# Water Quality Report: 2021
# Quabbin Reservoir Watershed
# Ware River Watershed

*Island from Quabbin Reservoir (Katharine Langley, 2021)*

August 2022

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 27 surface water sites located throughout the Quabbin Reservoir and Ware River Watersheds, as well as other special assessment samples and periodic hydrologic event sampling. The Department of Conservation and Recreation (DCR), Division of Water Supply Protection (DWSP), is the state agency charged with the responsibility of managing Quabbin Reservoir and its surrounding natural resources in order to protect, preserve, and enhance the environment of the Commonwealth and to assure the availability of safe drinking water to future generations. The Environmental Quality Section manages a comprehensive water quality monitoring program to ensure that Quabbin Reservoir water meets state drinking water quality standards. As part of this task, the Environmental Quality Section performs field work, collects water samples, interprets water quality data, and prepares reports of findings. This annual summary is intended to meet the needs of watershed managers, the interested public, and others whose decisions must reflect 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 2021. Monitoring of tributaries is a proactive measure aimed at identifying trends and potential problem areas that may require additional investigation or corrective action. Compliance with state surface water quality standards among the tributaries varied, with minor exceedances attributed to higher solute loads measured during storm events, wildlife impacts on water quality, and/or natural attributes of the landscape.

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



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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 | Department of Conservation and Recreation, 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 |
| ROS | Regression on Order Statistics |
| Si | Silica |
| SMCL | Secondary Maximum Contaminant Level |
| SOP | Standard Operating Procedure |
| SWE | Snow Water Equivalent |
| SWTR | Surface Water Treatment Rule |
| TKN | Total Kjeldahl Nitrogen |
| TN | Total Nitrogen |
| TOC | Total Organic Carbon |
| TP | Total Phosphorus |
| UMass | University of Massachusetts, Amherst |
| U.S. | United States |
| $UV_{254}$ | Ultraviolet Absorbance at 254 Nanometers |
| USGS | U.S. Geological Survey |
| WDI | Winsor Dam Intake |
| WRF | Warm water fish habitat |

## Units of Measurement

Chemical concentrations of constituents in solution or suspension are reported in milligrams per liter (mg/L) or micrograms per liter (μg/L). These units express the concentration of chemical constituents in solution as mass (mg or μg) of solute per unit of volume of water (L). One mg/L is equivalent to 1,000 μg/L. Fecal coliform results are reported as the number of presumptive colony forming units per 100 milliliters of water (CFU/100 mL). Total coliform and *Escherichia coli (E. coli)* are reported as the most probable number (MPN/100 mL), which is equivalent to CFU/100 mL and acceptable for regulatory reporting. $UV_{254}$ results are reported as the amount of ultraviolet light at a 254 nm wavelength that is able to transmit through a water sample in absorbance units per centimeter of path length (ABU/cm).

The following units of measurement are used in this report:

| | |
|---|---|
| ABU/cm | Absorbance units per centimeter of path length |
| ASU/mL | Areal standard units per milliliter |
| cfs | Cubic feet per second |
| CFU | Colony-forming unit |
| °C | Degrees Celsius |
| ft | Feet |
| in | Inches |
| μS/cm | Microsiemens per centimeter |
| L/mg-M | Liters per milligram per meter |
| MG | Million gallons |
| MGD | Million gallons per day |
| μg/L | Microgram per liter |
| mg/L | Milligram per liter |
| m | Meters |
| MPN | Most probable number (equivalent to CFU) |
| nm | Nanometers |
| NTU | Nephelometric turbidity units |
| S. U. | Standard Units (pH) |

# 1 Introduction

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management (DWSP) manages and maintains a system of watersheds and reservoirs to provide water to the Massachusetts Water Resources Authority (MWRA), which in turn supplies drinking water to approximately 3.1 million people and thousands of industrial users in 53 communities in Massachusetts. The watershed system includes the Quabbin Reservoir, Ware River, Wachusett Reservoir, and Sudbury Reservoir Watersheds, interconnected by a series of aqueducts (Figure 1).

The U.S. EPA introduced the Federal Surface Water Treatment Rule (SWTR) in 1989, followed by the introduction of the Interim Enhanced Surface Water Treatment Rule (IESWTR) in 2002 (US EPA, 1989; US EPA, 2002), to ensure that public water supply systems that use surface water or groundwater under the direct influence of surface water provide safeguards against the contamination of water by viruses and bacteria. The regulations require filtration by every surface water supplier unless strict source water quality criteria and watershed protection goals can be met, including the development and implementation of a detailed watershed protection plan (US EPA, 2003). The DWSP and the MWRA have maintained a joint waiver for the filtration requirement of the SWTR since 1989 and work together to manage the watershed in fulfillment of the waiver.

DWSP monitors the water quality and quantity within the watersheds (Commonwealth of MA, 2004). Water quality sampling and field inspections help identify surface waters with potential water quality issues, aid in the implementation of watershed protection plans, and ensure compliance with state and federal water quality criteria for public drinking water supply sources (e.g., the filtration avoidance requirements stipulated under the SWTR). Routine monitoring of bacteria and nutrients in the reservoirs and tributaries provides an indication of sanitary quality of water sources, ensuring security of water resources and public health. Monitoring is also conducted by DWSP staff to better understand the responses of the reservoir and tributaries to a variety of physical, chemical, and biological inputs, and to assess the ecological health of the reservoirs and watersheds. A long-term record of water quality statistics provides information regarding potential controls on observed changes 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 2021.

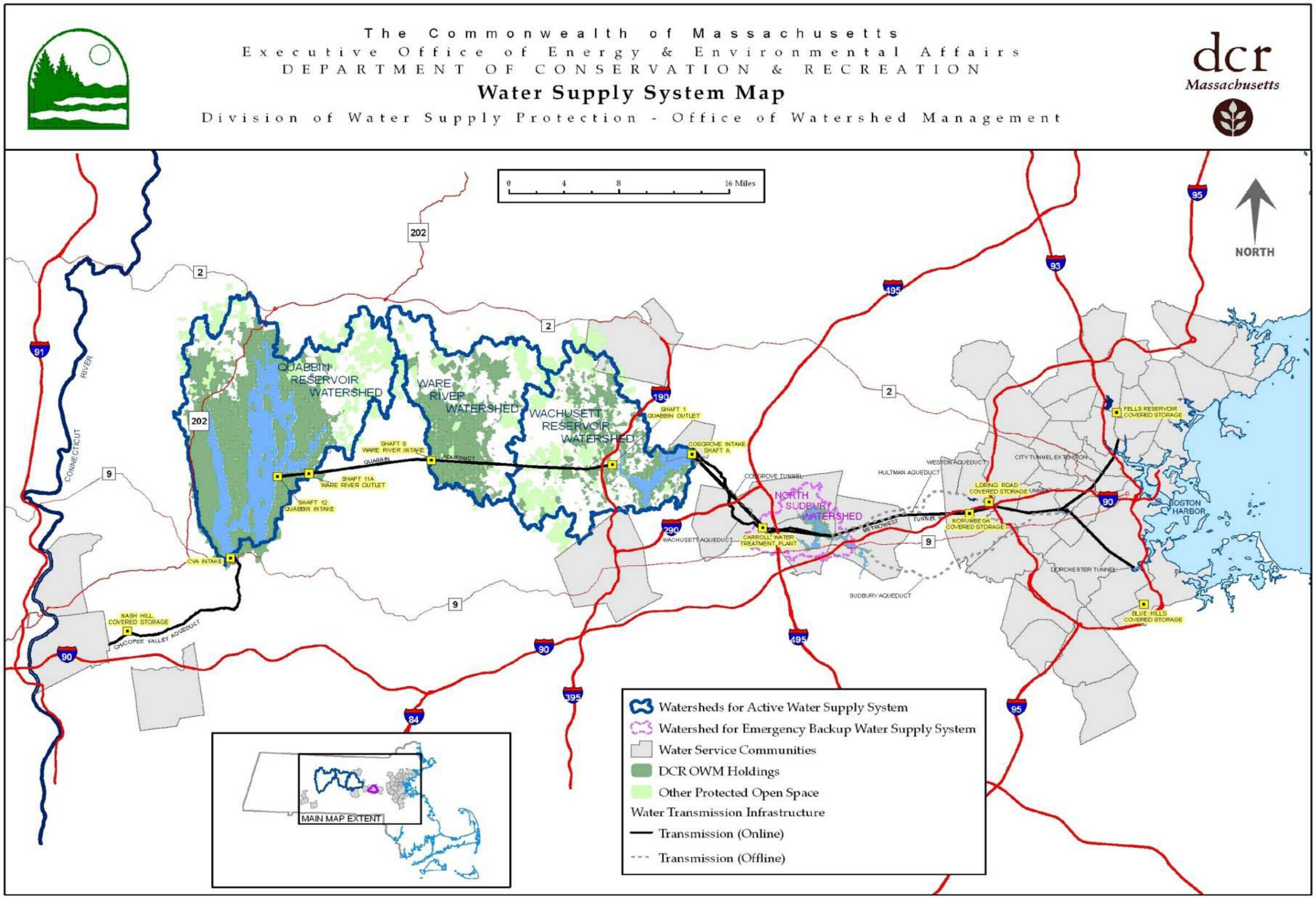



**Figure 1:** Quabbin Reservoir, Ware River, and Wachusett Reservoir Watershed system. Interstate highways are represented by red lines. Inset map in lower left depicts location of the watershed system relative to MA.

## 1.1 Public Water Supply System Regulations

The U.S. EPA introduced the SWTR in 1989 to ensure that public water supply systems using surface waters were providing 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. The DWSP and MWRA have maintained a waiver from the filtration requirement since 1989.

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 remain below one NTU. Authority to enforce the SWTR has been delegated to MassDEP.

The Quabbin Reservoir is designated as Class A Public Water Supply (314 CMR 4.06(1)(d)1) and 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 (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. As MWRA produces reports that detail results of regulatory monitoring, monitoring results at each of the water system stages is not discussed as part of this report.

## 1.2 DWSP Monitoring Program Objectives

MWRA, as an unfiltered water supplier, is required to have a watershed protection program intended to promote and preserve high quality source water by utilizing a range of methods and strategies that ultimately control the release, transport and fate of pollutants in the watersheds. A primary function of DWSP is to design and implement this watershed protection program for the DCR/MWRA water supply system. Watershed protection measures enacted by DWSP have been detailed in DWSP Watershed Protection Plans (WPPs) and WPP updates since 1991 (DWSP, 2018a). The goals of WPPs are to provide structured methodology to assess changes in existing threats to water quality across DWSP-managed watersheds, develop proactive strategies to prevent threats to water quality, and respond to potential threats to water quality to limit negative impacts. Environmental quality monitoring is one element of the WPPs developed by DWSP. The Watershed Protection Act of 1992 gives DWSP the authority to regulate certain land uses and activities that take place within critical areas of the watershed in order to protect drinking water quality (313 CMR 11.00). The high ambient water quality of the Quabbin Reservoir and Ware River watersheds can be attributed largely to the effectiveness of the WPPs.

DWSP staff rely on data generated by long-term monitoring programs to inform modifications to current WPPs. Data generated by long-term monitoring programs conducted by DWSP are used to assess current and historical water quality conditions, establish expected ranges of various water quality parameters, allow for routine screening of potential threats to water quality, provide early detection of trends, and assess current watershed trends. Shorter-term investigations may also be conducted to evaluate specific issues. Monitoring efforts are reviewed and updated annually by DWSP to ensure that DWSP programs remain current, appropriate, and informative for the WPP goals. Changes to annual water quality monitoring programs performed by DWSP staff are discussed in the annual water quality report for the affected watersheds (DWSP, 2019a; DWSP, 2019b).

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

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

DWSP monitoring programs continuously evolve to respond to emergent and high priority threats to water quality, while utilizing current scientific information, tools, and technologies. The achievement of water supply protection goals, including specific water quality targets, can be credited to the coordinated implementation of each 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 ultimately serve as a source of drinking water to 53 communities in Massachusetts. The water sources connected by the Quabbin Aqueduct, from west to east, include the Quabbin Reservoir, the Ware River Watershed, and the Wachusett Reservoir (Figure 1). The Quabbin Reservoir is the largest of the sources, with a capacity of 412 billion gallons. In comparison, the Wachusett Reservoir holds 65 billion gallons at full capacity (Table 1).

Water from the Quabbin Reservoir is transferred to the Wachusett Reservoir via the Quabbin Aqueduct Intake at Shaft 12 (Figure 2). Transfers at Shaft 12 typically account for more than half of the of MWRA system supply. Water is also transferred directly to three western Massachusetts communities daily via the Chicopee Valley Aqueduct (CVA) from the Winsor Dam Intake (WDI) (Figure 2). Water from Ware River may be used to supplement Quabbin Reservoir. Ware River water is diverted into the Quabbin Aqueduct at Shaft 8 in Barre, MA, near DWSP Core tributary monitoring site 101 (Figure 3) and delivered to the Quabbin Reservoir via gravity flow. Ware River Watershed water enters the reservoir at Shaft 11A, east of the baffle dams in Hardwick, MA (Figure 2). The diversion of water from the Ware River is limited to the period from October 15 to June 15 and is not permitted when mean daily flow at Shaft 8 is less than 85 MGD (131.5 cfs), per Chapter 375 of the Massachusetts Acts of 1926. DWSP and MWRA coordinate on diversions. Additional information regarding land use and ownership in the Quabbin Reservoir and Ware River Watersheds is presented in the Watershed Protection Plan FY19-23 (DWSP, 2018a) and the 2017 Land Management Plan (DWSP, 2018b).

**Table 1:** a) General information on the Quabbin Reservoir, b) Quabbin Reservoir Watershed, and c) Ware River Watershed (DWSP, 2018a). Other protected lands include property identified by MassGIS as Open Space protected in perpetuity less DWSP, fee lands, and WPRs (WPR = Watershed Preservation Restriction, similar to a Conservation Restriction). Acreage may vary from that of from previous years due to increased accuracy of MassGIS data.

| **a) Quabbin Reservoir General Information** | | |
|---|---|---|
| **Description** | **Units** | **Quantity** |
| Capacity | Billion gallons | 412 |
| Surface Area (at full capacity) | Acres | 24,469 |
| Length of Shoreline | Miles | 118 |
| Maximum Depth | Feet | 141 |
| Mean Depth | Feet | 45 |
| Surface Elevation, at Full Capacity | Feet, relative to Boston City Base | 530 |
| Reservoir gain (average) from 1” of precipitation | Billion gallons | 1.6 |

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

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

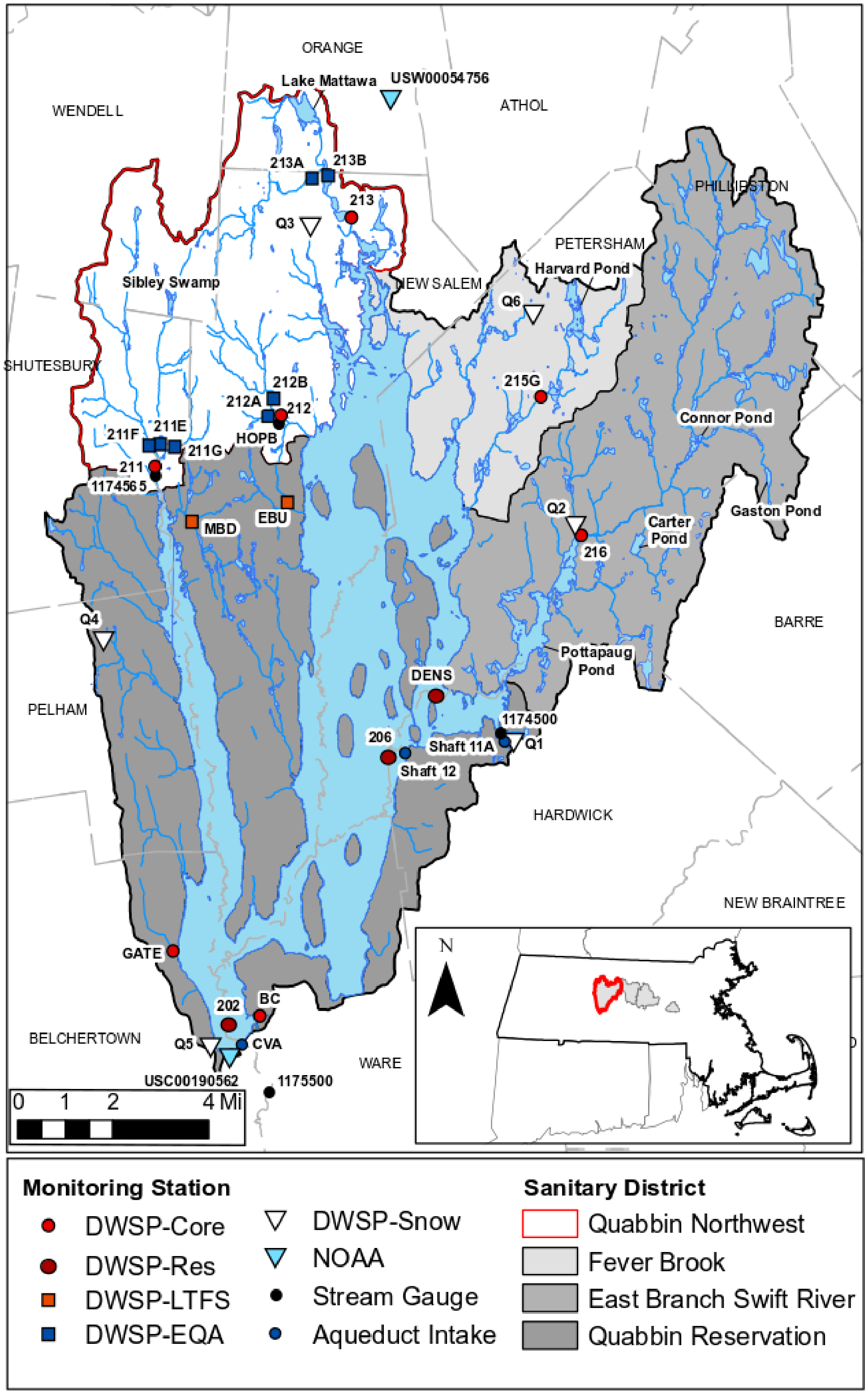



**Figure 2**: Map of Quabbin Reservoir Watershed showing locations of Core and EQA monitoring sites sampled in 2021. Also shown are DWSP sanitary districts. Inset map depicts the watershed relative to MA and MWRA system.

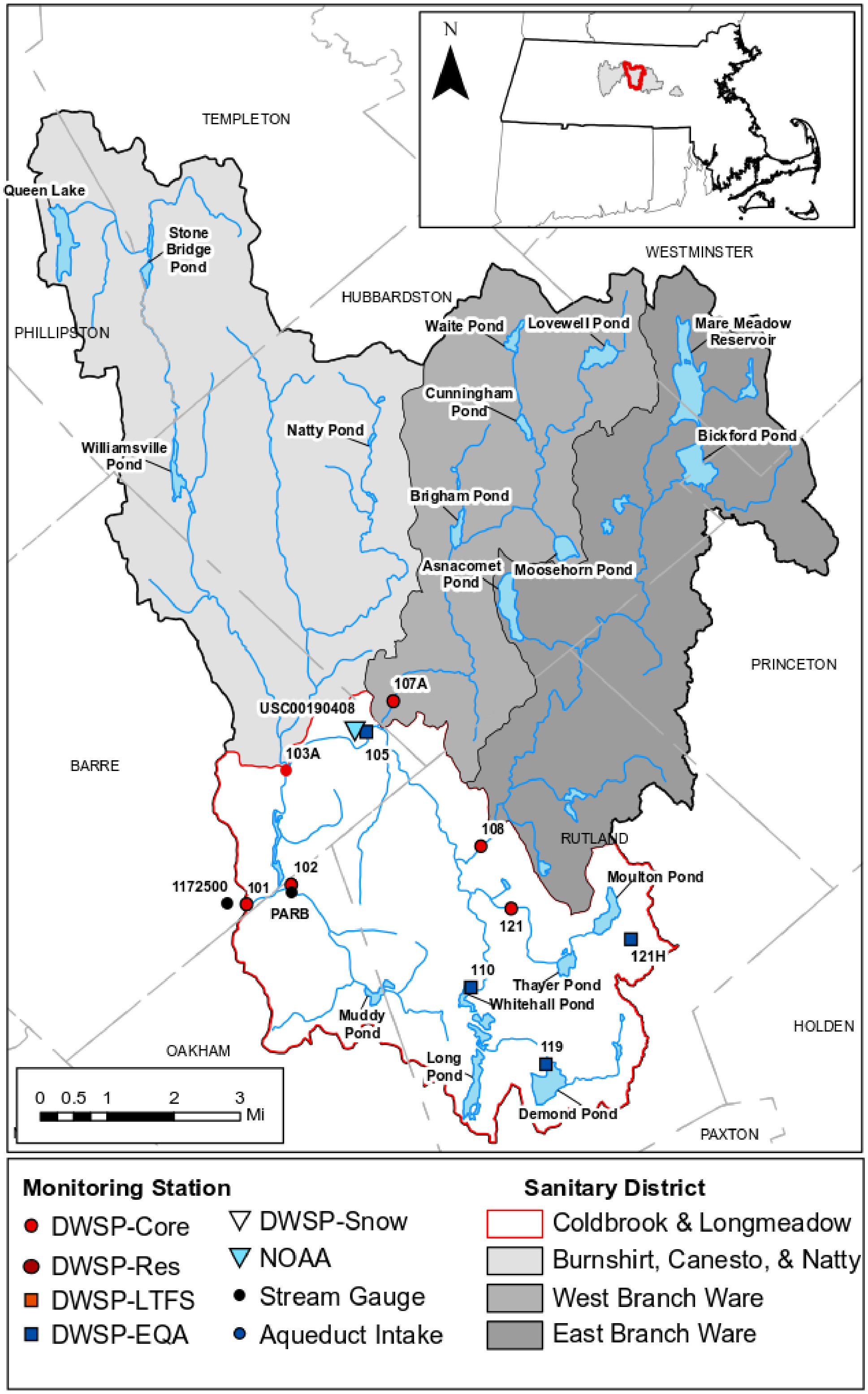



**Figure 3:** Map of Ware River Watershed showing locations of Core and EQA monitoring sites sampled in 2021. Also shown are DWSP sanitary districts. Inset map depicts the watershed relative to MA and MWRA system.

## 1.4 Description of Quabbin Reservoir and Ware River Watersheds

The Quabbin Reservoir Watershed is situated in the former Swift River sub-basin of the Chicopee River, a major tributary of the Connecticut River, and is located in the Central Uplands of north central Massachusetts. The Quabbin Reservoir Watershed encompasses approximately 187.5 sq. mi. (119,935 acres), including that of nearly all of the towns of New Salem and Petersham, considerable portions of Pelham, Shutesbury, and Wendell, and smaller portions of Orange, Hardwick, Phillipston, Belchertown, Ware, and Athol, MA (Figure 2). At full capacity, the surface area of the Quabbin Reservoir spans roughly 38.2 sq. mi. (24,469 acres), or 20.4% of the total watershed area, with nearly 118 miles of shoreline (Table 1). Mean and maximum depths of the Quabbin Reservoir are 45 and 141 ft, respectively.

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

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

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

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

| | | Percentage land cover, per sanitary district | | | |
|---|---|---|---|---|---|
| **Watershed** | **Land cover class** | **East Branch Swift** | **Fever Brook** | **Quabbin Northwest** | **Quabbin Reservation** |
| Quabbin Reservoir | Forest | 82.0 | 87.5 | 88.0 | 53.5 |
| | Agriculture | 3.05 | 0.58 | 1.41 | 0.16 |
| | Developed | 2.45 | 1.46 | 2.82 | 0.51 |
| | Grassland | 1.56 | 1.52 | 1.63 | 1.96 |
| | Wetlands | 6.74 | 6.07 | 4.29 | 1.54 |
| | Barren | 0.19 | 0.09 | 0.27 | 1.16 |
| | Shrub | 0.85 | 0.93 | 0.40 | 0.29 |
| | Water / Shoreline | 3.20 | 1.90 | 1.20 | 40.9 |
| **Watershed** | **Land cover class** | **Burnshirt, Canesto, & Natty** | **Coldbrook & Longmeadow** | **East Branch Ware** | **West Branch Ware** |
| Ware River | Forest | 81.8 | 71.5 | 70.3 | 71.0 |
| | Agriculture | 2.53 | 2.29 | 1.94 | 2.02 |
| | Developed | 4.99 | 4.94 | 6.16 | 4.97 |
| | Grassland | 2.00 | 1.15 | 1.50 | 1.54 |
| | Wetlands | 5.66 | 14.4 | 12.8 | 14.8 |
| | Barren | 0.17 | 0.21 | 0.25 | 0.38 |
| | Shrub | 1.21 | 1.93 | 0.99 | 1.74 |
| | Water / Shoreline | 1.64 | 3.59 | 6.12 | 3.54 |

# 2 Methods

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

## 2.1 Monitoring Programs

DWSP staff monitored water quality at 24 surface water sites in the Quabbin Reservoir and Ware River Watersheds and three sites within the Quabbin Reservoir (Figure 2, Figure 3) in 2021. The tributary monitoring locations within each watershed include Core sites and Environmental Quality Assessment (EQA) sites. Core sites represent long-term monitoring sites throughout the watershed that are included in the monitoring plan each year. Core sites are critical for DWSP assessments, as they provide a long-term record of water quality data from primary tributaries within each watershed. Each watershed is divided into sub-watersheds, referred to as sanitary districts (Figure 2, Figure 3). EQA sites within a single sanitary district are sampled approximately once every four to five years. Data from EQA sites are used to support assessments of potential threats to water quality within each sanitary district. Monitoring of EQA sites provides a year-long assessment of water quality within a specific area of each watershed, allowing for greater spatial coverage, higher-resolution understanding of transport processes operating across the watershed, and elucidation of potential upstream impacts to Core sites. The Quabbin Northwest sanitary district and the Coldbrook and Longmeadow sanitary district were monitored in 2021.

DWSP staff also conduct several special investigations, spanning multiple years of collection. These may vary across watersheds, but include storm water sampling, monitoring of potential short-term and long-term water quality changes following forest management activities, and evaluation of spatial and temporal trends in conductivity and chloride concentrations of waters impacted by de-icing practices. Results of special investigative efforts are discussed in Section 3.2.7.1.

### 2.1.1 Meteorological and Hydrological Monitoring

#### *2.1.1.1 Precipitation and Air Temperature*

Daily measurements of precipitation and air temperatures were recorded at three locations within Quabbin Reservoir and Ware River Watersheds in 2021 (Table 3). DWSP 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). Historical records are also available from the Ware, MA NOAA weather station (USC00198793). As of 2017, this station is no longer active, and records from this station are not summarized in this report.

DWSP staff measured snow depth and snow water equivalent (SWE) weekly (during periods of snow cover) at six locations in the Quabbin Reservoir Watershed in 2021 (Table 3). Reported snowpack measurements (depth and SWE) represent the average depth and weight, respectively, of six snow cores for each sample site, for each site visit. Weekly results were reported to NOAA and the National Operational Hydrologic Remote Sensing Center (NOHRSC).

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

| Measurement | Site Name | Site ID | Managed by | Period of Record |
|---|---|---|---|---|
| Air Temperature, Precipitation | Belchertown, MA | USC00190562 | DWSP | 1947-2021 |
| | Orange Municipal Airport, Orange, MA | USW00054756 | NOAA | 1996-2021 |
| | Barre Falls Dam, MA | USC00190408 | | 1959-2021 |
| | Ware, MA | USC00198793 | | 1947-2017 |
| Snowpack | 4NW Hardwick - Q1 (Gate 43A) | Q1 | DWSP | 2018-2021 |
| | 3SW Petersham - Q2 (Gate 40) | Q2 | | 2018-2021 |
| | 2NW New Salem - Q3 (West of 202) | Q3 | | 2018-2021 |
| | 1N Pelham - Q4 (Pelham Lookout) | Q4 | | 2018-2021 |
| | 4E Belchertown - Q5 (Blue Meadow) | Q5 | | 2018-2021 |
| | 3NW Petersham - Q6 (Balls Crn) | Q6 | | 2018-2021 |
| Mean Daily Streamflow (cfs) | Ware River, Barre | 1172500 | USGS | 1987-2021 |
| | Ware River, Intake Works, Barre | 1173000 | | 1987-2021 |
| | Ware River, Gibbs Crossing | 1173500 | | 1987-2021 |
| | Swift River, West Ware | 1175500 | | 1995-2021 |
| | East Branch Swift River, Hardwick | 1174500 | | 1987-2021 |
| | West Branch Swift River, Shutesbury | 1174565 | | 1987-2021 |
| | Lower Hop Brook | HOPB | NEON | 2017-2021 |
| | Parker's Brook | PARB | DFW-DER | 2012-2021 |

### 2.1.2 Hydrologic Monitoring

#### *2.1.2.1 Streamflow*

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 2021 (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 gauge at Parkers Brook in the Ware River Watershed, generating daily streamflow data beginning in late 2012 (DWSP site ID 102). The National Ecological Observatory Network (NEON) began the development of a streamflow monitoring station along Lower Hop Brook (DWSP site 212) in 2017. Daily streamflow data generated by NEON are available beginning in late 2020 (NEON, 2020). DWSP maintained staff gauges at several monitoring locations (sites GB, 211, 213, 215G, and 216) in 2021. Development of rating curves from these stream gauges will continue in 2022.

### 2.1.3 Tributary Monitoring

DWSP staff monitored water quality at 24 surface water sites in the Quabbin Reservoir and Ware River Watersheds (Table 4) in 2021. 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 five years. Data from EQA sites are used to support assessments of potential threats to water quality within each sanitary district. Monitoring of EQA sites provides a year-long assessment of water quality within a specific area of each watershed, allowing for greater spatial coverage, higher-resolution understanding of transport processes operating across the watershed, and elucidation of potential upstream impacts to Core sites. The Quabbin Northwest sanitary district and the Coldbrook and Langmeadow sanitary district were monitored in 2021.

Samples were collected at Core tributary sites approximately biweekly in 2021, with sampling in Quabbin Reservoir Watershed and Ware River Watershed alternating weekly. Frequency of analyses for nutrients (NO3-N, NH3-N, TN, and TP) increased from quarterly to biweekly in 2020 and remained at biweekly through 2021. Total organic carbon was incorporated into monitoring programs, biweekly at Core sites in the Quabbin Reservoir Watershed in 2021. The impacts of changes to sampling frequency on seasonal statistics and variability across sites are discussed in Section 3.2. Samples were analyzed by MWRA laboraties per standard methods (Table 5).

**Table 4:** DWSP tributary monitoring program components for Quabbin Reservoir Watershed and Ware River Watershed, 2021 (DWSP, 2019b; DWSP, 2007; MassDEP, 2009; DWSP, 2015).

| Watershed | Site Type | Site Description | DWSP Site ID | Sub-catchment Characteristics | | |
|---|---|---|---|---|---|---|
| | | | | Drainage Area (mi$^2$) | Wetland (%) | DWSP Owned Land (%) |
| Quabbin Reservoir | Core | West Branch Swift River, at Route 202 | 211 | 12.42 | 3.4 | 45.0 |
| | | Hop Brook, inside Gate 22 | 212 | 4.62 | 2.5 | 32.2 |
| | | Middle Branch Swift River, at Gate 30 | 213 | 9 | 8.2 | 25.2 |
| | | East Branch of Fever Brook, at Camel Hump Rd | 215G | 5.9 | 11.4 | 13.2 |
| | | East Branch Swift River at Route 32A | 216 | 30.3 | 9.5 | 2.1 |
| | | Gates Brook, at mouth | GB | 0.93 | 3 | 100 |
| | | Boat Cove Brook, at mouth | BC | 0.15 | <1 | 100 |
| | EQA | West Branch Swift River (Sibley) | 211E | 3.85 | 3.0 | 41.9 |
| | | West Branch Swift River (New Boston) | 211F | 6.84 | 4.0 | 44.9 |
| | | West Branch Swift River (Cooleyville) | 211G | 1.73 | 2.1 | 58.0 |
| | | Hop Brook at Gate 22 | 212A | 0.95 | 2.1 | 38.0 |
| | | Hop Brook at Gate 24 | 212B | 3.39 | 2.7 | 29.1 |
| | | Middle Branch Swift River at Fay Road | 213A | 7.5 | 7.8 | 12.8 |
| | | Middle Branch Swift River at Elm St | 213B | 4.8 | 4.9 | 18.3 |
| Ware River | Core | Ware River, at Shaft 8 (intake) | 101 | 96.5 | 13.9 | 37.8 |
| | | Parkers Brook, at Coldbrook Road | 102 | 4.9 | 9.6 | 82.7 |
| | | Burnshirt River, at Riverside Cemetery | 103A | 31.1 | 10.5 | 28.3 |
| | | West Branch Ware River, at Brigham Road | 107A | 16.6 | 15.6 | 45.8 |
| | | East Branch Ware River, at Intervale Road | 108 | 22.3 | 16.8 | 12.6 |
| | | Mill Brook, at Charnock Hill Road | 121 | 3.42 | 15.6 | 9 |
| | EQA | Barre Falls Dam, upstream of Dam | 105 | 55.0 | 16.3 | 34.1 |
| | | Whitehall Pond Outlet at Rutland State Park | 110 | 5.29 | 17.6 | 36.8 |
| | | Demond Pond outlet | 119P | 2.3 | 18.2 | 14.2 |
| | | Moulton Pond Tributary at Britney Drive | 121H | 0.38 | 6.8 | 0 |

Analytical methods for TKN were modified in 2020. Prior to January 01, 2020, TKN concentrations were derived via EPA Method 351.2 (O'Dell, 1993a). Beginning in 2020, analysis shifted to Valderrama (1981) to facilitate monthly monitoring frequencies of N-species and TP in Core sites in Quabbin Reservoir, and biweekly monitoring in Core tributary sites. Results were reported as total nitrogen (TN) in 2020 and 2021. TKN concentrations for 2020 and 2021 were derived by subtracting concentrations of $NO_3$-N and $NO_2$-N from TN concentrations. Concentrations below laboratory detection limits were substituted with the detection limit. $NO_2$-N has been measured previously (2010) in samples collected from Core sites and was below laboratory detection limits in all samples in the Quabbin Reservoir (n=18) and in all but four samples (n=2,005 total measurements) in Core tributaries. Thus, $NO_2$-N was assumed to remain below laboratory detection limits (<0.005 mg/L) in all samples collected in 2020 and 2021. DWSP did not modify sample collection methods, thus uncertainty associated with TKN concentration data is limited to assumptions made during calculations and/or sensitivity of different analytical methods. The detection limits for TN via Valderrama (1981) were 0.0034 mg/L.

**Table 5:** Analytes included in DWSP tributary monitoring programs, analytical methods, and monitoring frequency for 2021. * Alkalinity concentrations results were historically reported by titration to pH of 4.5 endpoint via Standard Method 2320B (DWSP, 2018c).

| Group | Analyte | Method (2021) | Monitoring Frequency (2021) |
|---|---|---|---|
| Bacteria | Total Coliform | SM 9223B | Biweekly |
| | Fecal Coliform | SM 9222D | |
| | *E. coli* | SM 9223B | |
| Misc. | Turbidity | SM 2130 B | |
| | Alkalinity | SM 2320 B* | Quarterly |
| Nutrients & Organic Matter | $NO_3$-N | EPA 353.2 | Biweekly |
| | $NH_3$-N | EPA 350.1 | |
| | TN | Valderrama (1981) | |
| | TP | EPA 365.1 | |
| | TOC | SM 5310 B | |
| | $UV_{254}$ | SM 5910B 19th edition | |
| Metals | Ca | EPA 200.7 | |
| | Na | | |
| Anions | Cl | EPA 300.0 | |
| Field Parameters | Temperature | Gibs et al. (2012) | |
| | Dissolved Oxygen | | |
| | pH | | |
| | Specific Conductance | | |

### 2.1.4 Reservoir Monitoring

The Quabbin Reservoir was sampled regularly in 2021 to monitor phytoplankton densities, anticipate potential taste and odor problems, and recommend management actions as necessary. At site 202, phytoplankton was sampled biweekly from May to September, and monthly from January through April and from October through December (Appendix C). At site 206, phytoplankton was sampled monthly. Phytoplankton sampling frequency was increased to weekly at site 202 in response to elevated densities of *Chrysosphaerella* from May 24 through July 13, 2021. Samples were collected biweekly for phytoplankton enumeration at site 206 during May in response to elevated densities of *Synura*. Samples were collected monthly in 2021 from April to December at three depths from three stations within the reservoir for analyses of nutrients, $UV_{254}$, total organic carbon, and bacteria (in addition to collection of depth-profiles of temperature, pH, dissolved oxygen specific conductance, chlorphyll *a*, and phycocyanin via a Yellow Springs Instruments (YSI) EXO2 sonde). Alkalinity was sampled monthly from April to November. Sodium and chloride were measured in July, October, and December (quarterly). Calcium was measured quarterly at three depths, with the exception of May, when it was sampled at one depth. Water-column profiles of temperature, pH, dissolved oxygen, specific conductance, chlorophyll *a*, and phycocyanin were measured in conjunction with phytoplankton sampling. Changes in sensor manufacturers, sonde configurations, and water column profile collection methods complicate direct comparisons to historical data for physiochemical parameters. Reservoir monitoring results are discussed in Section 3.3 of this report.

**Table 6:** Core monitoring locations in Quabbin Reservoir, 2021. Depth represents the approximate water column depth, based on surface elevation of Quabbin Reservoir at maximum capacity.

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

In addition to manual water column profiles, a remote sensing profiling buoy was deployed by MWRA starting in 2020, located close to sampling site 202 in Winsor Basin. Profiles are collected with YSI EXO2 sondes, identical to those used by DWSP for manual profiles. The profilers automatically run every six hours (12 am, 6 am, 12 pm, and 6 pm) and collect data at 1-m increments. Results are frequently used by DWSP to augment the routine profiles and phytoplankton sampling program. For example, if elevated chlorophyll *a* values are observed in remote sensing data, DWSP may sample earlier than scheduled to capture associated phytoplankton data. The high frequency profile data also allows for identification and visualization of diurnal patterns and both short and long-term effects of environmental forces such as cooling temperatures during turnover and seiche effects due to wind events.

Vertical net tows using a 53-µm mesh net were performed at the Core reservoir water quality monitoring sites, approximately monthly in 2021. Vertical net tows were taken of the entire water column, from a depth around three meters above sediments. Oblique tows (1 min, 53-µm mesh) were also performed quarterly in proximity to the Boat Launch Areas. Samples collected via vertical and oblique net tows were screened to monitor for invasive zooplankton.

#### *2.1.4.1 Aquatic Macrophyte Monitoring*

Eighteen water bodies in the Quabbin Reservoir (n=7) and Ware River Watersheds (n=11) were surveyed by DWSP for the presence of aquatic invasive species (AIS) in 2021 (Table 7). The regulating ponds (O'Loughlin and Pottapaug) and portions of the reservoir shoreline and Ware River were also surveyed for AIS in 2021. The latter assessments were conducted by ESS Group Inc., under a MWRA contract. MWRA and the contracted consultant assist DWSP with early detection of AIS by surveying portions of the Quabbin Reservoir and the Ware River annually.

DWSP additionally monitors for AIS in the watersheds. Several water bodies within the Quabbin Reservoir and Ware River Watersheds are monitored for AIS annually, whereas additional water bodies are evaluated every five years as a component of the current Environmental Quality Assessment. The Quabbin Reservoir consists of four sanitary districts, which comprise the area investigated for the purpose of the annual Environmental Quality Assessments, completed on a five-year basis. Thus, the water bodies in a single sanitary district, for each the Quabbin Reservoir Watershed and the Ware River Watershed, are surveyed for AIS every five years. Select water bodies in the Quabbin Northwest sanitary district and Coldbrook and Longmeadow sanitary district were surveyed for AIS in 2021.

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

**Table 7:** Water bodies surveyed in 2021 for aquatic invasive macrophyte species by DWSP and ESS.

<table>
<tr><th>Watershed</th><th>Water Body Name</th><th>Location</th><th>Surveyed by</th></tr>
<tr><td rowspan="11">Quabbin Reservoir</td><td>Quabbin Reservoir, west arm</td><td>Pelham</td><td rowspan="4">ESS</td></tr>
<tr><td>Quabbin Reservoir, BLA2 shore</td><td rowspan="2">New Salem</td></tr>
<tr><td>O'Loughlin Pond</td></tr>
<tr><td>Pottapaug Pond</td><td>Hardwick</td></tr>
<tr><td>Connor Pond</td><td rowspan="2">Petersham</td><td rowspan="7">DWSP</td></tr>
<tr><td>Harvard Pond</td></tr>
<tr><td>Bassett Pond</td><td rowspan="2">New Salem</td></tr>
<tr><td>South Spectacle Pond</td></tr>
<tr><td>Mattawa Lake</td><td>Orange</td></tr>
<tr><td>Peppers Mill Pond</td><td>Ware</td></tr>
<tr><td>Sibley Swamp</td><td>Wendell</td></tr>
<tr><td rowspan="12">Ware River</td><td>Ware River, upstream of Shaft 8</td><td>Barre</td><td>ESS</td></tr>
<tr><td>Comet Pond</td><td rowspan="3">Hubbardston</td><td rowspan="11">DWSP</td></tr>
<tr><td>Brigham Pond</td></tr>
<tr><td>Moosehorn Pond</td></tr>
<tr><td>Demond Pond</td><td rowspan="7">Rutland</td></tr>
<tr><td>Thayer Pond</td></tr>
<tr><td>Long Pond</td></tr>
<tr><td>Whitehall Pond</td></tr>
<tr><td>Muddy Pond</td></tr>
<tr><td>Edson Pond</td></tr>
<tr><td>Moulton Pond</td></tr>
<tr><td>Queen Lake</td><td>Phillipston</td></tr>
</table>

## 2.1.5 Special Investigations

### *2.1.5.1 Forestry Monitoring*

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

#### *2.1.5.1.1 Long-term Forestry Monitoring*

DWSP conducts long-term monitoring for the potential impacts of timber harvesting on water quality at two surface water sites in the Quabbin Reservoir Watershed (Figure 2). The monitoring follows a paired-watershed study design, where data 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 as climate and hydrological differences over years is statistically controlled, allowing for attribution of water quality changes to treatment rather than climatic drivers (Hewlett and Pienaar, 1973).

Water quality sampling is conducted at two intervals to ensure that monitoring captures a full range of streamflow conditions and solute mobilization. Routine monthly grab sampling and quarterly event-based sampling occurred in 2021, meeting sampling objectives for the project. Monthly grab samples have been collected at the Middle Branch Dickey (MBD) Brook (control site) and the East Branch Underhill (EBU) Brook (treatment site) on Prescott Peninsula since April 2002. Monthly grab samples have been analyzed for nutrients ($NO_3$-N, $NO_2$-N, TKN, and TP) since 2002, and total suspended solids (TSS), $UV_{254}$, $NH_3$-N, TOC, and DOC since 2014, and continued through 2021. Periodic event-based sampling of MBD and EBU was initiated in 2014 to characterize stream response during a variety of hydrologic events (e.g., rainfall, snowmelt, rain-on-snow). Primary data generated by DWSP include measurements of precipitation, stream flow, and concentrations of solutes collected across the event hydrograph ($NO_3$-N, $NH_3$-N, $NO_2$-N, TKN, TP, TSS, $UV_{254}$, TOC, and DOC). Concentration data collected during events 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 2021 also included installation and routine maintenance of water-level loggers and precipitation gauges, downloading of field data, monitoring of weather forecasts, continued development of field procedures, sample and data collection during four events, and associated data analysis.

#### *2.1.5.1.2 Short-term Forestry Monitoring*

Short-term forestry monitoring performed by DWSP involves monitoring forestry operations through site inspections and targeted water quality sampling. Inspections and water quality sampling were conducted prior to the start of logging to establish a baseline, during operations to monitor potential short-term impacts, and following completion of harvesting activities to document potential long-term impacts to water quality of sites adjacent to timber harvesting operations.

#### *2.1.5.2 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 2021 focused on the Quabbin Northwest sanitary district and the Coldbrook and Longmeadow sanitary district (Figure 2, and Figure 3, respectively). Concentrations of constituents measured in tributary monitoring sites in 2021 were compared to results from prior monitoring (DWSP, 2022b-c). Lastly, concentration data from 2021 was compared to regulatory thresholds/limits, when applicable.

## 2.2 2021 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 2021 (Appendix A). Parameters monitored by DWSP included those that may directly affect water quality (and thus, potability) and/or may indicate the presence of potential future negative impacts to water quality. An extensive discussion including relevant regulatory and guidance thresholds for the parameters monitored by DWSP is provided in Appendix A, along with analytical methods for concentration data. Results for various water quality parameters are compared to regulatory levels (e.g., maximum contaminant levels (MCLs)), thresholds for aquatic life protection, recreational contact, and the EPA Ecoregional Nutrient Criteria for Rivers and Streams, when applicable (Appendix A).

## 2.3 Statistical Methods and Data Management

In 2020, monitoring frequency of several parameters was increased in Core tributaries from quarterly to biweekly (DWSP, 2021a). Select tributary monitoring sites previously established as EQA sites were converted to long-term (Core) monitoring sites in 2021 to provide better spatial coverage of either watershed (215G replaced 215 in the Quabbin Reservoir Watershed and 121 replaced 121B in the Ware River Watershed). Parkers Brook (102) was added to the Ware River Watershed monitoring program as a Core site in 2021. Changes in the frequency of analysis of select analytes, or transitions from EQA to Core site sampling frequencies may impact seasonal statistics, long-term patterns in water quality, and comparisons to historical ranges relative to sites that have not undergone significant changes to monitoring program structure (Figure 4).

Monitoring frequency of select analytes in Quabbin Reservoir changed from quarterly to monthly in 2020. Total organic carbon was added to the suite of analyses for these sites in 2020, monthly. Changes in the frequency of analysis of select analytes have the potential to alter seasonal statistics, long-term patterns in water quality, and comparisons to historical ranges relative to parameters that have not undergone changes to monitoring frequency (e.g., bacteria) (Figure 5).


**Figure 4:** Period of record for analytes measured in Core tributaries in Quabbin Reservoir and Ware River Watersheds. Field parameters include specific conductance, water temperature, pH, and dissolved oxygen. Bacteria includes total coliform and *E. coli*, the latter of which was added to DWSP monitoring programs in 2005. Inorganic-N represents $NO_3$-N and $NH_3$-N, with the addition of $NH_3$-N in 2011. TN/TP encompasses data for concentrations of TKN, total nitrogen, and total phosphorus. Organics includes $UV_{254}$, with the addition of total organic carbon at Core sites in the Quabbin Reservoir Watershed in 2021. Metals and anions incorporate Ca, Na, and Cl concentrations.

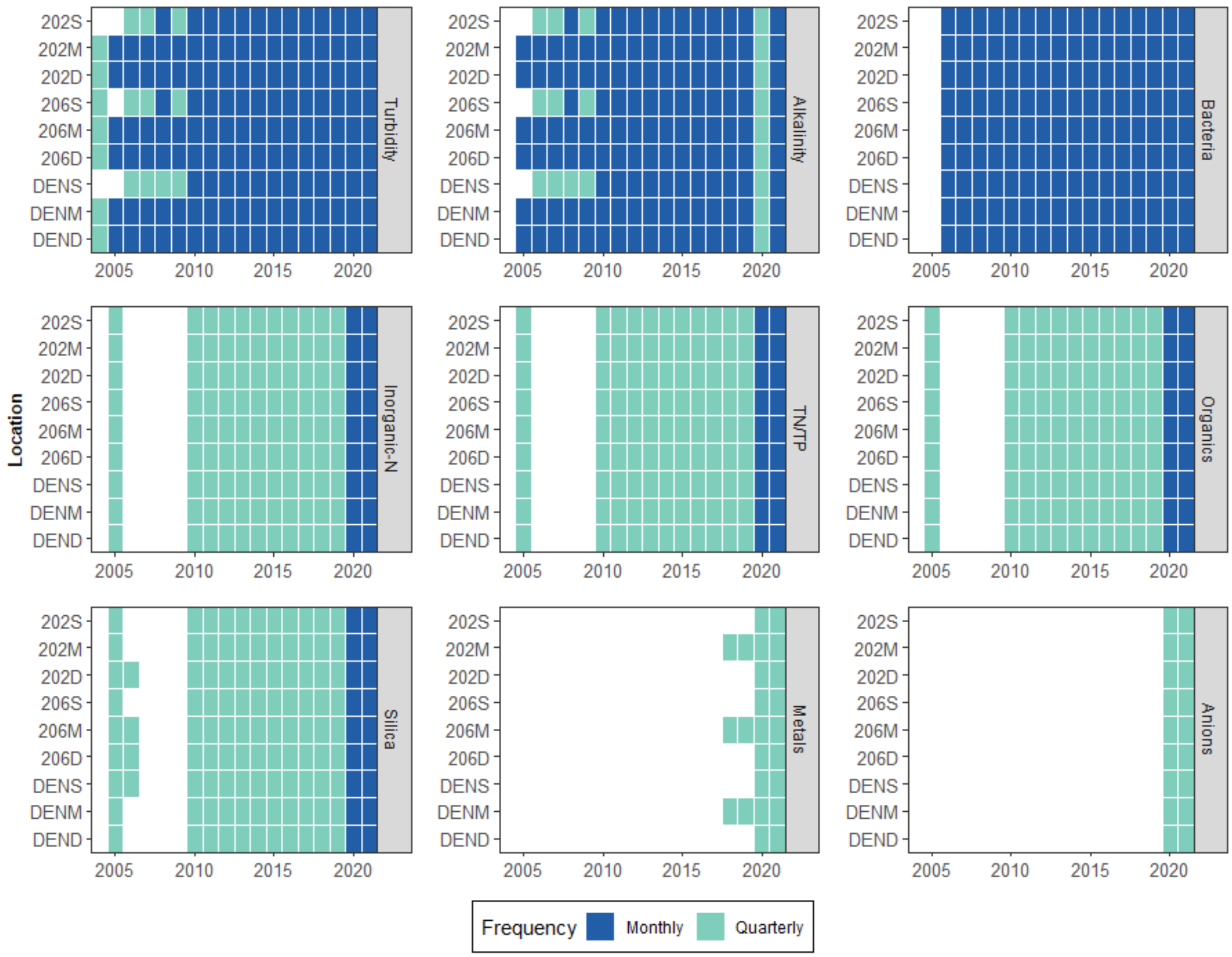



**Figure 5:** Period of record for analytes measured in Quabbin Reservoir monitoring sites. Field parameters including specific conductance, water temperature, pH, and dissolved oxygen were collected in conjunction with phytoplankton sampling. Bacteria includes total coliform and *E. coli*, the latter of which was added to DWSP monitoring programs in 2005. Inorganic-N represents $NO_3$-N and $NH_3$-N, with the addition of $NH_3$-N proceding $NO_3$-N in 2011. TN/TP encompasses data for concentrations of total Kjeldahl nitrogen, total nitrogen, and total phosphorus. Organics includes $UV_{254}$ data, with the addition of total organic carbon at Core sites in the Quabbin Reservoir Watershed in 2020. Metals and anions incorporate calcium and sodium, and chloride concentrations, respectively. Silica was reported as dissolved and total silica in 2005, and as total silica thereafter.

Water quality, precipitation, and streamflow data collected since 1989 are stored in a Microsoft SQL Server database, maintained by DWSP-EQ. The WAtershed system data Visualization Environment (WAVE) is a custom R/Shiny (R Core Team, 2019; Winston et al., 2019) application developed as a collaborative effort between individuals from the Department of Civil and Environmental Engineering at the University of Massachusetts Amherst and DWSP. WAVE serves as a portal to view and track data within the SQL Server database. Data generated from tributary and reservoir water quality monitoring in 2021 are available upon request.

Field parameters (temperature, dissolved oxygen, pH, specific conductance, chlorophyll *a*, and phycocyanin) were routinely recorded and uploaded to the DWSP water quality database in 2021. Laboratory data (including concentrations of various constituents and plankton densities) were uploaded to the DWSP water quality database upon receipt via R-scripts and Shiny application tools designed for data download and database standardization (R Core Team, 2019; Winston et al., 2019). DWSP efforts related to development and management of the water quality database for Quabbin and Ware River Watersheds in 2021 are summarized in Section 2.3.

Concentrations below laboratory reporting limits were replaced with the detection limit for all calculations performed in this report. Concentrations above upper reporting limits were assigned a value equal to the upper detection limit. Censored data are flagged in the DWSP database. This method of handling censored data may vary from that of previous Annual Water Quality Reports for the Quabbin Reservoir and Ware River Watersheds, although is consistent with that used in the 2021 annual water quality report for the Wachusett Reservoir Watershed (DWSP, 2022d). 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 2021 (Helsel, 2012).

Furthermore, annual statistics (mean, median, geometric mean) were calculated using methods depending on the occurrence of non-detects within each data grouping. Left-censored results were substituted with the detection limit concentration and the normal statistic was calculated using base R functions when fewer than four values are detected in a data group. Statistics were calculated using functions from the NADA package (Lee, 2020) when four or more censored values were present in a data group. A parametric method, Maximum Likelihood Estimation (MLE), was used to compute annual geometric mean *E. coli* concentrations. A non-parametric method, Regression on Order Statistics (ROS), was used with other censored data (namely nutrients) to calculate seasonal mean and median concentrations. This modification to statistical methods may produce deviations from standard methods for calculating measures of central tendency for select parameters, as reported previously (DWSP, 2021b-c). To account for this, seasonal mean and median concentration results calculated via standard methods have been incorporated into reporting tables throughout this report, in addition to those derived via either MLE or ROS methods. 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.

# 3 Results

## 3.1 Hydrology and Climate

Climate in the Quabbin Reservoir and Ware River Watersheds exhibits a distinct seasonality and is characterized as humid and temperate, with warm to hot and moist summers and cold, snowy winters (Flanagan et al., 1999). The region lies in an area of prevailing westerly winds and drier continental airflow (Weider and Boutt, 2011). Precipitation events originate in colder region including the Arctic, Mid/North Atlantic, and Pacific, as well as events from Continental and Gulf regions (Puntsang et al., 2016; Cole, 2019).

### 3.1.1 Climatic Conditions

#### *3.1.1.1 Air Temperature*

Average daily median air temperatures of 9.8°C, 9.8°C, and 9.9°C were observed at the three Quabbin Reservoir Watershed and Ware River Watershed weather stations in 2021 (Belchertown, Barre, and Orange, respectively). Minimum and maximum recorded temperatures in 2021 ranged from -18.3°C to 35.6°C (Belchertown), -20.6°C to 37.8°C (Barre), and 21.7°C to 36.1°C (Orange) at the three weather stations. Daily median temperatures throughout the Quabbin Reservoir and Ware River Watersheds during 2021 typically fell within average daily temperature ranges for the period of record (Figure 6), although March and December records included several unseasonably warm days observed across all three weather stations. Maximum air temperatures of 15.6°C to 16.1°C were recorded at all weather stations across the two watersheds between December 11 and 12, 2021. March records included 12 days above 15.6°C maximum daily air temperatures (reaching a maximum of 25.6°C on March 26, 2021) at the Barre weather station. Median monthly temperatures for 2021 at Barre weather station were higher compared to the period of record for all months except November, with 2021 median monthly values 4.4°C higher in January and August.

Average monthly air temperatures in the winter months (December, January, February) of 2021 ranged from -9.5°C to 5.4°C across the Quabbin Reservoir and Ware River Watersheds (Table 8). Mean monthly minimum temperatures during the winter months (December, January, February) were on average, approximately 2.8°C warmer in 2021 compared to historical monthly minimum temperature means (2021 results exceeded historical mean monthly minimum temperatures by 0.34°C to 4.8°C). Mean monthly maximum temperatures were also approximately 1°C warmer (on average) during the winter months in 2021 compared to historical means. Spring months (March, April, May) exhibited an average monthly temperature range in 2021 (-5.4°C to 21.7°C) only slightly higher than the historical ranges (-5.9°C to 20.6°C). Average monthly minimum temperatures in the summer months (June, July, August) were approximately 2.6°C higher in 2021 (12.7°C) compared to the historical record across watershed weather stations (10.1°C), while average monthly maximum temperature in the summer were similar between 2021 (29.3°C) and the historical record (29°C). Temperatures in the fall trended within the average range, with 2021 average monthly temperature ranges (-3.4°C to 24.5°C) similar to the historical range (-2.9°C to 23.6°C ).

**Table 8:** Average monthly temperature range (presented as average daily min - max per month) for the period of record and 2021 for each meteorological station in the Quabbin Reservoir and Ware River Watersheds. Years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis.

| Month | Barre (°C) | | Belchertown (°C) | | Orange (°C) | |
|---|---|---|---|---|---|---|
| | 1959 - 2020 | 2021 | 1947 - 2020 | 2021 | 1996 - 2020 | 2021 |
| Jan | -12.11 - -0.65 | -7.53 - 1.56 | -9.39 - 0.57 | -6.88 - 1.08 | -10.71 - 0.22 | -7.22 - 0.98 |
| Feb | -11.34 - 0.78 | -9.53 - 1.34 | -9.24 - 2.14 | -7.74 - 1.13 | -9.6 - 2.09 | -9.27 - 0.79 |
| Mar | -5.87 - 5.94 | -5.43 - 11.76 | -3.83 - 7.48 | -4.61 - 9.5 | -4.66 - 7.16 | -3.94 - 9.52 |
| Apr | -0.31 - 12.67 | 0.72 - 16.85 | 1.48 - 13.74 | 2 - 14.54 | 0.56 - 14.31 | 1.43 - 15.33 |
| May | 5.31 - 19.66 | 6.14 - 21.74 | 7.81 - 20.63 | 6.84 - 20.14 | 6.86 - 20.62 | 7.24 - 21.26 |
| Jun | 10.14 - 23.92 | 12.74 - 29.04 | 12.42 - 24.83 | 13.5 - 26.65 | 12.21 - 25.05 | 14.26 - 28.22 |
| Jul | 13.19 - 26.79 | 15 - 27.24 | 16.15 - 28.41 | 16.13 - 25.97 | 15.22 - 28.15 | 15.79 - 25.94 |
| Aug | 12.02 - 25.66 | 15.92 - 29.28 | 14.92 - 27.23 | 17.19 - 27.54 | 14.3 - 27.18 | 17.62 - 28.23 |
| Sep | 7.51 - 21.7 | 10.78 - 24.52 | 11.41 - 23.58 | 11.44 - 23.48 | 9.64 - 23.06 | 11.56 - 23.33 |
| Oct | 1.75 - 15.34 | 6.09 - 18.08 | 5.29 - 16.77 | 7.33 - 18.19 | 3.16 - 15.57 | 7.58 - 18.3 |
| Nov | -12.11 - -0.65 | -3.41 - 10.11 | -0.48 - 9.57 | -2.74 - 9.94 | -1.87 - 9.61 | -2.89 - 9.61 |
| Dec | -11.34 - 0.78 | -3.58 - 5.09 | -5.86 - 3.19 | -3.17 - 5.41 | -6.98 - 3.32 | -3.44 - 5.32 |

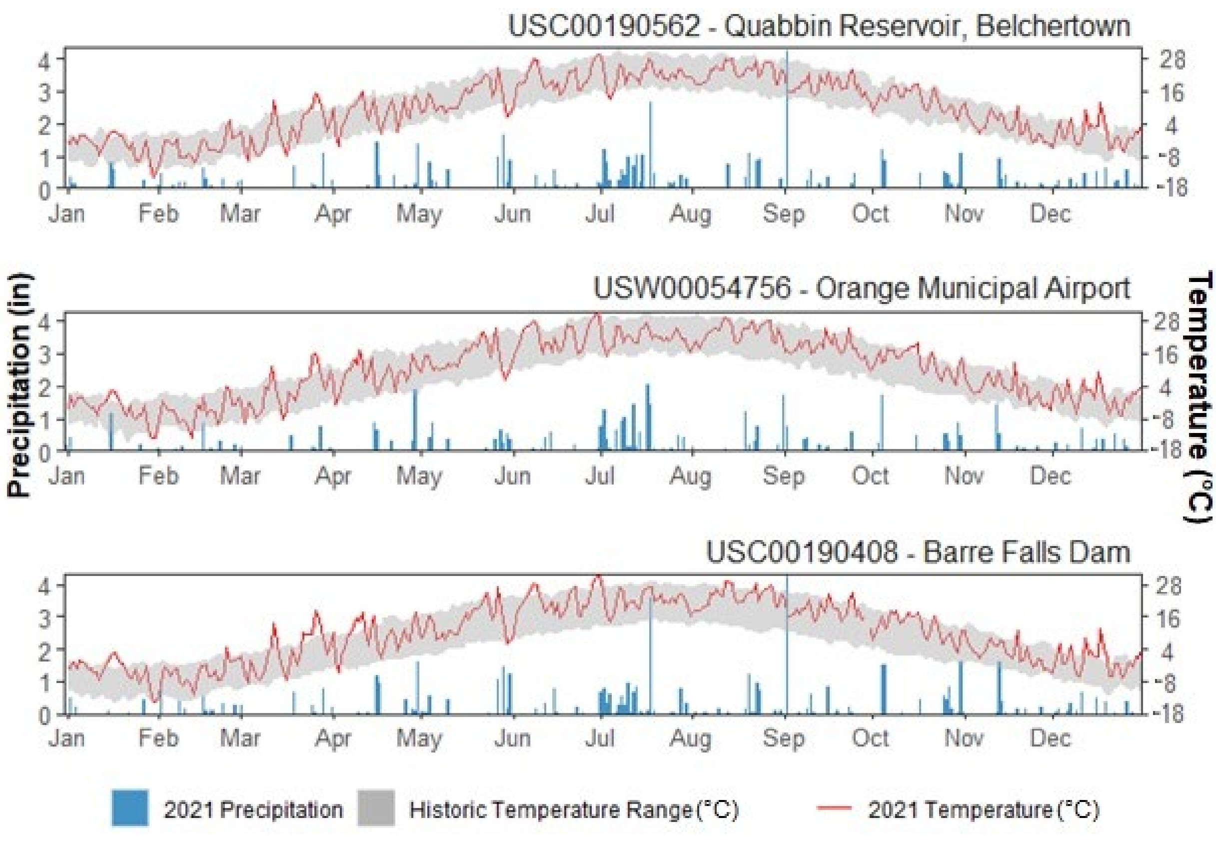



**Figure 6:** Climatograph of precipitation totals and daily median temperatures for weather stations in the Quabbin and Ware watersheds from January 01 through December 31, 2021. Shaded band represents historical mean daily temperature ranges for Belchertown (1947 to 2021), Orange (1996 to 2021), and Barre (1959 to 2021) weather stations.

### *3.1.1.2 Precipitation*

In 2021, total annual rainfall ranged from 45.6 to 52 inches (Orange Municipal Airport and Belchertown weather stations, respectively) across weather stations in the Quabbin Reservoir and Ware River Watersheds (Figure 6). Total annual precipitation was in the upper 50th percentile for the period of record at the three weather stations. Annual rainfall was above the long-term annual rainfall averages by 6.62, 5.33, and 3.07 inches for Barre, Belchertown, and Orange, respectively. Relatively low monthly precipitation totals in the beginning quarter of 2021 were followed by a dramatic increase in annual cumulative precipitation in July 2021. A range of 11.04 to 12.1 inches of rainfall were recorded at watershed weather stations during July 2021 (Table 9). This is more than 7 inches higher than monthly averages and the highest rainfall totals for July at all weather stations. The July rains also were the highest monthly rainfall total of any month on record at Orange Municipal Airport weather station (25-year period of record), and the third highest monthly rainfall total of any month at the Belchertown weather station (74-year period of record). Monthly precipitation totals were also higher than average in the fall months of September and October, upwards of 7.05 inches of precipitation in Barre in October 2021, 3.09 inch greater than the historical monthly rainfall average. The highest precipitation event in Belchertown was the September 01, 2021 rainfall event associated with Hurricane Ida, which yielded 4.24 inches of precipitation in a 24-hour period.

**Table 9:** Average total monthly precipitation (period of record) and total monthly precipitation (2021) for each meteorological station in the Quabbin Reservoir and Ware River Watersheds. Years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis.

| Month | Barre (in) | | Belchertown (in) | | Orange (in) | |
|---|---|---|---|---|---|---|
| | 1951 - 2020 | 2021 | 1947 - 2020 | 2021 | 1998 - 2020 | 2021 |
| Jan | 3.24 | 1.26 | 3.43 | 2.30 | 2.61 | 2.08 |
| Feb | 2.70 | 2.83 | 3.02 | 2.55 | 2.79 | 1.83 |
| Mar | 3.37 | 2.00 | 3.66 | 2.26 | 3.18 | 1.71 |
| Apr | 3.87 | 4.7 | 3.88 | 4.08 | 3.40 | 4.16 |
| May | 3.79 | 5.05 | 3.93 | 5.43 | 3.09 | 3.98 |
| Jun | 3.91 | 1.50 | 4.13 | 1.74 | 4.60 | 1.49 |
| Jul | 3.76 | 11.04 | 4.19 | 11.73 | 3.66 | 12.1 |
| Aug | 4.14 | 3.56 | 4.58 | 4.30 | 3.9 | 2.88 |
| Sep | 3.91 | 6.42 | 4.12 | 6.29 | 4.38 | 4.51 |
| Oct | 4.10 | 7.05 | 4.01 | 5.37 | 4.27 | 5.23 |
| Nov | 3.68 | 2.67 | 3.86 | 2.24 | 3.23 | 2.50 |
| Dec | 3.75 | 2.75 | 3.87 | 3.72 | 3.63 | 3.11 |

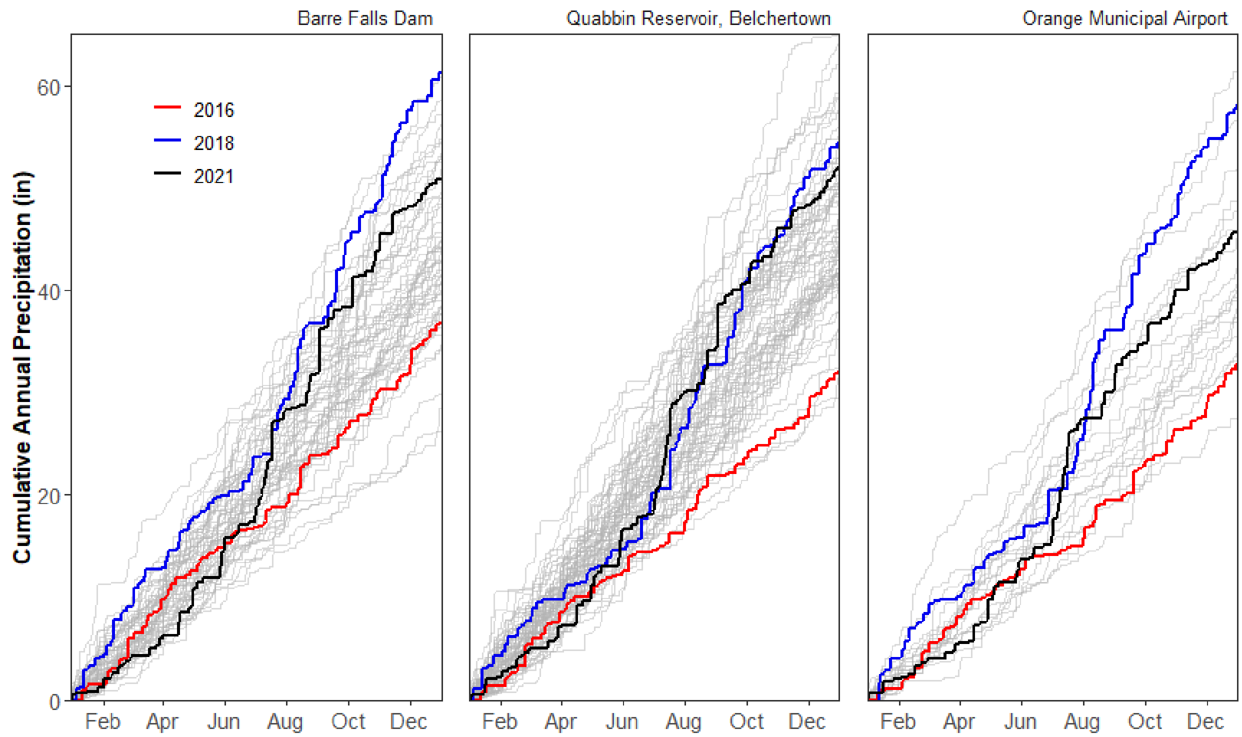



**Figure 7:** Annual cumulative monthly precipitation totals for Barre Falls Dam (USC00190408), Quabbin Administrative Building in Belchertown, MA (USC00190562), and Orange Municipal Airport (USW00054756) weather stations. Colored lines indicate recent years of high and low annual precipitation totals (2018, and 2016, respectively) compared to the period of record (shaded lines, see table 3 for site-specific record ranges) and 2021 (black line) at the three weather stations. Note: years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis.

