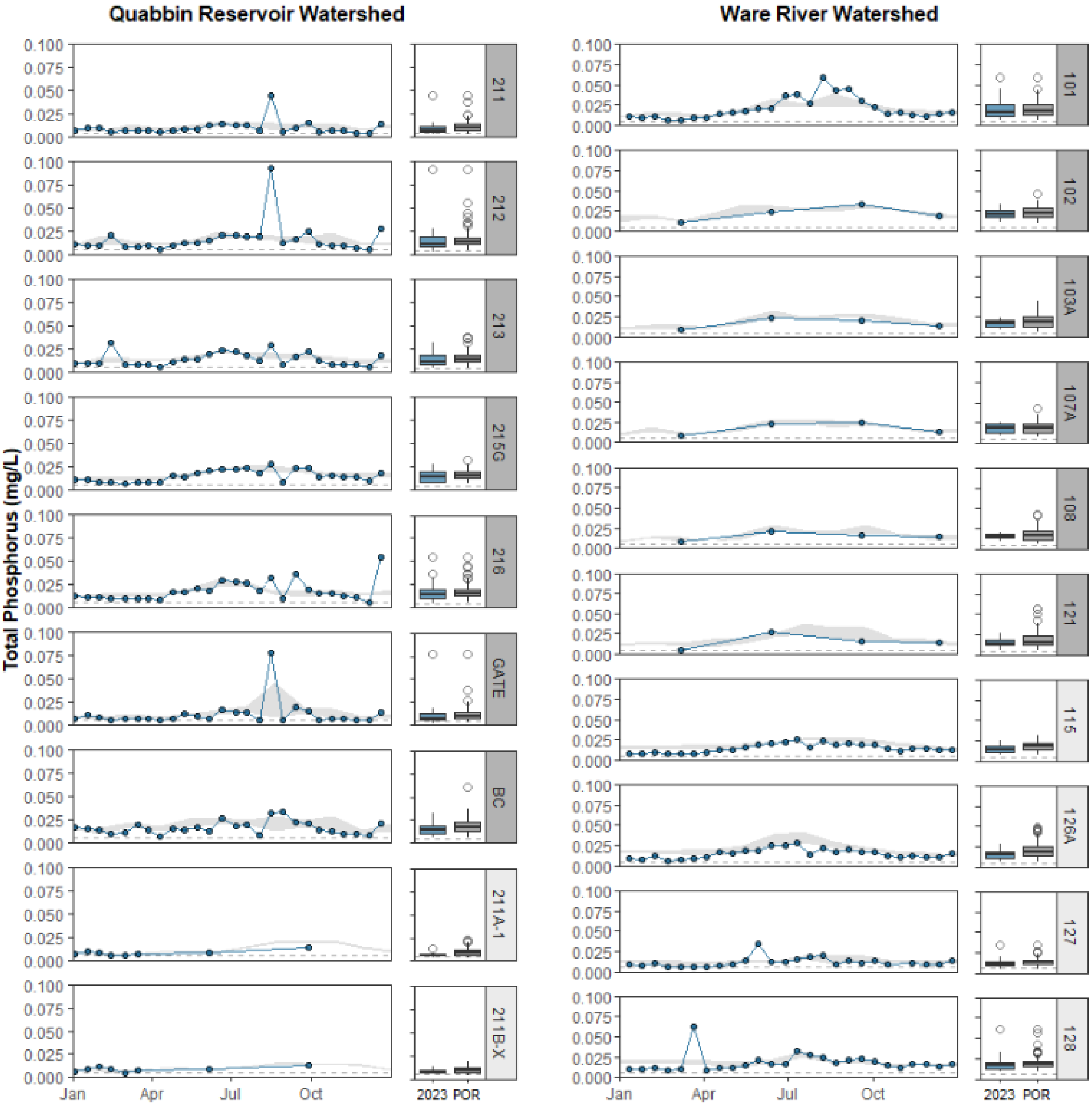


Figure 25: Time series and boxplots of 2023 total phosphorus results (blue) from tributary monitoring sites compared against each site's period of record (gray). The horizontal dashed grey line corresponds to laboratory detection limits (0.005 mg/L).

3.3.6 Total Organic Carbon and UV_{254}

3.3.6.1 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 added to site 101 (Ware River at Shaft 8 Intake) and EQA sites during 2023. Thus annual monitoring continues to inform the full range of variability of concentrations of TOC in time and space throughout the Quabbin Reservoir and Ware River watersheds, with limited insight into long-term patterns from this analyte at this time. However, when considered with historical observations of mean UV_{254}, these analytes provide insight regarding the quantity and type of organic matter, as wells as controls on its transport at the catchment scale (see also section 3.3.6.2). 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.

Concentrations of TOC ranged from 1.58 to 14.3 mg/L in tributaries of the Quabbin Reservoir Watershed and site 101 of the Ware River Watershed in 2023 (Table 33). Average seasonal monitoring results for TOC were generally greater in 2023 compared with the previous two years for Quabbin Core sites (e.g., 211, 212, 213, 215G, 216, GATE, and BC, see Figure 26). Summer and fall seasonal averages were >1 mg/L higher in a number of sites (211, 213, 215G, 216). New seasonal maximum values were established for most seasons at all sites with historical record in 2023, including new summer maximum observations for all sites. The Ware River location (101) had the highest average summer concentrations of all sites and exhibited seasonal ranges more similar to sites in the Quabbin Reservoir with a greater proportion upstream wetland cover relative to other sites (e.g., 215G, 216, see Table 4).

A large proportion of annual TOC export occurs during later summer and fall sampling in the Quabbin Reservoir Watershed, due to seasonal changes in temperature and streamflow (Wen et al., 2020), 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 (Raymond and Saiers, 2010). However, observations from small streams during high-intensity rainfall and rising stream levels showed large pulses of TOC transport, as seen in the elevated TOC concentration at GATE and BC during August and September rainfall events (Figure 26). The result of an August 15 sample at BC was the highest recorded TOC observation at all tributaries monitored for TOC from routine sampling in 2023 (14.3 mg/L). These finding highlight the importance of event-based sampling for understanding the full range of variability of TOC concentrations under different hydrological contexts.

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. This monitoring could leverage insights and additional data resulting from foundational investigations in DBP-precursor potential across the watershed (Garvey and Tobiason, 2003). 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; Gavin et al., 2018).

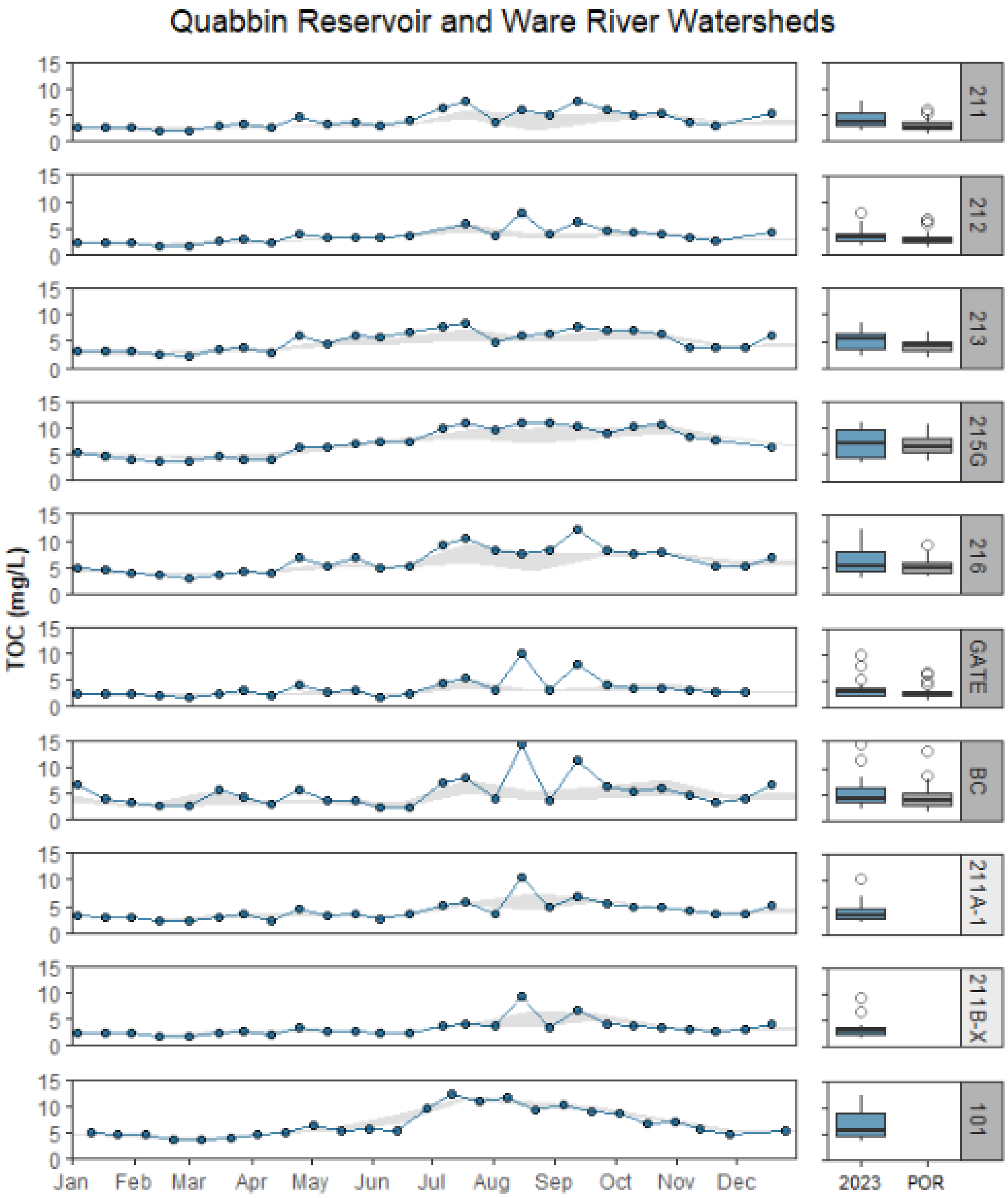


Figure 26: Time series and boxplots of 2023 total organic carbon results (blue) from tributary monitoring sites compared against each site's period of record (gray).

Table 33: Seasonal statistics for total organic carbon measured in the Quabbin Reservoir and Ware River Watershed tributary sites. Detection limits for TOC were 0.3 mg/L.

		Total Organic Carbon (mg/L)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	5	12	2.09	1.79	2.79	2.81	3.14	2.85	5.39	4.30
	Spring	7	14	2.02	2.13	3.37	2.62	3.24	2.76	4.54	3.81
	Summer	7	14	3.19	1.38	5.17	2.97	5.09	3.22	7.74	5.47
	Fall	6	12	3.15	2.70	5.23	3.71	5.16	3.98	7.68	6.15
212	Winter	5	12	1.75	1.32	2.23	2.29	2.54	2.30	4.22	3.19
	Spring	7	14	1.58	1.89	3.01	2.42	2.83	2.53	4.04	3.77
	Summer	6	14	3.25	2.41	3.68	3.38	4.62	3.75	7.90	6.73
	Fall	6	12	2.70	2.54	4.17	3.21	4.14	3.55	6.17	6.45
213	Winter	6	12	2.39	1.96	3.18	3.23	3.60	3.26	5.97	5.17
	Spring	7	14	2.31	2.65	3.96	3.25	4.21	3.54	6.22	5.61
	Summer	7	14	4.88	4.28	6.38	4.82	6.60	5.03	8.36	6.80
	Fall	6	12	3.78	3.49	6.67	4.96	6.01	5.11	7.92	6.96
215G	Winter	5	11	3.78	4.87	4.61	5.69	4.86	5.87	6.41	7.96
	Spring	7	14	3.63	3.74	4.61	4.75	5.14	5.07	6.90	7.76
	Summer	7	13	7.24	6.28	9.90	7.93	9.61	8.06	11.00	10.00
	Fall	6	12	7.50	6.28	9.70	8.40	9.40	8.69	10.70	10.80
216	Winter	6	12	3.44	3.57	4.69	4.65	4.76	4.68	6.77	6.29
	Spring	7	14	2.99	3.46	4.22	4.17	4.88	4.36	7.00	5.90
	Summer	7	14	4.75	3.69	8.07	5.00	7.67	5.52	10.60	9.40
	Fall	5	12	5.05	5.49	8.00	6.96	8.21	6.72	12.20	7.94
BC	Winter	5	12	2.24	1.34	2.42	2.39	2.43	2.30	2.70	2.81
	Spring	7	14	1.91	1.82	2.82	2.32	2.80	2.44	4.07	3.49
	Summer	7	12	1.88	1.77	3.10	2.81	4.32	3.07	9.98	6.55
	Fall	6	12	2.70	2.39	3.52	2.83	4.17	3.25	7.95	6.38
GATE	Winter	6	12	2.69	1.61	4.07	3.53	4.56	3.75	6.56	5.31
	Spring	7	14	2.70	2.55	3.63	3.31	4.04	3.73	5.57	6.25
	Summer	7	11	2.38	2.69	3.97	3.57	5.95	4.30	14.30	7.93
	Fall	6	12	3.23	3.87	5.51	4.41	6.13	5.51	11.40	13.20
211A-1	Winter	6	-	2.26	-	3.04	-	3.32	-	5.17	-
	Spring	7	-	2.18	-	3.28	-	3.18	-	4.56	-
	Summer	7	-	2.61	-	4.72	-	5.16	-	10.50	-
	Fall	6	-	3.40	-	4.96	-	4.99	-	6.97	-
211B-X	Winter	6	-	1.81	-	2.45	-	2.67	-	4.00	-
	Spring	7	-	1.81	-	2.81	-	2.62	-	3.41	-
	Summer	7	-	2.35	-	3.64	-	4.18	-	9.45	-
	Fall	6	-	2.82	-	3.62	-	3.98	-	6.71	-
101	Winter	5	-	3.69	-	4.52	-	4.61	-	5.42	-
	Spring	7	-	3.53	-	4.86	-	4.89	-	6.43	-
	Summer	6	-	5.42	-	10.25	-	9.81	-	12.20	-
	Fall	7	-	4.74	-	7.04	-	7.43	-	10.40	-

3.3.6.2 UV_{254}

UV_{254} absorbance in Quabbin Reservoir Watershed Core tributary monitoring sites ranged from 0.029 to 0.587 ABU/cm in 2023 (Figure 27, Table 34). UV_{254} followed similar seasonal patterns as Total Organic Carbon in 2023, with results generally elevated above seasonal averages in the summer and fall. New maximum UV_{254} readings were recorded during the August 15 rain event and rising streamflow conditions at several sites (GATE, BC, and EQA sites 211A). Variability across sites in the timing of peak UV_{254} results highlights the spatial variability of summer rainfall as well as differences in upstream catchment characteristics (e.g., percent upland wetland cover, stream order, and other factors) across Quabbin sites. Measurements of UV_{254} were also elevated above seasonal normal ranges across sites during the rain-on-snow event of December 19, 2023 (see section 3.2.1), resulting in UV_{254} level more typically seen in the summer or fall months at most Quabbin Reservoir monitoring locations. 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 2023 relative to historical seasonal ranges may be attributed to differences in sample frequencies, with more frequent samples more likely to capture hydrological-driven variability in stream UV_{254} dynamics.

UV_{254} absorbance in Ware River Watershed tributary monitoring sites ranged from 0.084 to 0.985 ABU/cm in 2023 (Table 35, Figure 27). Annual average (mean and median) UV_{254} in Core monitoring tributaries in the Ware River Watershed were slightly elevated in 2023 relative to the period of record. Summer average UV_{254} were particularly elevated in 2023 relative to the period of record at all Ware River sampling locations, coinciding with elevated streamflow conditions and increased biological productivity. Site 107A (West Branch Ware upstream of Barre Falls Dam) experienced particularly elevated UV_{254} results during this time, with a new maximum UV_{254} observation (0.985 ABU/cm) recorded on Jul 11, 2023. During this time extensive flooding was observed at this site due to downstream flow regulation at the Barre Falls Dam. The reduced flow rates and increased floodplain inundated area likely contributed to the persistent elevated UV_{254} observation at this site during July.

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 2023 (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.

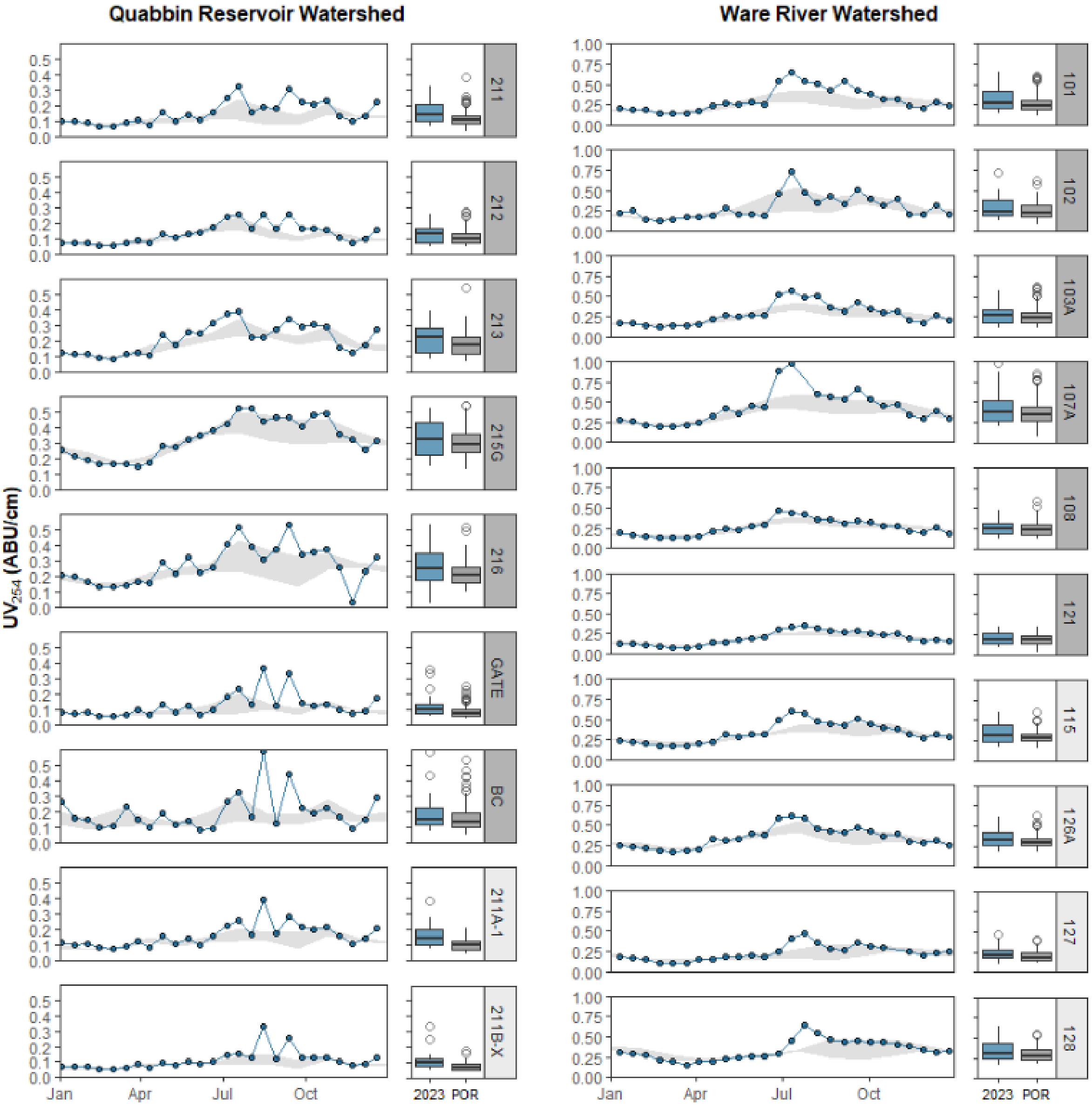


Figure 27: Time series and boxplots of 2023 UV$_{254}$ results (blue) from tributary monitoring sites compared against each site's period of record (gray).

Table 34: Seasonal statistics for UV_{254} measured in the Quabbin Reservoir Watershed tributary sites.

				Mean UV_{254} Absorbance (ABU/cm)							
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	28	0.071	0.066	0.101	0.109	0.121	0.101	0.226	0.159
	Spring	7	31	0.071	0.060	0.099	0.086	0.108	0.093	0.160	0.221
	Summer	7	33	0.109	0.033	0.185	0.120	0.199	0.140	0.329	0.39
	Fall	6	30	0.101	0.041	0.218	0.127	0.202	0.122	0.309	0.231
212	Winter	6	28	0.060	0.049	0.078	0.079	0.091	0.080	0.161	0.142
	Spring	7	31	0.056	0.048	0.090	0.078	0.096	0.084	0.136	0.157
	Summer	7	32	0.139	0.067	0.178	0.154	0.201	0.165	0.257	0.279
	Fall	6	30	0.079	0.052	0.161	0.108	0.156	0.110	0.258	0.223
213	Winter	6	28	0.088	0.072	0.123	0.129	0.15	0.133	0.277	0.227
	Spring	7	31	0.085	0.065	0.128	0.111	0.16	0.129	0.258	0.292
	Summer	7	33	0.225	0.182	0.277	0.236	0.294	0.249	0.392	0.546
	Fall	6	30	0.124	0.135	0.295	0.199	0.254	0.200	0.346	0.327
215G	Winter	6	22	0.170	0.200	0.234	0.277	0.234	0.273	0.314	0.361
	Spring	7	25	0.153	0.132	0.177	0.207	0.221	0.217	0.328	0.342
	Summer	7	27	0.351	0.262	0.441	0.366	0.445	0.388	0.524	0.547
	Fall	6	25	0.323	0.230	0.437	0.316	0.422	0.347	0.489	0.548
216	Winter	6	28	0.134	0.130	0.205	0.22	0.211	0.216	0.322	0.308
	Spring	7	31	0.131	0.108	0.164	0.167	0.202	0.175	0.320	0.264
	Summer	7	33	0.227	0.121	0.376	0.249	0.355	0.267	0.514	0.520
	Fall	6	30	0.029	0.103	0.349	0.258	0.315	0.236	0.537	0.401
BC	Winter	6	28	0.059	0.041	0.079	0.072	0.093	0.072	0.175	0.103
	Spring	7	31	0.058	0.046	0.079	0.066	0.089	0.073	0.134	0.156
	Summer	7	30	0.060	0.055	0.135	0.097	0.171	0.114	0.362	0.254
	Fall	6	29	0.070	0.062	0.127	0.087	0.15	0.096	0.333	0.225
GATE	Winter	6	28	0.097	0.052	0.150	0.155	0.182	0.158	0.290	0.285
	Spring	7	31	0.100	0.08	0.137	0.111	0.146	0.146	0.229	0.358
	Summer	7	27	0.082	0.092	0.162	0.133	0.233	0.182	0.587	0.467
	Fall	6	26	0.090	0.080	0.205	0.152	0.22	0.185	0.437	0.535
211A-1	Winter	6	15	0.081	0.059	0.110	0.067	0.124	0.082	0.207	0.12
	Spring	7	12	0.075	0.044	0.102	0.096	0.108	0.095	0.154	0.151
	Summer	7	14	0.095	0.086	0.174	0.123	0.206	0.13	0.387	0.191
	Fall	6	12	0.106	0.064	0.205	0.136	0.193	0.127	0.282	0.211
211B-X	Winter	6	14	0.058	0.042	0.073	0.048	0.082	0.058	0.131	0.106
	Spring	7	12	0.057	0.043	0.081	0.073	0.079	0.072	0.103	0.101
	Summer	7	14	0.084	0.052	0.127	0.09	0.152	0.092	0.333	0.181
	Fall	6	12	0.077	0.05	0.127	0.087	0.137	0.089	0.254	0.158

Table 35: Seasonal statistics for UV$_{254}$ measured in the Ware River Watershed tributary sites.

