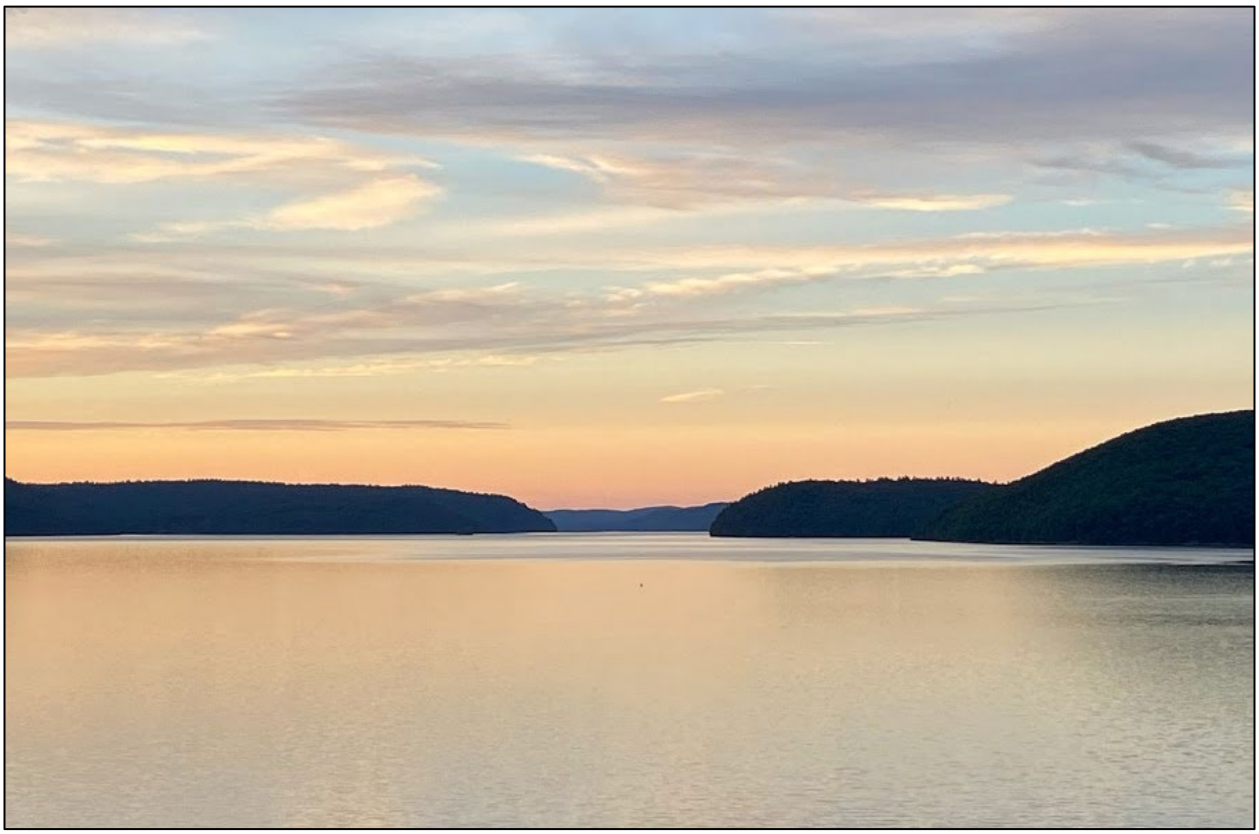
Water Quality Report: 2019

Quabbin Reservoir Watershed

Ware River Watershed



Quabbin Reservoir at dusk - Belchertown, MA (Kristina Gutchess, 2020)

August 2020

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

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Abstract

This report is a summary of water quality monitoring methods and results from 22 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 2019. 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, summary information on mean daily flows of gauged tributaries, water quality data summary tables, and plots of reservoir and tributary water quality results and flow statistics. Some of the ancillary data presented in this report has been compiled with the help 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
CVA	Chicopee Valley Aqueduct
DCR	Massachusetts Department of Conservation and Recreation
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
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
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
U.S.	United States
UV_{254}	Ultraviolet Absorbance at 254 Nanometers
USGS	U.S. Geological Survey
WDI	Winsor Dam Intake