The Quabbin Reservoir-Ware River region was under drought designations for two consecutive months in 2021 (portions of Franklin and Worcester Counties). According to the Massachusetts Drought Management Task Force, the Quabbin region entered mild drought conditions on March 1, 2021 and remained so until the end of April. No other drought designations were made through 2021 following late spring, summer, and fall rainfalls.

##### *3.1.1.2.1 Snow*

Results from snow monitoring in Quabbin Reservoir Watershed are presented in an annual memo summarizing seasonal patterns and multi-year trends prepared by the DWSP Civil Engineering Section (DWSP, 2022e). Total annual snowfall at Belchertown was 27-in, below the 82-year historical annual average of 46.4-in and one of the lowest snowfall years on record. The largest 24-hour cumulative snowfall recorded in Belchertown was 7.0 inches between February 01 and 02, 2021 (DWSP, 2022a). The highest average watershed snow depth observed was 10.4 inches on February 02, 2021.

### 3.1.2 Streamflow

Daily average streamflow records from two USGS stream gauges in major tributaries to the Quabbin Reservoir (West Branch River and East Branch Swift River) capture a large spike in discharge during the high rainfall of July 2021 corresponding to annual peak discharge (Figure 8). The numerous rainfall events in this month led to sustained high flows throughout the month, culminating in a peak of 556 cfs recorded on July 17, 2021 at the East Branch Swift River. The discharge peak was particularly high for the West Branch Swift (Figure 9), where the July 17 streamflow of 515 cfs was the fifth highest mean daily streamflow on record for the site. The July 17 discharge event was also rare in that the magnitude of streamflow response was similar at the two tributaries, despite the East Branch Swift having a higher drainage area (43.7 $mi^2$) compared to the West Branch Swift (12 $mi^2$) and thus higher daily average streamflow records. The high flow events of July resulted in record high maximum daily discharge values for that month at both the West Branch Swift and Ware River stream gauges (Table 10). Corresponding precipitation records preceding July 2021 suggest that heterogeneity of daily precipitation rates across spatial gradients, and thus local groundwater levels, may have in part contributed to this response.

**Table 10:** Monthly stream discharge range (presented as min - max of daily mean per month) for the period of record and 2021 for USGS gauging stations in the Quabbin Reservoir and Ware River Watersheds. Years with incomplete records (e.g., missing >5% of measurements) were excluded from this analysis.

| Month | West Branch Swift (01174565) | | East Branch Swift (01174500) | | Ware River (01173000) | |
|---|---|---|---|---|---|---|
| | 1995-2020 | 2021 | 1988-2020 | 2021 | 1988-2020 | 2021 |
| Jan | 1.57 - 249 | 16.8 - 58.6 | 7.1 - 1030 | 49 – 259 | 20 - 1310 | 104 - 379 |
| Feb | 2.2 - 338 | 9.81 - 28 | 11 - 695 | 45.8 - 88.7 | 30 - 1220 | 89.2 - 180 |
| Mar | 7.7 - 688 | 12.6 - 47.1 | 18.8 - 1310 | 55.3 – 134 | 37.8 - 1400 | 108 - 264 |
| Apr | 5.86 - 489 | 12.4 - 164 | 20.1 - 985 | 35.5 – 264 | 59 - 1230 | 83.5 - 426 |
| May | 5.68 - 160 | 10.4 - 116 | 15 - 479 | 26 – 340 | 34.9 - 727 | 55.8 - 521 |
| Jun | 1.1 - 377 | 3.26 - 25.2 | 0.54 - 690 | 10.8 – 122 | 7.1 - 602 | 28 - 351 |
| Jul | 0.54 - 515 | 19.6 - 515 | 0 - 873 | 41.7 – 556 | 2 - 636 | 88.7 - 636 |
| Aug | 0.4 - 385 | 4.25 - 57.5 | 0 - 716 | 27 – 165 | 2 - 931 | 35.3 - 235 |
| Sep | 0.35 - 636 | 5.17 - 187 | 0 - 692 | 61.5 – 486 | 2.2 - 839 | 92.8 - 649 |
| Oct | 0.36 - 687 | 4.84 - 96.4 | 0 - 887 | 63.2 – 407 | 5.02 - 1110 | 76.2 - 644 |
| Nov | 0.89 - 293 | 16.4 - 88.2 | 1.2 - 488 | 98.6 – 387 | 14 - 807 | 147 - 764 |
| Dec | 1.48 - 374 | 15.5 - 39.5 | 3 - 737 | 104 – 202 | 25 - 912 | 150 - 302 |

A series of high flow events were also recorded at the Quabbin Reservoir Watershed stream gauge sites during the following fall months, the magnitude of which was much higher in East Branch Swift River compared to the West Branch Swift River. This included high flows on September 01 to 02, October 04, and November 12 to 13, 2021 at both sites. The East Branch Swift River ranged in mean daily streamflow in 2021 from a minimum of 10.8 cfs (June 26, 2021) to a maximum of 556 cfs (July 17, 2021), with an average of 105 cfs. The West Branch Swift ranged in mean daily streamflow in 2021 from a minimum of 3 cfs (June 28, 2021) to a high of 515 cfs (July 17, 2021), with an average of 22 cfs. Daily discharge records were generally lower than normal range for the first months of 2021 but reached normal and above normal status following the July and fall rain events.

Patterns of stream discharge from the USGS gauge located on the Ware River at the Intake Works in Barre, MA exhibit similar responses to rainfall events but the magnitude of hydrograph response varies from that of the Quabbin Reservoir Watershed streams (Figure 8). Peak streamflow at this site was 764 cfs on November 01, 2021, and hydrograph peaks were higher during the fall months compared with those associated with the same events for the Quabbin Reservoir Watershed sites. Overall flows were lower than historical averages in the early winter through spring. The annual minimum average daily streamflow of 28 cfs was recorded on June 28, 2021. Streamflow conditions were at or above normal through the rest of 2021 beginning in July, with marked spikes in the hydrograph on July 19 to 20, September 03 to 04, October 05, and November 01 to 02, 2021. Average mean daily streamflow for the Ware River at Intake Works station in 2021 was 197 cfs.

Downstream releases from the Quabbin Reservoir into the Swift River can be observed from the daily average discharge records from the USGS gauge in West Ware (Figure 8). The minimum average daily streamflow at this site was 44.5 cfs (February 07 to 13, 2021) and the maximum average daily streamflow was 119 cfs (July 17) in 2021. Average daily streamflow was consistently on the low end of the normal range throughout 2021, apart from June and July flow conditions. The unique meteorological conditions that occurred during June and July resulted in sustained mean daily streamflows above the long-term historical daily average for much of June and July 2021 with discharge from the Quabbin spillway. A small number of years with very high spillover volumes (e.g., 2019, 2006, 1997) contribute to a winter historical streamflow average above the normal range at this site.

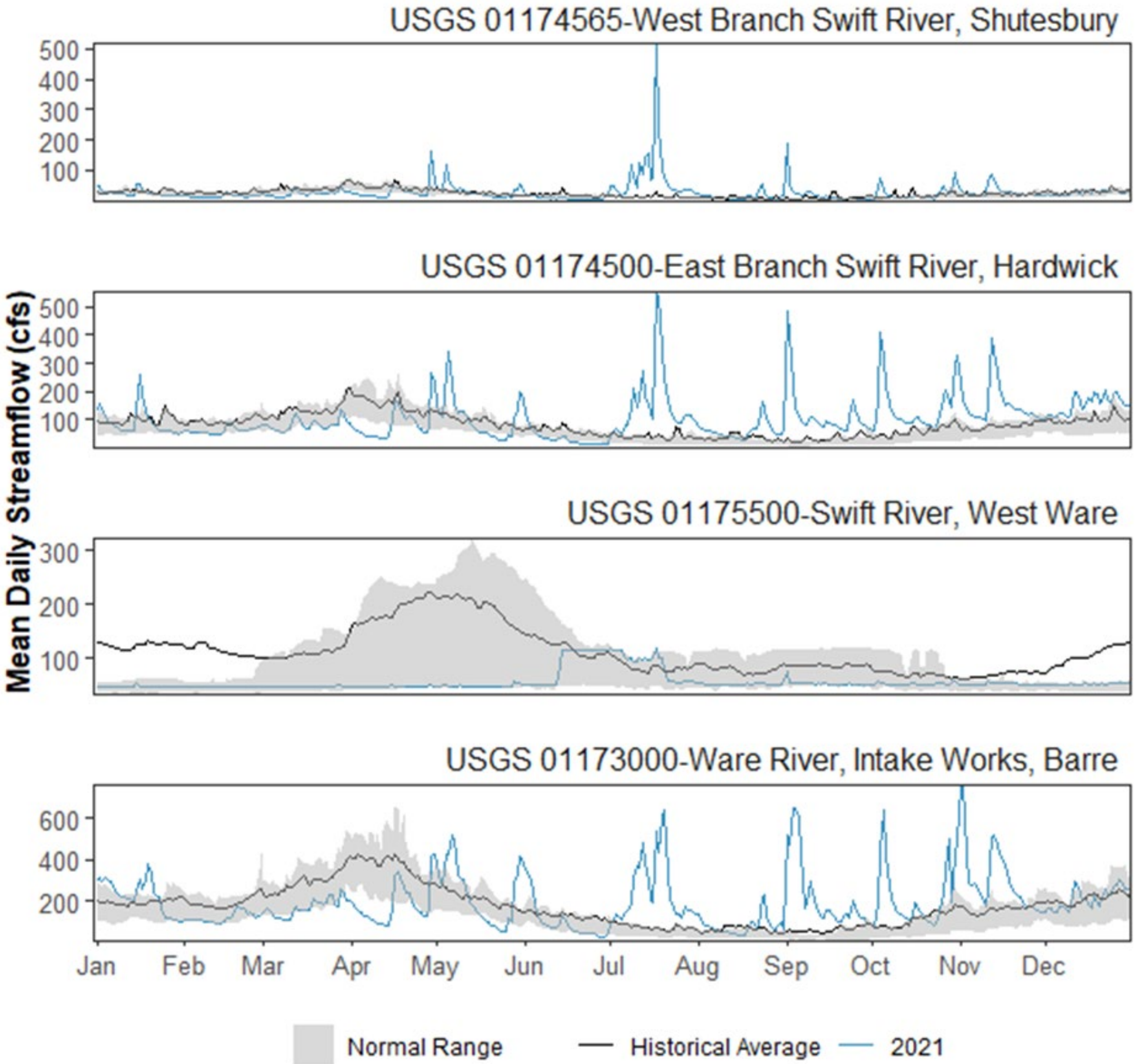



**Figure 8:** Hydrograph of mean daily streamflow (cfs) at four USGS stream gauges in the Quabbin Reservoir and Ware River Watersheds. The average of mean daily flows for the period of record are represented by the solid black lines. Average daily flows in 2021 are represented by the blue lines. The gray bands denote the normal (25th to 75th percentile) flow range for the period of record.

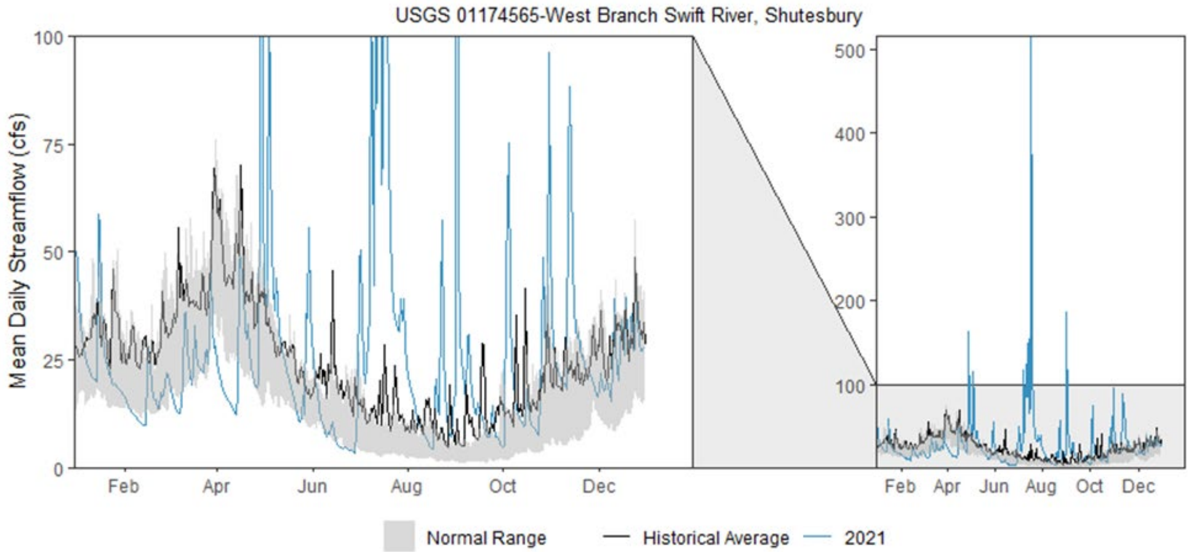



**Figure 9:** Hydrograph of mean daily streamflow from the West Branch Swift River USGS gauge in Shutesbury, MA. The high discharge event from July 2021 is placed in context with the historical range of normal flow conditions. The average of mean daily flows for the period of record are represented by the solid black line. Average daily discharge in 2021 are represented by the blue line. The gray band denotes the normal (25th to 75th percentile) daily flow range for the period of record.

Cumulative annual discharge calculated from average daily discharge records were higher than average across three stream gauges in the Quabbin Reservoir and Ware River Watersheds (Figure 10). The West Branch Swift stream gauge recorded a cumulative discharge total of 6,633 MG in 2021, a value in the upper half of annual cumulative totals from the 26-year period of record for the gauge. Annual cumulative discharge in 2021 was higher than the historical mean annual discharge (5,903 MG) at the site (range 2,871 to 10,353 MG). Cumulative discharge at the East Branch Swift River gauge totaled 24,748 MG in 2021, the 8th highest value recorded from the 33-year period of record corresponding to this gauge (range of 8,138 to 31,507 MG) and higher than the historical mean on record (19,998 MG). The stream gauge on Ware River at the Intake Works in Barre, MA recorded a cumulative total of 46,354 MG, above the historical mean (42,526 MG) based on the 34-year period of record (range 22,796 to 65,891 MG). Cumulative discharge across all sites exhibited a similar seasonal pattern, with lower-than-average discharge in the early months of 2021 followed by a marked increase in cumulative discharge following the record-breaking July rainfall. Cumulative discharge at the three sites continued to rise above average following the significant fall rain and subsequent discharge events (see also Figure 7, Figure 8, Figure 9).

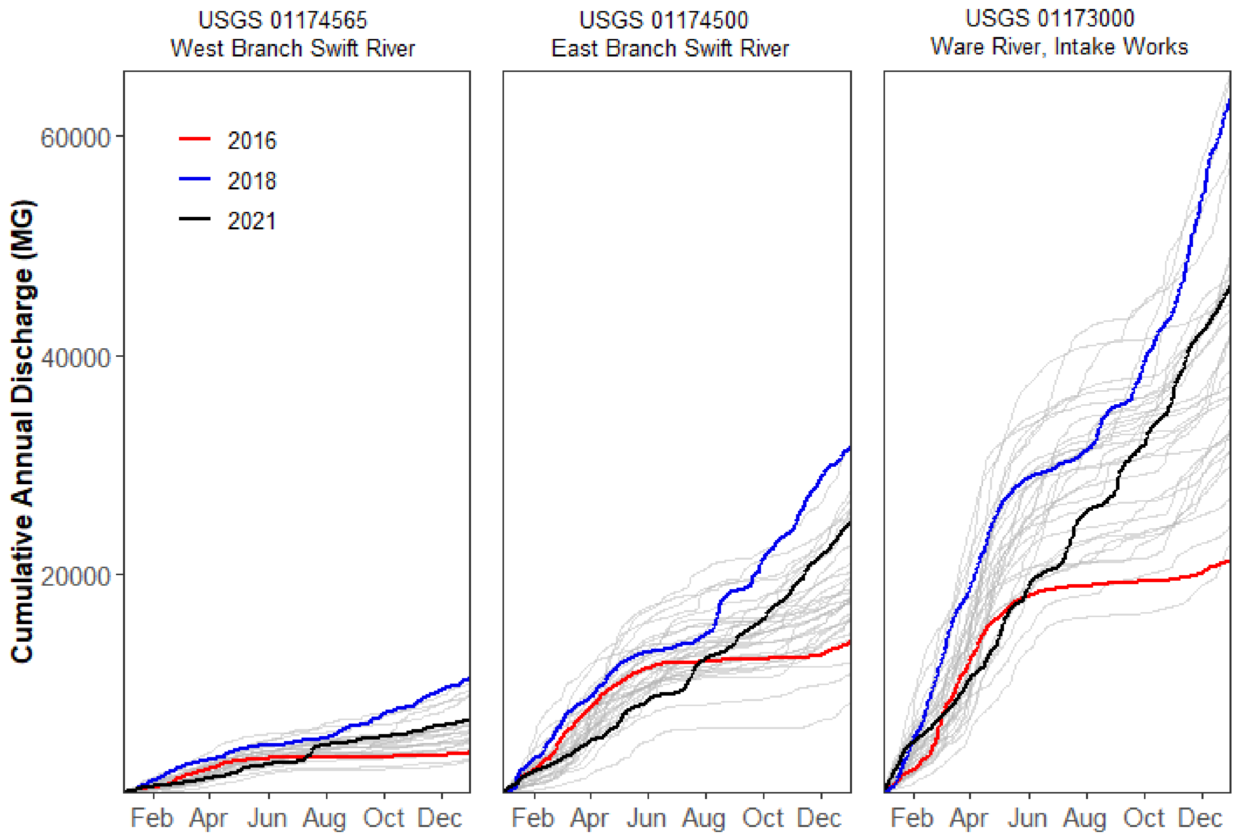



**Figure 10:** Cumulative annual discharge (in millions of gallons) calculated from average daily discharge records at three USGS stream gauges in the Quabbin Reservoir and Ware River Watersheds. Colored lines indicate recent years of high and low cumulative annual discharge totals (2018, and 2016, respectively) compared to the period of record (gray lines, see Table 10 for site-specific record ranges) and 2021 (black line) at the three USGS stream gauges. Note: years with incomplete records (e.g., missing >5% of measurements) were excluded from this visualization.

#### *3.1.2.1 Reservoir Elevation*

Daily surface elevation of the Quabbin Reservoir is recorded by DWSP. The DWSP Civil Engineering Section has established various spillway watch triggers to aid in management decisions such as drought management and flood control. Quabbin Reservoir elevation remained within normal (25th to 75th percentile) operating range throughout select months during 2021. Elevation of the water surface of Quabbin Reservoir ranged from a minimum of 523.68 to 530.07 ft BCB on November 23, 2021 and May 19, 2021, respectively (Figure 11). A single row of stop logs was in place until March 24, 2021.

Daily reservoir elevation was trending below seasonal normals into the beginning of July, but rapidly rebounded to the upper bounds of normal (e.g., 75th percentile daily elevations) by mid-July following record high precipitation totals that occurred during the month of July 2021. Daily reservoir elevation exceeded the spillway watch trigger of 528 ft BCB beginning on July 20 and continuing through August 05, 2021. The reservoir was actively discharging via the spillway during this time (approximately 20 MG total discharge). Reservoir elevation again rose rapidly in the beginning of September, following the impacts of Hurricane Ida on the watershed, exceeding the 75th percentile daily elevation into September and remaining above normal elevations throughout the remainder of 2021. Annual dynamics of reservoir elevation followed that of previous years, driven predominantly by seasonal changes in precipitation/snowmelt and subsequent riverine inputs.

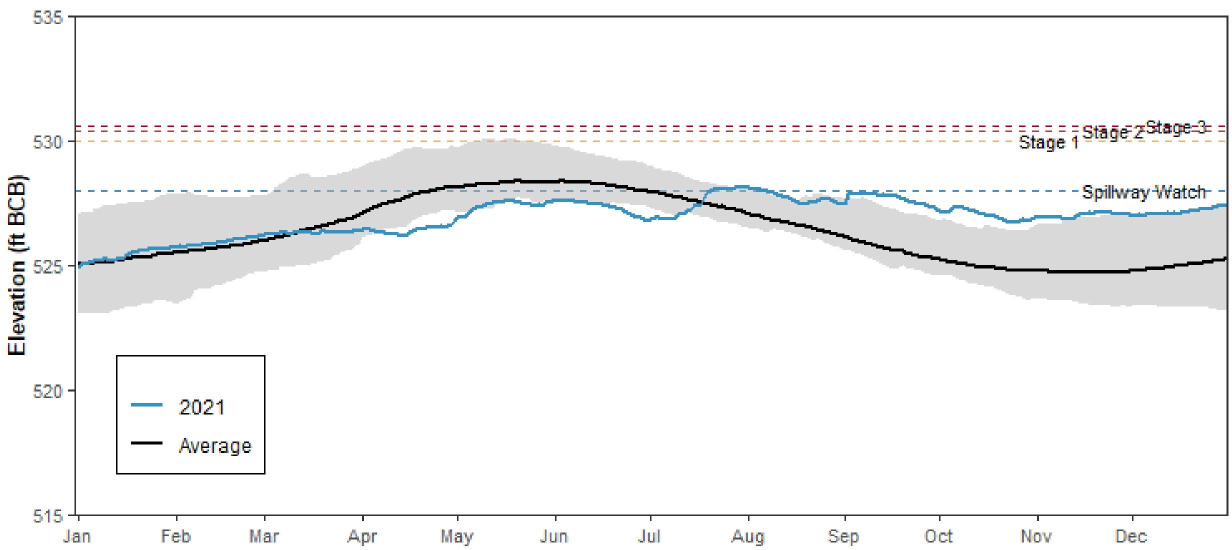



**Figure 11:** Daily elevation of the Quabbin Reservoir from January 01 through December 31, 2021, relative to spillway watch triggers (DWSP, 2019d) established by DWSP Civil Engineering Section. Gray band represent daily normals (defined as 25th to 75th percentiles) and the black line is the average daily elevation for the period of record (1980 through 2021).

## 3.2 Tributary Monitoring

### 3.2.1 Water Temperature and Dissolved Oxygen

#### *3.2.1.1 Water Temperature*

Water temperature in Quabbin Reservoir Watershed Core tributaries ranged from -0.1 to 25.2˚C in 2021 (Table 11). Water temperature exhibited a typical distinct seasonality during 2021, falling within established seasonal ranges for each site (215G was omitted from this analysis because of limited historical data). Seasonal median temperatures in 2021 were generally comparable to that of the period of record for each site, although fall temperature departures were most pronounced. Individual sites were 1.8 to 2.85˚C warmer during the fall of 2021 relative to the period of record. This observation may be directly related to air temperatures during the same time interval, as air temperatures at multiple weather stations across the watershed were above average during the fall months of 2021. Sites situated in the eastern and southern regions of the watershed exhibited a greater divergence in median winter water temperatures, when compared to the period of record, than sites located within the northwestern region of the watershed.

MassDEP designates cold water fish (CFR) habitats as rivers and streams in which average and maximum daily temperatures over a seven-day period generally do not exceed 20˚C (314 CMR 4.06). In contrast, warm water fish (WRF) habitats are designated as those with maximum daily temperatures ranging from 20˚C to 28.3˚C over a seven-day period. Water temperature data generated by DWSP represent a discrete collection time, thus these data cannot be compared directly to cold water fish habitat criteria. Rather, comparisons to these thresholds may indicate the potential for a location to become impaired. Sites 211, 212, and 216 in the Quabbin Reservoir Watershed represent rivers that have been identified as suitable habitat for cold water fish by MassDEP. Instantaneous water temperatures exceeded the 20˚C threshold on four dates at site 216 in 2021 (20.3 to 24˚C). Sites 211 and 212 remained below 20˚C throughout 2021, as did GATE and BC. No sites in the Quabbin Reservoir Watershed exceeded the temperature criteria for warm water fish habitat (28.3˚C) in 2021.

**Table 11:** Descriptive statistics (minimum, median, average, and maximum) for water temperature measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Temperature (°C) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Spring | 8 | (240) | -0.1 | (-0.11) | 6.56 | (5.87) | 5.99 | (5.77) | 12.4 | (18.2) |
| | Summer | 6 | (243) | 14.4 | (9.00) | 16.6 | (16.2) | 16.9 | (16.1) | 19.7 | (21.0) |
| | Fall | 6 | (238) | 5.20 | (0) | 11.1 | (9.00) | 10.8 | (8.94) | 16.4 | (19.0) |
| | Winter | 6 | (243) | 0 | (-0.40) | 0.75 | (0.28) | 1.03 | (0.74) | 2.30 | (5.25) |
| 212 | Spring | 8 | (228) | -0.1 | (-0.35) | 6.44 | (6.00) | 6.02 | (6.25) | 13.1 | (19.7) |
| | Summer | 6 | (232) | 15.3 | (10.0) | 17.1 | (17.1) | 17.4 | (17.2) | 19.9 | (22.6) |
| | Fall | 6 | (223) | 5.50 | (0) | 11.4 | (9.55) | 11.2 | (9.45) | 16.9 | (20.0) |
| | Winter | 6 | (224) | -0.10 | (-0.42) | 0.55 | (0.03) | 0.87 | (0.66) | 2.20 | (6.00) |
| 213 | Spring | 8 | (237) | 0.10 | (-0.42) | 10.2 | (7.80) | 8.79 | (7.60) | 18.3 | (23.1) |
| | Summer | 6 | (237) | 18.2 | (5.30) | 20.0 | (20.0) | 20.5 | (19.7) | 23.5 | (24.8) |
| | Fall | 6 | (228) | 4.30 | (1.00) | 12.2 | (10.0) | 11.4 | (10.1) | 18.7 | (21.3) |
| | Winter | 6 | (235) | 0.10 | (-0.15) | 0.75 | (0.17) | 0.92 | (0.58) | 2.40 | (9.00) |
| 215G | Spring | 7 | (11) | 0.90 | (2.42) | 11.2 | (12.9) | 10.4 | (11.4) | 19.9 | (16.6) |
| | Summer | 6 | (13) | 19.5 | (14.2) | 21.5 | (20.6) | 21.8 | (20.4) | 25.2 | (25.0) |
| | Fall | 6 | (13) | 5.60 | (1.45) | 12.8 | (13.5) | 12.4 | (12.2) | 19.9 | (22.0) |
| | Winter | 4 | (11) | 0.50 | (0.86) | 1.90 | (1.37) | 1.75 | (1.72) | 2.70 | (3.90) |
| 216 | Spring | 8 | (239) | -0.10 | (-0.47) | 8.98 | (8.23) | 8.53 | (7.97) | 17.7 | (22.5) |
| | Summer | 6 | (243) | 18.9 | (8.80) | 20.5 | (20.0) | 20.8 | (19.6) | 24.0 | (25.2) |
| | Fall | 6 | (234) | 5.50 | (0.28) | 12.6 | (10.5) | 12.3 | (10.4) | 20.1 | (21.7) |
| | Winter | 6 | (240) | 0 | (-0.46) | 1.30 | (0.04) | 1.33 | (0.69) | 3.30 | (6.50) |
| GATE | Spring | 8 | (170) | 0 | (0) | 5.20 | (6.29) | 5.11 | (6.23) | 10.9 | (15.1) |
| | Summer | 6 | (174) | 14.8 | (9.75) | 16.1 | (16.0) | 15.9 | (15.9) | 16.8 | (20.1) |
| | Fall | 6 | (188) | 8.60 | (0.31) | 12.5 | (10.6) | 12.3 | (10.4) | 16.5 | (19.2) |
| | Winter | 6 | (169) | 0.10 | (-0.43) | 2.30 | (1.23) | 2.27 | (1.87) | 4.10 | (7.00) |
| BC | Spring | 8 | (175) | 0.10 | (-0.04) | 9.50 | (8.06) | 8.32 | (8.04) | 15.3 | (20.1) |
| | Summer | 6 | (146) | 15.7 | (11.1) | 17.8 | (18.5) | 17.5 | (18.3) | 18.4 | (23.6) |
| | Fall | 6 | (151) | 8.10 | (0.14) | 12.9 | (10.0) | 12.6 | (10.5) | 17.4 | (20.9) |
| | Winter | 6 | (170) | 0.20 | (-0.39) | 2.25 | (0.99) | 2.05 | (1.42) | 3.60 | (10.0) |

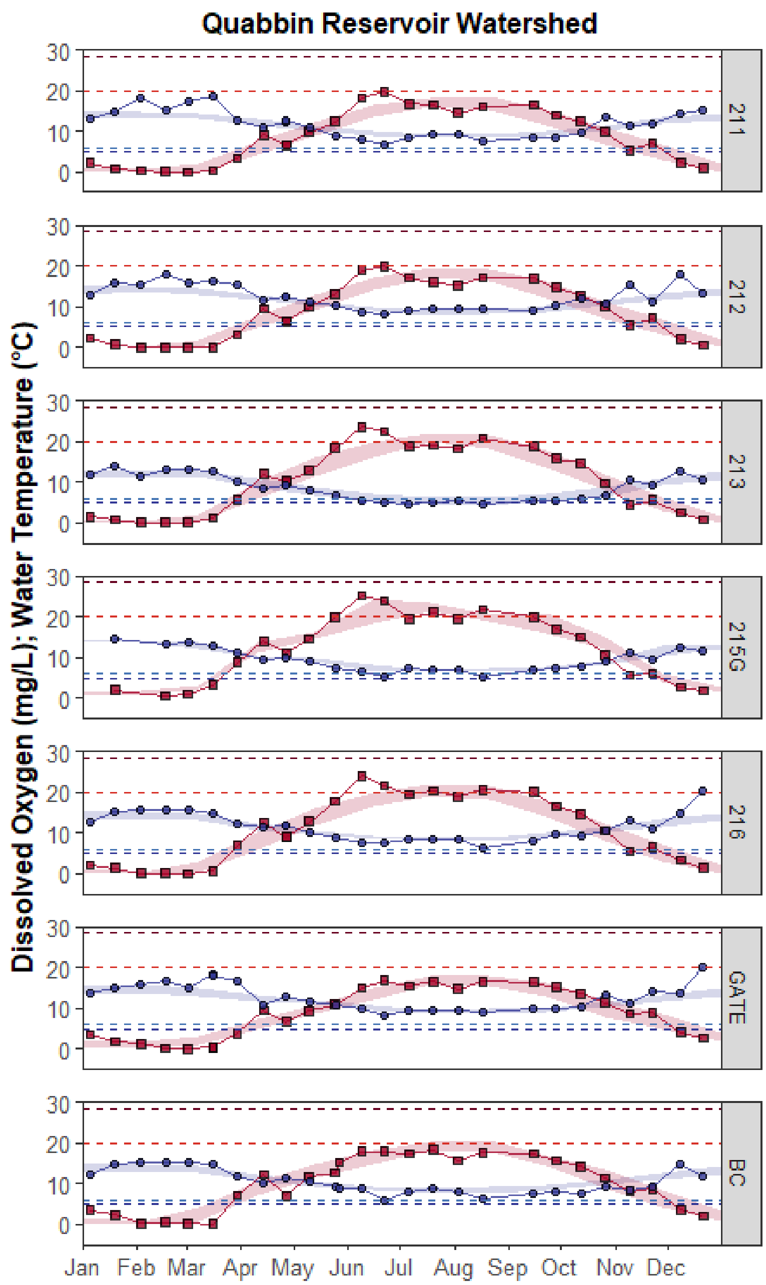



**Figure 12:** Time series of water temperature and dissolved oxygen measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent seasonal interquartile ranges (25th to 75th percentile) for the period of record at each location. The dashed horizontal lines correspond to the lower recommended dissolved oxygen concentration for CFR (6.0 mg/L; light blue) and WFR (5.0 mg/L; dark blue), and the upper temperature limits for CFR (20˚C; red) and WFR (28.3˚C; burgundy) waters. Note: the period of record may be variable across sites, thus impacting seasonal statistics (Section 2.2).

Water temperature in Ware River Watershed Core tributaries ranged from 0 to 27˚C in 2021 (Table 12). Water temperature followed a distinct seasonality during 2021, generally remaining within historical seasonal ranges. Seasonal median temperatures in 2021 were comparable to that of the period of record for Ware River tributary sites, although median temperatures in the spring and summer were greater than that of the period of record for all Core sites. Individual sites were 1.88 to 3.67˚C warmer during the spring of 2021 relative to the period of record. Temperature deviations from historical medians were less extreme during summer months (0.27 to 1.75˚C warmer), although sites remained warmer than historical median summer temperatures. Historical seasonal maximum temperatures were exceeded by one site (108) on a single date in 2021. The maximum annual temperature at all Core sites occurred on June 29, 2021, coincident with the lowest mean daily streamflow for the Ware River at intake works (USGS 1173000) and the greatest maximum daily temperature in 2021 in Barre, MA (USC00190408).

Sites 102, 107A, and 108 in the Ware River Watershed are rivers that have been identified as suitable habitat for cold water fish by MassDEP. Instantaneous water temperatures exceeded the 20˚C threshold on four dates at sites 107A and 108 in 2021 (21.9 to 26.3˚C). Site 102 remained below 20˚C throughout 2021, as did 121. No sites in the Ware River Watershed exceeded the temperature criteria for warm water fish habitat (28.3˚C) in 2021.

**Table 12:** Descriptive statistics (minimum, median, average, and maximum) for water temperature measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Temperature (°C) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Spring | 8 | (204) | 5.40 | (-0.47) | 12.2 | (9.00) | 12.1 | (8.35) | 16.9 | (21.1) |
| | Summer | 6 | (209) | 11.5 | (13.6) | 21.8 | (21.0) | 19.8 | (21.0) | 23.7 | (27.0) |
| | Fall | 6 | (208) | 1.40 | (0.75) | 10.8 | (11.0) | 9.83 | (11.1) | 17.4 | (23.9) |
| | Winter | 6 | (199) | 0.10 | (-0.45) | 0.35 | (0.08) | 0.67 | (0.60) | 2.10 | (8.00) |
| 102 | Spring | 8 | (104) | 3.30 | (1.00) | 9.12 | (7.00) | 8.50 | (6.97) | 11.2 | (16.0) |
| | Summer | 7 | (107) | 10.1 | (10.0) | 16.4 | (15.0) | 15.8 | (14.8) | 18.7 | (20.2) |
| | Fall | 6 | (106) | 1.70 | (1.00) | 8.30 | (8.00) | 8.00 | (8.53) | 12.7 | (19.0) |
| | Winter | 6 | (103) | 0 | (0) | 1.20 | (1.00) | 1.45 | (1.38) | 3.10 | (8.00) |
| 103A | Spring | 8 | (90) | 4.10 | (-0.41) | 10.9 | (8.97) | 10.5 | (8.43) | 14.6 | (19.0) |
| | Summer | 7 | (102) | 11.5 | (11.7) | 19.9 | (19.6) | 18.8 | (19.4) | 23.3 | (24.5) |
| | Fall | 6 | (102) | 0.60 | (0.46) | 9.50 | (10.1) | 8.62 | (10.0) | 14.5 | (21.7) |
| | Winter | 6 | (74) | 0.10 | (-0.39) | 0.30 | (0.16) | 0.62 | (0.70) | 1.80 | (6.95) |
| 107A | Spring | 8 | (97) | 4.50 | (-0.10) | 11.0 | (8.86) | 11.0 | (8.34) | 16.1 | (20.4) |
| | Summer | 7 | (101) | 12.2 | (11.67) | 21.9 | (20.6) | 20.1 | (20.2) | 25.6 | (25.6) |
| | Fall | 6 | (102) | 0.40 | (0.41) | 12.0 | (10.4) | 10.5 | (10.2) | 17.6 | (23.0) |
| | Winter | 6 | (83) | 0 | (-0.45) | 0.50 | (0.10) | 0.67 | (0.59) | 1.60 | (6.98) |
| 108 | Spring | 8 | (201) | 4.70 | (-0.47) | 11.8 | (8.20) | 11.4 | (8.09) | 16.1 | (21.4) |
| | Summer | 7 | (202) | 12.3 | (12.2) | 21.9 | (20.2) | 20.3 | (20.3) | 26.3 | (25.6) |
| | Fall | 6 | (202) | 0.50 | (0) | 9.95 | (10.0) | 9.27 | (10.4) | 16.8 | (23.6) |
| | Winter | 6 | (194) | 0 | (-0.45) | 0.05 | (0.02) | 0.50 | (0.53) | 1.90 | (7.26) |
| 121 | Spring | 8 | (117) | 5.70 | (0) | 12.4 | (9.80) | 12.7 | (9.13) | 18.5 | (22.2) |
| | Summer | 7 | (125) | 12.3 | (12.0) | 21.6 | (20.2) | 20.6 | (20.2) | 27.0 | (28.0) |
| | Fall | 6 | (127) | 2.40 | (1.00) | 10.1 | (10.0) | 9.87 | (10.4) | 18.1 | (21.0) |
| | Winter | 6 | (117) | 0.20 | (0) | 0.85 | (0.53) | 1.18 | (0.98) | 3.00 | (8.00) |

#### *3.2.1.2 Dissolved Oxygen*

Dissolved oxygen concentrations in Quabbin Reservoir Watershed Core tributaries ranged from 4.62 to 20.3 mg/L in 2021 (Table 13). Dissolved oxygen concentrations demonstrated a typical seasonality in 2021, relatively depleted during warmer months and elevated in winter and fall. Concentrations of dissolved oxygen were inversely related to water temperature and within established seasonal ranges for each site, aside from 215G for which long-term records are limited. Seasonal median dissolved oxygen concentrations in 2021 were comparable to the period of record for each site, although difference in seasonal results were most pronounced at sites 211, 212, 216, and GATE. Median dissolved oxygen concentrations during the winter and spring at these sites were 0.02 to 1.85 mg/L greater in 2021 relative to historical medians.

**Table 13:** Descriptive statistics (minimum, median, average, and maximum) for dissolved oxygen measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Dissolved Oxygen (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Spring | 8 | (240) | 8.95 | (6.45) | 12.4 | (12.4) | 13.1 | (12.4) | 18.8 | (21.6) |
| | Summer | 6 | (243) | 6.87 | (4.72) | 8.31 | (9.06) | 8.17 | (9.03) | 9.18 | (12.2) |
| | Fall | 6 | (238) | 8.18 | (5.76) | 10.4 | (10.8) | 10.5 | (11.0) | 13.6 | (19.6) |
| | Winter | 6 | (243) | 13.0 | (10.2) | 14.9 | (13.7) | 15.1 | (14.1) | 18.1 | (23.1) |
| 212 | Spring | 8 | (228) | 10.4 | (6.26) | 12.4 | (12.2) | 13.2 | (12.4) | 16.4 | (21.2) |
| | Summer | 6 | (232) | 8.36 | (4.49) | 9.17 | (8.90) | 9.02 | (8.79) | 9.63 | (11.8) |
| | Fall | 6 | (223) | 8.99 | (4.90) | 10.9 | (10.7) | 11.5 | (10.9) | 15.1 | (19.1) |
| | Winter | 6 | (224) | 12.9 | (10.7) | 15.6 | (13.8) | 15.6 | (14.2) | 18.0 | (23.1) |
| 213 | Spring | 8 | (237) | 6.56 | (3.63) | 9.10 | (9.92) | 9.60 | (9.93) | 13.0 | (18.0) |
| | Summer | 6 | (237) | 4.62 | (1.60) | 4.86 | (5.44) | 5.00 | (5.54) | 5.51 | (21.4) |
| | Fall | 6 | (228) | 5.41 | (2.50) | 6.42 | (7.54) | 7.23 | (7.92) | 10.7 | (15.9) |
| | Winter | 6 | (235) | 10.4 | (7.20) | 12.2 | (11.6) | 12.1 | (11.9) | 13.8 | (19.4) |
| 215G | Spring | 7 | (11) | 7.21 | (8.85) | 9.94 | (10.2) | 10.5 | (10.6) | 13.7 | (14.2) |
| | Summer | 6 | (13) | 5.40 | (6.48) | 6.58 | (7.22) | 6.34 | (7.29) | 7.13 | (9.25) |
| | Fall | 6 | (13) | 7.09 | (6.29) | 8.38 | (9.16) | 8.70 | (9.56) | 11.4 | (14.2) |
| | Winter | 4 | (11) | 11.7 | (11.7) | 12.8 | (13.6) | 13.0 | (13.6) | 14.6 | (14.9) |
| 216 | Spring | 8 | (239) | 8.90 | (5.77) | 11.7 | (11.8) | 12.0 | (11.9) | 15.6 | (19.8) |
| | Summer | 6 | (243) | 6.43 | (4.68) | 7.96 | (8.60) | 7.79 | (8.67) | 8.53 | (21.2) |
| | Fall | 6 | (234) | 8.15 | (5.71) | 10.0 | (10.6) | 10.2 | (10.9) | 12.9 | (16.7) |
| | Winter | 6 | (240) | 12.8 | (9.80) | 15.4 | (13.9) | 15.7 | (14.1) | 20.3 | (20.5) |
| GATE | Spring | 8 | (170) | 10.8 | (6.88) | 13.8 | (12.4) | 14.2 | (12.9) | 18.3 | (25.2) |
| | Summer | 6 | (174) | 8.42 | (5.08) | 9.49 | (9.48) | 9.38 | (9.55) | 9.95 | (14.4) |
| | Fall | 6 | (188) | 10.1 | (6.06) | 10.7 | (11.0) | 11.5 | (11.2) | 14.1 | (21.1) |
| | Winter | 6 | (169) | 13.7 | (10.5) | 15.3 | (14.2) | 15.8 | (14.6) | 20.1 | (23.5) |
| BC | Spring | 8 | (175) | 8.81 | (6.02) | 11.0 | (11.5) | 11.5 | (11.7) | 15.2 | (20.0) |
| | Summer | 6 | (146) | 5.75 | (4.63) | 7.99 | (8.53) | 7.58 | (8.55) | 8.77 | (11.5) |
| | Fall | 6 | (151) | 7.42 | (5.67) | 8.35 | (10.4) | 8.40 | (10.7) | 9.34 | (16.1) |
| | Winter | 6 | (170) | 11.8 | (10.9) | 14.8 | (13.5) | 14.1 | (13.8) | 15.3 | (19.7) |

In addition to temperature, dissolved oxygen concentrations of Class A inland waters are criteria used to determine suitability of water resources for aquatic life habitat. MassDEP designates cold water fish habitats as rivers and streams in which dissolved oxygen remains above 6 mg/L and warm water fish habitats as those with dissolved oxygen concentrations greater than 5 mg/L (314 CMR 4.06). Dissolved oxygen concentrations remained above 6 mg/L in locations in the Quabbin Reservoir Watershed identified as cold water fish habitats (e.g., 211, 212, and 216) for the entirety of 2021. Dissolved oxygen concentrations measured at GATE also remained above 6 mg/L for the entirety of 2021.

A period of relatively low dissolved oxygen (4.62 to 5.98 mg/L) observed at site 213 occurred from June 09 to October 12, 2021. Dissolved oxygen concentrations at 215G fell below 5 mg/L on two dates in 2021 (June 22 and August 17, 2021). These results were likely attributed to extreme low flows coupled with warm water temperatures. The minimum streamflow observed at the East Branch Swift River in 2021 occurred on August 18, 2021. Low streamflow conditions impacted sites across the watershed throughout the month of June. Greater minimum water temperatures during the summer months at 213 combined with extended low flow conditions throughout June and August 2021 may have also contributed to the observed low dissolved oxygen concentrations, as it is atypical for 213 to remain below threshold concentrations across multiple consecutive sample dates.

Dissolved oxygen concentrations in Ware River Watershed Core tributaries ranged from 4.2 to 16.12 mg/L in 2021 (Table 14). Dissolved oxygen concentrations were relatively depleted during warmer months and elevated in winter and fall, inversely related to water temperature. Dissolved oxygen concentrations for Ware River Watershed Core tributaries were typically greater than historical seasonal minimum concentrations for each site, with new maximum seasonal dissolved oxygen concentrations measured on several dates in over half of the Core tributaries in the Ware River Watershed during 2021. Seasonal median dissolved oxygen concentrations in 2021 were comparable to that of the period of record for most sites. The median dissolved oxygen concentration during the spring at 101 was 2.73 mg/L lower in 2021 relative to the period of record. This site also exhibited the greatest increase in median spring temperature relative to the period of record.

Dissolved oxygen concentrations remained above 6 mg/L in locations watershed identified as cold water fish habitats in the Ware River Watershed (e.g., 102, 107A, and 108) for the entirety of 2021. Dissolved oxygen concentrations measured at 101 also remained above 6 mg/L for the entirety of 2021. Concentrations of dissolved oxygen fell below 5 mg/L at site 108 on June 29, 2021. This date coincides with the minimum annual dissolved oxygen concentration observed at all other Core sites in the Ware River Watershed. The ubiquity of these results further suggests extreme low flows coupled with warm water temperatures may have impacted oxygen content of surface waters across the watershed.

**Table 14:** Descriptive statistics (minimum, median, average, and maximum) for dissolved oxygen measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Dissolved Oxygen (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Spring | 8 | (19) | 8.17 | (8.39) | 10.1 | (12.8) | 10.3 | (12.1) | 14.3 | (15.3) |
| | Summer | 6 | (18) | 6.92 | (7.62) | 8.04 | (8.67) | 8.43 | (8.79) | 10.9 | (10.2) |
| | Fall | 6 | (19) | 9.03 | (7.72) | 11.0 | (10.9) | 11.5 | (10.9) | 14.1 | (14.4) |
| | Winter | 6 | (20) | 13.8 | (11.9) | 14.6 | (14.6) | 14.5 | (14.7) | 14.9 | (16.1) |
| 102 | Spring | 8 | (104) | 10.4 | (6.20) | 11.2 | (11.6) | 11.8 | (11.6) | 15.9 | (14.5) |
| | Summer | 7 | (107) | 8.24 | (7.70) | 8.77 | (9.30) | 9.05 | (9.33) | 11.0 | (10.8) |
| | Fall | 6 | (106) | 9.74 | (8.40) | 11.5 | (11.0) | 11.6 | (10.9) | 13.5 | (13.3) |
| | Winter | 6 | (103) | 13.0 | (9.14) | 14.7 | (13.1) | 14.7 | (13.1) | 16.1 | (16.6) |
| 103A | Spring | 8 | (90) | 9.11 | (6.62) | 10.4 | (10.9) | 10.7 | (11.5) | 14.1 | (19.1) |
| | Summer | 7 | (102) | 5.95 | (4.16) | 7.70 | (7.57) | 7.77 | (7.49) | 10.0 | (9.94) |
| | Fall | 6 | (101) | 8.83 | (4.14) | 10.0 | (10.0) | 10.6 | (10.4) | 13.4 | (19.6) |
| | Winter | 6 | (74) | 13.3 | (11.2) | 14.1 | (14.1) | 14.1 | (14.6) | 14.6 | (24.5) |
| 107A | Spring | 8 | (97) | 8.56 | (6.70) | 9.92 | (11.0) | 10.2 | (11.4) | 13.0 | (20.2) |
| | Summer | 7 | (101) | 6.32 | (4.91) | 7.15 | (7.7) | 7.32 | (7.72) | 9.16 | (10.1) |
| | Fall | 6 | (102) | 8.14 | (6.47) | 9.15 | (10.2) | 10.0 | (10.8) | 13.6 | (21.3) |
| | Winter | 6 | (83) | 11.9 | (11.3) | 13.1 | (13.9) | 13.3 | (14.1) | 15.3 | (23.4) |
| 108 | Spring | 8 | (201) | 7.57 | (4.55) | 9.77 | (10.7) | 9.71 | (10.8) | 11.8 | (20.6) |
| | Summer | 7 | (202) | 4.20 | (3.50) | 6.12 | (6.52) | 6.45 | (6.55) | 9.26 | (9.10) |
| | Fall | 6 | (202) | 6.92 | (4.10) | 9.6 | (8.70) | 9.75 | (9.06) | 12.9 | (20.0) |
| | Winter | 6 | (194) | 12.4 | (4.92) | 13.3 | (13.0) | 13.3 | (13.3) | 14.3 | (21.0) |
| 121 | Spring | 8 | (117) | 7.77 | (6.80) | 9.08 | (9.70) | 9.22 | (9.99) | 11.7 | (13.6) |
| | Summer | 7 | (125) | 5.38 | (4.10) | 6.33 | (6.60) | 6.71 | (6.67) | 9.80 | (10.1) |
| | Fall | 6 | (127) | 7.10 | (6.10) | 9.16 | (8.80) | 9.50 | (8.89) | 11.9 | (14.3) |
| | Winter | 6 | (117) | 11.58 | (9.40) | 12.9 | (12.0) | 12.8 | (12.1) | 13.7 | (15.2) |

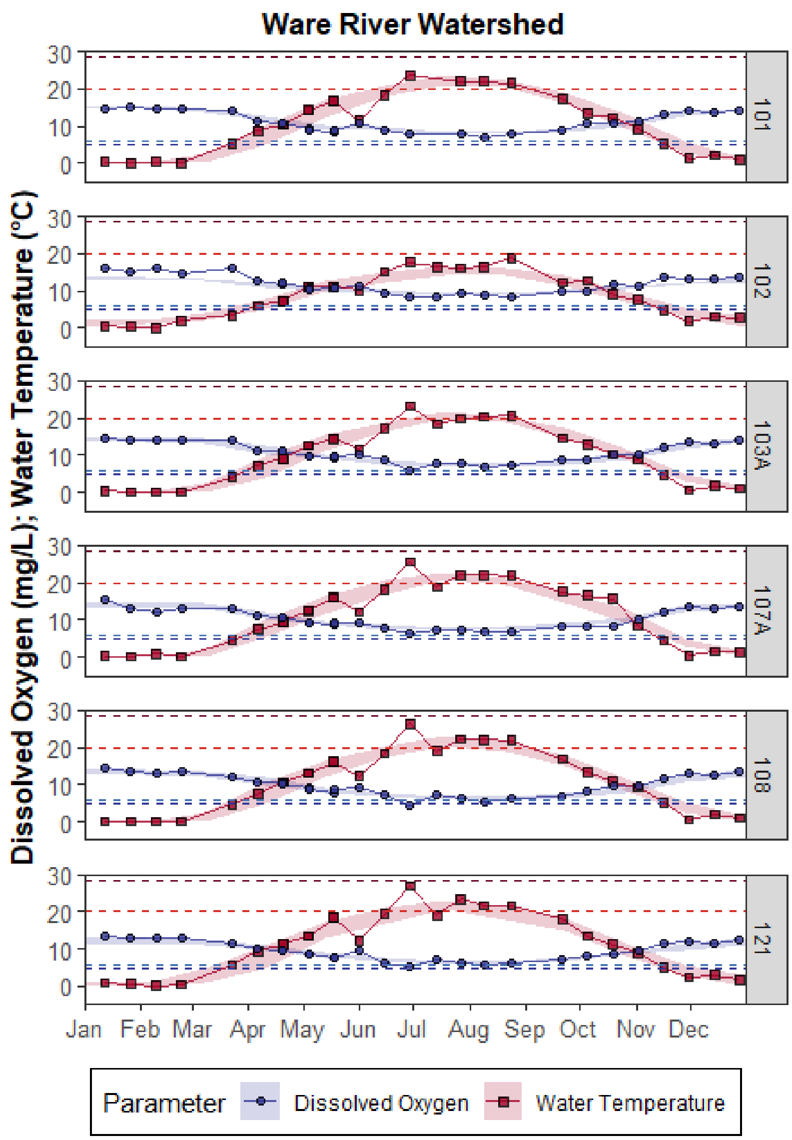



**Figure 13:** Time series of water temperature and dissolved oxygen measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent seasonal interquartile ranges (25th to 75th percentile) for the period of record at each location. The dashed horizontal lines correspond to the lower recommended dissolved oxygen concentration for CFR (6.0 mg/L; light blue) and WFR (5.0 mg/L; dark blue), and the upper temperature limits for CFR (20˚C; red) and WFR (28.3˚C; burgundy) waters. Note: the period of record may be variable across sites, thus impacting seasonal statistics (Section 2.2).

## 3.2.2 Specific Conductance, Sodium, and Chloride

### *3.2.2.1 Specific Conductance*

Specific conductance ranged from 19.8 to 139.6 µS/cm in Quabbin Reservoir Watershed Core monitoring tributaries and from 64.3 to 380.5 µS/cm in Core monitoring tributaries in the Ware River Watershed during 2021. Chronic (904 µS/cm) and acute (3,193 µS/cm) thresholds for conductivity established by MassDEP were not exceeded at any DWSP monitoring sites in the Quabbin Reservoir or Ware River Watersheds during 2021.

Specific conductance was generally elevated during low flow conditions and declined with increasing streamflow. The extended period of below normal stream flow during the spring of 2021 resulted in a prolonged interval of elevated specific conductance, relative to typical seasonal normals. Intra-annual patterns of elevated specific conductance were most pronounced in Boat Cove Brook in the Quabbin Reservoir Watershed and tributaries in the Ware River Watershed – a pattern potentially driven by spatial variability in specific conductance of groundwater.

The median specific conductance for the period of record for each Core monitoring site was exceeded during at least one season, at each site, in 2021 (Figure 14). Annual median specific conductance has been on an upward trajectory since the onset of routine monitoring at select sites in the Quabbin Reservoir Watershed, and the majority of Core sites in the Ware River Watershed. Although annual median specific conductance measured in Core tributaries in 2021 was comparable to that of prior years, some locations continue to exhibit an increasing pattern in annual specific conductance (e.g., $p<0.05$; 212, 213, 216, and BC). In contrast, other locations exhibit no significant change (e.g., 211 in the Quabbin Reservoir Watershed), or have demonstrated a notable decrease annual median specific conductance since the onset of monitoring (Gates Brook in the Quabbin Reservoir Watershed). In the Ware River Watershed, annual median specific conductance has increased at all Core sites that have maintained a consistent monitoring record (e.g., 101, 103A, 107A, and 108), albeit to different degrees of severity (slope).

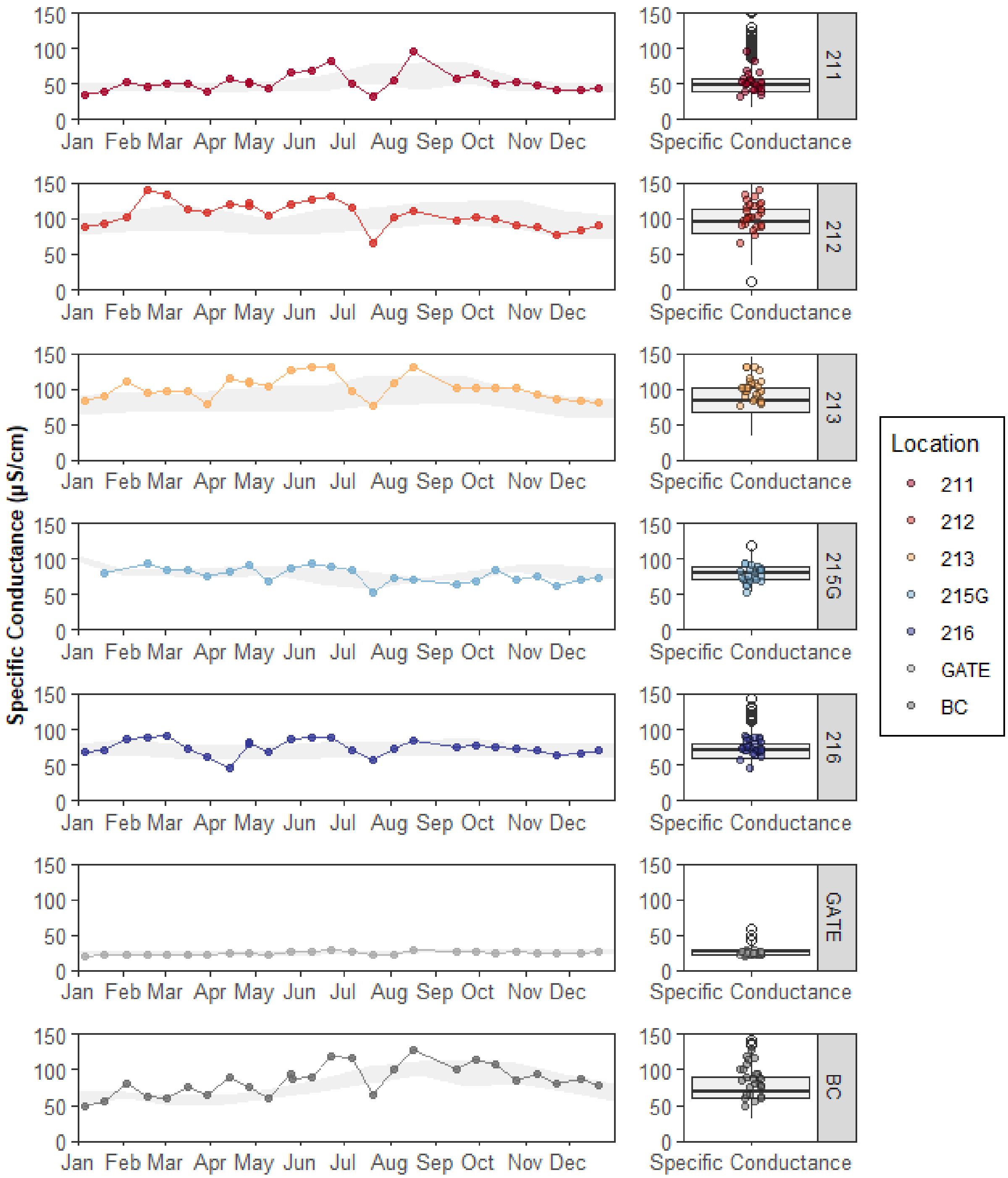



**Figure 14:** Time series and boxplots of specific conductance measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. Note: the period of record may be variable across sites, thus impacting long-term statistics (See Figure 4).

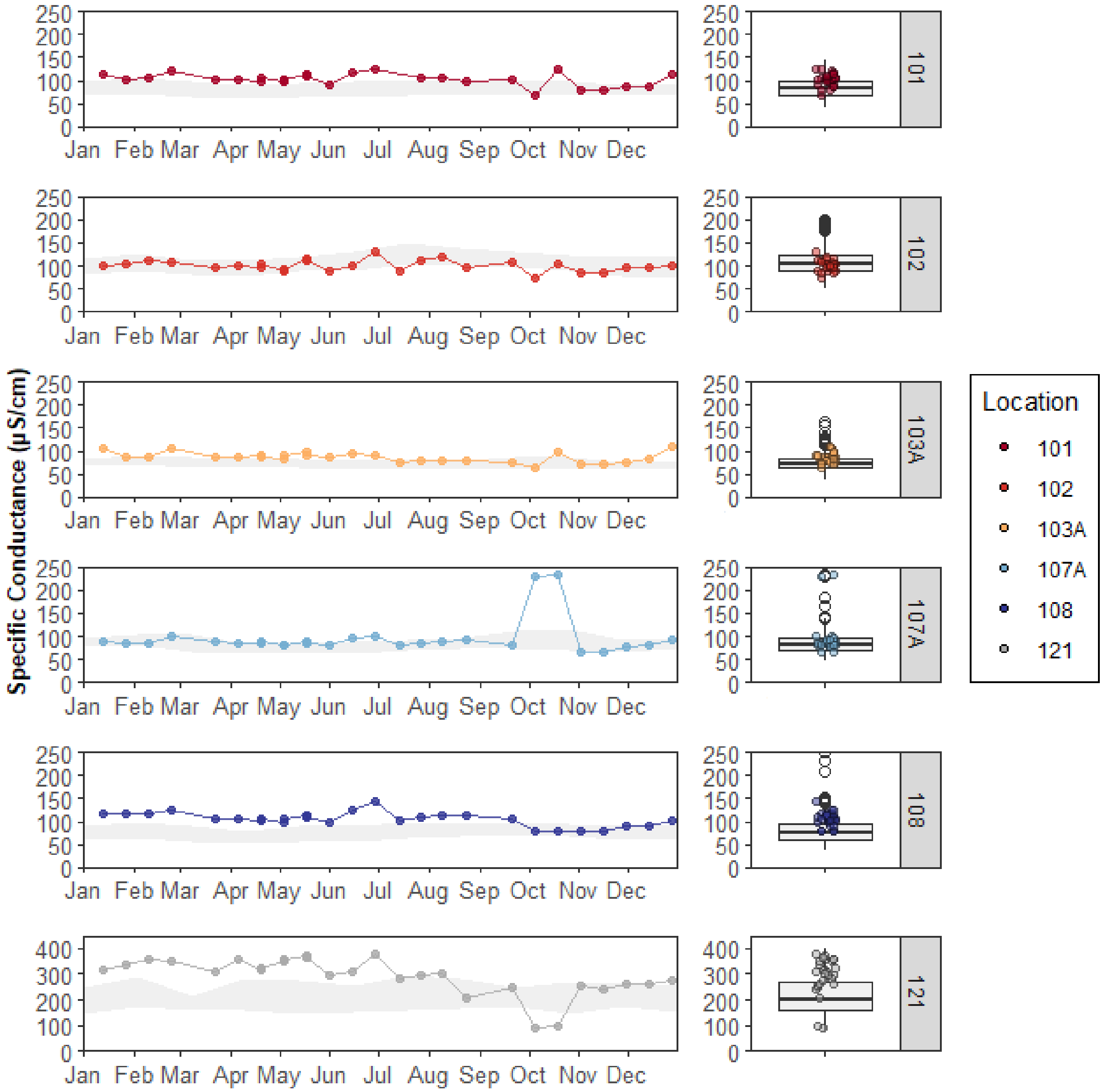



**Figure 15:** Time series and boxplots of specific conductance measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. Note: the period of record may be variable across sites, thus impacting long-term statistics (See Figure 4).

### *3.2.2.2 Sodium and Chloride*

Routine monitoring for sodium (Na) and chloride (Cl) began in DWSP Core monitoring sites in Quabbin Reservoir Watershed in September 2018 and Ware River Watershed in January 2019. Concentrations of Na and Cl observed in Core monitoring tributaries in the Ware River Watershed ranged from 7.85 to 52.8 mg/L and from 5.13 to 101 mg/L, respectively, in 2021. Concentrations of these solutes in Core tributaries in the Quabbin Reservoir Watershed were notably lower (1.49

to 18.3 mg/L for Na and 1.25 to 32.1 mg/L for Cl). The spatial contrast in Cl concentrations in tributaries across the two watersheds generally mirrors that of specific conductance. Thus, similar processes may contribute to the dynamics and transport of Na, Cl, and specific conductance in tributaries in the Quabbin Reservoir and Ware River Watersheds. The spatial heterogeneity in concentrations of Na and Cl observed in 2021 was consistent with prior monitoring. This likely reflects differences in land cover and watershed characteristics, such as impervious surface cover, that may contribute to variable inputs of Na and Cl to individual tributaries across the two watersheds.

The secondary MCL for Cl in drinking water (250 mg/L) established by the US EPA was not exceeded in any Core tributary samples collected in 2021 from the Quabbin Reservoir or Ware River Watersheds. Concentrations of Na in samples collected at 121 in the Ware River Watershed exceeded the MassDEP Office of Research and Standards (ORS) guidelines for Na in drinking water for the entirety of 2021 (n = 26 samples > 20 mg/L Na). Prior to 2021, Mill Brook was sampled at DWSP Core site 121B, located upstream of 121. Concentrations of Na at 121B were also regularly above the MassDEP ORS guidelines. Contributions of road-salt laden runoff originating in the upstream reaches of the Mill Brook (e.g., potentially sourced from several high-density residential housing developments, and runoff from Route 122 and 56 in Rutland, MA) may drive the dynamics observed in downstream reaches. The remaining Core sites in the Ware River Watershed exhibit less pronounced impacts from roadway deicing and development (ranges of Na and Cl were 7.85 to 17.8 mg/L and 5.13 to 27.9 mg/L in 2021, respectively), relative to Mill Brook (Site 121).

Spatial and temporal patterns in specific conductance and associated concentrations of Na and Cl observed in 2021 generally presented as repeated patterns of concentration during low flow and dilution during episodic high flow and following spring snowmelt. Contributions from groundwater during an extended period of below-normal streamflow observed during the spring of 2021 likely resulted in elevated stream Cl concentrations during this time. Gradients in specific conductance between monitoring sites were associated with differences in land cover, proximity to major paved surfaces (e.g., roads and parking lots), and geogenic variability (Figure 14, Figure 15). Median annual concentrations of Na, Cl, and specific conductance were generally greater in tributaries within the Ware River Watershed, relative to Core monitoring sites in the Quabbin Reservoir Watershed in 2021 (Table 15,Table 16, Appendix C). The latter may be reflective of the high ratio of protected and forested lands, relative to developed lands, in the Quabbin Reservoir Watershed, with comparatively more developed areas in Ware River Watershed. Likewise, spatial variability of annual trends in specific conductance was generally reflective of differences in watershed characteristics (e.g., proximity to major transportation corridors, impervious surface cover, population, etc.) for a given tributary. The approximate 1:1 molar ratios of Na to Cl and linear relationship between Cl concentrations and specific conductance in surface waters suggests that increasing concentrations of Cl may be driving changes in annual median specific conductance for the majority of Core monitoring tributaries (Appendix C).