		Mean UV$_{254}$ Absorbance (ABU/cm)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	72	0.138	0.119	0.196	0.198	0.207	0.206	0.288	0.398
	Spring	7	69	0.144	0.114	0.244	0.193	0.219	0.207	0.282	0.337
	Summer	6	72	0.252	0.132	0.528	0.316	0.490	0.330	0.651	0.599
	Fall	7	70	0.206	0.128	0.319	0.269	0.348	0.289	0.547	0.613
102	Winter	6	12	0.122	0.151	0.214	0.191	0.212	0.200	0.323	0.288
	Spring	7	13	0.141	0.144	0.192	0.198	0.194	0.209	0.290	0.308
	Summer	6	13	0.185	0.117	0.448	0.283	0.437	0.326	0.726	0.623
	Fall	7	14	0.203	0.087	0.325	0.303	0.338	0.314	0.515	0.471
103A	Winter	6	90	0.116	0.103	0.170	0.180	0.177	0.185	0.267	0.384
	Spring	7	106	0.135	0.103	0.218	0.176	0.204	0.191	0.266	0.622
	Summer	6	114	0.264	0.150	0.501	0.339	0.453	0.344	0.571	0.587
	Fall	7	116	0.172	0.136	0.310	0.266	0.297	0.280	0.422	0.609
107A	Winter	6	94	0.198	0.172	0.270	0.270	0.273	0.276	0.385	0.550
	Spring	7	110	0.202	0.070	0.330	0.273	0.320	0.287	0.455	0.484
	Summer	5	111	0.442	0.155	0.597	0.479	0.696	0.482	0.985	0.864
	Fall	7	115	0.289	0.164	0.464	0.406	0.467	0.418	0.669	0.772
108	Winter	6	109	0.135	0.119	0.174	0.176	0.180	0.185	0.264	0.312
	Spring	7	115	0.130	0.116	0.212	0.173	0.195	0.185	0.272	0.324
	Summer	6	113	0.286	0.204	0.388	0.330	0.386	0.332	0.466	0.579
	Fall	7	115	0.200	0.189	0.277	0.263	0.278	0.278	0.344	0.481
121	Winter	6	32	0.090	0.091	0.125	0.147	0.134	0.145	0.185	0.191
	Spring	7	35	0.084	0.029	0.152	0.123	0.136	0.136	0.194	0.257
	Summer	6	36	0.212	0.180	0.308	0.237	0.302	0.242	0.352	0.338
	Fall	7	40	0.165	0.139	0.253	0.212	0.239	0.213	0.284	0.312
115	Winter	6	19	0.176	0.152	0.236	0.257	0.244	0.258	0.318	0.302
	Spring	7	20	0.173	0.171	0.230	0.221	0.242	0.227	0.315	0.309
	Summer	6	20	0.321	0.279	0.488	0.342	0.486	0.359	0.600	0.605
	Fall	7	18	0.268	0.262	0.396	0.320	0.394	0.353	0.516	0.497
126A	Winter	6	19	0.188	0.200	0.244	0.279	0.245	0.271	0.324	0.304
	Spring	7	20	0.179	0.176	0.321	0.238	0.281	0.253	0.398	0.419
	Summer	6	20	0.372	0.276	0.524	0.401	0.509	0.402	0.617	0.634
	Fall	7	18	0.276	0.246	0.393	0.334	0.379	0.338	0.478	0.506
127	Winter	6	19	0.099	0.139	0.181	0.197	0.181	0.196	0.242	0.263
	Spring	7	20	0.098	0.124	0.145	0.150	0.150	0.155	0.196	0.240
	Summer	6	20	0.179	0.121	0.318	0.181	0.325	0.202	0.469	0.399
	Fall	6	18	0.209	0.126	0.277	0.261	0.280	0.253	0.360	0.386
128	Winter	6	17	0.210	0.276	0.303	0.351	0.288	0.346	0.325	0.424
	Spring	7	20	0.158	0.187	0.203	0.229	0.213	0.241	0.264	0.357
	Summer	6	20	0.256	0.221	0.467	0.285	0.445	0.300	0.642	0.501
	Fall	7	18	0.341	0.201	0.432	0.287	0.415	0.339	0.451	0.552

3.3.7 Alkalinity and pH

3.3.7.1 Alkalinity

Alkalinity analyses were performed quarterly during 2023. Alkalinity results among streams in the Quabbin Reservoir Watershed ranged from 0.87 to 27.00 mg/L in 2023 (Table 36). Quarterly results were within historical seasonal ranges for all sites in Quabbin. Alkalinity observations were lower relative to the seasonal averages from the period of record at several sites in the summer (BC, 211A-1, 211B-X) and fall (213, 211). Alkalinity results among streams in the Ware River Watershed ranged from 0.05 to 20.50 mg/L in 2023 (Table 37). Results were largely within historical seasonal ranges in the Ware River Watershed, with one exception being a new seasonal maximum observed at site 103A during spring of 2023. Quarterly observations were slightly below seasonal historical averages, particularly at site 121 (Mill River) in the Ware River Watershed. Maximum annual alkalinity for each site was typically recorded in samples collected during the summer (July) or fall (September). Temporal changes in alkalinity concentrations in surface water may be attributed to a variety of 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). Thus, much of the heterogeneity of alkalinity concentrations observed in tributaries within the Quabbin Reservoir and Ware River Watersheds is likely the result of the interactions of multiple variable forces, rather than readily attributable to a single direct cause.

Table 36: Seasonal statistics for alkalinity measured in the Quabbin Reservoir Watershed tributary sites.

Alkalinity (mg/L)

		2023		***Period of Record***				
Location	**Season**	**Count**	**Result**	**Count**	**Minimum**	**Median**	**Mean**	**Maximum**
211	Winter	-	-	100	1.31	2.61	2.26	2.95
	Spring	1	2.01	106	1.64	2.40	2.23	2.60
	Summer	1	3.86	108	2.85	3.80	4.76	7.03
	Fall	1	2.64	102	3.54	6.17	5.75	7.04
212	Winter	-	-	90	5.22	6.50	6.53	7.68
	Spring	1	4.80	97	4.16	4.94	5.02	6.24
	Summer	1	9.87	101	8.39	9.64	11.14	15.10
	Fall	1	9.17	96	8.70	12.65	12.16	15.60
213	Winter	-	-	100	2.28	5.95	5.26	6.46
	Spring	1	4.96	103	4.32	5.37	5.29	6.44
	Summer	1	12.70	107	6.66	11.40	11.44	17.00
	Fall	1	6.48	99	6.90	12.30	11.73	15.10
215G	Winter	-	-	12	1.65	3.04	2.96	4.02
	Spring	1	1.38	12	1.23	1.81	1.94	3.30
	Summer	1	3.97	15	2.12	4.32	4.17	5.97
	Fall	1	3.25	14	2.26	4.71	4.66	6.39
216	Winter	-	-	96	3.04	4.13	4.07	4.91
	Spring	1	3.39	103	2.52	3.37	3.38	4.69
	Summer	1	6.44	107	3.52	6.00	6.06	7.90
	Fall	1	4.88	101	4.56	8.07	7.31	8.62
BC	Winter	-	-	71	0.05	0.97	0.90	2.19
	Spring	1	0.87	79	0.05	0.62	0.57	1.13
	Summer	1	2.06	78	1.00	2.01	1.77	2.41
	Fall	1	1.86	75	0.76	3.24	2.72	3.67
GATE	Winter	-	-	70	11.80	16.20	16.28	21.10
	Spring	1	10.40	82	10.50	11.80	12.13	14.10
	Summer	1	22.10	49	9.10	25.80	22.97	29.20
	Fall	1	27.00	46	3.86	23.85	23.64	36.40
211A-1	Winter	-	-	15	0.65	1.39	1.42	2.58
	Spring	1	1.50	12	0.85	1.38	1.41	2.00
	Summer	1	3.06	14	2.34	5.35	4.57	6.40
	Fall	1	4.36	12	2.79	5.32	5.23	7.91
211B-X	Winter	-	-	107	0.05	0.89	0.94	2.07
	Spring	1	1.09	102	0.70	0.97	1.09	1.66
	Summer	1	3.43	114	2.42	5.45	4.70	6.52
	Fall	1	1.04	108	2.53	5.31	5.08	7.49

Table 37: Seasonal statistics for alkalinity measured in the Ware River Watershed tributary sites.

Alkalinity (mg/L)

		2023		***Period of Record***				
Location	**Season**	**Count**	**Result**	**Count**	**Minimum**	**Median**	**Mean**	**Maximum**
101	Winter	1	2.15	6	1.39	3.15	3.14	4.45
	Spring	1	3.45	7	2.85	3.35	3.34	4.19
	Summer	1	7.03	7	3.64	7.08	6.77	8.55
	Fall	1	3.98	6	2.41	7.68	6.88	8.95
102	Winter	1	3.47	94	4.55	4.55	4.55	4.55
	Spring	1	4.07	95	3.68	3.82	3.82	3.96
	Summer	1	6.95	101	3.20	5.02	5.02	6.83
	Fall	1	5.24	97	16.30	16.30	16.30	16.30
103A	Winter	1	1.90	6	1.33	2.36	2.91	6.60
	Spring	1	3.24	12	1.53	2.10	2.19	3.10
	Summer	1	6.04	7	2.99	4.80	4.91	6.30
	Fall	1	2.92	6	1.96	7.10	7.25	11.40
107A	Winter	1	1.85	6	1.16	2.08	2.05	2.70
	Spring	1	0.05	11	1.81	2.28	2.45	3.01
	Summer	1	6.03	7	3.06	5.41	5.33	7.10
	Fall	1	3.62	6	1.09	5.68	4.98	6.86
108	Winter	1	2.67	91	2.55	4.03	4.04	5.84
	Spring	1	4.01	100	2.25	3.38	3.45	5.53
	Summer	1	9.73	100	4.06	8.64	8.65	11.50
	Fall	1	5.22	97	3.28	9.65	8.82	14.00
121	Winter	1	9.25	107	9.55	11.20	11.51	15.10
	Spring	1	8.14	109	7.10	9.96	10.37	16.60
	Summer	1	20.50	118	9.83	22.80	23.58	44.60
	Fall	1	15.60	119	7.55	19.40	21.25	37.50
115	Winter	1	2.84	107	1.54	2.59	2.71	4.23
	Spring	1	2.42	106	0.57	2.41	2.57	4.70
	Summer	1	5.22	107	3.81	5.55	5.59	6.79
	Fall	1	4.04	104	1.61	3.29	3.71	6.03
126A	Winter	1	2.10	19	1.96	2.71	3.06	4.61
	Spring	1	2.40	20	0.76	2.42	2.59	4.94
	Summer	1	4.73	20	3.12	4.85	4.65	5.20
	Fall	1	2.91	19	1.50	2.33	2.99	5.60
127	Winter	1	2.41	19	2.96	4.08	4.09	5.76
	Spring	1	3.46	20	0.89	3.00	3.18	6.51
	Summer	1	4.68	20	3.84	5.41	5.43	6.86
	Fall	1	4.46	19	2.64	3.99	4.34	7.48
128	Winter	1	3.55	19	1.96	3.45	3.50	5.74
	Spring	1	3.08	20	0.95	2.04	2.39	6.43
	Summer	1	3.08	20	1.67	2.49	2.43	3.13
	Fall	1	3.64	19	1.90	2.47	2.49	3.08

3.3.7.2 pH

The pH in Core monitoring tributaries ranged from 4.90 to 7.36 in the Quabbin Reservoir watershed in 2023. pH of Core tributaries in the Ware River watershed spanned from a minimum of 5.54 to 6.92 (Table 38, Table 39). Observations of pH fell within historical ranges at all sites with long term monitoring records across both watersheds (see Figure 4, Figure 5). 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 monitoring tributaries of both watershed were within, or fell below, the minimum standards for Class A inland waters as established by MassDEP (6.5 to 8.3) in 2023, consistent with prior observations throughout the period of record (DWSP, 2023a).

The annual precipitation-weighted mean pH of rainfall within the Quabbin Reservoir watershed has increased steadily over the past several decades (Feng et al., 2021). The established pattern of inter-site variability in pH was preserved in the 2023 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 2023 were generally within established seasonal ranges for each site for the period of record.

Table 38: Seasonal statistics for pH measured in the Quabbin Reservoir Watershed tributary sites.

		pH									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
211	Winter	6	254	5.74	4.10	6.00	6.10	6.00	6.07	6.29	7.23
	Spring	7	253	5.82	4.85	6.20	6.02	6.20	6.02	6.51	7.09
	Summer	7	256	5.92	4.40	6.47	6.30	6.39	6.19	6.77	6.93
	Fall	6	250	5.90	4.90	6.13	6.13	6.15	6.11	6.46	6.93
212	Winter	6	235	6.34	4.86	6.45	6.51	6.47	6.47	6.77	7.38
	Spring	7	241	6.40	4.65	6.76	6.58	6.73	6.52	6.95	7.64
	Summer	7	245	6.83	5.10	6.96	6.80	6.95	6.70	7.04	7.43
	Fall	6	235	6.76	5.56	6.81	6.68	6.83	6.62	6.93	7.13
213	Winter	6	246	5.93	5.01	6.11	6.10	6.08	6.11	6.20	7.07
	Spring	7	250	6.10	5.02	6.23	6.20	6.25	6.13	6.40	7.07
	Summer	7	250	5.87	4.95	6.14	6.20	6.10	6.16	6.37	7.20
	Fall	6	240	5.99	5.04	6.05	6.16	6.08	6.11	6.33	6.60
215G	Winter	6	21	5.62	4.80	5.70	5.58	5.73	5.57	5.96	6.58
	Spring	7	25	5.67	4.81	6.03	5.84	5.96	5.68	6.16	6.37
	Summer	7	25	5.71	4.77	5.75	5.48	5.87	5.58	6.14	6.37
	Fall	6	25	5.67	4.73	5.82	5.74	5.85	5.65	6.11	6.05
216	Winter	6	251	6.22	4.77	6.25	6.40	6.34	6.34	6.70	7.17
	Spring	7	252	6.33	5.31	6.70	6.40	6.65	6.35	6.87	7.56
	Summer	7	256	6.67	5.37	6.75	6.70	6.81	6.65	7.05	7.63
	Fall	5	246	6.36	5.53	6.63	6.57	6.60	6.54	6.81	7.13
BC	Winter	6	180	4.90	4.09	5.06	5.66	5.23	5.70	5.84	7.75
	Spring	7	183	5.06	4.32	5.98	5.45	5.82	5.49	6.20	6.62
	Summer	7	185	4.98	4.39	6.01	5.99	5.89	5.93	6.47	7.21
	Fall	6	200	5.68	4.72	5.97	6.17	5.93	6.04	6.20	7.20
GATE	Winter	6	181	6.73	4.23	6.78	6.80	6.86	6.73	7.17	7.71
	Spring	7	189	6.72	5.59	7.22	6.91	7.11	6.86	7.27	7.97
	Summer	7	156	7.08	5.69	7.29	7.11	7.26	7.04	7.36	7.84
	Fall	5	163	7.00	5.15	7.17	6.95	7.14	6.90	7.18	7.50
211A-1	Winter	6	15	5.59	5.42	5.96	6.21	5.93	6.31	6.33	7.11
	Spring	7	12	5.70	5.77	6.17	6.10	6.15	6.14	6.40	6.72
	Summer	7	14	6.15	5.85	6.44	6.44	6.41	6.44	6.60	6.87
	Fall	6	12	6.27	6.12	6.47	6.59	6.44	6.56	6.56	6.85
211B-X	Winter	6	113	5.50	5.20	5.68	5.80	5.73	5.80	6.24	6.90
	Spring	7	109	5.49	5.20	6.05	5.68	6.04	5.73	6.38	6.49
	Summer	7	119	5.90	5.21	6.49	6.40	6.36	6.34	6.70	7.10
	Fall	6	113	5.89	5.20	6.29	6.34	6.25	6.23	6.42	6.80

Table 39: Seasonal statistics for pH measured in the Ware River Watershed tributary sites.

		pH									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
101	Winter	6	212	5.81	5.22	5.98	6.20	6.01	6.22	6.19	7.44
	Spring	7	223	6.08	5.11	6.42	6.20	6.40	6.19	6.66	7.04
	Summer	6	219	6.04	5.03	6.39	6.47	6.38	6.41	6.64	7.21
	Fall	7	218	6.00	4.51	6.36	6.40	6.32	6.34	6.48	7.18
102	Winter	6	115	6.09	5.70	6.26	6.40	6.27	6.37	6.45	6.80
	Spring	7	117	6.39	5.80	6.58	6.40	6.64	6.33	6.86	6.81
	Summer	6	120	6.35	5.80	6.73	6.50	6.70	6.49	6.92	6.90
	Fall	6	119	6.35	5.60	6.51	6.50	6.53	6.47	6.79	6.90
103A	Winter	6	88	5.61	5.16	6.02	6.08	6.00	6.01	6.34	6.81
	Spring	7	108	5.99	4.65	6.25	6.05	6.27	6.02	6.44	7.17
	Summer	6	112	6.01	4.43	6.36	6.13	6.36	6.04	6.86	7.02
	Fall	7	111	5.96	4.56	6.14	6.10	6.15	6.03	6.33	6.90
107A	Winter	6	95	5.60	1.11	5.78	5.80	5.78	5.75	5.90	7.06
	Spring	7	109	6.04	4.48	6.13	6.00	6.25	5.96	6.52	6.91
	Summer	5	114	5.92	4.77	6.19	6.23	6.21	6.13	6.45	6.85
	Fall	7	115	5.76	3.93	6.15	6.06	6.09	6.00	6.31	7.01
108	Winter	6	206	5.92	5.21	6.07	6.10	6.08	6.07	6.29	6.92
	Spring	7	214	6.14	5.04	6.39	6.18	6.39	6.12	6.56	7.13
	Summer	6	215	5.92	5.06	6.25	6.30	6.24	6.24	6.51	7.03
	Fall	7	215	6.17	4.43	6.35	6.20	6.34	6.14	6.43	6.72
121	Winter	6	129	6.19	2.63	6.31	6.40	6.37	6.42	6.62	6.85
	Spring	7	130	6.33	6.02	6.66	6.50	6.60	6.48	6.79	6.88
	Summer	6	138	6.43	6.04	6.57	6.60	6.59	6.63	6.85	7.40
	Fall	7	140	6.52	5.61	6.60	6.50	6.59	6.51	6.67	7.10
115	Winter	6	118	5.59	4.81	5.69	5.80	5.73	5.79	6.00	6.40
	Spring	7	116	5.82	4.90	6.33	5.90	6.24	5.89	6.59	6.73
	Summer	6	114	5.88	4.66	6.28	6.25	6.27	6.18	6.59	7.06
	Fall	7	113	5.95	5.20	6.18	6.10	6.19	6.03	6.57	6.60
126A	Winter	6	19	5.60	4.63	5.76	5.80	5.76	5.69	5.91	6.25
	Spring	7	20	5.54	4.73	6.14	5.56	6.09	5.57	6.40	6.55
	Summer	6	20	5.88	4.60	6.20	5.72	6.15	5.70	6.42	6.90
	Fall	7	19	5.84	5.27	6.02	5.78	6.04	5.84	6.30	6.38
127	Winter	6	19	5.74	4.70	6.07	5.90	6.05	5.81	6.33	6.67
	Spring	7	20	6.29	4.77	6.33	5.51	6.38	5.58	6.55	6.51
	Summer	6	20	6.01	4.54	6.27	5.45	6.25	5.54	6.42	6.68
	Fall	7	19	6.00	5.25	6.21	5.85	6.21	5.88	6.36	6.50
128	Winter	6	19	5.61	4.67	5.68	5.69	5.83	5.65	6.24	6.34
	Spring	6	20	5.70	4.93	6.34	5.58	6.26	5.54	6.49	6.24
	Summer	6	20	6.07	4.67	6.37	5.47	6.33	5.55	6.46	6.53
	Fall	7	19	6.06	5.54	6.29	5.80	6.27	5.84	6.38	6.22

3.3.8 Special Investigations

3.3.8.1 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. The post-treatment period of the long-term forestry monitoring project began with data collected in late 2020 and is ongoing into 2024. Preliminary analyses of calibration period data have been summarized in anticipation of study completion and subsequent compilation of a final report, which will focus on analyzing potential changes between pre-treatment and post-treatment study periods.

3.3.8.2 Environmental Quality Assessments

Surface water samples collected in 2023 throughout the Quabbin Reservation and West Branch Ware sanitary districts ultimately revealed no widespread indicators of impairment/degradation of water quality. Quabbin Reservation district will continue to be evaluated in 2024, with summary reporting in 2025. West Brach Ware district will be reported in 2024. Monitoring of EQA sites in the Ware River Watershed will shift to sites in the East Branch Ware in 2024, with subsequent reporting in 2025.

3.4 Reservoir Monitoring

Water quality of the Quabbin Reservoir in 2023 continued to meet the 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 2023 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, chlorophyll *a*, and phycocyanin) from each site were selected to demonstrate changes in seasonal conditions and show periods of peak primary productivity. 2023 was the third 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 of parameters (dissolved oxygen, chlorophyll *a*, pH, and specific conductance) were calculated for each site to summarize the variation of conditions throughout 2023, relative to prior monitoring years using the EXO2 sonde (2021-2022). While water temperature was calculated to summarize the variation of conditions throughout 2023, relative to historical data (2006 to 2022) due to the documented relationship (near 1:1) between the Eureka Manta and the EXO2 for this parameter.

3.4.1 Surface Water Treatment Rule Compliance Monitoring

Regulatory monitoring results provided from MWRA fulfilled requirements specified for turbidity and fecal coliform under the SWTR in 2023 (Figure 28). Turbidity is monitored via an in-line turbidity meter inside the BWTF. Turbidity in Quabbin Reservoir source water remained below one NTU for the entirety of 2023. Average (mean) and maximum daily turbidity in source water measured at the BWTF ranged between 0.19 and 0.31 NTU and 0.19 and 0.40 NTU, respectively.

Fecal coliform was not detected above 20 CFU/100-mL from MWRA sampling at BWTF in 2023. Mean and median daily fecal coliform counts of Quabbin Reservoir source water in samples collected at BWTF were <1 CFU/100 mL (0.77 and 0 CFU/100 mL, respectively). 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 3 CFU/100 mL in samples collected by DWSP from Quabbin Reservoir in 2023 (n=81). *E. coli* was detected at 10 MPN/100 mL in three samples collected by DWSP in Quabbin Reservoir monitoring locations during 2023 (approximately 4% of samples).