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
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)

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1 Introduction

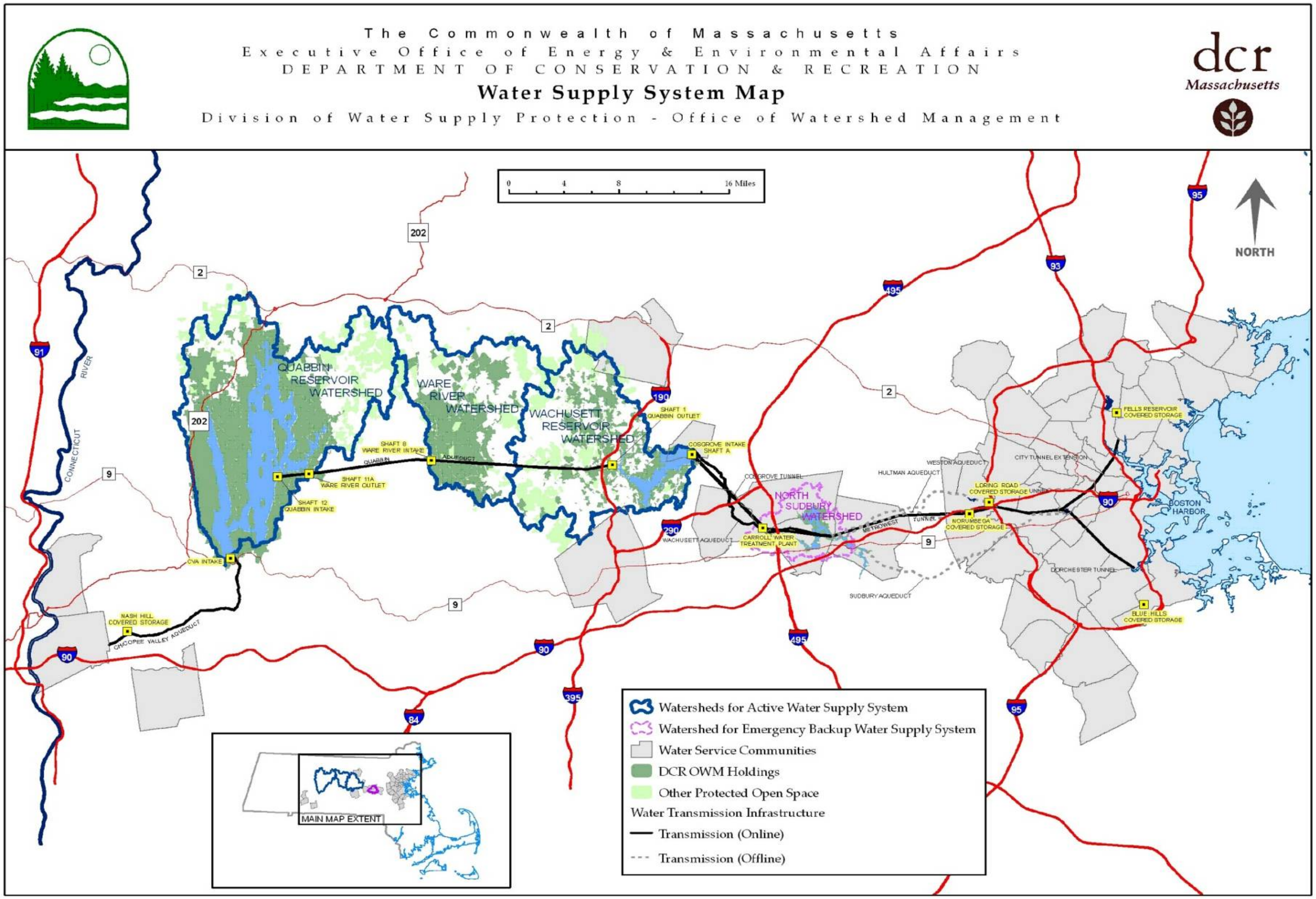
The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management (DWSP) manages and maintains a system of watersheds and reservoirs to provide water to the Massachusetts Water Resources Authority (MWRA), which in turn supplies drinking water to approximately 3.1 million people and thousands of industrial users in 51 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 2019.