**Table 15:** Descriptive statistics (minimum, median, average, and maximum) for specific conductance measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Specific Conductance (µS/cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Spring | 8 | (240) | 39.3 | (28.0) | 51.0 | (44.2) | 51.6 | (46.9) | 66.7 | (130) |
| | Summer | 6 | (243) | 33.0 | (25.0) | 61.9 | (57.0) | 64.3 | (60.1) | 95.4 | (153) |
| | Fall | 6 | (238) | 42.0 | (26.7) | 52.1 | (50.0) | 52.7 | (56.0) | 63.9 | (152) |
| | Winter | 6 | (243) | 35.7 | (17.7) | 43.1 | (43.0) | 43.3 | (45.7) | 51.8 | (194) |
| 212 | Spring | 8 | (228) | 103.7 | (35.0) | 119 | (91.4) | 118.1 | (94.1) | 134.2 | (190) |
| | Summer | 6 | (232) | 65.7 | (52.0) | 113 | (100) | 108.6 | (101) | 131 | (170) |
| | Fall | 6 | (223) | 77.0 | (48.0) | 93.7 | (100) | 92.1 | (103) | 101 | (180) |
| | Winter | 6 | (224) | 83.0 | (10.5) | 92.6 | (91.0) | 99.6 | (94.9) | 140 | (212) |
| 213 | Spring | 8 | (237) | 79.2 | (33.0) | 106 | (80.1) | 105 | (81.7) | 126 | (141) |
| | Summer | 6 | (237) | 76.6 | (42.0) | 120 | (94.5) | 112 | (94.4) | 130 | (167) |
| | Fall | 6 | (228) | 85.4 | (40.0) | 101 | (83.7) | 97.0 | (86.4) | 102 | (166) |
| | Winter | 6 | (235) | 81.0 | (42.0) | 87.0 | (78.0) | 90.4 | (77.8) | 110 | (136) |
| 215G | Spring | 7 | (11) | 69.8 | (64.9) | 84.8 | (83.2) | 82.1 | (85.2) | 90.6 | (115) |
| | Summer | 6 | (13) | 52.1 | (58.2) | 79.5 | (68.6) | 77.5 | (70.1) | 94.9 | (87.8) |
| | Fall | 6 | (13) | 63.0 | (67.3) | 69.9 | (89.4) | 71.2 | (86.3) | 84.4 | (97.8) |
| | Winter | 4 | (11) | 72.4 | (73.5) | 77.3 | (94.6) | 80.0 | (92.0) | 93.2 | (120) |
| 216 | Spring | 8 | (239) | 45.3 | (40.0) | 75.5 | (67.0) | 73.6 | (68.5) | 91.8 | (115) |
| | Summer | 6 | (243) | 56.9 | (38.0) | 78.9 | (72.0) | 77.0 | (73.0) | 89.6 | (144) |
| | Fall | 6 | (234) | 64.6 | (43.0) | 74.7 | (70.0) | 73.0 | (72.7) | 76.9 | (133) |
| | Winter | 6 | (240) | 65.2 | (5.60) | 70.9 | (69.2) | 75.0 | (73.0) | 88.5 | (190) |
| GATE | Spring | 8 | (170) | 21.3 | (18.1) | 22.8 | (23.0) | 23.5 | (24.2) | 26.4 | (30) |
| | Summer | 6 | (174) | 22.9 | (17.0) | 26.7 | (25.3) | 26.0 | (25.6) | 28.4 | (58) |
| | Fall | 6 | (188) | 23.9 | (15.0) | 25.5 | (28.2) | 25.8 | (27.8) | 27.8 | (42) |
| | Winter | 6 | (169) | 19.8 | (17.0) | 22.9 | (26.0) | 23.1 | (26.1) | 26.2 | (48.5) |
| BC | Spring | 8 | (175) | 59.8 | (30.0) | 77.0 | (60.0) | 76.4 | (59.9) | 94.0 | (94.7) |
| | Summer | 6 | (146) | 64.7 | (40.0) | 108 | (87.3) | 103 | (88.5) | 127 | (142) |
| | Fall | 6 | (151) | 80.2 | (29.9) | 97.6 | (89.4) | 96.9 | (89.0) | 114 | (141) |
| | Winter | 6 | (170) | 48.6 | (37.0) | 69.9 | (64.2) | 68.6 | (66.2) | 86.8 | (137) |

**Table 16:** Descriptive statistics (minimum, median, average, and maximum) for specific conductance measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Specific Conductance (µS/cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Spring | 8 | (199) | 99.5 | (43.0) | 104 | (76.9) | 105 | (77.9) | 115 | (126) |
| | Summer | 6 | (202) | 92.0 | (42.0) | 107 | (85.0) | 108 | (83.7) | 126 | (137) |
| | Fall | 6 | (200) | 68.3 | (40.0) | 82.6 | (82.0) | 90.3 | (82.8) | 126 | (140) |
| | Winter | 6 | (193) | 88.1 | (43.0) | 110 | (83.4) | 107 | (84.2) | 119 | (142) |
| 102 | Spring | 8 | (104) | 88.6 | (50.0) | 100 | (95.0) | 101 | (103) | 117 | (200) |
| | Summer | 7 | (107) | 89.9 | (55.0) | 98.7 | (112) | 105 | (122) | 131 | (200) |
| | Fall | 6 | (106) | 74.1 | (55.0) | 91.8 | (105) | 92.5 | (112) | 109 | (200) |
| | Winter | 6 | (103) | 96.0 | (58.0) | 102 | (99.0) | 103 | (105) | 113 | (270) |
| 103A | Spring | 8 | (90) | 82.8 | (50.0) | 88.7 | (69.25) | 89.0 | (73.8) | 96.4 | (126) |
| | Summer | 7 | (101) | 76.1 | (38.0) | 78.3 | (68.0) | 82.8 | (72.4) | 92.8 | (163) |
| | Fall | 6 | (98) | 64.3 | (52.0) | 73.8 | (67.8) | 76.4 | (74.0) | 99.3 | (141) |
| | Winter | 6 | (74) | 83.0 | (54.0) | 96.3 | (74.3) | 95.9 | (75.5) | 109 | (109) |
| 107A | Spring | 8 | (97) | 79.7 | (47.0) | 85.8 | (73.0) | 85.8 | (78.4) | 90.4 | (129) |
| | Summer | 7 | (101) | 80.1 | (46.0) | 90.2 | (81.5) | 88.8 | (81.7) | 99.8 | (142) |
| | Fall | 6 | (102) | 66.5 | (50.0) | 79.4 | (80.6) | 126 | (88.3) | 233 | (185) |
| | Winter | 6 | (83) | 79.8 | (57.0) | 86.7 | (86.7) | 87.7 | (87.5) | 98.8 | (133) |
| 108 | Spring | 8 | (201) | 100 | (43.0) | 104 | (70.0) | 105 | (74.0) | 114 | (250) |
| | Summer | 7 | (202) | 98.1 | (42.0) | 112 | (77.0) | 115 | (79.8) | 146 | (151) |
| | Fall | 6 | (202) | 77.3 | (38.0) | 78.6 | (80.0) | 84.8 | (82.5) | 105 | (139) |
| | Winter | 6 | (194) | 90.4 | (40.0) | 116 | (77.0) | 111 | (79.5) | 124 | (209) |
| 121 | Spring | 8 | (117) | 310 | (92.0) | 353 | (180) | 344 | (194) | 371 | (350) |
| | Summer | 7 | (125) | 211 | (78.0) | 298 | (190) | 298 | (207) | 381 | (370) |
| | Fall | 6 | (127) | 90 | (98.0) | 248 | (200) | 200 | (214) | 264 | (400) |
| | Winter | 6 | (117) | 261 | (108) | 327 | (200) | 317 | (212) | 358 | (401) |

### 3.2.3 Turbidity

Turbidity in Core tributaries in Quabbin Reservoir and Ware River Watersheds was within historical seasonal ranges for the entirety of 2021 (Figure 16, Figure 17). Turbidity ranged from 0.1 to 4.8 NTU in Quabbin Reservoir Core tributaries and from 0.39 to 2.9 NTU in Ware River Watershed Core tributaries (Table 17, Table 18). Turbidity in all Core monitoring sites remained below the five NTU SWTR requirement for the entirety of 2021. Turbidity levels above one NTU were associated with samples collected from Core tributaries in the Ware River Watershed during the summer and early fall of 2021, or high flow events in either watershed.

Turbidity levels in 2021 increased during the summer months and declined during the winter, with peaks corresponding to precipitation events and/or higher sediment mobilization following high flow events. Seasonal dynamics in turbidity were comparable across tributaries in the Quabbin Reservoir Watershed and the Ware River Watershed. Annual peak summer turbidity levels were greater in Ware River tributaries (approximately 2.1 to 2.7 NTU) than in Quabbin Reservoir tributaries (generally <1 NTU). Variability in turbidity dynamics observed across sites may be attributed to land use differences across sites, localized meteorological effects, and sub-catchment hydrology, and is not necessarily indicative of long-term trends. Turbidity levels observed in 2021 were generally consistent with those of previous years, indicating the continued high quality of surface waters in the Quabbin Reservoir and Ware River Watersheds.

**Table 17:** Descriptive statistics (minimum, median, average, and maximum) for turbidity measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Turbidity (NTU) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Spring | 7 | (234) | 0.28 | (0.15) | 0.32 | (0.30) | 0.32 | (0.37) | 0.38 | (8.00) |
| | Summer | 7 | (240) | 0.32 | (0.20) | 0.37 | (0.36) | 0.42 | (0.47) | 0.57 | (4.58) |
| | Fall | 6 | (238) | 0.23 | (0.18) | 0.40 | (0.30) | 0.44 | (0.39) | 0.82 | (2.76) |
| | Winter | 6 | (242) | 0.23 | (0.16) | 0.26 | (0.28) | 0.28 | (0.31) | 0.44 | (2.70) |
| 212 | Spring | 7 | (222) | 0.41 | (0.20) | 0.48 | (0.42) | 0.50 | (0.63) | 0.66 | (10.0) |
| | Summer | 7 | (229) | 0.88 | (0.30) | 0.98 | (1.14) | 1.19 | (1.45) | 1.80 | (15.0) |
| | Fall | 6 | (224) | 0.64 | (0.30) | 1.20 | (0.75) | 1.37 | (1.06) | 2.60 | (8.46) |
| | Winter | 6 | (221) | 0.38 | (0.20) | 0.50 | (0.44) | 0.60 | (0.51) | 1.20 | (3.00) |
| 213 | Spring | 7 | (229) | 0.40 | (0.30) | 0.54 | (0.50) | 0.58 | (0.59) | 0.94 | (3.00) |
| | Summer | 7 | (236) | 0.50 | (0.40) | 0.82 | (1.00) | 0.87 | (1.07) | 1.20 | (3.17) |
| | Fall | 6 | (227) | 0.72 | (0.30) | 0.76 | (0.73) | 0.81 | (0.79) | 1.00 | (2.00) |
| | Winter | 6 | (234) | 0.40 | (0.29) | 0.49 | (0.49) | 0.61 | (0.52) | 1.20 | (2.14) |
| 215G | Spring | 7 | (11) | 0.28 | (0.36) | 0.46 | (0.52) | 0.51 | (0.55) | 0.90 | (0.82) |
| | Summer | 7 | (13) | 0.71 | (0.56) | 0.95 | (0.96) | 0.99 | (0.98) | 1.30 | (1.46) |
| | Fall | 6 | (13) | 0.45 | (0.40) | 0.78 | (0.65) | 0.74 | (0.68) | 1.00 | (1.00) |
| | Winter | 5 | (11) | 0.21 | (0.45) | 0.43 | (0.58) | 0.55 | (0.6) | 0.89 | (0.86) |
| 216 | Spring | 7 | (232) | 0.52 | (0.30) | 0.58 | (0.51) | 0.62 | (0.64) | 0.76 | (5.00) |
| | Summer | 7 | (239) | 0.62 | (0.30) | 0.73 | (0.70) | 0.75 | (0.75) | 0.97 | (2.24) |
| | Fall | 6 | (236) | 0.53 | (0.29) | 0.73 | (0.56) | 0.74 | (0.64) | 1.00 | (5.86) |
| | Winter | 6 | (238) | 0.41 | (0.30) | 0.58 | (0.50) | 0.68 | (0.56) | 1.30 | (2.88) |
| GATE | Spring | 7 | (165) | 0.10 | (0.09) | 0.19 | (0.20) | 0.20 | (0.29) | 0.27 | (8.00) |
| | Summer | 7 | (173) | 0.11 | (0.10) | 0.19 | (0.21) | 0.22 | (0.29) | 0.39 | (1.92) |
| | Fall | 6 | (168) | 0.13 | (0.08) | 0.22 | (0.20) | 0.39 | (0.29) | 1.40 | (3.80) |
| | Winter | 6 | (163) | 0.13 | (0.08) | 0.16 | (0.20) | 0.18 | (0.23) | 0.28 | (2.00) |
| BC | Spring | 7 | (168) | 0.53 | (0.30) | 1.10 | (0.76) | 1.68 | (1.15) | 4.80 | (6.00) |
| | Summer | 7 | (137) | 0.34 | (0.23) | 0.50 | (0.72) | 0.65 | (1.16) | 1.20 | (23.00) |
| | Fall | 6 | (128) | 0.40 | (0.16) | 0.49 | (0.53) | 0.84 | (1.02) | 2.60 | (6.59) |
| | Winter | 6 | (163) | 0.83 | (0.30) | 1.75 | (0.98) | 1.78 | (1.26) | 3.40 | (6.85) |

**Table 18:** Descriptive statistics (minimum, median, average, and maximum) for turbidity measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Turbidity (NTU) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Spring | 6 | (54) | 0.54 | (0.40) | 0.77 | (0.88) | 0.82 | (1.11) | 1.20 | (2.71) |
| | Summer | 7 | (56) | 1.20 | (1.48) | 2.00 | (2.75) | 1.94 | (2.78) | 2.50 | (5.20) |
| | Fall | 7 | (58) | 0.68 | (0.85) | 1.20 | (1.55) | 1.38 | (1.69) | 2.50 | (3.20) |
| | Winter | 6 | (59) | 0.47 | (0.51) | 0.60 | (0.78) | 0.65 | (0.80) | 0.87 | (1.60) |
| 102 | Spring | 6 | (104) | 0.60 | (0.40) | 0.87 | (0.60) | 0.97 | (0.71) | 1.80 | (2.00) |
| | Summer | 7 | (105) | 0.94 | (0.60) | 2.00 | (1.70) | 1.89 | (1.80) | 2.50 | (4.50) |
| | Fall | 7 | (105) | 0.85 | (0.50) | 1.50 | (1.00) | 1.60 | (1.24) | 2.80 | (4.00) |
| | Winter | 6 | (103) | 0.58 | (0.40) | 0.75 | (0.60) | 0.76 | (0.77) | 1.00 | (2.50) |
| 103A | Spring | 6 | (94) | 0.47 | (0.19) | 0.57 | (0.75) | 0.65 | (0.94) | 0.98 | (3.83) |
| | Summer | 7 | (100) | 0.92 | (0.83) | 1.80 | (2.41) | 1.65 | (2.52) | 2.10 | (6.63) |
| | Fall | 7 | (105) | 0.50 | (0.33) | 0.96 | (1.10) | 1.22 | (1.31) | 2.00 | (5.63) |
| | Winter | 6 | (79) | 0.41 | (0.33) | 0.61 | (0.61) | 0.74 | (0.69) | 1.60 | (2.70) |
| 107A | Spring | 6 | (95) | 0.46 | (0.32) | 0.59 | (0.74) | 0.65 | (0.95) | 1.00 | (8.93) |
| | Summer | 7 | (98) | 0.93 | (0.82) | 1.40 | (1.82) | 1.44 | (1.95) | 2.30 | (5.05) |
| | Fall | 7 | (105) | 0.51 | (0.42) | 0.74 | (0.93) | 0.89 | (1.03) | 2.00 | (2.89) |
| | Winter | 6 | (83) | 0.39 | (0.41) | 0.44 | (0.62) | 0.53 | (0.72) | 0.95 | (2.54) |
| 108 | Spring | 6 | (199) | 0.52 | (0.30) | 0.63 | (0.70) | 0.70 | (0.92) | 1.10 | (2.94) |
| | Summer | 7 | (199) | 0.93 | (0.60) | 2.00 | (2.20) | 1.9 | (2.34) | 2.90 | (5.50) |
| | Fall | 7 | (205) | 0.60 | (0.30) | 1.00 | (1.20) | 1.15 | (1.40) | 2.20 | (4.01) |
| | Winter | 6 | (193) | 0.47 | (0.30) | 0.55 | (0.67) | 0.64 | (0.75) | 1.00 | (3.10) |
| 121 | Spring | 6 | (117) | 0.49 | (0.30) | 0.65 | (0.60) | 0.67 | (0.69) | 0.90 | (1.83) |
| | Summer | 7 | (122) | 1.10 | (0.65) | 1.20 | (1.80) | 1.53 | (2.20) | 2.70 | (8.50) |
| | Fall | 7 | (127) | 0.79 | (0.30) | 0.98 | (1.05) | 1.27 | (1.44) | 2.60 | (7.65) |
| | Winter | 6 | (116) | 0.58 | (0.30) | 0.69 | (0.60) | 0.75 | (0.66) | 1.10 | (3.00) |

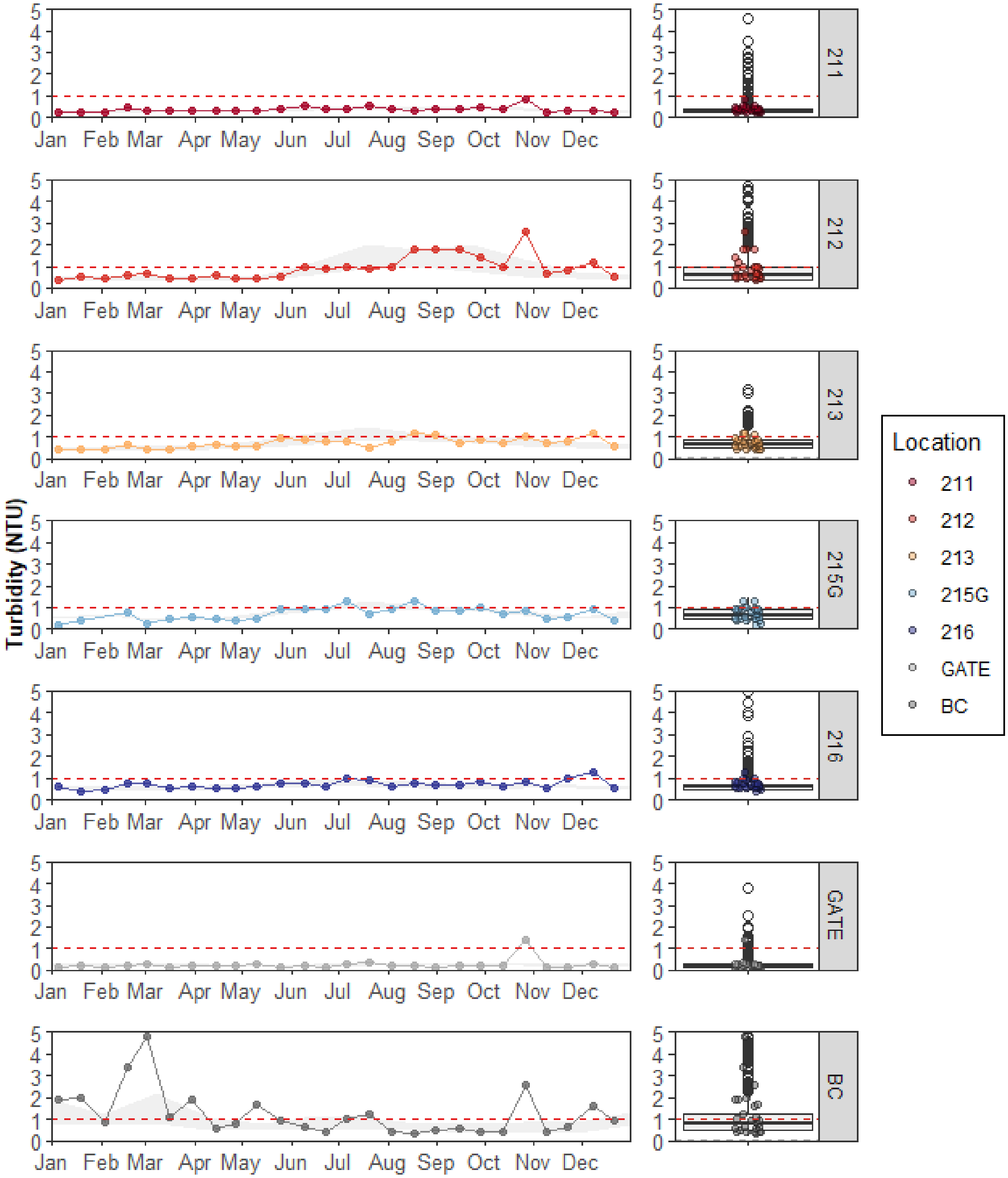



**Figure 16:** Time series and boxplots of turbidity measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. Note: the period of record may be variable across sites, thus impacting long-term statistics (See Figure 4).

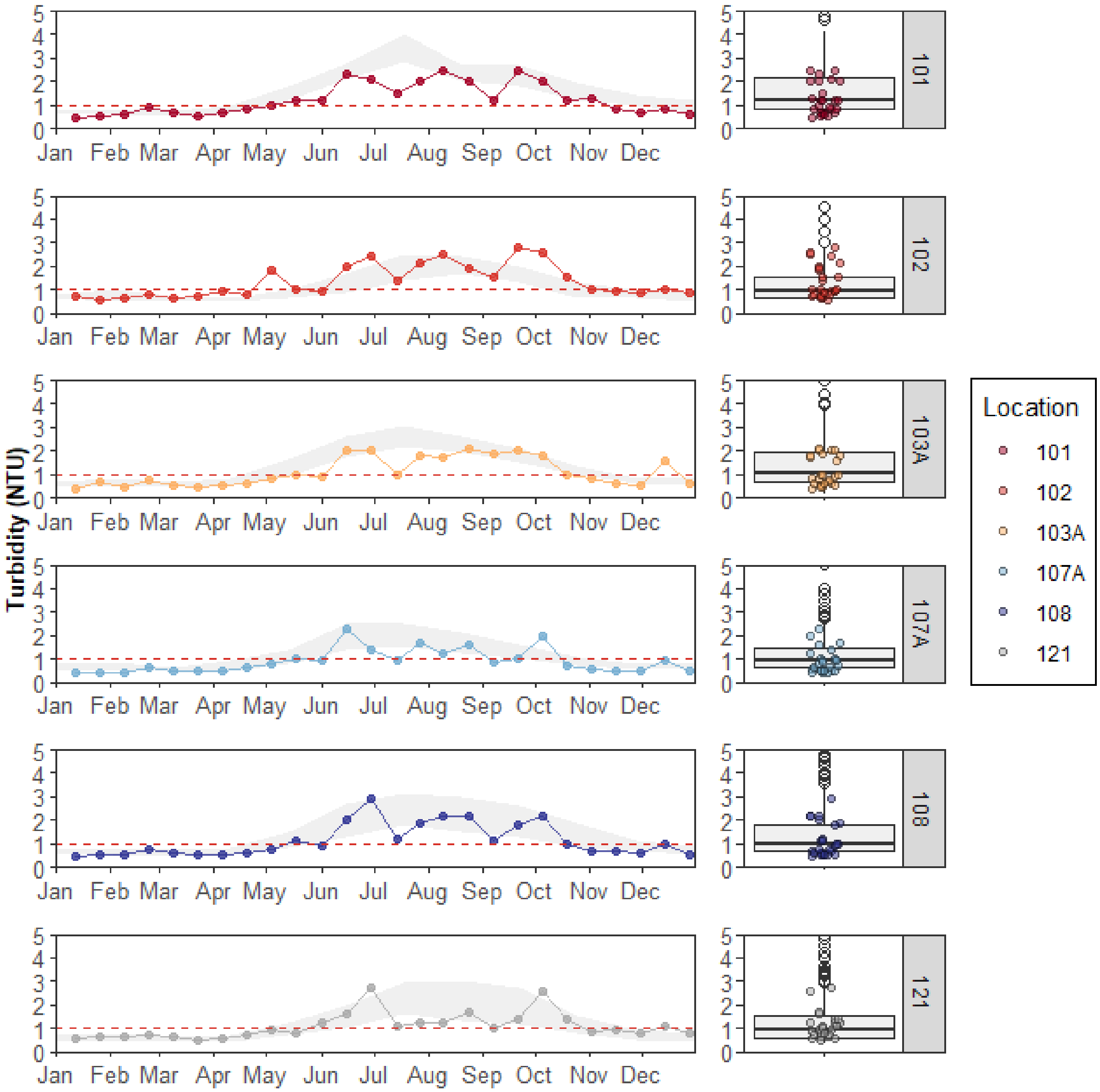



**Figure 17:** Time series and boxplots of turbidity measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. Note: the period of record may be variable across sites, thus impacting long-term statistics (See Figure 4).

### 3.2.4 Total Coliform and *E. coli* Bacteria

Water quality monitoring of bacteria in the Quabbin Reservoir and Ware River Watershed Core tributary sites primarily includes *E. coli* and total coliform bacteria. Analyses for fecal coliform in Core tributaries in the Quabbin Reservoir and Ware River Watersheds was not performed in 2021.

Elevated bacteria results from Quabbin Reservoir and Ware River tributaries that exceed the upper bounds of seasonal normals (75th percentiles) and that cannot be attributed to a recent meteorological event are followed up with site inspection and re-sampling for *E. coli* concentrations. Historically, follow-up sampling has previously attributed elevated *E. coli* concentrations to wildlife activity, recent precipitation, or findings were inconclusive. No follow-up samples were collected in 2021.

#### *3.2.4.1 Total Coliform*

Variability in total coliform concentrations observed in Core tributaries in Quabbin Reservoir and Ware River Watersheds largely mirrored that of stream temperature throughout 2021 (Section 3.2.1.1). Total coliform in Quabbin Reservoir Watershed Core monitoring tributaries ranged from 134 to greater than 24,200 MPN/100 mL (Table 19) and from 75 to greater than 17,300 MPN/100 mL in Core monitoring tributaries in the Ware River Watershed in 2021 (Table 20).

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

**Table 19:** Descriptive statistics (minimum, median, average, and maximum) for total coliform measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Total Coliform (MPN/100 mL) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Spring | 7 | (68) | 160 | (108) | 594 | (7,012) | 761 | (932) | 2,190 | (3,450) |
| | Summer | 7 | (70) | 2,010 | (1,220) | 2,760 | (3,760) | 3,409 | (5,602) | 6,130 | (>24,200) |
| | Fall | 6 | (73) | 733 | (488) | 1,680 | (1,670) | 2,274 | (3,234) | 4,880 | (>24,200) |
| | Winter | 6 | (70) | 175 | (110) | 355 | (441) | 344 | (543) | 504 | (2,190) |
| 212 | Spring | 7 | (69) | 221 | (84) | 504 | (495) | 1,693 | (861) | 8,660 | (7,700) |
| | Summer | 7 | (72) | 2,040 | (813) | 6,490 | (5,790) | 8,197 | (8,299) | 24,200 | (>24,200) |
| | Fall | 6 | (73) | 657 | (393) | 2,920 | (2,140) | 2,822 | (4,609) | 5,790 | (>24,200) |
| | Winter | 6 | (69) | 241 | (110) | 461 | (395) | 702 | (503) | 2,250 | (2850) |
| 213 | Spring | 7 | (70) | 203 | (98) | 1,180 | (857) | 1,376 | (2,244) | 3,450 | (>24,200) |
| | Summer | 7 | (72) | 3,080 | (2,250) | 4,880 | (5,480) | 5,166 | (7,130) | 7,270 | (>24,200) |
| | Fall | 6 | (73) | 359 | (504) | 1,040 | (2,100) | 1,125 | (3,926) | 2,600 | (>24,200) |
| | Winter | 6 | (70) | 228 | (121) | 321 | (348) | 419 | (695) | 933 | (6,870) |
| 215G | Spring | 7 | (11) | 135 | (156) | 2,190 | (1,220) | 2,315 | (1,330) | 5,480 | (3,260) |
| | Summer | 7 | (13) | 4,880 | (3,870) | 5,480 | (5,790) | 6,106 | (6,670) | 8,660 | (17,300) |
| | Fall | 6 | (13) | 504 | (520) | 1,855 | (2,140) | 1,866 | (2,719) | 4,110 | (7,700) |
| | Winter | 5 | (11) | 197 | (156) | 309 | (350) | 302 | (412) | 393 | (909) |
| 216 | Spring | 7 | (68) | 233 | (95) | 471 | (570) | 687 | (956) | 1,860 | (5,170) |
| | Summer | 7 | (70) | 1,990 | (1,070) | 5,170 | (3,440) | 7,991 | (5,293) | 24,200 | (>24,200) |
| | Fall | 6 | (73) | 404 | (288) | 947 | (1,110) | 1,005 | (2,144) | 1,780 | (19,900) |
| | Winter | 6 | (70) | 187 | (86) | 361 | (357) | 396 | (633) | 733 | (6,490) |
| GATE | Spring | 7 | (69) | 195 | (199) | 435 | (670) | 715 | (911) | 2,250 | (7,270) |
| | Summer | 7 | (69) | 1,090 | (1,180) | 2,610 | (4,110) | 2,407 | (6,287) | 3,870 | (>24,200) |
| | Fall | 6 | (70) | 473 | (388) | 1,700 | (2,340) | 3,472 | (3,922) | 14,100 | (>24,200) |
| | Winter | 6 | (69) | 259 | (135) | 302 | (355) | 309 | (401) | 373 | (1,270) |
| BC | Spring | 8 | (69) | 145 | (86) | 650 | (743) | 3,448 | (1,513) | 13,000 | (15,500) |
| | Summer | 7 | (71) | 1,250 | (1,170) | 6,490 | (7,270) | 6,380 | (8,771) | 14,100 | (>24,200) |
| | Fall | 6 | (70) | 228 | (464) | 781 | (3,260) | 2,295 | (6,203) | 9,800 | (>24,200) |
| | Winter | 6 | (69) | 134 | (122) | 362 | (399) | 317 | (738) | 414 | (8,660) |

**Table 20:** Descriptive statistics (minimum, median, average, and maximum) for total coliformmeasured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Total Coliform (MPN/100 mL) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Spring | 6 | (55) | 75 | (73) | 883 | (852) | 885 | (1,169) | 1,940 | (7,700) |
| | Summer | 7 | (56) | 2,280 | (1,330) | 6,130 | (5,790) | 7,007 | (7,470) | 15,500 | (>24,200) |
| | Fall | 7 | (60) | 331 | (350) | 3,260 | (2,195) | 3,866 | (3,190) | 12,000 | (>24,200) |
| | Winter | 6 | (60) | 197 | (109) | 295 | (397) | 345 | (678) | 565 | (3,450) |
| 102 | Spring | 6 | (0) | 181 | - | 652 | - | 764 | - | 2,010 | - |
| | Summer | 7 | (0) | 2,760 | - | 4,350 | - | 4,794 | - | 7,700 | - |
| | Fall | 7 | (0) | 435 | - | 1,990 | - | 3,732 | - | 13,000 | - |
| | Winter | 6 | (0) | 171 | - | 270 | - | 283 | - | 504 | - |
| 103A | Spring | 6 | (63) | 134 | (110) | 860 | (908) | 877 | (1,3134) | 1,610 | (4,610) |
| | Summer | 7 | (70) | 2,850 | (1,920) | 5,170 | (6,870) | 6,367 | (8,243) | 15,500 | (>24,200) |
| | Fall | 7 | (70) | 404 | (529) | 2,600 | (2,610) | 4,581 | (3,747) | 14,100 | (>24,200) |
| | Winter | 6 | (60) | 253 | (173) | 323 | (547) | 337 | (726) | 481 | (6,490) |
| 107A | Spring | 6 | (68) | 285 | (160) | 1,120 | (948) | 2,049 | (1,525) | 5,790 | (9,210) |
| | Summer | 7 | (70) | 2,600 | (1,170) | 3,870 | (4,230) | 4,859 | (6,044) | 11,200 | (>24,200) |
| | Fall | 7 | (70) | 464 | (546) | 1,130 | (1,645) | 3,709 | (2,994) | 17,300 | (>24,200) |
| | Winter | 6 | (68) | 160 | (203) | 224 | (521) | 236 | (713) | 327 | (4,350) |
| 108 | Spring | 6 | (68) | 189 | (121) | 781 | (817) | 759 | (1,145) | 1,410 | (4,610) |
| | Summer | 7 | (71) | 3,870 | (1,520) | 5,170 | (5,170) | 5,989 | (6,549) | 11,200 | (>24,200) |
| | Fall | 7 | (70) | 537 | (504) | 2,050 | (1,840) | 3,773 | (3,096) | 14,100 | (>24,200) |
| | Winter | 6 | (72) | 135 | (75) | 221 | (362) | 262 | (605) | 404 | (4,610) |
| 121 | Spring | 6 | (13) | 145 | (228) | 1,030 | (1,530) | 1,085 | (2,242) | 2,910 | (6,130) |
| | Summer | 7 | (13) | 2,810 | (1,940) | 5,170 | (4,610) | 5,680 | (4,688) | 9,800 | (9,800) |
| | Fall | 7 | (13) | 988 | (759) | 1,970 | (1,670) | 3,894 | (2,353) | 14,100 | (5,480) |
| | Winter | 6 | (13) | 110 | (256) | 203 | (428) | 267 | (825) | 529 | (2,490) |

#### 3.2.4.2 *E. coli*

*E. coli* results corresponding to Core monitoring tributaries in the Quabbin Reservoir Watershed and Ware River Watershed were compared to the Class A standards for non-intake waters, and annual geometric means were compared to those of previous years. *E. coli* concentrations ranged from less than 10 to 1,850 MPN/100 mL in Quabbin Reservoir Watershed tributaries (Table 21) and from less than 10 to 663 MPN/100 mL in the Ware River Watershed tributaries in 2021 (Table 22). The maximum *E. coli* result observed in 2021 occurred on August 31, 2021, at site 212 in the Quabbin Reservoir Watershed. Of the 338 samples collected from Core tributaries and analyzed for *E. coli* in 2021, approximately 30% (n=103) were below detection limits (<10 MPN/100 mL).

Nineteen samples exceeded the Class A Standard for single samples (*E. coli* >235 MPN/100 mL) in Core sites in the Quabbin Reservoir and Ware River Watersheds in 2021. *E. coli* concentrations in excess of 235 MPN/100 mL occurred primarily during the latter half of 2021 (Figure 18, Figure 19). Exceedances of the Class A single sample threshold typically followed precipitation events. Of the nineteen results in excess of 235 MPN /100 mL, nine corresponded to samples collected from 103A in the Ware River Watershed and BC in the Quabbin Reservoir Watershed (n=4 and n=5, respectively). No potential sources of pollution were observed during or following sample collection, and *E. coli* concentrations decreased in subsequent samples (Figure 18, Figure 19). *E. coli* concentrations in Core tributaries in 2021 continued to demonstrate a high sanitary quality.

**Table 21:** Descriptive statistics (minimum, median, average, and maximum) for *E. coli* measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection Limits for *E. coli* were <10 MPN/100 mL.

| Location | Season | ***E. coli* (MPN/100 mL)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **n** | | **Minimum** | | **Median** | | **Mean** | | **Maximum** | |
| 211 | Winter | 6 | (101) | 10 | (10) | 5 | (4) | 10 | (7) | 30 | (63) |
| | Summer | 7 | (98) | 10 | (10) | 20 | (31) | 45 | (154) | 187 | (6,870) |
| | Spring | 7 | (92) | 10 | (10) | 5 | (9) | 15 | (17) | 52 | (156) |
| | Fall | 6 | (99) | 10 | (10) | 36 | (10) | 32 | (37) | 52 | (644) |
| 212 | Winter | 6 | (99) | 10 | (10) | 20 | (5) | 44 | (10) | 189 | (84) |
| | Summer | 7 | (100) | 10 | (10) | 85 | (63) | 333 | (225) | 1,850 | (5,480) |
| | Spring | 7 | (93) | 10 | (10) | 41 | (10) | 59 | (28) | 203 | (481) |
| | Fall | 6 | (99) | 20 | (10) | 74 | (20) | 75 | (98) | 135 | (2,360) |
| 213 | Winter | 6 | (101) | 10 | (10) | 20 | (10) | 32 | (25) | 98 | (327) |
| | Summer | 7 | (101) | 41 | (10) | 63 | (63) | 166 | (303) | 820 | (12,000) |
| | Spring | 7 | (94) | 10 | (10) | 31 | (30) | 29 | (51) | 63 | (426) |
| | Fall | 6 | (99) | 10 | (10) | 36 | (31) | 40 | (127) | 75 | (3,260) |
| 215G | Winter | 5 | (11) | 10 | (10) | 5 | (10) | 6 | (12) | 10 | (41) |
| | Summer | 7 | (13) | 10 | (10) | 41 | (20) | 46 | (56) | 85 | (448) |
| | Spring | 7 | (11) | 10 | (10) | 5 | (8) | 13 | (13) | 31 | (31) |
| | Fall | 6 | (13) | 10 | (10) | 8 | (10) | 20 | (15) | 62 | (63) |
| 216 | Winter | 6 | (101) | 10 | (10) | 12 | (10) | 16 | (16) | 41 | (292) |
| | Summer | 7 | (98) | 10 | (10) | 63 | (41) | 63 | (82) | 173 | (1,010) |
| | Spring | 7 | (92) | 10 | (10) | 5 | (10) | 6 | (17) | 10 | (187) |
| | Fall | 6 | (98) | 10 | (10) | 25 | (20) | 26 | (107) | 63 | (6,870) |
| BC | Winter | 6 | (99) | 10 | (10) | 10 | (6) | 15 | (18) | 31 | (189) |
| | Summer | 7 | (98) | 10 | (10) | 97 | (104) | 130 | (699) | 341 | (19,900) |
| | Spring | 8 | (93) | 10 | (10) | 10 | (10) | 119 | (32) | 428 | (697) |
| | Fall | 6 | (88) | 10 | (10) | 5 | (31) | 60 | (218) | 323 | (3,870) |
| GATE | Winter | 6 | (98) | 10 | (10) | 5 | (2) | 7 | (10) | 10 | (249) |
| | Summer | 7 | (96) | 10 | (10) | 5 | (30) | 11 | (67) | 20 | (1,660) |
| | Spring | 7 | (93) | 10 | (10) | 5 | (1) | 6 | (17) | 10 | (529) |
| | Fall | 6 | (96) | 10 | (10) | 20 | (10) | 71 | (107) | 345 | (5,170) |

**Table 22:** Descriptive statistics (minimum, median, average, and maximum) for *E. coli* measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection Limits for *E. coli* were <10 MPN/100 mL.

| Location | Season | *E. coli* (MPN/100 mL) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Winter | 6 | (60) | 10 | (10) | 10 | (10) | 12 | (15) | 20 | (146) |
| | Summer | 7 | (56) | 52 | (10) | 122 | (80) | 149 | (141) | 341 | (1,220) |
| | Spring | 6 | (55) | 10 | (10) | 18 | (10) | 20 | (30) | 41 | (228) |
| | Fall | 7 | (60) | 10 | (10) | 63 | (31) | 92 | (71) | 288 | (1,550) |
| 102 | Winter | 6 | (0) | 10 | - | 5 | - | 11 | - | 41 | - |
| | Summer | 7 | (0) | 41 | - | 52 | - | 87 | - | 206 | - |
| | Spring | 6 | (0) | 10 | - | 5 | - | 14 | - | 41 | - |
| | Fall | 7 | (0) | 10 | - | 41 | - | 118 | - | 609 | - |
| 103A | Winter | 6 | (79) | 10 | (10) | 8 | (10) | 13 | (14) | 31 | (197) |
| | Summer | 7 | (94) | 31 | (10) | 109 | (121) | 175 | (184) | 448 | (1,420) |
| | Spring | 6 | (88) | 10 | (10) | 15 | (20) | 17 | (36) | 41 | (228) |
| | Fall | 7 | (100) | 10 | (10) | 63 | (41) | 147 | (84) | 663 | (1,040) |
| 107A | Winter | 6 | (83) | 10 | (10) | 8 | (10) | 9 | (13) | 20 | (96) |
| | Summer | 7 | (92) | 10 | (10) | 31 | (62) | 45 | (112) | 120 | (1,400) |
| | Spring | 6 | (91) | 10 | (10) | 15 | (10) | 24 | (32) | 52 | (488) |
| | Fall | 7 | (100) | 10 | (10) | 30 | (20) | 94 | (113) | 504 | (4,880) |
| 108 | Winter | 6 | (98) | 10 | (10) | 5 | (10) | 8 | (14) | 20 | (107) |
| | Summer | 7 | (95) | 31 | (10) | 108 | (84) | 115 | (143) | 183 | (1,780) |
| | Spring | 6 | (96) | 10 | (10) | 8 | (10) | 14 | (31) | 41 | (189) |
| | Fall | 7 | (100) | 10 | (10) | 52 | (31) | 104 | (68) | 495 | (1,350) |
| 121 | Winter | 6 | (21) | 10 | (10) | 5 | (4) | 13 | (15) | 52 | (148) |
| | Summer | 7 | (25) | 20 | (10) | 97 | (63) | 110 | (94) | 309 | (336) |
| | Spring | 6 | (23) | 10 | (10) | 15 | (20) | 34 | (30) | 97 | (256) |
| | Fall | 7 | (27) | 10 | (10) | 52 | (20) | 80 | (54) | 275 | (282) |

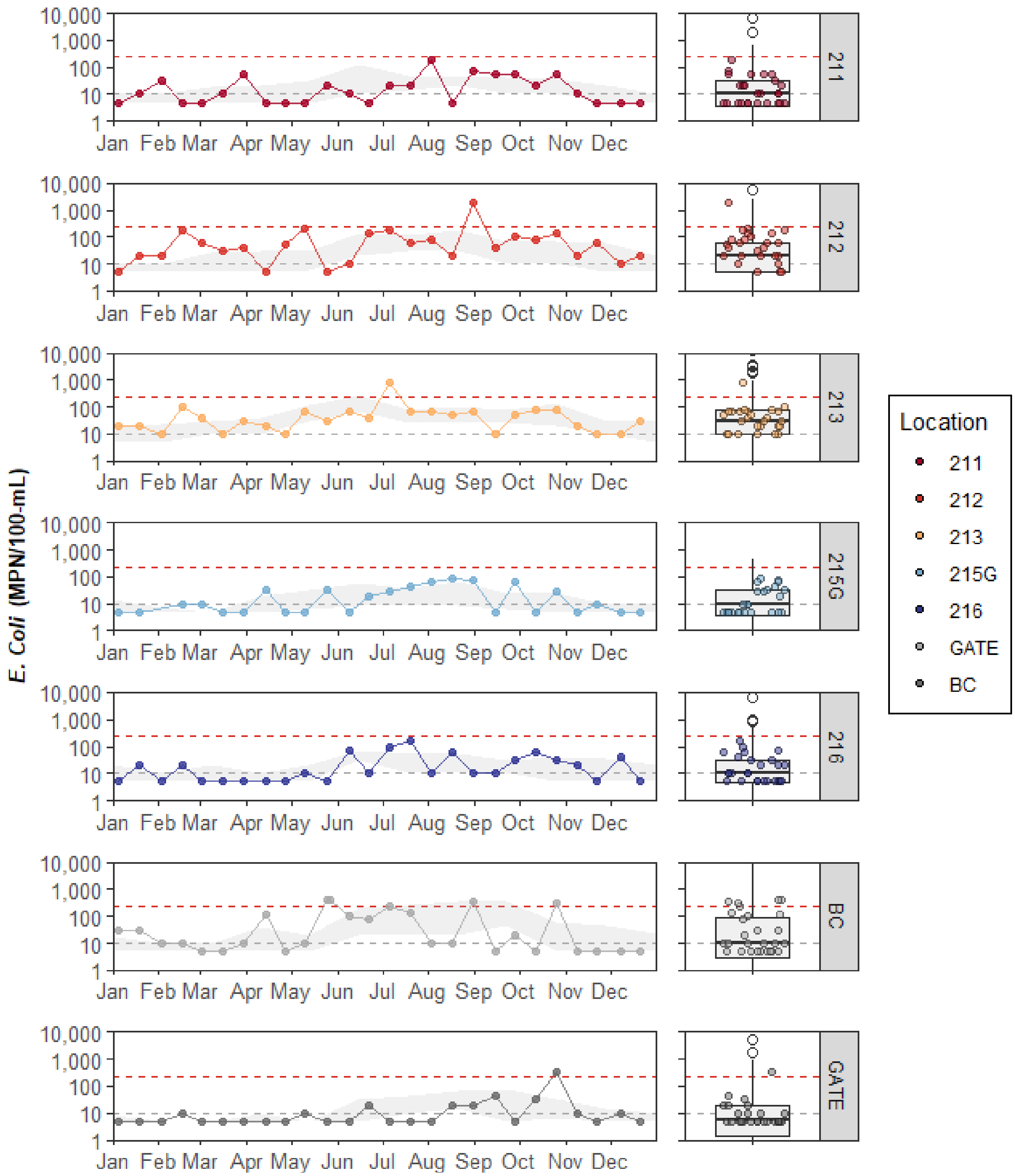



**Figure 18:** Time series and boxplots of *E. coli* measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey and red lines correspond to laboratory detection limits (10 MPN/100 mL) and the MassDEP Class A single sample maximum standard of 235 MPN/100 mL.

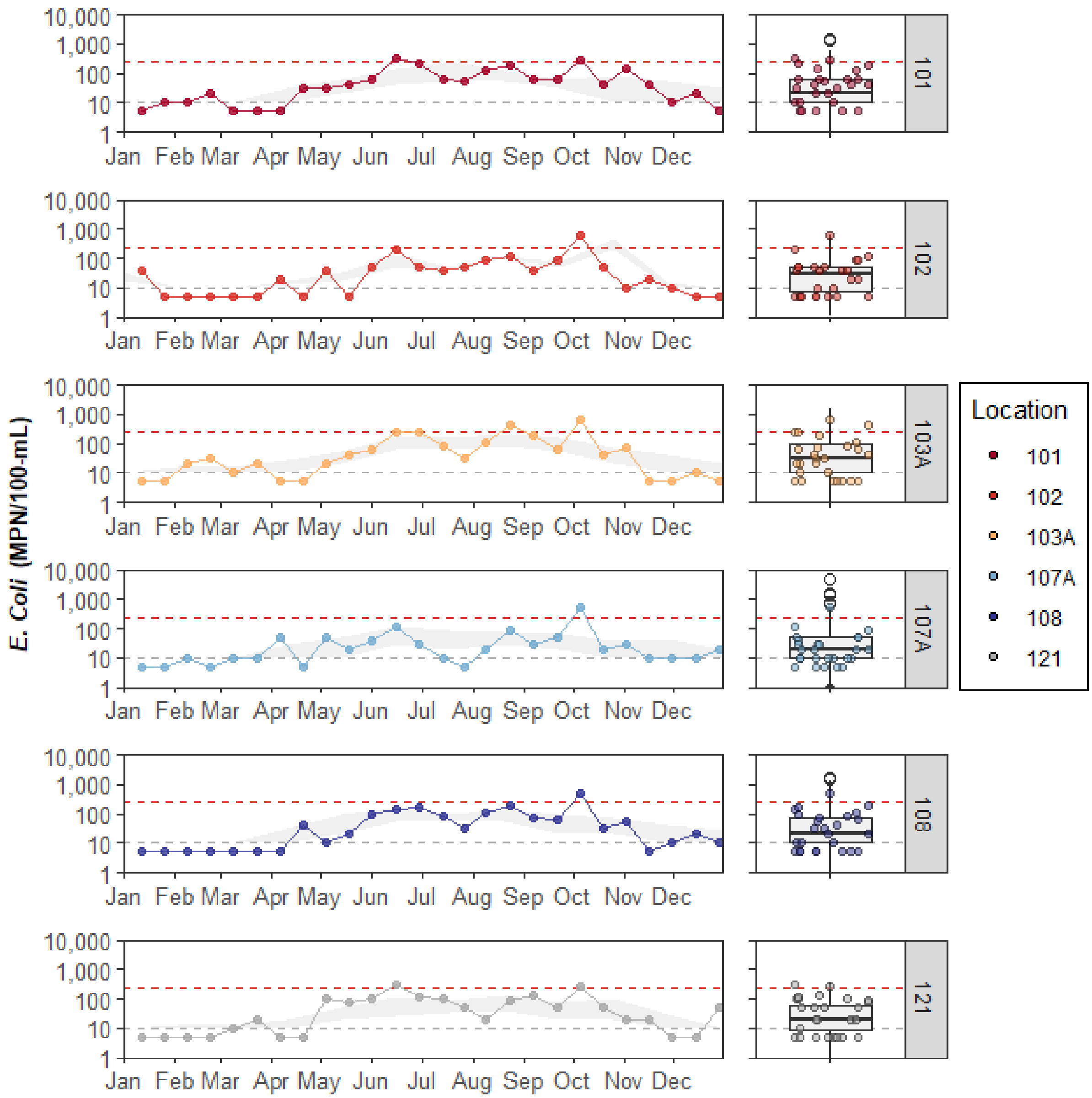



**Figure 19:** Time series and boxplots of *E. coli* measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey and red lines correspond to laboratory detection limits (10 MPN/100 mL) and the MassDEP Class A single sample maximum standard of 235 MPN/100 mL.

The annual geometric mean *E. coli* concentration remained below 126 MPN/100 mL and the Class A standards for all Core monitoring sites in 2021 (Table 23, Table 24), regardless of treatment of censored data. Long-term records of annual geometric mean *E. coli* results do not exhibit unidirectional trends in any Core monitoring sites. Although annual geometric mean *E. coli* at Site 212 in the Quabbin Reservoir Watershed has been on an upward trajectory in recent years (19

MPN/100 mL in 2019 to a 47 MPN/100 mL in 2021), results to for this location in 2021 did not exceed the maximum annual geometric mean *E. coli* for the POR (Appendix C). Temporal variability in annual geometric mean *E. coli* concentrations exhibited a non-uniform response to climate extremes (e.g., drought in 2016 and 2020, extreme precipitation excess in summer 2021). This contrast may reflect the timing of sample collection relative to precipitation events throughout the period of record, differences in the degree to which the two watersheds may have been impacted by saturation excess overland flow, or variations in factors controlling the sources of *E. coli* to the watersheds.

Boat Cove Brook, in the Quabbin Reservoir Watershed, had demonstrated an upward trend in annual *E. coli* concentrations from 2012 to 2017 (DWSP, 2018c; DWSP, 2019a). However, annual geometric mean *E. coli* concentrations in 2021 (30 MPN/100 mL) marked the fourth consecutive year that annual results for this location have declined from previous years (Appendix C). Work to assess potential bacteria sources near this sample location has been described in previous reports (DWSP, 2018c).

**Table 23:** Annual geometric mean *E. coli* calculated for Core tributary sites in the Quabbin Reservoir Watershed. The detection limit (10 MPN/100 mL) was substituted for censored data for these calculations (MassDEP, 2018).

| Year | 211 | 212 | 213 | 215G | 216 | BC | GATE |
|---|---|---|---|---|---|---|---|
| 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 |
| 2011 | 11 | 19 | 44 | - | 26 | 9 | 9 |
| 2010 | 18 | 24 | 57 | - | 19 | 25 | 18 |
| 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 | 64 | 8 |
| 2018 | 13 | 29 | 35 | - | 18 | 38 | 2 |
| 2019 | 9 | 11 | 25 | - | 11 | 30 | 10 |
| 2020 | 15 | 26 | 16 | - | 21 | 23 | 13 |
| 2021 | 12 | 44 | 34 | 11 | 13 | 19 | 6 |

**Table 24:** Annual geometric mean *E. coli* for Core tributary sites in the Ware River Watershed. The detection limit (10 MPN/100 mL) was substituted for censored data for these calculations (MassDEP, 2018).

| Year | 101 | 102 | 103A | 107A | 108 | 121 |
|---|---|---|---|---|---|---|
| 2006 | - | - | 29 | 14 | 20 | - |
| 2007 | - | - | 34 | 46 | 22 | 67 |
| 2008 | - | - | 40 | 40 | 30 | 19 |
| 2009 | - | - | 21 | 18 | 23 | - |
| 2010 | - | | 28 | 19 | 31 | - |
| 2011 | - | - | 21 | 14 | 32 | - |
| 2012 | 29 | - | 20 | 17 | 22 | 15 |
| 2013 | 23 | - | 26 | 22 | 21 | - |
| 2014 | 17 | - | 33 | 16 | 21 | - |
| 2015 | 16 | - | 35 | 23 | 24 | - |
| 2016 | 20 | - | 28 | 17 | 25 | 21 |
| 2017 | 34 | - | 36 | 26 | 27 | - |
| 2018 | 33 | - | 59 | 36 | 40 | - |
| 2019 | 21 | - | 35 | 14 | 25 | - |
| 2020 | 24 | - | 42 | 21 | 22 | - |
| 2021 | 33 | 20 | 29 | 20 | 23 | 26 |

## 3.2.5 Nutrient Dynamics

### *3.2.5.1 Nitrogen Species*

#### *3.2.5.1.1 Ammonia-Nitrogen*

Concentrations of ammonia ($NH_3$-N) in Quabbin Reservoir and Ware River Watershed tributaries have routinely been below detection limits (63% of samples from Core tributaries in 2021). Concentrations of $NH_3$-N in Quabbin Reservoir and Ware River Watershed Core monitoring tributaries ranged from <0.005 to 0.198 mg/L and <0.005 to 0.093 mg/L, respectively, in 2021 (Table 25, Table 26). Concentrations of $NH_3$-N were generally within historical ranges for most Core tributary sites in 2021, with exceedances of previous seasonal maximum concentrations observed at several sites. Concentrations of $NH_3$-N in Core monitoring tributaries in the Quabbin Reservoir and Ware River Watersheds were below the MA acute and chronic aquatic life criteria (17 mg/L and 1.9 mg/L, respectively) and the WHO taste and odor thresholds for drinking water (1.5 mg/L and 1.9 mg/L) for the entirety of 2021.

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 $NH_3$N concentrations and corresponding relative depletion in $NO_3$-N concentrations observed in Fever Brook and Mill Brook in 2021 suggest that the beaver continue to impact N-cycling in the upstream reaches of these particular sub-watersheds during 2021.

2021 marked the second year of biweekly monitoring of $NH_3$-N in Core tributaries. The increased monitoring frequency likely impacted seasonal descriptive statistics, as well as intra-annual and site-to-site variability (Jones et al., 2012; Elwan et al., 2018). For example, the range of concentrations of $NH_3$-N observed biweekly at site 108 in summer 2021 was comparable to the range of concentrations across all seasons for the period of record (<0.005 to 0.03 mg/L vs. <0.005 to 0.034 mg/L, respectively) at this location. As different factors may play variable roles in terrestrial aquatic N-cycling across watersheds (e.g., 211, vs. 215G, vs. Boat Cove Brook; Quabbin Reservoir Watershed vs. Ware River Watershed), the insights on controls on riverine N-loading to Quabbin Reservoir derived from the introduction of biweekly analyses of $NH_3$-N may also vary. Namely, $NH_3$-N was below laboratory detection limits for the entirety of 2020 and 2021 in Gates Brook. In contrast, concentrations of $NH_3$-N varied over several orders of magnitude in samples collected during the summer at site 215G, and maximum $NH_3$-N concentrations for the period of record at site 213 were observed in March 2021 (0.198 mg/L in 2021, compared to

0.033 mg/L for the period of record). Site 108 and 121 in the Ware River Watershed also demonstrated distinct intra-seasonal variability in concentrations of $NH_3$-N in both 2020 and 2021. Despite the intra-seasonal variability introduced by increased monitoring frequency, $NH_3$-N concentrations observed in Ware River Watershed tributaries exhibited a comparable seasonal variability to large tributaries in the Quabbin Reservoir Watershed (e.g., 211, 212, 213, 215G, and 216) in 2021. The general timing of annual increases in instream $NH_3$-N concentrations was consistent across watersheds (Appendix C).

**Table 25:** Descriptive statistics (minimum, median, average, and maximum) for $NH_3$-N measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection limits for $NH_3$-N were <0.005 mg/L.

| Location | Season | $NH_3N$ (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Winter | 6 | (15) | 0.005 | (0.005) | 0.002 | (0.002) | 0.002 | (0.003) | 0.005 | (0.006) |
| | Summer | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.003) | 0.004 | (0.012) | 0.011 | (0.082) |
| | Spring | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.002) | 0.002 | (0.002) | 0.005 | (0.005) |
| | Fall | 6 | (15) | 0.005 | (0.005) | 0.004 | (0.003) | 0.004 | (0.004) | 0.007 | (0.010) |
| 212 | Winter | 6 | (14) | 0.005 | (0.005) | 0.004 | (0.004) | 0.004 | (0.004) | 0.007 | (0.008) |
| | Summer | 7 | (13) | 0.005 | (0.005) | 0.008 | (0.005) | 0.009 | (0.008) | 0.018 | (0.039) |
| | Spring | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.004) | 0.005 | (0.008) | 0.023 | (0.034) |
| | Fall | 6 | (15) | 0.005 | (0.005) | 0.002 | (0.002) | 0.004 | (0.006) | 0.006 | (0.038) |
| 213 | Winter | 6 | (15) | 0.005 | (0.005) | 0.005 | (0.006) | 0.007 | (0.007) | 0.016 | (0.014) |
| | Summer | 7 | (13) | 0.005 | (0.005) | 0.007 | (0.013) | 0.008 | (0.014) | 0.014 | (0.030) |
| | Spring | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.009) | 0.032 | (0.013) | 0.198 | (0.033) |
| | Fall | 6 | (15) | 0.005 | (0.005) | 0.007 | (0.008) | 0.007 | (0.01) | 0.009 | (0.015) |
| 215G | Winter | 5 | (11) | 0.005 | (0.005) | 0.002 | (0.006) | 0.006 | (0.011) | 0.016 | (0.025) |
| | Summer | 7 | (13) | 0.005 | (0.005) | 0.007 | (0.011) | 0.014 | (0.013) | 0.032 | (0.024) |
| | Spring | 7 | (11) | 0.005 | (0.005) | 0.002 | (0.002) | 0.005 | (0.003) | 0.012 | (0.007) |
| | Fall | 6 | (13) | 0.005 | (0.005) | 0.002 | (0.007) | 0.004 | (0.008) | 0.01 | (0.017) |
| 216 | Winter | 6 | (15) | 0.005 | (0.005) | 0.002 | (0.001) | 0.007 | (0.005) | 0.026 | (0.046) |
| | Summer | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.004) | 0.007 | (0.006) | 0.028 | (0.014) |
| | Spring | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.002) | 0.003 | (0.01) | 0.005 | (0.054) |
| | Fall | 6 | (15) | 0.005 | (0.005) | 0.002 | (0.002) | 0.004 | (0.004) | 0.013 | (0.013) |
| BC | Winter | 6 | (15) | 0.005 | (0.005) | 0.002 | (0.002) | 0.002 | (0.004) | 0.005 | (0.015) |
| | Summer | 7 | (11) | 0.005 | (0.005) | 0.002 | (0.004) | 0.004 | (0.005) | 0.015 | (0.011) |
| | Spring | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.002) | 0.002 | (0.003) | 0.005 | (0.007) |
| | Fall | 6 | (12) | 0.005 | (0.005) | 0.002 | (0.002) | 0.002 | (0.003) | 0.005 | (0.012) |
| GATE | Winter | 6 | (15) | 0.005 | (0.005) | 0.002 | (0.002) | 0.002 | (0.002) | 0.005 | (0.005) |
| | Summer | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.002) | 0.003 | (0.003) | 0.005 | (0.006) |
| | Spring | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.002) | 0.002 | (0.002) | 0.005 | (0.005) |
| | Fall | 6 | (15) | 0.005 | (0.005) | 0.002 | (0.002) | 0.002 | (0.003) | 0.005 | (0.007) |

**Table 26:** Descriptive statistics (minimum, median, average, and maximum) for $NH_3$-N measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection limits for $NH_3$-N were <0.005 mg/L.

| Location | Season | $NH_3$N (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Winter | 6 | (16) | 0.005 | (0.005) | 0.005 | (0.005) | 0.007 | (0.006) | 0.016 | (0.013) |
| | Summer | 7 | (15) | 0.005 | (0.005) | 0.007 | (0.012) | 0.009 | (0.012) | 0.016 | (0.025) |
| | Spring | 6 | (12) | 0.005 | (0.005) | 0.002 | (0.003) | 0.005 | (0.007) | 0.012 | (0.031) |
| | Fall | 7 | (14) | 0.005 | (0.005) | 0.002 | (0.006) | 0.01 | (0.007) | 0.055 | (0.012) |
| 102 | Winter | 6 | (0) | 0.005 | - | 0.007 | - | 0.007 | - | 0.012 | - |
| | Summer | 7 | (0) | 0.005 | - | 0.002 | - | 0.005 | - | 0.012 | - |
| | Spring | 6 | (0) | 0.005 | - | 0.002 | - | 0.004 | - | 0.01 | - |
| | Fall | 7 | (0) | 0.005 | - | 0.005 | - | 0.016 | - | 0.093 | - |
| 103A | Winter | 6 | (16) | 0.005 | (0.005) | 0.004 | (0.005) | 0.008 | (0.007) | 0.018 | (0.027) |
| | Summer | 7 | (15) | 0.005 | (0.005) | 0.006 | (0.007) | 0.007 | (0.011) | 0.016 | (0.027) |
| | Spring | 6 | (11) | 0.005 | (0.005) | 0.002 | (0.006) | 0.004 | (0.009) | 0.009 | (0.028) |
| | Fall | 7 | (14) | 0.005 | (0.005) | 0.002 | (0.006) | 0.003 | (0.006) | 0.006 | (0.011) |
| 107A | Winter | 6 | (16) | 0.005 | (0.005) | 0.007 | (0.006) | 0.008 | (0.006) | 0.018 | (0.012) |
| | Summer | 7 | (15) | 0.005 | (0.005) | 0.007 | (0.006) | 0.008 | (0.007) | 0.013 | (0.019) |
| | Spring | 6 | (12) | 0.005 | (0.005) | 0.002 | (0.003) | 0.003 | (0.009) | 0.006 | (0.046) |
| | Fall | 7 | (14) | 0.005 | (0.005) | 0.002 | (0.004) | 0.003 | (0.006) | 0.005 | (0.017) |
| 108 | Winter | 6 | (16) | 0.005 | (0.005) | 0.007 | (0.009) | 0.01 | (0.016) | 0.023 | (0.123) |
| | Summer | 7 | (15) | 0.005 | (0.005) | 0.014 | (0.021) | 0.015 | (0.02) | 0.03 | (0.034) |
| | Spring | 6 | (12) | 0.005 | (0.005) | 0.004 | (0.005) | 0.006 | (0.01) | 0.013 | (0.039) |
| | Fall | 7 | (14) | 0.005 | (0.005) | 0.002 | (0.01) | 0.004 | (0.01) | 0.009 | (0.017) |
| 121 | Winter | 6 | (13) | 0.008 | (0.005) | 0.032 | (0.008) | 0.03 | (0.01) | 0.053 | (0.019) |
| | Summer | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.026) | 0.014 | (0.036) | 0.072 | (0.136) |
| | Spring | 6 | (13) | 0.005 | (0.005) | 0.002 | (0.007) | 0.004 | (0.008) | 0.011 | (0.011) |
| | Fall | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.015) | 0.011 | (0.024) | 0.033 | (0.103) |

#### *3.2.5.1.2 Nitrate-Nitrogen*

Concentrations of nitrate ($NO_3$-N) ranged from <0.005 to 0.132 mg/L in Quabbin Reservoir Watershed Core sites in 2021 (Table 27). Concentrations of $NO_3$-N observed in Ware River Watershed during 2021 ranged from <0.005 to 0.092 mg/L (Table 28). Concentrations of $NO_3$-N observed in Core tributary monitoring sites in Quabbin Reservoir and Ware River Watersheds during 2021 were largely within historical seasonal ranges but revealed differences in seasonal median concentrations when compared to those for the period of record for most sites. For locations with a continuous monitoring record, median winter $NO_3$-N concentrations were greater in 2021 compared to the period of record. The latter may reflect differences in sampling frequency introduced in 2020 (e.g., winter $NO_3$-N samples were previously collected once, each December. Beginning in 2020, winter $NO_3$-N samples represent biweekly samples collected during the months of January, February, and December).

Seasonal concentration ranges of $NO_3$-N were generally similar in Core tributaries in the Ware River Watershed compared to Core tributaries in the Quabbin Reservoir Watershed. Variations in concentrations of $NO_3$-N across Core tributaries likely reflect differences in watershed characteristics combined with land use and management across the two watersheds. Core monitoring tributaries in the Quabbin Reservoir and Ware River Watersheds were well below the EPA MCL for drinking water of 10 mg/L for the entirety of 2021 and within local ecoregional background levels (0.16 – 0.31 mg/L) throughout 2021. Concentrations of $NO_3$-N in Quabbin Reservoir and Ware River Watersheds followed expected seasonal patterns in 2021, 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 summer and fall, where uptake or increases in denitrification rates likely contributed to $NO_3$-N removal/reduction. Small Core tributaries in the Quabbin Reservoir Watershed (e.g., Gates Brook and Boat Cove Brook) did not follow these patterns, rather these locations favored greater concentrations during low flows (e.g., summer) and relative depletion of $NO_3$-N concentrations during spring and winter high flows (Appendix C). The latter indicates key differences in controls on biogeochemical N-cycling in small low-order tributaries compared to higher-order (larger) tributaries to the Quabbin Reservoir and those in the Ware River Watershed. Median winter $NO_3$-N concentrations in 2021 were greater than those for the period of record for select Core tributary sites in either watershed (Appendix C). Below normal streamflow present throughout much of February 2021 may have resulted in a lack of dilution of stream $NO_3$-N concentrations (Section 3.1.2).

Biweekly analyses of $NO_3$-N in 2021 revealed several key patterns not presented by single quarterly (seasonal) results. Temporally, within a seasonal period, in-stream $NO_3$-N concentrations may vary from below 25th percentile concentrations to maximum concentrations observed for the period of record (Appendix C). This is to be expected, given the dynamic controls on $NO_3$-N transport across terrestrial and aquatic ecosystems. Other sites offered little to no intraseasonal variability in $NO_3$-N concentrations at a biweekly monitoring frequency. The latter typically occurred at locations where $NO_3$-N concentrations remained below laboratory detection limits for the entire three-month window (e.g., Gates Brook) and ultimately serves to provide meaningful information relative to N-loading in small tributary systems. Furthermore, seasonal median $NO_3$-N concentrations for some sites in 2021 illustrated patterns distinct from that of the period of record. This observation may also have been impacted by the high flow conditions during July 2021, discussed previously. This pattern was most notable in samples collected during the summer of 2021 in Quabbin Reservoir Watershed Core tributaries. Biweekly monitoring of $NO_3$-N through 2022 may provide additional insights toward the implications of the increase in monitoring frequency of nutrients in Core tributaries in the Quabbin Reservoir Watershed and Ware River Watershed. Higher frequency sampling of nutrients in surface waters generally results in more accurate annual load estimates (Jones et al., 2012; Elwan et al 2018). As variations in $NO_3$-N concentrations may drastically impact estimates of N-loading, thoroughly understanding the processes controlling $NO_3$-N concentrations – including typical intra- and interannual variability - is critical for deriving accurate estimates of N-delivery to Quabbin Reservoir.