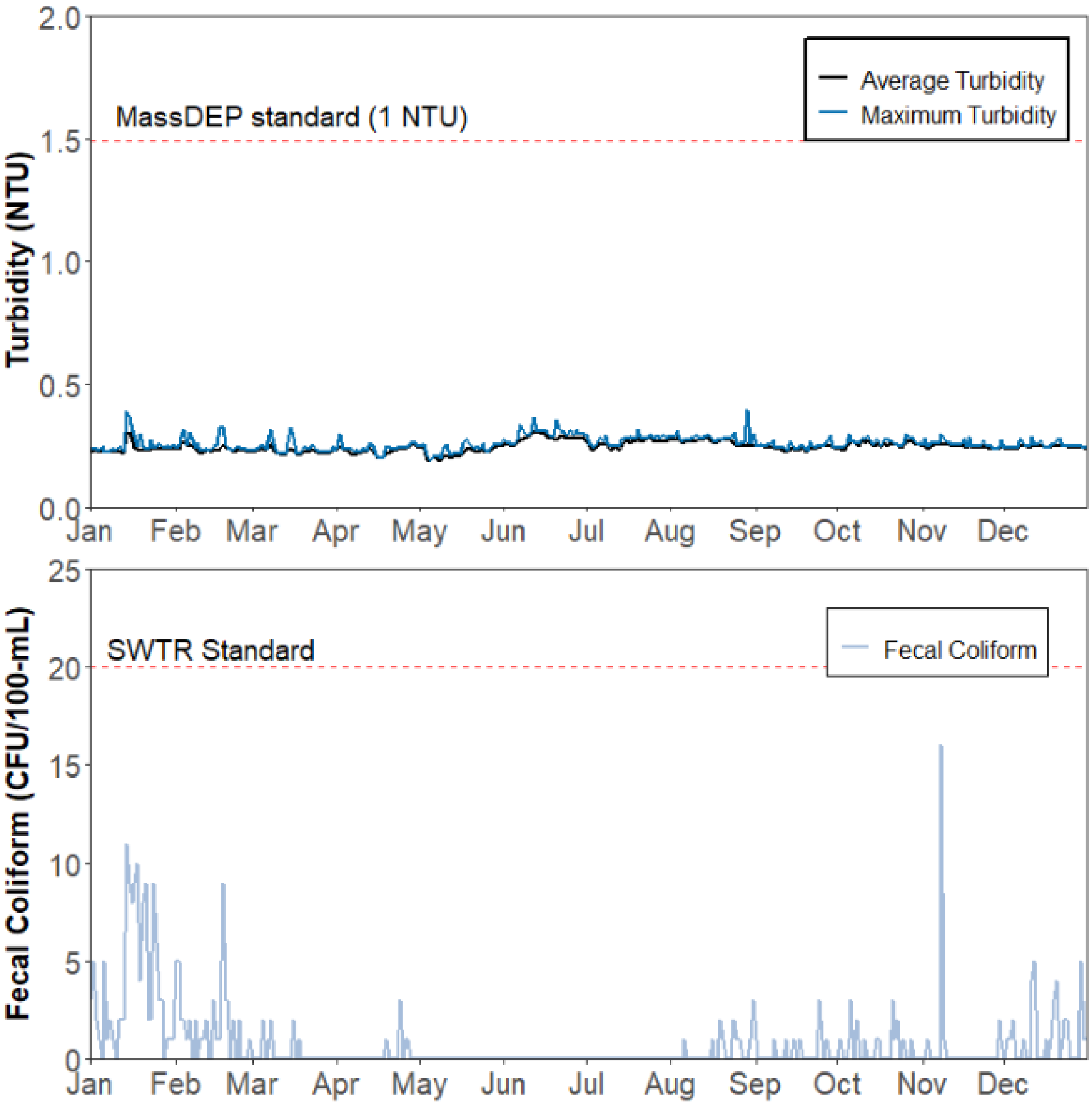


Figure 28: a) Results of daily average (mean) and maximum turbidity, and b) fecal coliform monitoring of Quabbin Reservoir source water collected from Winsor Dam Intake during 2023.

3.4.2 Water Temperature

Water column temperature profiles indicate the timing of seasonal changes in stratification throughout the Quabbin Reservoir (Figure 29). 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 2023. The timing of seasonal turnover was consistent with the historical record. Minimum temperatures were warmer than that of the period of record across all sites and all seasons, with the greatest divergence from historical minimums during the fall at site 206 (4.31°C warmer than the period of record). Overall, mean temperatures measured in 2023 remained within the established historical monitoring range for all sites. Mean summer temperatures for 2023 were slightly greater (less than 1°C warmer) than that of the period of record across all sites, with the greatest divergence from seasonal means occurring at site 202 (0.60°C warmer than the period of record). Maximum temperatures in 2023 did not exceed the established historical range (Table 40). Variations in temporal coverage across years (resulting from ice coverage) may in part drive deviations in observed temperatures during the winter and spring months. Statistics provided include measurements conducted in conjunction with monthly Quabbin Reservoir water quality monitoring (April to December 2023) and routine phytoplankton sampling (January to December, except for February and March at Den Hill due to ice conditions).

Table 40. Seasonal statistics of water temperature in Quabbin Reservoir during 2023 relative to the period of record (2006 -2022) at DWSP monitoring sites.

		Temperature (°C)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Spring	335	2274	2.68	1.25	6.28	6.75	7.30	7.28	14.98	16.97
	Summer	503	6126	6.87	5.78	11.40	10.57	13.85	13.25	26.34	26.70
	Fall	175	4997	7.94	7.00	11.96	11.73	14.53	13.20	23.70	23.37
	Winter	122	820	3.13	2.04	4.12	7.29	5.58	6.66	9.35	9.98
206	Spring	84	1502	3.07	1.81	6.23	7.79	5.92	8.07	10.26	16.94
	Summer	81	3736	8.99	6.25	13.21	12.54	15.24	14.89	26.56	26.84
	Fall	54	3001	10.62	6.31	11.56	13.09	13.87	14.53	19.84	23.59
	Winter	81	559	2.35	1.38	2.92	6.37	4.59	5.67	8.49	9.77
Den Hill	Spring	40	756	6.28	4.41	7.72	8.92	8.18	9.35	11.29	20.24
	Summer	80	2037	8.50	7.71	17.18	17.34	17.44	17.26	26.23	26.93
	Fall	39	1488	9.49	6.88	10.20	14.80	13.47	15.40	19.86	24.07
	Winter	41	243	1.78	1.44	2.16	5.36	4.26	5.26	6.74	8.42

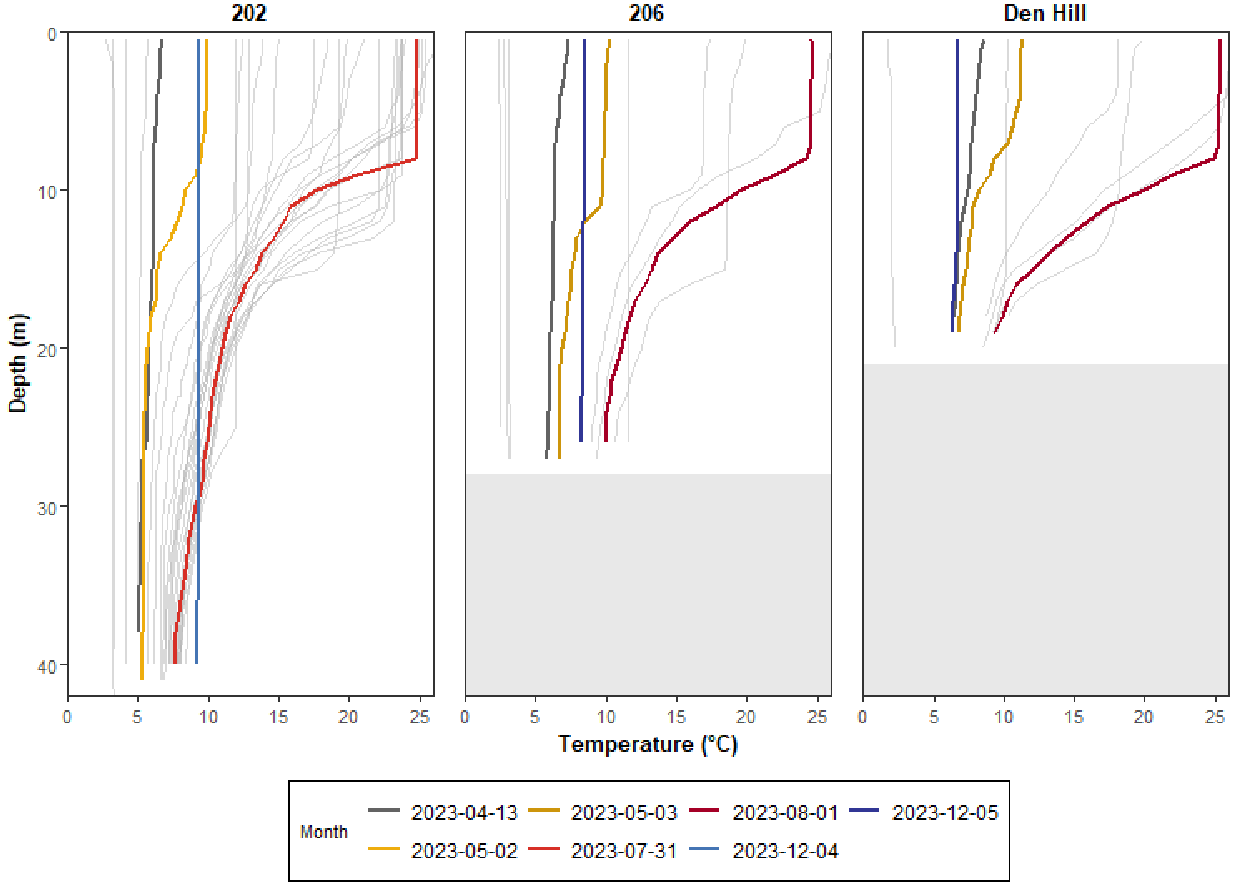


Figure 29. Profiles of temperature at Quabbin Reservoir Core sites on select dates in 2023. The April profile (dark gray) illustrates spring isothermy, which existed from the start of the sampling season through most of April at site 202 and was established sooner at 206 and Den Hill. The May profiles (yellow) corresponds to the onset of reservoir stratification. The July and August profiles (red) represents summer stratification. The December profiles (blue) show a return to isothermy at all sites following fall turnover. Gray lines in each plot show profiles from other 2023 sample dates. Gray bands at sites 206 and Den Hill indicate the max water column depth recorded for 2023.

3.4.3 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 2023, chlorophyll *a* concentrations remained low (below 5 µg/L) throughout the year and no phytoplankton aggregations were observed (Table 41, Figure 30). Unlike previous years, the maximum chlorophyll *a* concentrations at all three sites were observed in winter rather than in summer. The maximum chlorophyll *a* concentrations observed via manual profiles collected by DWSP staff were 3.21

µg/L at 18 m for site Den Hill, 2.33 µg/L at 14 m for site 206, and 2.07 µg/L at 31 m for site 202, all observed on January 25, 2023 (Figure 30). The maximum chlorophyll *a* concentration observed for data collected by the MWRA EXO2 buoy was 3.06 µg/L at 19 m depth on July 2, 2023 (Figure 31). In 2023, the mean summer chlorophyll *a* concentration at site 202 for the water column was 0.77 µg/L for data collected by DWSP via manual profiles (Table 41). As is typical, mean chlorophyll *a* concentrations were highest at Den Hill, followed by site 206, and then site 202. The low concentrations of chlorophyll *a* throughout the summer resulted in small variations across the timeseries attributed to sensor replacement and routine calibrations (Figure 31).

Table 41. Seasonal statistics for chlorophyll *a* in Quabbin Reservoir during 2023 relative to the period of record (2021 – 2022) at DWSP monitoring sites.

Chlorophyll *a* (µg/L)

		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Spring	335	362	0.15	0.09	0.94	1.23	0.86	1.14	1.50	3.80
	Summer	503	801	0.14	0.00	0.71	0.76	0.77	1.58	1.99	43.15
	Fall	175	371	0.16	0.01	0.67	0.55	0.66	0.49	1.27	1.07
	Winter	122	146	0.35	0.41	1.03	0.93	1.07	0.92	2.07	1.28
206	Spring	84	172	0.19	0.08	1.00	1.27	0.91	1.23	1.64	2.38
	Summer	81	247	0.14	0.12	0.83	1.08	0.80	2.01	1.86	26.81
	Fall	54	193	0.44	0.06	1.04	0.83	1.00	0.82	1.41	3.06
	Winter	81	82	0.49	0.16	1.39	0.97	1.44	0.92	2.33	1.43
Den Hill	Spring	40	82	0.85	0.57	1.52	1.66	1.50	1.62	2.08	2.71
	Summer	80	122	0.42	0.42	0.91	1.28	1.08	1.69	2.51	15.22
	Fall	39	122	0.48	0.19	1.10	1.07	1.15	1.01	1.89	1.96
	Winter	41	38	0.82	0.61	1.48	1.41	1.94	1.37	3.21	1.73

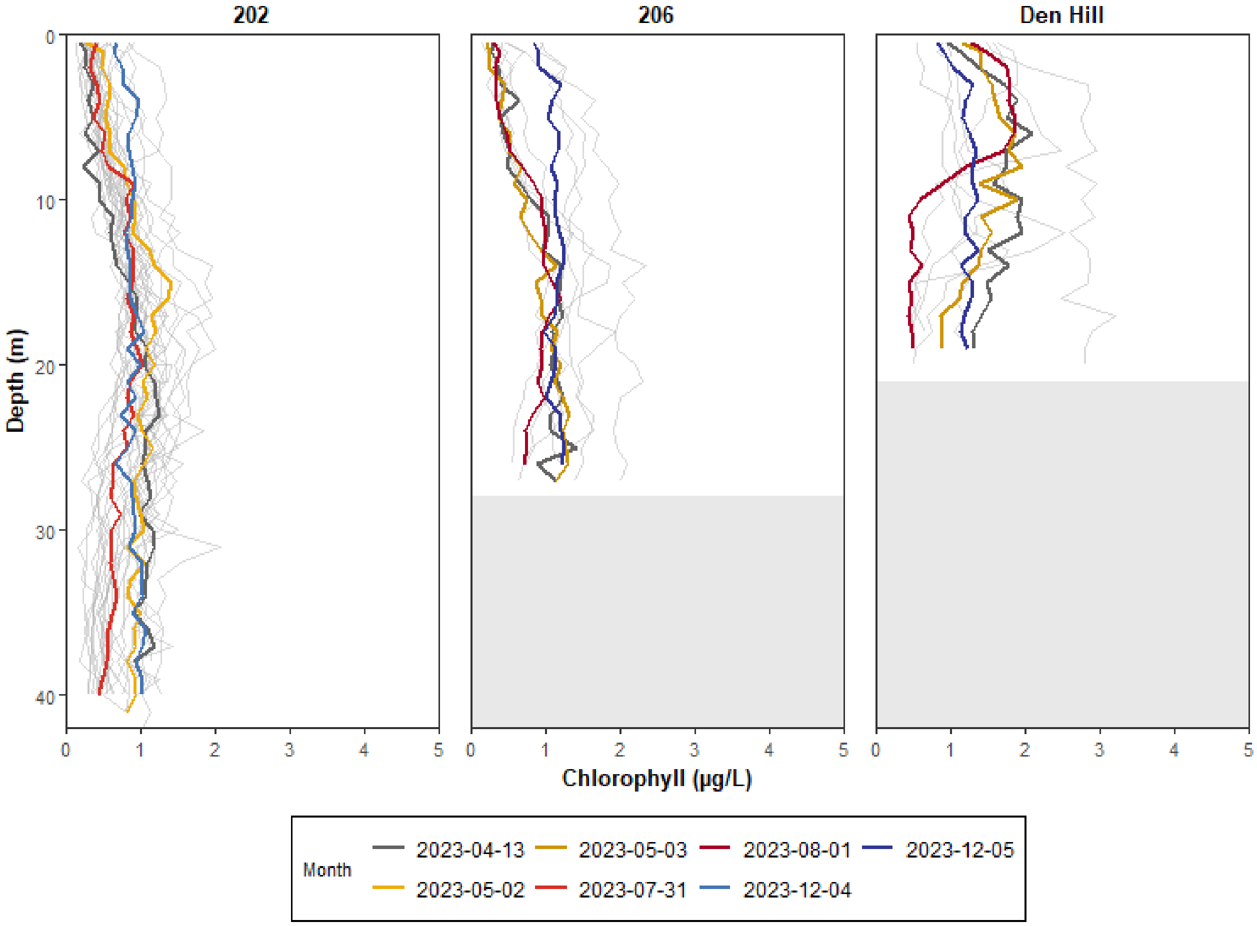


Figure 30. Profiles of chlorophyll *a* at Quabbin Reservoir Core sites on select dates in 2023. The April profile (dark gray) corresponds to a fully mixed water column. The May profile (yellow) corresponds to the onset of reservoir stratification. The July and August profiles (red) represents summer stratification. The December profile (blue) shows a return to a mixed water column following fall turnover. Gray lines in each plot show profiles from other 2023 sample dates. Gray bands at sites 206 and Den Hill indicate the max water column depth recorded for 2023.

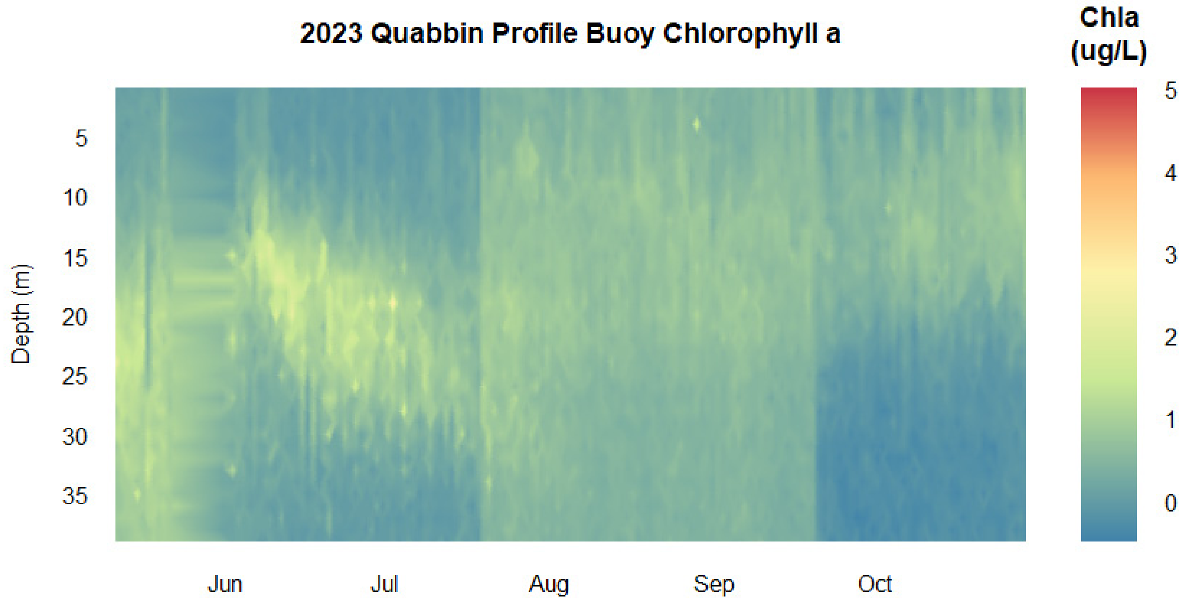


Figure 31. Chlorophyll *a* heatmap from buoy EXO2 noon profile collections from May through November.

3.4.4 Dissolved Oxygen

Concentrations of dissolved oxygen in Quabbin Reservoir followed expected seasonal patterns in 2023. 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. Dissolved oxygen concentrations were typically greater in the spring and winter, likely attributed to cooler water temperatures, and lowest in fall due to a decline in phytoplankton productivity prior to fall turnover (Table 42). During summer 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 due to phytoplankton activity (Figure 32). Mean summer dissolved oxygen levels were lower than what was observed last year, likely attributed to low phytoplankton productivity in 2023, but remained within historical range.

Table 42. Seasonal statistics for dissolved oxygen in Quabbin Reservoir during 2023 relative to the period of record (2021 – 2022) at DWSP monitoring sites.

		Dissolved Oxygen (mg/L)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Season**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Spring	335	363	10.2	10.0	12.5	12.2	12.1	12.4	13.0	13.6
	Summer	503	809	8.3	8.1	10.7	10.7	10.3	10.5	11.6	12.5
	Fall	175	371	6.7	6.0	9.5	9.0	9.3	8.8	10.7	11.1
	Winter	122	147	10.1	9.8	12.4	11.4	11.8	11.2	13.1	12.2
206	Spring	84	172	11.4	10.3	12.8	12.9	12.5	12.3	13.0	13.8
	Summer	81	247	8.2	8.1	10.2	10.3	9.9	10.0	11.0	11.6
	Fall	54	193	7.6	6.9	9.5	8.8	9.4	9.0	10.2	10.6
	Winter	81	82	10.8	10.7	13.1	12.1	12.5	11.9	13.6	12.9
Den Hill	Spring	40	82	11.1	9.6	11.8	11.5	11.8	11.3	12.2	12.3
	Summer	80	122	5.6	4.8	8.2	8.5	8.4	8.6	10.1	10.7
	Fall	39	122	2.0	0.1	9.7	8.3	8.6	7.9	10.0	10.0
	Winter	41	38	11.0	11.1	13.2	11.8	12.2	11.8	13.4	12.6

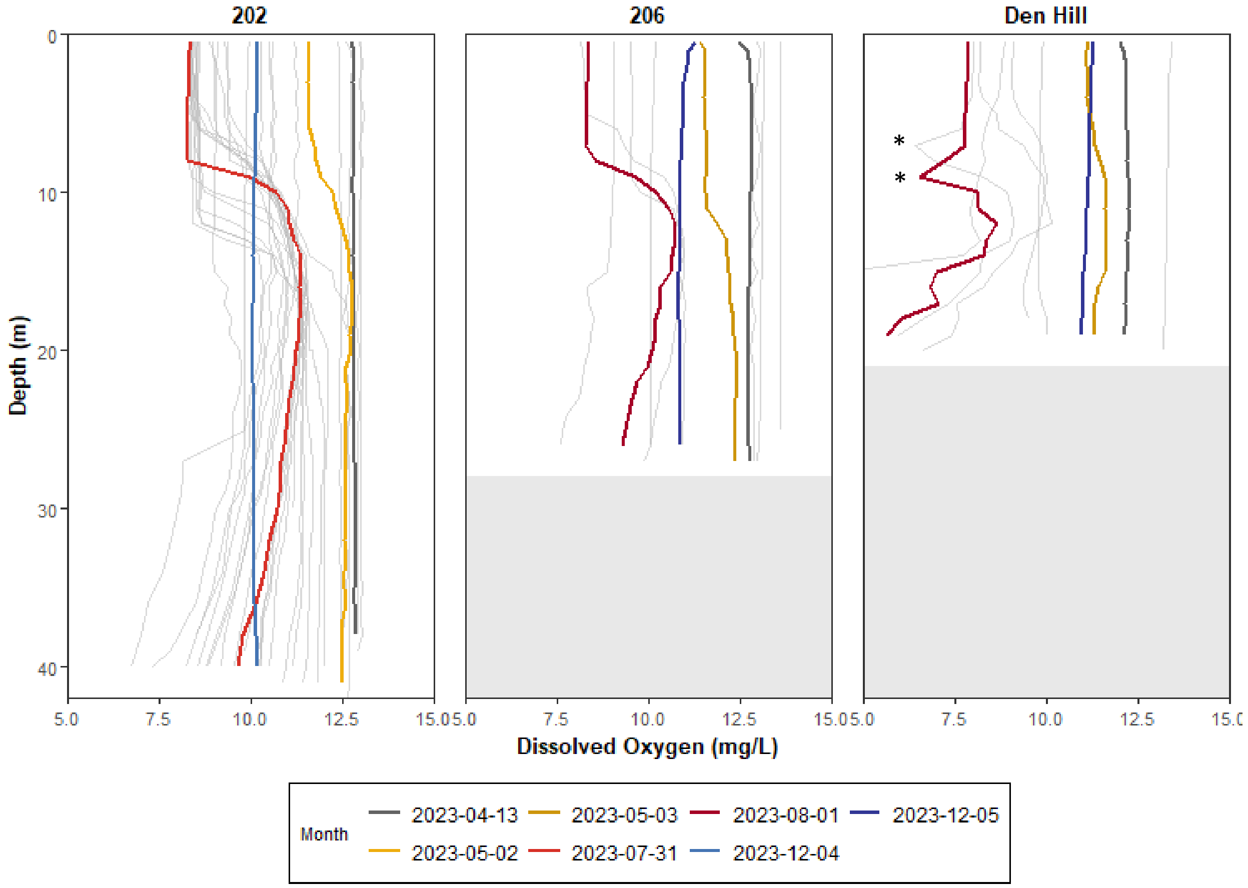


Figure 32: Profiles of dissolved oxygen at Quabbin Reservoir Core sites on select dates in 2023. The April profile (dark gray) illustrates the dissolved oxygen concentrations of a fully mixed water column in the spring, which existed from the start of the sampling season through most of April at site 202 and was established sooner at 206 and Den Hill. The May profile (yellow) corresponds to the onset of reservoir stratification. The July and August profiles (red) depicts an increase in dissolved oxygen concentrations at depth, during summer stratification. The December profile (blue) shows a return to a mixed water column following fall turnover. Gray lines in each plot show profiles from other 2023 sample dates. Gray bands at sites 206 and Den Hill indicate the max water column depth recorded for 2023. * These profiles show the effect of the high stream flow event observed on July 21, 2023 on dissolved oxygen at Den Hill.