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 1 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 goal of WPPs is 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, respond to potential threats to water quality to limit negative impacts, and to prioritize staff assignments to ensure that DWSP maintains adequate staffing and organization congruent with current and future watershed management issues. 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, 2017). 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. Long-term monitoring programs conducted by DWSP generated data 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 (Table 1). These objectives are as follows:

1. Maintain long-term water quality statistics relative to the protection of public health.
2. Document achievement 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 51 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).

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	119,935
Land Area	Acres	95,466
	(% Total watershed area)	80
DWSP Controlled Area (includes Quabbin Reservoir)	Acres	77,747
	(% Total watershed area)	64.8

c) Ware River Watershed General Information		
Description	**Units**	**Quantity**
Watershed Area	Acres	61,737
DWSP Controlled Area	Acres	25,486
	(% Total watershed area)	41.3

Figure 2. Map of Quabbin Reservoir watershed showing locations of Core and EQA monitoring sites sampled in 2019. Inset map in lower left depicts location of the watershed relative to MA and MWRA system.

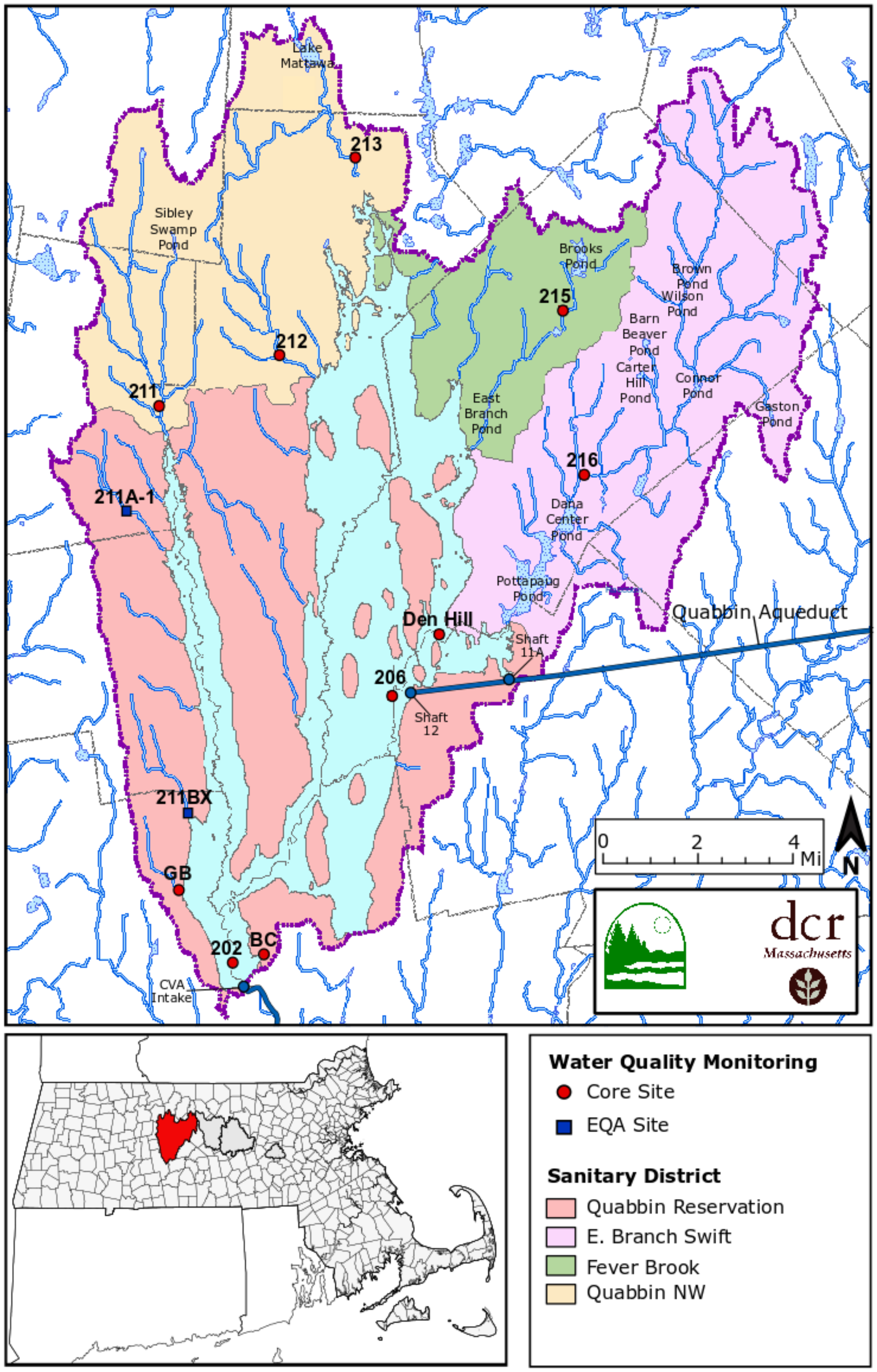
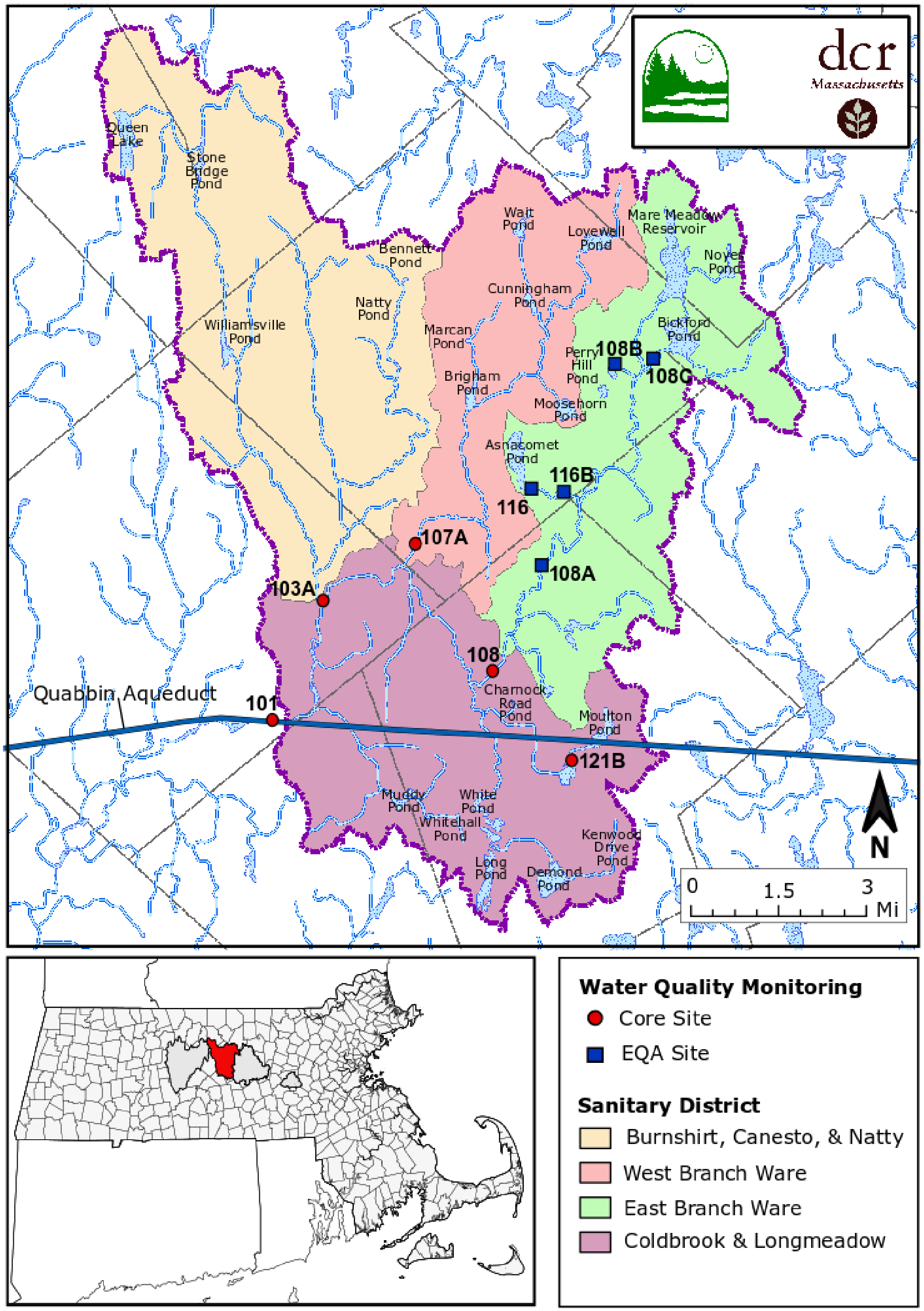