**Table 27:** Descriptive statistics (minimum, median, average, and maximum) for $NO_3$-N measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection limits for $NO_3$-N were <0.005 mg/L.

| Location | Season | $NO_3$N (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Winter | 6 | (20) | 0.016 | (0.009) | 0.019 | (0.020) | 0.028 | (0.025) | 0.052 | (0.104) |
| | Summer | 7 | (24) | 0.005 | (0.005) | 0.022 | (0.045) | 0.026 | (0.057) | 0.048 | (0.133) |
| | Spring | 7 | (21) | 0.005 | (0.005) | 0.012 | (0.024) | 0.016 | (0.028) | 0.041 | (0.071) |
| | Fall | 6 | (25) | 0.008 | (0.007) | 0.013 | (0.036) | 0.017 | (0.050) | 0.032 | (0.139) |
| 212 | Winter | 6 | (19) | 0.040 | (0.038) | 0.052 | (0.062) | 0.059 | (0.064) | 0.084 | (0.173) |
| | Summer | 7 | (23) | 0.008 | (0.015) | 0.044 | (0.062) | 0.039 | (0.064) | 0.074 | (0.116) |
| | Spring | 7 | (21) | 0.020 | (0.025) | 0.039 | (0.062) | 0.040 | (0.067) | 0.068 | (0.122) |
| | Fall | 6 | (25) | 0.010 | (0.005) | 0.025 | (0.040) | 0.024 | (0.042) | 0.034 | (0.084) |
| 213 | Winter | 6 | (20) | 0.048 | (0.047) | 0.071 | (0.075) | 0.083 | (0.090) | 0.132 | (0.266) |
| | Summer | 7 | (23) | 0.005 | (0.005) | 0.006 | (0.013) | 0.006 | (0.016) | 0.011 | (0.044) |
| | Spring | 7 | (21) | 0.005 | (0.012) | 0.022 | (0.070) | 0.037 | (0.075) | 0.109 | (0.186) |
| | Fall | 6 | (25) | 0.009 | (0.005) | 0.017 | (0.014) | 0.023 | (0.020) | 0.042 | (0.058) |
| 215G | Winter | 5 | (11) | 0.005 | (0.005) | 0.015 | (0.010) | 0.016 | (0.014) | 0.034 | (0.043) |
| | Summer | 7 | (13) | 0.005 | (0.005) | 0.002 | (0.007) | 0.004 | (0.008) | 0.009 | (0.026) |
| | Spring | 7 | (11) | 0.005 | (0.005) | 0.002 | (0.004) | 0.006 | (0.005) | 0.021 | (0.012) |
| | Fall | 6 | (13) | 0.005 | (0.005) | 0.002 | (0.005) | 0.002 | (0.006) | 0.005 | (0.011) |
| 216 | Winter | 6 | (20) | 0.038 | (0.017) | 0.052 | (0.044) | 0.067 | (0.054) | 0.119 | (0.194) |
| | Summer | 7 | (23) | 0.007 | (0.013) | 0.014 | (0.040) | 0.025 | (0.045) | 0.061 | (0.096) |
| | Spring | 7 | (21) | 0.008 | (0.015) | 0.020 | (0.048) | 0.031 | (0.057) | 0.098 | (0.133) |
| | Fall | 6 | (24) | 0.008 | (0.005) | 0.015 | (0.011) | 0.018 | (0.016) | 0.030 | (0.036) |
| BC | Winter | 6 | (20) | 0.005 | (0.006) | 0.014 | (0.015) | 0.016 | (0.025) | 0.027 | (0.099) |
| | Summer | 7 | (18) | 0.005 | (0.005) | 0.019 | (0.039) | 0.016 | (0.041) | 0.025 | (0.108) |
| | Spring | 7 | (21) | 0.005 | (0.005) | 0.007 | (0.009) | 0.009 | (0.014) | 0.018 | (0.043) |
| | Fall | 6 | (18) | 0.005 | (0.005) | 0.002 | (0.013) | 0.003 | (0.024) | 0.005 | (0.114) |
| GATE | Winter | 6 | (20) | 0.005 | (0.005) | 0.006 | (0.002) | 0.006 | (0.003) | 0.008 | (0.011) |
| | Summer | 7 | (22) | 0.005 | (0.005) | 0.002 | (0.005) | 0.005 | (0.010) | 0.011 | (0.041) |
| | Spring | 7 | (21) | 0.005 | (0.005) | 0.002 | (0.004) | 0.002 | (0.004) | 0.005 | (0.008) |
| | Fall | 6 | (23) | 0.005 | (0.005) | 0.002 | (0.005) | 0.002 | (0.012) | 0.005 | (0.055) |

**Table 28:** Descriptive statistics (minimum, median, average, and maximum) for $NO_3$-N measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection limits for $NO_3$-N were <0.005 mg/L.

| Location | Season | $NO_3N$ (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Winter | 6 | (16) | 0.027 | (0.012) | 0.043 | (0.035) | 0.045 | (0.034) | 0.058 | (0.054) |
| | Summer | 7 | (15) | 0.006 | (0.014) | 0.019 | (0.026) | 0.018 | (0.026) | 0.027 | (0.048) |
| | Spring | 6 | (12) | 0.005 | (0.005) | 0.005 | (0.023) | 0.012 | (0.032) | 0.043 | (0.105) |
| | Fall | 7 | (14) | 0.005 | (0.005) | 0.002 | (0.010) | 0.008 | (0.011) | 0.028 | (0.016) |
| 102 | Winter | 6 | (NA) | 0.018 | - | 0.027 | - | 0.025 | - | 0.031 | - |
| | Summer | 7 | (NA) | 0.005 | - | 0.014 | - | 0.013 | - | 0.024 | - |
| | Spring | 6 | (NA) | 0.006 | - | 0.01 | - | 0.012 | - | 0.026 | - |
| | Fall | 7 | (NA) | 0.007 | - | 0.013 | - | 0.014 | - | 0.021 | - |
| 103A | Winter | 6 | (22) | 0.030 | (0.013) | 0.066 | (0.040) | 0.060 | (0.047) | 0.072 | (0.085) |
| | Summer | 7 | (24) | 0.005 | (0.017) | 0.024 | (0.031) | 0.023 | (0.035) | 0.048 | (0.071) |
| | Spring | 6 | (19) | 0.005 | (0.007) | 0.017 | (0.041) | 0.026 | (0.046) | 0.076 | (0.115) |
| | Fall | 7 | (24) | 0.005 | (0.005) | 0.014 | (0.009) | 0.015 | (0.012) | 0.041 | (0.030) |
| 107A | Winter | 6 | (22) | 0.031 | (0.011) | 0.037 | (0.038) | 0.044 | (0.039) | 0.070 | (0.106) |
| | Summer | 7 | (24) | 0.005 | (0.005) | 0.01 | (0.019) | 0.015 | (0.024) | 0.048 | (0.090) |
| | Spring | 6 | (19) | 0.005 | (0.005) | 0.002 | (0.030) | 0.013 | (0.039) | 0.050 | (0.132) |
| | Fall | 7 | (24) | 0.005 | (0.005) | 0.006 | (0.014) | 0.008 | (0.020) | 0.023 | (0.109) |
| 108 | Winter | 6 | (22) | 0.030 | (0.012) | 0.068 | (0.046) | 0.061 | (0.047) | 0.078 | (0.113) |
| | Summer | 7 | (24) | 0.005 | (0.014) | 0.023 | (0.035) | 0.024 | (0.034) | 0.054 | (0.082) |
| | Spring | 6 | (20) | 0.008 | (0.01) | 0.014 | (0.050) | 0.024 | (0.049) | 0.069 | (0.122) |
| | Fall | 7 | (24) | 0.007 | (0.005) | 0.012 | (0.011) | 0.016 | (0.014) | 0.034 | (0.041) |
| 121 | Winter | 6 | (20) | 0.054 | (0.006) | 0.079 | (0.033) | 0.077 | (0.048) | 0.092 | (0.154) |
| | Summer | 7 | (22) | 0.005 | (0.005) | 0.002 | (0.010) | 0.004 | (0.021) | 0.008 | (0.092) |
| | Spring | 6 | (21) | 0.005 | (0.005) | 0.004 | (0.009) | 0.013 | (0.018) | 0.053 | (0.120) |
| | Fall | 7 | (26) | 0.005 | (0.005) | 0.012 | (0.007) | 0.018 | (0.016) | 0.043 | (0.087) |

#### *3.2.5.1.3 Total Kjeldahl Nitrogen*

Total Kjeldahl Nitrogen (TKN) concentrations in Quabbin Reservoir Watershed Core tributary sites ranged from 0.047 to 0.466 mg/L in 2021 (Table 29). TKN concentrations in Ware River Watershed Core tributary sites ranged from 0.092 to 0.563 mg/L during 2021 (Table 30). TKN concentrations observed in Quabbin Reservoir Watershed tributaries in 2021 were within historical seasonal ranges (Figure 20, Figure 21). TKN concentrations in 2021 exceeded historical seasonal maximums for site 101 in the Ware River Watershed in samples (n=3) following precipitation events that occurred in the fall (e.g., Hurricane Ida in September) and spring (March and May). TKN concentrations measured in 2021 in most Core tributaries in the Quabbin Reservoir and Ware River Watersheds fell within established ranges for local ecoregional background concentrations (0.1 – 0.3 mg/L; Appendix A), except for sites with a greater percentage of wetland cover or immediately downstream of a wetland (e.g., 215G, 107A, and 121).

TKN dynamics in Core tributaries in the Quabbin Reservoir and Ware River Watersheds loosely mirrored that of TP and organic content (Figure 20, Figure 21), with relative enrichment during summer (Section 3.2.6). Similar to patterns presented by biweekly concentrations of other N-species in 2021, TKN concentrations exhibited considerable variability for select Core sites within seasons. Organic nitrogen (TKN – NH3-N) was the most abundant nitrogen form in Core tributaries in either watershed in 2021. Dominance of organic nitrogen in headwater streams in the US has been documented previously (Scott et al., 2007). Notably, the fraction of total nitrogen comprised of organic nitrogen did not increase ubiquitously with hydrologic events (Figure 22, Figure 23) across sites, suggesting that the increase in TN during high flows is driven predominantly by increases in inorganic N-species (namely, NO3-N and NH3-N), and that these relationships may be both site-specific and dependent on event characteristics. This is further corroborated by observed patterns in concentrations of in-stream inorganic N-forms during 2021. These relationships were elucidated more clearly in 2020 and 2021 relative to prior years, in part due to the increased monitoring frequency of all N-forms for both watersheds.

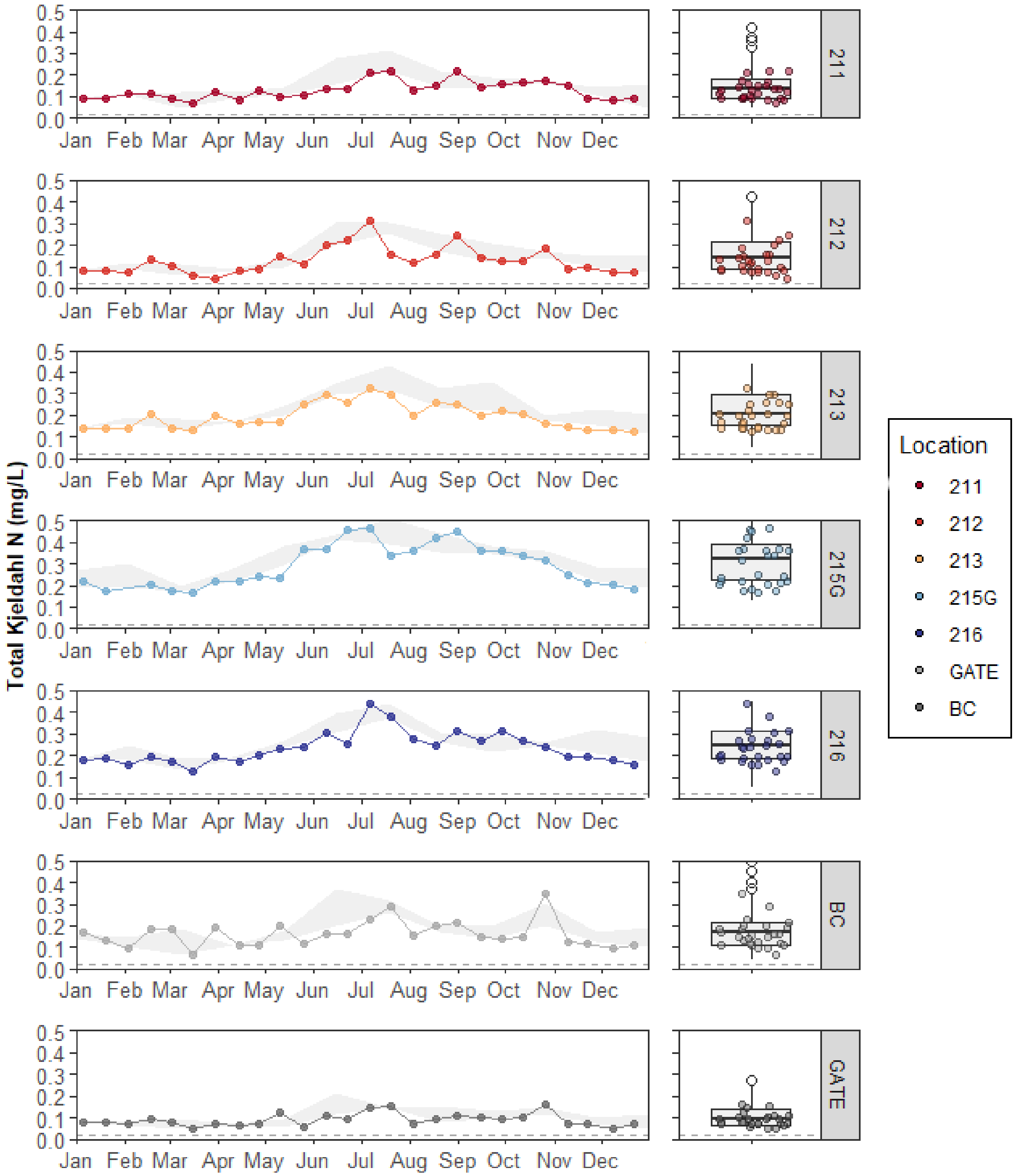



**Figure 20:** Time series and boxplots of TKN measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey line corresponds to laboratory detection limits (0.2 mg/L).

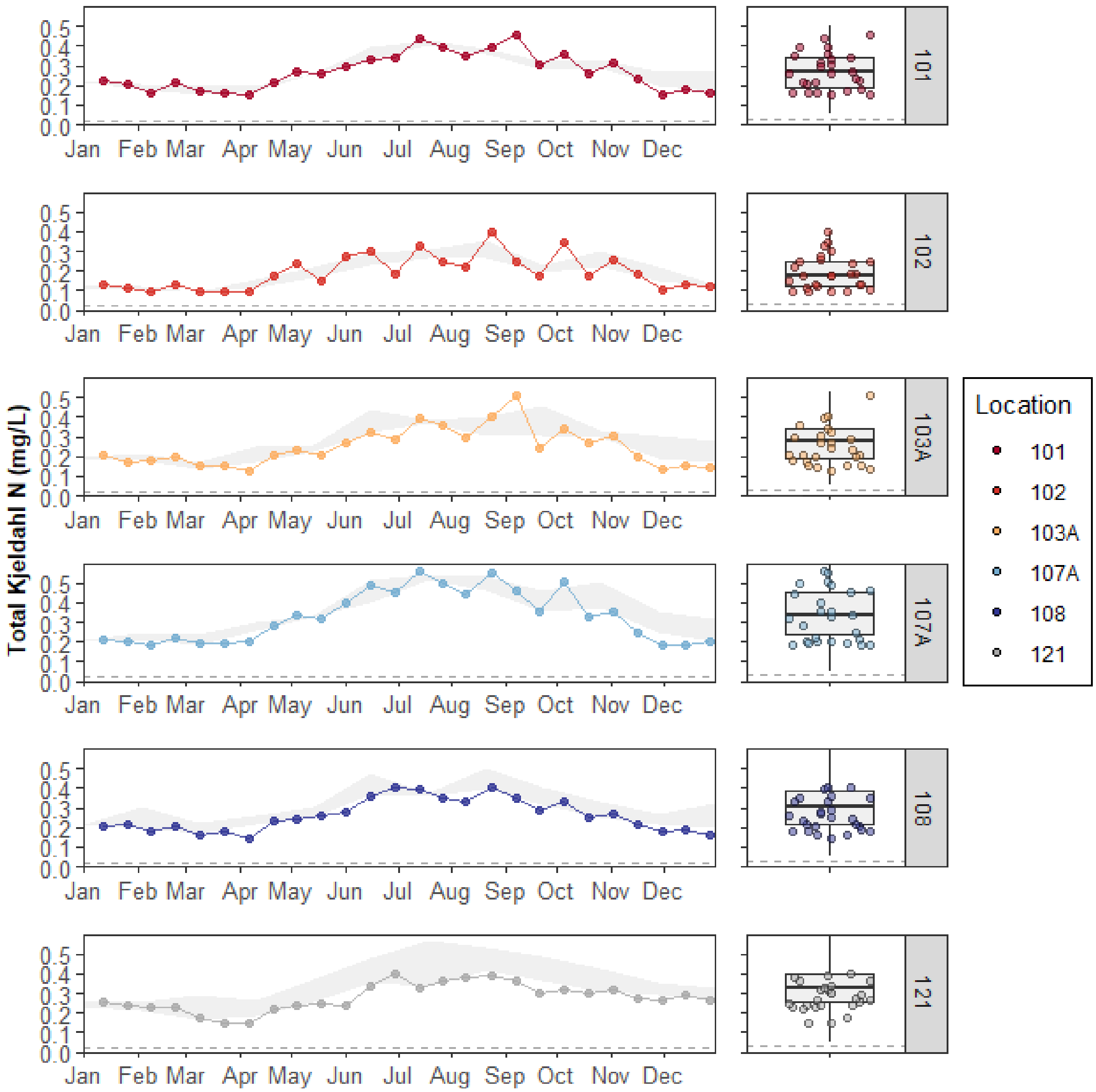



**Figure 21:** Time series and boxplots of TKN measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey line corresponds to laboratory detection limits (0.2 mg/L).

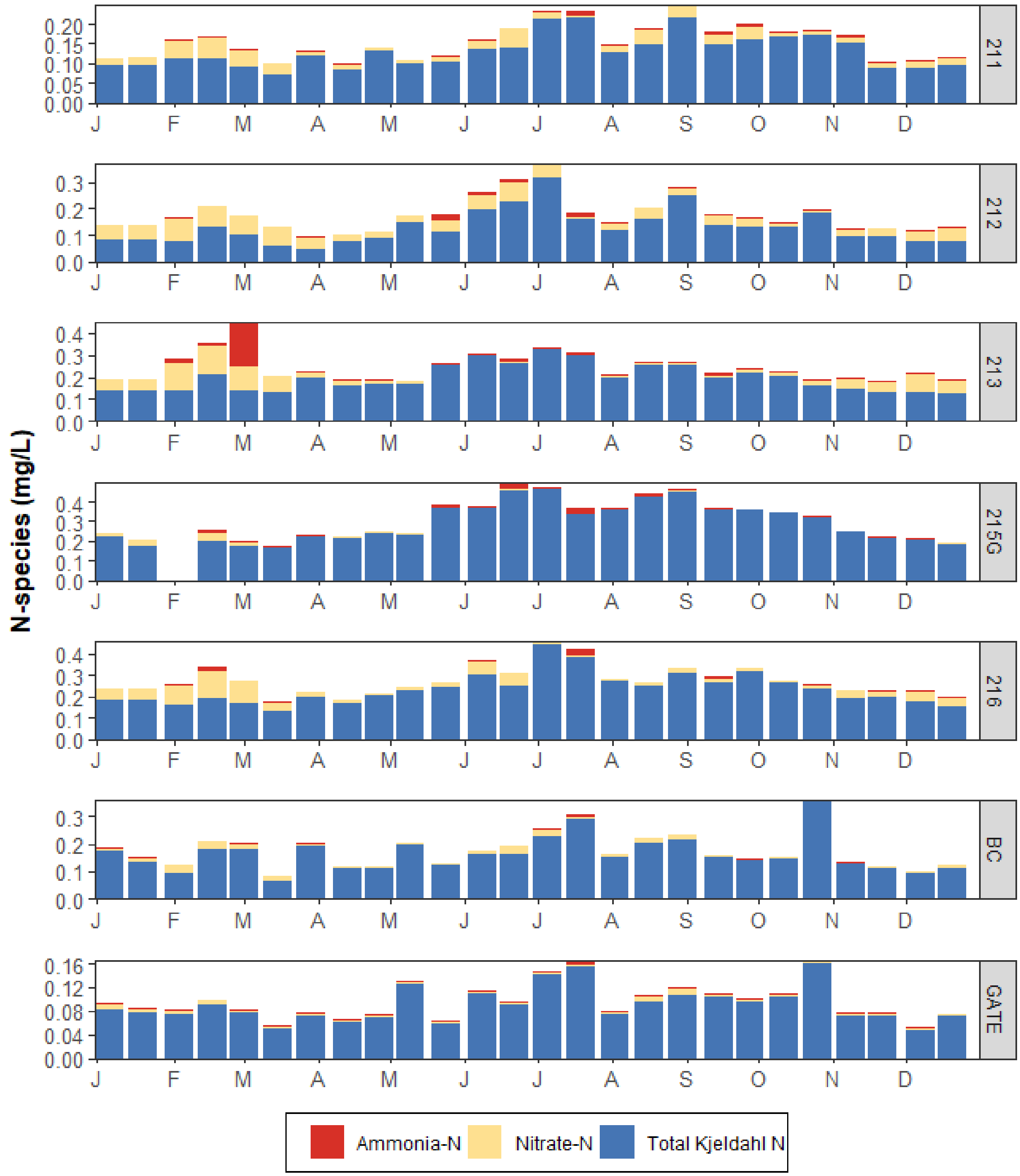



**Figure 22:** Bar plots depicting the temporal distributions of nitrogen species observed in Quabbin Reservoir Watershed Core tributary sites during 2021.

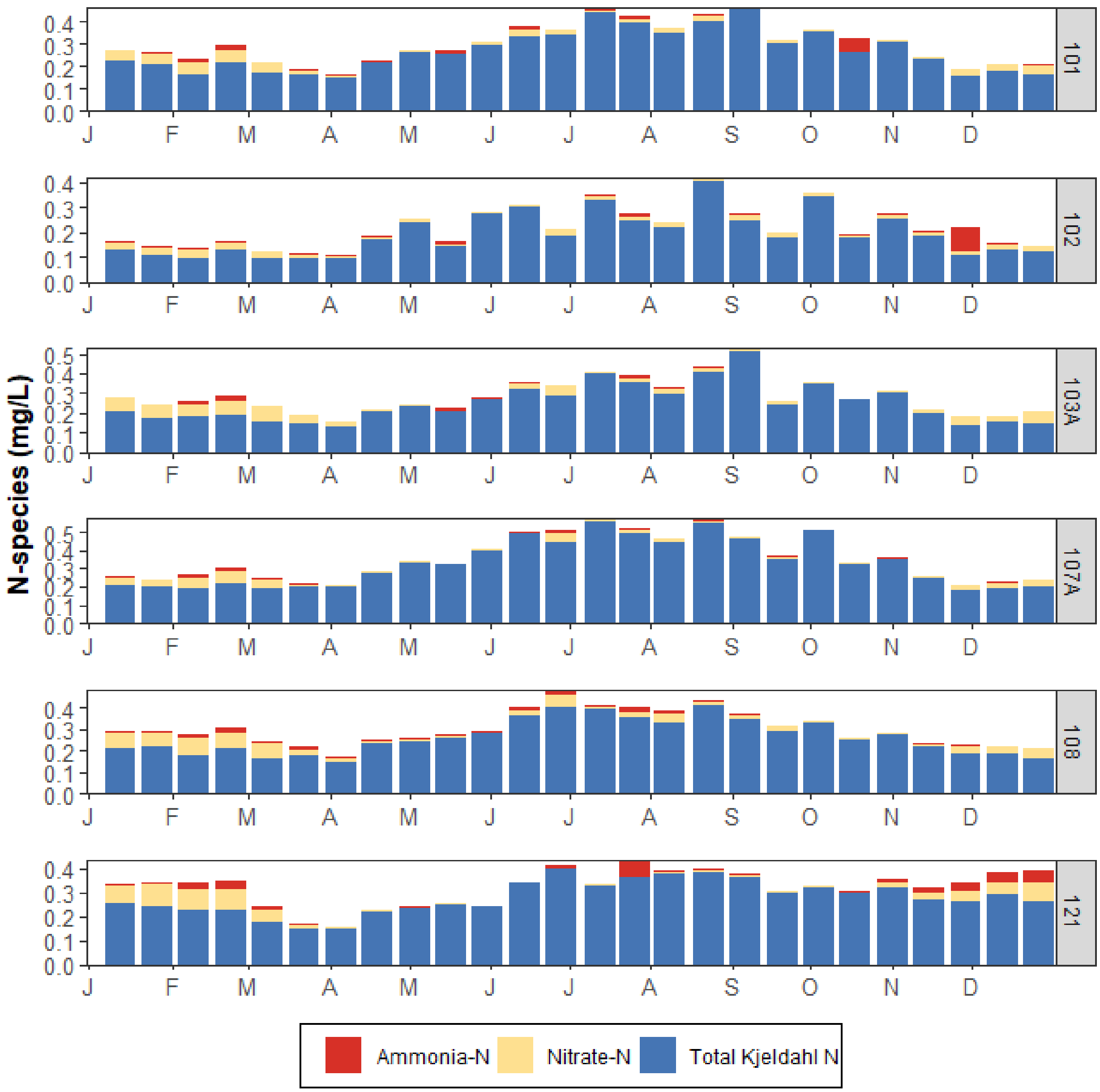



**Figure 23:** Bar plots depicting the temporal distributions of nitrogen species observed in Ware River Watershed Core tributary sites during 2021.

**Table 29:** Descriptive statistics (minimum, median, average, and maximum) for TKN measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection limits for TKN were 0.100 mg/L prior to 2020.

| Location | Season | TKN (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Winter | 6 | (14) | 0.087 | (0.050) | (0.100) | 0.094 | 0.098 | (0.110) | 0.112 | (0.208) |
| | Summer | 7 | (18) | 0.126 | (0.077) | (0.234) | 0.148 | 0.171 | (0.231) | 0.218 | (0.417) |
| | Spring | 7 | (16) | 0.071 | (0.050) | (0.080) | 0.101 | 0.100 | (0.099) | 0.131 | (0.331) |
| | Fall | 6 | (17) | 0.088 | (0.050) | (0.144) | 0.155 | 0.147 | (0.152) | 0.172 | (0.215) |
| 212 | Winter | 6 | (13) | 0.074 | (0.050) | (0.111) | 0.078 | 0.087 | (0.133) | 0.131 | (0.339) |
| | Summer | 7 | (17) | 0.117 | (0.175) | (0.256) | 0.199 | 0.202 | (0.257) | 0.314 | (0.396) |
| | Spring | 7 | (16) | 0.047 | (0.037) | (0.090) | 0.091 | 0.092 | (0.138) | 0.150 | (0.421) |
| | Fall | 6 | (17) | 0.093 | (0.050) | (0.156) | 0.128 | 0.128 | (0.160) | 0.183 | (0.258) |
| 213 | Winter | 6 | (14) | 0.126 | (0.050) | (0.165) | 0.138 | 0.147 | (0.166) | 0.208 | (0.266) |
| | Summer | 7 | (16) | 0.199 | (0.225) | (0.329) | 0.262 | 0.270 | (0.338) | 0.326 | (0.440) |
| | Spring | 7 | (16) | 0.129 | (0.050) | (0.166) | 0.169 | 0.175 | (0.170) | 0.253 | (0.283) |
| | Fall | 6 | (17) | 0.133 | (0.146) | (0.247) | 0.180 | 0.178 | (0.277) | 0.222 | (0.408) |
| 215G | Winter | 5 | (11) | 0.178 | (0.127) | (0.261) | 0.202 | 0.198 | (0.262) | 0.221 | (0.392) |
| | Summer | 7 | (13) | 0.337 | (0.321) | (0.421) | 0.421 | 0.409 | (0.426) | 0.466 | (0.567) |
| | Spring | 7 | (11) | 0.163 | (0.172) | (0.272) | 0.219 | 0.23 | (0.316) | 0.366 | (0.566) |
| | Fall | 6 | (13) | 0.215 | (0.191) | (0.339) | 0.330 | 0.306 | (0.370) | 0.359 | (0.713) |
| 216 | Winter | 6 | (14) | 0.156 | (0.110) | (0.265) | 0.178 | 0.175 | (0.251) | 0.195 | (0.337) |
| | Summer | 7 | (16) | 0.248 | (0.169) | (0.360) | 0.302 | 0.315 | (0.353) | 0.440 | (0.448) |
| | Spring | 7 | (16) | 0.129 | (0.050) | (0.168) | 0.196 | 0.192 | (0.190) | 0.242 | (0.41) |
| | Fall | 6 | (17) | 0.195 | (0.151) | (0.260) | 0.251 | 0.246 | (0.265) | 0.317 | (0.415) |
| BC | Winter | 6 | (14) | 0.093 | (0.050) | (0.178) | 0.121 | 0.131 | (0.165) | 0.182 | (0.259) |
| | Summer | 7 | (14) | 0.153 | (0.148) | (0.255) | 0.202 | 0.202 | (0.296) | 0.292 | (0.538) |
| | Spring | 7 | (16) | 0.067 | (0.042) | (0.123) | 0.121 | 0.140 | (0.131) | 0.199 | (0.242) |
| | Fall | 6 | (14) | 0.114 | (0.050) | (0.168) | 0.142 | 0.172 | (0.195) | 0.352 | (0.450) |
| GATE | Winter | 6 | (14) | 0.048 | (0.050) | (0.064) | 0.074 | 0.073 | (0.088) | 0.091 | (0.244) |
| | Summer | 7 | (15) | 0.074 | (0.047) | (0.145) | 0.106 | 0.110 | (0.184) | 0.155 | (0.592) |
| | Spring | 7 | (16) | 0.050 | (0.050) | (0.074) | 0.070 | 0.074 | (0.080) | 0.126 | (0.188) |
| | Fall | 6 | (16) | 0.071 | (0.050) | (0.110) | 0.099 | 0.101 | (0.109) | 0.161 | (0.199) |

**Table 30:** Descriptive statistics (minimum, median, average, and maximum) for TKN measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection limits for TKN were 0.100 mg/L until 2020.

| Location | Season | TKN (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Winter | 6 | (9) | 0.162 | (0.139) | 0.197 | (0.232) | 0.195 | (0.253) | 0.229 | (0.391) |
| | Summer | 7 | (8) | 0.294 | (0.269) | 0.348 | (0.380) | 0.365 | (0.378) | 0.440 | (0.500) |
| | Spring | 6 | (8) | 0.152 | (0.050) | 0.195 | (0.190) | 0.205 | (0.181) | 0.266 | (0.222) |
| | Fall | 7 | (7) | 0.157 | (0.132) | 0.303 | (0.281) | 0.297 | (0.274) | 0.459 | (0.399) |
| 102 | Winter | 6 | (0) | 0.096 | - | 0.124 | - | 0.119 | - | 0.131 | - |
| | Summer | 7 | (0) | 0.187 | - | 0.277 | - | 0.280 | - | 0.404 | - |
| | Spring | 6 | (0) | 0.092 | - | 0.120 | - | 0.140 | - | 0.242 | - |
| | Fall | 7 | (0) | 0.107 | - | 0.183 | - | 0.213 | - | 0.343 | - |
| 103A | Winter | 6 | (15) | 0.147 | (0.129) | 0.175 | (0.208) | 0.175 | (0.231) | 0.207 | (0.391) |
| | Summer | 7 | (16) | 0.269 | (0.260) | 0.322 | (0.380) | 0.333 | (0.421) | 0.405 | (0.971) |
| | Spring | 6 | (15) | 0.130 | (0.050) | 0.181 | (0.168) | 0.181 | (0.188) | 0.234 | (0.386) |
| | Fall | 7 | (17) | 0.137 | (0.155) | 0.265 | (0.325) | 0.286 | (0.355) | 0.513 | (0.670) |
| 107A | Winter | 6 | (15) | 0.188 | (0.122) | 0.20 | (0.261) | 0.201 | (0.280) | 0.217 | (0.526) |
| | Summer | 7 | (16) | 0.401 | (0.332) | 0.490 | (0.474) | 0.484 | (0.492) | 0.563 | (0.926) |
| | Spring | 6 | (15) | 0.192 | (0.050) | 0.240 | (0.240) | 0.253 | (0.236) | 0.334 | (0.339) |
| | Fall | 7 | (17) | 0.185 | (0.239) | 0.352 | (0.385) | 0.349 | (0.391) | 0.511 | (0.519) |
| 108 | Winter | 6 | (15) | 0.164 | (0.101) | 0.196 | (0.276) | 0.193 | (0.271) | 0.217 | (0.383) |
| | Summer | 7 | (16) | 0.281 | (0.284) | 0.362 | (0.462) | 0.361 | (0.457) | 0.408 | (0.590) |
| | Spring | 6 | (16) | 0.148 | (0.050) | 0.207 | (0.222) | 0.204 | (0.225) | 0.258 | (0.359) |
| | Fall | 7 | (17) | 0.182 | (0.189) | 0.274 | (0.338) | 0.270 | (0.352) | 0.348 | (0.498) |
| 121 | Winter | 6 | (20) | 0.225 | (0.080) | 0.247 | (0.253) | 0.250 | (0.283) | 0.289 | (0.644) |
| | Summer | 7 | (21) | 0.238 | (0.050) | 0.362 | (0.487) | 0.348 | (0.558) | 0.399 | (2.040) |
| | Spring | 6 | (21) | 0.149 | (0.120) | 0.200 | (0.292) | 0.197 | (0.286) | 0.250 | (0.398) |
| | Fall | 7 | (25) | 0.263 | (0.253) | 0.299 | (0.366) | 0.304 | (0.398) | 0.361 | (0.591) |

#### *3.2.5.2 Total Phosphorus*

Total phosphorus (TP) concentrations measured in Core monitoring tributaries in the Quabbin Reservoir during 2021 ranged from <0.005 to 0.031 mg/L (Figure 24). TP concentrations were comparable to previously established seasonal ranges for all sites with a consistent monitoring record in 2021. Seasonal median TP concentrations of TP were typically less than those of the period of record. Concentrations of TP in Core tributaries in the Quabbin Reservoir Watershed exhibited typical season dynamics (e.g., enrichment in summer/fall and relative depletion during winter/spring) observed previously (DWSP, 2020a). Relative site-to-site variability was consistent with prior monitoring periods, although variable concentration-discharge relationships existed across sites. TP concentrations in Core tributary monitoring locations in the Quabbin Reservoir Watershed exceeded EPA ecoregional background TP concentrations for Region VIII - Subregion 58 and Region XIV - Subregion 59 (0.012 mg/L and 0.024 mg/L) on select dates during 2021.

In the Ware River Watershed, TP concentrations were between 0.006 to 0.038 mg/L in 2021 (Figure 25). Similar to patterns observed in the Quabbin Reservoir Watershed during 2021, TP concentrations were comparable to seasonal medians for the period of record at all sites and during all seasons in 2021. EPA ecoregional background TP concentrations for Region VIII - Subregion 58 and Region XIV - Subregion 59 (0.012 mg/L and 0.024 mg/L) were exceeded by Core tributaries in the Ware River Watershed for much of 2021.

TP concentrations exhibited distinct seasonality for select Core sites in both watersheds (Figure 24, Figure 25). In tributaries in the Quabbin Reservoir Watershed and Ware River Watershed, TP concentrations were greatest during the summer and fall and comparatively lower during the spring and winter, behavior consistent with other forested headwater catchments in the NE USA (Lisboa et al., 2016). The observed gradient in TP concentrations across Quabbin Reservoir and Ware River Watersheds may be partially attributed to variations in land cover, wetland connectivity, groundwater contributions, and timing of sample collection relative to large hydrometeorological events (Reddy et al., 1999; Lisboa et al., 2016). Precipitation events in March and October 2021 resulted in observable peaks in stream TP concentrations in Core tributaries (Figure 24, Figure 25). Whereas, TP concentrations in Core tributaries in the Quabbin Reservoir Watershed decreased below seasonal normals following precipitation events in June and July 2021. The mixed response of observed TP concentrations in response to variable antecedent wetness and temperature regimes highlights the complexities of process-driven loading of TP to Quabbin Reservoir (Morris et al. 2014, Lisboa et al., 2016). The biweekly monitoring of TP in 2021 allowed for observation of these relationships.

Analytical methods for TP in Core and EQA site in Quabbin Reservoir and Ware River Watersheds were modified in 2020. TP concentration data for Quabbin Reservoir and Ware River Watershed tributaries were derived via EPA Method 365.1 (O'Dell, 1993b) until January 01, 2020. Analysis was performed via Valderrama (1981) thereafter to facilitate biweekly monitoring frequencies of TP in Core tributaries in Quabbin Reservoir and Ware River Watersheds. 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.

**Table 31:** Descriptive statistics (minimum, median, average, and maximum) for TP measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection limits for TP were 0.005 mg/L.

| Location | Season | TP (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Winter | 6 | (14) | 0.005 | (0.005) | 0.007 | (0.01) | 0.008 | (0.011) | 0.015 | (0.018) |
| | Summer | 7 | (18) | 0.006 | (0.01) | 0.012 | (0.015) | 0.012 | (0.016) | 0.017 | (0.038) |
| | Spring | 7 | (16) | 0.009 | (0.005) | 0.011 | (0.012) | 0.011 | (0.013) | 0.014 | (0.028) |
| | Fall | 6 | (19) | 0.007 | (0.005) | 0.009 | (0.013) | 0.010 | (0.012) | 0.015 | (0.022) |
| 212 | Winter | 6 | (13) | 0.006 | (0.007) | 0.009 | (0.011) | 0.010 | (0.012) | 0.019 | (0.022) |
| | Summer | 7 | (17) | 0.011 | (0.015) | 0.016 | (0.021) | 0.016 | (0.025) | 0.023 | (0.056) |
| | Spring | 7 | (16) | 0.010 | (0.005) | 0.014 | (0.014) | 0.013 | (0.016) | 0.016 | (0.059) |
| | Fall | 6 | (19) | 0.011 | (0.005) | 0.012 | (0.014) | 0.016 | (0.015) | 0.027 | (0.034) |
| 213 | Winter | 6 | (14) | 0.006 | (0.008) | 0.009 | (0.012) | 0.011 | (0.012) | 0.018 | (0.016) |
| | Summer | 7 | (17) | 0.008 | (0.020) | 0.018 | (0.022) | 0.017 | (0.024) | 0.022 | (0.039) |
| | Spring | 7 | (16) | 0.012 | (0.005) | 0.014 | (0.014) | 0.014 | (0.014) | 0.018 | (0.024) |
| | Fall | 6 | (19) | 0.009 | (0.008) | 0.012 | (0.016) | 0.013 | (0.016) | 0.018 | (0.023) |
| 215G | Winter | 5 | (11) | 0.008 | (0.007) | 0.010 | (0.015) | 0.012 | (0.014) | 0.019 | (0.020) |
| | Summer | 7 | (13) | 0.011 | (0.016) | 0.021 | (0.020) | 0.020 | (0.022) | 0.025 | (0.028) |
| | Spring | 7 | (11) | 0.009 | (0.010) | 0.014 | (0.013) | 0.015 | (0.014) | 0.027 | (0.019) |
| | Fall | 6 | (13) | 0.009 | (0.012) | 0.014 | (0.018) | 0.015 | (0.017) | 0.02 | (0.02) |
| 216 | Winter | 6 | (14) | 0.009 | (0.008) | 0.011 | (0.015) | 0.012 | (0.015) | 0.02 | (0.021) |
| | Summer | 7 | (17) | 0.009 | (0.017) | 0.021 | (0.028) | 0.019 | (0.029) | 0.028 | (0.045) |
| | Spring | 7 | (16) | 0.011 | (0.007) | 0.016 | (0.015) | 0.015 | (0.017) | 0.017 | (0.060) |
| | Fall | 6 | (18) | 0.011 | (0.005) | 0.016 | (0.015) | 0.016 | (0.016) | 0.023 | (0.044) |
| BC | Winter | 6 | (14) | 0.007 | (0.009) | 0.013 | (0.013) | 0.014 | (0.016) | 0.026 | (0.031) |
| | Summer | 7 | (15) | 0.010 | (0.010) | 0.019 | (0.024) | 0.018 | (0.027) | 0.029 | (0.061) |
| | Spring | 7 | (16) | 0.012 | (0.007) | 0.017 | (0.019) | 0.019 | (0.019) | 0.029 | (0.031) |
| | Fall | 6 | (15) | 0.008 | (0.009) | 0.013 | (0.021) | 0.015 | (0.021) | 0.031 | (0.037) |
| GATE | Winter | 6 | (14) | 0.005 | (0.005) | 0.008 | (0.009) | 0.010 | (0.009) | 0.017 | (0.015) |
| | Summer | 7 | (16) | 0.005 | (0.009) | 0.011 | (0.016) | 0.012 | (0.016) | 0.019 | (0.038) |
| | Spring | 7 | (16) | 0.008 | (0.005) | 0.010 | (0.011) | 0.010 | (0.011) | 0.013 | (0.023) |
| | Fall | 6 | (17) | 0.006 | (0.005) | 0.009 | (0.012) | 0.011 | (0.014) | 0.022 | (0.025) |

**Table 32:** Descriptive statistics (minimum, median, average, and maximum) for TP measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Detection limits for TP were 0.005 mg/L.

| Location | Season | TP (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Winter | 6 | (9) | 0.009 | (0.011) | 0.013 | (0.017) | 0.014 | (0.017) | 0.021 | (0.026) |
| | Summer | 7 | (8) | 0.020 | (0.022) | 0.027 | (0.033) | 0.025 | (0.033) | 0.030 | (0.043) |
| | Spring | 6 | (8) | 0.008 | (0.007) | 0.011 | (0.015) | 0.012 | (0.015) | 0.021 | (0.022) |
| | Fall | 7 | (7) | 0.009 | (0.022) | 0.020 | (0.027) | 0.021 | (0.026) | 0.035 | (0.028) |
| 102 | Winter | 6 | (0) | 0.010 | - | 0.017 | - | 0.017 | - | 0.026 | - |
| | Summer | 7 | (0) | 0.022 | - | 0.028 | - | 0.029 | - | 0.038 | - |
| | Spring | 6 | (0) | 0.013 | - | 0.014 | - | 0.016 | - | 0.022 | - |
| | Fall | 7 | (0) | 0.014 | - | 0.028 | - | 0.025 | - | 0.033 | - |
| 103A | Winter | 6 | (15) | 0.008 | (0.010) | 0.011 | (0.016) | 0.012 | (0.016) | 0.018 | (0.029) |
| | Summer | 7 | (16) | 0.020 | (0.019) | 0.026 | (0.034) | 0.025 | (0.034) | 0.035 | (0.045) |
| | Spring | 6 | (15) | 0.008 | (0.007) | 0.010 | (0.013) | 0.010 | (0.014) | 0.015 | (0.026) |
| | Fall | 7 | (17) | 0.011 | (0.018) | 0.017 | (0.025) | 0.020 | (0.030) | 0.035 | (0.081) |
| 107A | Winter | 6 | (15) | 0.007 | (0.010) | 0.013 | (0.014) | 0.013 | (0.015) | 0.019 | (0.022) |
| | Summer | 7 | (16) | 0.020 | (0.018) | 0.027 | (0.032) | 0.026 | (0.034) | 0.032 | (0.057) |
| | Spring | 6 | (15) | 0.010 | (0.009) | 0.011 | (0.014) | 0.013 | (0.015) | 0.018 | (0.021) |
| | Fall | 7 | (17) | 0.010 | (0.014) | 0.019 | (0.024) | 0.019 | (0.026) | 0.025 | (0.044) |
| 108 | Winter | 6 | (15) | 0.006 | (0.007) | 0.010 | (0.012) | 0.011 | (0.015) | 0.018 | (0.034) |
| | Summer | 7 | (16) | 0.016 | (0.019) | 0.022 | (0.031) | 0.020 | (0.031) | 0.024 | (0.049) |
| | Spring | 6 | (16) | 0.008 | (0.008) | 0.008 | (0.014) | 0.010 | (0.013) | 0.013 | (0.020) |
| | Fall | 7 | (17) | 0.008 | (0.011) | 0.017 | (0.026) | 0.015 | (0.025) | 0.020 | (0.037) |
| 121 | Winter | 6 | (20) | 0.008 | (0.007) | 0.012 | (0.013) | 0.012 | (0.012) | 0.018 | (0.020) |
| | Summer | 7 | (23) | 0.015 | (0.021) | 0.018 | (0.034) | 0.019 | (0.034) | 0.024 | (0.056) |
| | Spring | 6 | (22) | 0.007 | (0.009) | 0.009 | (0.017) | 0.010 | (0.018) | 0.015 | (0.036) |
| | Fall | 7 | (26) | 0.014 | (0.013) | 0.015 | (0.022) | 0.016 | (0.025) | 0.019 | (0.056) |

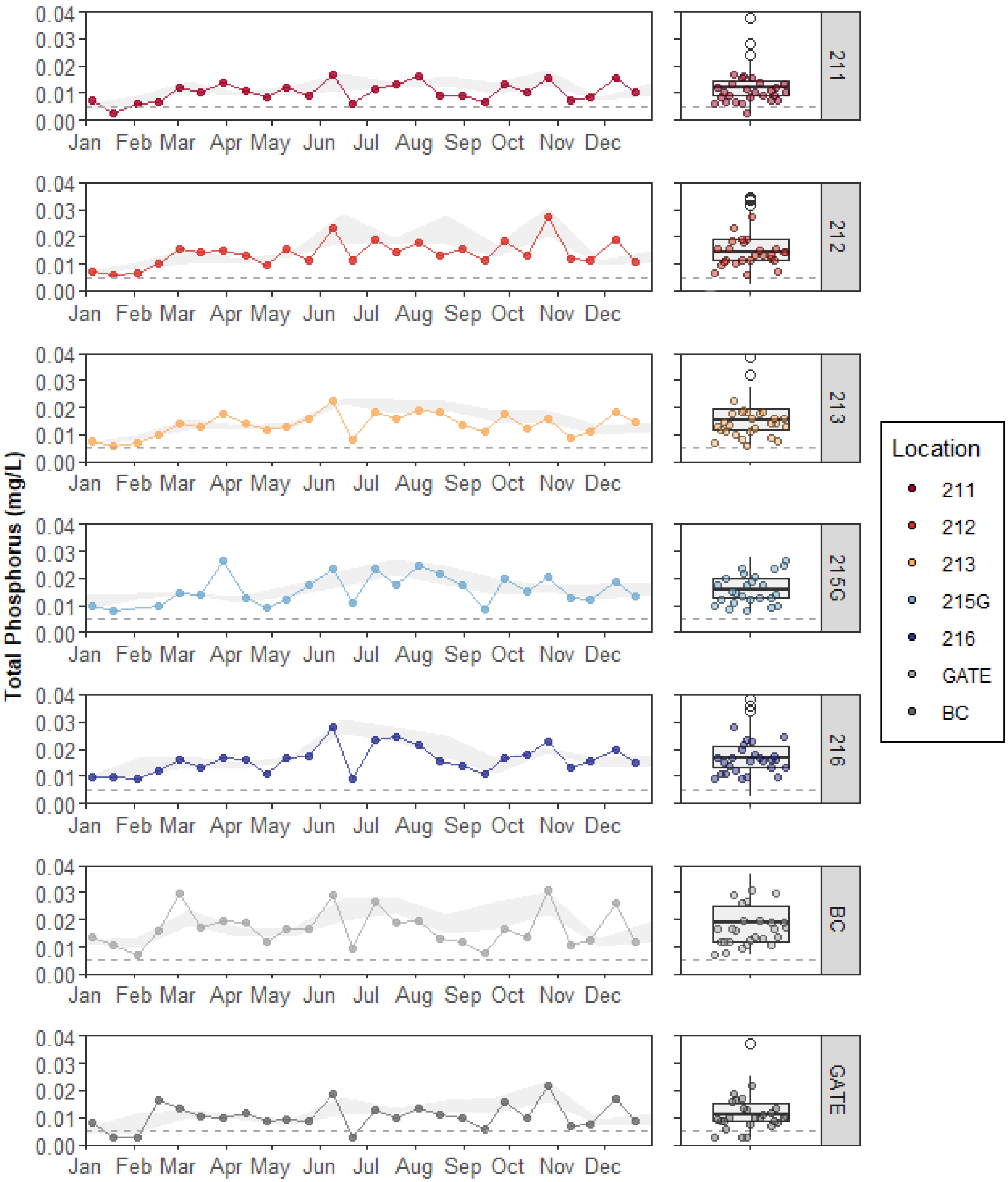



**Figure 24:** Time series and boxplots of TP measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey line corresponds to laboratory detection limits (0.005 mg/L).

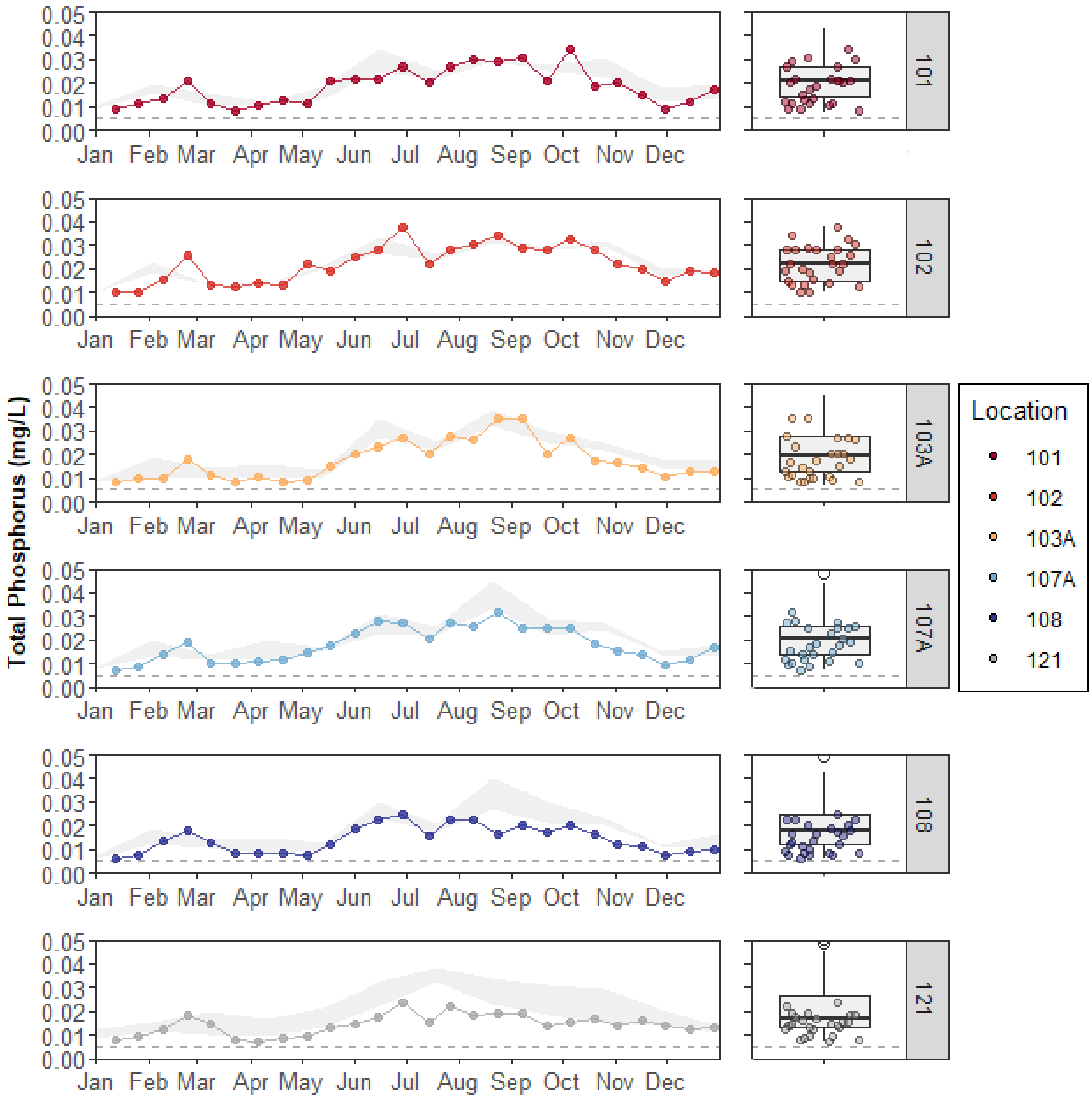



**Figure 25:** Time series and boxplots of TP measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey line corresponds to laboratory detection limits (0.005 mg/L).

## 3.2.6 Total Organic Carbon and $UV_{254}$

### *3.2.6.1 Total Organic Carbon*

Total organic carbon (TOC) was introduced to DWSP monitoring programs in 2021 as an additional proxy for understanding disinfection-byproduct precursor potential of source waters in the Quabbin Reservoir Watershed (Golea et al., 2017). TOC was monitored biweekly in Core tributaries in the Quabbin Reservoir Watershed beginning in January 2021. TOC was not measured in Ware River Watershed tributaries during 2021. Concentrations of TOC in Core tributaries in the Quabbin Reservoir Watershed ranged from 1.61 to 13.2 mg/L in 2021. TOC was elevated during the summer and fall months at each site, with seasonality most pronounced at sites 216 and 215G in the northeastern region of the watershed (Table 33), consistent with spatial gradients established several decades prior (Garvey and Tobiason, 2003). Maximum annual TOC concentrations at several locations occurred during July 2021, coincident with peak seasonal streamflow. A large proportion of annual TOC export occurs during later summer and fall sampling, due to seasonal changes in temperature and streamflow (Clark et al., 2012), and during high flow events (Raymond and Saiers, 2010, Dhillon and Inamdar, 2013). Locations downstream of wetlands in Quabbin Reservoir Watershed (e.g., 215G and 216) generally had elevated TOC relative to locations with a lower proportion of wetland cover (e.g., GATE). Organic carbon export from catchments in the northern hemisphere has been linked to the proportion of the catchment that constitutes wetland land cover (Curtis 1998, Raymond and Saiers, 2010).

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

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

**Table 33:** Descriptive statistics (minimum, median, average, and maximum) for TOC in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021, the first year of routine TOC monitoring in tributary sites.

| Location | Season | TOC (mg/L) | | | | |
|---|---|---|---|---|---|---|
| | | n | Minimum | Median | Mean | Maximum |
| 211 | Spring | 7 | 2.13 | 2.73 | 2.79 | 3.78 |
| | Summer | 7 | 2.47 | 3.38 | 3.86 | 5.47 |
| | Fall | 6 | 3.25 | 3.71 | 4.20 | 6.15 |
| | Winter | 6 | 2.20 | 2.86 | 2.78 | 3.06 |
| 212 | Spring | 7 | 1.89 | 2.52 | 2.57 | 3.28 |
| | Summer | 7 | 3.12 | 3.54 | 3.99 | 5.88 |
| | Fall | 6 | 2.67 | 3.21 | 3.69 | 6.45 |
| | Winter | 6 | 1.61 | 2.29 | 2.32 | 2.82 |
| 213 | Spring | 7 | 2.65 | 3.40 | 3.66 | 5.00 |
| | Summer | 7 | 4.28 | 5.05 | 5.22 | 6.80 |
| | Fall | 6 | 3.49 | 4.62 | 4.41 | 5.33 |
| | Winter | 6 | 2.25 | 3.23 | 3.10 | 3.66 |
| 215G | Spring | 7 | 3.74 | 5.34 | 5.19 | 6.53 |
| | Summer | 6 | 7.51 | 9.10 | 8.83 | 10.00 |
| | Fall | 6 | 7.77 | 9.63 | 9.38 | 10.80 |
| | Winter | 5 | 4.99 | 5.90 | 5.78 | 6.33 |
| 216 | Spring | 7 | 3.60 | 4.63 | 4.61 | 5.80 |
| | Summer | 7 | 4.74 | 6.62 | 6.45 | 9.40 |
| | Fall | 6 | 5.56 | 6.99 | 6.91 | 7.94 |
| | Winter | 6 | 3.62 | 4.85 | 4.60 | 5.40 |
| GATE | Spring | 7 | 1.82 | 2.35 | 2.48 | 3.49 |
| | Summer | 7 | 1.77 | 2.85 | 2.89 | 4.41 |
| | Fall | 6 | 2.69 | 2.97 | 3.51 | 6.38 |
| | Winter | 6 | 1.77 | 2.56 | 2.42 | 2.81 |
| BC | Spring | 7 | 2.55 | 3.49 | 4.15 | 6.25 |
| | Summer | 7 | 2.69 | 3.82 | 4.47 | 7.93 |
| | Fall | 6 | 3.87 | 4.29 | 5.69 | 13.20 |
| | Winter | 6 | 2.44 | 4.19 | 4.02 | 5.26 |

#### *3.2.6.2 $UV_{254}$*

$UV_{254}$ absorbance in Quabbin Reservoir Watershed Core tributary monitoring sites ranged from 0.05 to 0.548 ABU/cm in 2021 (Table 34). $UV_{254}$ was lower in tributaries along the west arm of the Quabbin Reservoir and on Prescott Peninsula (e.g., GB, 211, 212) than those located within the northernmost reaches of the watershed (e.g., 213, 215G) or on the east arm (216). Seasonal dynamics in $UV_{254}$ absorbance measured in Core tributaries in the Quabbin Reservoir Watershed were comparable to that of the period of record for the majority of Core tributary monitoring sites in the watershed during 2021. The Core sites located along the east arm of the Quabbin Reservoir (215G and 216) demonstrated a greater deviation from historical seasonal medians during the summer and fall months when streamflow conditions were routinely above normal and several extreme precipitation events impacted the region (Section 3.1.1.2). Following high volume precipitation events in July, September, and October, $UV_{254}$ increased above 75th percentile seasonal values at select sites. Prior to 2020, $UV_{254}$ was measured quarterly in Quabbin Reservoir Watershed Core tributaries (DWSP, 2019a). Thus, some of the variability in $UV_{254}$ observed in 2021 relative to historical seasonal ranges may be attributed to differences in sample frequencies, with more frequent samples more likely to capture hydrologic-driven variability in stream $UV_{254}$ dynamics. Furthermore, deviations from the seasonal medians for each site for the periods of record may also be attributed to the distinct hydrologic conditions presented in 2021 (e.g., low flow through spring months followed by record-breaking precipitation totals in July).

$UV_{254}$ absorbance in Ware River Watershed Core tributary monitoring sites ranged from 0.083 to 0.828 ABU/cm in 2021 (Table 35). Median $UV_{254}$ in Core monitoring tributaries in the Ware River Watershed in 2021 trended near or below seasonal medians for the period across seasons for most Core sites. Monitoring frequency for $UV_{254}$ in Core tributaries in the Ware River Watershed did not change in 2021. $UV_{254}$ 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 2021 (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. biweekly) 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.

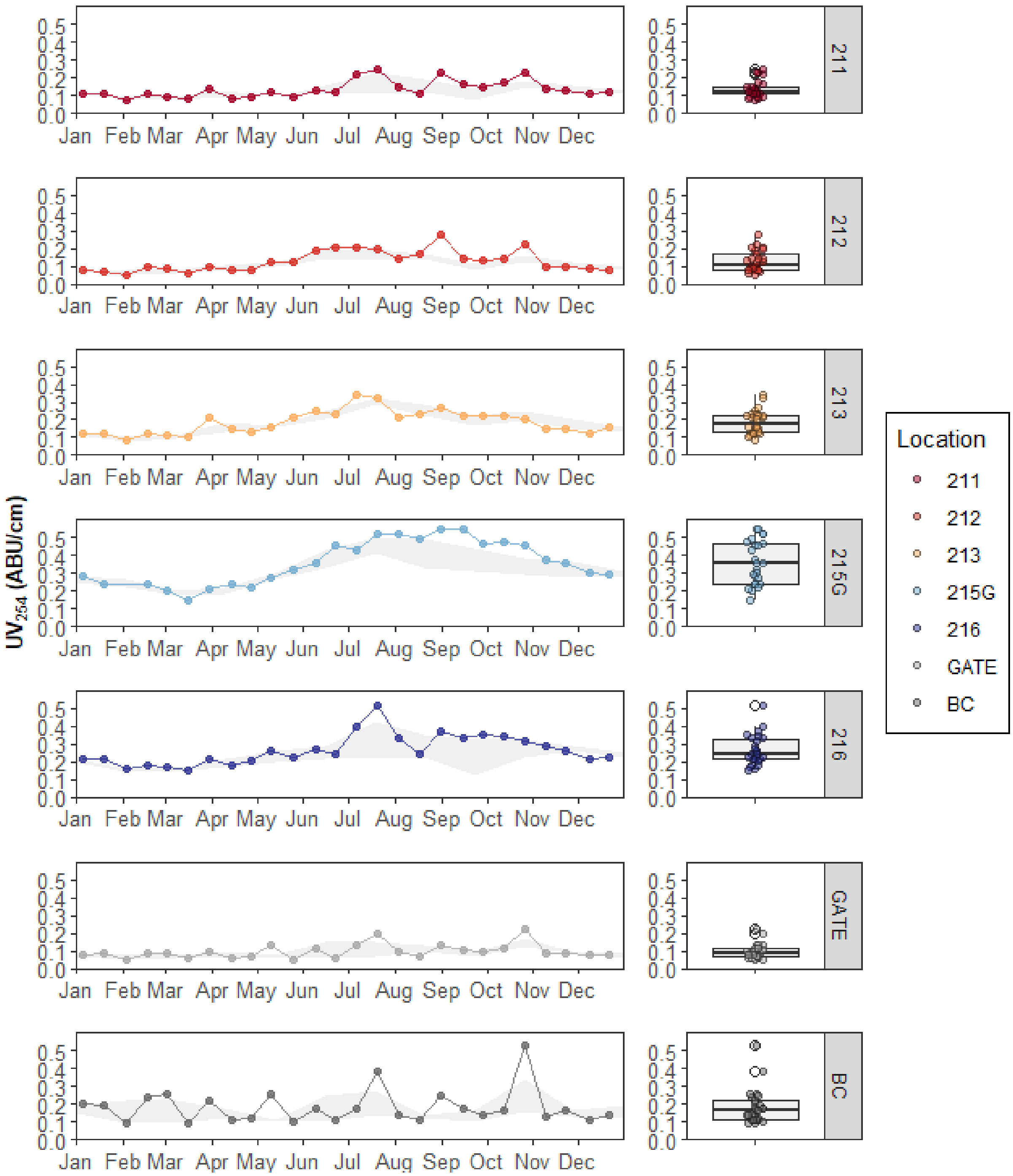



**Figure 26:** Time series and boxplots of $UV_{254}$ measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel.

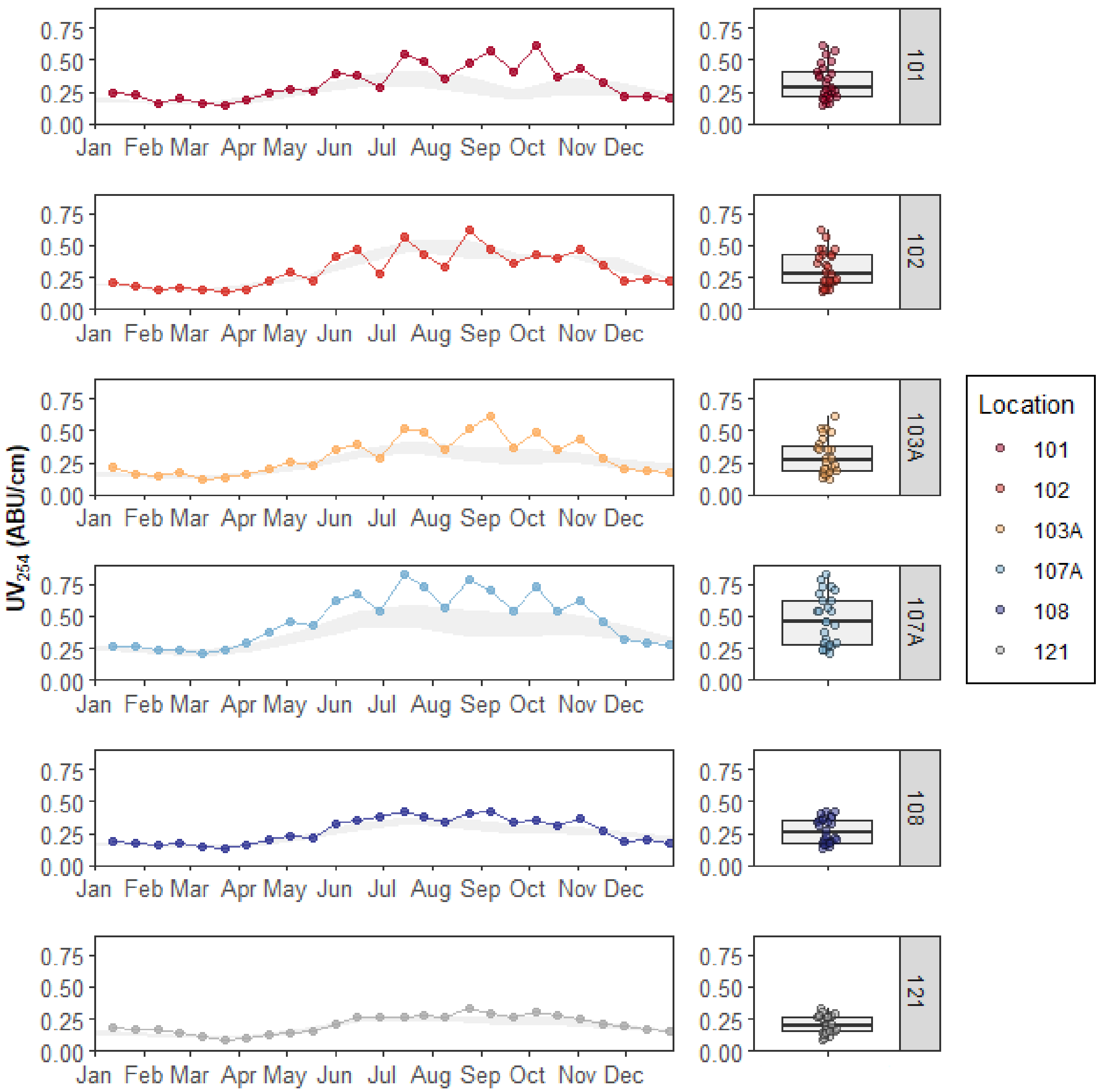



**Figure 27:** Time series and boxplots of $UV_{254}$ measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel.

**Table 34:** Descriptive statistics (minimum, median, average, and maximum) for $UV_{254}$ measured in Core tributary monitoring sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | $UV_{254}$ (ABU/cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Spring | 7 | (17) | 0.080 | (0.060) | 0.092 | (0.083) | 0.100 | (0.090) | 0.137 | (0.221) |
| | Summer | 7 | (19) | 0.108 | (0.076) | 0.147 | (0.120) | 0.170 | (0.150) | 0.244 | (0.390) |
| | Fall | 6 | (18) | 0.128 | (0.041) | 0.154 | (0.107) | 0.160 | (0.110) | 0.231 | (0.185) |
| | Winter | 6 | (16) | 0.074 | (0.066) | 0.108 | (0.115) | 0.100 | (0.120) | 0.117 | (0.159) |
| 212 | Spring | 7 | (17) | 0.059 | (0.048) | 0.086 | (0.068) | 0.090 | (0.080) | 0.124 | (0.157) |
| | Summer | 7 | (18) | 0.146 | (0.067) | 0.194 | (0.147) | 0.200 | (0.160) | 0.279 | (0.265) |
| | Fall | 6 | (18) | 0.100 | (0.052) | 0.138 | (0.096) | 0.140 | (0.100) | 0.223 | (0.170) |
| | Winter | 6 | (16) | 0.054 | (0.053) | 0.078 | (0.082) | 0.080 | (0.080) | 0.101 | (0.142) |
| 213 | Spring | 7 | (17) | 0.104 | (0.065) | 0.152 | (0.106) | 0.150 | (0.120) | 0.211 | (0.292) |
| | Summer | 7 | (19) | 0.211 | (0.182) | 0.254 | (0.238) | 0.270 | (0.260) | 0.337 | (0.546) |
| | Fall | 6 | (18) | 0.148 | (0.135) | 0.209 | (0.193) | 0.190 | (0.20) | 0.225 | (0.327) |
| | Winter | 6 | (16) | 0.084 | (0.072) | 0.124 | (0.137) | 0.120 | (0.140) | 0.157 | (0.227) |
| 215G | Spring | 7 | (11) | 0.151 | (0.132) | 0.219 | (0.210) | 0.230 | (0.220) | 0.320 | (0.304) |
| | Summer | 7 | (13) | 0.353 | (0.303) | 0.489 | (0.360) | 0.470 | (0.380) | 0.547 | (0.529) |
| | Fall | 6 | (13) | 0.360 | (0.253) | 0.457 | (0.296) | 0.440 | (0.310) | 0.548 | (0.447) |
| | Winter | 5 | (11) | 0.239 | (0.120) | 0.283 | (0.277) | 0.270 | (0.270) | 0.301 | (0.326) |
| 216 | Spring | 7 | (17) | 0.157 | (0.108) | 0.207 | (0.156) | 0.200 | (0.170) | 0.264 | (0.261) |
| | Summer | 7 | (19) | 0.241 | (0.121) | 0.340 | (0.256) | 0.340 | (0.270) | 0.520 | (0.495) |
| | Fall | 6 | (18) | 0.260 | (0.103) | 0.327 | (0.157) | 0.320 | (0.200) | 0.352 | (0.401) |
| | Winter | 6 | (16) | 0.161 | (0.130) | 0.217 | (0.237) | 0.200 | (0.230) | 0.225 | (0.308) |
| GATE | Spring | 7 | (17) | 0.053 | (0.046) | 0.070 | (0.062) | 0.080 | (0.070) | 0.132 | (0.156) |
| | Summer | 7 | (18) | 0.059 | (0.055) | 0.114 | (0.095) | 0.110 | (0.110) | 0.194 | (0.207) |
| | Fall | 6 | (17) | 0.086 | (0.062) | 0.103 | (0.083) | 0.120 | (0.090) | 0.225 | (0.151) |
| | Winter | 6 | (16) | 0.050 | (0.054) | 0.078 | (0.071) | 0.080 | (0.070) | 0.088 | (0.103) |
| BC | Spring | 7 | (17) | 0.092 | (0.080) | 0.123 | (0.104) | 0.170 | (0.150) | 0.258 | (0.358) |
| | Summer | 7 | (16) | 0.112 | (0.093) | 0.172 | (0.129) | 0.190 | (0.190) | 0.383 | (0.467) |
| | Fall | 6 | (14) | 0.134 | (0.080) | 0.166 | (0.146) | 0.220 | (0.170) | 0.535 | (0.426) |
| | Winter | 6 | (16) | 0.089 | (0.093) | 0.168 | (0.160) | 0.160 | (0.170) | 0.239 | (0.285) |

**Table 35:** Descriptive statistics (minimum, median, average, and maximum) for $UV_{254}$ measured in Core tributary monitoring sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses. Site 102 was added in 2021.

| Location | Season | $UV_{254}$ (ABU/cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Spring | 6 | (56) | 0.149 | (0.115) | 0.212 | (0.198) | 0.210 | (0.210) | 0.275 | (0.337) |
| | Summer | 7 | (59) | 0.292 | (0.167) | 0.397 | (0.314) | 0.420 | (0.330) | 0.548 | (0.599) |
| | Fall | 7 | (56) | 0.224 | (0.128) | 0.404 | (0.265) | 0.420 | (0.270) | 0.613 | (0.583) |
| | Winter | 6 | (60) | 0.168 | (0.119) | 0.215 | (0.197) | 0.210 | (0.200) | 0.240 | (0.398) |
| 102 | Spring | 6 | - | 0.144 | - | 0.189 | - | 0.200 | - | 0.287 | - |
| | Summer | 7 | - | 0.283 | - | 0.424 | - | 0.450 | - | 0.623 | - |
| | Fall | 7 | - | 0.229 | - | 0.406 | - | 0.390 | - | 0.471 | - |
| | Winter | 6 | - | 0.151 | - | 0.197 | - | 0.200 | - | 0.239 | - |
| 103A | Spring | 6 | (93) | 0.122 | (0.103) | 0.179 | (0.176) | 0.180 | (0.19) | 0.254 | (0.622) |
| | Summer | 7 | (101) | 0.289 | (0.208) | 0.394 | (0.339) | 0.420 | (0.340) | 0.516 | (0.587) |
| | Fall | 7 | (102) | 0.201 | (0.136) | 0.369 | (0.262) | 0.390 | (0.270) | 0.609 | (0.557) |
| | Winter | 6 | (78) | 0.150 | (0.103) | 0.177 | (0.183) | 0.180 | (0.190) | 0.217 | (0.384) |
| 107A | Spring | 6 | (97) | 0.210 | (0.070) | 0.328 | (0.267) | 0.330 | (0.280) | 0.454 | (0.484) |
| | Summer | 7 | (98) | 0.543 | (0.155) | 0.671 | (0.472) | 0.680 | (0.470) | 0.828 | (0.864) |
| | Fall | 7 | (101) | 0.313 | (0.164) | 0.541 | (0.395) | 0.560 | (0.400) | 0.724 | (0.772) |
| | Winter | 6 | (82) | 0.233 | (0.172) | 0.264 | (0.272) | 0.260 | (0.280) | 0.297 | (0.550) |
| 108 | Spring | 6 | (102) | 0.138 | (0.116) | 0.186 | (0.173) | 0.180 | (0.180) | 0.228 | (0.300) |
| | Summer | 7 | (100) | 0.328 | (0.204) | 0.376 | (0.322) | 0.370 | (0.330) | 0.426 | (0.579) |
| | Fall | 7 | (101) | 0.189 | (0.193) | 0.337 | (0.260) | 0.320 | (0.280) | 0.419 | (0.481) |
| | Winter | 6 | (97) | 0.165 | (0.119) | 0.175 | (0.178) | 0.180 | (0.180) | 0.201 | (0.312) |
| 121 | Spring | 6 | (22) | 0.083 | (0.029) | 0.115 | (0.130) | 0.120 | (0.140) | 0.152 | (0.209) |
| | Summer | 7 | (23) | 0.209 | (0.180) | 0.263 | (0.236) | 0.270 | (0.240) | 0.338 | (0.274) |
| | Fall | 7 | (26) | 0.190 | (0.139) | 0.269 | (0.201) | 0.260 | (0.200) | 0.312 | (0.270) |
| | Winter | 6 | (20) | 0.145 | (0.091) | 0.164 | (0.140) | 0.160 | (0.140) | 0.181 | (0.191) |

## 3.2.7 Calcium, Alkalinity, and pH

### *3.2.7.1 Calcium*

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

Ca concentrations in Quabbin Reservoir Watershed Core sites in 2021 ranged from 0.90 to 11.6 mg/L and were largely within historical ranges observed for each site (Appendix C). The 12 mg/L Ca threshold was not exceeded at any Core tributaries in the Quabbin Reservoir Watershed during 2021. In 2021, the 12 mg/L Ca threshold was exceeded at Boat Cove Brook in the Quabbin Reservoir Watershed in samples collected during the summer and fall months, although pH at this location was consistently below 7.4, thus this site remains at low risk for colonization by zebra mussels.