Following typical seasonal patterns for Quabbin Reservoir, dissolved oxygen depletion was most pronounced during the late stages of stratification, with 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 2023 was 2.00 mg/L, at 19 m on October 18 at Den Hill (Table 42). Dissolved oxygen is typically depleted at depth at Den Hill with an annual minimum between 0.1 and 2.41 mg/L in the last three years. 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 winter, with an annual maximum concentration of 13.60 mg/L at 206 (Figure 32). The median dissolved oxygen concentrations in 2023 remained above 6 mg/L at all sites (Table 42), sustaining concentrations required to support cold water aquatic species (314 CMR 4.06).

After a high stream flow event on July 21, 2023 (see Section 3.2.1), dissolved oxygen at Den Hill was observed to decline between 7 to 9 m, likely attributed to the increase in stream input bringing in more sediment and increasing turbidity. High inflow events can impact phytoplankton productivity due to high turbidity water lowering light availability for phytoplankton. This combined with heterotrophic activity associated with decomposition could explain the decreasing dissolved oxygen in the water. The decline in dissolved oxygen was observed in the July 27 and August 1, 2023, profiles (Figure 32).

3.4.5 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 5.3 to 7.6 in 2023, 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 6.0 to 6.7 in 2023 (Table 43).

Table 43. Seasonal statistics for pH in Quabbin Reservoir during 2023 relative to the period of record (2021 – 2022) at DWSP monitoring sites.

		pH									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Spring	335	363	6.0	6.3	6.4	6.6	6.5	6.7	7.4	7.8
	Summer	503	809	5.5	5.8	6.5	6.6	6.5	6.6	7.4	7.9
	Fall	175	371	5.3	5.0	6.5	6.1	6.4	6.1	7.6	7.5
	Winter	122	147	6.1	6.0	6.6	6.6	6.5	6.6	7.3	7.8
206	Spring	84	172	6.4	6.6	6.7	6.9	6.7	6.9	7.0	7.9
	Summer	81	247	5.9	5.8	6.7	6.9	6.6	6.8	7.3	7.4
	Fall	54	193	5.9	5.8	6.0	6.6	6.3	6.5	6.8	7.4
	Winter	81	82	6.2	6.1	6.6	6.6	6.5	6.6	6.9	7.2
Den Hill	Spring	40	82	6.1	6.5	6.5	6.7	6.5	6.7	7.3	7.4
	Summer	80	122	5.6	5.8	6.4	6.8	6.4	6.6	7.2	7.1
	Fall	39	122	5.7	5.6	6.3	6.6	6.4	6.5	7.4	7.3
	Winter	41	38	6.1	6.2	6.4	6.6	6.4	6.6	7.0	7.1

Alkalinity in Quabbin Reservoir remained low (<7 mg/L as $CaCO_3$) throughout 2023 and exhibited little variability with depth, changes in stratification, or seasonality (Table 44). Alkalinity concentrations ranged from 3.80 to 4.96 mg/L as $CaCO_3$ in 2023. Median alkalinity was generally greatest at Den Hill in 2023 (4.52 to 4.70 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 2023 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. 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 (Feng et al., 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).

Table 44. Seasonal statistics for alkalinity as $CaCO_3$ in Quabbin Reservoir during 2023 relative to the period of record at DWSP monitoring sites.

		Alkalinity									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	5	133	3.80	2.66	3.94	3.66	3.96	3.56	4.15	6.37
	Mid	5	148	3.78	2.47	3.92	3.63	3.92	3.49	4.13	4.50
	Deep	5	155	3.80	2.51	3.98	3.57	4.01	3.45	4.25	4.51
206	Surface	5	132	3.86	2.44	3.95	3.76	4.01	3.61	4.32	4.27
	Mid	5	146	3.91	2.44	4.01	3.66	3.99	3.54	4.07	4.33
	Deep	5	153	3.69	2.63	3.95	3.63	3.93	3.53	4.12	5.51
Den Hill	Surface	5	129	3.85	2.54	4.53	3.92	4.36	3.82	4.64	5.10
	Mid	5	142	4.07	2.76	4.52	3.85	4.40	3.76	4.68	4.62
	Deep	5	149	3.84	2.60	4.70	3.84	4.47	3.80	4.96	7.50

3.4.6 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, such as highly urbanized watersheds that may exceed 1,000 µS/cm. The relatively low observed specific conductance in Quabbin Reservoir waters is likely a reflection of land cover (e.g., percent developed lands, total land 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. In 2023, higher specific conductance was observed around the thermocline depth during the summer in all DWSP monitoring sites. Specific conductance during the spring was lower than observations in summer, fall, and winter for sites 202 and 206. In contrast to that, the highest mean specific conductance for Den Hill was observed during the spring (Table 45, Figure 33). Annual minimums exceeded the POR ranges across all sites, while annual means and maximums exceeded the POR ranges only at Den Hill (Table 45). Higher mean specific conductance during winter and spring at Den Hill, are consistent with increasing concentrations of specific conductance documented in major east Quabbin tributaries, likely attributed to road salt runoff. Specific conductance measured in Quabbin Reservoir during 2023, ranged from an annual minimum of 47.1 µS/cm at site 202 in the spring, to an annual maximum of 57.8 µS/cm at Den Hill in the winter (Table 45).

Table 45. Seasonal statistics for specific conductance in Quabbin Reservoir during 2023 relative to the period of record (2021 – 2022) at DWSP monitoring sites.

Specific Conductance

		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Spring	335	363	47.1	46.9	47.6	47.9	47.7	47.9	48.6	49.2
	Summer	503	809	48.0	46.1	48.7	47.7	48.6	47.8	49.8	49.6
	Fall	175	371	48.2	47.0	48.8	48.0	48.8	47.9	49.7	49.0
	Winter	122	146	47.9	47.0	48.6	48.0	48.4	49.3	48.9	56.1
206	Spring	84	172	47.3	47.0	47.7	48.0	47.7	47.9	48.1	49.0
	Summer	81	247	48.3	47.2	49.1	48.0	49.0	48.1	49.9	49.4
	Fall	54	193	48.6	47.4	48.6	47.9	48.8	47.9	50.0	49.0
	Winter	81	82	48.1	47.5	48.8	48.1	48.6	48.7	49.2	51.4
Den Hill	Spring	40	82	51.6	48.8	54.8	50.9	54.6	50.7	55.9	52.5
	Summer	80	122	50.1	48.0	52.2	49.6	52.8	50.1	55.7	54.5
	Fall	39	122	50.5	48.9	50.9	49.4	51.6	50.0	56.7	54.5
	Winter	41	38	50.9	50.3	55.9	51.0	54.2	51.0	57.8	52.0

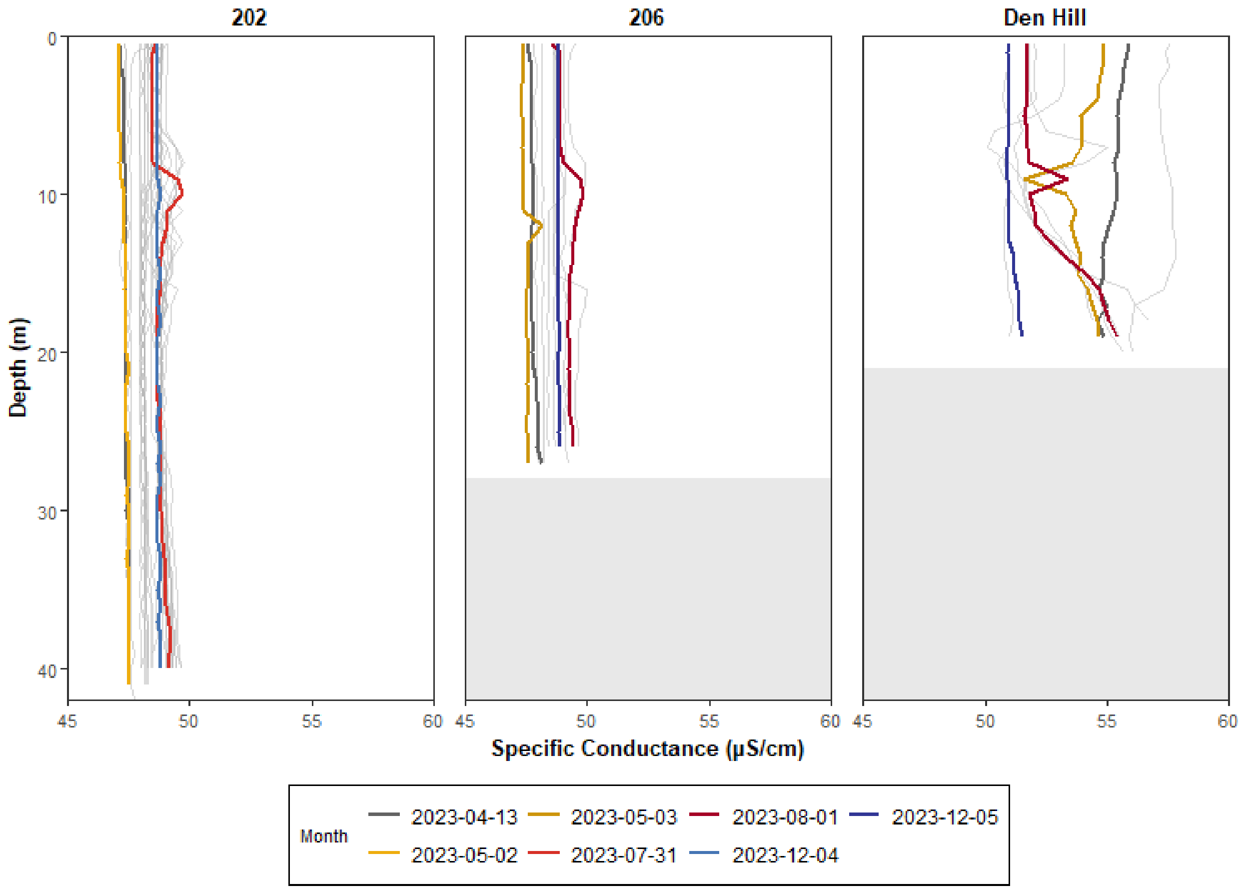


Figure 33. Profiles of specific conductance at Quabbin Reservoir Core sites in 2023. Selected colors represent the different stages of the water column in a year. The April profile (dark gray) corresponds to a mixed water column in the spring, which existed from March through most of April. The May profile (yellow) corresponds to the onset of reservoir stratification. The July and August profiles (red) depict an increase in specific conductance at the thermocline depth, during summer stratification. 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 2023 sample dates.

Routine monitoring of concentrations of sodium (Na) and chloride (Cl) in Quabbin Reservoir began in 2020. In 2023, monitoring for Na and Cl in Quabbin Reservoir was conducted quarterly. Sodium concentrations ranged from a minimum of 4.99 mg/L at the middle of the water column of site 202, to a maximum of 6.45 mg/L in a surface sample collected at Den Hill (Table 46). Chloride concentrations ranged from a minimum of 8.00 mg/L at site 206 to a maximum of 9.98 mg/L at Den Hill (Table 46). 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 46). Median annual concentrations of Na and Cl measured in 2023 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 2023.

Table 46. Concentration results for Na and Cl measured in Quabbin Reservoir during 2023 relative to the period of record (POR) at DWSP monitoring sites.

Sodium

		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	5	11	5.26	5.11	5.41	5.51	5.39	5.47	5.51	5.79
	Mid	5	11	4.99	5.35	5.41	5.54	5.35	5.52	5.57	5.74
	Deep	5	11	5.01	5.34	5.45	5.61	5.39	5.61	5.59	6.00
206	Surface	5	11	5.16	5.39	5.39	5.58	5.38	5.64	5.57	6.15
	Mid	5	11	5.38	5.20	5.41	5.44	5.46	5.50	5.66	6.11
	Deep	5	11	5.15	5.35	5.33	5.54	5.33	5.58	5.51	6.08
Den Hill	Surface	5	11	5.30	5.39	5.87	5.74	5.86	5.79	6.45	6.16
	Mid	5	11	5.58	5.45	5.70	5.66	5.82	5.73	6.09	6.00
	Deep	5	11	5.41	5.55	5.62	5.94	5.83	5.88	6.31	6.15

Chloride

		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	5	13	8.03	7.74	8.17	7.93	8.23	8.02	8.53	8.59
	Mid	5	13	8.11	7.77	8.32	7.94	8.33	8.01	8.61	8.29
	Deep	5	13	8.07	7.74	8.23	7.89	8.22	7.98	8.33	8.37
206	Surface	5	13	8.01	7.74	8.24	8.02	8.17	8.08	8.29	8.42
	Mid	5	13	8.07	7.78	8.39	8.04	8.44	8.06	8.74	8.32
	Deep	5	13	8.00	7.75	8.32	7.98	8.33	7.97	8.64	8.29
Den Hill	Surface	5	13	8.61	8.16	8.64	8.41	8.94	8.50	9.98	9.39
	Mid	5	13	8.76	8.17	8.99	8.47	9.12	8.50	9.51	9.15
	Deep	5	13	8.58	8.15	9.71	8.44	9.46	8.48	9.86	9.02

3.4.7 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 0.16 NTU to 0.67 NTU during 2023 (Table 47), largely falling within the historical range of turbidity observed at DWSP monitoring sites (Figure 34). Turbidity remained below 1.0 NTU in Quabbin Reservoir in all samples collected by DWSP in 2023.

Table 47. Seasonal statistics for Turbidity (NTU) in Quabbin Reservoir during 2023 relative to the period of record (POR) at DWSP monitoring sites.

		Turbidity									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	9	139	0.17	0.16	0.23	0.27	0.24	0.28	0.34	0.67
	Mid	9	158	0.23	0.19	0.24	0.28	0.25	0.30	0.29	0.73
	Deep	9	166	0.22	0.16	0.29	0.26	0.29	0.28	0.44	1.04
206	Surface	9	139	0.16	0.18	0.26	0.28	0.26	0.30	0.34	0.88
	Mid	9	155	0.22	0.19	0.27	0.31	0.30	0.32	0.45	0.82
	Deep	9	164	0.23	0.18	0.28	0.31	0.29	0.35	0.39	1.21
Den Hill	Surface	9	135	0.26	0.25	0.43	0.40	0.43	0.42	0.58	0.98
	Mid	9	151	0.30	0.24	0.42	0.44	0.42	0.46	0.66	1.13
	Deep	9	159	0.26	0.22	0.45	0.47	0.47	0.58	0.67	4.00

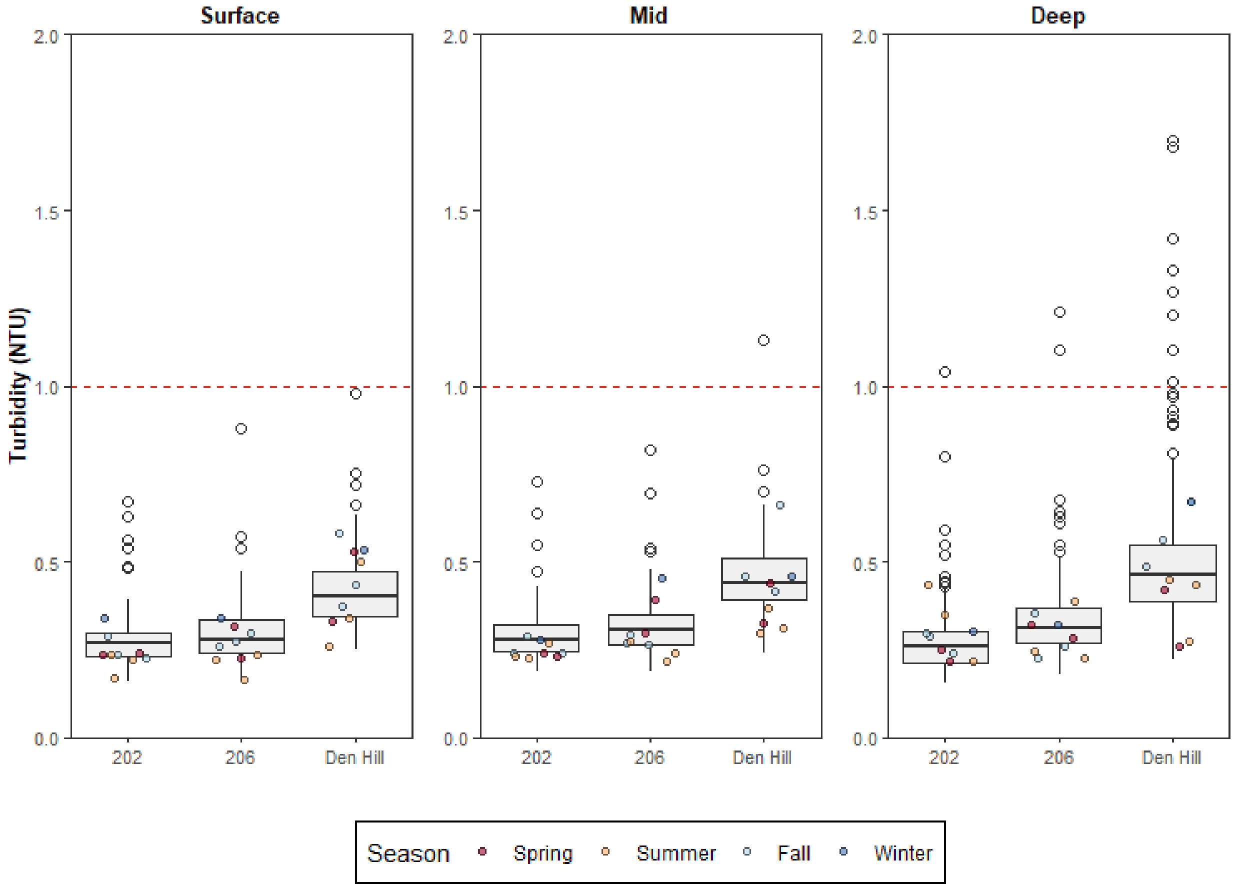


Figure 34. Boxplots depicting the seasonal and vertical distributions of turbidity in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2023 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented 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). While turbidity was relatively higher at Den Hill than in the other core monitoring sites, this year's turbidity levels were comparable across sites, unlike last year's high turbidity observation from Den Hill deep samples (4.0 NTU) (DWSP, 2022). Overall, turbidity remained low at all sites.

3.4.8 Secchi Disk Depth/Transparency

Simultaneous aided and unaided Secchi disk transparencies were measured in the Quabbin Reservoir in 2023. 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 1.23-m deeper than unaided measurements. The largest difference between aided and unaided measurements was 4.15-m, taken at sampling site 206 on July 12, 2023 (Figure 35). This large difference was most likely due to surface glare. On one date at 202 (March 21, 2023), there was a 0.04-m difference between transparencies. This was likely due to low waves and partial cloud conditions which increased ambient light paired with low surface glare.

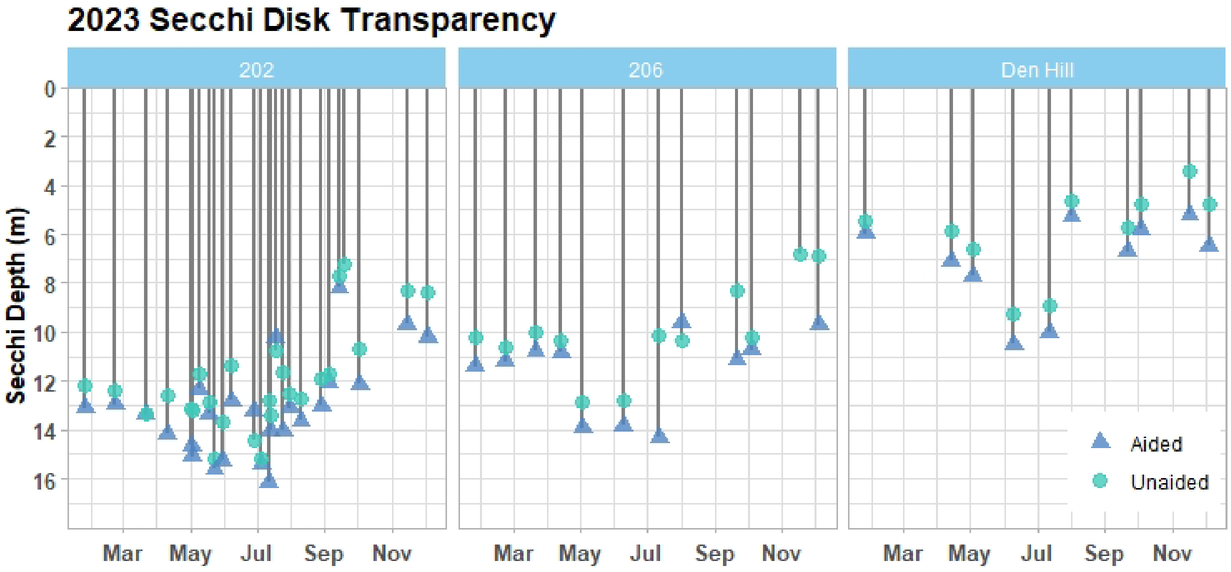


Figure 35. Secchi disk transparencies measured in 2023 in Quabbin Reservoir at DWSP monitoring sites 202 (maximum depth 44.6 m), 206 (maximum depth 29.3 m), and Den Hill (maximum depth 21.5 m). Light blue/green circle data points are unaided measurements, and darker blue triangle points are aided, collected using a view scope.

Water in the Quabbin Reservoir continued to demonstrate exceptional clarity in 2023, with a median aided Secchi disk transparency of 13.2, 11.1, and 6.6-m, and median unaided Secchi of 12.4, 10.2, and 5.5-m 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 2023 was 3.4-m unaided (November 17, 2023) and 5.2-m aided (November 17, 2023) at Den Hill monitoring site. The maximum Secchi disk transparency was 15.1-m unaided (July 5, 2023) and 16.1-m aided (July 12, 2022) at monitoring site 202.

Transparency at Den Hill monitoring site was characteristically lower than at sites 202 and 206 (Figure 35), 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 2023, from January 9 – 12, and from December 19 -21). 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. Secchi disk depths show an inverse relationship to phytoplankton densities, thus reductions in Secchi disk depths may be related to increases in phytoplankton densities in the spring and late summer/fall (Section 3.4.10).

3.4.9 Nutrients

Patterns of nutrient distributions in Quabbin Reservoir in 2023 were generally consistent with those documented previously by Worden (2000) and historical ranges observed in Quabbin Reservoir by DWSP monitoring. 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.

3.4.9.1 Total Nitrogen (Ammonia-Nitrogen, Nitrate-Nitrogen, and Total Kjeldahl Nitrogen)

Concentrations of ammonia (NH_3-N) nitrate (NO_3-N) ranged from <0.005 to 0.047 mg/L and from <0.005 to 0.068 mg/L, respectively in Quabbin Reservoir in 2023. Overall, concentrations of NH_3-N and NO_3-N followed the vertical and temporal variation characteristic of historical seasonal ranges for each site (Table 48). Concentrations of NH_3-N and NO_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 site 202 and for the majority of samples collected from the epilimnion at site 206. NH_3-N and NO_3-N are typically low in the spring. As is characteristically observed, NH_3-N and NO_3-N concentrations increased in the hypolimnion in the late summer and fall at all sites, likely coincident with decomposition. Following fall turnover in the reservoir, NH_3-N and NO_3-N concentrations decreased at each site, homogenizing across depths. Winter concentrations of NH_3-N and NO_3-N were comparable to historical medians (Table 48, Figure 36).