Figure 3. Map of Ware River watershed showing locations of Core and EQA monitoring sites sampled in 2019. Inset map in lower left depicts location of the watershed relative to MA and MWRA system.



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 self-certification and Cold Weather Quarantine Programs (Appendix B), 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 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 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, featuring 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).

2.1.1 Land Cover Characteristics of the Quabbin Reservoir Watershed

Approximately 88% of the land surface in the Quabbin Reservoir watershed is forested cover, with total area comprised of less than 2% each of developed (further classified as rural-residential) or agricultural cover (Tables 2). DWSP owns and controls 77,747 acres (64.8% of the total watershed area) for water supply protection purposes (Table 1). The relatively high proportion of forested, DWSP-owned lands in the Quabbin Reservoir watershed helps maintain a level of exceptional water quality in the Quabbin Reservoir.

2.1.2 Land Cover Characteristics of the Ware River Watershed

Land use in the Ware River watershed is predominantly forested (74.5%), with approximately 39% of the watershed area (24,263 acres) controlled by DWSP. The Army Corps of Engineers controls approximately 600 acres (<1%) for creation of 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 = includes 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.

Watershed	Sanitary District	Land Cover Class (% Area)							
		Forest	Agriculture	Developed	Grassland	Wetlands	Barren	Shrub	Water / Shoreline
Quabbin Reservoir Watershed	East Branch Swift	81.99	3.05	2.45	1.56	6.74	0.19	0.85	3.2
	Fever Brook	87.47	0.58	1.46	1.52	6.07	0.09	0.93	1.9
	Quabbin Northwest	87.97	1.41	2.82	1.63	4.29	0.27	0.4	1.2
	Quabbin Reservation	53.46	0.16	0.51	1.96	1.54	1.16	0.29	40.91
Ware River Watershed	Burnshirt, Canesto, & Natty	81.81	2.53	4.99	2.0	5.66	0.17	1.21	1.64
	Coldbrook & Longmeadow	71.48	2.29	4.94	1.15	14.41	0.21	1.93	3.59
	East Branch Ware	70.25	1.94	6.16	1.5	12.78	0.25	0.99	6.12
	West Branch Ware	71	2.02	4.97	1.54	14.82	0.38	1.74	3.54

2.2 Monitoring Programs

DWSP staff monitored water quality at 19 surface water sites in the Quabbin Reservoir and Ware River watersheds and three sites within the Quabbin Reservoir (Figure 2, Table 3) in 2019. 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 (Figures 2-3). EQA sites within a single sanitary district are sampled approximately once every four 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 Reservation sanitary district and the East Branch Ware River sanitary district were monitored in 2019.

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 3.2.6.

2.2.1 Meteorological and Hydrological Monitoring

2.2.1.1 Precipitation and Air Temperature

Daily measurements of precipitation and air temperatures were recorded at four locations within Quabbin Reservoir and Ware River watersheds in 2019 (Table 3). DWSP maintains one weather station in the Quabbin Reservoir watershed. Meteorological summaries presented in this report correspond to DWSP monitoring site (USC00190562).