The range of Ca concentrations observed in Core monitoring tributaries in the Ware River Watershed was 2.09 to 14.4 mg/L Ca (Appendix C). Previously, the 12 mg/L Ca threshold was exceeded at site 121B (upstream of 121) in the Ware River Watershed throughout the year. In 2021, 12 mg/L Ca was exceeded in five samples collected across spring, summer, and winter months at 121.

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

#### *3.2.7.2 Alkalinity*

Alkalinity data from Core tributary monitoring sites in the Quabbin Reservoir Watershed and Ware River Watershed were compared to acid rain assessment criteria established under the Acid Rain Monitoring (ARM) Project at the University of Massachusetts. The ARM assessment criteria are used to evaluate the sensitivity of water bodies to acid deposition in MA. The ARM criteria are based on average results for the month of April (Godfrey et al., 1996). Surface waters with Average April alkalinity concentrations less than 5.0 mg/L are classified as Endangered with regard to sensitivity to acidification using the ARM criteria.

Alkalinity of Core monitoring tributaries in the Quabbin Reservoir Watershed ranged from <0.5 to 26.9 mg/L in 2021. Alkalinity in Core monitoring sites in the Ware River Watershed ranged from 2.27 to 16.3 mg/L. 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.

Concentrations of alkalinity measured in Core tributaries in the Quabbin Reservoir Watershed during 2021 were typically greater than seasonal medians for the period of record, oftentimes exceeding seasonal 75th percentile concentrations (Appendix C). The results of applying the ARM sensitivity classifications for alkalinity concentrations to samples collected in the spring of 2021 from Core tributaries within the Quabbin Reservoir Watershed suggests that sensitivity to acid deposition has improved relative to the period of record for several sites (namely, 211, 212, and 213), while falling within previous classifications for the remaining sites (215, 216, BC, and GB). With alkalinity concentrations of <2 mg/L in April 2021, sites 215G and GB fell within the most sensitive category (Critical), as outlined by Godfrey et al. (1996). The remaining sites were deemed less susceptible to the effects of acid deposition based on these criteria.

In the Ware River Watershed, alkalinity remained above 2 mg/L throughout the entirety of 2021. The majority of Core monitoring tributaries in the Ware River Watershed were within the sensitivity category indicative of surface waters that are endangered by acid deposition (alkalinity of 2-5 mg/L) established under the UMass ARM Project, with only alkalinity measured at site 121 routinely falling within the range of alkalinities corresponding to the Highly Sensitive category (alkalinity of 5-10 mg/L). The observed alkalinity concentration at site 103A in April 2021 resulted in a relative improvement in sensitivity classification for this site, compared to long-term averages (i.e., from Critical to Endangered). Sensitivity classifications for all other Core tributary monitoring sites in the Ware River Watershed during 2021 were consistent with that for the period of record.

#### *3.2.7.3 pH*

The pH in Core monitoring tributaries ranged from 4.1 to 7.53 in the Quabbin Reservoir Watershed in 2021. pH of Core tributaries in the Ware River Watershed spanned a comparable range in 2021, from a minimum of 5.18 to 6.91. MassDEP has established a recommended range of pH for the protection of aquatic life (6.5 – 8.3 SU and within 0.5 SU of the natural background range). Median pH values observed in Core monitoring tributaries in the Quabbin Reservoir Watershed typically approached or fell below the minimum established standards for Class A inland waters as established by MassDEP (6.5 to 8.3) in 2021, consistent with prior observations throughout the period of record (DWSP, 2020a). The same was observed in tributaries in the Ware River Watershed, although in both watersheds individual measurements of pH in 2021 exceeded the interquartile range for each site.

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

Median spring pH at Core tributary monitoring sites in the Quabbin Reservoir Watershed in 2021 was greater than that of the period of record across all sites with a consistent monitoring record (i.e., excluding 215G in the Quabbin Reservoir Watershed, and 102 and 121 in the Ware River Watershed). This may have been driven by below-normal streamflow conditions present during much of the spring months of 2021, and subsequent lack of low-pH rainfall inputs during this time.

### 3.2.8 Special Investigations

#### *3.2.8.1 Forestry Water Quality Monitoring*

##### *3.2.8.1.1 Long-term Forestry Monitoring*

Timber harvest in the treatment watershed (EBU) began on December 18, 2019 and was completed October 11, 2020, ending the calibration period of the long-term forestry monitoring study. Data from the calibration period is currently being analyzed and summarized for an upcoming report describing the pre-treatment relationship between watersheds. This reporting will serve as a basis for analyzing change during the post-treatment study period, beginning with data collected in late 2020 and into 2021.

##### *3.2.8.1.2 Short-term Forestry Monitoring*

The Environmental Quality Section reviewed forestry lot proposals, inspected sites, and updated the forestry water quality monitoring database in 2021. Field review of proposed DWSP timber lots was conducted in the Ware River and Quabbin Reservoir Watersheds. Post-harvest monitoring for turbidity occurred at one stream crossing in the Quabbin Reservoir Watershed in 2021 (Appendix B). No issues were identified in 2021.

#### *3.2.8.2 Environmental Quality Assessments*

##### *3.2.8.2.1 Quabbin Northwest Sanitary District*

Water quality in surface water in the Quabbin Northwest sanitary district in 2021 was generally comparable to that of previous monitoring periods, with some exceptions (DWSP, 2022b). Data collected in 2021 were compared to historical data for these locations.

Surface water samples collected in 2021 throughout the Quabbin Northwest sanitary district ultimately revealed no widespread indicators of impairment/degradation of water quality. Monitoring of EQA sites in the Quabbin Reservoir Watershed will shift to sites in the Fever Brook sanitary district in 2022. Monitoring of tributaries in the Quabbin Northwest sanitary district is anticipated to resume in 2026.

##### *3.2.8.2.2 Coldbrook & Longmeadow Sanitary District*

Water quality in surface water in the Coldbrook and Longmeadow sanitary district in 2021 was similar to that of previous monitoring periods, with some exceptions (DWSP, 2022c). Data collected in 2021 were compared to historical data for these locations.

No widespread impairment/degradation of water quality was observed in surface waters in the Coldbrook and Longmeadow sanitary district in 2021. Monitoring of EQA sites in the Ware River

Watershed will shift to sites in the Burnshirt, Canesto, and Natty sanitary district in 2022. Monitoring of tributaries in the Coldbrook and Longmeadow sanitary district is anticipated to resume in 2026.

#### *3.2.8.3 Water Quality Database*

In 2021, DWSP migrated their water-quality database across platforms from Microsoft Access to SQL Server. The SQL database allows for cloud-based storage and access of DWSP records. The current database contains historical water quality data including field parameters (water temperature, dissolved oxygen, oxygen saturation, specific conductance, pH, chlorophyll a, and phycocyanin) and concentration results (alkalinity, $NO_3$-N, $NO_2$-N, $NH_3$-N, TP, TKN, Ca, Na, Cl, dissolved and total Si, *E. coli*, total and fecal coliform, hardness, $UV_{254}$, and turbidity), spanning the onset of DWSP monitoring (1987) through present. Workflows are developed using R, RStudio, 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. In total there are 405,404 unique data records generated by DCR and MWRA dating from 1987 through 2021 in the DWSP water-quality database for Quabbin Reservoir and Ware River Watersheds. This includes 24,899 individual records processed and imported in 2021. Data generated from Quabbin Reservoir and Ware River Watershed monitoring in 2021 and prior years are available upon request. 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.

## 3.3 Reservoir Monitoring

Water quality of the Quabbin Reservoir in 2021 continued to meet the stringent source water quality criteria stipulated under the SWTR and associated filtration avoidance waiver. The following sections provide a detailed summary of DWSP monitoring efforts conducted in 2021 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. Several complete manual depth profiles of various physiochemical water quality parameters (temperature, pH, dissolved oxygen, specific conductance, pH, chlorophyll *a*, and phycocyanin) from each site were selected to demonstrate changes in seasonal conditions and show periods of peak primary productivity. 2021 was the first year an EXO2 multiparameter sonde was used for manualdepth profiles, in place of the Eureka Manta used from 2006 to 2020. Seasonal descriptive statistics were calculated for each site to summarize the variation of conditions throughout 2021, relative to prior monitoring conditions (Table 36, Appendix C).

### 3.3.1 Water Temperature

Water column temperature profiles indicate the timing of seasonal changes in stratification throughout the Quabbin Reservoir (Figure 28). 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 wide ice coverage in February, the reservoir did not fully freeze over in 2021. Trends in temperature changes throughout the water column over the course of the year remained consistent with the historical record. Despite this, winter and spring minimum temperatures were not as low as 2020, and winter and spring maximums were higher than 2020 at all sites. Though a wider range of temperature values were observed in 2021 compared to 2020, all temperature measurements recorded in 2021 remained within the established historical monitoring range. The minimum water column temperature at site 202 was 4.03 °C on January 21, 2021 (Table 36; 1.99 °C warmer than the minimum temperature observed in 2020 at site 202, and likely reflective of variations in temporal coverage from year to year as no measurements were collected in February 2021 due to ice cover). Summer and fall water temperatures were consistent with temperatures measured in 2020 at all sites.

Stratification began building at the end of April at site 202. The regularly collected MWRA EXO2 buoy profiles provide greater resolution on the formation and stability of stratification in Winsor Basin (Figure 29). Den Hill was already stratified by the first sampling event of 2021 in April, as the epilimnion warmed and greater than 1 °C change per 1-m depth was reached (Appendix C). Surface water temperatures reached a maximum of 25.02 °C at site 202 at the end of August (1.68 °C cooler than the 2020 summer maximum at site 202) then began decreasing in September. Fall turnover began in November, as indicated by the deepening epilimnion and diminishing metalimnion (Figure 28). The water column was fully mixed by winter sampling in

December at site 202, and by late fall sampling in November at sites 206 and Den Hill. The timing of reservoir stratification and mixing during 2021 was consistent with previous years. As is typically observed, average (and median) spring, summer, and fall temperatures for the full water column were greater at site 206 than site 202, and greatest at Den Hill (Appendix C), with the warmest water occurring at shallow depths.

Two mixing events occurred in August and September of 2021 that were observed due to the fine resolution of water column changes provided by the MWRA EXO2 buoy. High winds associated with Hurricane Henri on August 22, 2021, and Hurricane Ida on September 02, 2021, show the transient deepening of the warmer epilimnion water, in both cases to around 17 m, before returning to the typical 10-m depth by the following day.

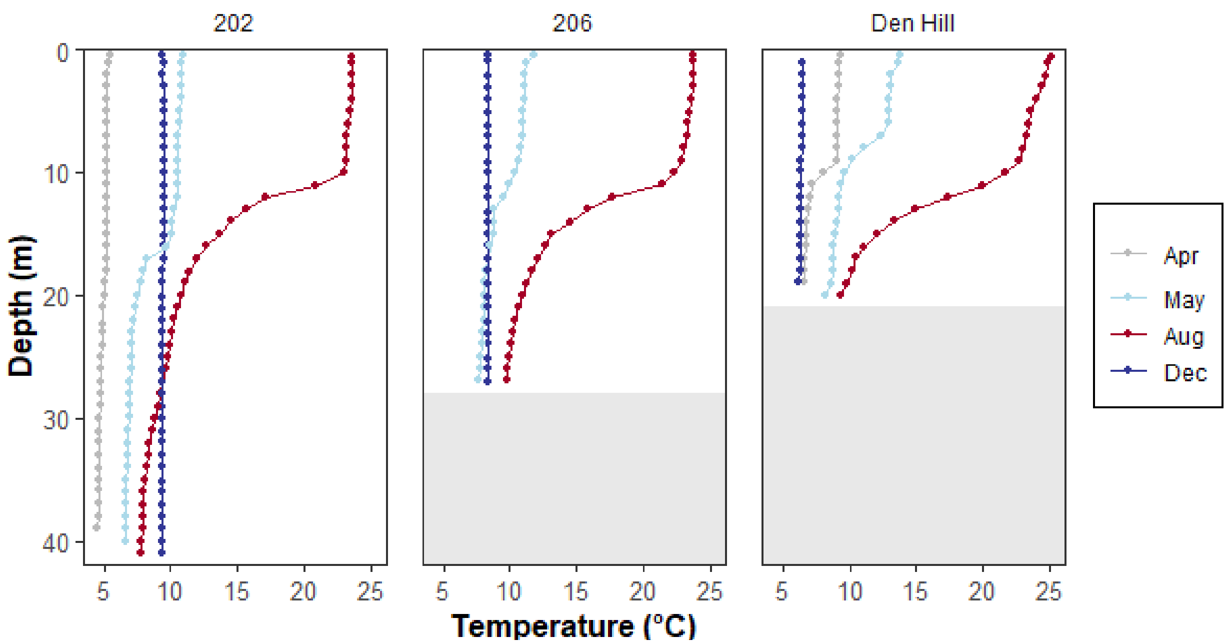



**Figure 28:** Profiles of temperature at Quabbin Reservoir Core sites on select dates in 2021. The April profile illustrates spring isothermy, which existed from the start of the sampling season through most of April at site 202 and was established sooner at 206 and Den Hill. The May profile corresponds to the onset of reservoir stratification. The August profile represents the maximum surface temperature observed at site 202 and continued stratification at all sites. The December profile shows a return to isothermy at all sites following fall turnover. Gray bands at sites 206 and Den Hill indicate the max water column depth recorded for 2021.

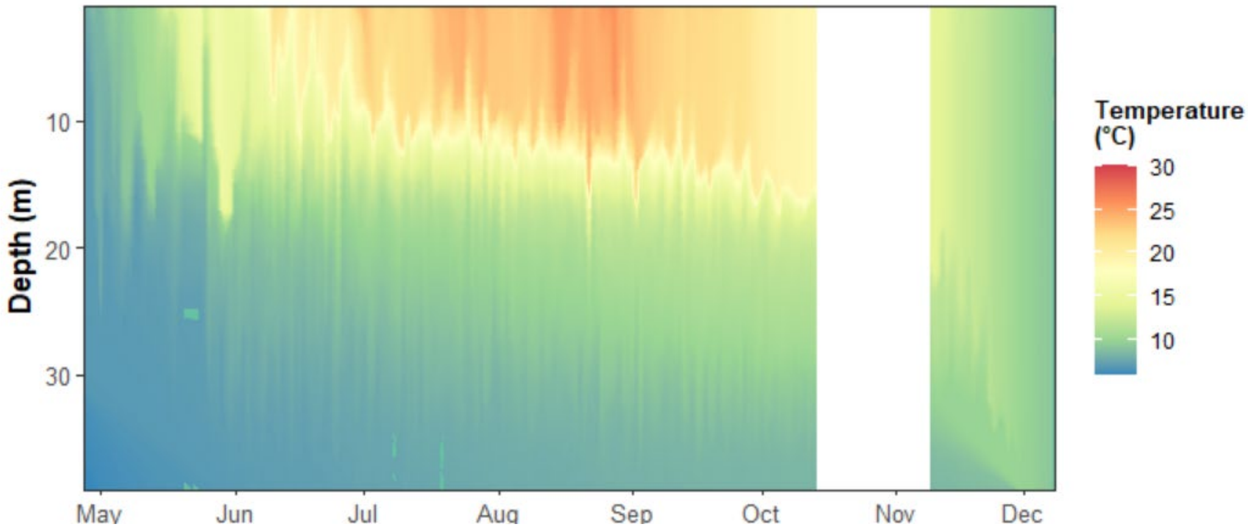



**Figure 29:** Temperature heatmap from buoy EXO2 noon profile collections from May through mid-December. The buoy did not collect data from October 14 through November 09, 2021 due to technical issues.

### 3.3.2 Chlorophyll *a*

Chlorophyll *a* may be used to estimate the overall biomass of the phytoplankton community. DWSP staff reference *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 2021, however, a temporary aggregation of *Chrysosphaerella* at sites 202 and 206 drove maximum chlorophyll *a* concentrations much higher than is typically observed in the Quabbin Reservoir (Figure 30). Maximum chlorophyll *a* concentrations were 43.15 µg/L (at 23 m depth on June 21, 2021) and 56.18 µg/L (at 21 m depth on June 19, 2021), for data collected by DWSP via manual profiles (Figure 31) and the MWRA EXO2 buoy (Figure 30), respectively. Chlorophyll *a* concentrations in excess of 30.0 µg/L were observed within a discrete depth band, spanning approximately 21 m to 23 m depth at site 202 on June 21, 2021, based on manual profile data generated by DWSP (Figure 31). Though unusual for the Quabbin Reservoir, similar maximum values (34.63 µg/L at 18 m on September 03, 2019) were recorded in association with a *Chrysosphaerella* aggregation that occurred in 2019 (DWSP, 2021a). Despite these high maximum concentrations (the aggregation persisted for approximately one month in 2021 at site 202) chlorophyll *a* returned to baseline concentrations for the remainder of 2021 (Figure 30). The average summer chlorophyll *a* concentration at site 202 for the water column was 1.67 µg/L in 2021 (Table 36). Average and median water column chlorophyll *a* concentrations at all sites in 2021 were similar to 2020, and often slightly lower. In contrast to the trends typically observed in chlorophyll *a* across sites, Den Hill had the lowest summer maximum (6.87 µg/L) (Appendix C).

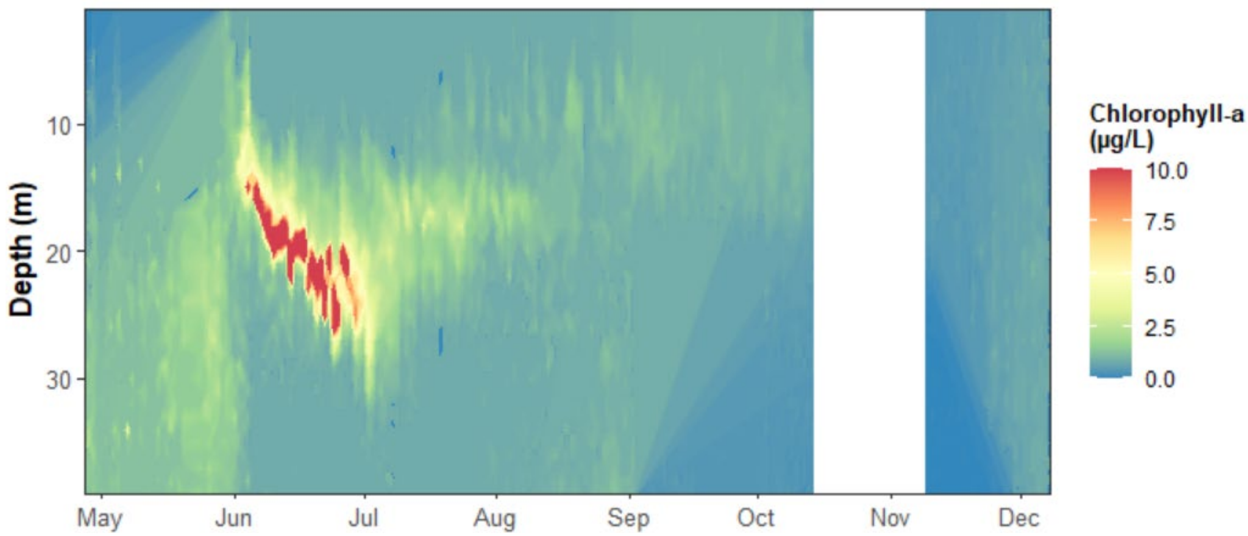



**Figure 30:** Chlorophyll *a* heatmap from buoy EXO2 noon profile collections from May through mid-December. The buoy did not collect data from October 14 through November 9, 2021 due to technical issues.

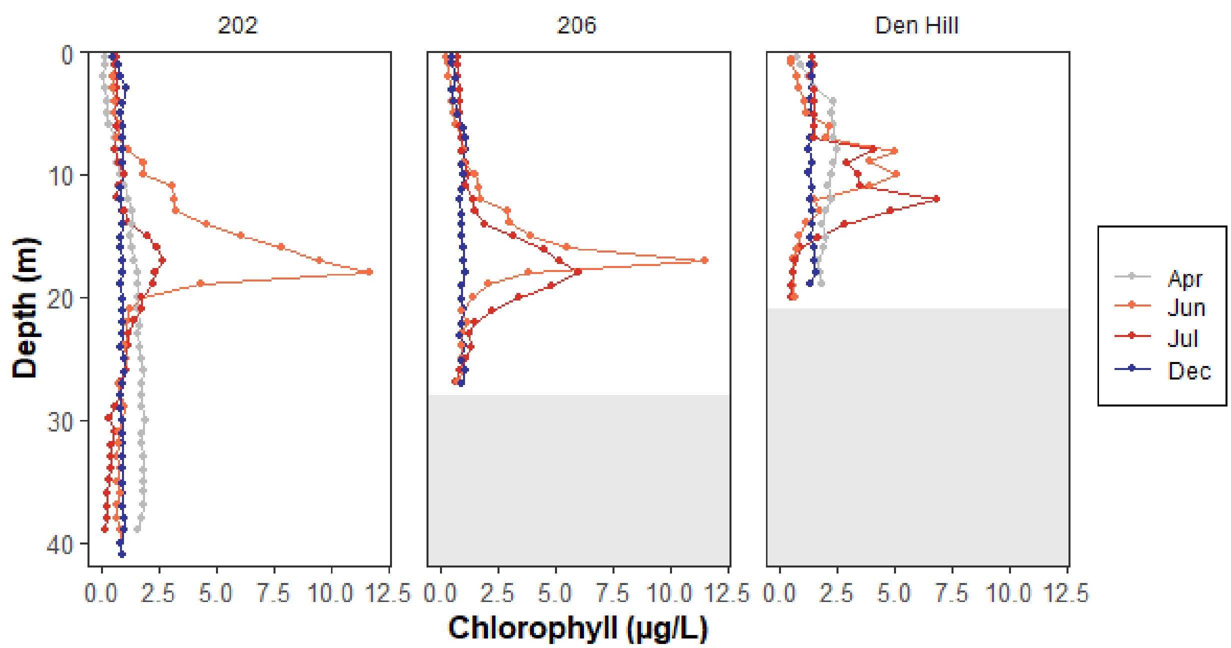



**Figure 31:** Profiles of chlorophyll *a* at Quabbin Reservoir Core sites on select dates in 2021. The April profile corresponds to a fully mixed water column and low to moderate density of diatoms in the spring, which existed from March through most of April at site 202. The June and July profiles correspond to documented Chrysophyte presence at sites 202 and 206. The December profile shows a return to a mixed water column following fall turnover. Gray bands at sites 206 and Den Hill indicate the max water column depth recorded for 2021.

### 3.3.3 Dissolved Oxygen

Concentrations of dissolved oxygen in Quabbin Reservoir followed expected seasonal patterns in 2021. Changes in dissolved oxygen concentrations in Quabbin Reservoir generally coincided with changes in water temperatures, followed stratification stages, and/or rose with relative increases in phytoplankton abundance (Figure 32). Dissolved oxygen concentrations were typically greater in the winter or spring, likely explained by cooler temperatures (Table 36, Appendix C). Concentrations of dissolved oxygen in surface water decreased with stratification, as the warmer water in the epilimnion became unable to hold as much oxygen as colder deep water. Once stratified, dissolved oxygen levels below the thermocline became elevated alongside an increase in phytoplankton activity in June at both sites 202 and 206 and persisted below the epilimnion through October (Figure 32). Dissolved oxygen increased below the epilimnion in July at Den Hill (Figure 32), potentially driven by phytoplankton abundance at depth in the water column (Figure 31). Although, corresponding phytoplankton taxa densities were not generated for this location. This increase persisted through August at Den Hill.

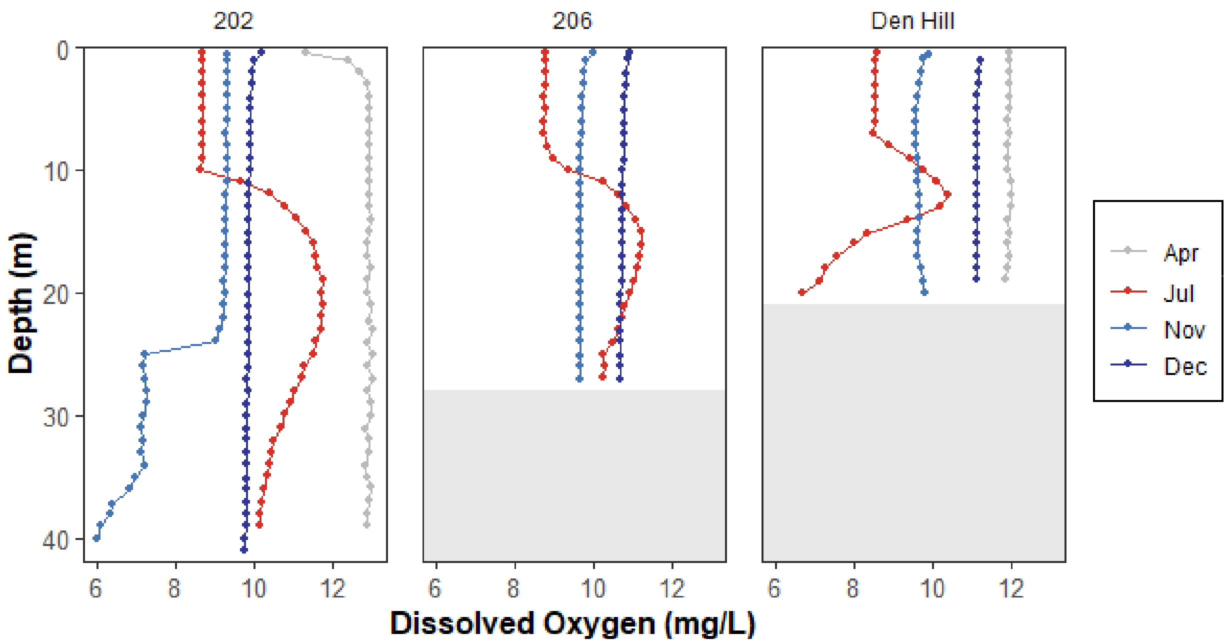



**Figure 32:** Profiles of dissolved oxygen at Quabbin Reservoir Core sites on select dates in 2021. The April profile illustrates the dissolved oxygen concentrations of a fully mixed water column in the spring, which existed from the start of the sampling season through most of April at site 202 and was established sooner at 206 and Den Hill. The July profile depicts an increase in dissolved oxygen concentrations at depth, coincident with documented Chrysophytes at sites 202 and 206. The November profile shows declining dissolved oxygen concentrations throughout the water column as productivity declined in the fall, prior to seasonal turnover. The December profile shows a return to a mixed water column following fall turnover. Gray bands at sites 206 and Den Hill indicate the max water column depth recorded for 2021.

Following typical seasonal patterns for Quabbin Reservoir, dissolved oxygen depletion was most pronounced during the late stages of stratification, with dissolved oxygen concentrations declining with depth. This was particularly distinct for water below the thermocline that remains isolated from atmospheric influence, and where rates of decomposition, a process that consumes oxygen, exceed photosynthesis. The minimum dissolved oxygen concentration in 2021 was 0.87 mg/L, at 20 m in October at Den Hill (Appendix C). This is lower than the minimum dissolved oxygen concentration observed in 2020, but within the range of historically observed concentrations. Following fall turnover in late

November to early December, oxygen was recirculated throughout the water column. Dissolved oxygen was the highest during the spring (annual maximum concentration of 13.28 mg/L at 202) (Figure 32). The median dissolved oxygen concentrations in 2021 remained above 6 mg/L at all sites (Table 36, Appendix C), sustaining concentrations required to support cold water aquatic species (314 CMR 4.06).

**Table 36:** Descriptive statistics (minimum, median, average, and maximum) for physical water quality parameters monitored in Quabbin Reservoir during 2021 at DWSP monitoring site 202. (See Appendix C for descriptive statistics on physical water quality parameters for DWSP monitoring sites 206 and Den Hill). Statistics provided include measurements conducted in conjunction with monthly Quabbin Reservoir water quality monitoring and routine phytoplankton sampling (January through December 2021). Negative phycocyanin concentrations (n=34) were excluded from calculations for descriptive statistics, as they likely represent sensor interference.

| Analyte | Season | Count | Minimum | Median | Mean | Maximum |
|---|---|---|---|---|---|---|
| Water Temperature (°C) | Winter | 63 | 4.03 | 9.42 | 7.65 | 9.45 |
| | Spring | 195 | 3.37 | 6.67 | 6.80 | 16.07 |
| | Summer | 354 | 7.1 | 10.13 | 12.68 | 25.02 |
| | Fall | 207 | 8.08 | 12.04 | 13.73 | 22.76 |
| Chlorophyll (µg/L) | Winter | 62 | 0.47 | 0.89 | 0.89 | 1.15 |
| | Spring | 194 | 0.09 | 1.305 | 1.20 | 3.8 |
| | Summer | 354 | 0.01 | 0.785 | 1.67 | 43.15 |
| | Fall | 207 | 0.01 | 0.51 | 0.47 | 1.07 |
| Phycocyanin (µg/L) | Winter | 62 | 0.25 | 0.46 | 0.43 | 0.51 |
| | Spring | 194 | 0.03 | 0.57 | 0.56 | 0.83 |
| | Summer | 331 | 0 | 0.45 | 0.40 | 1.5 |
| | Fall | 207 | 0 | 0.3 | 0.29 | 0.54 |
| Dissolved Oxygen (mg/L) | Winter | 63 | 9.75 | 9.87 | 10.64 | 12.23 |
| | Spring | 195 | 9.97 | 12.06 | 12.20 | 13.28 |
| | Summer | 354 | 8.24 | 10.67 | 10.44 | 12.27 |
| | Fall | 207 | 6 | 8.72 | 8.67 | 9.81 |
| Oxygen Saturation (% Sat.) | Winter | 63 | 85.1 | 86.3 | 88.53 | 93.5 |
| | Spring | 195 | 89.4 | 99.6 | 99.55 | 105.4 |
| | Summer | 354 | 70.8 | 99.7 | 97.65 | 109 |
| | Fall | 207 | 51.5 | 86.8 | 83.77 | 97.7 |
| pH | Winter | 63 | 6.04 | 6.18 | 6.30 | 7.54 |
| | Spring | 195 | 6.31 | 6.62 | 6.66 | 7.78 |
| | Summer | 354 | 5.75 | 6.53 | 6.54 | 7.68 |
| | Fall | 207 | 5.02 | 5.82 | 5.90 | 7.05 |
| Specific Conductance (µS/cm) | Winter | 62 | 47.4 | 47.5 | 49.83 | 56.1 |
| | Spring | 195 | 47.4 | 48 | 47.93 | 48.2 |
| | Summer | 354 | 46.1 | 48 | 48.05 | 49.6 |
| | Fall | 207 | 47 | 48.1 | 47.90 | 49 |

### 3.3.4 Alkalinity and pH

The dynamics of pH in Quabbin Reservoir are largely governed by the exchange of inorganic carbon between the atmosphere and water (carbon dioxide-bicarbonate-carbonate buffering). The pH of Quabbin Reservoir generally decreases with depth and may vary with changes in photosynthesis and respiration, and contributions from various weather events (e.g., freshwater inputs, Figure 30). Generally, pH within Quabbin Reservoir is unremarkable, ranging from 5.02 to 7.78 in 2021, 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 5.02 to 7.78 in 2021 (Table 36).

Alkalinity in Quabbin Reservoir remained low (<5 mg/L as $CaCO_3$) throughout 2021 and exhibited little variability with depth, changes in stratification, or seasonality (Appendix C). Alkalinity concentrations ranged from 3.14 to 4.61 mg/L as $CaCO_3$ in 2021. Alkalinity was generally greatest at Den Hill in 2021 (3.88 to 4.61 mg/L as $CaCO_3$), relative to other routine monitoring sites in Quabbin Reservoir. This pattern was consistent with previous years during which alkalinity concentrations were reported via titration to a pH 4.2 endpoint (Standard Methods 2320B). Alkalinity measured at each site in the Quabbin Reservoir during 2021 approached or exceeded historical medians, particularly in the spring and summer, but remained within the established range of values for each site. Although an increase in alkalinity has been observed since 2015 in the Wachusett Reservoir (DWSP, 2021b), median annual alkalinity throughout the water column of the Quabbin Reservoir has remained relatively stable since 2015, following an initial increase from 2005 alkalinity concentrations (Appendix C). Increasing trends in low-alkalinity lakes and large rivers have been observed across the US, and attributed to recovery from acid rain and contamination from road salt runoff (Stoddard et al., 1999; Stets et al., 2014; NH DES, 2020). Additionally, the pH (annual precipitation-weighted mean) of rainfall within the Quabbin Reservoir Watershed has been increasing steadily for decades (NADP, 2021). Temporal changes in alkalinity concentrations in lakes and reservoirs in New England may be attributed to interactions of multiple factors (e.g., natural geogenic variability, urbanization and associated chemical weathering of the built environment, acid rain inputs, or changes in or introduced during sample collection and analysis).

### 3.3.5 Specific Conductance, Sodium, and Chloride

Specific conductance measured in the Quabbin Reservoir has historically been quite low, relative to other water bodies in the northeastern United States, which may exceed 1,000 µS/cm in highly urbanized watersheds. The relatively low observed specific conductance in Quabbin Reservoir waters is likely a reflection of land cover (e.g., percent developd lands, total lane miles, and/or percentage of impervious surface cover), the low catchment area-to-surface area ratio of the Quabbin Reservoir, geogenic characteristics of the watershed, and land management practices across the watershed. Specific conductance in Quabbin Reservoir generally varies little with depth but does demonstrate a slight stratification at times, usually within the growing season when the water column is stratified. Typically, when specific conductance does display a slight stratification, it is greatest at the surface and declines with depth. In contrast to that, 2021 showed lower specific conductance at the surface, and higher concentrations at depth at all sites (Figure 33). Specific conductance measured in Quabbin Reservoir waters was within the historical ranges during 2021, ranging from an annual minimum across all sites of 46.1 µS/cm at site 202 in the summer, to an annual maximum across all sites of 56.1 µS/cm at site 202 in the winter (Table 36). In contrast to 2020, the highest specific conductance observed in the reservoir was not at Den Hill, but at site 202. A larger range of specific conductance values was observed in 2021 than is typically observed at site 202. The range of specific conductance values at the two other sampling sites was more similar to the range observed in 2020 (Appendix C).

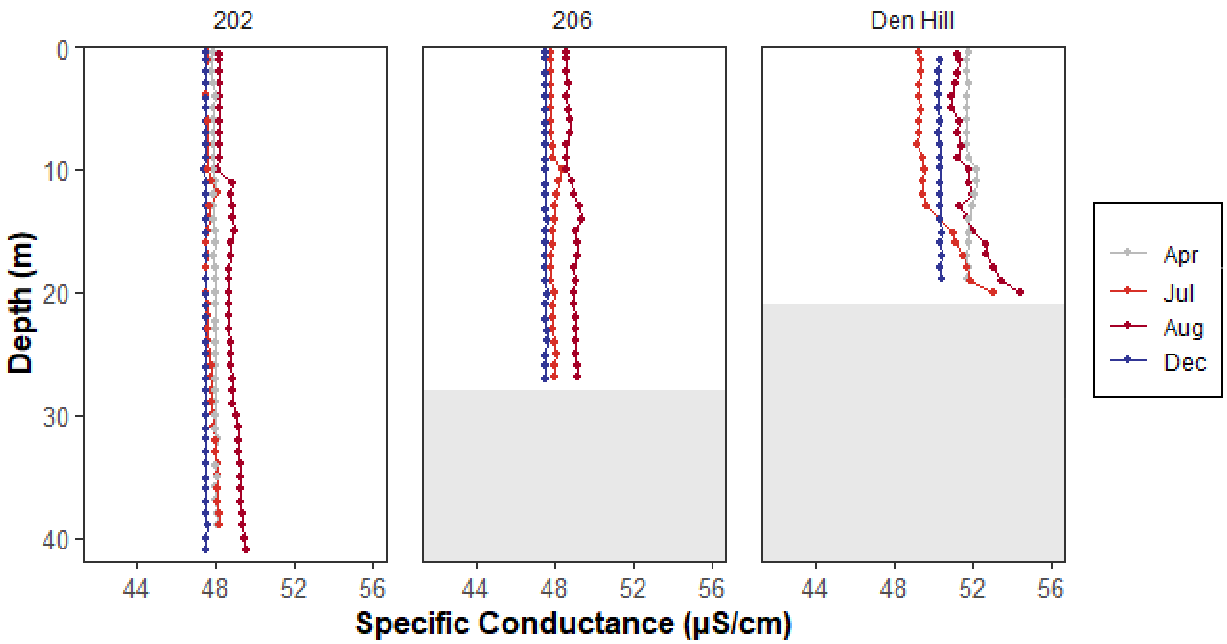



**Figure 33:** Profiles of specific conductance at Quabbin Reservoir Core sites on select dates in 2021. The April profile corresponds to a fully mixed water column in the spring, which existed from the start of the sampling season through most of April at site 202 and was established sooner at 206 and Den Hill. The July and August profiles represent the dates of the minimum and maximum specific conductance at site 202 during stratification, respectively. The December profile shows a return to a mixed water column following fall turnover.

Routine monitoring of concentrations of sodium (Na) and chloride (Cl) in Quabbin Reservoir began in 2020. In 2021, monitoring for Na and Cl in Quabbin Reservoir was conducted quarterly, beginning in July. Na concentrations ranged from a minimum of 5.2 mg/L at the middle of the water column of site 206, to a maximum of 6.07 in the deep sample collected in July at Den Hill (Table 37). Chloride concentrations ranged from a minimum of 7.75 at site 202 to a maximum of 8.66 mg/L at Den Hill. Sodium and chloride concentrations varied little with season, or with depth in the reservoir. Similar to other analytes, concentrations of both sodium and chloride were typically highest at Den Hill (Table 37). Median annual concentrations of Na and Cl measured in 2021 were comparable to 2020 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 2021.

**Table 37:** Concentration results for Na and Cl measured in Quabbin Reservoir during 2021.

| Depth | Season | Na (mg/L) | | | Cl (mg/L) | | |
|---|---|---|---|---|---|---|---|
| | | 202 | 206 | Den | 202 | 206 | Den |
| Surface | Winter | 5.45 | 5.41 | 5.73 | 7.8 | 7.89 | 8.4 |
| | Spring | - | - | - | - | - | - |
| | Summer | 5.51 | 5.46 | 5.74 | 8.16 | 8.21 | 8.57 |
| | Fall | 5.64 | 5.58 | 5.83 | 7.9 | 7.96 | 8.16 |
| Mid | Winter | 5.41 | 5.2 | 5.58 | 7.77 | 7.95 | 8.23 |
| | Spring | - | - | - | - | - | - |
| | Summer | 5.64 | 5.46 | 5.45 | 8.29 | 8.32 | 8.66 |
| | Fall | 5.35 | 5.67 | 5.97 | 8.08 | 8.02 | 8.5 |
| Deep | Winter | 5.44 | 5.35 | 5.61 | 7.75 | 7.83 | 8.35 |
| | Spring | - | - | - | - | - | - |
| | Summer | 5.52 | 5.47 | 6.07 | 8.23 | 8.29 | 8.62 |
| | Fall | 5.66 | 5.68 | 5.76 | 8.03 | 8.09 | 8.44 |

### 3.3.6 Turbidity

Turbidity levels measured in the Quabbin Reservoir were low and relatively stable throughout the year, reflective of the low productivity of the reservoir. Turbidity levels in Quabbin Reservoir ranged from 0.16 to 2.7 NTU during 2021 (Table 38), largely falling within the historical range of turbidity observed at DWSP monitoring sites (Figure 34).

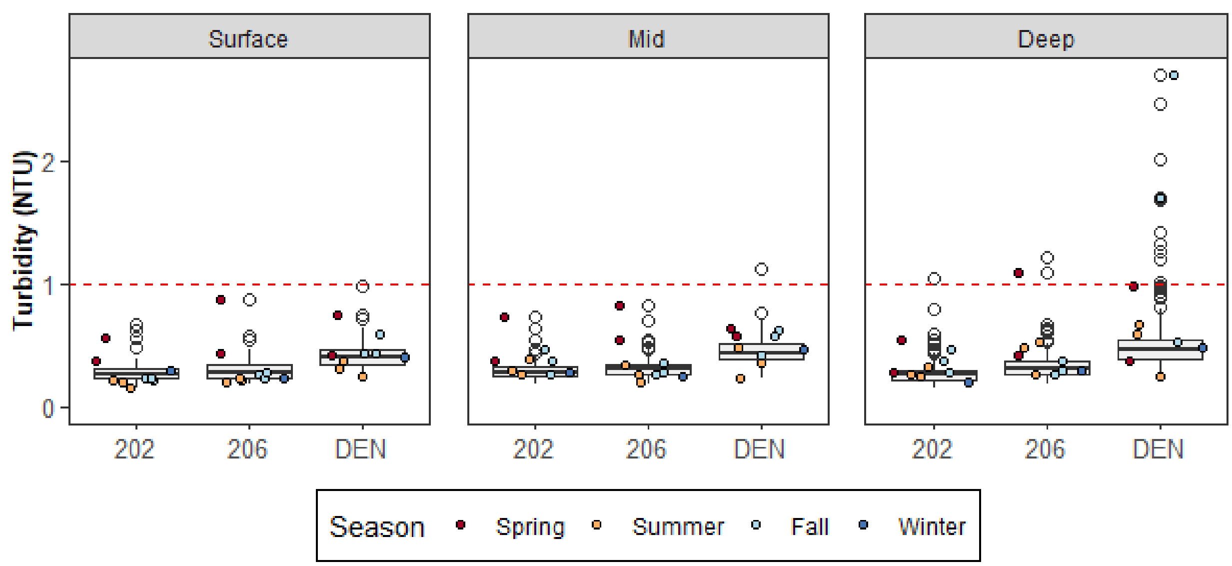



**Figure 34:** Boxplots depicting the seasonal and vertical distributions of turbidity in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2021 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are 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 is marked by the red dashed line in each panel.

**Table 38:** Descriptive statistics (minimum, median, average, and maximum) for turbidity measured in Core reservoir monitoring sites in the Quabbin Reservoir during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Station | Depth | Season | Turbidity (NTU) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | n | | Minimum | | Median | | Mean | | Maximum | |
| 202 | Surface | Spring | 2 | (28) | 0.38 | (0.19) | 0.47 | (0.27) | 0.47 | (0.30) | 0.56 | (0.67) |
| | | Summer | 3 | (36) | 0.16 | (0.18) | 0.20 | (0.24) | 0.19 | (0.25) | 0.21 | (0.39) |
| | | Fall | 3 | (41) | 0.22 | (0.22) | 0.24 | (0.28) | 0.23 | (0.29) | 0.24 | (0.37) |
| | | Winter | 1 | (16) | 0.29 | (0.21) | 0.29 | (0.28) | 0.29 | (0.31) | 0.29 | (0.63) |
| | Mid | Spring | 2 | (26) | 0.38 | (0.19) | 0.56 | (0.28) | 0.55 | (0.29) | 0.73 | (0.64) |
| | | Summer | 3 | (49) | 0.26 | (0.20) | 0.30 | (0.27) | 0.32 | (0.29) | 0.39 | (0.43) |
| | | Fall | 3 | (48) | 0.26 | (0.20) | 0.38 | (0.29) | 0.37 | (0.30) | 0.47 | (0.55) |
| | | Winter | 1 | (17) | 0.28 | (0.20) | 0.28 | (0.28) | 0.28 | (0.29) | 0.28 | (0.38) |
| | Deep | Spring | 2 | (30) | 0.28 | (0.19) | 0.42 | (0.27) | 0.42 | (0.30) | 0.55 | (0.80) |
| | | Summer | 3 | (49) | 0.25 | (0.16) | 0.27 | (0.24) | 0.28 | (0.26) | 0.33 | (0.59) |
| | | Fall | 3 | (51) | 0.28 | (0.16) | 0.37 | (0.24) | 0.37 | (0.26) | 0.46 | (1.04) |
| | | Winter | 1 | (18) | 0.20 | (0.20) | 0.20 | (0.28) | 0.2 | (0.29) | 0.20 | (0.44) |
| 206 | Surface | Spring | 2 | (28) | 0.44 | (0.18) | 0.66 | (0.27) | 0.66 | (0.30) | 0.88 | (0.54) |
| | | Summer | 3 | (37) | 0.20 | (0.19) | 0.22 | (0.24) | 0.22 | (0.24) | 0.23 | (0.33) |
| | | Fall | 3 | (41) | 0.24 | (0.22) | 0.27 | (0.33) | 0.26 | (0.33) | 0.28 | (0.43) |
| | | Winter | 1 | (15) | 0.23 | (0.25) | 0.23 | (0.34) | 0.23 | (0.36) | 0.23 | (0.57) |
| | Mid | Spring | 2 | (24) | 0.54 | (0.24) | 0.68 | (0.32) | 0.68 | (0.34) | 0.82 | (0.70) |
| | | Summer | 3 | (49) | 0.20 | (0.19) | 0.26 | (0.28) | 0.27 | (0.29) | 0.34 | (0.54) |
| | | Fall | 3 | (48) | 0.27 | (0.20) | 0.28 | (0.34) | 0.3 | (0.33) | 0.36 | (0.46) |
| | | Winter | 1 | (16) | 0.25 | (0.24) | 0.25 | (0.32) | 0.25 | (0.33) | 0.25 | (0.48) |
| | Deep | Spring | 2 | (28) | 0.42 | (0.18) | 0.76 | (0.29) | 0.76 | (0.32) | 1.10 | (0.64) |
| | | Summer | 3 | (50) | 0.27 | (0.19) | 0.48 | (0.31) | 0.43 | (0.31) | 0.53 | (0.63) |
| | | Fall | 3 | (51) | 0.26 | (0.23) | 0.29 | (0.33) | 0.31 | (0.39) | 0.38 | (1.21) |
| | | Winter | 1 | (17) | 0.29 | (0.20) | 0.29 | (0.30) | 0.29 | (0.32) | 0.29 | (0.55) |
| DEN | Surface | Spring | 2 | (28) | 0.42 | (0.28) | 0.59 | (0.40) | 0.58 | (0.43) | 0.75 | (0.98) |
| | | Summer | 3 | (36) | 0.25 | (0.26) | 0.31 | (0.34) | 0.31 | (0.35) | 0.38 | (0.52) |
| | | Fall | 3 | (40) | 0.43 | (0.34) | 0.43 | (0.45) | 0.49 | (0.46) | 0.60 | (0.72) |
| | | Winter | 1 | (13) | 0.41 | (0.35) | 0.41 | (0.42) | 0.41 | (0.45) | 0.41 | (0.57) |
| | Mid | Spring | 2 | (25) | 0.58 | (0.34) | 0.61 | (0.42) | 0.61 | (0.45) | 0.64 | (1.13) |
| | | Summer | 3 | (50) | 0.24 | (0.25) | 0.36 | (0.40) | 0.36 | (0.42) | 0.48 | (0.63) |
| | | Fall | 3 | (45) | 0.42 | (0.30) | 0.57 | (0.51) | 0.54 | (0.51) | 0.63 | (0.76) |
| | | Winter | 1 | (13) | 0.46 | (0.38) | 0.46 | (0.42) | 0.46 | (0.43) | 0.46 | (0.56) |
| | Deep | Spring | 2 | (29) | 0.38 | (0.24) | 0.68 | (0.37) | 0.68 | (0.37) | 0.98 | (0.54) |
| | | Summer | 3 | (50) | 0.25 | (0.22) | 0.60 | (0.42) | 0.51 | (0.43) | 0.67 | (0.90) |
| | | Fall | 3 | (48) | 0.53 | (0.40) | 1.70 | (0.57) | 1.64 | (0.77) | 2.70 | (2.46) |
| | | Winter | 1 | (14) | 0.48 | (0.40) | 0.48 | (0.42) | 0.48 | (0.44) | 0.48 | (0.58) |

Den Hill is routinely elevated in turbidity relative to other Core monitoring locations within the Quabbin Reservoir. This well-established spatial gradient has previously been attributed to local inputs from the East Branch Swift River (DWSP, 2021a). The timing of the elevated turbidity observed at Den Hill in 2021 coincides with two extreme events that impacted the region. Tropical Storm Ida, which traversed western Massachusetts between August 31 and September

01, 2021, brought high winds and rainfall totals in excess of 4" over a 24-hour period to the watershed (Section 3.1.1.2). A low-pressure system impacted the region on October 04 and 05, 2021, resulting in over 2" of precipitation recorded on these dates. Average annual turbidity had been declining at surface and mid-depths since 2017. Average annual turbidity increased at the majority of station depths monitored in 2021 (Appendix C), relative to the previous four years. Contributions from tributaries to the Quabbin Reservoir during high streamflow, wind-driven and hydrodynamic currents, and shoreline erosion may further contribute to instances of elevated turbidity measured in Quabbin Reservoir.

### 3.3.7 Secchi Disk Depth/Transparency

Simultaneous aided and unaided Secchi disk transparency was measured in the Quabbin Reservoir in 2021. 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 the variability introduced by surface glare and waves. The aided Secchi measurements resulted in greater transparency than unaided. On average, aided transparency was approximately 1.4-m deeper than unaided measurements. The largest difference between aided and unaided measurements was 6.6-meters, taken at sampling site 206 on June 21, 2021 (Figure 35). This large difference was driven by 12 inch waves and surface glare. On one date at Den Hill on June 08, 2021, there was no difference between transparencies. This was likely due to low waves (3 inch) and partially cloudy weather which maximized ambient light paired with low surface glare.

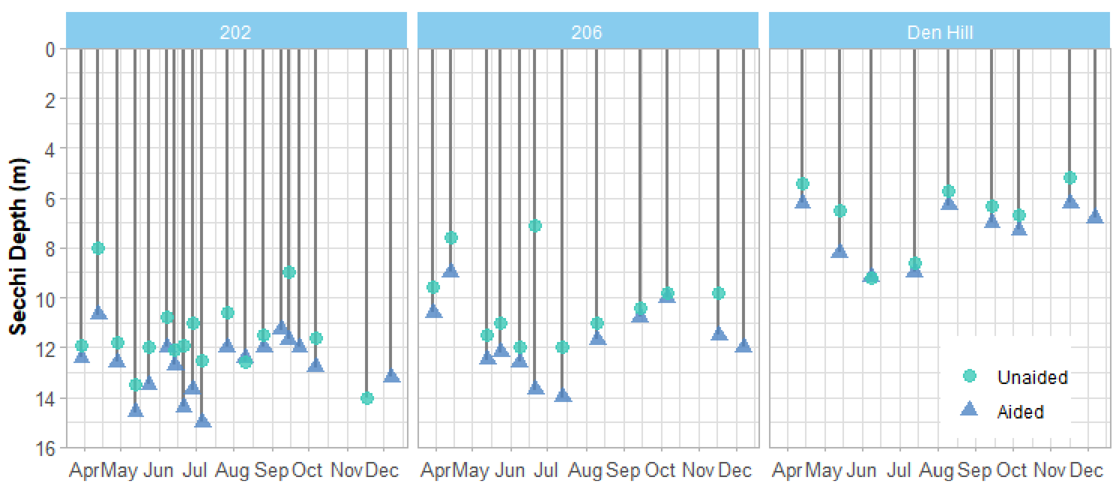



**Figure 35:** Secchi disk transparencies measured in 2021 in Quabbin Reservoir at DWSP monitoring sites 202 (maximum depth 42 m), 206 (maximum depth 27 m), and Den Hill (maximum depth 19 m). Light blue circle data points are unaided measurements, and darker blue triangle points are aided, collected using a view scope.

Water in the Quabbin Reservoir continued to demonstrate exceptional clarity in 2021, with a median aided Secchi transparency of 12.0-m and median unaided Secchi of 10.8-m across all sites. Secchi disk transparency in Quabbin Reservoir during 2021 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 2021 was 5.2-m unaided (November 17, 2021) and 6.2-m aided (April 13 2021) at Den Hill monitoring site. The maximum Secchi disk transparency was 14.0-m unaided (November 17 2021), and 15.0-m aided

(July 06, 2021) at monitoring site 202. Transparency at Den Hill monitoring site was characteristically lower than 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 not occur in 2021). 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 may act as a source of color and sediment, reducing transparency and resulting in elevated levels of turbidity within the Quabbin Reservoir, most pronounced at the Den Hill monitoring site due to proximity. Reductions in Secchi disk depths from August through October at all sites may have been caused by regular large rain events in July, and higher than average stream inputs (Section 3.1.2). Phytoplankton in the epilimnion peaked around June at site 202 and April at site 206, potentially driving corresponding temporary decreases in transparency at those sites (Section 3.3.9).

### 3.3.8 Nutrients

Patterns of nutrient distributions in Quabbin Reservoir in 2021 were generally consistent with those documented previously by Worden (2000) and historical ranges observed in Quabbin Reservoir. Prominent seasonal, spatial, and vertical variations were present, likely due to the interactions of demand by phytoplankton in the epilimnion and metalimnion, the decomposition of organic matter in the hypolimnion, and the timing and extent of terrestrial-derived sources of nutrients delivered via riverine loading to the Quabbin Reservoir. 2021 experienced greater than typical summer inflows in to the Quabbin Reservoir (Section 3.1.2).

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

Concentrations of nitrate ($NO_3$-N) and ammonia ($NH_3$-N) ranged from <0.005 to 0.094 mg/L and from <0.005 to 0.049 mg/L, respectively in Quabbin Reservoir in 2021. Overall, concentrations of $NO_3$-N and $NH_3$-N followed the vertical and temporal variation characteristic of historical seasonal ranges for each site (Table 39). Over half of the concentration results for $NH_3$-N were below laboratory detection limits (60%). Concentrations of $NO_3$-N and $NH_3$-N were generally elevated in the hypolimnion and at Den Hill relative to other sites. $NO_3$-N and $NH_3$-N were below detection limits (<0.005 mg/L) in all samples collected from the epilimnion and metalimnion in the spring and summer at site 206. $NO_3$-N and $NH_3$-N are typically low in the spring. As is characteristically observed, $NO_3$-N and $NH_3$-N levels increased in the hypolimnion in the late summer and fall at all sites, likely coincident with decomposition. Monthly sampling performed throughout the fall revealed variability in seasonal concentrations of $NO_3$-N and $NH_3$-N, with concentrations generally elevated relative to historical seasonal medians. Following fall turnover in the reservoir, $NO_3$-N and $NH_3$-N concentrations decreased at each site, homogenizing across depths. Winter concentrations of $NO_3$-N and $NH_3$-N were elevated relative to historical medians.

Concentrations of TKN in Quabbin Reservoir Core sites ranged from 0.090 to 0.196 mg/L in 2021 (Table 40). TKN concentrations in Quabbin Reservoir exhibited little temporal variability in 2021 and were elevated in samples collected at Den Hill, relative to 202 and 206, similar to spatial patterns exhibited by other nutrients (Table 40). Seasonal concentrations of TKN in Quabbin Reservoir in spring of 2021 were below historical seasonal median concentrations throughout the water column. Concentrations of TKN in samples collected during the remainder of the calendar year were comparable to respective seasonal medians. A proportion of the variability in concentrations of TKN observed within seasons for each site, when compared to the historical records, may be attributed to assumptions made during calculations of TKN concentrations for 2020 and 2021 data (e.g., substituting the detection limit of $NO_2$-N and $NO_3$-N), or related to differences in sensitivity of different laboratory methods (e.g., the detection limits for TN via Valderrama (1981) were lower than that of EPA 351.2 used previously). Additional variability within seasonal TKN concentrations could also be related to the increased monitoring frequency of this nutrient beginning in 2020, as demonstrated by patterns presented by other N-species, TP, and Si. Monitoring of TKN will continue monthly during calendar year 2022. Additional years of monthly data may better reveal key drivers in TKN dynamics in Quabbin Reservoir.

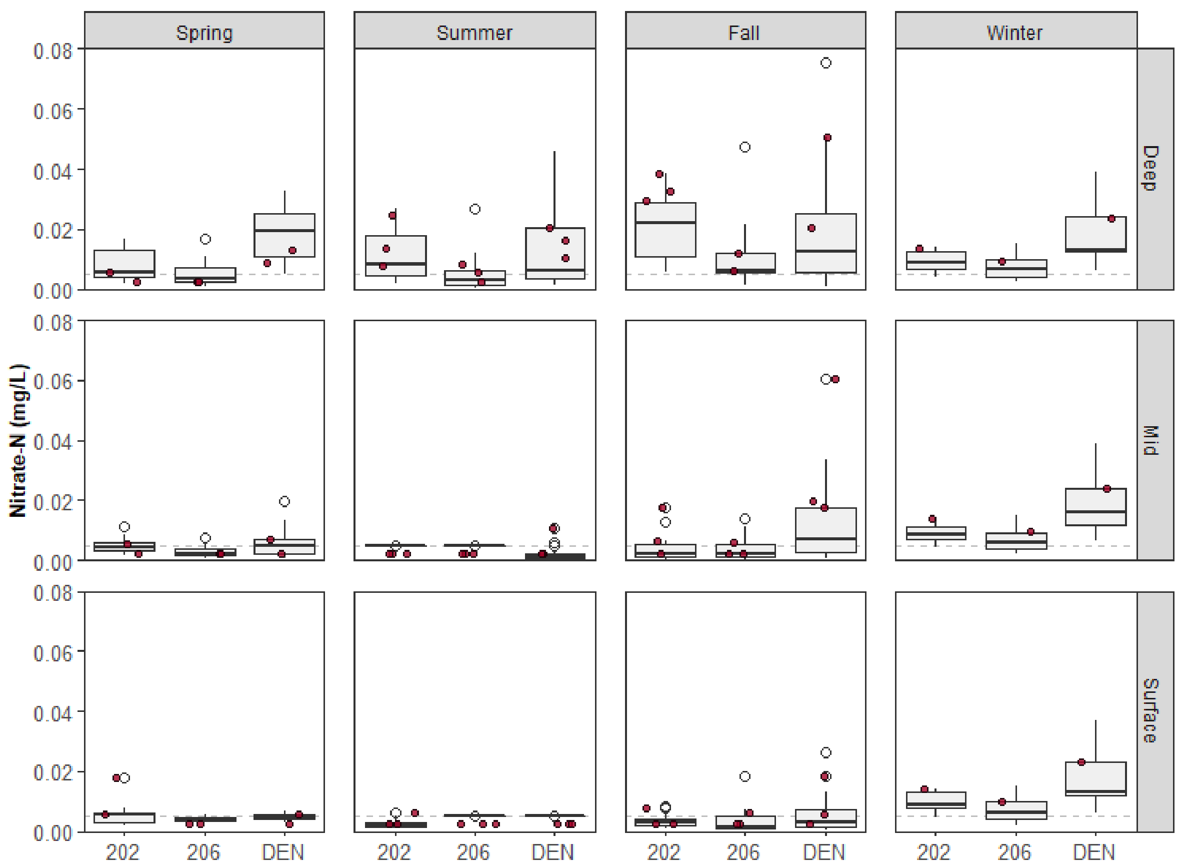



**Figure 36:** Boxplots depicting the seasonal and vertical distributions of $NO_3$-N in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2021 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented 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 39:** Descriptive statistics (minimum, median, mean, and maximum) for $NO_3$-N, $NH_3$-N, and TKN in Quabbin Reservoir during 2021. 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.

| Analyte | Station | Depth | n | | Minimum | | Median | | Mean | | Maximum | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $NO_3$-N (mg/L) | 202 | Surface | 9 | (50) | 0.005 | (0.005) | 0.002 | (0.002) | 0.004 | (0.003) | 0.011 | (0.013) |
| | | Mid | 9 | (50) | 0.005 | (0.005) | 0.002 | (0.002) | 0.005 | (0.003) | 0.016 | (0.014) |
| | | Deep | 9 | (50) | 0.005 | (0.005) | 0.008 | (0.007) | 0.011 | (0.008) | 0.022 | (0.021) |
| | 206 | Surface | 9 | (50) | 0.005 | (0.005) | 0.002 | (0.003) | 0.003 | (0.003) | 0.006 | (0.010) |
| | | Mid | 9 | (50) | 0.005 | (0.005) | 0.002 | (0.001) | 0.003 | (0.002) | 0.008 | (0.020) |
| | | Deep | 8 | (50) | 0.005 | (0.005) | 0.002 | (0.004) | 0.004 | (0.006) | 0.009 | (0.032) |
| | Den Hill | Surface | 9 | (48) | 0.005 | (0.005) | 0.002 | (0.004) | 0.005 | (0.005) | 0.013 | (0.019) |
| | | Mid | 9 | (48) | 0.005 | (0.005) | 0.014 | (0.004) | 0.015 | (0.007) | 0.036 | (0.028) |
| | | Deep | 9 | (48) | 0.005 | (0.005) | 0.018 | (0.009) | 0.024 | (0.010) | 0.049 | (0.034) |
| $NH_3$-N (mg/L) | 202 | Surface | 9 | (51) | 0.005 | (0.005) | 0.006 | (0.004) | 0.007 | (0.005) | 0.018 | (0.014) |
| | | Mid | 9 | (51) | 0.005 | (0.005) | 0.003 | (0.005) | 0.006 | (0.005) | 0.018 | (0.013) |
| | | Deep | 9 | (51) | 0.005 | (0.005) | 0.014 | (0.010) | 0.019 | (0.012) | 0.038 | (0.029) |
| | 206 | Surface | 9 | (51) | 0.005 | (0.005) | 0.002 | (0.002) | 0.004 | (0.004) | 0.010 | (0.018) |
| | | Mid | 9 | (51) | 0.005 | (0.005) | 0.002 | (0.003) | 0.004 | (0.004) | 0.010 | (0.015) |
| | | Deep | 8 | (51) | 0.005 | (0.005) | 0.006 | (0.005) | 0.007 | (0.008) | 0.012 | (0.047) |
| | Den Hill | Surface | 9 | (49) | 0.005 | (0.005) | 0.003 | (0.004) | 0.007 | (0.007) | 0.023 | (0.037) |
| | | Mid | 9 | (49) | 0.005 | (0.005) | 0.011 | (0.005) | 0.016 | (0.008) | 0.060 | (0.039) |
| | | Deep | 9 | (49) | 0.009 | (0.005) | 0.021 | (0.013) | 0.029 | (0.016) | 0.094 | (0.076) |
| TKN (mg/L) | 202 | Surface | 9 | (52) | 0.090 | (0.100) | 0.121 | (0.128) | 0.117 | (0.151) | 0.137 | (0.560) |
| | | Mid | 9 | (52) | 0.094 | (0.100) | 0.115 | (0.138) | 0.115 | (0.149) | 0.132 | (0.399) |
| | | Deep | 9 | (52) | 0.096 | (0.100) | 0.119 | (0.134) | 0.123 | (0.139) | 0.159 | (0.278) |
| | 206 | Surface | 9 | (52) | 0.094 | (0.100) | 0.117 | (0.135) | 0.117 | (0.148) | 0.139 | (0.342) |
| | | Mid | 9 | (52) | 0.100 | (0.100) | 0.120 | (0.135) | 0.119 | (0.153) | 0.138 | (0.322) |
| | | Deep | 8 | (52) | 0.100 | (0.100) | 0.118 | (0.138) | 0.117 | (0.157) | 0.136 | (0.309) |
| | Den Hill | Surface | 9 | (50) | 0.119 | (0.100) | 0.151 | (0.174) | 0.151 | (0.183) | 0.169 | (0.457) |
| | | Mid | 9 | (50) | 0.123 | (0.100) | 0.155 | (0.169) | 0.149 | (0.186) | 0.173 | (0.449) |
| | | Deep | 9 | (50) | 0.117 | (0.100) | 0.161 | (0.160) | 0.159 | (0.180) | 0.196 | (0.389) |

#### *3.3.8.2 Total Phosphorus*

Vertical and spatial patterns in TP concentrations observed in Quabbin Reservoir remained consistent with those previously observed. Measured concentrations of TP in 2021 ranged from <0.005 to 0.010 mg/L in 2021 (Table 33), with approximately 82% of samples (60/73) below laboratory detection limits (0.005 mg/L). Consistent with previously established spatial and temporal variation, TP was slightly elevated at depth and at Den Hill compared to the other sampling depths and sites (Figure 37). Concentrations of TP increased following fall turnover. TP concentrations in all 2021 samples remained well below the 10 µg/L threshold for classification as an oligotrophic water body (Carlson, 1977). Concentrations of TP remained low throughout the water column for the entirety of 2021. Despite an increase in monitoring frequency introduced in 2020, TP concentration results did not exhibit greater intra-annual variability than quarterly concentration results collected in 2019. The latter may in part be attributed to the low concentrations of TP present in Quabbin Reservoir, relative to the sensitivity of analytical methods (e.g., detection limits). Continued monthly monitoring of TP in Quabbin Reservoir through 2022 will serve to further elucidate controls on TP-cycling in Quabbin Reservoir.

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 37).