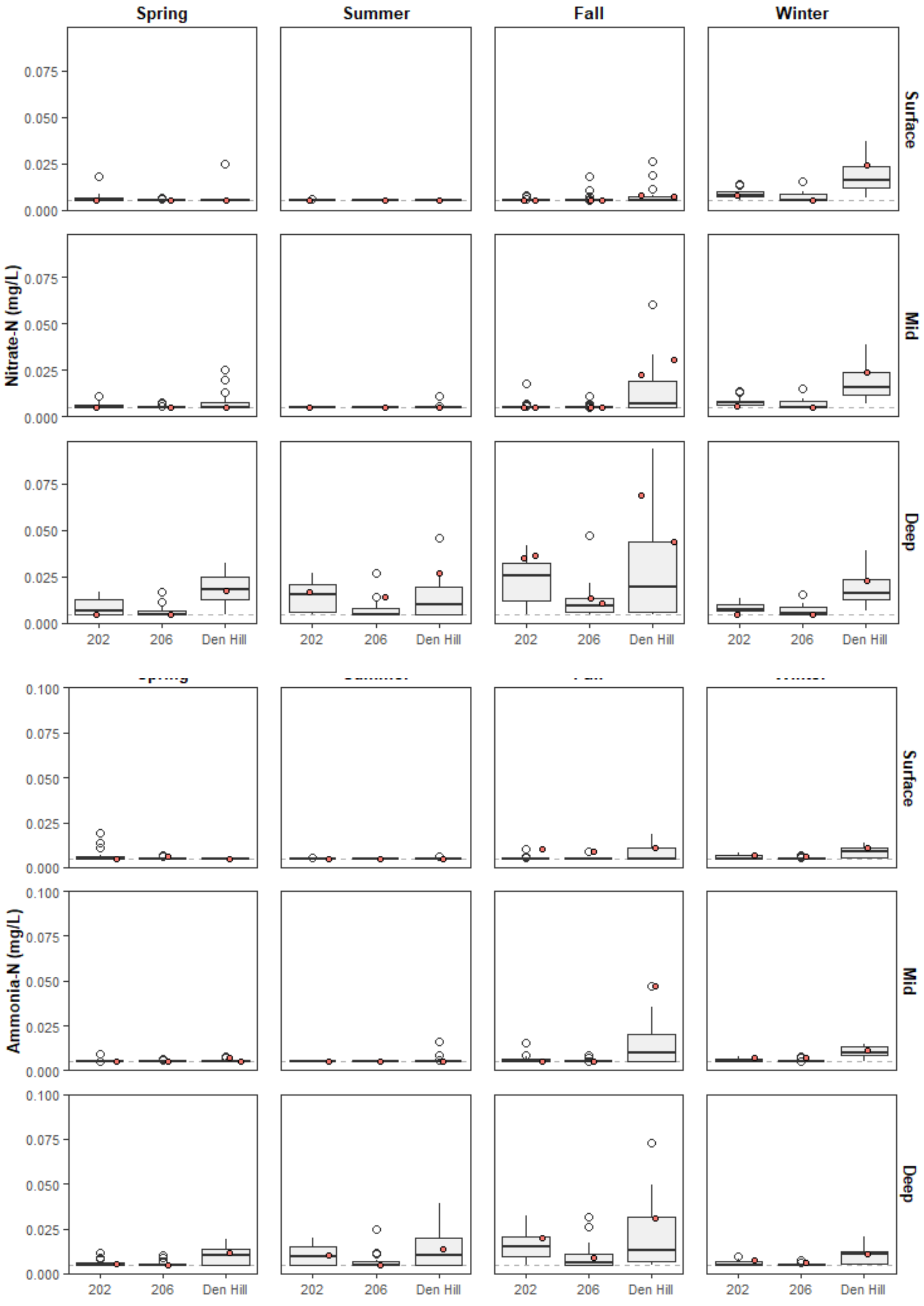


Figure 36. Boxplots depicting the seasonal and vertical distributions of NO_3-N and NH_3-N in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2023 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record 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.

Concentrations of TKN in Quabbin Reservoir Core sites ranged from 0.052 to 0.342 mg/L in 2023 (Table 48). TKN concentrations in Quabbin Reservoir exhibited little temporal or spatial variability in 2023 (Figure 37). Overall, concentrations of TKN in Quabbin Reservoir were below or approached the historical seasonal medians throughout the water column, except for the 0.342 mg/L TKN concentration observed in the surface water of 206 during the fall (Figure 37). A proportion of the variability in concentrations of TKN observed in 2023, when compared to the historical records, may be attributed to assumptions made during calculations of TKN concentrations for 2020 through 2023 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).

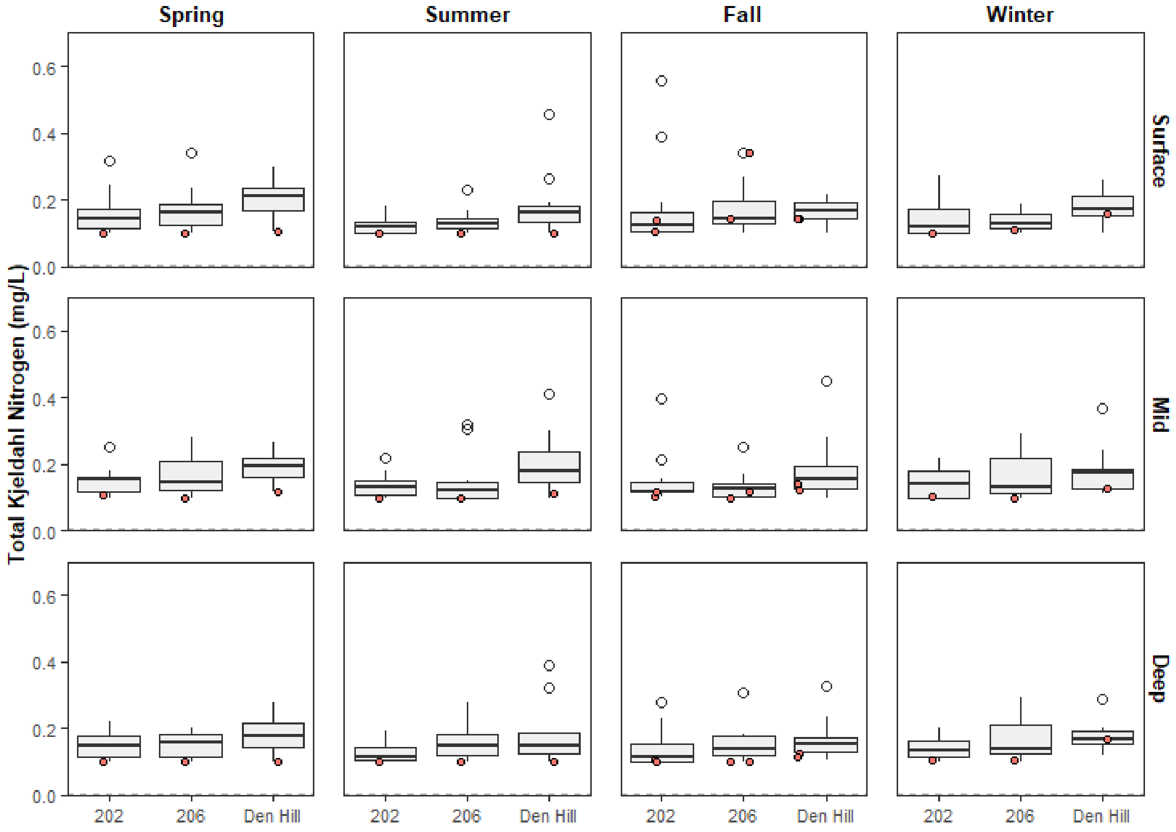


Figure 37. Boxplots depicting the seasonal and vertical distributions of total Kjeldahl nitrogen (TKN) in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2023 are signified by the colored points. The solid black line represents the historical median, outliers for the period 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 48. Descriptive statistics for NH_3-N, NO_3-N, and TKN in Quabbin Reservoir during 2023 relative to the period of record (POR). 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.

Ammonia-N (mg/L)

		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	4	68	0.005	0.005	0.005	0.002	0.005	0.003	0.01	0.019
	Mid	4	68	0.005	0.005	0.002	0.003	0.004	0.004	0.007	0.016
	Deep	4	68	0.005	0.005	0.009	0.008	0.011	0.010	0.020	0.032
206	Surface	4	68	0.005	0.005	0.006	0.002	0.006	0.003	0.009	0.010
	Mid	4	68	0.005	0.005	0.002	0.001	0.004	0.002	0.007	0.020
	Deep	4	67	0.005	0.005	0.006	0.004	0.006	0.006	0.009	0.032
Den Hill	Surface	4	66	0.005	0.005	0.007	0.004	0.007	0.005	0.011	0.019
	Mid	5	66	0.005	0.005	0.007	0.005	0.014	0.008	0.047	0.036
	Deep	4	66	0.011	0.005	0.012	0.01	0.017	0.014	0.031	0.073

Nitrate-N (mg/L)

		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	5	69	0.005	0.005	0.002	0.004	0.004	0.005	0.008	0.018
	Mid	5	69	0.005	0.005	0.002	0.004	0.003	0.005	0.005	0.018
	Deep	5	69	0.005	0.005	0.017	0.012	0.019	0.014	0.036	0.042
206	Surface	5	69	0.005	0.005	0.002	0.003	0.002	0.004	0.005	0.018
	Mid	5	69	0.005	0.005	0.002	0.003	0.002	0.004	0.005	0.015
	Deep	5	68	0.005	0.005	0.011	0.006	0.009	0.007	0.014	0.047
Den Hill	Surface	5	67	0.005	0.005	0.007	0.004	0.009	0.007	0.024	0.037
	Mid	5	67	0.005	0.005	0.022	0.005	0.016	0.009	0.031	0.060
	Deep	5	67	0.017	0.005	0.027	0.015	0.036	0.019	0.068	0.094

Total Kjeldahl N (mg/L)

		Count		*Minimum*		*Median*		*Mean*		*Maximum*	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	5	86	0.087	0.082	0.093	0.125	0.100	0.155	0.137	0.56
	Mid	5	86	0.090	0.082	0.098	0.135	0.099	0.149	0.117	0.399
	Deep	5	86	0.059	0.078	0.082	0.128	0.082	0.135	0.105	0.278
206	Surface	5	86	0.090	0.08	0.105	0.134	0.151	0.148	0.342	0.342
	Mid	5	86	0.090	0.09	0.09	0.134	0.095	0.154	0.117	0.322
	Deep	5	86	0.081	0.09	0.086	0.146	0.088	0.157	0.104	0.309
Den Hill	Surface	5	82	0.09	0.058	0.128	0.174	0.122	0.183	0.156	0.457
	Mid	5	82	0.095	0.082	0.110	0.172	0.113	0.188	0.142	0.449
	Deep	5	82	0.052	0.070	0.090	0.158	0.098	0.174	0.168	0.389

3.4.9.2 Total Phosphorus

Vertical and spatial patterns in total phosphorus (TP) concentrations observed in Quabbin Reservoir remained consistent with those previously observed. Concentrations of TP ranged from <0.005 to 0.013 mg/L in 2023 (Table 49). 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 38). TP concentrations in all 2023 samples remained well below the 10 µg/L threshold for classification as an oligotrophic water body (Carlson, 1977), except for a deep sample from Den Hill (0.013 mg/L). Concentrations of TP remained low throughout the water column for the entirety of 2023.

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 38).

Table 49. Descriptive statistics for total phosphorus (TP) in Quabbin Reservoir during 2023 relative to the period of record (POR). Detection limits for TP in 2023 were <0.005 mg/L.

Total Phosphorus (mg/L)

		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	5	58	0.005	0.005	0.002	0.004	0.002	0.005	0.005	0.010
	Mid	5	57	0.005	0.005	0.002	0.004	0.003	0.005	0.006	0.014
	Deep	5	57	0.005	0.005	0.002	0.005	0.004	0.005	0.007	0.010
206	Surface	5	57	0.005	0.005	0.002	0.003	0.006	0.004	0.010	0.009
	Mid	5	57	0.005	0.005	0.002	0.003	0.002	0.004	0.005	0.015
	Deep	5	57	0.005	0.005	0.005	0.004	0.004	0.005	0.005	0.010
Den Hill	Surface	5	56	0.005	0.005	0.002	0.006	0.004	0.006	0.009	0.027
	Mid	5	56	0.005	0.005	0.006	0.006	0.005	0.006	0.008	0.014
	Deep	5	56	0.005	0.005	0.008	0.007	0.008	0.007	0.013	0.014

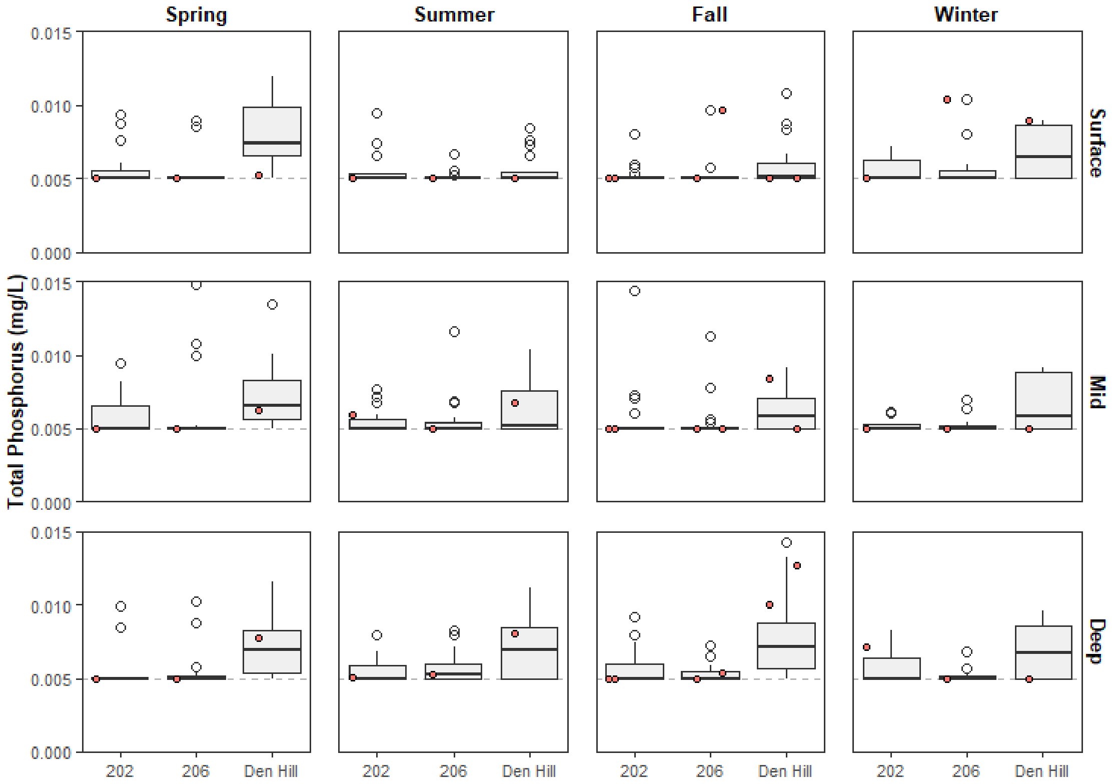


Figure 38. Boxplots depicting the seasonal and vertical distributions of total phosphorus in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2023 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are 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.

3.4.9.3 Silica

Silica is utilized by phytoplankton, particularly diatoms and chrysophytes (Reynolds, 2006). Silica concentrations in Quabbin Reservoir ranged from 1.46 to 3.81 mg/L in 2023, compared to a range of 1.00 to 3.97 mg/L for the period of record (Table 50). Observed ranges of monthly silica concentrations in 2023 varied relative to historical medians, but largely fell within seasonal interquartile ranges for each site/collection depth (Figure 39), except for Den Hill. In 2023, silica concentrations at sites 202 and 206 typically approached seasonal medians, while many of the silica concentrations at Den Hill fell above the 75th percentile. Overall, silica at Den Hill, and particularly at depth, has been increasing over time (2005 to 2023 - POR).

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, consistent with previous results and likely attributed to uptake by phytoplankton. Higher silica concentrations were observed in the late spring (May) and in the fall (September and October) in 2023, coincident with relative low diatom and chrysophyte densities across the reservoir (Section 3.4.10) and increased riverine inputs (Section 3.2.1). Silica concentrations were greatest at Den Hill at depth (3.23 to 3.81 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.

Table 50. Descriptive statistics for silica in Quabbin Reservoir during 2023 relative to the period of record (POR).

		Silica (mg/L)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	5	69	1.74	1.297	1.99	1.77	1.99	1.799	2.23	2.32
	Mid	5	69	1.67	1.24	1.76	1.78	1.88	1.789	2.15	2.34
	Deep	5	71	2.04	1.373	2.23	2.12	2.272	2.113	2.51	2.93
206	Surface	5	69	1.58	1.233	1.77	1.71	1.766	1.702	2.03	2.4
	Mid	5	70	1.6	1.19	1.81	1.665	1.788	1.665	1.99	2.27
	Deep	5	70	1.93	1.318	2.07	1.843	2.064	1.857	2.21	2.6
Den Hill	Surface	5	68	1.46	1.245	2.44	1.825	2.626	2.037	3.52	3.75
	Mid	5	67	1.49	1	3.21	1.83	2.72	2.077	3.4	3.84
	Deep	5	67	3.23	1.55	3.47	2.55	3.516	2.55	3.81	3.97

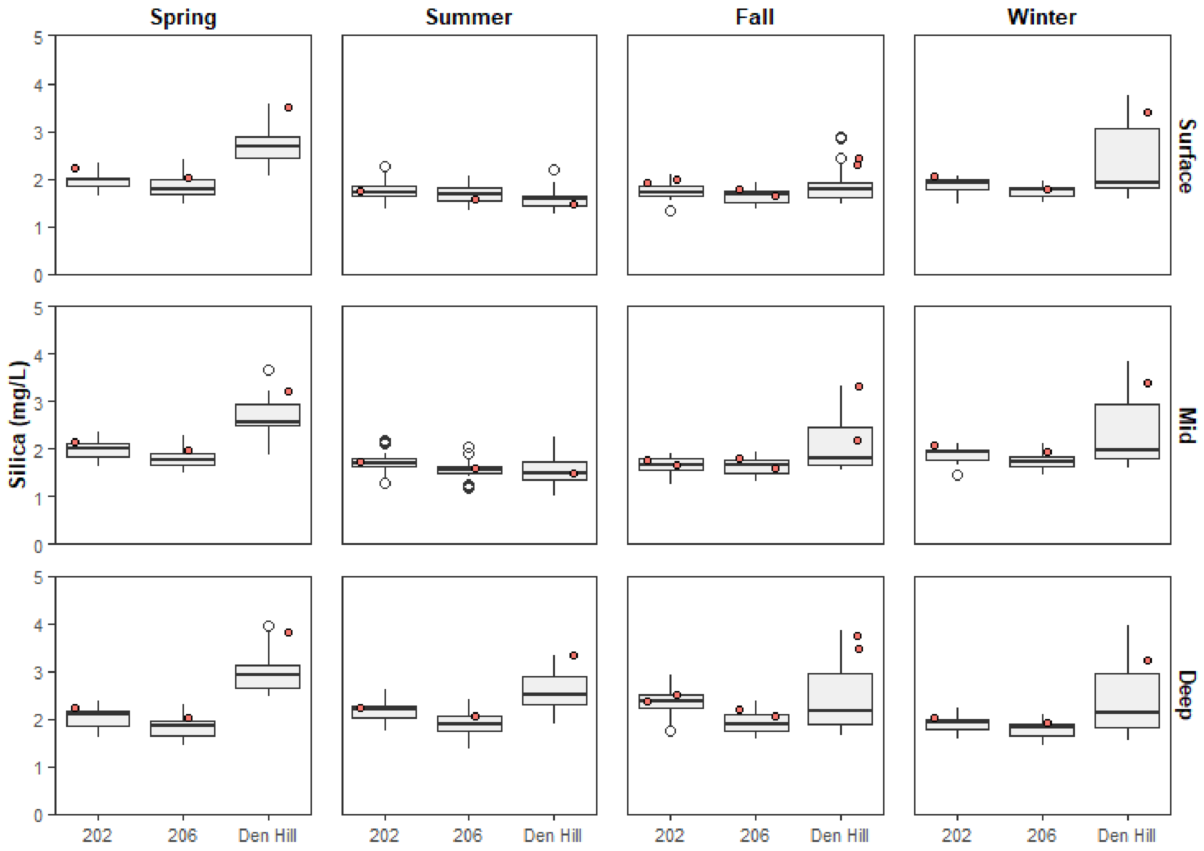


Figure 39. Boxplots depicting the seasonal and vertical distributions of silica observed in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2023 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are 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.

3.4.9.4 UV_{254} and Total Organic Carbon

3.4.9.4.1 UV_{254} Absorbance

UV_{254} absorbance in Quabbin Reservoir ranged from 0.021 to 0.029 ABU/cm at sampling site 202, from 0.021 to 0.026 ABU/cm at 206, and from 0.034 to 0.096 ABU/cm at Den Hill (Table 51). Notably, UV_{254} absorbance measured at Den Hill in 2023 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 three 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.

Table 51. Descriptive statistics for UV_{254} measured in Core reservoir monitoring sites in the Quabbin Reservoir in 2023 relative to the period of record (POR).

		UV_{254} (ABU/cm)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	9	69	0.021	0.016	0.023	0.023	0.023	0.023	0.024	0.034
	Mid	9	69	0.022	0.017	0.024	0.024	0.024	0.024	0.029	0.038
	Deep	9	69	0.021	0.017	0.022	0.022	0.022	0.023	0.024	0.031
206	Surface	9	69	0.021	0.017	0.024	0.023	0.024	0.024	0.025	0.093
	Mid	9	69	0.024	0.017	0.025	0.024	0.025	0.024	0.026	0.036
	Deep	9	69	0.022	0.017	0.024	0.024	0.024	0.024	0.025	0.034
Den Hill	Surface	9	67	0.043	0.023	0.071	0.040	0.069	0.049	0.086	0.122
	Mid	9	67	0.034	0.022	0.056	0.040	0.060	0.048	0.096	0.139
	Deep	9	67	0.045	0.023	0.053	0.045	0.064	0.051	0.095	0.171

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 2023 (Figure 40). Similar to last year's pattern, seasonality in UV_{254} absorbance was well established for Den Hill, with higher UV_{254} absorbances during winter and spring mainly. Unlike last year, higher UV_{254} absorbances were also observed during fall in the epilimnion and metalimnion of Den Hill, likely attributed to potential increased loading from the East Branch Swift River during high stream flow events in the late summer and fall.