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 2019 (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 the National Oceanographic and Atmospheric Association (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	1985-2019
	Orange Municipal Airport, Orange, MA	USW00054756	NOAA	1998-2019
	Barre Falls Dam, MA	USC00190408		1985-2019
	Ware, MA	USC00198793		1985-2017
Snowpack	4NW Hardwick - Q1 (Gate43A)	Q1	DWSP	2018-2019
	3SW Petersham - Q2 (Gate40)	Q2		2018-2019
	2NW New Salem - Q3 (West of 202)	Q3		2018-2019
	1N Pelham - Q4 (Pelham Lookout)	Q4		2018-2019
	4E Belchertown - Q5 (Blue Meadow)	Q5		2018-2019
	3NW Petersham - Q6 (Balls Crn)	Q6		2018-2019
Mean Daily Streamflow (cfs)	Ware River, Barre	1172500	USGS	1987-2019
	Ware River, Intake Works, Barre	1173000		1987-2019
	Ware River, Gibbs Crossing	1173500		1987-2019
	Swift River, West Ware	1175500		1995-2019
	East Branch Swift River, Hardwick	1174500		1987-2019
	West Branch Swift River, Shutesbury	1174565		1987-2019
	Lower Hop Brook	HOPB	NEON	2017-2019

2.2.2 Hydrologic Monitoring

2.2.2.1 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 2019 (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. 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 anticipated to be available in 2020 (NEON, 2020). DWSP maintained a staff gauge at one location (site GB) in 2019. Installation of staff gauges at the remaining tributaries to the Quabbin Reservoir is anticipated to resume in 2020.

2.2.2.2 Reservoir Elevation

Daily surface elevation of the Quabbin Reservoir has been measured since 2000. The DWSP Civil Engineering Section has established various spillway watch triggers (Figure 7), to aid in management decisions relative to the volume of water contained in Quabbin Reservoir. Daily Quabbin Reservoir elevation data presented are generated by DWSP Civil Engineering Section.

2.2.3 Tributary Monitoring

DWSP staff monitored water quality at 19 surface water sites in the Quabbin Reservoir and Ware River watersheds and 3 sites within the Quabbin Reservoir (Figure 2, Table 3) in 2019. 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 (Figures 2-3). 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 Reservation sanitary district and the East Branch Ware River sanitary district were monitored in 2019.

Table 4: 2019 Tributary Monitoring Program Components

Watershed	Site Type	Site Description	DWSP Site ID	Sub-catchment Characteristics		
				Drainage Area (sq. mi.)	Wetland (%)	DWSP Owned Land (%)
Quabbin Reservoir Watershed	Core	West Branch Swift River, at Route 202	211	12.42	3.4	45
		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 West Street	215	3.93	11.9	12.6
		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	<1.0	100
	EQA	Atherton Brook, at mouth	211A-1	2.07	4.0	43.9
		Cadwell Creek, at mouth	211B-X	2.59	2.9	99.0
Ware River Watershed	Core	Ware River, at Shaft 8 (intake)	101	96.5	13.9	37.8
		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
		Thayer Pond, at inlet 2	121B	2	16.5	3.1
	EQA	East Branch Ware River at Route 68	108A	17.1	0.17	0.10
		Cushing Pond Outlet at Bemis Rd	108B	0.91	0.18	0.53
		East Branch Ware River at Lombard Rd	108C	3.39	0.14	0.00
		Comet Pond Outlet	116	0.84	0.30	0.21
		Comet Pond Outlet Trib. Near Clark Rd	116B	1.5	0.22	0.26

2.2.4 Reservoir Monitoring

The Quabbin Reservoir was sampled biweekly in 2019 from April through December to monitor plankton densities, anticipate possible potential taste and odor problems, and recommend management actions, as necessary. Water-column profiles of temperature, pH, dissolved oxygen, specific conductance, chlorophyll *a*, and phycocyanin were measured biweekly in conjunction with plankton sampling. Samples were collected in May, July, October, and December at three depths from three stations within the Reservoir for analyses of nutrients, alkalinity, UV_{254}, sodium, chloride, and at one depth for calcium. Samples for bacteriological analyses, turbidity, and alkalinity were collected monthly at three depths at three sites within the Reservoir. Reservoir monitoring results are discussed in Section 3.3 of this report. Additional diagnostic sampling of the Quabbin Reservoir for phytoplankton enumeration was performed from August through October 2019 (Section 3.3.8).