**Table 40:** Descriptive statistics (minimum, median, mean, and maximum) for TP in Quabbin Reservoir during 2021. Detection limits for TP in 2021 were <0.005 mg/L.

| Station | Depth | Total Phosphorus (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 202 | Surface | 9 | (44) | 0.005 | (0.005) | 0.002 | (0.004) | 0.003 | (0.005) | 0.007 | (0.010) |
| | Mid | 8 | (44) | 0.005 | (0.005) | 0.002 | (0.004) | 0.003 | (0.005) | 0.006 | (0.014) |
| | Deep | 8 | (44) | 0.005 | (0.005) | 0.002 | (0.005) | 0.002 | (0.005) | 0.005 | (0.010) |
| 206 | Surface | 8 | (44) | 0.005 | (0.005) | 0.002 | (0.004) | 0.003 | (0.004) | 0.006 | (0.009) |
| | Mid | 8 | (44) | 0.005 | (0.005) | 0.002 | (0.004) | 0.003 | (0.005) | 0.005 | (0.012) |
| | Deep | 8 | (44) | 0.005 | (0.005) | 0.002 | (0.005) | 0.003 | (0.005) | 0.005 | (0.010) |
| Den Hill | Surface | 8 | (42) | 0.005 | (0.005) | 0.002 | (0.007) | 0.003 | (0.007) | 0.009 | (0.027) |
| | Mid | 8 | (42) | 0.005 | (0.005) | 0.002 | (0.006) | 0.005 | (0.007) | 0.010 | (0.014) |
| | Deep | 8 | (42) | 0.005 | (0.005) | 0.002 | (0.007) | 0.005 | (0.007) | 0.009 | (0.014) |

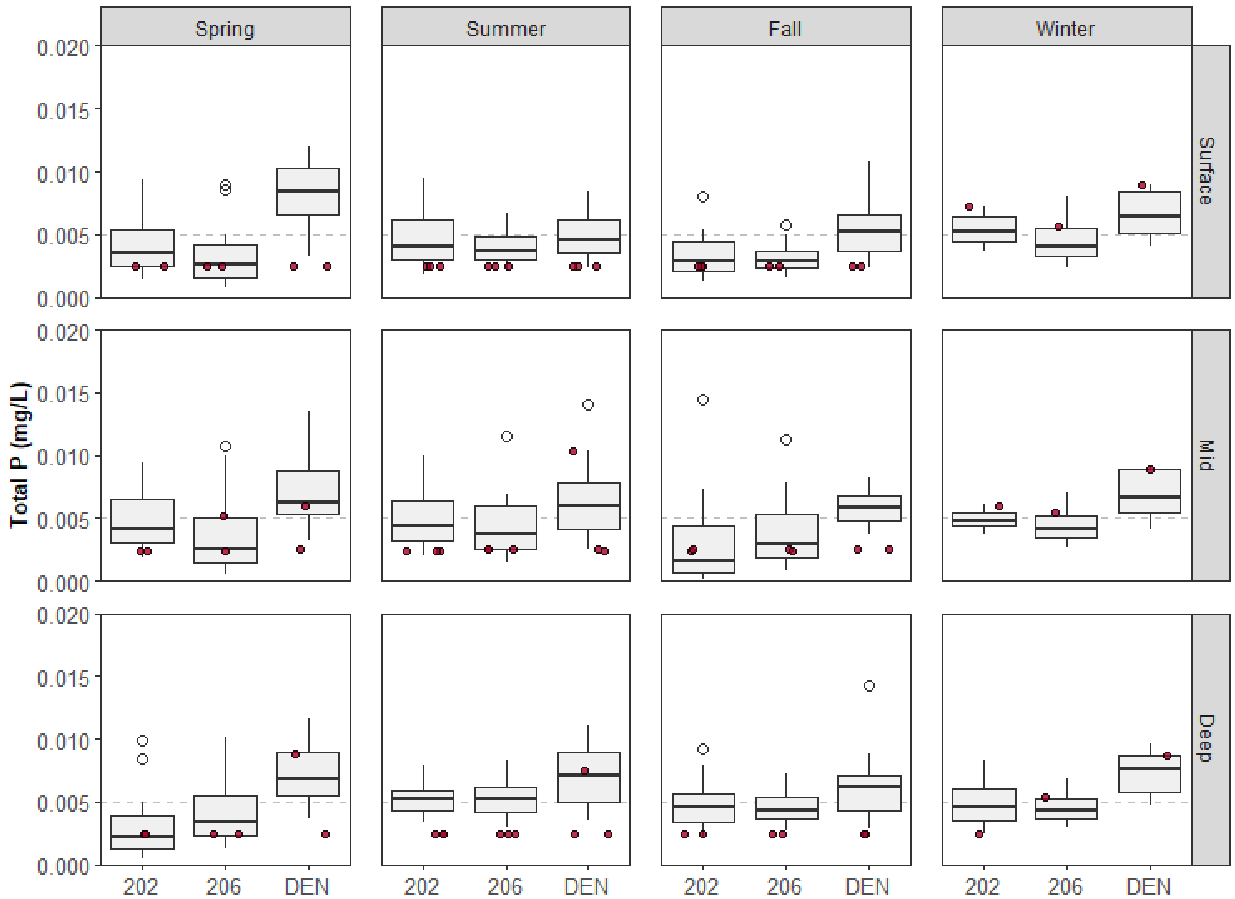


**Figure 37:** Boxplots depicting the seasonal and vertical distributions of total phosphorus in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2021 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

### *3.3.8.3 Calcium and Silica*

#### *Calcium*

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

Concentrations of calcium in Quabbin Reservoir exhibited little spatial or temporal variability (1.92 to 2.40 mg/L) in 2021 (Appendix C). Calcium concentrations were slightly greater in samples collected in the winter and fall (October and December, respectively) across sites (Appendix C). Additional sampling performed in the surface and deep layers of the reservoir revealed little variation in calcium throughout the water column. Calcium analyses was not performed for samples collected in May 2021. Calcium concentrations observed in 2021 in Quabbin Reservoir continue to demonstrate a low risk of zebra mussel colonization. Given the latter, in addition to the relative spatial and temporal uniformity in observed Ca concentrations in Quabbin Reservoir, quarterly sampling at the midpoint of the metalimnion at each location likely adequately captures intra-annual variability in Ca concentrations in Quabbin Reservoir.

***Silica***

Silica is utilized by phytoplankton, particularly diatoms and chrysophytes (Reynolds, 2006). Silica concentrations in Quabbin Reservoir ranged from 1.0 to 3.12 mg/L in 2021, compared to a range of 1.19 to 3.97 mg/L for the period of record. Observed ranges of monthly silica concentrations in 2021 varied relative to historical medians, but largely fell within seasonal interquartile ranges for each site/collection depth (Figure 38). Silica concentrations in 2021 typically approached or fell below seasonal median concentrations for the period of record at sites 202 and 206. In contrast, silica concentrations at Den Hill during the latter half of the year generally exceeded seasonal median concentrations throughout the water column at Den Hill. The increase in sampling frequency from quarterly to monthly that was introduced in 2020 may have contributed to the observed divergence from established seasonal ranges.

Concentrations of silica in Quabbin Reservoir exhibited spatial and temporal gradients consistent with seasonal productivity and subsequent riverine loading of silica to the Quabbin Reservoir. Silica concentrations in the Quabbin Reservoir were generally lower in the epilimnion and metalimnion during the summer and fall, consistent with previous results and likely attributed to uptake by phytoplankton (e.g., diatoms). The maximum silica concentration observed at each site during 2021 occurred from October through December, coincident with a period of relative low productivity across the reservoir (Section 3.3.2, Section 3.3.9) and increased riverine inputs (Section 3.1.2). Silica concentrations were greatest at Den Hill (1.0 to 3.12 mg/L), similar to patterns observed in turbidity, TOC, and $UV_{254}$ across monitoring sites and is likely the result of the proximity of Den Hill to the confluence of the East Branch Swift River with the Quabbin Reservoir.

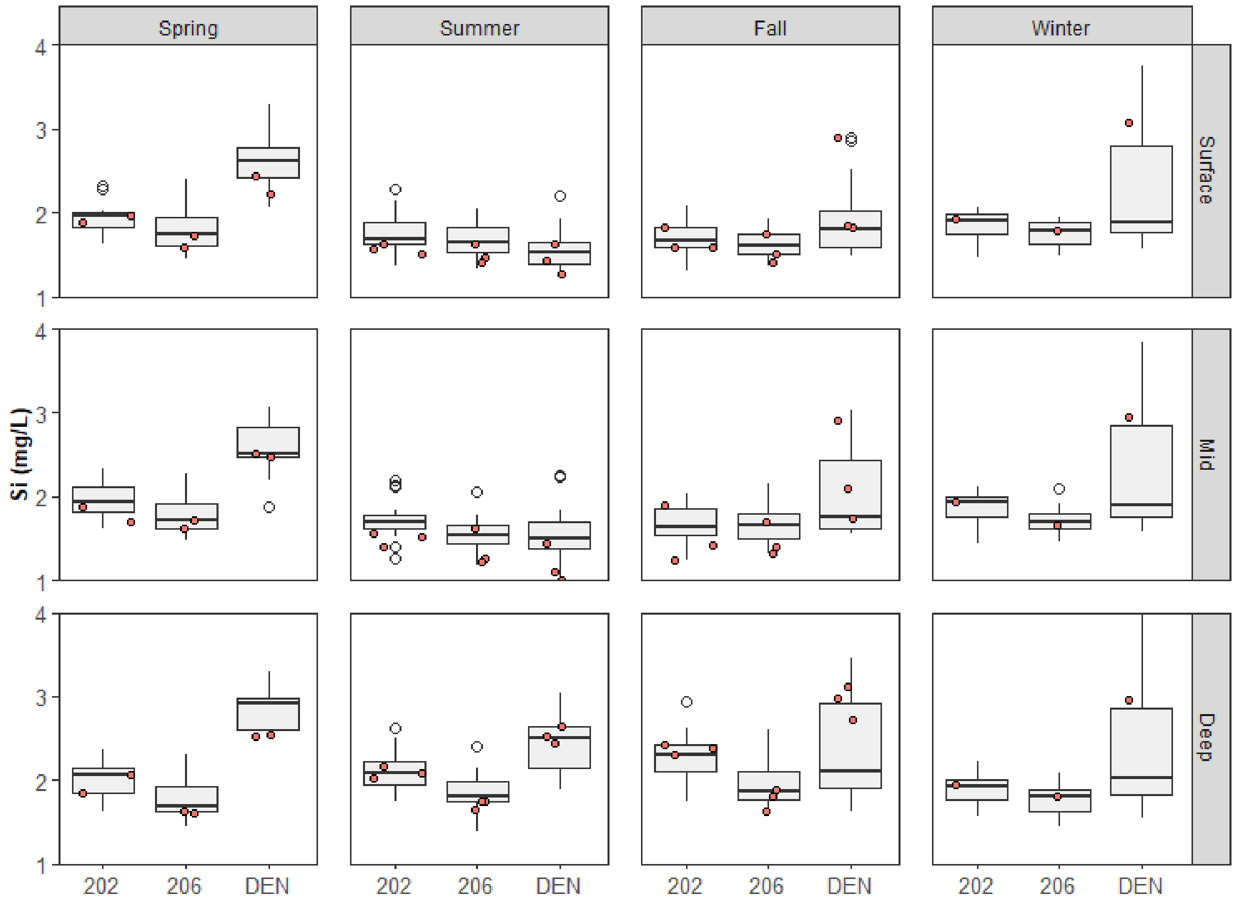



**Figure 38:** Boxplots depicting the seasonal and vertical distributions of silica observed in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2021 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

### *3.3.8.4 $UV_{254}$ and Total Organic Carbon*

**$UV_{254}$ Absorbance**

$UV_{254}$ absorbance in Quabbin Reservoir ranged from 0.022 to 0.028 ABU/cm at sampling site 202, from 0.022 to 0.026 ABU/cm at 206, and from 0.037 to 0.088 ABU/cm at Den Hill (Table 41). Notably, $UV_{254}$ absorbance measured at Den Hill in 2021 trended above median absorbance results for the period of record. An increase in monitoring frequency for $UV_{254}$ in Quabbin Reservoir was introduced in 2020. The higher resolution dataset generated in the previous two years may elucidate new insights regarding intra-annual variability in $UV_{254}$ absorbance in Quabbin Reservoir, and also driving annual median results above historical measures.

$UV_{254}$ absorbance in the Quabbin Reservoir is impacted by contributions from major tributaries, reservoir circulation, and mixing. Spatial gradients in $UV_{254}$ are largely reflective of localized inputs (e.g., elevated $UV_{254}$ at Den Hill relative to other monitoring sites). Median annual $UV_{254}$ was greatest at Den Hill and displayed little seasonal variation in samples collected from 202 and 206 in 2021 (Figure 39). Seasonality in $UV_{254}$ absorbance was well established for Den Hill, however. This pattern may be attributed to potential increased loading from the East Branch Swift River during the fall and winter months, when streamflow was high, coupled with the impacts of the timing of sample collection relative to fall turnover and subsequent water column mixing. Furthermore, the higher resolution dataset generated in the previous two years may reveal previously undocumented seasonal dynamics of $UV_{254}$ in Quabbin Reservoir.

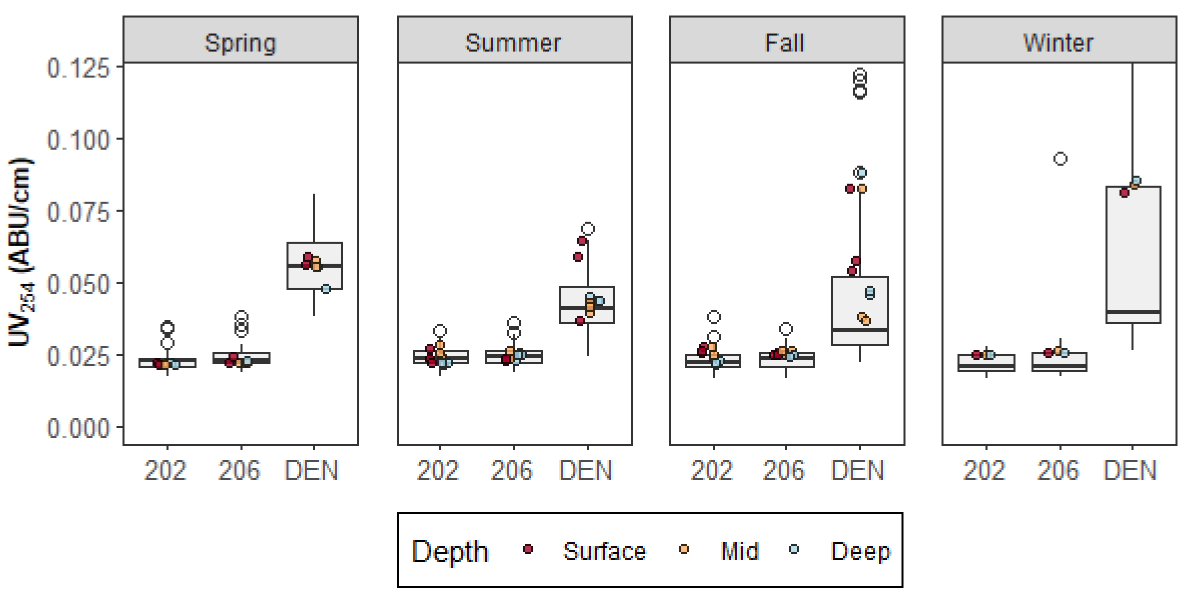



**Figure 39:** Boxplots depicting the seasonal and vertical distributions of $UV_{254}$ observed in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2021 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record 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 41:** Descriptive statistics (minimum, median, mean, and maximum) for $UV_{254}$ measured in Core reservoir monitoring sites in the Quabbin Reservoir during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Station | Depth | Season | $UV_{254}$ (ABU/cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | n | | Minimum | | Median | | Mean | | Maximum | |
| 202 | Surface | Spring | 2 | (11) | 0.021 | (0.0189) | 0.0219 | (0.0232) | 0.0219 | (0.0235) | 0.0221 | (0.0344) |
| | | Summer | 3 | (14) | 0.0221 | (0.0174) | 0.0233 | (0.0223) | 0.0241 | (0.0228) | 0.0270 | (0.0307) |
| | | Fall | 3 | (14) | 0.0253 | (0.0165) | 0.0265 | (0.0216) | 0.0266 | (0.0218) | 0.0280 | (0.0271) |
| | | Winter | 1 | (12) | 0.0246 | (0.0173) | 0.0246 | (0.0207) | 0.0246 | (0.0218) | 0.0246 | (0.0277) |
| | Mid | Spring | 2 | (11) | 0.0218 | (0.0185) | 0.0220 | (0.0231) | 0.0220 | (0.0234) | 0.0221 | (0.0339) |
| | | Summer | 3 | (14) | 0.0245 | (0.0186) | 0.0258 | (0.0246) | 0.0261 | (0.0249) | 0.0281 | (0.0330) |
| | | Fall | 3 | (14) | 0.0235 | (0.0166) | 0.0250 | (0.0219) | 0.0254 | (0.0233) | 0.0277 | (0.0380) |
| | | Winter | 1 | (12) | 0.0247 | (0.0168) | 0.0247 | (0.0204) | 0.0247 | (0.0218) | 0.0247 | (0.0280) |
| | Deep | Spring | 2 | (11) | 0.0215 | (0.0174) | 0.0218 | (0.0221) | 0.0217 | (0.0224) | 0.0220 | (0.0294) |
| | | Summer | 3 | (14) | 0.0217 | (0.0180) | 0.0219 | (0.0229) | 0.0218 | (0.0233) | 0.0219 | (0.0289) |
| | | Fall | 3 | (14) | 0.0217 | (0.0180) | 0.0222 | (0. 022) | 0.0222 | (0.0226) | 0.0227 | (0.0309) |
| | | Winter | 1 | (12) | 0.0246 | (0.0169) | 0.0246 | (0.0201) | 0.0246 | (0.0215) | 0.0246 | (0.0272) |
| 206 | Surface | Spring | 2 | (11) | 0.0221 | (0.0198) | 0.0231 | (0.0246) | 0.0231 | (0.0252) | 0.0240 | (0.0380) |
| | | Summer | 3 | (14) | 0.0227 | (0.0185) | 0.0233 | (0.0224) | 0.0233 | (0.0233) | 0.0238 | (0.0324) |
| | | Fall | 3 | (14) | 0.0248 | (0.0168) | 0.0249 | (0.0215) | 0.0250 | (0.0217) | 0.0253 | (0.0276) |
| | | Winter | 1 | (12) | 0.0257 | (0.0170) | 0.0257 | (0.0205) | 0.0257 | (0.0275) | 0.0257 | (0.0930) |
| | Mid | Spring | 2 | (11) | 0.0224 | (0.0195) | 0.0225 | (0.0243) | 0.0224 | (0.0248) | 0.0225 | (0.0352) |
| | | Summer | 3 | (14) | 0.0239 | (0.0197) | 0.0255 | (0.0261) | 0.0253 | (0.0259) | 0.0264 | (0.0360) |
| | | Fall | 3 | (14) | 0.0250 | (0.0169) | 0.0260 | (0.0223) | 0.0257 | (0.0228) | 0.0262 | (0.0306) |
| | | Winter | 1 | (12) | 0.0260 | (0.0170) | 0.0260 | (0.0206) | 0.0260 | (0.0221) | 0.0260 | (0.030) |
| | Deep | Spring | 2 | (11) | 0.0221 | (0.0186) | 0.0226 | (0.0227) | 0.0226 | (0.0234) | 0.0230 | (0.0336) |
| | | Summer | 3 | (14) | 0.0230 | (0.0204) | 0.0250 | (0.0241) | 0.0242 | (0.0245) | 0.0249 | (0.0317) |
| | | Fall | 3 | (14) | 0.0243 | (0.0183) | 0.0250 | (0.0237) | 0.0248 | (0.0239) | 0.0250 | (0.0339) |
| | | Winter | 1 | (12) | 0.0259 | (0.0170) | 0.0259 | (0.0205) | 0.0259 | (0.0221) | 0.0259 | (0.0302) |
| DEN | Surface | Spring | 2 | (11) | 0.0562 | (0.0405) | 0.0578 | (0.0562) | 0.0577 | (0.0607) | 0.0593 | (0.0802) |
| | | Summer | 3 | (14) | 0.0368 | (0.0244) | 0.0589 | (0.0351) | 0.0534 | (0.0387) | 0.0645 | (0.0689) |
| | | Fall | 3 | (14) | 0.0542 | (0.0229) | 0.0575 | (0.0301) | 0.0647 | (0.0449) | 0.0823 | (0.1220) |
| | | Winter | 1 | (10) | 0.0815 | (0.0265) | 0.0815 | (0.0387) | 0.0815 | (0.0542) | 0.0815 | (0.1195) |
| | Mid | Spring | 2 | (11) | 0.0552 | (0.0383) | 0.0564 | (0.0489) | 0.0563 | (0.0545) | 0.0575 | (0.0726) |
| | | Summer | 3 | (14) | 0.0394 | (0.0265) | 0.0417 | (0.0372) | 0.0413 | (0.0404) | 0.0427 | (0.0602) |
| | | Fall | 3 | (14) | 0.0365 | (0.0224) | 0.0382 | (0.0302) | 0.0525 | (0.0462) | 0.0828 | (0.1390) |
| | | Winter | 1 | (10) | 0.0837 | (0.0266) | 0.0837 | (0.0384) | 0.0837 | (0.0542) | 0.0837 | (0.1252) |
| | Deep | Spring | 2 | (11) | 0.0477 | (0.0418) | 0.0516 | (0.0527) | 0.0516 | (0.0546) | 0.0555 | (0.0702) |
| | | Summer | 3 | (14) | 0.0437 | (0.0331) | 0.0438 | (0.0441) | 0.0443 | (0.044) | 0.0454 | (0.0507) |
| | | Fall | 3 | (14) | 0.0461 | (0.0234) | 0.0474 | (0.0306) | 0.0606 | (0.0489) | 0.0883 | (0.1710) |
| | | Winter | 1 | (10) | 0.0854 | (0.0266) | 0.0854 | (0.0398) | 0.0854 | (0.0551) | 0.0854 | (0.1285) |

## Total Organic Carbon

Routine monitoring for total organic carbon (TOC) in Quabbin Reservoir began in 2020. TOC concentrations ranged from a minimum of 1.63 to 3.32 mg/L in 2021 (Table 42). TOC concentrations in 2021 were comparable to those generated during initial DWSP monitoring in

2020 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 2021 were less than global mean concentrations for deep and north temperate lakes (3.463 mg/L and 5.809 mg/L, respectively) (Chen et al., 2015).

Similar to results from 2020, TOC exhibited little variability with depth or changes in stratification (Figure 40). TOC concentrations were slightly elevated in samples collected in the spring and summer, relative to those collected in the fall and winter. However, results from Den Hill in December 2021 represent the greatest TOC concentrations across years. High stream flows present throughout much of the preceding fall in additional to the proximity of this station to a major tributary inflow may have resulted in above normal organic matter loading to this station in the latter half of 2021 (Raymond and Saiers, 2010; Yoon and Raymond 2012). Additionally, stratification conditions at the time of sample collection may have further contributed to mixing of OM-rich bottom waters with the upper water column (Figure 40).

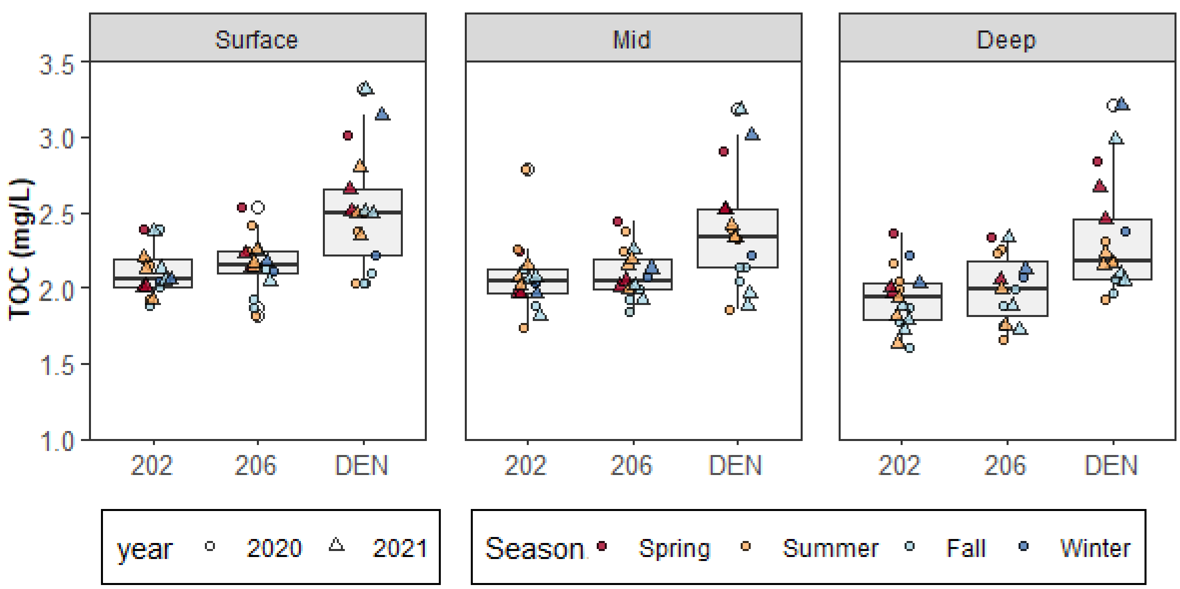



**Figure 40:** Boxplots depicting the seasonal and vertical distributions of TOC in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2021 are signified by the colored triangles. The solid black line represents the historical median, outliers for the period of record are represented 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.

Spatial gradients in TOC generally mirrored that of $UV_{254}$ absorbance – with relative enrichment in samples collected from the Den Hill station compared to 202 and 206. However, correlations among these parameters were mixed, with the strongest relationships presented by Den Hill data and comparatively poor relationships between $UV_{254}$ absorbance and TOC at 202 and 206 (Appendix C).

**Table 42:** Descriptive statistics (minimum, median, average, and maximum) for total organic carbon measured in Core reservoir monitoring sites in the Quabbin Reservoir in 2021.

| Station | Depth | Season | TOC (mg/L) | | | | |
|---|---|---|---|---|---|---|---|
| | | | n | Minimum | Median | Mean | Maximum |
| 202 | Surface | Spring | 2 | 2.00 | 2.01 | 2.00 | 2.01 |
| | | Summer | 3 | 1.92 | 2.13 | 2.08 | 2.20 |
| | | Fall | 3 | 2.05 | 2.13 | 2.19 | 2.38 |
| | | Winter | 1 | 2.06 | 2.06 | 2.06 | 2.06 |
| | Mid | Spring | 2 | 1.96 | 1.97 | 1.96 | 1.97 |
| | | Summer | 3 | 2.02 | 2.07 | 2.08 | 2.15 |
| | | Fall | 3 | 1.82 | 2.06 | 1.98 | 2.07 |
| | | Winter | 1 | 1.97 | 1.97 | 1.97 | 1.97 |
| | Deep | Spring | 2 | 1.97 | 1.99 | 1.98 | 2.00 |
| | | Summer | 3 | 1.63 | 1.82 | 1.80 | 1.94 |
| | | Fall | 3 | 1.73 | 1.79 | 1.80 | 1.89 |
| | | Winter | 1 | 2.03 | 2.03 | 2.03 | 2.03 |
| 206 | Surface | Spring | 2 | 2.14 | 2.19 | 2.18 | 2.23 |
| | | Summer | 3 | 2.14 | 2.17 | 2.19 | 2.25 |
| | | Fall | 2 | 2.04 | 2.14 | 2.14 | 2.24 |
| | | Winter | 1 | 2.18 | 2.18 | 2.18 | 2.18 |
| | Mid | Spring | 2 | 2.01 | 2.03 | 2.03 | 2.05 |
| | | Summer | 3 | 1.99 | 2.15 | 2.11 | 2.19 |
| | | Fall | 3 | 1.92 | 2.02 | 2.07 | 2.26 |
| | | Winter | 1 | 2.13 | 2.13 | 2.13 | 2.13 |
| | Deep | Spring | 1 | 2.06 | 2.06 | 2.06 | 2.06 |
| | | Summer | 2 | 1.75 | 1.87 | 1.87 | 1.99 |
| | | Fall | 3 | 1.73 | 1.88 | 1.98 | 2.33 |
| | | Winter | 1 | 2.12 | 2.12 | 2.12 | 2.12 |
| DEN | Surface | Spring | 2 | 2.51 | 2.58 | 2.58 | 2.65 |
| | | Summer | 3 | 2.35 | 2.49 | 2.55 | 2.80 |
| | | Fall | 3 | 2.5 | 2.51 | 2.78 | 3.32 |
| | | Winter | 1 | 3.15 | 3.15 | 3.15 | 3.15 |
| | Mid | Spring | 2 | 2.52 | 2.52 | 2.52 | 2.52 |
| | | Summer | 3 | 2.33 | 2.33 | 2.36 | 2.42 |
| | | Fall | 3 | 1.88 | 1.96 | 2.34 | 3.19 |
| | | Winter | 1 | 3.01 | 3.01 | 3.01 | 3.01 |
| | Deep | Spring | 2 | 2.46 | 2.57 | 2.56 | 2.67 |
| | | Summer | 3 | 2.15 | 2.16 | 2.18 | 2.23 |
| | | Fall | 3 | 2.05 | 2.10 | 2.38 | 2.99 |
| | | Winter | 1 | 3.21 | 3.21 | 3.21 | 3.21 |

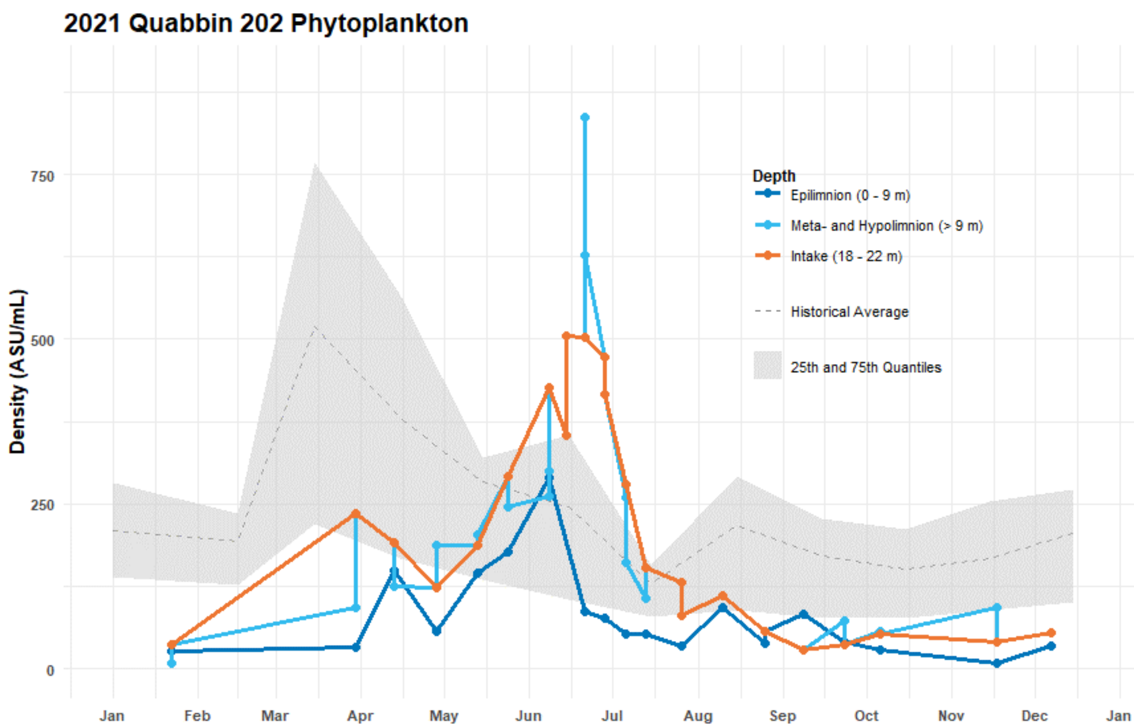
### 3.3.9 Phytoplankton

Samples for phytoplankton enumeration were collected from Quabbin Reservoir Core monitoring sites 202 and 206 on 20 and 13 days in 2021, respectively. Samples for phytoplankton enumeration were collected from two to three depths depending on the location: 1) from 1 to 5 m at the chlorophyll *a* maximum, corresponding with the epilimnion, 2) at the chlorophyll *a* maximum with simultaneous high dissolved oxygen, typically within the metalimnion, and 3) near intake(s) to closely monitor phytoplankton community composition and potential taste and odor impacts (DWSP, 2020a). 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 are collected for routine monitoring at site 202 monthly from October through April (weather and ice conditions permitting) and biweekly during the growing season from May through September. At site 206, samples are collected monthly (weather and ice conditions permitting) year-round. Under special circumstances (e.g., exceedance of early monitoring threshold densities, see Table 43) sampling frequency of phytoplankton may increase, and additional samples are collected based on *in-situ* readings of chlorophyll *a* and dissolved oxygen (Appendix C).

The first samples of the year were collected on January 21, 2021 at site 202. Site 206 could not be reached due to inclement weather. The reservoir froze over on February 16 which prevented sampling until March 30 2021. Spring total phytoplankton densities were low and remained below 300 ASU/mL at both sampling sites until the end of May (Figure 41). At site 202, stratification of the water column began building at the end of April and was fully achieved by May 13, 2021. A combination of wind and sporadic warm and cold periods resulted in an unstable interface between the epilimnion and metalimnion from spring into early summer. The epilimnion became more stable towards the end of June. As is typically observed in Quabbin Reservoir, spring samples were dominated by diatoms (initially *Asterionella* and increasingly *Urosolenia*). Towards the end of May, densities began rising (primarily at site 202), driven by *Urosolenia*.

Following increased stability of stratification in June, phytoplankton composition became dominated by *Chrysosphaerella* at both sites 202 and 206. *Chrysosphaerella* densities drove total densities in the metalimnion at both sites and the intake depth at 202 to the maximum total densities observed in 2021. This aggregation at depth persisted until June 21 and July 06, 2021, at sites 206 and 202, respectively. Total density maximums were reached later in the year (late June) compared to the historical average peak that typically occurs in Spring (March/April).



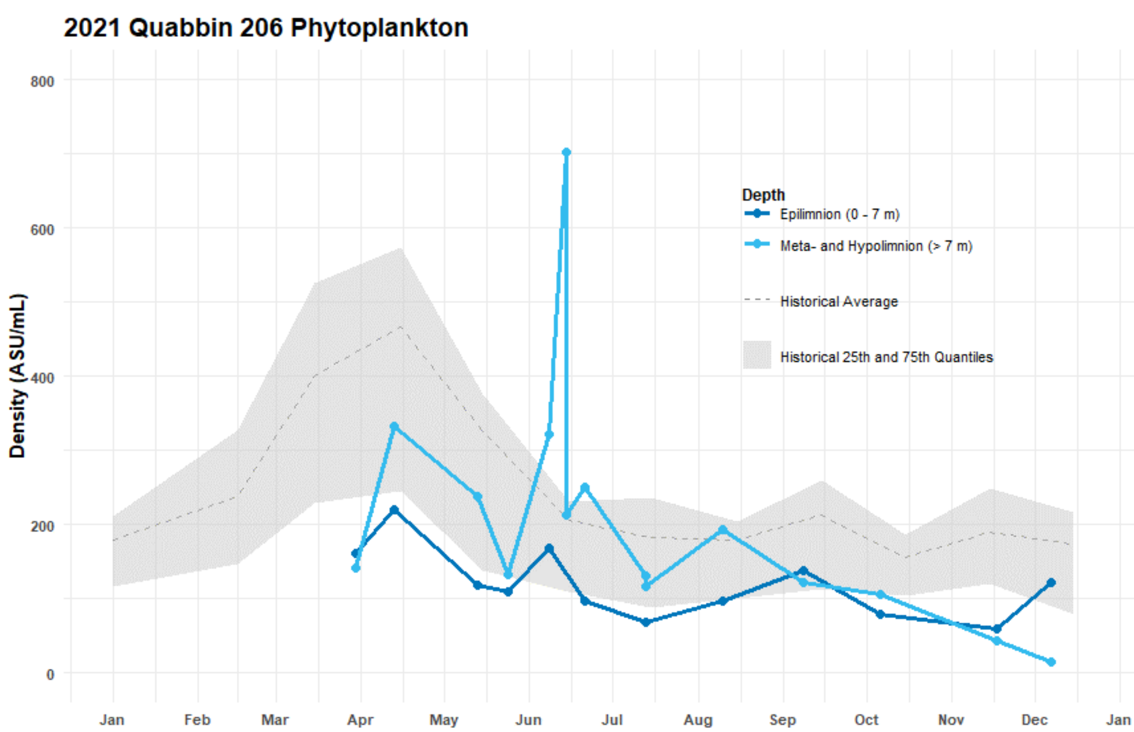




**Figure 41:** Total phytoplankton densities during 2021 from sampling sites 202 (top) and 206 (bottom). Sample classification (epilimnion or meta- and hypolimnion) based on depth as defined by summer temperature profiles. The average for historical data covering 2007 – 2021 indicated by the dashed line, with 25th and 75th quantiles represented as gray bands, corresponding to all sample depths.

Following the dissipation of the *Chrysosphaerella* aggregation, total phytoplankton densities decreased and remained around 200 ASU/mL at both sites through December (Figure 41). Total densities remained below the historical average at both sites from July through December (except for one sample from site 206 in August). Phytoplankton diversity increased following the 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 and Weihe, 2016; Section 3.3.8). Community composition shifted from chrysophyte dominance driven by *Chrysosphaerella* and *Dinobryon*, to a greater variety (albeit, at lower densities) of diatoms, chlorophytes, and cyanophytes. The most common diatoms in 2021 were *Urosolenia* and *Cyclotella*, the most common chlorophytes were *Elakatothrix* and *Gloeocystis*. Cyanobacteria became more dominant in fall samples. The most common cyanobacteria in 2021 were *Aphanocapsa* and *Rhabdoderma*, although these taxa occurred at low overall densities. It is typical to have cyanobacteria dominance during the late summer and fall due to their heightened performance in warm water compared to other phytoplankton (Whitton, 2012).

Densities at different sampling depths also exhibited similar patterns across sites. Epilimnion samples typically had lower densities than samples collected from deeper in the water column. This was particularly true during the metalimnetic aggregations of *Chrysosphaerella*, which did not affect epilimnion total densities. Phytoplankton densities in samples collected from the intake depths at site 202 demonstrated similar seasonal shifts in phytoplankton community composition, and total densities, to the other depths sampled for site 202. Unlike the epilimnion samples, the intake depths were affected by the metalimnetic aggregation of *Chrysosphaerella*, which persisted above, within and just below the intake depths for the duration of the event.

Despite the later and more intense peak in total densities than is typically observed in the Quabbin Reservoir, overall total densities, and changes in community composition were consistent with trends observed in the Quabbin Reservoir over the period of record. These dynamics are also typical of oligotrophic systems. Monitoring for phytoplankton in Quabbin Reservoir will be conducted monthly (October through April) or biweekly (May through September) at site 202, and monthly at site 206 in 2022. If an exceedance of an early monitoring trigger is observed, phytoplankton monitoring will be increased, as appropriate.

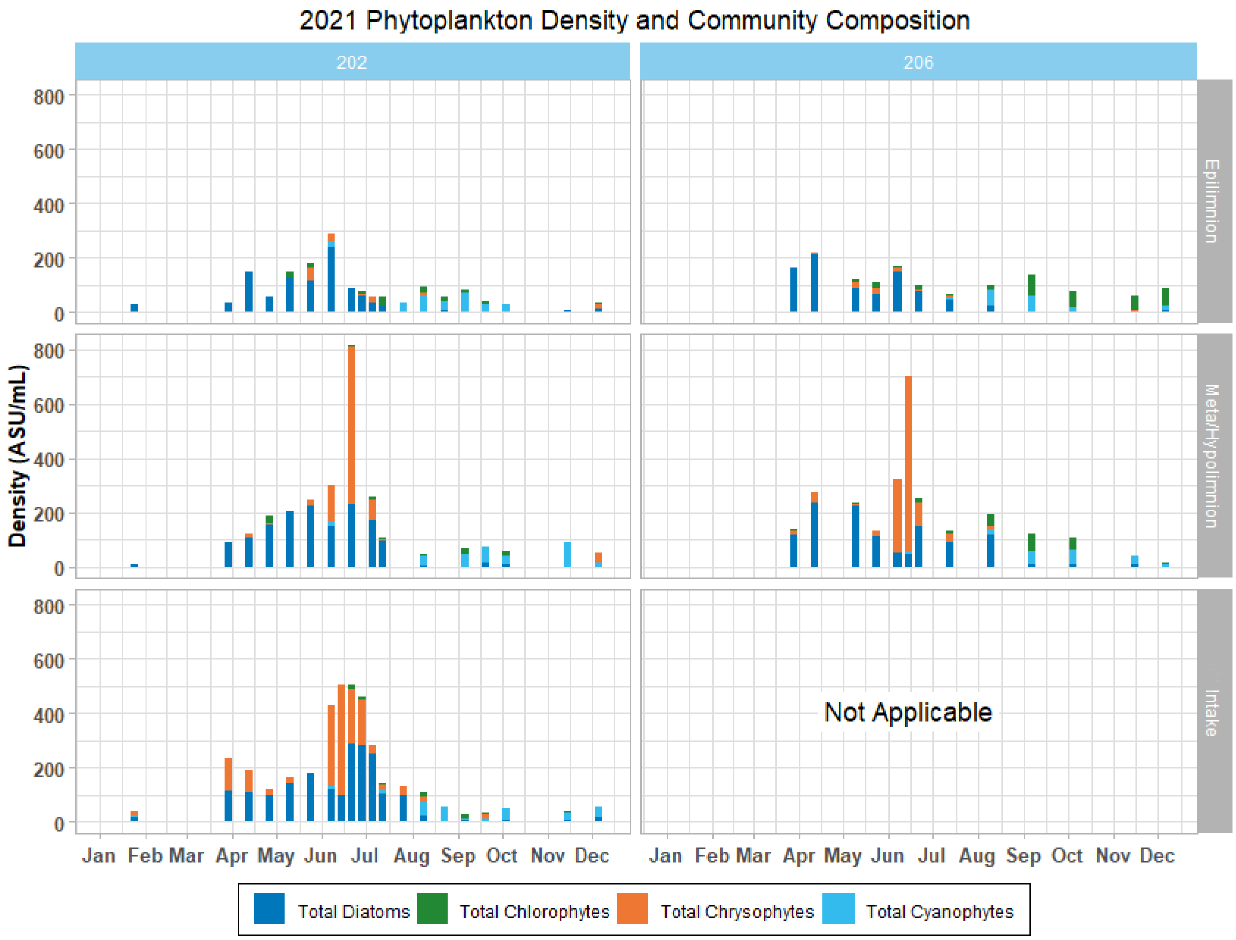



**Figure 42:** Phytoplankton community composition, observed in 2021 from the epilimnion and metalimnion at sampling sites 202 and 206. Additional samples were taken at the CVA intake depth at sampling site 202.

### *3.3.9.1 Taste and Odor Taxa*

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 43).

**Table 43:** Phytoplankton monitoring thresholds for various nuisance organisms in MWRA source waters.

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

*Chrysosphaerella* was the only taxa of concern to exceed the established early monitoring and treatment consideration triggers in 2021 (Figure 43). The early monitoring trigger for *Synura* was exceeded in one sample (15 ASU/mL), collected on June 08, 2021, coincident with the *Chrysosphaerella* aggregation. *Dinobryon* was the second most common chrysophyte identified in samples but remained at levels below the early monitoring trigger. *Uroglenopsis* was observed at countable densities in May and June but was not observed for the remainder of the year. *Dolichospermum* was observed at very low densities in three samples from August through December.

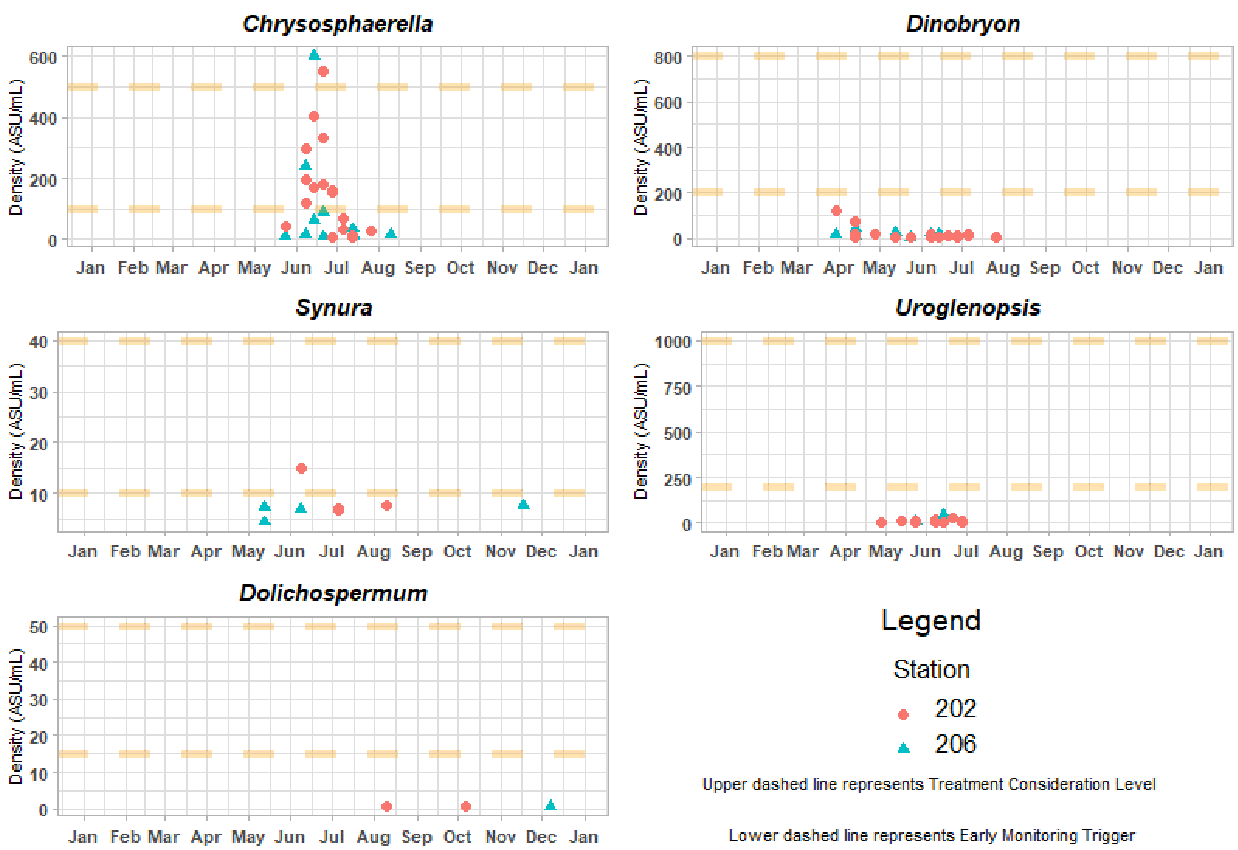



**Figure 43:** Occurrence of nuisance phytoplankton taxa at Quabbin sampling sites 202 and 206 during 2021. Upper dashed line represents the treatment consideration level, and the lower dashed line represents the early monitoring trigger specific to each taxa.

### *3.3.9.2 Chrysophyte Aggregations*

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

Chrysophyte densities have been elevated over the past three years, driven by metalimnetic aggregations.

Changes in phytoplankton community composition and diversity can occur over relatively short time periods (e.g., hours to days) in response to natural environmental variability (Litaker et al., 1993; Paerl et al., 2010; Egerton et al., 2014). Thus, short-lived blooms may preclude detection via routine monitoring. In addition, changes to methodologies governing sample collection depths were introduced in 2019, and thus the increase in phytoplankton densities noted in 2019, may in part, be reflective of more targeted sampling techniques. Prior to 2016, sample depths were selected primarily based on the temperature profile. Routine profiling of chlorophyll *a* began in 2016, serving to better inform sample collection depths for phytoplankton enumeration, than temperature profiles alone. The official change in sample depth selection occurred in 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 in phytoplankton abundance in Quabbin Reservoir, as the sampling focus is now directly driven by chlorophyll *a* values, and thus, higher phytoplankton densities.

Prior to 2019, there were very few instances of chrysophyte densities exceeding current early monitoring triggers (Figure 44). *Uroglenopsis* has never exceeded the early monitoring trigger in Quabbin Reservoir, despite routine detection at low densities. *Chrysosphaerella, Dinobryon,* and *Synura* are the three chrysophyte taxa that have formed high density aggregations in recent years. *Dinobryon* is the chrysophyte that is most frequently present in the Quabbin Reservoir. Preceding 2019, two samples in 2011 (255 ASU/mL and 390 ASU/mL) and one sample in 2013 (447 ASU/mL), all from site 206 had *Dinobryon* densities above the current early monitoring trigger. In September of 2019, three samples from site 206 exceeded the early monitoring trigger (282 ASU/mL, 537 ASU/mL, 209 ASU/mL). In March 2020 there was a transient aggregation of *Dinobryon* at sites 202 and 206, but the treatment consideration level was not exceeded (DWSP, 2021). Prior to 2019, *Synura* had exceeded the current early monitoring trigger in one sample collected at site 202 in 2013 (39 ASU/mL), and two samples at sites 202 and 206 in 2018 (12 ASU/mL, 19 ASU/mL). In 2019, *Synura* was detected above the early monitoring trigger in eight samples, and above the treatment consideration level in 14 samples between sites 202 and 206 (maximum density 125 ASU/mL), in association with the *Chrysosphaerella* aggregation that occurred that year. In 2020, densities of *Synura* exceeded the treatment consideration level once (51 ASU/mL), but remained below countable densities in subsequent samples.

Before 2019, *Chrysosphaerella* was detected above early monitoring triggers in one sample in 2017 (138 ASU/mL at site 202), and in one sample in 2018 (149 ASU/mL at site 206). From August to September of 2019, a proliferation of *Chrysosphaerella* concentrated within the depth range of the CVA intake was observed in Quabbin Reservoir (DWSP, 2020a; DWSP, 2020b). There were only two samples with *Chrysosphaerella* densities that exceeded the early monitoring trigger in 2020 (113 ASU/mL, 141 ASU/mL, both from site 206). During the summer of 2021, an aggregation of *Chrysosphaerella* occurred in Quabbin Reservoir at sites 202 and 206 (Figure 43).

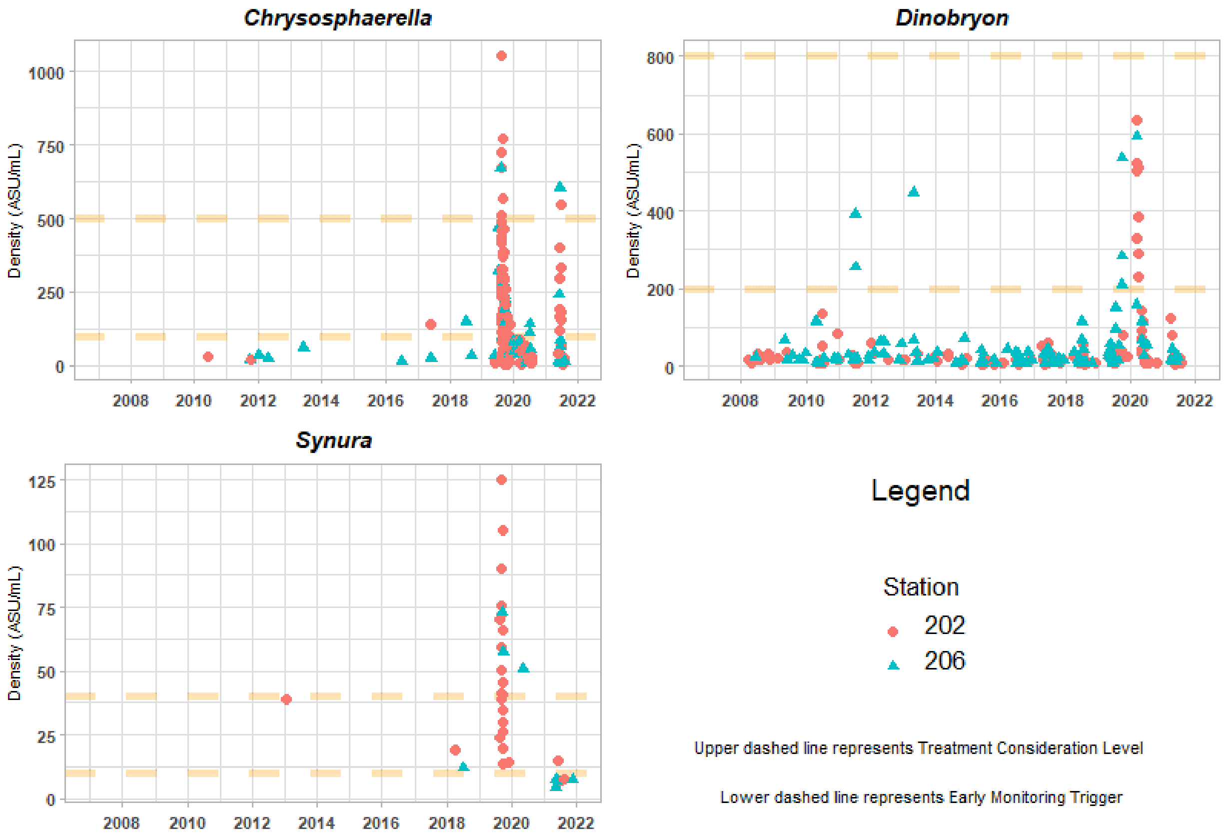



**Figure 44:** Chrysophyte densities from 2007 to 2021. *Chrysosphaerella* was the dominant chrysophyte taxa in 2019 and 2021, while *Dinobryon* dominated in 2020. Sampling was suspended March 24 to April 23, 2020 due to COVID-19 restrictions. Elevated *Synura* densities in 2019 were associated with the *Chrysosphaerella* aggregation.

#### *3.3.9.2.1 2021 CVA Intake/Winsor Basin Chrysosphaerella Aggregation*

*Chrysosphaerella* was first present at sampling site 202 on May 13, 2021, but remained below a countable density. By May 24, 2021, *Chrysosphaerella* was counted at 43 ASU/mL in the 4-m sample and was present but remained below countable densities in the 18 and 25-m samples. Maximum chlorophyll *a* concentration collected by the YSI EXO2 on the MWRA buoy increased from 4.54 µg/L on June 02 to 11.54 µg/L on June 03, 2021 (Figure 30). Increased chlorophyll *a* measurements coincided with a rise in *Chrysosphaerella* densities. On June 8, 2021, *Chrysosphaerella* densities were above the early monitoring trigger (100 ASU/mL) at 193, 120, and 296 ASU/mL in the 16, 17, and 18-m samples, respectively (Figure 43). The highest observed *Chrysosphaerella* density during this event was 550 ASU/mL, collected at 23-m on June 21, 2021. This was the only sampling event that exceeded the treatment consideration level of 500 ASU/mL at site 202 in 2021. Overall, *Chrysosphaerella* densities were above the early monitoring trigger between June 08 and July 06, 2021. Densities of *Chrysosphaerella* fell below the early monitoring trigger on July 6, 2021 (69 ASU/mL), remaining below 100 ASU/mL for the remainder of 2021. *Chrysosphaerella* was present below countable density from August 10, 2021 through the end of year at site 202. Chlorophyll *a* values associated with the *Chrysosphaerella* aggregation collected by the buoy YSI EXO2 ranged from around 10 to a maximum of 59.42 µg/L (June 21, 2021, at 22-m).

##### *3.3.9.2.2 2021 Shaft 12 Intake Chrysosphaerella Aggregation*

Samples collected at site 206 are representative of water that is transferred to the Wachusett Reservoir via Shaft 12 (Quabbin Intake) during periods of active Quabbin transfers. Similar to site 202, *Chrysosphaerella* was first detected at sampling site 206 on May 13, 2021, but remained below a countable density. On May 24, 2021, *Chrysosphaerella* was 12 ASU/mL in the 4-m sample and was not observed in the 22-m sample. Maximum chlorophyll *a* concentration collected with a DWSP manual YSI EXO2 profile increased from 2.19 µg/L on May 24 to 11.53 µg/L on June 08, 2021. This was coincident with a steep rise in *Chrysosphaerella* densities. On June 08, *Chrysosphaerella* reached a density of 14 ASU/mL in the 5-m sample, and 240 ASU/mL in the 17-m sample, revealing the formation of an aggregation at densities above the early monitoring trigger at the same depth as site 202. The highest observed *Chrysosphaerella* density during this event was 601 ASU/mL, occurring at 19-m on June 14, 2021 (Figure 43). This peak in density occurred a week sooner than the peak observed at site 202. Similar to the aggregation observed at site 202, there was only one sampling event that exceeded the treatment consideration level of 500 ASU/mL. *Chrysosphaerella* densities were above the early monitoring trigger (100 ASU/mL) for two sampling events (June 08 and 14, 2021). *Chrysosphaerella* densities decreased to below the early monitoring trigger on June 21, 2021 (88 ASU/mL), three weeks earlier than the decline observed at site 202. Densities continued to decline and remained below the early monitoring trigger after June 21, 2021. *Chrysosphaerella* was below countable density from August 25, 2021 through December 07, 2021 at site 206. The maximum chlorophyll *a* value observed via DWSP profiles during the aggregation event from June 08 to June 21, 2021 was 26.81 µg/L.

Compared to the 2019 *Chrysosphaerella* aggregation, the 2021 event was shorter in intensity and duration. In 2019, *Chrysosphaerella* densities remained above the early monitoring trigger for 11 weeks at sampling site 202, and 12 weeks at sampling site 206. In 2020, *Chrysosphaerella* densities were above the early monitoring trigger for four weeks at sampling site 202, and two weeks at sampling site 206. Over the duration of these events, the treatment consideration level was exceeded by six samples in 2019, and only two samples in 2021. It is notable that many of these detection occurred during periods of increased monitoring in recent years and may not have been detected under routine sampling schedules. This and the change in sample depth selection (i.e., reiance on chlorophyll *a* rather than temperature and dissolved oxygen) suggests these exceedences may have occurred undected in previous years.

## 3.3.10 Bacteria and Turbidity Monitoring for SWTR Compliance

A population of waterfowl that roost on Quabbin Reservoir during fall and winter months have been 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 to the reservoir. Fecal coliform and *E. coli* levels in Quabbin Reservoir are historically low, reflecting microbial die-off and predation. Fecal coliform ranged from <1 to 5 CFU/100 mL in samples collected by DWSP from Quabbin Reservoir in 2021 (n=92). Of the 92 samples collected from Quabbin Reservoir in 2021, fecal coliform was detected in just six samples, five of which were collected from Den Hill. *E. coli* was detected at 10 MPN/100 mL in two samples collected at Den Hill and in one sample collected at the surface at site 206 during the fall of 2021 (one sample each in September, October, and November). *E. coli* remained below 10 MPN/100 mL in the remainder of samples collected by DWSP from Quabbin Reservoir in 2021 (n=81).

The MWRA monitors bacteria levels and turbidity of Quabbin Reservoir water daily prior to disinfection to ensure compliance with the SWTR. Monitoring is performed by MWRA at the Brutsch Water Treatment Facility (BWTF) in Ware, MA. Turbidity is monitored daily by MWRA via an in-line turbidity meter inside the BWTF. Average and maximum daily turbidity levels in Quabbin Reservoir source water measured at the BWTF ranged between 0.21 to 0.49 NTU and 0.21 to 0.62 NTU, respectively. Turbidity levels in Quabbin Reservoir source water remained below the one NTU MassDEP threshold and the five NTU SWTR requirement for the entirety of 2021 (Figure 45). Fecal coliform bacteria were not detected above 20 CFU/100 mL in samples collected at the BWTF (Figure 45). The average and median daily fecal coliform bacteria count of Quabbin Reservoir source water in samples collected at the BWTF were less than 1.00 CFU/100 mL (0.51 and 0 CFU/100 mL, respectively).

*Cryptosporidium* was not detected in samples (n=60) of raw water at the BWTF in 2021. *Giardia* was present in 11 samples collected in 2021, although at four or fewer total cysts. Monitoring for *Cryptosporidium* and *Giardia* will continue to be conducted on a biweekly basis at the BWTF in 2022. No violations of drinking water standards for these organisms occurred during 2021.

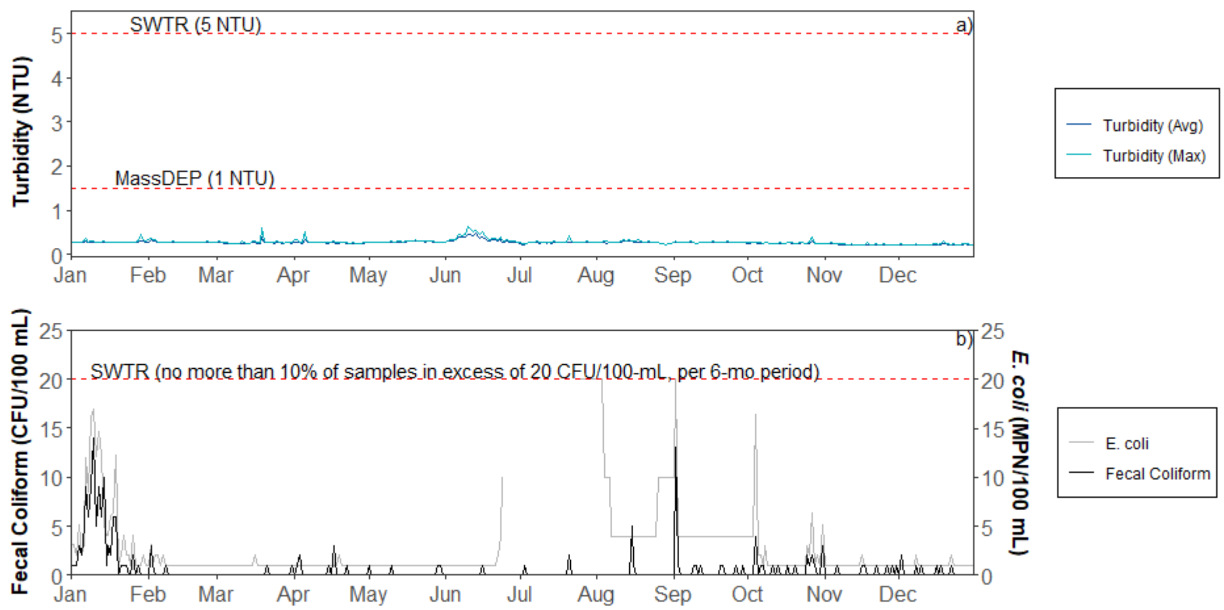



**Figure 45:** a) Results of daily average and maximum turbidity, and b) fecal coliform and E. coli monitoring of Quabbin Reservoir source water, Winsor Dam Intake, collected at BTWF. Note: Detection limits for *E. coli* in source water ranged from <2 MPN/100 mL to <100 MPN/100 mL from June 22 through October 03, 2021, thus fecal coliform served as a better indicator of the sanitary quality of Quabbin Reservoir source water during this interval. *E. coli* remained below minimum laboratory detection limits in source water for the entirety of this affected interval. Data below laboratory detection limits were replaced with the detection limit.

## 3.4 Aquatic Invasive Species Monitoring and Management

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

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

### *3.4.1 Invasive Aquatic Macrophyte Monitoring and Distribution*

Macrophyte surveys are conducted during the growing season and have been performed periodically since 1998, and on a regular basis since 2006 and 2010 in the Quabbin Reservoir and Ware River Watersheds, respectively. Shoreline assessments entail visual observations of the littoral zone via kayak, small boat, or on foot depending on water level. Some water bodies are surveyed annually, while others are surveyed every five years, on a rotating schedule based on the Sanitary District that the water body is located within. Routine monitoring prioritizes water bodies with ramps suitable for launching trailered boats, as this type of activity increases the risk of AIS spread (Rothlisberger et al., 2011). In total, there are currently 41 watershed ponds (including the Reservoir holding ponds, and the Ware River itself) across the two watersheds that are surveyed either annually or on a rotating schedule.

The following sections summarize the distribution of invasive aquatic macrophytes in the reservoir, the Quabbin Reservoir Watershed, and Ware River Watershed (Table 44). In 2021, seven waterbodies were surveyed for aquatic macrophytes in the Quabbin Reservoir Watershed. In addition to these ponds, the three Boat Launch Areas of the reservoir itself, the two holding ponds (O'Loughlin and Pottapaug Ponds), and the West Arm of the reservoir were also surveyed. A total of twelve water bodies were surveyed in the Ware River Watershed in 2021. Three of the ponds surveyed in the Quabbin Reservoir Watershed were associated with the Quabbin Northwest Sanitary District, and six pond surveys were completed in Ware River watershed in association with the Coldbrook and Longmeadow Sanitary District.

**Table 44:** Aquatic invasive species in the Quabbin Reservoir, Quabbin Reservoir Watershed, and Ware River Watershed. * Includes O'Loughlin and Pottapaug holding ponds. ** No evidence of brittle naiad found since 2014, or one row yellowcress since 2013.

| Scientific Name | Common Name | Documented Presence | | |
|---|---|---|---|---|
| | | Quabbin Reservoir* | Quabbin Reservoir Watershed | Ware River Watershed |
| *Cabomba caroliniana* | Fanwort | | | x |
| *Iris pseudacorus* | Yellow Flag | x | x | x |
| *Lythrum salicaria* | Purple Loosetrife | x | x | x |
| *Myosotis scorpioides* | True Forget-me-nots | x | x | x |
| *Myriophyllum heterophyllum* | Var.Leaf Milfoil | x | x | x |
| *Najas minor* | Brittle Naiad | x** | | |
| *Potamogeton crispus* | Curly-leaf Pond Weed | | | x |
| *Phragmites australis* | Common Reed | x | x | x |
| *Rorrippa microphyllum* | One Row Yellowcress | x** | x | x |
| *Utricularia inflata* | Swollen Bladderwort | x | x | x |
| *Cipangopaludina chinensis* | Chinese Mystery Snail | x | x | x |

#### *3.4.1.1 Contracted Aquatic Macrophyte Surveys*

Since 2013, MWRA has contracted annually with ESS Group, Inc. to carry out point-intercept surveys of DWSP/MWRA source and emergency reservoirs. No new AIS were discovered in Quabbin Reservoir during the 2021 survey. *Myriophyllum heterophyllum* (variable-leaf milfoil) was the only documented submersed AIS found in both the Quabbin Reservoir and Ware River Watersheds. Emergent invasives are not specifically included in ESS surveys, but the continued presence of *Phragmites australis* and *Lythrum salicaria* in the Quabbin Reservoir was noted. The extent and density of the *M. heterophyllum* in Quabbin Reservoir increased slightly compared to 2020 (observed at 16% of surveyed points) (ESS Group Inc., 2022). In the Ware River *M. heterophyllum* covered 5.1 acres above Shaft 8, reflecting an increase in both plant growth and survey efforts (ESS Group Inc., 2022).

#### *3.4.1.2 Myriophyllum heterophyllum*

*Myriophyllum heterophyllum* (variable-leaf milfoil) is the most frequently encountered submersed AIS in the watersheds and is well distributed in portions of Quabbin Reservoir. In the reservoir itself, *M. heterophyllum* is well established at all three Boat Launch Areas. Of the 41 watershed ponds, 41% have *M. heterophyllum* present (17 waterbodies, including the holding ponds). Due to the aggressive nature of this species, it is abundant and widely distributed in the waterbodies where it has become established.

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

#### *3.4.1.3 Phragmites australis*

*Phragmites australis* (common reed) is the most widely distributed emergent AIS in the Reservoir and the watersheds. It is well established in parts of the reservoir, forming dense patches along the shoreline. *Phragmites* islands are formed in some shallow locations of the reservoir where this AIS completely dominates. *Phragmites* stands are present at all three Boat Launch Areas, in the western arm of the reservoir, and in the ponds on Prescott Peninsula. Within the 41 watershed ponds, 39% have *Phragmites* present (16 waterbodies, including the holding ponds). A pioneer infestation was found in Edson Pond (Rutland, MA) in the Ware River Watershed during the 2021 survey.