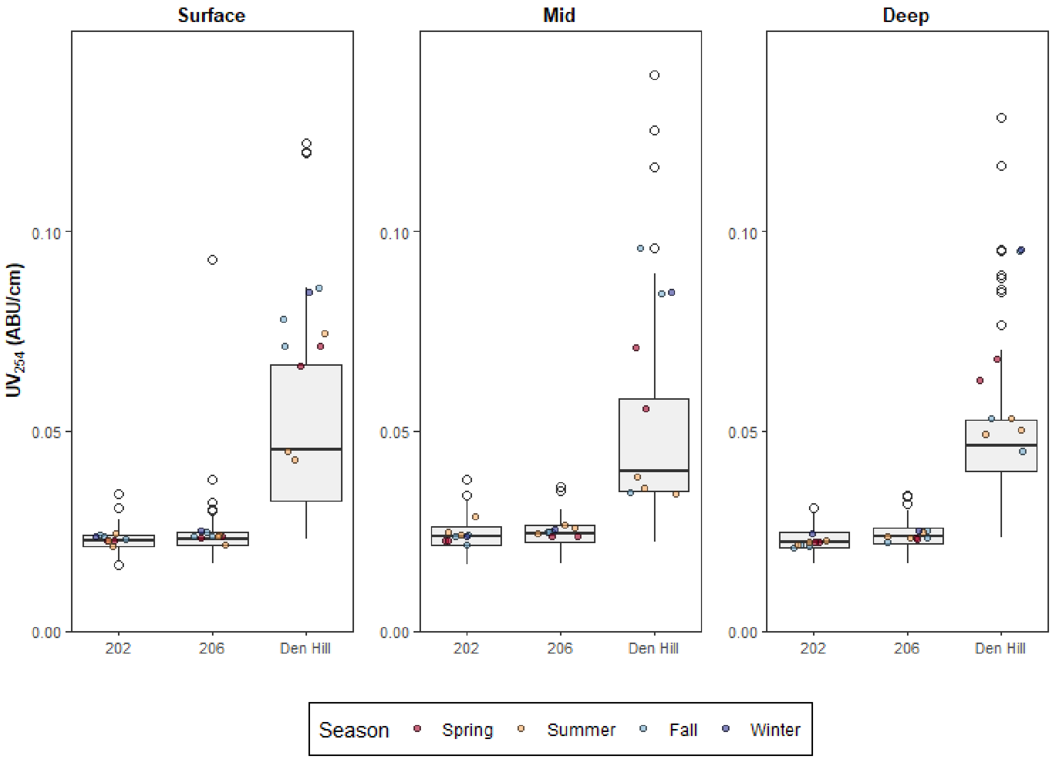


Figure 40. Boxplots depicting the seasonal and vertical distributions of UV_{254} observed in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2023 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record 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.

3.4.9.4.2 Total Organic Carbon

Routine monitoring for total organic carbon (TOC) in Quabbin Reservoir began in 2020. TOC concentrations ranged from a minimum of 1.68 to 3.83 mg/L in 2023 (Table 52). TOC concentrations in 2023 were slightly higher but comparable to those observed during monitoring in 2020, 2021, and 2022 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 2023 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 previous years, TOC exhibited little variability with depth or changes in stratification (Figure 41). Unlike last year, TOC concentrations showed little seasonal variation due to higher concentrations during the summer and fall compared to observations from 2022. The difference in seasonal TOC variability between 2022 and 2023, is likely attributed to the difference in riverine inputs during drought conditions (2022) and flood conditions (2023) across MA (Raymond and Saiers, 2010; Yoon and Raymond 2012).

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 52. Descriptive statistics for total organic carbon measured in Core reservoir monitoring sites in the Quabbin Reservoir in 2022 relative to the period of record (POR).

		Total Organic Carbon (mg/L)									
		Count		***Minimum***		***Median***		***Mean***		***Maximum***	
Location	**Depth**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**	**2023**	**POR**
202	Surface	9	26	2.05	1.89	2.41	2.17	2.41	2.18	2.68	2.44
	Mid	9	26	1.99	1.74	2.25	2.08	2.25	2.14	2.64	2.79
	Deep	9	26	1.68	1.60	1.95	1.98	2.01	1.97	2.42	2.36
206	Surface	9	25	1.95	1.82	2.28	2.23	2.32	2.21	2.66	2.53
	Mid	9	26	2.11	1.84	2.40	2.14	2.40	2.16	2.69	2.56
	Deep	9	24	1.91	1.66	2.41	2.09	2.33	2.07	2.58	2.49
Den Hill	Surface	9	26	2.94	2.03	3.03	2.49	3.16	2.53	3.57	3.32
	Mid	9	26	1.98	1.86	2.96	2.36	2.80	2.42	3.59	3.19
	Deep	9	26	2.24	1.92	2.76	2.29	2.79	2.38	3.83	3.21

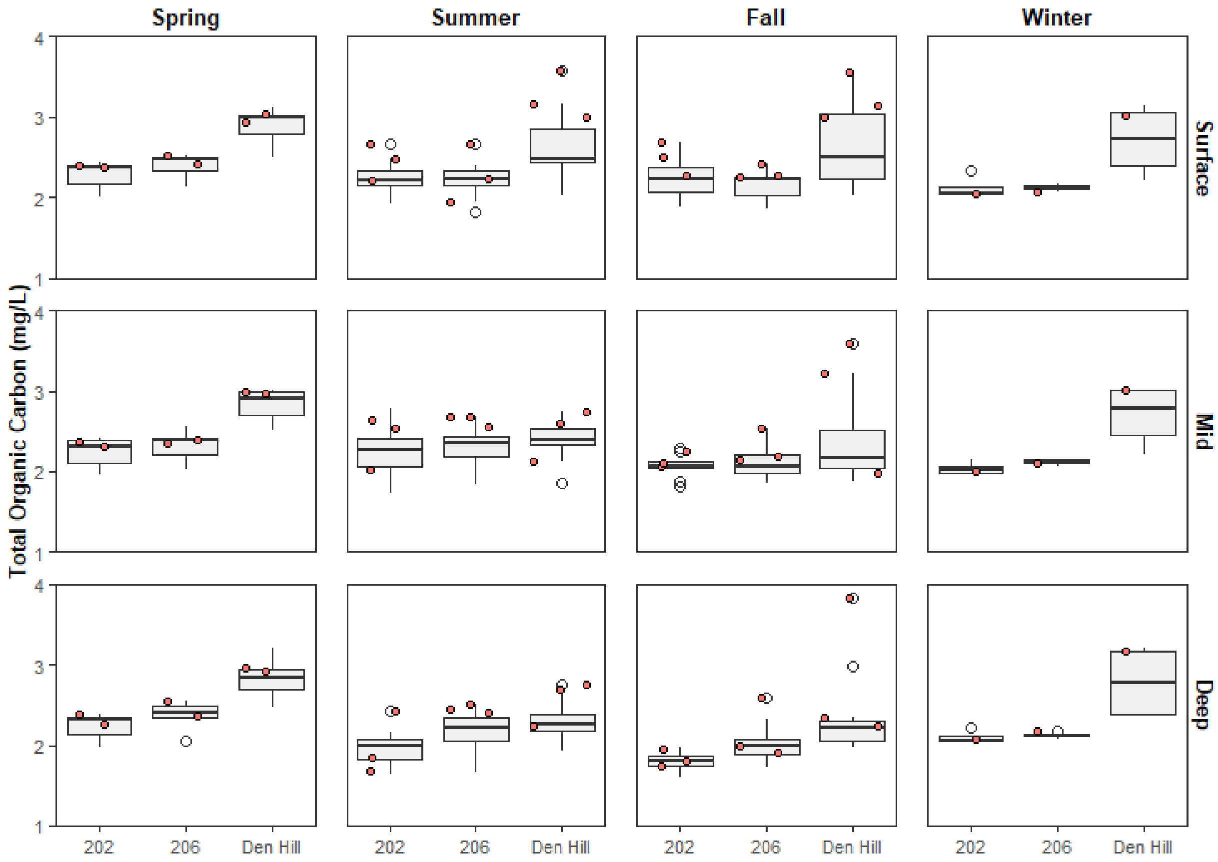


Figure 41. Boxplots depicting the seasonal and vertical distributions of TOC in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2023 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented 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.

3.4.10 Phytoplankton

Samples for phytoplankton enumeration were collected from Quabbin Reservoir core monitoring sites 202, 206, and Den Hill on 29, 12, and 11 days in 2023, 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 weekly during the growing season from May through September. At sites 206 and Den Hill, samples were collected monthly (weather and ice conditions permitting) year-round. Under special circumstances (e.g., exceedance of alert levels, see Table 53) sampling frequency of phytoplankton was increased, and additional samples were collected based on *in-situ* readings of chlorophyll *a* and dissolved oxygen.

The first samples of the year were collected on January 25, 2023, at all sites. The reservoir partially froze over in mid-February which prevented sampling at Den Hill until April 10, 2023. Access to sites 202 and 206 were ice-free all winter long, allowing sampling of these two sites year-round. For the majority of the year, total phytoplankton densities in 2023 remained below 300 ASU/mL at both 202 and 206. However, elevated densities of diatoms in the spring and cyanophytes in the summer, drove total densities at 206 and 202 to the maximum observed values in 2023. At site 202, the maximum total density observed was 685 ASU/mL and was driven by late summer cyanophytes (mainly *Aphanocapsa* and *Anathece*). In contrast, the maximum total density observed at site 206 (937 ASU/mL) was observed in the spring and was driven by diatoms (mainly *Asterionella;* Figure 42).

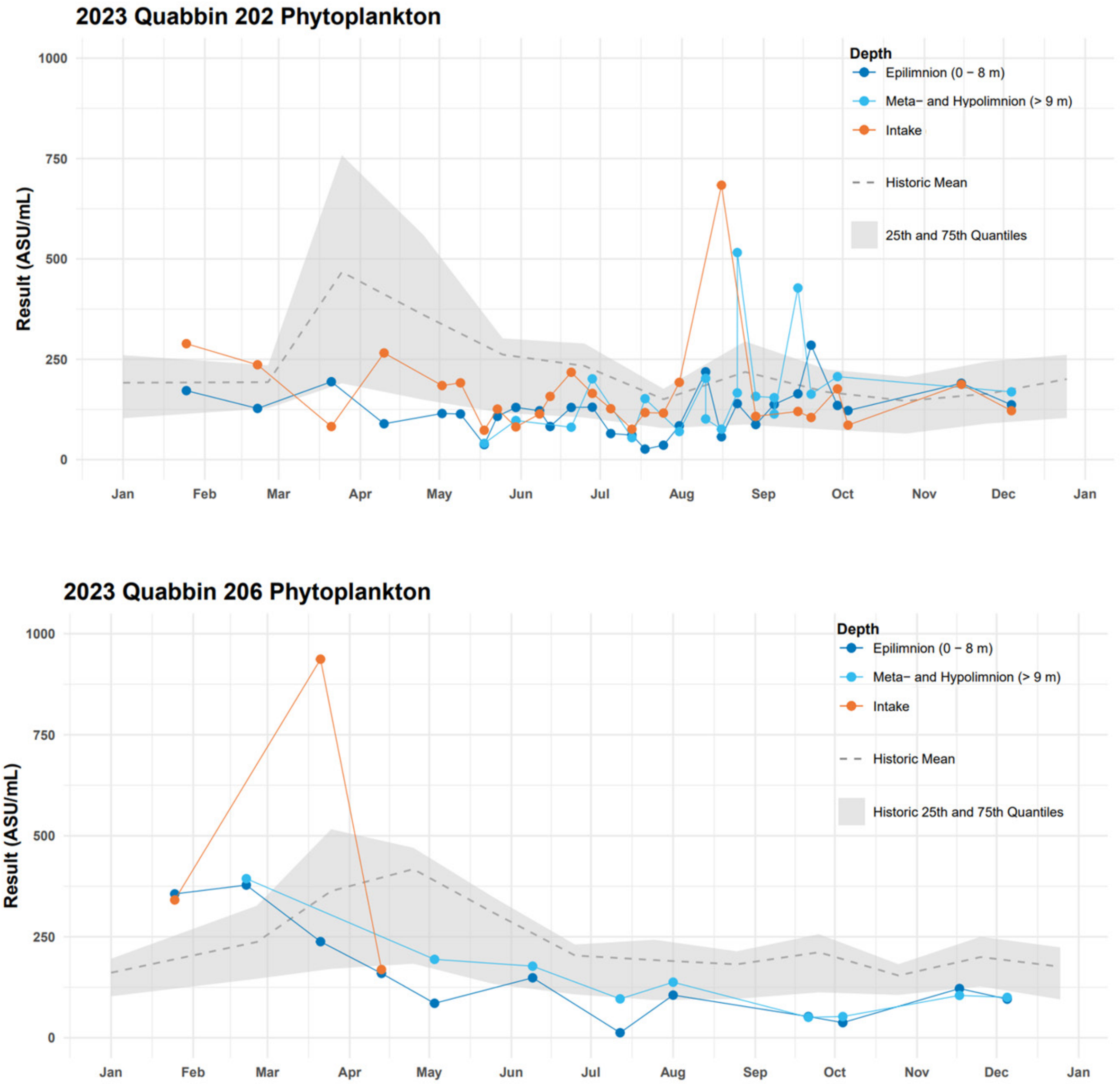


Figure 42. Total phytoplankton densities during 2023 from sampling sites 202 (top) and 206 (bottom). Sample classification (epilimnion or meta- and hypolimnion) based on depth as defined by summer temperature profiles. The average for historical data covering 2007-2023 is indicated by the dashed line, with 25th and 75th quantiles represented as gray bands, corresponding to all sample depths.

At site 202, stratification of the water column began building in mid-April and was fully achieved by May 9, 2023. As is typically observed in Quabbin Reservoir, spring samples from all sites were dominated by diatoms, with the highest densities corresponding to *Asterionella* and *Tabellaria*. Following increased stability of stratification in late May, phytoplankton diversity increased following a slight decline in total densities (Figure 42). This is likely explained by a depletion of available nutrients limiting growth, and increasing competition, resulting in a shift in community composition (Cole & Weihe, 2016). Community composition shifted from diatom dominance driven mainly by *Asterionella*, to a greater variety (albeit at lower densities) of chlorophytes, chrysophytes, and cyanophytes (Figure 43). Starting in July, an increase in cyanophytes was observed at both sites, eventually becoming the dominant phytoplankton group for the remainer of the year. 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). Unlike previous years (2019, 2021, and 2022), *Chrysosphaerella* aggregations were not observed in 2023.

Densities at different sampling depths exhibited similar patterns across sites. The epilimnion samples typically had lower densities than samples collected from the metalimnion and hypolimnion. This was particularly true during the spring and late summer period of elevated densities previously discussed, which did not affect the 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 in January and February at site 206 (see Figure 42). Unlike previous years, phytoplankton community composition did not differ across depths. Comparable community composition was observed in the epi, meta, and hypolimnion of each site.

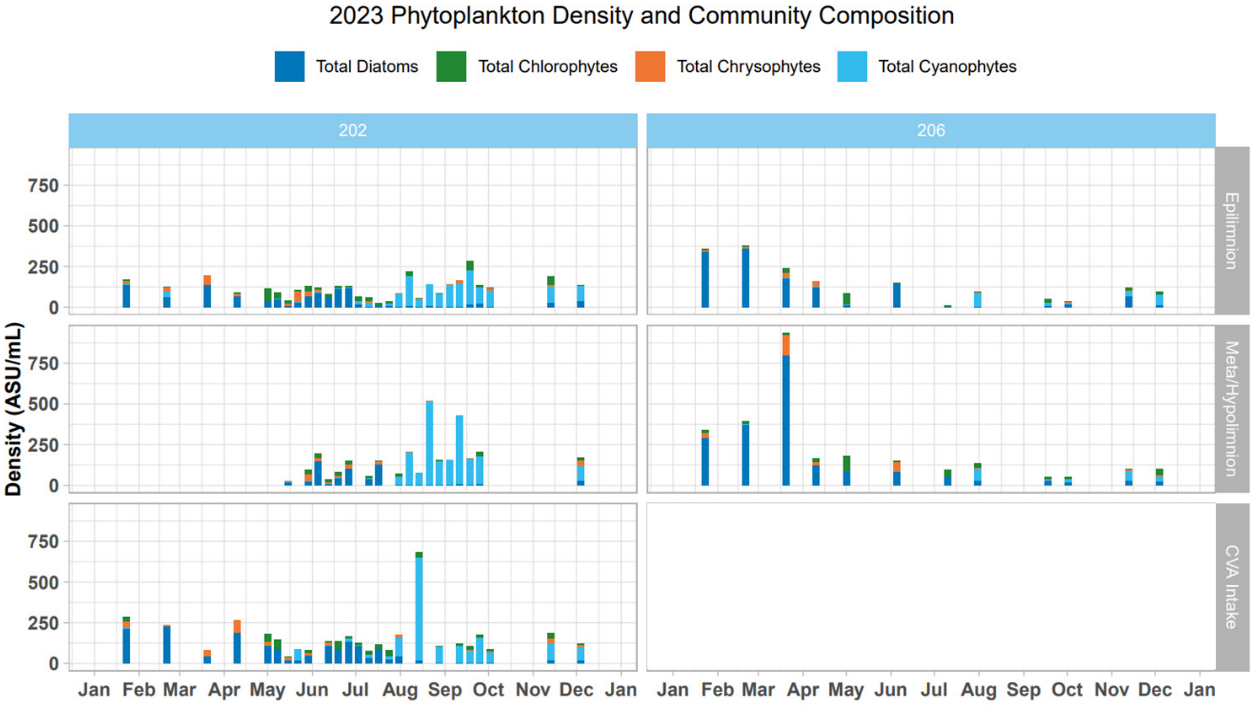


Figure 43. Phytoplankton community composition, observed in 2023 from the epilimnion and meta/hypolimnion at sampling sites 202 and 206. Additional samples were taken at the CVA intake depth at sampling site 202.

Overall total densities and changes in community composition were consistent with trends observed in the Quabbin Reservoir over the last five years. These dynamics are also typical of oligotrophic systems. Same as in 2023, monitoring for phytoplankton in Quabbin Reservoir will be conducted monthly (October through April) or weekly (May through September) at site 202, and monthly at sites 206 and Den Hill in 2024. 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 modified 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, often resulting in higher phytoplankton densities.

To better understand the impact of riverine inputs on phytoplankton dynamics in the reservoir, site Den Hill was added to the phytoplankton monitoring protocol in 2022. Samples were collected monthly starting in January 25 and then again on April 10, 2023. Den Hill was inaccessible in February and March due to ice condition on the reservoir. Overall, phytoplankton dynamics (densities and community composition) at Den Hill showed similar patterns to what was observed for sites 202 and 206. Phytoplankton densities were low at Den Hill year-round, with higher densities in the winter followed by a decrease during spring and summer, and a slight increase in the late summer and fall (Figure 44). Den Hill had the lowest maximum total density of all three sites in 2023. The maximum total density at Den Hill was 360 ASU/mL, observed at 3 m on January 25, 2023. Phytoplankton community composition at Den Hill was similar to what was observed at the other two sites with diatoms dominating the community in winter and spring and higher diversity observed in the summer and fall. Phytoplankton monitoring at Den Hill will continue on a monthly basis in 2024.

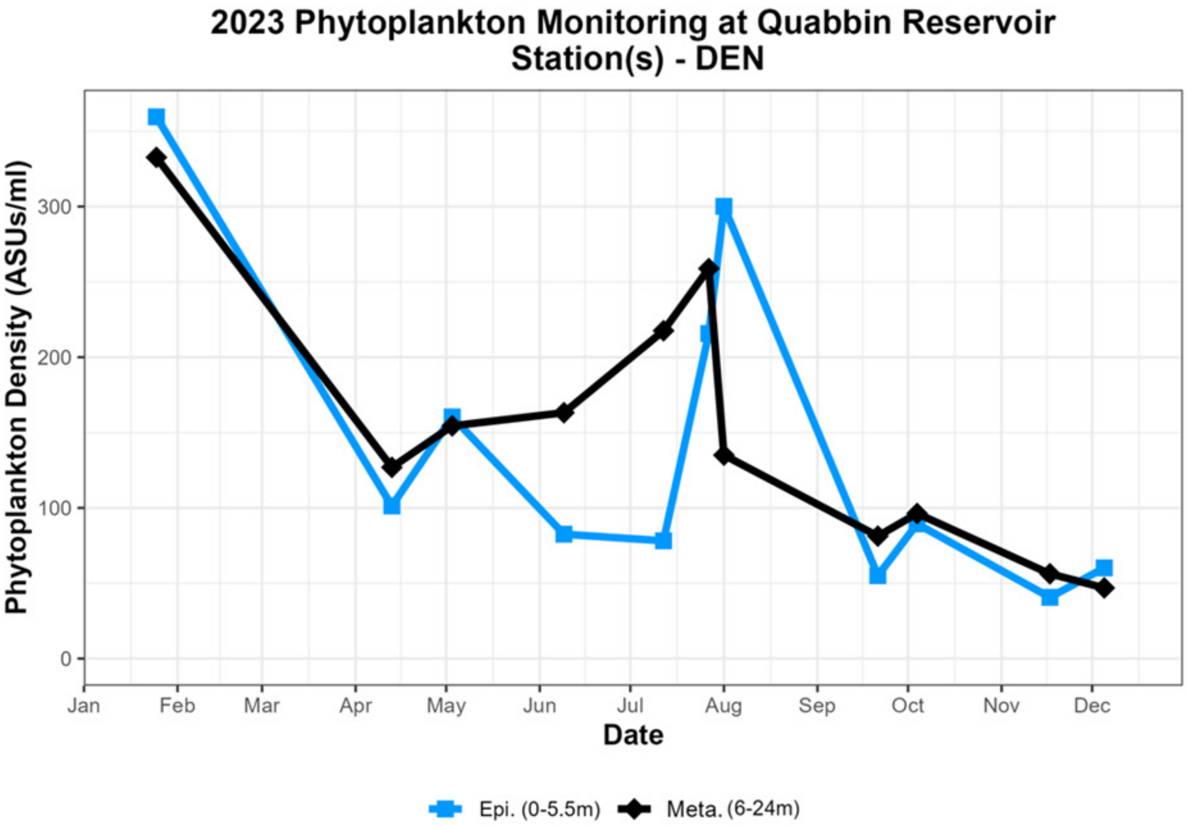


Figure 44. Total phytoplankton densities during 2023 from sampling site Den Hill. Sample classification (epilimnion or meta- and hypolimnion) based on depth as defined by summer temperature profiles. Samples collected from the epilimnion are shown in blue and samples collected from the meta-and hypolimnion are shown in black. Due to ice conditions on the reservoir, site Den Hill was not sampled between January 26 and April 12, 2023.

3.4.10.1 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, 2019a). Chrysophyte densities have been elevated over the past four 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 53).

Table 53. Nuisance phytoplankton alert levels in MWRA source waters.

Nuisance Organism		
Class	**Genus**	**Quabbin Reservoir Alert Levels (ASU/mL)**
Cyanophyte	*Dolichospermum*	15
Chrysophyte	*Synura*	10
Chrysophyte	*Chrysosphaerella*	100
Chrysophyte	*Uroglenopsis*	200
Chrysophyte	*Dinobryon*	200

Chrysosphaerella was the only taxa of concern to exceed the established alert levels in 2023 (Figure 45), and only on one occasion. On July 12, 2023, *Chrysosphaerella* levels at Den Hill (12 m) exceeded the established *Chrysosphaerella* alert level by 9 ASU/mL (total *Chrysosphaerella* density observed was 109 ASU/mL). Due to the exceedance of the alert level, monitoring frequency was increased from monthly to twice a month at Den Hill to track *Chrysosphaerella* levels and determine if an aggregation was occurring. On July 27, 2023, samples were collected again from Den Hill and *Chrysosphaerella* was not observed. The rest of the chrysophytes of concern (*Synura*, *Dinobryon*, and *Uroglenopsis*) were observed in 2023, but remined at low densities. *Dolichospermum* was observed during the summer and fall, but below countable densities.