Table 5: 2019 Quabbin Reservoir Monitoring Program Components

Site Name	Site ID	Location	Approximate Depth (m)
Winsor Dam	202	Quabbin Reservoir west arm, offshore of Winsor Dam along former Swift River riverbed	42
Shaft 12	206	Quabbin Reservoir at site of former Quabbin Lake, offshore of Shaft 12	28
Den Hill	Den Hill	Quabbin Reservoir eastern basin, north of Den Hill	19

2.2.4.1 Aquatic Macrophyte Monitoring

Eighteen water bodies in the Quabbin Reservoir (n=11) and Ware River watersheds (n=7) were surveyed for the presence of aquatic invasive species (AIS) between June 7 and September 10, 2019 (Table 6). Assessments of the designated fishing areas within the Quabbin Reservoir were conducted by DWSP, in collaboration with ESS Group Inc. ESS assists DWSP with early detection of AIS by surveying portions of the Quabbin Reservoir and the Ware River annually.

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 Reservation sanitary district and East Branch Ware River sanitary district were surveyed for AIS in 2019.

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 (Appendix B), in addition to annual aquatic macrophyte surveys.

Table 6: Water bodies surveyed in 2019 for aquatic invasive macrophyte species by DWSP and ESS.

<table>
<tr><th>Watershed</th><th>Location</th><th>Water Body Name</th></tr>
<tr><td rowspan="14">Quabbin Reservoir</td><td rowspan="3">Quabbin Reservoir</td><td>Fishing Area 2 - Shoreline</td></tr>
<tr><td>West Arm</td></tr>
<tr><td>Fishing Area 2</td></tr>
<tr><td>Hardwick</td><td>Pottapaug Pond</td></tr>
<tr><td>New Salem</td><td>O'Loughlin Pond</td></tr>
<tr><td>Orange</td><td>Lake Mattawa</td></tr>
<tr><td>Petersham</td><td>Connor Pond</td></tr>
<tr><td rowspan="6">Prescott Peninsula (New Salem)</td><td>Atkins Hollow Road</td></tr>
<tr><td>Fish Hill Pond</td></tr>
<tr><td>Gate 18 - 1 Pond</td></tr>
<tr><td>Gate 20 - 1 & 2 Ponds</td></tr>
<tr><td>Gate 20-15 Pond South</td></tr>
<tr><td>North Prescott Pond</td></tr>
<tr><td>Ware</td><td>Peppers Mill Pond</td></tr>
<tr><td rowspan="7">Ware River</td><td>Barre</td><td>Ware River (upstream of Shaft 8)</td></tr>
<tr><td rowspan="4">Hubbardston</td><td>Brigham Pond</td></tr>
<tr><td>Comet Pond</td></tr>
<tr><td>Cunningham Pond</td></tr>
<tr><td>Moosehorn Pond</td></tr>
<tr><td>Phillipston</td><td>Queen Lake</td></tr>
<tr><td>Rutland</td><td>Demond Pond</td></tr>
</table>

2.2.5 Special Investigations

2.2.5.1 Forestry Monitoring

When properly executed, forestry 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. Water quality sampling is conducted to ensure water quality standards are maintained on DWSP lands. Short-term monitoring (Section 3.6.1.1) focuses on direct water quality impacts that can occur during timber harvesting, whereas long-term monitoring (Section 3.2.6) involves evaluating water quality parameters as the forest regenerates following timber harvesting operations.

2.2.5.2 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 2019 focused on the Quabbin Reservation sanitary district (Figure 2) and the East Branch Ware River sanitary district (Figure 3). Concentrations of constituents measured in tributary monitoring sites in 2019 were compared to results from prior monitoring periods using the non-parametric Wilcoxon-Mann-Whitney (WMW) test (Appendix B). Non-parametric statistical methods were appropriate due to non-normal distributions of the data (Helsel and Hirsch, 2002; Helsel 2012). Lastly, concentration data from 2019 was compared to regulatory thresholds/limits, when applicable.