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

#### *3.4.1.4 Cabomba caroliniana*

*Cabomba caroliniana* (fanwort) has not been observed in the reservoir, or in the Quabbin Reservoir Watershed. It has been found in four ponds within the Ware River Watershed, including a newly identified infestation in Long Pond (Rutland, MA). During the 2021 survey, *C. caroliniana* plant fragments were found at the boat launch, and an established patch was observed in the cove between the boat launch and Rt. 122. Based on the extent of the patch, and individual plant sizes (topping out and flowering), it is likely this invasive was introduced at some point in the previous two years when the pond was not surveyed due to staffing constraints. DWSP is investigating management options.

The other three ponds in the Ware River Watershed with *C. caroliniana* infestations are Demond Pond (Rutland, MA), Moulton Pond (Rutland, MA), and Queen Lake (Phillipson, MA). This species was first identified in the watershed in 2010 when it was documented in Queen Lake. The Queen Lake Association contracted a lake and pond management firm to manage the population with herbicides in 2020. The DWSP 2021 survey noted the presence of *C. caroliniana*, but the population appeared to be greatly reduced following herbicide application. Fanwort was identified in Moulton Pond in 2012 but it has not been actively managed. It is now the dominant plant in this waterbody, growing in dense and widespread beds throughout the entire pond.

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

Hardwick Pond (Hardwick, MA), and Lake Rohunta (Orange, MA) are also infested with *C. caroliniana*. These waterbodies are outside the Quabbin and Ware River Watersheds, but are geographically close to the reservoir, thus contributing to the risk of potential introduction into the reservoir. These waterbodies are surveyed when possible to stay informed about the present *C. caroliniana* populations.

#### *3.4.1.5 Utricularia inflata*

*Utricularia inflata* (swollen bladderwort) has been found in two ponds in the Ware River Watershed, and in the Quabbin Reservoir itself. It was found in Whitehall Pond (Rutland, MA), and Long Pond (Rutland, MA) in 2017. This AIS has not been documented in Long Pond in the two most recent surveys (performed in 2018 and 2021). *U. inflata* was found in Whitehall Pond from 2017 to 2019 but was not found during the 2021 survey. A single *U. inflata* was also found in a cove west of Boat Launch Area 2 in 2017. This one plant was removed, and no additional plants have been found in the reservoir since. When not blooming, *U. inflata* is difficult to distinguish from a native bladderwort species. It is possible the seasonality of surveys is affecting the understanding of the presence and distribution of this species.

#### *3.4.1.6 Iris pseudacorus*

*Iris pseudacorus* (yellow flag iris) is a relatively aggressive invasive species that closely resembles the native blue flag iris when not flowering. It has been documented in the reservoir and in both watersheds. *I. pseudacorus* was first documented in Connor Pond (Petersham, MA) in 2013 where it now colonizes large stretches of the western shoreline and has become densely distributed in many small coves. It is hypothesized this population of invasive irises in Connor Pond is contributing to the plants observed in Pottapaug Pond and at Boat Launch Area 3 via seed pods floating down stream. In 2019, the fragment barrier at Area 3 was repositioned to catch floating seed pods more effectively. Seedpods were not observed in the fragment barrier in 2021. *I. pseudacorus* plants were also found in Lovewell Pond (Hubbardston, MA), and Demond Pond (Rutland, MA), both in 2017. Members of the Demond Pond Association were notified of the locations of these plants, and hand harvesting was recommended, but several plants were found during the 2021 survey.

#### *3.4.1.7 Lythrum salicaria*

*Lythrum salicaria* (purple loosestrife) has been documented in 37% of the 41 surveyed watershed ponds (15 waterbodies, including the holding ponds). It has also been found in the Quabbin Reservoir, as individual plants or in small clusters along the shoreline (ESS Group Inc., 2021). It is most extensively established in Pottapaug and O'Loughlin Ponds, compared to the main reservoir. *L. salicaria* was recorded for the first time in four watershed ponds during the 2021 surveys (Edson Pond, Moulton Pond, South Spectacle Pond, and Thayer Pond). Each of these ponds had not been surveyed for five years, indicating the likely slow spread of this invasive. This plant is difficult to identify when not in bloom, making accurate estimates of the extent through the watersheds difficult to attain. Despite this, populations of *L. salicaria* do not appear to be changing rapidly year to year in watershed ponds, demonstrating a relatively low threat to water quality.

#### *3.4.1.8 Rorippa microphylla*

*Rorippa microphylla*, (one row yellowcress) is widely distributed in Massachusetts (USDA, 2020) and in both the Quabbin Reservoir and Ware River Watersheds. *R. microphylla* was found on the shoreline of Boat Launch Area 2 in 2012 but was not observed in the 2021 survey. In 2013 a single plant was found in O'Loughlin Pond. This plant was hand-pulled and has not been found in O'Loughlin since. *R. microphylla* was documented in the Ware River by Shaft 8 in 2016 but has never been documented there again. Pepper's Mill Pond (Ware, MA) and Muddy Pond (Oakham, MA) also have populations of *R. microphylla*. In all locations where it has been observed for multiple years, there appear to be fluctuations in population sizes. It is common to see low densities one year, and no presence the follow year. It is possible herbivores are preventing excessive growth where *R. microphylla* becomes established. To date, impacts from infestations of *R. microphylla* appear to be minor in surveyed waterbodies.

#### *3.4.1.9 Najas minor*

*Najas minor* (brittle naiad) was documented by ESS Group Inc. in 2014 at O'Loughlin Pond. DWSP hypothesize that *N. minor* seeds were introduced into the pond via avian passage, as birds are known to feed on the indistinguishable native *Najas gracillima* seeds (Martin and Uhler 1939; Reynolds et al., 2015). The *N. minor* infestation in O'Loughlin Pond documented in 2014 was quickly harvested using DASH. *N. minor* plants were not observed in O'Laughlin Pond for the seventh year in a row in 2021. This invasive has not been found elsewhere in the Quabbin Reservoir Watershed, or in the Ware River Watershed.

#### 3.4.1.10 Potamogeton crispus

*Potamogeton crispus* (curly-leaf pondweed) has only found in one waterbody across the two watersheds. It was first identified in Whitehall Pond (Rutland, MA), in 2013. This initiated several years of management (2013 through 2017, annually), including mechanical and hand-harvesting plants as well as chemical control. These treatment actions reduced densities of *P. crispus*, but it is still present in the pond. The 2021 survey conducted in late August documented a sparse presence of *P. crispus*, despite the fact this species typically senesces in early summer.

#### 3.4.1.11 Myosotis scorpioides

*Myosotis scorpioides* (true forget-me-not) is not truly an aquatic plant but inhabits wet, disturbed shorelines and is found throughout New England. *M. scorpioides* are another very commonly found AIS around the reservoir and in the Quabbin Reservoir and Ware River Watersheds. It has been found in 32% of the 41 regularly surveyed watershed ponds (13 waterbodies). It was first documented in the Quabbin Reservoir in 2012, along the shoreline of Boat Launch Area 2. In 2013 it was found in Pottapaug Pond, then found in the ponds on Prescott Peninsula in 2014. Populations are removed via hand pulling when found and have not been seen in recent surveys performed in the reservoir. *M. scorpioides* is difficult to identify when not blooming, and this may account for variation of population presence year to year. *M. scrorpioides* can multiply by seed production and spread by an extensive and shallow underground root system. These reproductive methods make complete eradication of this invasive species difficult. Known impacts associated with this plant are minimal at this time.

### 3.4.2 Invasive Aquatic Fauna Monitoring and Distribution

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

#### 3.4.2.1 Dreissena polymorpha

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

#### *3.4.2.2 Invasive Zooplankton*

The potential invasive zooplankton of concern are *Bythotrephes longimanus* (spiny waterflea) and *Cercopagis pengoi* (fishhook waterflea). As of 2021, neither species has been documented in the Quabbin Reservoir. Vertical tows collected monthly from April to December at the Core water quality monitoring sites in the reservoir were scanned to begin establishing the current zooplankton community structure. In 2021, samples were often dominated by copepods in the order of Calanoida and Cyclopoida. The most frequent Cladocerans were Daphniidae, Bosminidae, and Holopedium, and the occasional Leptodora.

#### *3.4.2.3 Cipangopaludina chinensis*

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

### *3.4.3 AIS Management and Boat Decontamination Programs*

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

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

#### *3.4.3.1 Ware River Management of Myriophyllum heterophyllum*

Annual management of *M. heterophyllum* has occurred since 2016 in the basin above the Shaft 8 intake along the Ware River and in sections above the railroad and Route-122 bridges along the Ware River. Despite these efforts, *M. heterophyllum* remains an issue for water operations due to plant fragmentation. Control methods are currently restricted to physical removal of plants and drawdowns. Winter drawdowns may lessen the labor necessary to reduce *M. heterophyllum* in this area; however, the hard freezes required for this to be effective are not consistent or predictable. In addition to this, the presence of *M. heterophyllum* upstream of the Shaft 8 intake continue to repopulate the area.

*M. heterophyllum* upstream of the Route 122 bridge demonstrated the fifth consecutive year of substantial increase from the previous growing season (ESS Group Inc., 2022). Survey efforts in this area were also extended this year (ESS Group Inc., 2022). The density of *M. heterophyllum* downstream of the Route 122 bridge increased slightly in 2021 compared to 2020 (ESS Group Inc., 2022). Davey Resource Group was contracted by MWRA to physically remove plants via raking from land/boat for the fourth consecutive year. The 2021 harvest yielded a 41% increase in gallons of removed *M. heterophyllum* compared to the previous year, despite weather setbacks limiting time and access to plant beds in deep water (Davey Resource Group Inc., 2021). An aquatic rake was successfully used to remove plants from deeper sections, however heavy rains further limited access. Depopulating the entire river above Shaft 8 would be unpractical, daunting, and extremely expensive. This is an ongoing issue with no foreseeable permanent solution. For this reason, the focus is to keep the basin above the intake as free of *M. heterophyllum* as is feasible.

#### *3.4.3.2 Quabbin Boat Decontamination Program*

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

The Boat Decontamination Program was developed to prevent the spread of AIS including plants (variable-leaf milfoil, Eurasian milfoil, hydrilla, *etc.*), zooplankton (spiny and fish-hook water flea), and invertebrates (zebra mussels and Chinese mystery snails). Marine species and severely degraded freshwater plants pose little to no risk of being successfully introduced to the Quabbin Reservoir. Despite this, 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 19 dates in 2021 throughout the fishing season. During WWD boaters are asked what bodies of water their boats were in last, then boats are inspected for any plant material and washed. Samples of biological substances collected off boats inspected during either the WWD or CWQ programs are identified whenever possible. All parts of the boat (including hulls, all through-hull fittings, live wells, bilge, downriggers, anchors, lines, and trolling motors) in addition to the boat trailers (including rollers and bunks) are washed with warm water (140 °F) at a high pressure. Warm water is then run through the boat motor until 140 °F water runs out of the motor for 10 seconds to kill any organisms that may be present in the motor. While this program requires payment from anglers, it enables them to fish outside of the Quabbin Reservoir, then return following the completion of a decontamination event. This significantly reduces the risk of AIS introduction from other waterbodies without restricting anglers to exclusively fish at the Quabbin Reservoir. The cold-weather quarantine program occurred over five dates in 2021. The CWQ requires no fee. Boats are tagged at the beginning of the winter season, making sure boats remain on trailers for around four months. At least three consecutive days below 32 °F, or 46 days with an average low temperature of 30 °F is required to cause desiccation or cold thermal death for any potential AIS (McMahon et al., 1993).

In 2021, 201 boats were inspected and decontaminated through the WWD program. This is above the average number of decontaminations from the previous seven years (171 WWDs from 2014-2020). Ninety-two boats were inspected and sealed through the CWQ program in 2021. This is slightly lower than the average for the previous seven years (111 CWQs from 2014-2020). In 2021, around 44% of boaters used the WWD for the first time, and around 30% of boaters used the CWQ for the first time.

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

#### *3.4.3.3 Boat Ramp Monitoring and Self-Certification Programs*

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

Self-certification forms are prominently displayed at Comet and Long Ponds in boxes on the kiosks near each boat ramp, along with signage directing boaters to self-certify their watercraft as free of AIS before launching. Kiosks, signs, and forms were updated in 2021 to make the program clear and information accessible. Forms include questions about where boaters were last, how long ago, 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 throughout the boating season to monitor for compliance with the program. Vehicles/boaters not displaying a completed form are given instructions, and a blank form.

A new infestation of *Cabomba caroliniana* (fanwort) was identified at Long Pond during the annual macrophyte survey (see Section 3.4.1.4 for more details). Fragments of *C. caroliniana* were found near the boat launch, and a dense patch had formed in the cove between the boat launch and road. Plants were topping out and flowering at the time of the survey. The size of individual plants, and the spread of the patch indicate this invasive plant had been present in Long Pond for over a year. Due to the location of the infestation in the water body, it is very likely it was introduced by boaters. This new AIS introduction highlights the importance of the self-certification process and presents an example of the consequences that follow noncompliance.

# 4 Conclusions and Recommendations

Data generated by DWSP in 2021 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 2021. Water quality monitoring remains ongoing to assess and document water quality in the Quabbin Reservoir and Ware River Watersheds and ensure continued fulfillment of the requirements stipulated by the SWTR.

## 4.1 Quabbin Reservoir Watershed and Ware River Watershed Tributary Water Quality

Results generated from routine monitoring of Core tributaries in Quabbin Reservoir and Ware River Watersheds in 2021 were largely consistent with historical data and demonstrate continued adherence to drinking water quality standards. Infrequent individual *E. coli* concentrations above single-sample regulatory limits, attributed to flushing from storm water runoff events, returned to pre-event levels upon resampling. Biweekly results for specific conductance in Core tributaries in the Quabbin Reservoir and Ware River Watersheds suggest a subtle increasing baseline in specific conductance measured in some tributaries to the Quabbin Reservoir and Ware River Watersheds – a pattern ubiquitous with surface waters in the snowbelt region of the US. Routine nutrient monitoring results for Core tributary monitoring sites in 2021 revealed more detailed dynamics of terrestrial aquatic N-cycling than previously documented, largely attributed to increasing the monitoring frequency for nutrients (previously quarterly) in Core tributary sites. TP analysis in Core and EQA site in Quabbin Reservoir and Ware River Watersheds returned to EPA methods in 2021. TP concentrations remained within established background ranges at all Core sites.

Results of biweekly monitoring of select water quality parameters in Quabbin Reservoir Watershed and Ware River Watershed in 2021 were consistent with historical data, did not suggest the presence of any new substantial point-source contributions, and ultimately demonstrated continued adherence to drinking water quality standards.

## 4.2 Quabbin Reservoir Water Quality

Results of routine water quality profiles collected in Quabbin Reservoir in 2021 were comparable to historical data and indicated that the timing of turnover and stratification occurred in line with prior seasons. Profile data additionally served to guide phytoplankton sampling. Phytoplankton density and composition changes observed through 2021 were consistent with prior years. Climatic and hydrologic drivers contributed to seasonal and vertical shifts in phytoplankton assemblages and nutrient dynamics. Although *Chrysosphaerella* were present at countable densities in samples collected from the Quabbin Reservoir for much of 2021, this taxa did not exhibit similar growth patterns to those observed in 2019 (DWSP, 2020a). The frequency of nutrient monitoring in Quabbin Reservoir also remained monthly in 2021. Monthly results for concentrations of Si, N-species and TP highlighted unique spatial (lateral and vertical) and temporal dynamics of these solutes in the Reservoir, largely driven by hydrodynamics (e.g., seasonal turnover) and primary productivity. Analytical methods for TP in Core sites in the Quabbin Reservoir were returned to those used in previous reporting, prior to 2020. 2021 marked the second consecutive year that TOC was monitored routinely at Quabbin Reservoir Core sites. TOC concentrations in Quabbin Reservoir largely mirrored patterns in $UV_{254}$, highlighting the influence of the East Branch Swift River on water quality at Den Hill.

Monthly monitoring of select water quality parameters in the Quabbin Reservoir during 2021 was consistent with historical data and demonstrated continued adherence to drinking water quality standards.

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

The water quality sampling plan for the Quabbin Reservoir and Ware River Watersheds is reviewed and modified annually to direct focus to different sub-basins within the watersheds and adapt to changing conditions (including but not limited to changes in land use/land cover and/or climate-driven hydrometeorological changes). The 2022 sampling plan retains the long-term Core sites in both watersheds and replaces the sites used to support Environmental Quality Assessment (EQA) efforts.

### 4.3.1 Quabbin Reservoir and Ware River Watershed Tributary Monitoring

The Quabbin Reservoir Watershed tributary monitoring program includes seven Core sites and up to seven EQA sites. DCR will continue to sample biweekly at Core sites (Table 2), discontinue the EQA sites (211E, 211F, 211G, 212A, 212B, 213A, and 212B) monitored in 2021, and begin biweekly monitoring of three different EQA sites (215B, 215F, and 216H) in the Fever Brook sanitary district in 2022. Biweekly monitoring of nutrients ($NO_3$-N, $NH_3$-N, TKN, and TP), $UV_{254}$, and TOC (in Core sites) will continue for tributaries in the Quabbin Reservoir Watershed through 2022.

The Ware River Watershed tributary monitoring program includes six Core sites and up to six EQA sites. DCR will continue to sample biweekly at Core sites, discontinue monitoring at the EQA sites monitored in 2021 (105, 121H, 110, and 119P) and begin biweekly monitoring at five EQA sites (103, 111, 112, C2, and N1) located in the Burnshirt, Canesto, and Natty sanitary district in 2022. Biweekly monitoring of nutrients ($NO_3$-N, $NH_3$-N, TKN, and TP), and $UV_{254}$ will continue for tributaries in the Ware River Watershed through 2022. All other analyses, including DWSP hydrologic and meteorological monitoring will remain unchanged from 2021.

### 4.3.2 Quabbin Reservoir Monitoring

Monthly Quabbin Reservoir monitoring at Core sites (202, 206, and Den Hill) will continue to be conducted by DWSP from April through December 2022, weather and reservoir conditions permitting. This monitoring will include analyses for alkalinity, turbidity, total and fecal coliform, and *E. coli*. Quarterly Quabbin Reservoir monitoring will be conducted in May, July, October, and December. In addition to the monthly analytes, quarterly monitoring will include Na, Ca, Cl , and extracted chlorophyll *a* concentrations. DWSP monitoring of nutrients ($NO_3$-N, $NH_3$-N, TKN, TP, and Si) and $UV_{254}$ in Quabbin Reservoir Core monitoring sites will remain at a monthly frequency in 2022. Monthly analyses of TOC at three depths at Core sites within the Quabbin Reservoir will continue in 2022. Routine monitoring for phytoplankton will be performed by DWSP biweekly at site 202 during the growing season (May 01 through September 30, 2022), monthly at site 202 outside of the growing season, and monthly at site 206. *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 2022. Changes to the DWSP water quality monitoring program introduced in 2022 may aid in future management decisions and help to better elucidate potential controls on productivity and algal dynamics in Quabbin Reservoir.

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# 6 Appendices

## 6.1 Appendix A. 2021 Watershed Monitoring Parameters and Historical Context

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

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

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

| Parameter Name | Units | Sampling Group | Analysis Location(s) | Analysis Method | R | T |
|---|---|---|---|---|---|---|
| Total Organic Carbon | mg/L | Nutrients | MWRA Lab | SM 5310 B | | |
| Total Phosphorus | µg/mL | Nutrients | MWRA Lab | EPA 365.1 | X | X |
| Total Suspended Solids | mg/L | Nutrients | MWRA Lab | SM2540 | | |
| Turbidity FNU | FNU | Field parameter | Field-Sensor | ISO7027 | | |
| Turbidity NTU | NTU | Bacteria | DWSP Lab, USGS | EPA 180.1 | X | X |
| Water Depth | m | Field Parameter | Field-Sensor | N/A | X | |
| Water Temperature | Deg-C | Field Parameter | Field-Sensor, USGS | SM 2550 B-2000 | X | X |

## Ammonia-Nitrogen

Ammonia is an inorganic form of nitrogen that is usually present in surface water at low background concentrations (less than 0.1 mg/L) (USGS, 1999). Ammonia is soluble in water, highly reactive, and can be toxic to aquatic life under certain conditions. Ammonia is converted to nitrate naturally, which depletes water of dissolved oxygen, also negatively impacting aquatic life (Mallin et al., 2006). In 2013 the US EPA updated its aquatic life ammonia criteria to incorporate findings from more recent studies which demonstrated that aquatic life toxicity is highly dependent on water temperature and pH. The updated criteria also accounted for more sensitive taxa (such as mussels) that were not protected under the previous criteria. The acute criteria of 17 mg/L (1-hour duration) and chronic criteria of 1.9 mg/L (a 4-day average within the 30-days, more than once in three years on average) for $NH_3$-N are applicable at pH = 7 and 20 °C (US EPA, 2013). There are no drinking water specific action levels or maximum contaminant levels (MCLs) designated by any US statutes, however the World Health Organization guidelines on drinking water quality list odor and taste thresholds of 1.5 and 1.9 mg/L respectively (WHO, 1996). Potential sources of $NH_3$-N in the Quabbin Reservoir and Ware River Watersheds include septic systems, landfill leachate, agriculture (from fertilizer and livestock), atmospheric deposition, and natural biological processes.

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

## Nitrate-Nitrogen

Nitrate-nitrogen ($NO_3$-N) is an important macro-nutrient for plants and the most abundant inorganic form of nitrogen found in water (USGS, 1999). Sources of nitrate include runoff from agricultural sites and fertilized lawns, failing on-site septic systems, atmospheric deposition, and some industrial discharges. Background concentrations of $NO_3$-N + $NO_2$-N in rivers and streams of the Quabbin Reservoir and Ware River Watershed ecoregions were found to range between 0.1 mg/L and 4.12 mg/L, with the 25$^{th}$ percentile value (all seasons) of 0.16 mg/L (ecoregion 58) and 0.31 mg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical $NO_3$-N + $NO_2$-N criteria for these ecoregions (US, EPA 2001a; US EPA, 2001b). $NO_2$-N is generally below laboratory reporting limits for surface waters in the Quabbin Reservoir and Ware River Watersheds (see Section 2.2.3), thus, background concentrations are primarily composed of $NO_3$-N. At elevated concentrations, nitrates can result in water quality problems including increases in aquatic plant growth, reductions in dissolved oxygen concentrations, changes in plant and animal species composition, and loss of biodiversity (Camargo and Alsonso, 2006).

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

### Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) is the sum of organic nitrogen plus $NH_3$-N and ammonium-nitrogen ($NH_4$-N). It often constitutes a significant proportion of the total nitrogen present in a natural water body. Background concentrations of TKN in rivers and streams of the Quabbin Reservoir and Ware River Watersheds ecoregions were found to range between 0.05 mg/L and 1.45 mg/L, with the 25$^{th}$ percentile value (all seasons) of 0.10 mg/L (ecoregion 58) and 0.30 mg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by EPA for the development of numerical TKN criteria for these ecoregions (US EPA, 2000; US EPA 2001a). This fraction of nitrogen is important to account for because it can be converted to other forms of nitrogen through natural processes and can contribute to unwanted plant growth in the tributaries and lakes. There are no water quality standards for TKN, however this metric includes $NH_3$-N, which is toxic at low concentrations and has specific regulatory thresholds (see A 1.1.1). The current water quality goal for TKN in streams, rivers, and the Reservoir is to maintain existing local background concentrations.

### Total Nitrogen

Total nitrogen (TN), as measured in water, is the sum of TKN, $NO_3$-N and $NO_2$-N. This calculated parameter is important to examine in conjunction with TP because the ratio of nitrogen to phosphorus in aqueous systems controls primary production and has important implications for the ecology and drinking water quality of a water body. The dominant forms of nitrogen in surface waters are $NO_3$-N and organic nitrogen, with much smaller fractions of inorganic $NH_3$-N and $NH_4$-N species (See Sections 0 – 0).

Massachusetts has only developed numeric water quality criteria for nitrogen for specific water bodies with significant impairments from nutrient over-enrichment. Nitrogen criteria are usually created in conjunction with phosphorous criteria, as they are the two primary contributing agents for eutrophication. In absence of water body specific nitrogen criteria for Quabbin Reservoir and Ware River Watershed water bodies, only the narrative criteria for nutrients applies – to not '… *cause or contribute to impairment of existing or designated uses'*. Thus, the internal numerical goal for TN in streams and rivers is to maintain naturally occurring local background concentrations. Background concentrations of TN in rivers and streams of the Quabbin Reservoir and Ware River Watershed ecoregions were range between 0.34 mg/L and 5.57 mg/L, with the $25^{th}$ percentile value (all seasons) of 0.42 mg/L (ecoregion 58) and 0.59 mg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TN criteria for these ecoregions (US EPA, 2000; US EPA 2001a). Long-term (seasonal or annual) TN concentrations above these recommended criteria likely indicate that excess nitrogen is entering waters. Any tributaries exhibiting long-term concentrations above these recommended nitrogen criteria should be examined more closely to determine if any response variables (chlorophyll, macrophytes, turbidity, macroinvertebrates) indicate that water quality impairments are occurring.

## Total Phosphorus

Phosphorus is an important macronutrient, and the limiting factor controlling algal productivity in Quabbin Reservoir. Phosphorous is derived from the weathering of rocks and therefore it is naturally present in soils in varying concentrations as orthophosphate ($PO_4^{3-}$). Plants take up orthophosphate as they grow, which is then returned to the soil in organic compounds via animal waste and the decomposition of plant and animal tissue (USGS 2012). Through various human activities, additional phosphorous is released to both soil and water, often in highly concentrated quantities. Many agricultural operations intentionally add phosphorus to soils using chemical fertilizers and/or organic animal waste solids (manure). Concentrated animal feeding operations create large quantities of animal waste that can unintentionally release phosphorous to soils and groundwater when improperly managed. Sewage treatment discharges to streams and septic system effluent leaching to groundwater both usually contain elevated levels of phosphorous. Furthermore, human activities that accelerate erosion processes on the land surface and within streams can increase the release of phosphorous from soils and sediment into water bodies.

Lakes with TP concentrations exceeding 20-30 µg/L may experience nuisance algal growth (Vollenweider, 1976). Background concentrations of TP in rivers and streams of the Quabbin Reservoir and Ware River Watersheds ecoregions were found to range between 2.5 µg/L and 907.5 µg/L, with the $25^{th}$ percentile value (all seasons) of 12 µg/L (ecoregion 58) and 23.75 µg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TP criteria for these ecoregions (US EPA 2000; US EPA 2001b). Like nitrogen, there are no Massachusetts numerical water quality standards for phosphorus for any Quabbin Reservoir Watershed or Ware River Watershed water bodies. However, the narrative water quality criteria do apply as previously described.

While elevated TP concentrations pose no direct threat to drinking water quality, they can promote algal blooms, which can cause taste and odor issues when concentration thresholds for certain species are exceeded or become toxic in the case of specific cyanobacteria. With these concerns in mind, the DWSP goal for TP in streams, rivers, and Quabbin Reservoir are to maintain naturally occurring local background concentrations.

### Silica

Silica is a necessary element for the cellular function of all living organisms. It is required for protein synthesis in all phytoplankton and is essential for the formation of siliceous skeletons and scales of diatoms and chrysophytes (Reynolds, 2006). After oxygen, silica is the most abundant element, comprising approximately 30% of the Earth's crust. It enters aquatic systems through natural weathering processes although export can be accelerated by human activities such as mining, agriculture, and disturbances of terrestrial vegetation which serve as terrestrial silica sinks. Changes in silica abundance in freshwater reservoirs can be observed on a spatial and temporal gradient as water higher in silica enters from tributaries, disperses through the reservoir and is subsequently taken up by phytoplankton, particularly diatoms in the spring.

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

### Water Temperature

Temperature is a critical parameter in controlling the amount of dissolved oxygen that is available in aquatic environments. As water temperatures increase, the amount of oxygen that can be dissolved in water decreases. Moreover, higher stream temperatures increase the solubility of nutrients and may correlate well with an increase in the growth of filamentous algae and may threaten sensitive aquatic habitats. Due to these aquatic life concerns, MassDEP has set regulatory thresholds for warm and coldwater fisheries. Unless naturally occurring, coldwater fisheries may not exceed 20 °C (68 °F) as a mean of 7-day maximum temperature. Warmwater fisheries may not exceed 28.3 °C (83 °F) as a mean of 7-day maximum temperature (314 CMR 4.05(3)(a)2 (2013)). For tributaries, the water quality goal for water temperature is to remain under the threshold temperatures for cold and warmwater fisheries, depending on their respective fishery designations.

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

## Dissolved Oxygen

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

Dissolved oxygen values in the Quabbin Reservoir remain near 100% saturation in the epilimnion most of the year due to atmospheric exposure and mixing due to wind-induced turbulence. In contrast, saturation values in the metalimnion and hypolimnion decline progressively due to microbial decomposition and the isolation of these strata from the atmosphere. The supply of oxygen at depth is not replenished until thermal structure dissipates and turnover occurs.

## Alkalinity and pH

The Hydrogen ion activity (pH) of a stream is largely a function of the groundwater hydrogeology of the basins and the effectiveness of the stream water in buffering the effects of acid precipitation. The Class A water quality standard is a range between 6.5 – 8.3 (or no change from background levels). The pH in Quabbin Reservoir is determined ultimately by the exchange of inorganic carbon between the atmosphere and water (carbon dioxide-bicarbonate-carbonate buffering). Generally, pH values in Quabbin Reservoir are unremarkable, ranging from around neutral (pH = 7) to slightly acidic (pH = 5.5). Patterns of pH distribution vertically in the water column and seasonally over the year are mainly determined by the opposing processes of photosynthesis and respiration exhibiting only minor fluctuations in the Quabbin Reservoir.

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

## Bacteria

Water bodies naturally contain many microorganisms, most of which are benign. However, there are several harmful intestinal microorganisms (viruses, bacteria, and protozoa) that are sometimes present in water (e.g., *Cryptosporidium*, *Giardia, Salmonella*). Many of these are fecal microorganisms and are known to cause a host of illnesses such as intestinal and urinary tract infections, meningitis, and septicemia, dysentery, typhoid fever, and cholera (Myers et al., 2014; USGA, n.d.a). *Escherichia coli* (*E. coli*) is a species in the fecal coliform group, which originates from fecal material of humans and other warm-blooded animals (US EPA, 1986). Some strains of *E. coli* can be deadly, especially for small children or people with weakened immune systems (USEPA & Tetra Tech Inc., 2013). The presence of *E. coli* in water is often correlated with the presence of many other pathogenetic microorganisms (Myers et al., 2014), thus it has been selected as a useful indicator of pathogen contamination in waters. Human exposure to pathogens usually occurs through recreational contact or direct consumption of drinking water that was not adequately disinfected.

Sources of *E. coli* all stem from human or animal wastes: agricultural operations with livestock or that use manure to fertilize crops, treated wastewater, septic systems, urban runoff, land application of biosolids (sludge), pet waste, and wildlife (Myers et al., 2014). The only two common *E. coli* sources not applicable to the Quabbin Reservoir Watershed are biosolids, which are prohibited, and treated wastewater discharges, of which there are none.

Massachusetts Class A surface water quality standards differentiate between bacteria standards for water supply intakes and other Class A waters, which rely on *E. coli* bacteria as the indicator of sanitary quality. The Massachusetts Class A standard for non-intake waters (314 CMR 4.05(3)(a)4.c (2013)) states that the geometric mean of all *E. coli* within the most recent six months must remain below 126 MPN/100 mL (based on a minimum of five samples) and that no single sample shall exceed 235 MPN/100 mL. DWSP prohibits wading and swimming in Quabbin Reservoir and its tributary waters, however fishing is allowed and remains an avenue for public exposure to pathogens from the water supply prior to treatment. Despite there being low risk for pathogen exposure via recreation, DWSP uses these regulatory thresholds to evaluate the sanitary quality of waters within the Quabbin Reservoir and Ware River Watersheds. As a major public water supply, regulatory requirements for pathogens at drinking water intakes are much more stringent.

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

## Specific Conductance and Dissolved Salts

Specific conductance is a measure of the ability of water to conduct an electrical current at 25 °C, dependent on the concentrations of various ions in solution (Rhodes et al., 2001; Granato et al., 2015). Freshwater systems in Massachusetts naturally contain low levels of mineral salts in solution (Granato et al., 2015). Elevated levels of specific conductance and associated dissolved solutes (e.g., Na, Cl) may stress sensitive biota, threaten ecosystems (Jackson & Jobbágy, 2005; Corsi et al., 2010), and degrade drinking water quality (Kaushal et al., 2005; Daley et al., 2009; Kelly et al., 2010). Contamination of drinking water supplies with excess Cl may increase the corrosivity of affected waters (Stets et al., 2018), posing a risk to communities with infrastructure containing lead fixtures.

Excess sodium in drinking water may compromise the health of individuals on sodium-restricted diets, such as those with hypertension, and increase the cation-exchange capacity of nearby soils (Kaushal et al., 2017), resulting in the mobilization of base cations (e.g., calcium, potassium, magnesium) to streams thereby altering natural biogeochemical cycles. The EPA established aquatic life criteria for Cl in 1988 at chronic (4-day average) and acute (1-hour average) concentrations of 230 and 830 mg/L, respectively (US EPA, 1988). Neither threshold is to be exceeded more than once every three years. MassDEP has established a linear regression model to derive Cl concentrations from specific conductance values: "Instantaneous exceedances of the acute and chronic Cl criteria are estimated to occur at [specific conductance] readings greater than 3,193 and 904 µS/cm, respectively" (MassDEP-DWM, 2018). MassDEP also established an Office of Research and Standards Guideline (ORSG) of 20 mg/L sodium in drinking water, and a secondary maximum contaminant level (SMCL) for Cl of 250 mg/L (310 CMR 22.07D (2016)). MassDEP does not enforce regulatory standards for specific conductance in drinking water.

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

## Turbidity

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

There are two standards for turbidity levels at drinking water intakes. The SWTR (310 CMR 22.08(1) (2016)) mandates that raw water turbidity levels (at the intake) always remain below 5 NTU. MassDEP regulations specify that turbidity levels may exceed 1 NTU only if it does not interfere with effective disinfection. Background concentrations of turbidity in rivers and streams of the Quabbin Reservoir and Ware River Watersheds ecoregions were found to range between 0.28 NTU and 4.33 NTU, with the $25^{th}$ percentile value (all seasons) of 0.8 NTU (ecoregion 58) and 1.68 NTU (ecoregion 59)' which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical turbidity criteria for these ecoregions (US EPA, 2000; US EPA 2001b). The current water quality goal for turbidity in streams and rivers is to maintain existing local background concentrations.

## UV Absorbance

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

There are no regulatory limits for $UV_{254}$, however measurements are used to calculate the amount of carbon reduction required in the treatment process to meet the two DBP regulatory standards. Although there are few management options to address organic carbon loading in streams, DWSP does proactively manage riparian vegetation along the Reservoir shoreline specifically to reduce carbon inputs from leaf litter (DWSP 2018).

## Chlorophyll *a* and Phycocyanin

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

There are currently no MA statutory action levels for algal pigments in surface waters, including drinking water sources. The EPA Office of Water does include chlorophyll *a* in its Ambient Water Quality Criteria Recommendations which are specific to the fourteen U.S. nutrient Ecoregions. The reference condition ranges listed for subecoregions 58 and 59 are 2.1 – 6 µg/L and 1.38 – 2.7 µg/L, respectively (US EPA, 2001b).

Chlorophyll *a* and phycocyanin data are only collected from reservoir locations at this time. On average, measurements for these pigments are low (<3 µg/L); however, periodic increases are observed in association with increases in algal growth. Like the algae increases, increased values are often limited to specific strata rather than spread through the entire water column.

### Phytoplankton

Algae are a large, diverse group of organisms present in nearly every ecosystem from sandy deserts to artic permafrost to freshwater reservoirs (Reynolds, 2006). In fresh water they can be planktonic (free-floating) or attached to structures including plants and rocks. Growth of freshwater algae is largely dependent on abiotic factors such as sunlight, temperature, and nutrients present in the water column. Changes in the algae community composition and density can therefore provide early indication of changes in water quality. In drinking water supplies, especially unfiltered systems, monitoring for these organisms can be extremely important, as certain taxa can produce compounds causing undesirable tastes, odors, and in limited cases, toxins. Phytoplankton can proliferate rapidly when ideal conditions are available and routine monitoring is essential for detecting density increases early in the growth phase so that appropriate management actions can be taken. For Quabbin Reservoir, these management options include potential treatment of the algae present in the Reservoir with copper sulfate and adjustments within the treatment system such as increasing the ozone dose (ozone is used as the primary disinfectant at John J. Carroll Water Treatment Plant). The MWRA is responsible for in-reservoir treatment of algae and disinfection of waters prior to delivery to local distributors (Commonwealth of MA, 2004).

Phytoplankton undergo seasonal succession, with varying genera becoming dominant at different times throughout the year. In Quabbin Reservoir, phytoplankton follow the typical pattern of a freshwater temperate water body. Diatoms are most common in the spring followed by a period of decreased productivity where chlorophytes (green algae) typically become more diverse but remain at low density. An increase in chrysophytes (golden-brown algae) is often observed in mid-summer, and a relative increase in cyanophytes during the late summer and fall is occasionally observed as these organisms take advantage of warm temperatures and nutrient influxes in the fall. Following reservoir turnover, diatom densities often increase slightly and remain dominant in the phytoplankton community throughout the winter months.

While the entire phytoplankton community is assessed by DWSP biologists, MWRA and DWSP have established thresholds for five organisms (Table 28, main text). These four chrysophyte genera and one cyanobacteria genus have previously attained problematic densities in Quabbin Reservoir and can cause undesirable tastes and odors in the water supply. Once these thresholds are exceeded, monitoring frequency is increased (typically to weekly) and action is considered.

## Zooplankton

Zooplankton are small organisms found in nearly all surface waters and are the most abundant multicellular animal on earth. They maintain a vital role in the ecosystem as grazers, providing a pathway of energy from producers to consumers at higher trophic levels (Hintz et al., 2019 and Richardson, 2008). They are also considered indicators of climate change as they are highly sensitive to changes in temperature and have a life span of less than one year, which means the zooplankton community can rapidly reflect environmental signals as populations change (Richardson, 2008). The distribution of zooplankton, composed mostly of free-floating organisms, is largely affected by local factors of a water body, such as lake area, chemical composition, and predator abundance (Havel & Shurin, 2004).

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

The primary goal of current zooplankton monitoring in the Quabbin Reservoir is to identify new occurrences of invasive species as soon as possible. No invasive zooplankton have been found in the Reservoir to date, but these species have colonized all the Great Lakes, the Finger Lakes of New York, and Lake Champlain of Vermont (Dodson, 2005). During these invasive species assessments, observations of native zooplankton are also made, establishing baseline data that may be used in the future to detect impacts from potential invaders and other environmental changes. Sample collection and scanning for presence of invasive species began in 2009.

## Secchi Disk Depth/Transparency

A Secchi disk is a tool used to estimate water clarity and the amount of light penetration in a waterbody. The Secchi disk transparency is the water depth at which a Secchi disk, a round, alternately painted, black and white disk, is barely visible from the surface. This value can be used to estimate the depth of the euphotic zone; this area in which photosynthesis occurs is approximately three times the Secchi disk transparency (Dodson, 2005). In Quabbin Reservoir, Secchi disk transparency is most often affected by phytoplankton dynamics and contributions from the major tributaries to the Quabbin Reservoir. Weather patterns also affect visibility. The reference condition ranges listed for subecoregions 58 and 59 are 4.0 – 6.1 m and 1.2 – 4.9 m, respectively (US EPA, 2001b).

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## 6.2 Appendix B. Short Term Forestry Monitoring Report

**MEMORANDUM**

**To: Yuehlin Lee, Environmental Analyst IV**

**From: Gary Moulton**

**Date: May 09, 2022**

**Subject: Monitoring Report for Forestry Lot S11SQ (PE-20-02)**

The main purpose of the DWSP forest management program in Quabbin and Ware River Watersheds is to conduct silviculture which supports and maximizes water quality. Present management focuses on forest diversity and regeneration.

As a compliance measure to protect soil and water quality, EQ section staff conducts short-term forestry monitoring program which collects water samples to measure and monitor turbidity at the stream affected by the logging activities. Turbidity is a measure of the amount of suspended sediment in water column.

Forestry Lot PE-20-02 is located on Jucket Hill Road in Belchertown, MA. Two sample locations were determined on Gates Brook at stream crossing 4 (SC4, Figure 1), where a bridge had been installed on November 23, 2020. One sample location was located upstream of the crossing and one was located downstream of the crossing.

Monthly sampling events were conducted through three different phases; prior, during, and following completion of active work. “Prior” sampling events were conducted in three consecutive months prior to the active logging work occurred and served as baseline turbidity data. The post-work sampling was conducted for a 12-month period after the active work ended. Active logging had already begun when SC4 was added to the harvest plan, which precluded pre-harvest sampling from this monitoring. The short-term forestry monitoring program at this lot covered in this report occurred from November 2020 to February 2022.

The results of the turbidity sampling (in NTU) are shown on Table 1 below. The locations of the sample sites are shown on Figure 1. The minimum turbidity of 0.10 NTU was measured at SC4 following completion of logging work on June 25, 2021 (upstream and downstream) and January 26, 2022 (downstream). The maximum turbidity (7.80 NTU) was observed at the downstream site on July 09, 2021, during the post-harvest period. This date also corresponded to the maximum turbidity observed at the upstream site (6.80 NTU). The latter was collected following tropic storm Else which brought approximately 3” of rain to the region in days preceding sample collection.

**Table 1.** Turbidity Results (NTU) for upstream and downstream locations at SC4 for FL S11DQ.

| Harvest Status | Date | Upstream Turbidity (NTU) | Downstream Turbidity (NTU) |
|---|---|---|---|
| Baseline | *No samples collected*. | | |
| Active | 11/27/2020 | 0.23 | 0.24 |
| | 12/11/2020 | 0.22 | 0.18 |
| | 01/15/2021 | 0.38 | 0.16 |
| | 01/29/2021 | 0.37 | 0.23 |
| | 02/05/2021 | 0.20 | 0.49 |
| Post-Harvest | 03/05/2021 | 0.25 | 0.24 |
| | 04/09/2021 | 0.18 | 0.17 |
| | 05/07/2021 | 0.19 | 0.19 |
| | 06/25/2021 | 0.10 | 0.10 |
| | 07/09/2021 | 6.80 | 7.80 |
| | 08/27/2021 | 0.30 | 0.27 |
| | 09/24/2021 | 0.72 | 0.78 |
| | 10/29/2021 | 0.26 | 0.24 |
| | 11/26/2021 | 0.17 | 0.15 |
| | 12/21/2021 | 0.20 | 0.16 |
| | 01/26/2022 | 0.11 | 0.10 |
| | 02/18/2022 | 0.72 | 0.67 |

Gates Brook is a tributary to Quabbin Reservoir, downstream of the confluence of the S11SQ SC1 sampling location. Several Core tributary locations as monitored biweekly for turbidity (including Boat Cove Brook, Gates Brook, 211, 212, 213, 215G, and 216 – see main text). For comparison purposes, turbidity at Gates Brook in 2021 ranged from 0.097 to 1.4 NTU. The maximum turbidity recorded in 2021 at Gates Brook was which was recorded on October 26, 2021. The minimum turbidity observed in Quabbin Reservoir Watershed Core tributary sampling sites since 2010 was 0.081 NTU at Gates Brook in January 2011 and the greatest turbidity was 23.0 NTU at Boat Cove Brook in August 2018. Variations in turbidity can be affected by many factors such as storm events, beaver dam breaches, construction related disturbances, etc.

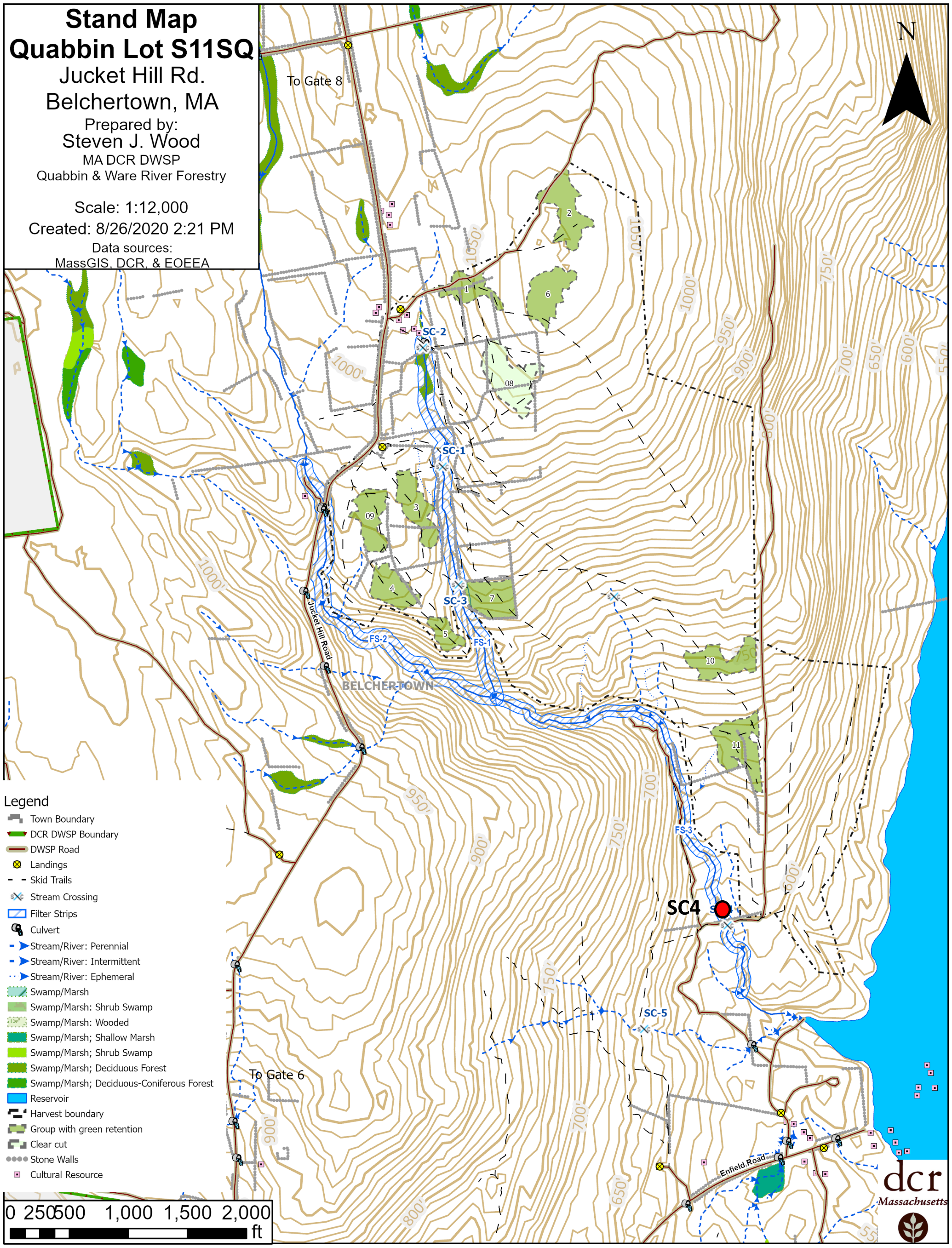


**Figure 1:** Map showing location of SC4 sampling locations relative to FL S11SQ.

## 6.3 Appendix C. Figures and Tables

### *Tables*

**Table C45:** Descriptive statistics (minimum, median, mean, and maximum) for Ca in Core tributary sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Ca (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Spring | 7 | (37) | 1.65 | (1.23) | 1.97 | (1.83) | 2.00 | (1.83) | 2.45 | (2.36) |
| | Summer | 7 | (39) | 1.42 | (1.57) | 2.10 | (2.57) | 2.27 | (2.64) | 3.08 | (4.05) |
| | Fall | 6 | (40) | 1.65 | (1.17) | 2.14 | (2.165) | 2.08 | (2.4) | 2.39 | (4.26) |
| | Winter | 6 | (37) | 1.54 | (1.15) | 1.71 | (1.83) | 1.75 | (1.85) | 2.22 | (2.8) |
| 212 | Spring | 7 | (37) | 3.06 | (0.2) | 4.00 | (3.46) | 3.87 | (3.31) | 4.30 | (4.27) |
| | Summer | 7 | (39) | 2.56 | (3.23) | 4.47 | (5.1) | 4.24 | (4.96) | 5.05 | (6.65) |
| | Fall | 6 | (40) | 3.12 | (1.35) | 3.93 | (4.795) | 3.86 | (4.64) | 4.41 | (6.51) |
| | Winter | 6 | (36) | 3.29 | (2.31) | 3.41 | (3.56) | 3.58 | (3.56) | 4.02 | (5.34) |
| 213 | Spring | 7 | (37) | 3.15 | (2.05) | 3.69 | (3.69) | 3.93 | (3.64) | 5.15 | (4.86) |
| | Summer | 7 | (39) | 2.67 | (2.17) | 4.60 | (5.41) | 4.49 | (5.22) | 5.79 | (6.9) |
| | Fall | 6 | (40) | 2.94 | (2.24) | 3.93 | (4.57) | 3.72 | (4.65) | 4.18 | (6.67) |
| | Winter | 6 | (37) | 2.95 | (1.72) | 3.19 | (3.4) | 3.39 | (3.47) | 4.62 | (5.96) |
| 215G | Spring | 7 | - | 1.94 | - | 2.02 | - | 2.07 | - | 2.27 | - |
| | Summer | 7 | - | 1.57 | - | 2.24 | - | 2.11 | - | 2.34 | - |
| | Fall | 6 | - | 1.64 | - | 1.97 | - | 1.96 | - | 2.20 | - |
| | Winter | 5 | - | 1.78 | - | 1.94 | - | 2.03 | - | 2.54 | - |
| 216 | Spring | 7 | (37) | 2.40 | (1.85) | 2.80 | (2.51) | 2.78 | (2.54) | 3.19 | (3.23) |
| | Summer | 7 | (39) | 2.50 | (2.39) | 3.14 | (3.26) | 3.05 | (3.29) | 3.34 | (4.14) |
| | Fall | 6 | (40) | 2.34 | (2.08) | 3.10 | (3.49) | 2.91 | (3.32) | 3.14 | (4.62) |
| | Winter | 6 | (37) | 2.53 | (1.98) | 2.67 | (2.92) | 2.89 | (3.07) | 3.58 | (8.01) |
| GATE | Spring | 7 | (37) | 1.11 | (0.795) | 1.13 | (1.02) | 1.14 | (1.05) | 1.18 | (1.45) |
| | Summer | 7 | (39) | 0.90 | (1.01) | 1.19 | (1.23) | 1.15 | (1.25) | 1.27 | (1.91) |
| | Fall | 6 | (37) | 0.98 | (0.852) | 1.13 | (1.42) | 1.10 | (1.36) | 1.18 | (1.92) |
| | Winter | 6 | (37) | 1.05 | (0.2) | 1.08 | (1.07) | 1.11 | (1.13) | 1.25 | (2) |
| BC | Spring | 7 | (37) | 4.55 | (2.7) | 6.28 | (5.77) | 6.27 | (5.85) | 7.75 | (8.77) |
| | Summer | 7 | (37) | 6.07 | (6.21) | 10.40 | (10.4) | 9.39 | (10.25) | 11.60 | (14.6) |
| | Fall | 6 | (35) | 3.36 | (4.18) | 9.17 | (8.51) | 8.26 | (8.73) | 9.91 | (14) |
| | Winter | 6 | (36) | 4.86 | (3.1) | 5.86 | (5.675) | 5.93 | (5.65) | 7.11 | (7.93) |

**Table C46:** Descriptive statistics (minimum, median, mean, and maximum) for Ca in Core tributary sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Ca (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Spring | 6 | (18) | 3.11 | (2.2) | 3.54 | (3.25) | 3.56 | (3.19) | 4.13 | (4.01) |
| | Summer | 7 | (19) | 2.84 | (3.12) | 4.00 | (4.22) | 3.82 | (4.22) | 4.46 | (4.94) |
| | Fall | 7 | (21) | 2.50 | (1.97) | 3.1 | (4.01) | 3.26 | (3.81) | 4.32 | (5.06) |
| | Winter | 6 | (18) | 2.86 | (2.28) | 3.88 | (3.39) | 3.74 | (3.39) | 4.27 | (4.46) |
| 102 | Spring | 6 | - | 2.79 | - | 3.11 | - | 3.11 | - | 3.47 | - |
| | Summer | 7 | - | 2.38 | - | 3.31 | - | 3.36 | - | 4.03 | - |
| | Fall | 7 | - | 2.45 | - | 3.01 | - | 2.98 | - | 3.59 | - |
| | Winter | 6 | - | 2.81 | - | 3.31 | - | 3.20 | - | 3.57 | - |
| 103A | Spring | 6 | (17) | 2.43 | (1.84) | 2.70 | (2.34) | 2.73 | (2.44) | 3.28 | (3.36) |
| | Summer | 7 | (19) | 2.48 | (2.4) | 2.88 | (3.05) | 2.97 | (3.11) | 3.98 | (4.44) |
| | Fall | 7 | (20) | 2.09 | (1.91) | 2.44 | (2.855) | 2.49 | (2.84) | 3.15 | (4.31) |
| | Winter | 6 | (15) | 2.21 | (2.14) | 3.08 | (2.65) | 3.00 | (2.7) | 3.77 | (3.36) |
| 107A | Spring | 6 | (18) | 2.77 | (2.05) | 2.87 | (2.58) | 2.95 | (2.6) | 3.34 | (3.05) |
| | Summer | 7 | (19) | 2.37 | (3.04) | 3.27 | (3.53) | 3.15 | (3.54) | 3.67 | (4.12) |
| | Fall | 7 | (20) | 2.12 | (2.04) | 2.48 | (3.35) | 2.55 | (3.36) | 3.08 | (5.28) |
| | Winter | 6 | (17) | 2.35 | (2.29) | 2.97 | (2.76) | 2.85 | (2.72) | 3.22 | (3.47) |
| 108 | Spring | 6 | (18) | 3.16 | (2.63) | 3.72 | (3.395) | 3.85 | (3.37) | 4.91 | (4.22) |
| | Summer | 7 | (19) | 3.18 | (4.4) | 4.5 | (5.71) | 4.44 | (5.5) | 5.58 | (6.56) |
| | Fall | 7 | (20) | 2.85 | (2.51) | 3.49 | (4.95) | 3.43 | (4.64) | 4.02 | (6.38) |
| | Winter | 6 | (18) | 3.18 | (2.94) | 4.47 | (3.7) | 4.15 | (3.71) | 4.70 | (4.81) |
| 121 | Spring | 6 | - | 10.9 | - | 11.4 | - | 11.8 | - | 14.4 | - |
| | Summer | 7 | - | 8.78 | - | 10.3 | - | 10.5 | - | 12.5 | - |
| | Fall | 7 | - | 6.55 | - | 9.91 | - | 9.43 | - | 10.5 | - |
| | Winter | 6 | - | 9.38 | - | 11.6 | - | 11.3 | - | 12.8 | - |

**Table C47:** Descriptive statistics (minimum, median, mean, and maximum) for alkalinity in Core tributary sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Alkalinity (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | n | | 2021 | Minimum | Median | Mean | Maximum |
| 211 | Spring | 1 | (105) | 2.44 | (0.1) | (1.6) | (1.73) | (5.2) |
| | Summer | 1 | (106) | 3.15 | (-0.2) | (3.95) | (3.9) | (7.4) |
| | Fall | 1 | (101) | 5.25 | (0.3) | (2.5) | (3.11) | (7.8) |
| | Winter | 1 | (99) | 2.66 | (-0.1) | (2) | (1.98) | (5) |
| 212 | Spring | 1 | (96) | 5.54 | (2.2) | (4.365) | (4.58) | (8) |
| | Summer | 1 | (99) | 9.28 | (3) | (10.1) | (9.98) | (18) |
| | Fall | 1 | (95) | 8.76 | (2.9) | (8.3) | (8.53) | (18) |
| | Winter | 1 | (89) | 6.59 | (1.3) | (5) | (4.94) | (8.1) |
| 213 | Spring | 1 | (102) | 5.71 | (1.7) | (4) | (4.3) | (7.8) |
| | Summer | 1 | (105) | 6.66 | (2.1) | (10) | (9.98) | (20.2) |
| | Fall | 1 | (98) | 9.96 | (2) | (6.6) | (7.33) | (15.1) |
| | Winter | 1 | (99) | 6.44 | (1.2) | (4.4) | (4.44) | (10.1) |
| 215G | Spring | 1 | (11) | 1.46 | (1.23) | (1.89) | (1.98) | (3.3) |
| | Summer | 1 | (13) | 4.32 | (2.12) | (4.13) | (4.12) | (5.97) |
| | Fall | 1 | (13) | 4.21 | (2.26) | (4.93) | (4.7) | (6.39) |
| | Winter | 1 | (11) | 3.06 | (1.65) | (3.02) | (2.95) | (4.02) |
| 216 | Spring | 1 | (102) | 3.43 | (0.5) | (2.3) | (2.51) | (5.3) |
| | Summer | 1 | (105) | 5.19 | (1.1) | (5.2) | (5.13) | (8.5) |
| | Fall | 1 | (100) | 6.08 | (1.3) | (4.58) | (4.81) | (8.62) |
| | Winter | 1 | (95) | 3.85 | (0.8) | (2.8) | (2.94) | (5.8) |
| GATE | Spring | 1 | (78) | 1.13 | (-0.6) | (0.1) | (0.1) | (0.93) |
| | Summer | 1 | (76) | 2.01 | (-0.6) | (0.75) | (0.81) | (2.5) |
| | Fall | 1 | (74) | 1.93 | (-0.4) | (1.25) | (1.25) | (3.67) |
| | Winter | 1 | (70) | <0.50 | (-0.7) | (0.225) | (0.41) | (3.5) |
| BC | Spring | 1 | (81) | 12.5 | (5.8) | (12.8) | (13.12) | (24.9) |
| | Summer | 1 | (47) | 26.9 | (9.1) | (24.8) | (24.46) | (37.2) |
| | Fall | 1 | (45) | 26.8 | (3.86) | (19.2) | (20.37) | (36.4) |
| | Winter | 1 | (69) | 16 | (5.6) | (13.1) | (13.42) | (33.5) |

**Table C48:** Descriptive statistics (minimum, median, mean, and maximum) for alkalinity in Core tributary sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | Alkalinity (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | n | | 2021 | Minimum | Median | Mean | Maximum |
| 101 | Spring | 1 | (5) | 3.60 | (2.85) | (3.35) | (3.37) | (4.19) |
| | Summer | 1 | (5) | 3.64 | (6.4) | (7.17) | (7.34) | (8.55) |
| | Fall | 1 | (5) | 6.48 | (2.41) | (8.07) | (6.96) | (8.95) |
| | Winter | 1 | (5) | 3.17 | (1.39) | (3.12) | (3.13) | (4.45) |
| 102 | Spring | 1 | (93) | 3.96 | (1.1) | (2.8) | (2.8) | (5.1) |
| | Summer | 1 | (99) | 3.20 | (1.5) | (5.5) | (5.27) | (8) |
| | Fall | 1 | (96) | 16.3 | (1.1) | (4.95) | (4.79) | (7.6) |
| | Winter | 1 | (93) | 4.55 | (1.3) | (3.4) | (3.42) | (6.4) |
| 103A | Spring | 1 | (10) | 2.41 | (0.4) | (1.565) | (1.66) | (3.1) |
| | Summer | 1 | (5) | 2.99 | (4.65) | (4.8) | (5.23) | (6.3) |
| | Fall | 1 | (5) | 11.4 | (1.96) | (6.43) | (6.42) | (10.1) |
| | Winter | 1 | (5) | 2.27 | (1.33) | (2.45) | (3.04) | (6.6) |
| 107A | Spring | 1 | (9) | 3.01 | (1.2) | (2.02) | (2.02) | (2.92) |
| | Summer | 1 | (5) | 3.06 | (4.49) | (5.41) | (5.43) | (6.25) |
| | Fall | 1 | (5) | 4.34 | (1.09) | (6.02) | (5.1) | (6.86) |
| | Winter | 1 | (5) | 2.70 | (1.16) | (2.04) | (1.92) | (2.43) |
| 108 | Spring | 1 | (98) | 2.71 | (0.4) | (2.45) | (2.57) | (5.53) |
| | Summer | 1 | (98) | 4.06 | (2.2) | (6.35) | (6.51) | (12.8) |
| | Fall | 1 | (96) | 4.96 | (0.7) | (5.05) | (5.48) | (14) |
| | Winter | 1 | (90) | 4.31 | (0.9) | (2.7) | (3.07) | (7) |
| 121 | Spring | 1 | (107) | 8.55 | (2.5) | (6.5) | (7.12) | (16.6) |
| | Summer | 1 | (116) | 9.83 | (4.5) | (14.4) | (17.85) | (95.1) |
| | Fall | 1 | (118) | 7.55 | (4.2) | (11.4) | (13.89) | (41) |
| | Winter | 1 | (106) | 10.5 | (3.37) | (7.355) | (8.03) | (15.1) |

**Table C49:** Descriptive statistics (minimum, median, mean, and maximum) for pH in Core tributary sites in the Quabbin Reservoir Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | pH | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 211 | Spring | 8 | (240) | 5.96 | (4.85) | 6.66 | (6) | 6.64 | (5.99) | 7.09 | (7.02) |
| | Summer | 6 | (243) | 5.44 | (4.4) | 6.21 | (6.3) | 6.11 | (6.19) | 6.71 | (6.93) |
| | Fall | 6 | (238) | 5.70 | (4.9) | 6.24 | (6.12) | 6.21 | (6.1) | 6.77 | (6.93) |
| | Winter | 6 | (242) | 4.10 | (4.61) | 5.62 | (6.1) | 5.54 | (6.08) | 6.65 | (7.23) |
| 212 | Spring | 8 | (228) | 6.00 | (4.65) | 6.75 | (6.55) | 6.76 | (6.5) | 7.53 | (7.64) |
| | Summer | 6 | (232) | 6.17 | (5.1) | 6.26 | (6.79) | 6.41 | (6.7) | 6.87 | (7.43) |
| | Fall | 6 | (223) | 6.18 | (5.56) | 6.81 | (6.68) | 6.77 | (6.61) | 7.13 | (7.09) |
| | Winter | 6 | (223) | 5.78 | (4.86) | 6.66 | (6.5) | 6.60 | (6.46) | 7.08 | (7.38) |
| 213 | Spring | 8 | (237) | 5.77 | (5.02) | 6.41 | (6.18) | 6.34 | (6.12) | 6.62 | (7.07) |
| | Summer | 6 | (237) | 5.84 | (4.95) | 6.19 | (6.2) | 6.10 | (6.16) | 6.27 | (7.2) |
| | Fall | 6 | (228) | 5.53 | (5.04) | 6.08 | (6.17) | 6.04 | (6.11) | 6.41 | (6.6) |
| | Winter | 6 | (234) | 5.87 | (5.01) | 5.96 | (6.1) | 6.06 | (6.12) | 6.56 | (7.07) |
| 215G | Spring | 7 | (11) | 4.86 | (4.81) | 6.10 | (5.255) | 5.97 | (5.24) | 6.37 | (5.8) |
| | Summer | 6 | (13) | 5.31 | (4.77) | 5.78 | (5.18) | 5.77 | (5.2) | 6.18 | (5.68) |
| | Fall | 6 | (13) | 5.37 | (4.73) | 5.90 | (5.65) | 5.82 | (5.51) | 6.03 | (6.05) |
| | Winter | 4 | (11) | 5.34 | (4.8) | 5.50 | (5.36) | 5.73 | (5.4) | 6.58 | (5.81) |
| 216 | Spring | 8 | (239) | 5.31 | (5.32) | 6.53 | (6.39) | 6.35 | (6.34) | 7.23 | (7.56) |
| | Summer | 6 | (243) | 5.81 | (5.37) | 6.45 | (6.7) | 6.35 | (6.64) | 6.77 | (7.63) |
| | Fall | 6 | (234) | 5.94 | (5.53) | 6.27 | (6.6) | 6.22 | (6.54) | 6.45 | (7.13) |
| | Winter | 6 | (239) | 6.01 | (4.77) | 6.09 | (6.4) | 6.19 | (6.34) | 6.71 | (7.17) |
| GATE | Spring | 8 | (170) | 4.94 | (4.32) | 6.16 | (5.4) | 6.03 | (5.45) | 6.69 | (6.45) |
| | Summer | 6 | (174) | 4.54 | (4.39) | 5.65 | (5.985) | 5.56 | (5.93) | 6.19 | (7.21) |
| | Fall | 6 | (188) | 5.41 | (4.72) | 5.89 | (6.175) | 5.90 | (6.04) | 6.30 | (7.2) |
| | Winter | 6 | (168) | 4.68 | (4.09) | 5.70 | (5.61) | 5.65 | (5.69) | 6.68 | (7.75) |
| BC | Spring | 8 | (175) | 6.20 | (5.59) | 7.06 | (6.9) | 6.90 | (6.84) | 7.47 | (7.97) |
| | Summer | 6 | (146) | 5.85 | (5.69) | 6.40 | (7.13) | 6.34 | (7.06) | 6.75 | (7.84) |
| | Fall | 6 | (151) | 6.30 | (5.15) | 6.73 | (6.97) | 6.62 | (6.91) | 6.82 | (7.5) |
| | Winter | 6 | (169) | 6.23 | (4.23) | 6.74 | (6.8) | 6.70 | (6.71) | 7.08 | (7.5) |

**Table C50:** Descriptive statistics (minimum, median, mean, and maximum) for pH in Core tributary sites in the Ware River Watershed during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Location | Season | pH | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | | Minimum | | Median | | Mean | | Maximum | |
| 101 | Spring | 8 | (211) | 5.12 | (5.11) | 6.34 | (6.2) | 6.26 | (6.18) | 6.91 | (7.04) |
| | Summer | 6 | (207) | 6.02 | (5.03) | 6.39 | (6.45) | 6.42 | (6.4) | 6.89 | (7.21) |
| | Fall | 6 | (205) | 5.46 | (4.51) | 6.01 | (6.4) | 6.01 | (6.34) | 6.70 | (7.18) |
| | Winter | 6 | (201) | 5.54 | (5.22) | 6.04 | (6.2) | 6.03 | (6.23) | 6.54 | (7.44) |
| 102 | Spring | 8 | (104) | 6.25 | (5.8) | 6.53 | (6.39) | 6.53 | (6.31) | 6.81 | (6.7) |
| | Summer | 7 | (107) | 5.90 | (5.8) | 6.14 | (6.5) | 6.09 | (6.52) | 6.28 | (6.9) |
| | Fall | 6 | (106) | 6.06 | (5.6) | 6.26 | (6.5) | 6.30 | (6.48) | 6.65 | (6.9) |
| | Winter | 6 | (103) | 6.04 | (5.7) | 6.46 | (6.4) | 6.40 | (6.36) | 6.69 | (6.8) |
| 103A | Spring | 8 | (95) | 5.91 | (4.65) | 6.24 | (6) | 6.25 | (5.99) | 6.71 | (7.17) |
| | Summer | 7 | (99) | 5.76 | (4.43) | 6.13 | (6.105) | 6.11 | (6.02) | 6.55 | (7.02) |
| | Fall | 6 | (98) | 5.39 | (4.56) | 5.75 | (6.115) | 5.79 | (6.04) | 6.36 | (6.9) |
| | Winter | 6 | (76) | 5.38 | (5.16) | 5.88 | (6.095) | 5.96 | (6.02) | 6.72 | (6.81) |
| 107A | Spring | 8 | (97) | 5.81 | (4.48) | 6.17 | (5.98) | 6.14 | (5.94) | 6.39 | (6.91) |
| | Summer | 7 | (101) | 5.64 | (4.77) | 6.04 | (6.215) | 6.05 | (6.12) | 6.65 | (6.85) |
| | Fall | 6 | (102) | 5.18 | (3.93) | 5.85 | (6.05) | 5.89 | (6) | 6.69 | (7.01) |
| | Winter | 6 | (83) | 1.11 | (4.8) | 5.64 | (5.8) | 5.01 | (5.8) | 6.39 | (7.06) |
| 108 | Spring | 8 | (201) | 6.06 | (5.04) | 6.39 | (6.145) | 6.35 | (6.1) | 6.70 | (7.13) |
| | Summer | 7 | (202) | 5.80 | (5.06) | 6.20 | (6.3) | 6.18 | (6.23) | 6.45 | (7.03) |
| | Fall | 6 | (202) | 5.46 | (4.43) | 5.58 | (6.2) | 5.71 | (6.15) | 6.39 | (6.72) |
| | Winter | 6 | (194) | 5.59 | (5.21) | 5.97 | (6.1) | 5.98 | (6.07) | 6.47 | (6.92) |
| 121 | Spring | 8 | (117) | 6.02 | (6.1) | 6.40 | (6.495) | 6.41 | (6.48) | 6.62 | (6.88) |
| | Summer | 7 | (125) | 6.04 | (6.17) | 6.23 | (6.6) | 6.28 | (6.64) | 6.54 | (7.4) |
| | Fall | 6 | (127) | 5.61 | (6.1) | 6.01 | (6.5) | 5.94 | (6.54) | 6.34 | (7.1) |
| | Winter | 6 | (117) | 2.63 | (5.6) | 6.25 | (6.4) | 5.72 | (6.45) | 6.62 | (6.85) |