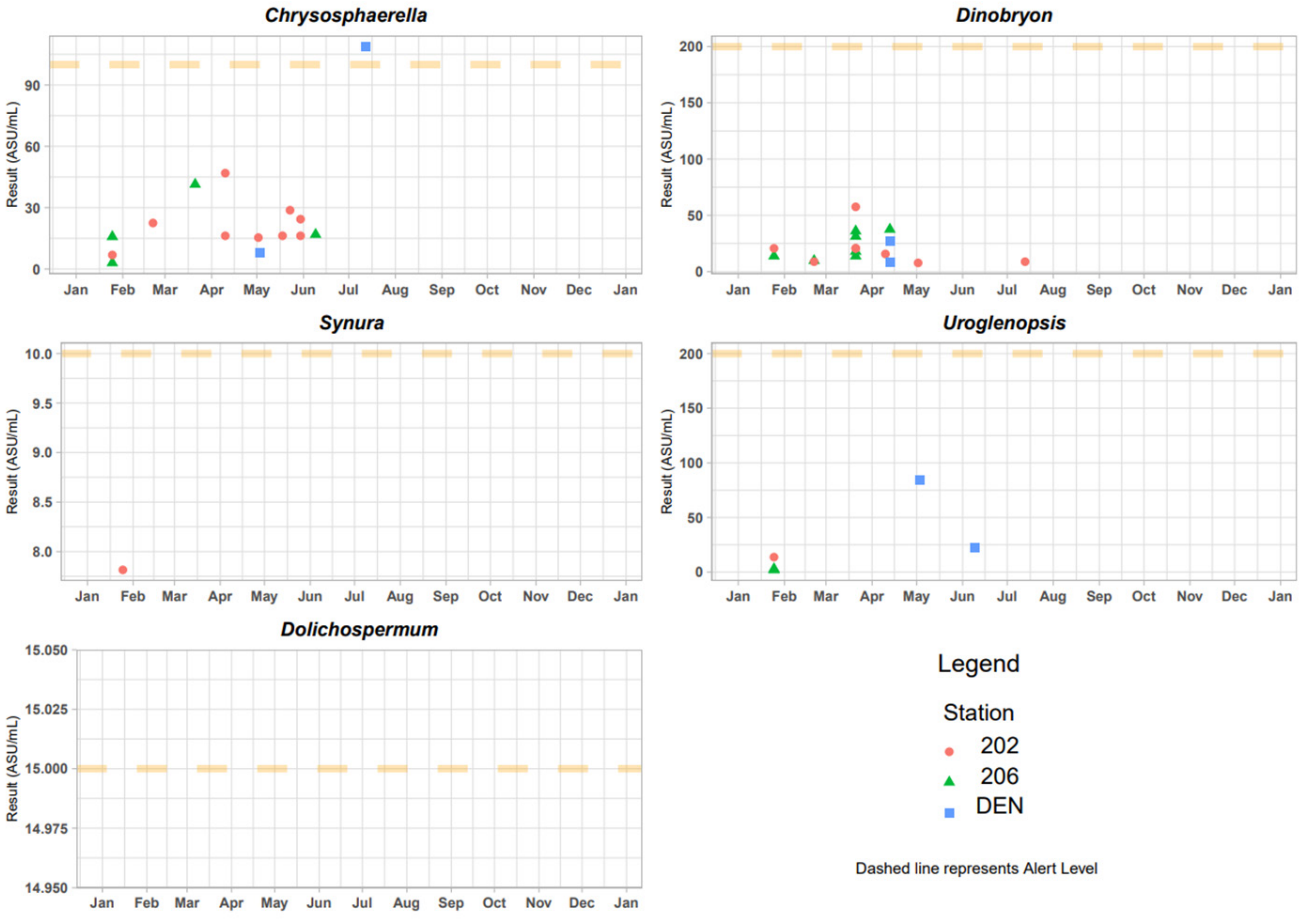


Figure 45. Occurrence of nuisance phytoplankton taxa at Quabbin sampling sites 202, 206, and Den Hill (DEN) during 2023. Dashed line represents the established alert levels specific to each taxa. Lack of occurrence indicates that taxa were not observed during regular monitoring.

3.5 Aquatic Invasive Species Monitoring and Management

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). 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 MWRA contractors. 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 observed AIS presence in the reservoir and watersheds during the 2023 survey season, and documents the prevention and management programs currently in place within the watersheds.

3.5.1 Invasive Aquatic Macrophyte Monitoring and Distribution

Aquatic 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 Environmental Quality Assessment (EQA) 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). Within the past 10 years, 46 different watershed ponds (including the Reservoir holding ponds, Prescott Peninsula ponds, and the Ware River itself) across the two watersheds were surveyed either annually or within the EQA schedule.

The following sections summarize the distribution of invasive aquatic macrophytes in the reservoir, the Quabbin Reservoir Watershed, and Ware River Watershed (Table 54). In 2023, three waterbodies were surveyed for aquatic macrophytes in the Quabbin Reservoir Watershed. In addition to these ponds, the reservoir’s Boat Launch Areas 1, 2, 3, and the two holding ponds (O’Loughlin and Pottapaug Ponds) were also surveyed. A total of five water bodies were surveyed in the Ware River Watershed in 2023. The 2023 EQA Districts were the Quabbin Reservation and West Branch Ware, with one pond belonging within these districts. Other waterbodies belonged to the Coldbrook and Longmeadow, East Branch Swift, East Branch Ware, Fever Brook, Quabbin Northwest, and West Branch Ware districts. In addition, two waterbodies surveyed were located outside of the watersheds, and were included in survey efforts due to their proximity to the Quabbin Reservoir.

Table 54: Aquatic invasive species observed in the Quabbin Reservoir, Quabbin Reservoir Watershed, and Ware River Watershed since the beginning of the AIS program. Quabbin Reservoir includes O'Loughlin and Pottapaug holding ponds. No evidence of true forget-me-not (in reservoir) since 2012, one row yellowcress since 2013 (in reservoir) and 2016 (both watersheds), brittle naiad found since 2014, fanwort since 2015 (Quabbin Watershed), or swollen bladderwort (both watersheds) since 2017.

		Documented Presence		
Scientific Name	**Common Name**	**Quabbin Reservoir**	**Quabbin Reservoir Watershed**	**Ware River Watershed**
Cabomba caroliniana	Fanwort		x	x
Iris pseudacorus	Yellow Flag Iris	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

3.5.1.1 Contracted Aquatic Macrophyte Surveys

Annually since 2013, MWRA contractors carry out point-intercept surveys of DWSP/MWRA source and emergency reservoirs. This year, MWRA contracted with GEI Consultants. *Utricularia inflata* (swollen bladderwort)*,* was documented this year within O'Loughlin Pond, Pottapaug Pond, and BLA3. Although the population within Pottapaug Pond was already known to DCR and MWRA, the others were not. More intensive surveys and possible management of these areas are planned for 2024.

Myriophyllum heterophyllum (variable leaf milfoil) was the only other documented submersed AIS found in both the Quabbin Reservoir and Ware River Watersheds. Emergent invasives are not specifically included in the contractor point-intercept surveys, but the continued presence of *Phragmites australis* in the Quabbin Reservoir was noted. The extent and density of *M. heterophyllum* in Quabbin Reservoir increased slightly compared to 2022 (observed at 16.2% of surveyed points; GEI, 2024).

3.5.1.2 *Cabomba caroliniana*

Cabomba caroliniana (fanwort) originates from the southeastern United States (Texas to Virginia) and was introduced outside its range through the aquarium plant trade, where it then spread via dumping and cultivation (Bickel, 2015; Bickel, 2017; Schooler et al., 2009). *C. caroliniana* reproduces via fragmentation, allowing it to spread quickly and outcompete native species. Unmanaged, this species will form dense mats at the water's surface, crowding out other plants and creating hazards for recreationists (Schooler et al., 2009). The long stems impede boats and can get tangled in propellers, paddles, and fishing lines. In addition, swimmers can also become entangled (Schooler et al., 2009). Like other mat-forming AIS, *C. caroliniana* can alter water quality and native composition by nutrient loading and decreasing available dissolved oxygen. Methods of control for this species attempt to limit fragmentation by using chemical treatments, drawdowns, biological control, or manual removal.

Although not present in the Quabbin Reservoir, *C. caroliniana* has been found in both watersheds with the first instance reported in Queen Lake (Phillipston, MA) in 2010. Since then, this species has spread to several other waterbodies within the watersheds. No new infestations were found during the 2023 survey season (Table 55).

In both Queen Lake and Demond Pond where *C. caroliniana* has been observed, and where a local lake association is present, management efforts have relied on chemical treatments to control this AIS. As of the 2022 survey, the population at Queen Lake seems to have dropped below detectable levels. Further surveys are required before we can say the population has been completely removed. In Demond Pond however, this species regularly rebounds following treatment, and annual control efforts will be required. In other waterbodies with no management efforts, *C. caroliniana* has spread throughout the waterbody, in some cases becoming the dominant plant, growing in dense and widespread beds.

Table 55: Ponds with *Cabomba caroliniana* present during the 2023 AIS survey with survey dates and date of first observation.

Waterbody Name	Town	Watershed	Last Obs.	First Obs.
Demond Pond	Rutland	Ware River	07/28/2023	09/07/2017
Long Pond	Rutland	Ware River	08/09/2023	08/06/2021

3.5.1.3 *Myriophyllum heterophyllum*

Myriophyllum heterophyllum (variable-leaf milfoil) is the most frequently encountered submersed AIS in the watersheds. Although native to the southeastern United States, *M. heterophyllum* is considered invasive in the northeastern states (Bailey, 2007). This species mainly spreads via seeds and fragmentation, where stem pieces with at least one node can regrow into a viable plant (Bailey, 2007; Gross et al., 2020; Halstead et al., 2003). As a result, this species can colonize and outcompete native species within a short period of time, making prevention and rapid response crucial to its management. Unfortunately, *M. heterophyllum* can grow undetected until it is already well-established (Halstead et al., 2003), resulting in higher management costs and effort. When left unchecked, this species creates dense mats throughout the water column, creating boating hazards (clogging propellers and fishing lines), swimming hazards, and decreasing native species' diversity (Bailey, 2007; Halstead et al., 2003). In addition, large amounts of decaying plant matter increase nutrient loading (phosphorus and nitrogen) which reduces dissolved oxygen levels that other species (namely fish) require (Halstead et al., 2003). Due to fragmentation, removal efforts seek to keep the plant intact by utilizing either diver assisted suction harvesting (DASH), herbicide treatments, or covering with benthic barriers.

M. heterophyllum is well distributed in portions of Quabbin Reservoir, with established populations at Boat Launch Areas 2 and 3 and the holding ponds (O'Loughlin and Pottapaug). In addition, *M. heterophyllum* is well established in the Ware River, most notably at (and upstream of) the Shaft 8 intake. 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 2023 DWSP-EQ surveys (Table 56).

Management of *M. heterophyllum* is conducted annually by DCR contractors above and below the Ware River Shaft 8 intake. This year, the macrophyte survey was conducted by GEI Consultants, with removal efforts by DRG (see section 3.5.3.1 for more information). In addition, the Asnacomet "Comet" Pond Lake Association has been working with DCR Lakes & Ponds since 2018, when *M. heterophyllum* was discovered, to manage plants. With financial support from DWSP, management efforts have included hand-harvesting and diver-assisted suction harvesting (DASH). Asnacomet Pond was surveyed again this year by DCR-Lakes & Ponds staff, with financial assistance totaling $7,900 from DWSP. Limited hand-harvesting occurred due to the lack of *M. heterophyllum* present at time of harvest (8 hours = 1 gallon of material removed). Personnel hours originally allocated for hand harvesting in 2023 have been pushed to the 2024 season.

Table 56: Ponds with *Myriophyllum heterophyllum* present during the 2023 AIS survey with survey dates and date of first observation.

Waterbody Name	Town	Watershed	Last Obs.	First Obs.
Boat Area 2 Shoreline	New Salem	Quabbin Reservoir	07/11/2023	2006
Boat Area 3 Shoreline	Petersham	Quabbin Reservoir	07/19/2023	2006
Demond Pond	Rutland	Ware River	07/28/2023	08/13/2010
Lake Mattawa	Orange	Quabbin Reservoir	09/01/2023	07/20/2001
Long Pond	Rutland	Ware River	08/09/2023	08/13/2010
O'Loughlin Pond	New Salem	Quabbin Reservoir	07/11/2023	2006
Pottapaug Pond	Hardwick	Quabbin Reservoir	09/08/2023	2006
Whitehall Pond	Rutland	Ware River	06/29/2023	10/14/2010

3.5.1.4 *Najas minor*

Najas minor (brittle naiad) was introduced to North America in the early 20th century from its native range of Eurasia and northern Africa (Wentz & Stuckey, 1971; Les et al., 2015; Volk, 2019). Although the exact method of introduction is unknown, its spread has been attributed to cultivation escapes and waterfowl food propagation programs (Les et al., 2015). Spreading mainly via seed dispersal (Les et al., 2015; Volk, 2019), *N. minor* has been documented throughout much of the eastern United States. Waterfowl and recreational equipment assist in *N. minor*'s dispersal, as the small and inconspicuous seeds remain viable after consumption and can cling to the outside of boats, trailers, and other equipment that come in contact with water (Volk, 2019). Although fragmentation itself does not produce separate viable plants, the fragments carry seeds that are then dispersed throughout the waterbody (Volk, 2019). Similar to other mat-forming AIS, *N. minor* can displace native plants, and impacts recreational activities such as swimming, boating, and fishing (Les et al., 2015; Volk, 2019).

N. minor was first documented by contractors 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 was quickly harvested using DASH, and have not been observed since. This invasive has not been found elsewhere in the Quabbin Reservoir Watershed, or in the Ware River Watershed.

3.5.1.5 *Potamogeton crispus*

Potamogeton crispus (curly-leaf pondweed) was first observed in Philadelphia in the 1840s, and is native to Eurasia, Africa, and Australia (Bolduan et al., 1994; Zhou et al., 2017). By the 1860s, *P. crispus* was abundant within the Lehigh River in Pennsylvania and Delaware, and by the 1880s had spread to Massachusetts and New York (Bolduan et al., 1994). The spread of this species seems to be associated with fish hatchery activity, as early reports from several states were either found in fish hatchery ponds or waters associated with them (Bolduan et al., 1994). Unlike other plant species that remain dormant in winter, *P. crispus* acts like a winter annual, continuing to grow during the winter season (Bolduan et al., 1994; Johnson et al., 2012; Zhou et al., 2017). This species reproduces via rhizomes and turions, which sprout in the fall and grow rapidly in the early spring, senescing and depositing turions in the sediment by midsummer (Bolduan et al., 1994; Johnson et al., 2012; Zhou et al., 2017). Although this plants' impact on native macrophytes is still being researched, it has been found to impact phosphorus (Owens et al., 2007), nitrogen, and other heavy metals (Zhou et al., 2017), acting as a nutrient loader once this species has senesced.

P. crispus was first identified in 2013 at Whitehall Pond, a waterbody located within Rutland State Park and owned by DCR. Fortunately, this species has not been observed elsewhere within either watershed. As Whitehall Pond has a DCR-owned beach, management and treatment is overseen by DCR Lakes & Ponds. Beginning in 2013, management of *P. crispus* has included mechanical and hand harvesting, as well as chemical control. These treatment actions have reduced *P. crispus* densities, however some plants are still present – most likely from turions sprouting after treatment occurred.

The 2023 macrophyte survey found no new infestations of *P. crispus*. Populations at Whitehall Pond were sparse, and had already begun to senesce, either due to warming weather or due to treatment (Table 57).

Table 57: Ponds with *Potamogeton crispus* present during the 2023 AIS survey with survey dates and date of first observation.

Waterbody Name	Town	Watershed	Last Obs.	First Obs.
Whitehall Pond	Rutland	Ware River	6/29/2023	08/06/2013

3.5.1.6 Phragmites australis

Phragmites australis (common reed) is the most widely distributed emergent AIS in the Reservoir and the watersheds. Unlike other AIS, not all *P. australis* are invasive. This species has 3 distinct subspecies (ssp.) – ssp. *americanus* (native), ssp. *berlandieri* (native), and ssp. *australis* (invasive) (Lambert et al., 2010; Hazelton et al., 2014). Here-after, *P.* australis is referring to the invasive subspecies. *P. australis* is native to Europe, and has spread to most of the U.S., occupying areas where the native subspecies inhabit and areas where they do not (Lambert et al., 2010). This AIS can spread via seed, but the main method is clonal propagation via rhizomes and stolons (Meyerson et al., 2000; Lambert et al., 2010; Hazelton et al., 2014). This allows *P. australis* to spread rapidly once introduced to an area, becoming denser and larger in the following years, and resulting in reductions in native plant biodiversity (Warren et al., 2001), declines in habitat quality for native fauna (Able & Hagan, 2003), and disruptions to natural nutrient cycling (Meyerson et al., 2000; Hazelton et al., 2014). Although labor intensive, pioneer or small infestations may be eradicated with annual management efforts and should be prioritized before they become dense established stands. Potential management practices include mechanical harvesting (excavation, cutting, hand-pulling, and benthic barriers) and herbicides (Warren et al., 2001; Hazelton et al., 2014). Each method has benefits and drawbacks, and use should be tailored to the area and management plan goals.

P. australis is well established throughout the reservoir, forming dense patches along the shoreline. In addition, '*Phragmites* islands' have formed in some shallow locations of the reservoir where this AIS completely dominates. Due to the presence of native subspecies, *P. australis* can be difficult to identify at early growth stages, and observations made at this stage are preliminary and require additional visits to confirm the ID. Observations made at O'Loughlin Pond during the 2023 DWSP-EQ survey fall into this category and have not been confirmed. No other new infestations were found during the 2023 DWSP-EQ survey season (Table 58).

Table 58: Ponds with *Phragmites australis* present during the 2023 AIS survey with survey dates and date of first observation.

Waterbody Name	Town	Watershed	Last Obs.	First Obs.
Boat Area 3 Shoreline	Petersham	Quabbin Reservoir	07/19/2023	08/11/2014
Long Pond	Rutland	Ware River	08/09/2023	09/07/2018
O'Loughlin Pond	New Salem	Quabbin Reservoir	07/11/2023	07/11/2023
Pottapaug Pond	Hardwick	Quabbin Reservoir	09/08/2023	1970s

3.5.1.7 Utricularia inflata

Utricularia inflata (swollen bladderwort) is a carnivorous aquatic plant native to much of the southeastern coastline, from Texas and Florida to Delaware (Titus & Grisé, 2009). This AIS has since expanded its range, first observed in the Adirondack Mountains in 1999 (Titus & Grisé, 2009; Urban & Titus, 2010), and now also present in several northeastern states including Massachusetts. *U. inflata* spreads via seeds and fragmentation, where its vegetative propagules separate from the main stem to form an independent plant (Urban & Dwyer, 2016). Unmanaged, this species will form dense mats at the water's surface, creating recreational hazards, disrupting the native food web, and altering water chemistry. Due to its carnivorous nature (Miranda et al., 2021), *U. inflata* competes with native species (such as fish larva/fry) that feed on aquatic insect larva, disrupting the food chain. In addition, due to its mat-forming properties, *U. inflata* can increase light attenuation and cause the extirpation of native species (Urban & Dwyer, 2016).

U. inflata was first documented in the Ware River Watershed and Quabbin Reservoir (Boat Launch Area 2) in 2017. The single plant at BLA2 was removed, and no additional plants have been found there since. Although no observations of *U. inflata* have been made since 2019 in either watershed, identification of this species when not in bloom is difficult, and it is possible the seasonality of surveys affects our understanding of its presence and distribution.

Unfortunately, this species seems to have gone undetected, as in May of 2023 several plants were caught in the fragment barrier at Boat Launch Area 3 (Table 59). In response, DCR Aquatic Biologists extensively surveyed Pottapaug Pond to map *U. inflata* population distribution. To prevent immediate spread, the boat launch on Pottapaug Pond was closed to private boaters and removal efforts began. Due to the extent of the infestation, contractors were brought on through a MWRA contract, and will return in 2024 to continue removal efforts. See Pottapaug summary report in Appendix Section 6.2.2 for more information.

Table 59: Ponds with *Utricularia inflata* present during the 2023 AIS survey with survey dates and date of first observation.

Waterbody Name	Town	Watershed	Last Obs.	First Obs.
Pottapaug Pond	Hardwick	Quabbin Reservoir	06/26/2023	05/26/2023

3.5.1.8 Iris pseudacorus

Iris pseudacorus (yellow flag iris) is an invasive species that closely resembles the native blue flag iris when not flowering. Originally introduced as a horticultural plant to North America in the 1900s (Jacobs et al., 2010; Stoneburner et al., 2021), *I. pseudacorus* has spread throughout most of the United States. Although terrestrial in nature, this species is closely tied to wetlands, and is often found along shorelines. *I. pseudacorus* spreads via seeds and rhizomes and may experience 'rhizome splitting', resulting in separate plants from the original (Sutherland, 1990; Jacobs et al., 2010; Hayasaka et al., 2018). If left unmanaged, *I. pseudacorus* can alter riparian zones by out-competing native sedges and rushes that support waterfowl and other native species (Jacobs et al., 2010; Hayasaka et al., 2018). It may also create dense stands that impede water flow (Stoneburner et al., 2021).

I. pseudacorus has been documented in the reservoir and within both watersheds (Table 60). This species 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 that this population is the source of plants observed in Pottapaug Pond and at Boat Launch Area 3 from seed pods floating down stream. In 2019, the fragment barrier at Area 3 was repositioned to catch floating seed pods more effectively.

No new *I. pseudacorus* infestations were observed during the 2023 DWSP-EQ surveys.

Table 60: Ponds with *Iris pseudacorus* present during the 2023 AIS survey with survey dates and date of first observation.

Waterbody Name	Town	Watershed	Last Obs.	First Obs.
Asnacomet "Comet" Pond	Hubbardston	Ware River	09/22/2023	06/17/2021
Boat Area 3 Shoreline	Petersham	Quabbin Reservoir	07/19/2023	08/24/2022
Demond Pond	Rutland	Ware River	07/28/2023	08/17/2017
Pottapaug Pond	Hardwick	Quabbin Reservoir	09/08/2023	2015

3.5.1.9 Lythrum salicaria

Lythrum salicaria (purple loosestrife) originates from Eurasia and was introduced to North America in the early 1800s (Stuckey, 1980; Mullin, 1998; Nagel & Griffin, 2001; Blossey et al., 2001). Since then, it has spread throughout most of the United States, usually inhabiting wetlands, marsh-like, or riparian sites (Mullin, 1998; Nagel & Griffin, 2001). *L. salicaria* is a prolific invasive, producing as many as 2.7 million seeds annually, which create long-lived seed banks that require regular maintenance to keep to manageable levels (Nagel & Griffin, 2001; Henne et al., 2005; Mahaney et al., 2006). If left unchecked, *L. salicaria* can disturb the native ecosystem by outcompeting native plants for space (Stuckey, 1980), decreasing food sources for songbirds, and reducing suitable nesting habitat for waterfowl (Mullin, 1998; Henne et al., 2005). Management of this species is usually either mechanical harvesting or chemical treatment (Mullin, 1998; Henne et al., 2005).

L. salicaria was first documented in 2011 in both watersheds. Since then, this invasive species has spread from the initial three waterbodies to almost twenty, with varying degrees of infestation levels (individual plants to small clusters). This plant is difficult to identify when not in bloom, making accurate estimates of its extent throughout the watersheds difficult to attain. Despite this, populations of *L.* salicaria do not appear to be changing rapidly year to year, demonstrating a relatively low threat to water quality. No new infestations were observed during the 2023 DWSP-EQ surveys (Table 61).

Table 61: Ponds with *Lythrum salicaria* present during the 2023 AIS survey with survey dates and date of first observation.

Waterbody Name	Town	Watershed	Last Obs.	First Obs.
Demond Pond	Rutland	Ware River	07/28/2023	08/06/2013
Long Pond	Rutland	Ware River	08/09/2023	08/19/2013

3.5.1.10 *Myosotis scorpioides*

Myositis scorpioides (true forget-me-not) is native to Eurasia, and although not considered a true aquatic plant, it does inhabit wet disturbed shorelines. Now found throughout the United States, *M. scorpioides* has naturalized in many areas, but has remained a potential invasive within the New England states. Scientific research regarding this species is sparse, resulting in a relatively unknown impact to water quality and native wetland vegetation. When not blooming, *M. scorpioides* can be difficult to identify, and may account for variations in observed populations from year-to-year. As a result, any populations observed during DWSP-EQ surveys are monitored and removed as needed. This species spreads via seed production and through an extensive and shallow root system. To effectively manage for this species, continuous removal efforts before plants seed would be required.