**Table C51:** Descriptive statistics (minimum, median, mean, and maximum) for physical water quality parameters monitored in Quabbin Reservoir during 2021 at DWSP monitoring site 206. Statistics provided include measurements conducted in conjunction with monthly Quabbin Reservoir water quality monitoring and routine phytoplankton sampling (January through December 2021). Negative phycocyanin concentrations (n=11) were excluded from calculations for descriptive statistics, as they likely represent sensor interference.

| Analyte | Season | n | Minimum | Median | Mean | Maximum |
|---|---|---|---|---|---|---|
| Water Temperature (°C) | Winter | 28 | 8.35 | 8.36 | 8.36 | 8.38 |
| | Spring | 85 | 4.53 | 8.2 | 8.44 | 15.56 |
| | Summer | 112 | 8.35 | 13.075 | 14.82 | 23.76 |
| | Fall | 112 | 10.27 | 13.15 | 15.88 | 22.85 |
| Chlorophyll (µg/L) | Winter | 28 | 0.46 | 0.925 | 0.87 | 1.06 |
| | Spring | 85 | 0.08 | 1.05 | 1.12 | 2.38 |
| | Summer | 112 | 0.2 | 1.05 | 1.93 | 26.81 |
| | Fall | 112 | 0.06 | 0.855 | 0.80 | 1.68 |
| Phycocyanin (µg/L) | Winter | 28 | 0.49 | 0.52 | 0.52 | 0.54 |
| | Spring | 85 | 0.22 | 0.51 | 0.51 | 0.73 |
| | Summer | 109 | 0 | 0.36 | 0.33 | 1.17 |
| | Fall | 110 | 0 | 0.25 | 0.22 | 0.44 |
| Dissolved Oxygen (mg/L) | Winter | 28 | 10.65 | 10.725 | 10.74 | 10.93 |
| | Spring | 85 | 10.28 | 11.54 | 11.87 | 13.17 |
| | Summer | 112 | 8.46 | 10.53 | 10.19 | 11.57 |
| | Fall | 112 | 6.87 | 8.63 | 8.70 | 9.97 |
| Oxygen Saturation (% Sat.) | Winter | 28 | 90.7 | 91.35 | 91.46 | 93.1 |
| | Spring | 85 | 94.7 | 101 | 100.76 | 104.9 |
| | Summer | 112 | 79.2 | 100.15 | 99.81 | 107.8 |
| | Fall | 112 | 62 | 90.35 | 87.89 | 97.8 |
| pH | Winter | 28 | 6.06 | 6.08 | 6.17 | 6.6 |
| | Spring | 85 | 6.75 | 6.93 | 6.97 | 7.47 |
| | Summer | 112 | 6.19 | 6.94 | 6.87 | 7.39 |
| | Fall | 112 | 5.76 | 6.625 | 6.47 | 7.09 |
| Specific Conductance (µS/cm) | Winter | 28 | 47.5 | 47.5 | 47.51 | 47.6 |
| | Spring | 85 | 47.7 | 48.1 | 48.07 | 48.9 |
| | Summer | 112 | 47.8 | 48 | 48.24 | 49.4 |
| | Fall | 112 | 47.4 | 47.5 | 47.88 | 49 |

**Table C52:** Descriptive statistics (minimum, median, mean, and maximum) for physical water quality parameters monitored in Quabbin Reservoir during 2021 at DWSP monitoring site Den Hill. Statistics provided include measurements conducted in conjunction with monthly Quabbin Reservoir water quality monitoring and routine phytoplankton sampling (January through December 2021). Negative phycocyanin concentrations (n=3) were excluded from calculations for descriptive statistics, as they likely represent sensor interference.

| Analyte | Season | Count | Minimum | Median | Mean | Maximum |
|---|---|---|---|---|---|---|
| Water Temperature (°C) | Winter | 19 | 6.26 | 6.37 | 6.38 | 6.49 |
| | Spring | 41 | 6.61 | 9.05 | 9.40 | 13.81 |
| | Summer | 64 | 8.72 | 15.86 | 16.25 | 25.09 |
| | Fall | 63 | 9.7 | 13.87 | 15.64 | 23.02 |
| Chlorophyll (µg/L) | Winter | 19 | 1.23 | 1.36 | 1.38 | 1.6 |
| | Spring | 41 | 0.57 | 1.67 | 1.65 | 2.71 |
| | Summer | 64 | 0.43 | 1.285 | 1.61 | 6.87 |
| | Fall | 63 | 0.19 | 1.14 | 0.99 | 1.61 |
| Phycocyanin (µg/L) | Winter | 19 | 0.59 | 0.63 | 0.63 | 0.69 |
| | Spring | 41 | 0.26 | 0.51 | 0.50 | 0.6 |
| | Summer | 64 | 0.02 | 0.265 | 0.28 | 0.55 |
| | Fall | 63 | 0.03 | 0.23 | 0.23 | 0.48 |
| Dissolved Oxygen (mg/L) | Winter | 19 | 11.09 | 11.1 | 11.11 | 11.19 |
| | Spring | 41 | 9.63 | 10.8 | 11.19 | 12.01 |
| | Summer | 64 | 4.77 | 8.515 | 8.59 | 10.65 |
| | Fall | 63 | 0.87 | 8.26 | 7.57 | 9.89 |
| Oxygen Saturation (% Sat.) | Winter | 19 | 89.7 | 90 | 90.13 | 91 |
| | Spring | 41 | 81.8 | 99 | 97.63 | 104 |
| | Summer | 64 | 41.6 | 93.9 | 87.63 | 107.6 |
| | Fall | 63 | 7.7 | 87.3 | 76.59 | 96.1 |
| pH | Winter | 19 | 6.21 | 6.24 | 6.30 | 6.62 |
| | Spring | 41 | 6.48 | 6.72 | 6.79 | 7.37 |
| | Summer | 64 | 5.96 | 6.685 | 6.61 | 7.14 |
| | Fall | 63 | 5.58 | 6.52 | 6.42 | 7.15 |
| Specific Conductance (µS/cm) | Winter | 19 | 50.3 | 50.4 | 50.39 | 50.5 |
| | Spring | 41 | 51.1 | 51.8 | 51.77 | 52.5 |
| | Summer | 64 | 48.8 | 51.05 | 50.80 | 54.5 |
| | Fall | 63 | 49 | 50.4 | 50.38 | 54.1 |

**Table C53:** Descriptive statistics (minimum, median, mean, and maximum) for alkalinity in Quabbin Reservoir Core sites during 2021. Descriptive statistics corresponding to the period of record for each site are provided in parentheses.

| Station | Depth | Season | Alkalinity (mg/L as CaCO3) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | n | | Minimum | | Median | | Mean | | Maximum | |
| 202 | Surface | Spring | 2 | (28) | 3.69 | (2.66) | 3.76 | (3.43) | 3.76 | (3.35) | 3.83 | (4.19) |
| | | Summer | 2 | (35) | 3.69 | (2.67) | 3.775 | (3.59) | 3.78 | (3.54) | 3.86 | (4.11) |
| | | Fall | 2 | (40) | 3.72 | (2.7) | 3.79 | (3.675) | 3.79 | (3.54) | 3.86 | (4.27) |
| | | Winter | 0 | (15) | - | (2.8) | - | (3.67) | - | (3.58) | - | (4.21) |
| | Mid | Spring | 2 | (25) | 3.53 | (2.64) | 3.655 | (3.61) | 3.65 | (3.44) | 3.78 | (4.4) |
| | | Summer | 2 | (47) | 3.72 | (2.47) | 3.765 | (3.45) | 3.77 | (3.39) | 3.81 | (4.09) |
| | | Fall | 2 | (45) | 3.67 | (2.73) | 3.695 | (3.63) | 3.7 | (3.52) | 3.72 | (4.5) |
| | | Winter | 0 | (16) | - | (2.75) | - | (3.515) | - | (3.47) | - | (4.38) |
| | Deep | Spring | 2 | (29) | 3.67 | (2.68) | 3.74 | (3.52) | 3.74 | (3.37) | 3.81 | (4.44) |
| | | Summer | 2 | (47) | 3.69 | (2.59) | 3.785 | (3.24) | 3.79 | (3.37) | 3.88 | (4.05) |
| | | Fall | 2 | (48) | 3.67 | (2.51) | 3.79 | (3.55) | 3.79 | (3.42) | 3.91 | (4.23) |
| | | Winter | 0 | (16) | - | (2.86) | - | (3.585) | - | (3.56) | - | (4.51) |
| 206 | Surface | Spring | 2 | (28) | 3.14 | (2.84) | 3.44 | (3.615) | 3.44 | (3.49) | 3.74 | (4.27) |
| | | Summer | 2 | (35) | 3.8 | (2.72) | 3.81 | (3.79) | 3.81 | (3.61) | 3.82 | (4.17) |
| | | Fall | 2 | (40) | 3.82 | (2.44) | 3.865 | (3.77) | 3.87 | (3.62) | 3.91 | (4.12) |
| | | Winter | 0 | (14) | - | (2.83) | - | (3.615) | - | (3.56) | - | (4.21) |
| | Mid | Spring | 2 | (24) | 3.87 | (2.7) | 3.94 | (3.63) | 3.94 | (3.57) | 4.01 | (4.33) |
| | | Summer | 2 | (47) | 3.71 | (2.44) | 3.755 | (3.42) | 3.76 | (3.41) | 3.8 | (4.09) |
| | | Fall | 2 | (45) | 3.75 | (2.61) | 3.85 | (3.63) | 3.85 | (3.57) | 3.95 | (4.31) |
| | | Winter | 0 | (15) | - | (2.84) | - | (3.49) | - | (3.51) | - | (4.12) |
| | Deep | Spring | 2 | (28) | 3.96 | (2.81) | 3.96 | (3.525) | 3.96 | (3.47) | 3.96 | (4.13) |
| | | Summer | 2 | (47) | 3.84 | (2.63) | 3.865 | (3.51) | 3.87 | (3.46) | 3.89 | (5.51) |
| | | Fall | 2 | (48) | 3.8 | (2.8) | 3.805 | (3.605) | 3.8 | (3.54) | 3.81 | (4.27) |
| | | Winter | 0 | (15) | - | (2.91) | - | (3.5) | - | (3.51) | - | (4.12) |
| DEN | Surface | Spring | 2 | (28) | 4.08 | (2.54) | 4.125 | (3.575) | 4.12 | (3.49) | 4.17 | (4.01) |
| | | Summer | 2 | (35) | 3.98 | (2.9) | 4 | (3.92) | 4 | (3.79) | 4.02 | (5.1) |
| | | Fall | 2 | (39) | 4.05 | (2.77) | 4.215 | (4.04) | 4.22 | (3.92) | 4.38 | (4.52) |
| | | Winter | 0 | (12) | - | (3.37) | - | (4.105) | - | (3.98) | - | (4.68) |
| | Mid | Spring | 2 | (25) | 3.88 | (2.76) | 3.945 | (3.58) | 3.94 | (3.52) | 4.01 | (3.91) |
| | | Summer | 2 | (47) | 4.06 | (2.84) | 4.065 | (3.71) | 4.06 | (3.6) | 4.07 | (4.46) |
| | | Fall | 2 | (43) | 4.23 | (2.97) | 4.325 | (3.95) | 4.32 | (3.87) | 4.42 | (4.62) |
| | | Winter | 0 | (12) | - | (3.41) | - | (4.1) | - | (3.96) | - | (4.37) |
| | Deep | Spring | 2 | (29) | 3.91 | (2.6) | 3.985 | (3.46) | 3.98 | (3.45) | 4.06 | (4.04) |
| | | Summer | 2 | (47) | 4.08 | (2.8) | 4.135 | (3.69) | 4.14 | (3.56) | 4.19 | (4.45) |
| | | Fall | 2 | (46) | 4.21 | (2.83) | 4.41 | (4.05) | 4.41 | (4.07) | 4.61 | (7.5) |
| | | Winter | 0 | (12) | - | (3.34) | - | (4.125) | - | (3.95) | - | (4.48) |

**Table C54:** Phytoplankton sample dates in 2021 and explanations for deviations from the standard sampling plan.

| Sampling Site | Season | Sampling Date | Frequency Summary | Reason for Deviation from Sampling Plan |
|---|---|---|---|---|
| 202 | Winter | 1/21/2021 | Monthly | Ice prevented sampling until March |
| | Spring | 3/30/2021<br>4/13/2021<br>4/28/2021<br>5/13/2021<br>5/24/2021 | Biweekly | Increased to biweekly frequency to monitor phytoplankton development following ice out. |
| | Summer | 6/8/2021<br>6/14/2021<br>6/21/2021<br>6/28/2021<br>7/6/2021<br>7/13/2021 | Weekly | Increased to weekly frequency, following June 8, 2021 results in response to elevated densities of *Chrysosphaerella.* |
| | | 7/26/2021<br>8/10/2021<br>8/25/2021 | Biweekly | n/a |
| | Fall | 9/8/2021<br>9/23/2021 | Biweekly | n/a |
| | | 10/6/2021<br>11/17/2021 | Monthly | Transition to monthly sampling, as outlined by the standard sampling plan. |
| | Winter | 12/7/2021 | Monthly | n/a |
| 206 | Spring | 3/30/2021<br>4/13/2021 | Monthly | Inclement weather and ice prevented sampling until March |
| | | 5/13/2021<br>5/24/2021 | Biweekly | Increased to biweekly frequency, following May 13, 2021 results in response to elevated densities of *Synura*. |
| | Summer | 6/8/2021<br>6/14/2021<br>6/21/2021 | Weekly | Increased to weekly frequency following June 8, 2021 in response to elevated densities of *Chrysosphaerella*. |
| | | 7/13/2021<br>8/10/2021 | Monthly | n/a |
| | Fall | 9/8/2021<br>10/6/2021<br>11/17/2021 | Monthly | n/a |
| | Winter | 12/7/2021 | Monthly | n/a |

## *Figures*

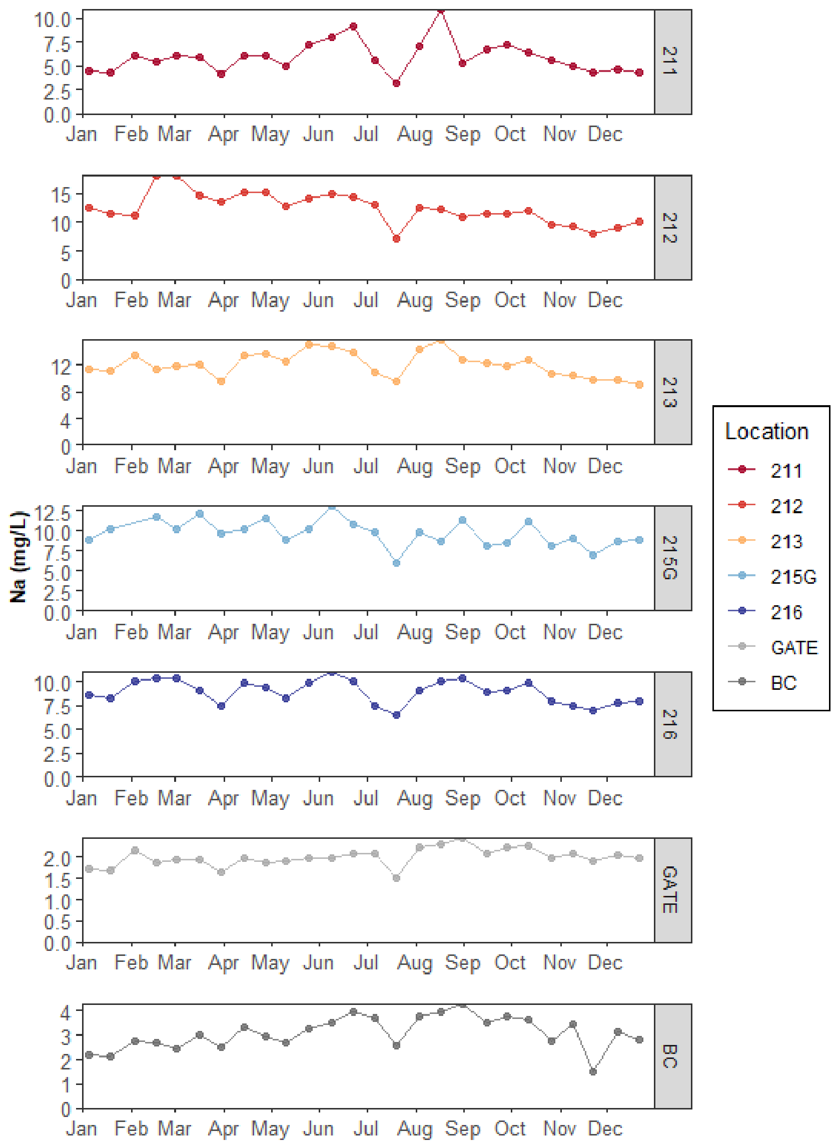


**Figure C46:** Time series of Na measured in Quabbin Reservoir Watershed Core tributary sites in 2021.

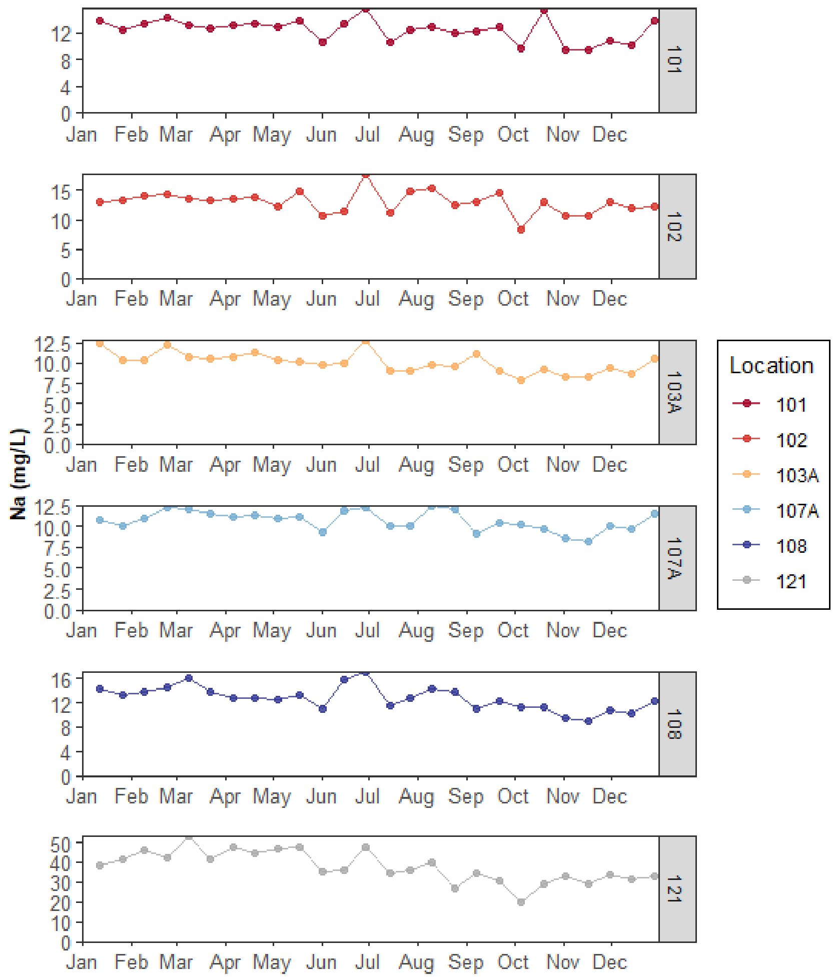


**Figure C47:** Time series of Na measured in Ware River Watershed Core tributary sites in 2021.

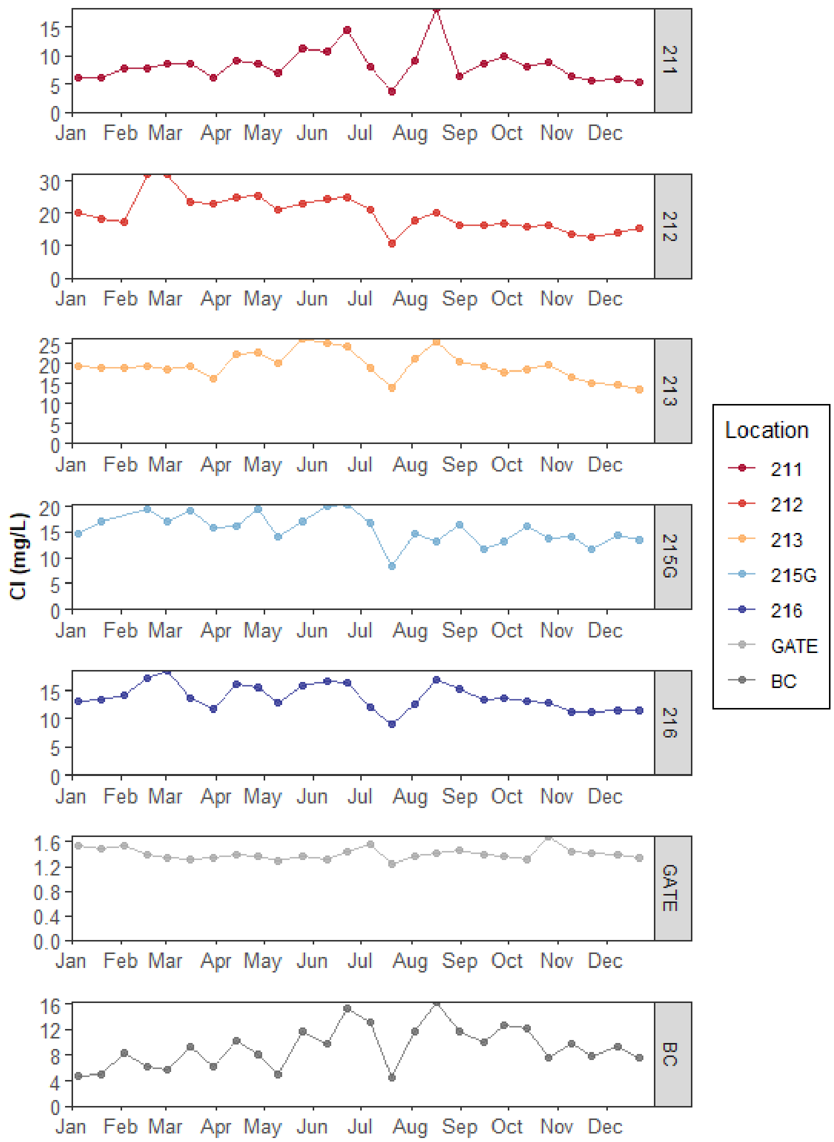


**Figure C48:** Time series of Cl measured in Quabbin Reservoir Watershed Core tributary sites in 2021.

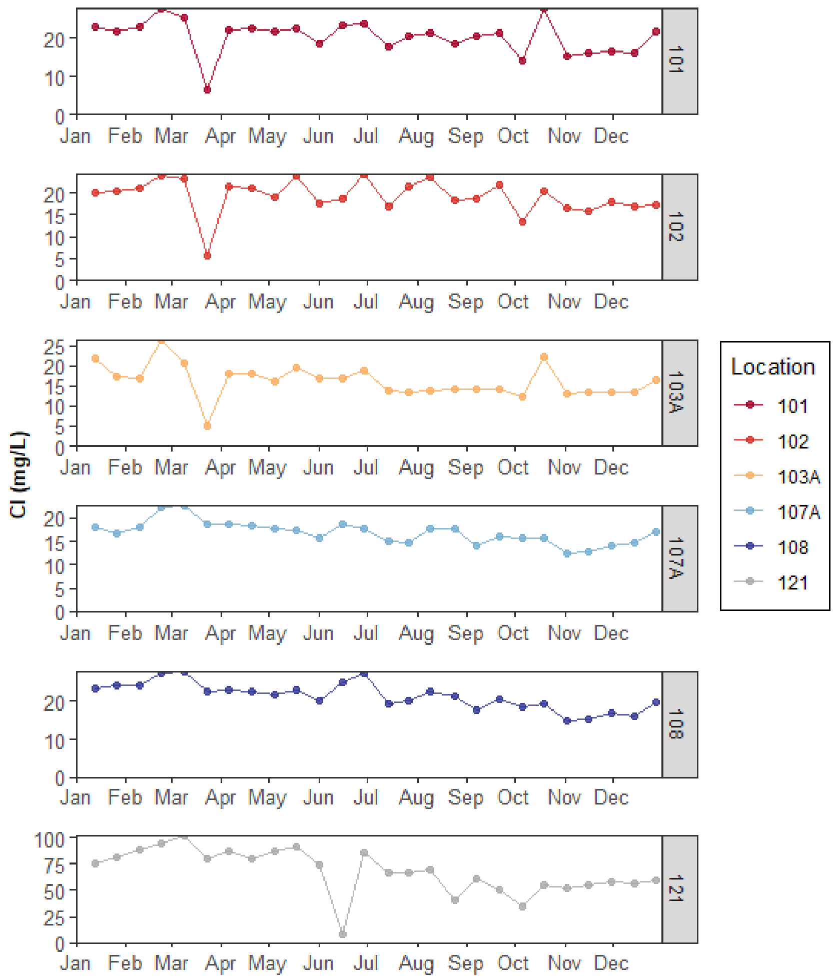


**Figure C49:** Time series of Cl measured in Ware River Watershed Core tributary sites in 2021.

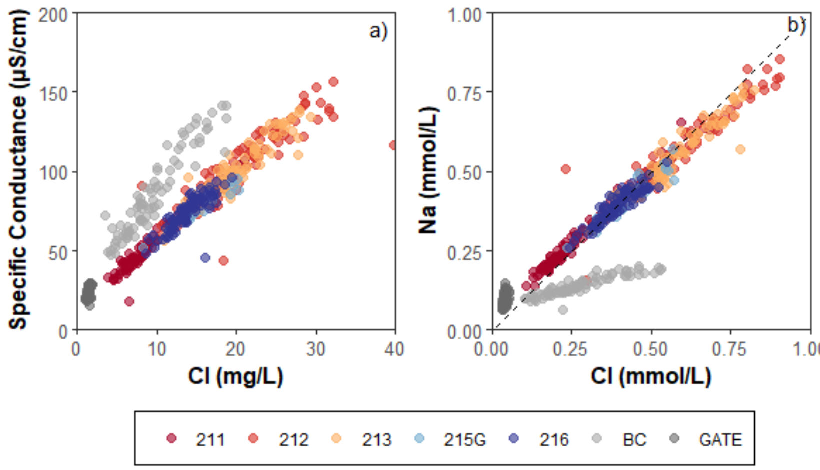


**Figure C50:** a) Specific conductance and concentrations of chloride and b) molar ratios of sodium and chloride in in Core tributaries in the Quabbin Reservoir Watershed in 2021. The dashed line denotes a 1:1 molar ratio of sodium to chloride. The clustering of results around the 1:1 line suggests that concentrations of sodium and chloride in most tributaries to the Quabbin Reservoir likely originate from halite sources (e.g. road salt). The linear relationship among variables reveals that specific conductance in most Core tributaries is predominantly controlled by concentrations of dissolved chloride.

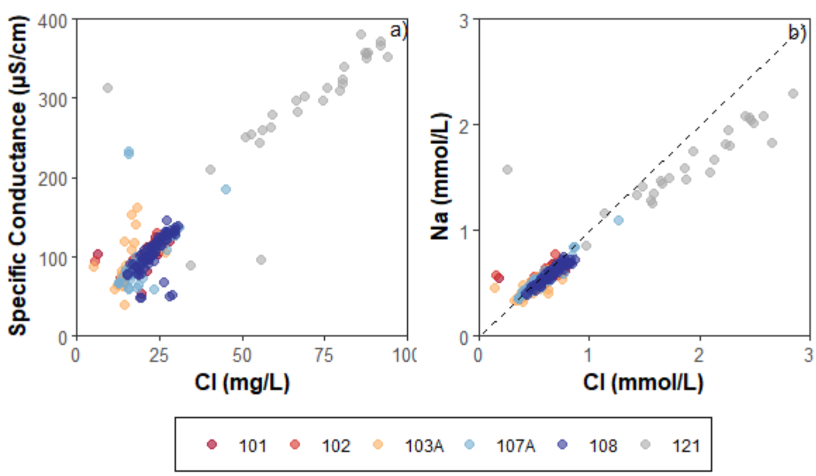


**Figure C51:** a) Specific conductance and concentrations of chloride and b) molar ratios of sodium and chloride in in Core tributaries in the Ware River Watershed in 2021. The dashed line denotes a 1:1 molar ratio of sodium to chloride. The clustering of results around the 1:1 line suggests that concentrations of sodium and chloride in most tributaries to the Quabbin Reservoir likely originate from halite sources (e.g. road salt). The linear relationship among variables reveals that specific conductance in most Core tributaries is predominantly controlled by concentrations of dissolved chloride.

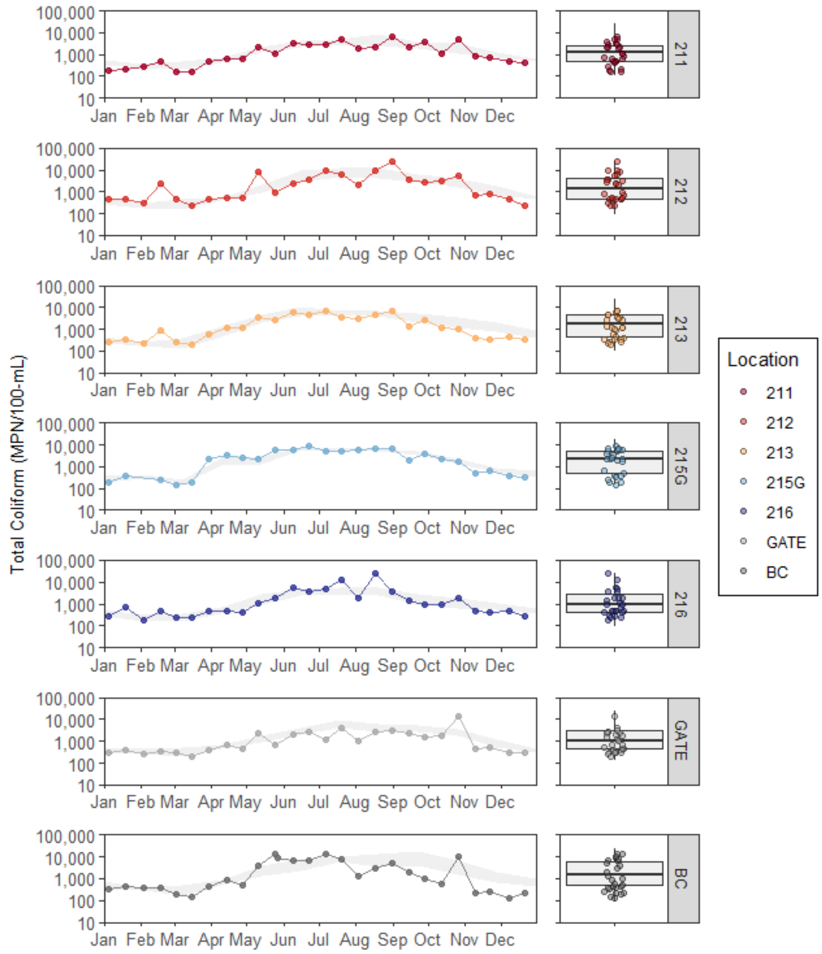


**Figure C52:** Time series and boxplots of total coliform measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel.

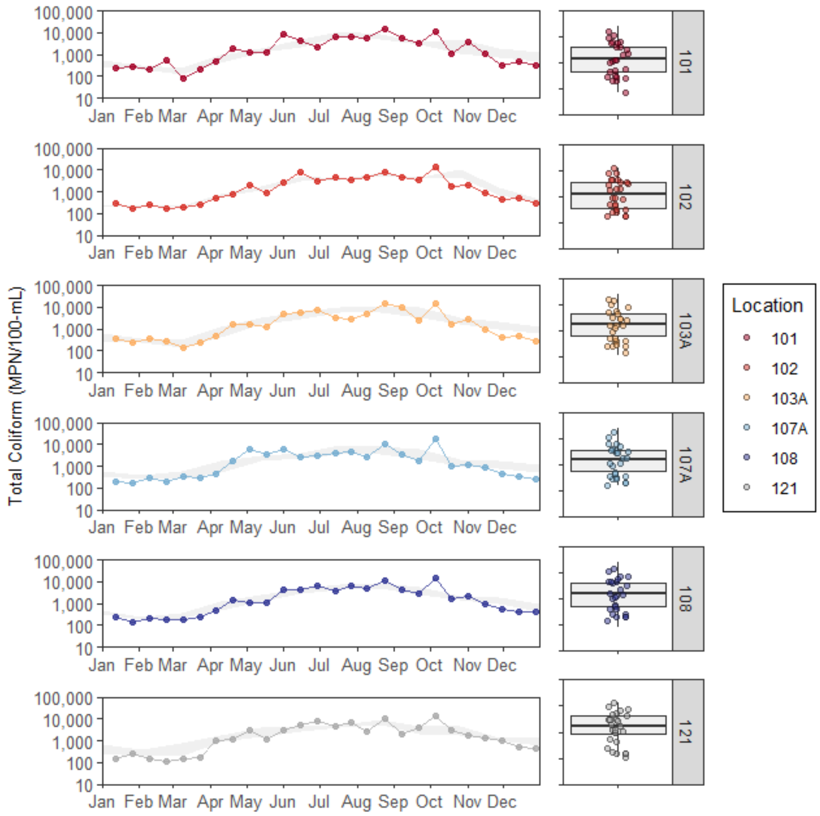


**Figure C53:** Time series and boxplots of total coliform measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel.

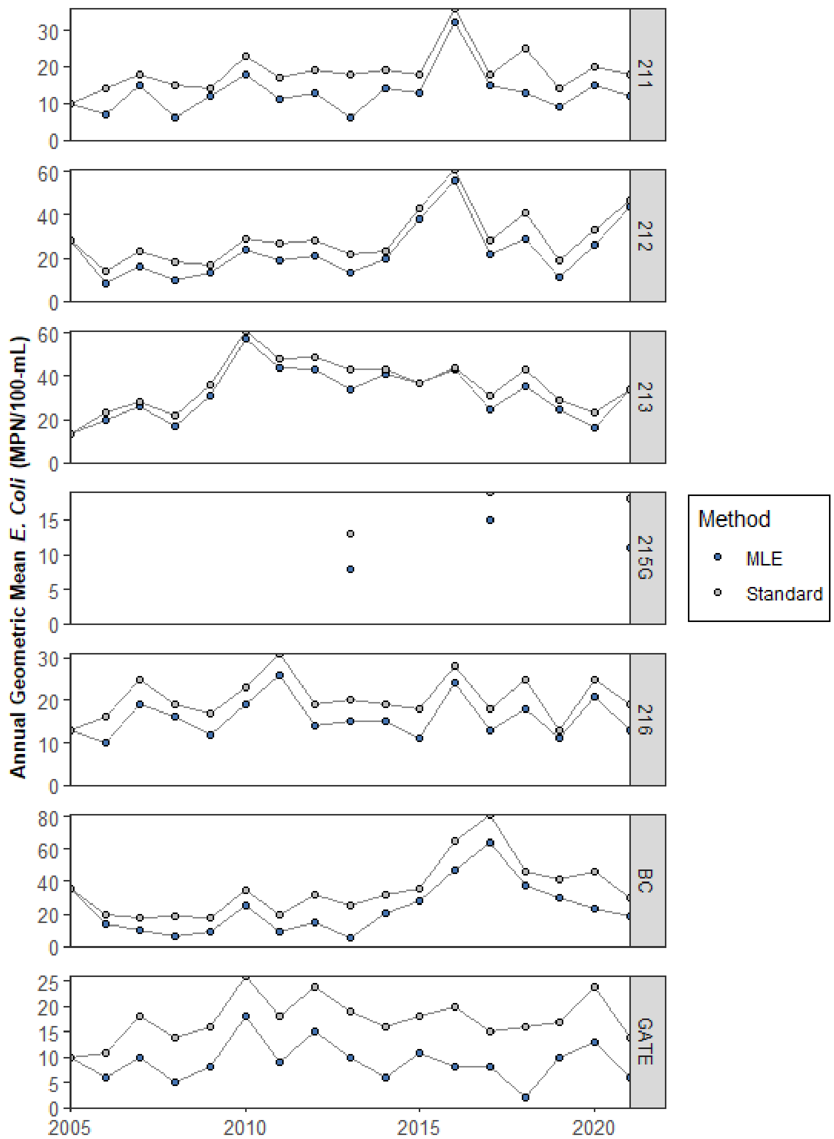


**Figure C54:** Time series of annual geometric mean *E. coli* in Quabbin Reservoir Watershed Core tributary sites from 2005 to 2021 derived via MLE and MassDEP (Standard) methods (MassDEP, 2018).

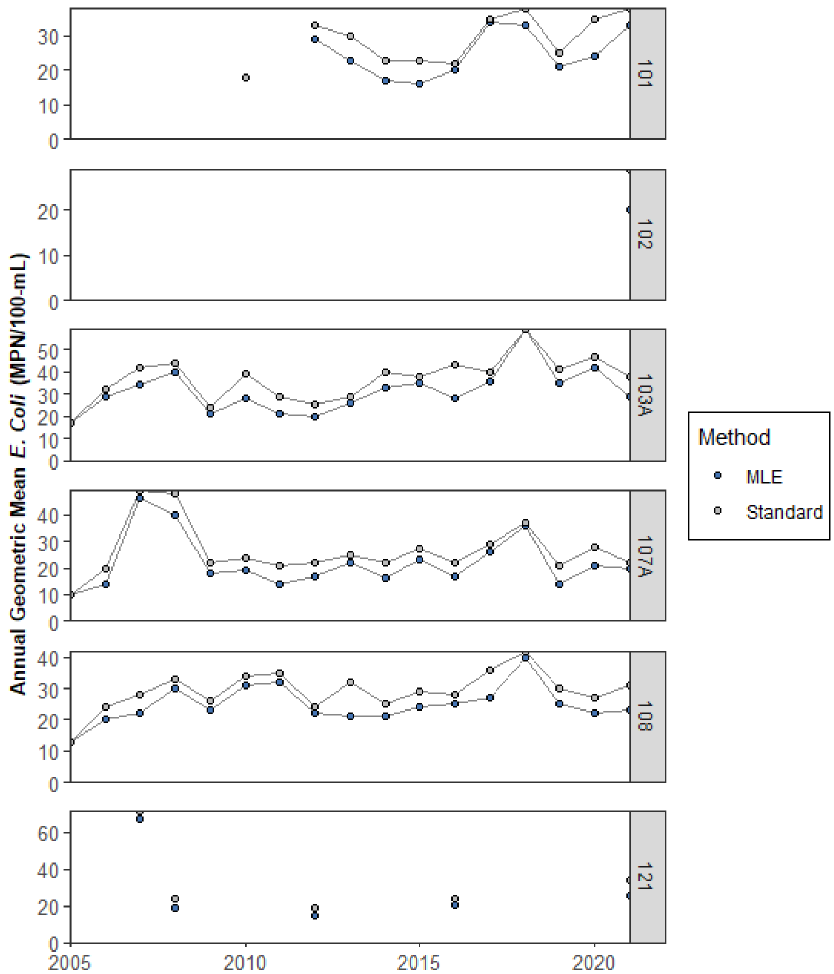


**Figure C55:** Time series of annual geometric mean *E. coli* in Ware River Watershed Core tributary sites from 2005 to 2021 derived via MLE and MassDEP (Standard) methods (MassDEP, 2018).

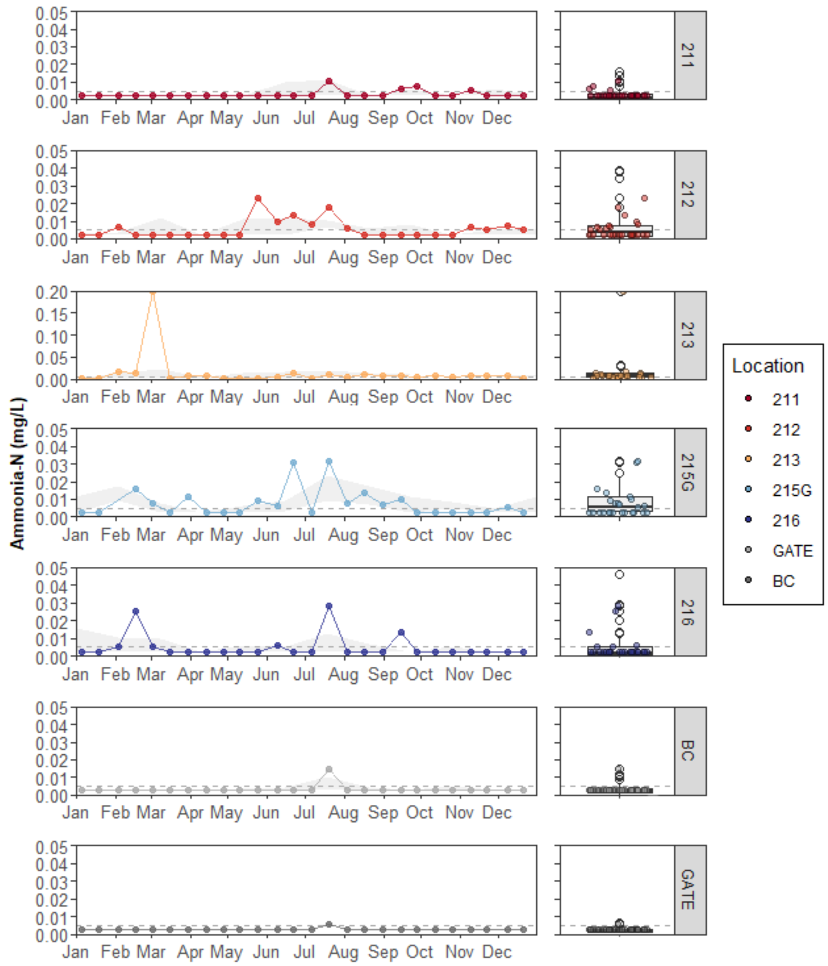


**Figure C56:** Time series and boxplots of $NH_3$-N measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey lines correspond to laboratory detection limits (10 MPN/100 mL).

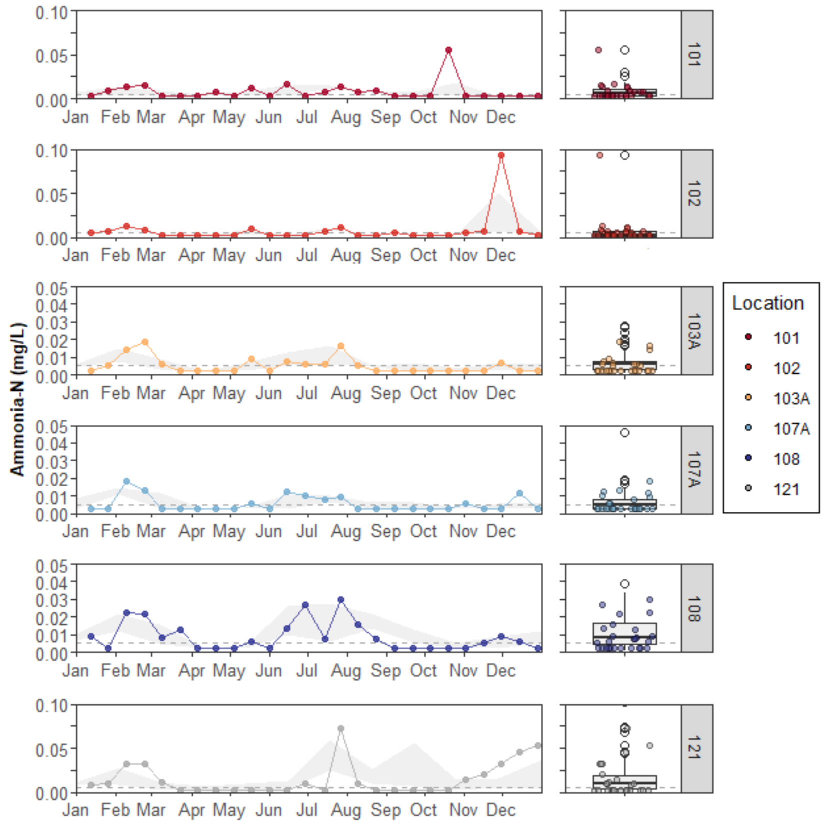


**Figure C57:** Time series and boxplots of $NH_3$-N measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey lines correspond to laboratory detection limits (10 MPN/100 mL).

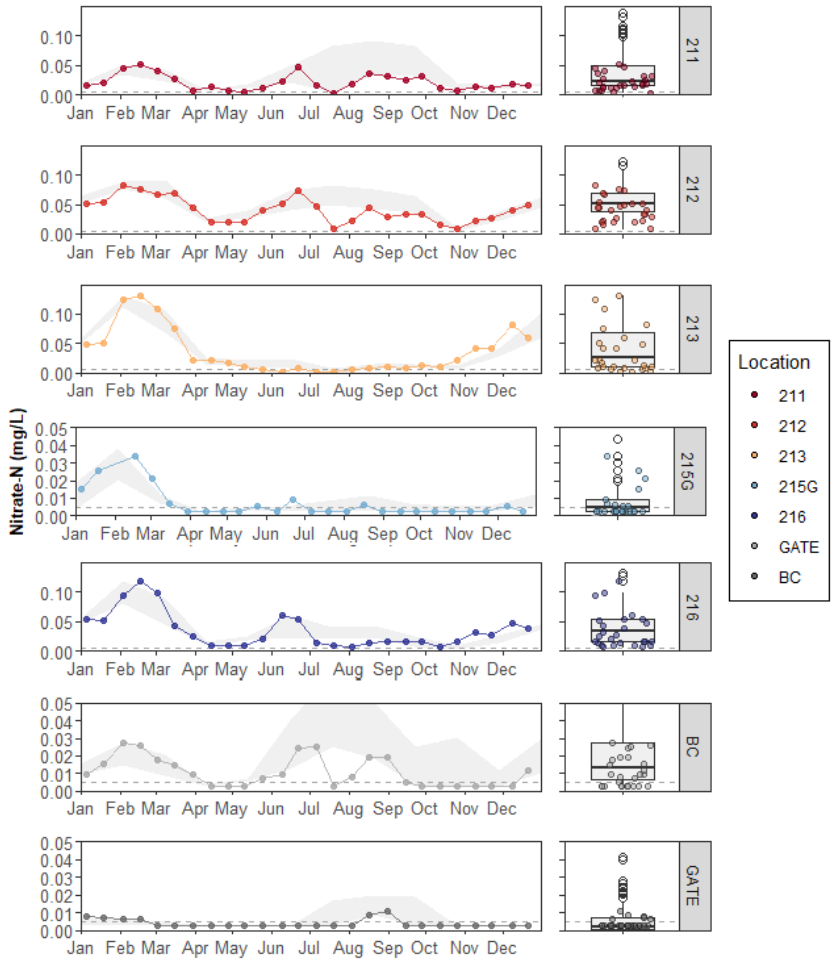


**Figure C58:** Time series and boxplots of $NO_3$-N measured in Quabbin Reservoir Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey lines correspond to laboratory detection limits (10 MPN/100 mL).

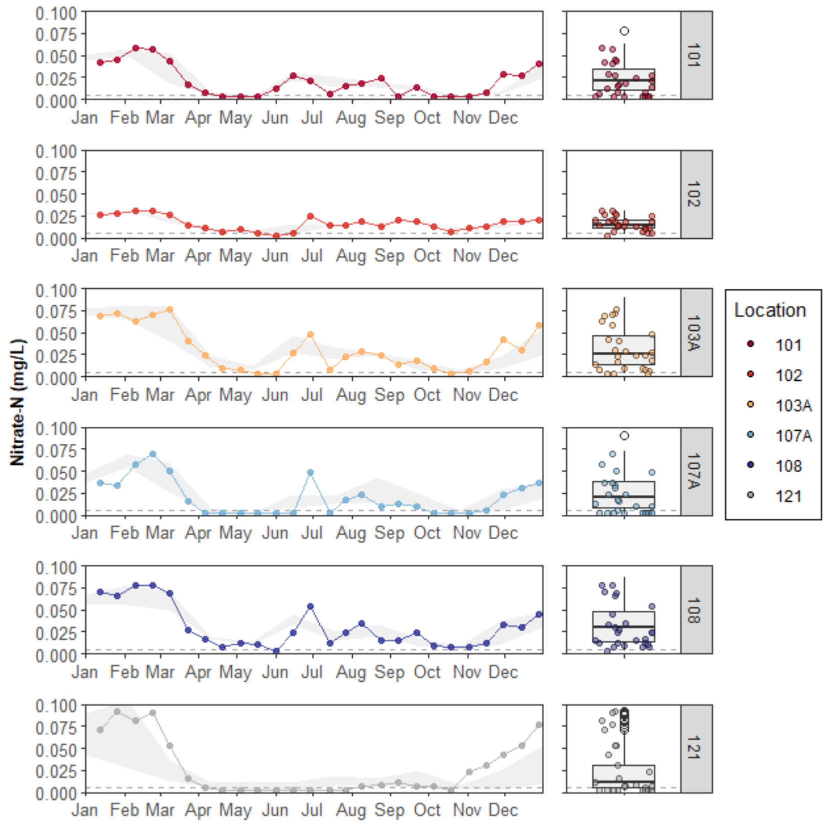


**Figure C59:** Time series and boxplots of $NO_3$-N measured in Ware River Watershed Core tributary sites in 2021. The shaded bands represent monthly interquartile ranges (25th to 75th percentile) for the period of record at each location. Data corresponding to 2021 are signified by the colored points in each panel. The horizontal dashed grey lines correspond to laboratory detection limits (10 MPN/100 mL).

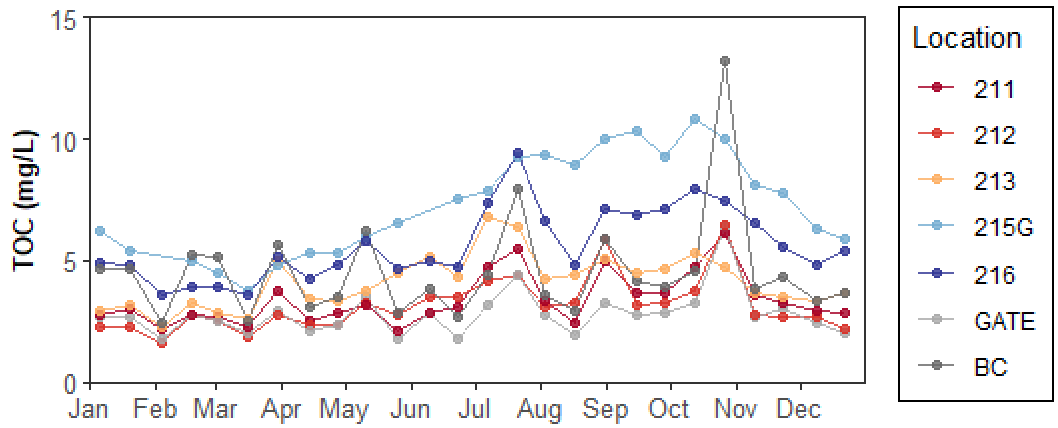


**Figure C60:** Time series of TOC measured in Quabbin Reservoir Watershed Core tributary sites in 2021.

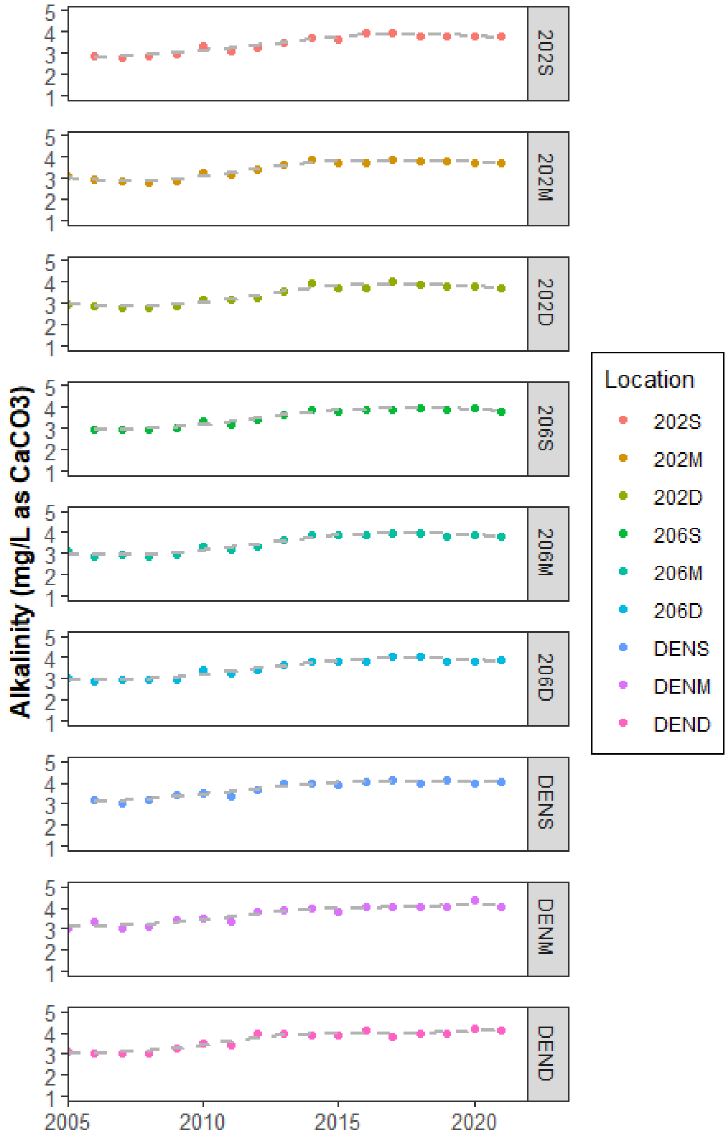


**Figure C61:** Time series of median annual alkalinity in Quabbin Reservoir Core sites, 2005 through 2021. Gray dashed line represents loess smoothing of annual median concentration results for each station/depth.

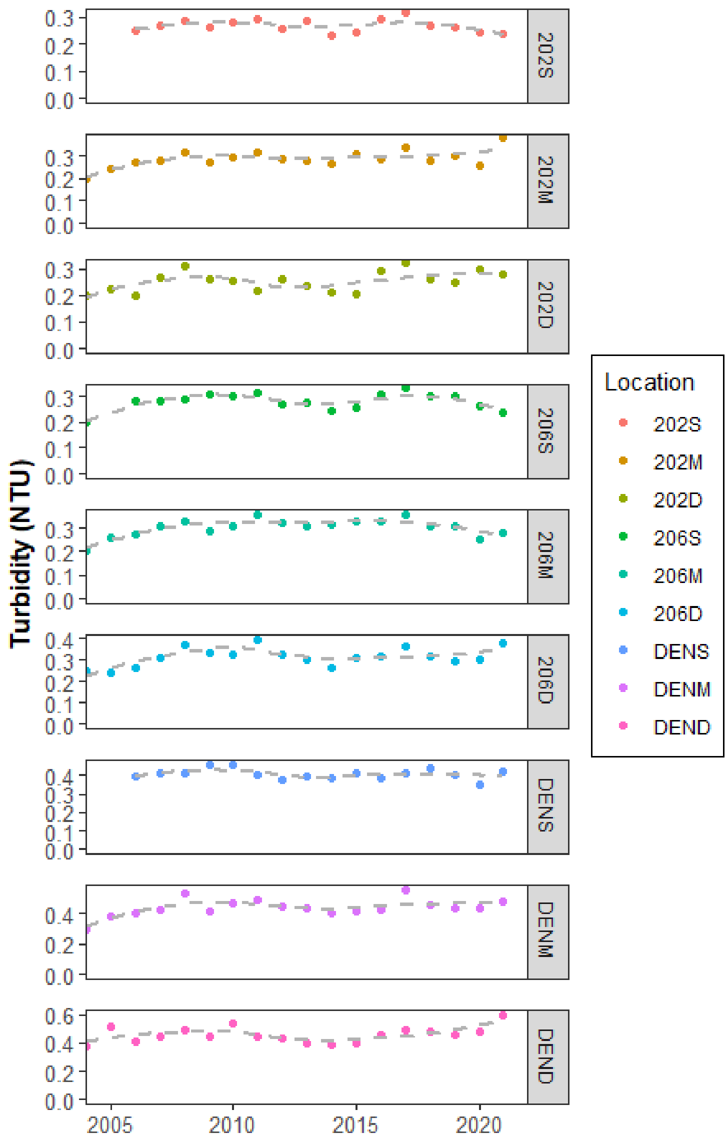


**Figure C62:** Time series of median annual turbidity in Quabbin Reservoir Core sites, 2005 through 2021. Gray dashed line represents loess smoothing of annual median concentration results for each station/depth.

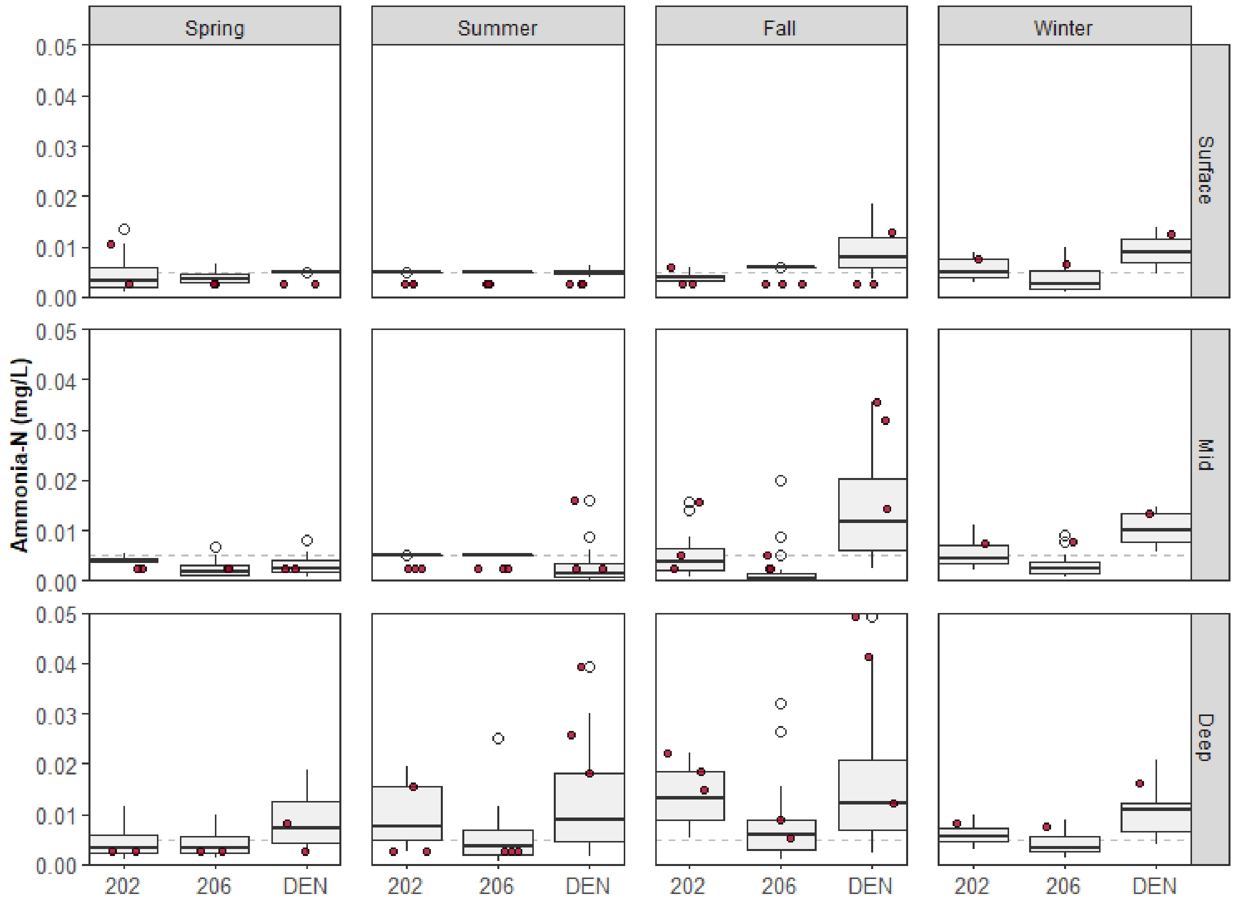


**Figure C18:** Boxplots depicting the seasonal and vertical distributions of $NH_3$-N in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2021 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

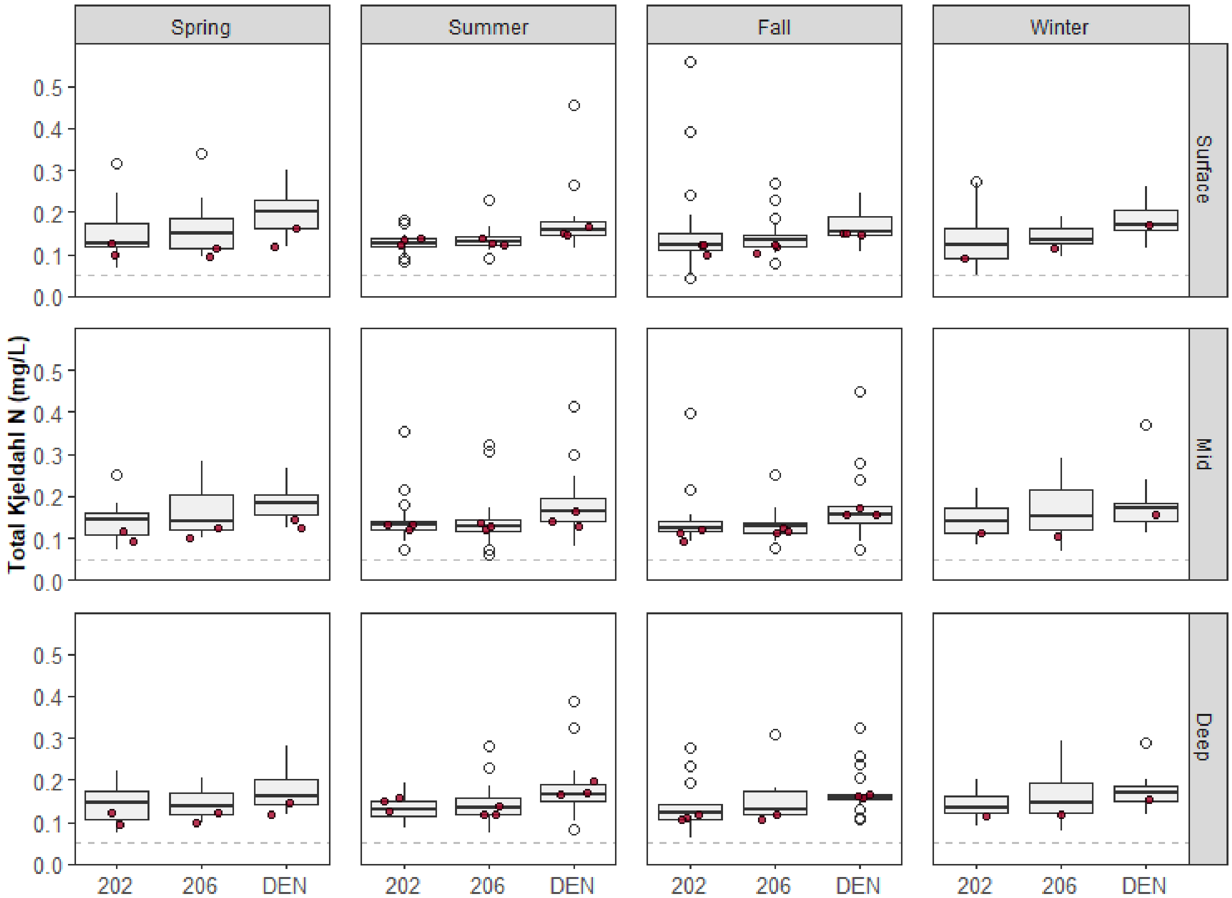


**Figure C63:** Boxplots depicting the seasonal and vertical distributions of TKN in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2021 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

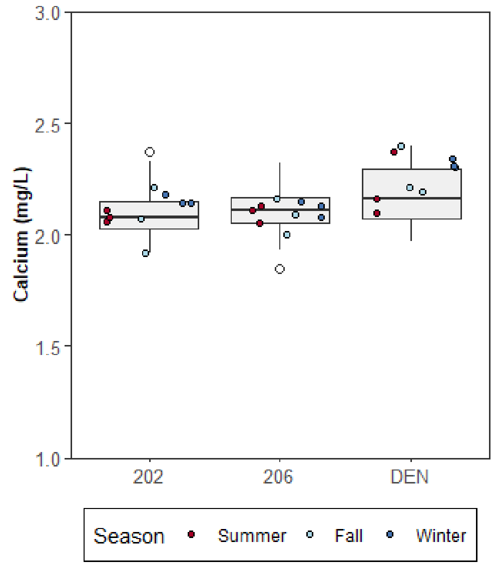


**Figure C64:** Boxplots depicting the seasonal distributions of Ca in Quabbin Reservoir Core sites. Results corresponding to samples collected in 2021 are signified by the colored points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

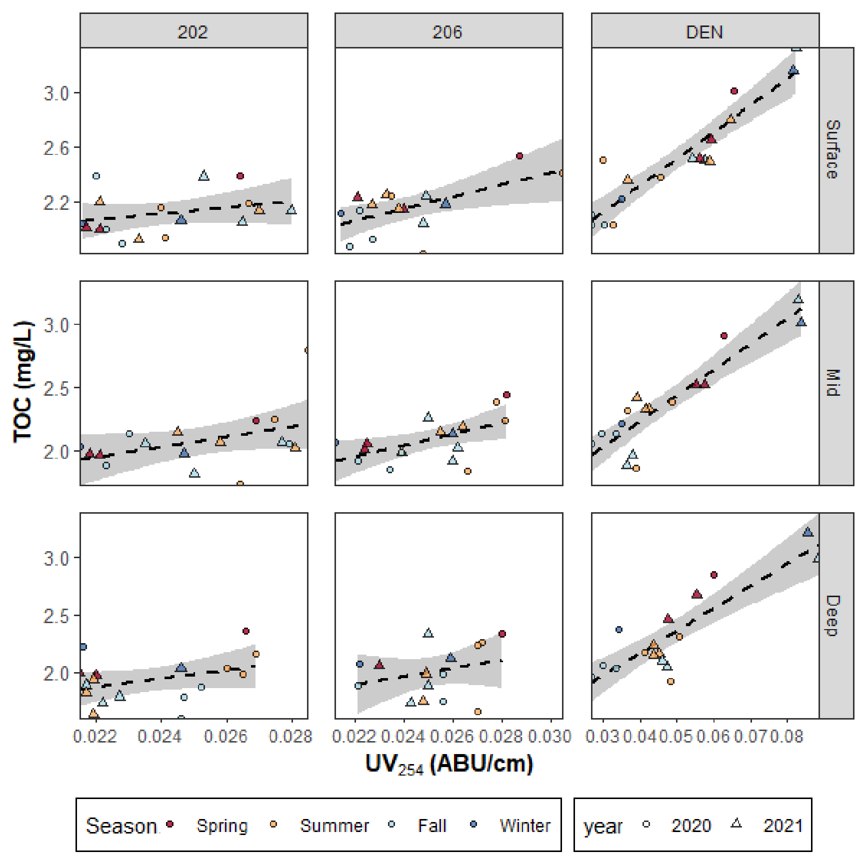


**Figure C65:** Bivariate plots of TOC and corresponding $UV_{254}$ absorbance in Quabbin Reservoir, 2020 through 2021. Linear regression and corresponding 95% CI are shown as the dashed line and gray bands, respectively.