M. scorpioides was first observed in the Quabbin Reservoir Watershed in 2012, along the shoreline of BLA2 and at Gaston Pond in Barre. Since then, it has been observed in several other ponds within both watersheds. Observations have been variable however, and some populations have not been observed in several years.

The 2023 macrophyte survey did not find any new infestations of *M. scorpioides* (Table 62). Populations at Demond and Pepper's Mill Pond remained small and did not appear to be spreading.

Table 62: Ponds with *Myosotis scorpioides* present during the 2023 AIS survey with survey dates and date of first observation.

Waterbody Name	Town	Watershed	Last Obs.	First Obs.
Demond Pond	Rutland	Ware River	7/28/2023	08/04/2016
Peppers Mill Pond	Ware	Quabbin Reservoir	5/31/2023	08/07/2015

3.5.1.11 *Rorippa microphylla*

Rorippa microphylla (one row yellowcress), also known as *Nasturtium microphyllum*, is native to Europe and has spread to much of the world due to its popularity as a salad green (GoBotany, 2024). This species is considered invasive in Connecticut but not in Massachusetts. Although a closely related species, *Rorippa amphibia* (water yellowcress), is on the Massachusetts prohibited plant list, *R. microphylla* remains absent (MDAR, 2023). Due to a lack of scientific literature on this species, observations of this non-native are closely monitored to determine its effect on native species.

R. microphylla is present in both watersheds. It was first observed in the Quabbin Reservoir (BLA2) in 2013 and the Ware River Watershed in 2014. When not flowering, this species can be difficult to identify, and closely resembles other native and state listed species. As a result, *R. microphylla* observations are not consistent, highlighting the importance of marking population locations for subsequent survey efforts. No *R. microphylla* were observed during the 2023 DCR-DWSP survey season.

3.5.2 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.

3.5.2.1 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 3.5.3.2). Since then, it has been determined that the low pH and calcium levels found in the Quabbin Reservoir (Section 3.4.5) 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.

3.5.2.2 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 2023, neither species has been documented in the Quabbin Reservoir.

3.5.3 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.

3.5.3.1 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.

The 2023 season experienced one of the wettest summers on record in Massachusetts, resulting in postponement of both the initial survey (GEI, 2024) and the drawdown for harvest (Davey Resource Group Inc., 2023). Due to higher-than-normal water levels delaying management actions, harvest operations were considerably shortened (unable to complete 2nd and 3rd passes), thus impacting the total amount of material removed.

M. heterophyllum upstream of Route 122 maintained similar distribution to the previous year, covering about 3.45 acres. However, the overall trend in coverage continues to increase for the eighth consecutive year (GEI, 2024). On the other hand, density of *M. heterophyllum* downstream of Route 122 remains low (GEI, 2024). Davey Resource Group was contracted by MWRA to physically remove plants for the sixth consecutive year. The 2023 harvest yielded a 45% reduction in total gallons removed compared to the previous year, most likely due to the water levels impeding removal efforts (Davey Resource Group Inc., 2023). Downstream of Route 122 saw a decrease of 38% in gallons removed and upstream saw a decrease of 60%, where efforts were limited by high water levels and the contracted time frame (Davey Resource Group Inc., 2023). 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.

3.5.3.2 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, which includes 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 16 dates in 2023 throughout the fishing season. During

WWD boaters are asked what bodies of water their boats were in last, boats are inspected for any plant material, and then washed. Samples of biological substances collected off inspected boats are identified whenever possible. Boat motors are flushed with hot water (140°F) until similar temperature water streams out for 10 seconds to kill any organisms that may be present. Afterwards, 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 then washed with hot water at a high pressure. 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. Unlike WWD, CWQ requires no fee. The CWQ program occurred over five dates in 2023. During CWQ, boats are tagged at the beginning of the winter season, ensuring 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 2023, 145 boats were inspected and decontaminated through the WWD program. This is below the average number of decontaminations from the previous nine years (171 WWDs from 2014-2022). Sixty-two boats were inspected and sealed through the CWQ program in 2023. This is lower than the average for the previous nine years (118 CWQs from 2014-2022). In 2023, around 41% of boaters used the WWD for the first time, and around 14% 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.

3.5.3.3 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 Asnacomet 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 Asnacomet 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.

Cabomba caroliniana was first identified in 2021 during an annual macrophyte survey at Long Pond, a DCR-owned pond that utilizes self-certification. 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. The size of individual plants and the spread of the patch indicate this invasive plant has been present in Long Pond for over a year before its discovery. Due to the location of the infestation in the water body, it is very likely it was introduced by boaters. This AIS introduction highlights the importance of the self-certification process and presents an example of the consequences that follow noncompliance.

4 Conclusions and Next Steps

Monitoring results generated by DWSP in 2023 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 2023. Increased sampling intervals for parameters of increased interest (e.g., nutrients, organics) has allowed DWSP to develop a better understanding of the range of variability across sites and across seasons for these analytes, as well as better characterize patterns under different meteorological and hydrological contexts (e.g., drought year of 2022 compared to high rainfall and streamflow year of 2023). 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. DWSP sampling plans will continue to be developed in coordination with MWRA and UMass partners to best adapt to emerging water quality concerns.

4.1 Discussion and Recommendations

4.1.1 Watershed Hydrological/Meteorological Conditions

In 2023, the NOAA weather stations in the Quabbin Reservoir and Ware River watersheds recorded annual mean air temperatures that were slightly higher than those recorded in 2022 and deviated significantly from the historical mean. Throughout the year, both minimum and maximum daily temperatures showed notable fluctuations, with some of the most extreme temperatures occurring within the Ware River watershed. Despite these variations, daily median temperatures generally remained within historical ranges, although occasional outliers were observed, particularly in winter and spring. Annual precipitation totals across the Quabbin Reservoir and Ware River watersheds exceeded historical averages, with NOAA weather stations in Orange, Barre, and Belchertown recording above-mean annual rainfall. Drought conditions fluctuated throughout the year, with periods of abnormally dry conditions transitioning to Level-0 Normal by the end of the year. Snow monitoring in the Quabbin Reservoir watershed indicated below-average total annual snowfall as compared to historical records, reflecting broader trends in precipitation patterns in the Northeast.

Streamflow monitoring conducted at six USGS gages across both watersheds revealed significant deviations from historical averages, reflecting the highly variable precipitation patterns observed throughout 2023. Notably, January and December experienced significantly higher rainfall rates as compared to historical records, resulting in high-magnitude flow events, especially in the Ware River at Gibbs Crossing. Conversely, a drier-than-average November saw reduced streamflow rates across monitoring locations. Overall, cumulative annual discharge reflected precipitation patterns for 2023, with notably higher discharge totals as compared to previous years, especially at the East Branch Swift River and Ware River Intake Works gages.

These findings highlight the dynamic nature of climate, precipitation, and hydrological responses in the Northeast, with notable variations observed across seasons and watersheds. They also reflect the impact of climate change on weather patterns in the Northeast, with 2023 meteorological and hydrological data from the Quabbin Reservoir and Ware River watersheds exhibiting broad variability when compared to historical observations. Studies in the region suggest that further impacts to climate in the Northeast will result in less predictable and increasingly extreme meteorological trends, and that these trends will be reflected in more frequent high magnitude streamflow events (Demaria et al., 2016; Siddique et al., 2020; Young & Young, 2021). Continued monitoring and the potential expansion of monitoring networks in both the Quabbin and Ware River watersheds are recommended in order to better understand and adapt to future changes

4.1.2 Quabbin Reservoir Watershed and Ware River Watershed Tributary Water Quality

Results generated from routine monitoring of tributaries in Quabbin Reservoir and Ware River Watersheds in 2023 were largely consistent with historical data and demonstrate continued adherence to drinking water quality standards. Results coincident with or close in time to high-intensity precipitation and subsequent high-discharge events (e.g., August 15, Sept 12, and the Dec 19 rain-on-snow event) allowed for a greater understanding of concentrations under constituent transport conditions, better representing the full range of variability in water quality concentrations in tributaries of these watersheds. Infrequent individual *E. coli* concentrations above single-sample regulatory limits, attributed to multiple high intensity rainfall events through the summer and fall of 2023, returned to pre-event levels upon resampling. Similarly, summer UV_{254} observations were elevated relative to the period of record across sampling locations in both watersheds, attributed to consistent high discharge simultaneous to timing of peak biological productivity in the watershed. Results for specific conductance in Core tributaries in the Quabbin Reservoir and Ware River Watersheds collected every two weeks showed a subtle increase in baseline specific conductance in certain watershed sampling locations during the first half of 2023. The heavy rainfall and subsequent high streamflows of the summer and fall resulted in a clear dilution signal and lowered specific conductance concentration in the second half of 2023. The increased temporal resolution of routine nutrient monitoring into 2023 continues to reveal more detailed dynamics of terrestrial aquatic N-cycling than previously documented, largely attributed to increasing the monitoring frequency for nutrients (previously quarterly) in select tributary sites. TP concentrations were largely within established background ranges at all sites, with annual maximum associated with the August 15 rainfall event close to or exceeding historical maximum at several Quabbin Reservoir sampling locations.

Results of monitoring of select water quality parameters in Quabbin Reservoir Watershed and Ware River Watershed in 2023 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.

4.1.3 Quabbin Reservoir Water Quality

Results of routine water quality profiles collected in Quabbin Reservoir in 2023 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 observed through 2023 was lower than previous years while composition changes observed were consistent with prior years. Climatic and hydrological drivers contributed to seasonal and vertical shifts in phytoplankton assemblages and nutrient dynamics. Unlike previous years (2019 – 2022), *Chrysosphaerella* aggregations were not observed in 2023. Nutrient monitoring in Quabbin Reservoir was reset to quarterly for 2023 (nutrient monitoring during 2021 – 2022 was monthly). Quarterly 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. 2023 marked the fourth consecutive year that TOC was monitored routinely at Quabbin Reservoir core sites. Notable increases in silica, chloride, and TOC concentrations over their periods of record were observed at site Den Hill, highlighting the influence of the East Branch Swift River on water quality at this site.

Monthly monitoring of select water quality parameters (UV_{254} and TOC) in the Quabbin Reservoir during 2023 was consistent with historical data and demonstrated continued adherence to drinking water quality standards.

4.1.4 Aquatic Invasive Species Monitoring and Management

Continued prevention efforts and monitoring of current and potential invaders are the main priority of the AIS Program at Quabbin. Changes in environmental factors due to climate change, which previously prevented certain species from establishing in New England, has led to an increase in invasive species' spread throughout the region. With the integration of digital data collection and GPS, information about AIS spread within waterbodies in the Quabbin and Ware River Watersheds will help aid future prevention, education, and management efforts.

Overall, AIS observations during the DWSP-EQ 2023 surveys remained similar to previous years with a few notable exceptions. The presence of *U. inflata* at Pottapaug Pond in the spring emphasized the need for early-season surveys to catch early-growth species such as *U. inflata* and *P. crispus*. It is recommended that future surveys of the holding ponds (O'Loughlin and Pottapaug) are conducted twice a year – once in spring (May) and once during the normal growing season (July-September) to align surveys to seasonal patterns of species' growth necessary for identification and monitoring. To manage the infestation of *U. inflata,* contractors should be brought in to remove this species from Pottapaug Pond and O'Loughlin Pond, and populations should be closely monitored.

4.2 Proposed Quabbin Reservoir and Ware River Watershed Monitoring Programs for 2024

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 in the Ware River Watershed.

4.2.1 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. In 2024, DCR will continue to sample every two weeks in the Quabbin Reservoir Watershed at the same Core and EQA sites as 2023, using the same suite of analytes and sample sampling frequency (Table 4, Table 5). Quabbin will continue to monitor 2023 EQA sites (211A-X and 211B-1) into 2024 in preparation for EQA reporting on the Quabbin Reservation District, anticipated in 2025.

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 2023 (115, 126A, 127, and 128) and begin monitoring at four EQA sites (108A, 108B, 108C, 117) located in the East 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 continue at a quarterly sampling interval in the remaining Core tributaries in the Ware River Watershed in 2023. All other analyses will remain unchanged from 2023 (Table 5).

4.2.2 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 2024, weather and reservoir conditions permitting. This monitoring will include analyses for turbidity, total and fecal coliform, *E. coli,* TOC, UV_{254}, and extracted chlorophyll *a*. 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 nutrients (NO_3-N, NH_3-N, TKN, TP, and Si). Routine monitoring for phytoplankton will be performed by DWSP weekly at site 202 during the growing season (May 1 through September 30, 2024), 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 2024. Changes to the DWSP water quality monitoring program introduced in 2024 may aid in future management decisions and help to better elucidate potential controls on productivity and algal dynamics in Quabbin Reservoir.

4.2.3 Aquatic Invasive Species Monitoring and Management

Every year, DWSP-EQ monitors select ponds for AIS in addition to contractors hired by MWRA who survey the Quabbin Reservoir, holding ponds, and the Ware River around the Shaft 8 intake. For the 2024 survey season 16 waterbodies are planned for DWSP-EQ surveys and include the two holding ponds and three boat launch areas (Table 63). Although most of these waterbodies reside in our watersheds, Hardwick Pond and Pepper's Mill Pond do not, and are included in our list due to their proximity to water resources. Hardwick Pond is considered by the AIS Program as an EQA pond and is surveyed on a rotating schedule as time allows and when deemed necessary. As this pond was last surveyed in 2015 and is a popular recreational site, it has been included in our 2024 survey schedule.

Table 63: Proposed AIS monitoring schedule for CY2024.

Watershed	Water Body Name	Location	Type	Last Survey Year	To Be Surveyed by
Quabbin Reservoir	Quabbin Reservoir	New Salem, Petersham, Hardwick	Annual	2023	TRC
	Quabbin Reservoir, west arm	Pelham, New Salem	Annual	2023	TRC
	Boat Launch Area 1	Belchertown	Annual	2023	TRC and DWSP
	Boat Launch Area 2	New Salem	Annual	2023	TRC and DWSP
	Boat Launch Area 3	Petersham	Annual	2023	TRC and DWSP
	O'Loughlin Pond	New Salem	Annual	2023	TRC and DWSP
	Pottapaug Pond	Hardwick	Annual	2023	TRC and DWSP
	Bassett Pond	New Salem	Annual	2023	DWSP
	Lake Mattawa	Orange	Annual	2023	DWSP
	Hardwick Pond	Hardwick	EQA	2015	DWSP
	Peppers Mill Pond	Ware	Annual	2023	DWSP
Ware River	Ware River, upstream of Shaft 8	Barre	Annual	2023	TRC
	Asnacomet Pond	Hubbardston	Annual	2023	DWSP
	Brigham Pond	Hubbardston	Annual	2021	DWSP
	Cloverdale Pond	Rutland	EQA	2011	DWSP
	Demond Pond	Rutland	Annual	2023	DWSP
	Long Pond	Rutland	Annual	2023	DWSP
	Queen Lake	Phillipston	Annual	2022	DWSP
	Whitehall Pond	Rutland	Annual	2023	DWSP

In response to the discovery of *Utricularia inflata* at the Pottapaug and O’Loughlin holding ponds, DWSP and MWRA plan to hire a contractor to assist in management efforts (please refer to Table 64 for a breakdown of responsibilities and overall schedule). Due to limited knowledge surrounding this plant’s growth period within Massachusetts, the contractor will be required to conduct initial growth surveys to determine presence of floating structures and flowers – a key feature in identification of this particular AIS. Following confirmation of floating structures, the contractor will then conduct point-intercept surveys at predetermined grid-based points within the littoral zones of Pottapaug, noting presence/absence and density. During harvesting efforts, contractors will be required to provide periodic updates, noting amount harvested and harvest locations through email and a DWSP Survey 123 form. Upon receipt of the final draft report, DWSP will work with MWRA to determine next management steps.

Table 64: Proposed timeline for contractor hire, *Utricularia inflata* surveys, harvest efforts, and reporting.

Month	Task
February	MWRA - Call for Proposals
February	DWSP - Development of Survey 123 Form
March	MWRA - Award Bid
April-May	Contractor - Growth Survey
May	DWSP - Silt Fence Disposal Site Set-up
May	Contractor - Point-intercept Survey
May-June	Contractor - Harvesting
June-July	Contractor - to Submit Draft Report
August	Contractor - to Submit Final Report

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6 Appendices

6.1 Appendix A. 2023 Watershed Monitoring Parameters

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 2023. 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. Discharge measurements were recorded from stream gages maintained by USGS. Adapted from DWSP, 2021c.

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	Field-Sensor			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
Mean 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	
Silica	µg/L	Nutrients	MWRA Lab	EPA 200.7		
Sodium	µg/L	Nutrients	MWRA Lab	EPA 200.7		
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		
Total Organic Carbon	mg/L	Nutrients	MWRA Lab	SM 5310 B		
Total Phosphorus	µg/mL	Nutrients	MWRA Lab	EPA 365.1	X	X

Parameter Name	Units	Sampling Group	Analysis Location(s)	Analysis Method	R	T
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

6.2 Appendix B. DWSP Investigations Reports

6.2.1 Investigations into bacterial sources at Boat Cove Brook, 2023

E. coli was elevated above normal background levels (25th to 75th percentile) in routine samples collected periodically from Boat Cove Brook across 2023. In particular, sample results exceeded MassDEP Class A standards of 235 MPN/100-mL on eight separate dates, mostly in the summer and early fall following rainfall events, while elevated results from winter were associated with rain-on-snow events (Figure A). Annual maximum *E. coli* level observed at this location in 2023 (1450 MPN/100 mL) were attributed to the August 15 high-intensity rainfall event. 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 hydrological events may indicate a potential wildlife presence in the near stream contributing areas.

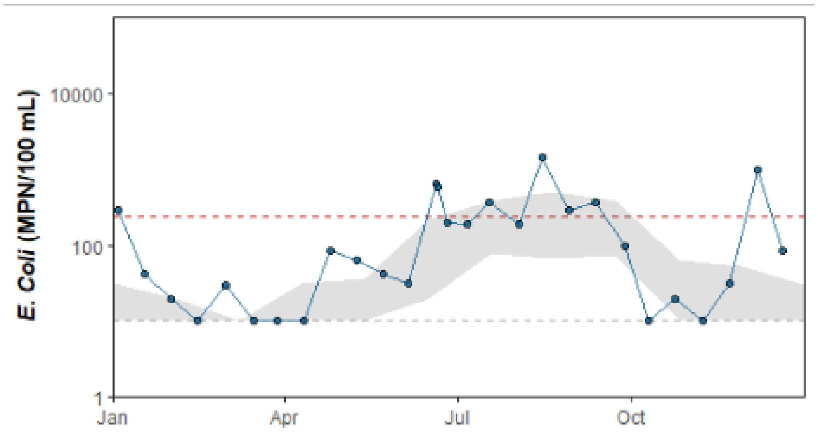

Figure A. Time series of *E. coli* measured in Boat Cove Brook tributary during 2023. Lower Gray line indicates the laboratory detection limit (10 MPN/100 mL). Red line indicates MassDEP Class A standards (235 MPN/100 mL). Shaded band signifies monthly 25th to 75th percentile values.

The *E. coli* result observed with June 20, 2023 routine monitoring (650 MPN/100 mL) triggered follow-up sampling to confirm the persistence of a potential threat as well as field investigations of the upstream and near-stream contributing areas to the Core site along Boat Cove Brook. The initial follow-up sample was collected on June 21, 2023 (result of 583 MPN/100 mL) coincident with a field investigation of the site. *E. coli* concentrations decreased from initial resampling results with each subsequent sampling, from 583 MPN/100 mL to 187 MPN/100 mL, on June 21 and July 6, 2023, respectively. Results within normal range but near or slightly above 235 MPN/100 mL continued throughout the summer, with the August 15, 2023 annual maximum result exceeding the historical normal range. *E. coli* counts subsequently declined in the fall and early winter following a return to monthly precipitation and daily streamflow rates closer to seasonal normal compared to the high rainfall, high streamflow summer and early fall 2023 conditions. A winter rain-on-snow event resulted in elevated *E. coli* on December 6, 2023 (result of 990 MPN/100 mL) with counts declining but remaining elevated above normal in December

19, 2023 routine sampling (86 MPN/100 mL), before returning to baseline and within seasonal normal ranges in early 2024.

DWSP staff inspected the near stream reaches of Boat Cove Brook on June 21, 2023. 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. Several signs of wildlife were documented consistent with previous inspections of the catchment (DWSP, 2018a; DWSP, 2023a). Deer signs such as tracks and deer bedding area were found near-stream in the riparian corridor. There were also signs of exposed soil in several locations within the riparian corridor with signs of deer tracks, indicating effects from high-intensity rainfall and wildlife movement (Figure B). Ultimately the small size and flashy nature of this stream, the recurring high-intensity rainfall of the summer and fall, and the documented wildlife presence in the near-stream and upstream area may have interacted to explain the elevated *E. coli* results at this site in 2023. Further investigation into the landscape context of this site will be explored in future Environmental Quality Assessment reporting of the Boat Cove catchment as part of the Quabbin Reservation District focus in 2024.

Figure B. Exposed soil and deer prints found in the riparian area of Boat Cove Brook, upstream of DWSP Core site. Photos taken on June 21, 2023.

6.2.2 Investigations into *Utricularia inflata* at Pottapaug Pond, 2023

Utricularia inflata (swollen bladderwort)
Regulating Pond, Fishing Area III
Pottapaug Pond, Hardwick, MA

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Date of Initial Investigation: 6/5/2023

Investigator(s): Tayelor Gosselin (ABI) and Shasten Sherwell (ABII)

Purpose: Confirm ID, extent, and collect specific location information

Is this a new AIS being investigated: Yes

Were pictures taken: Yes. See end of report.

Priority level: High

Brief Summary-

Utricularia inflata, commonly known as swollen bladderwort, was found during a routine fragment barrier inspection on Pottapaug Pond, a regulating pond at Fishing Area III by David Gatautis (EA I) on May 26, 2023. Preliminary identification confirmation was performed by Wachusett Aquatic Biologists, and an investigation was carried out on June 5, 2023 by DCR Aquatic Biologists to determine extent and specific location of populations. To prevent *U. inflata* from spreading elsewhere, Pottapaug Pond was closed to private boats beginning June 7, 2023. Removal efforts began on June 12, 2023 by the DCR Environmental Quality team, and consisted of two separate harvest dates. A total of 72.5 gallons of material was removed.

Relevant background-

Pottapaug Pond, a holding pond located above BLA3, has been annually surveyed by TRC (MWRA contractor) since 2010. These surveys usually occur in August using a point-intercept method. *Utricularia inflata* has not been encountered in any previous survey at this location.

Plant Removal-

Due to shallow conditions, kayaks and hand pulling were chosen as the removal method, and a 25ft x 50ft area was marked off by silt fence away from the water for disposal by drying. A total of 72.5 gallons of material was removed.

Removal began on June 12, 2023 by the DCR Environmental Quality team, and extended from the Pottapaug boat launch to the first cove on the western side. The small area west of the boat launch contained a small population of plants. Most were removed, but a secondary visit may be necessary. The first large cove along the western shoreline had an abundance of plants, denser in shallower water and sparse in deeper. *U. inflata* became more dense further into the cove. Wind conditions made concentrated removal difficult. Water depth is shallow, estimated 1ft-3ft on average, however the peat/muck layer makes removal via waders impractical in most areas.

A second removal occurred on June 15, 2023 focusing on the second cove on the western edge. *U. inflata* was denser here than in the first cove, with many flowers present creating a 'sea of yellow' when looking towards the back of the cove. The water was deeper here, estimated around 4ft-6ft, with numerous *Nuphar*, *Nymphaea,* and *Brasenia schreberi* (yellow and white water lilies and watershield) covering the water's surface. *U. inflata* was present in full-bloom and in degraded stages, often hiding under and between lily pads.

Pictures-

Pictures A and B *U. inflata* removal by hand via kayak.

Pictures C and D: Draining *U. inflata* and storing in coolers for transportation to disposal area.