2.3 2019 Watershed Monitoring Parameters and Historical Context

DWSP water quality monitoring was comprised of 22 unique water quality characteristics (e.g., physical, chemical, and biological) measured in the Quabbin Reservoir and Ware River watersheds in 2019 (Table 9). 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 (Section 3).

2.4 Statistical Methods and Data Management

Concentration below laboratory reporting limits were replaced with one-half 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 2019 Wachusett Reservoir Watershed Annual Water Quality Report (DWSP, 2020). 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 2019 (Helsel, 2012).

Water quality, precipitation, and streamflow data collected since 1989 are stored in a Microsoft Access database. 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 Access database. Data generated from tributary and reservoir water quality monitoring in 2019 are available upon request.

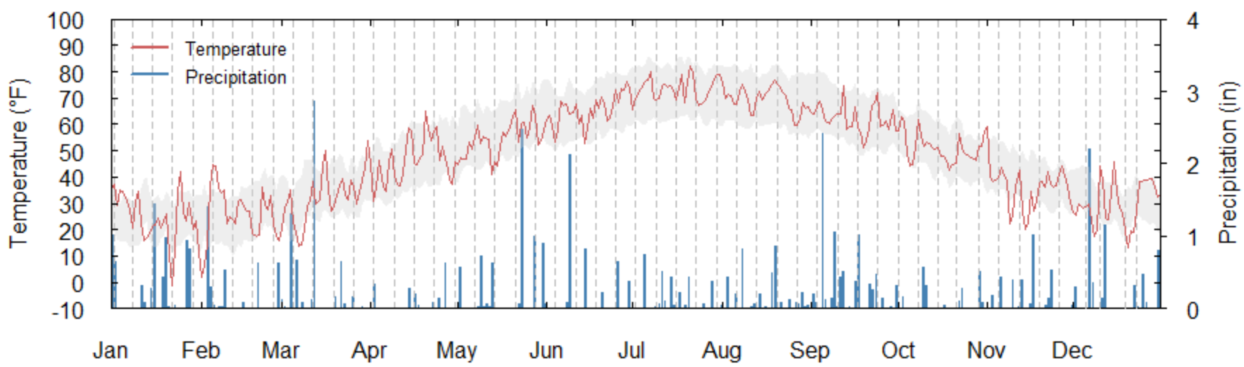
Field parameters (temperature, dissolved oxygen pH, specific conductance, chlorophyll *a*, and phycocyanin) were routinely downloaded and uploaded to the DWSP water quality database in 2019. Laboratory data (including concentrations of various constituents and plankton densities) were uploaded to the 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 2019 are summarized in Section 3.2.6.

3 Results

3.1 Hydrology and Climate

Climate in Belchertown, MA 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).

Figure 4. Climatograph of precipitation totals and daily median temperatures for Belchertown, MA (USC00190562) from January 1 through December 31, 2019. Vertical lines denote sample collection dates. Shaded band represents mean daily temperature ranges for the period of record (1985-2019).



3.1.1 Climatic Conditions

3.1.1.1 Air Temperature

Daily median temperatures in Belchertown, MA during 2019 typically fell within the average daily temperature range for the period of record. Exceptions occurred as unseasonably warm days during winter months (max. temperature of 55°F on January 25). The average daily median temperature observed at the Belchertown station during 2019 was 47.8°F, an approximate 1°F decrease from the long-term annual average median daily temperature (48.6 °F). Temperatures ranged from -9.9 to 93.9°F, with annual minimum and maximum daily temperatures occurring in February and July. Temperature extremes in January and February were sporadic, ranging from -9.9 to 55°F. Average daily temperatures during spring months (March, April, May) ranged from 24.28°F to 64.23°F (Table 7). Summer (June-August) temperatures were closer to average (54.34°F to 85.08 °F). Temperatures in the fall trended within the average range (Figure 4).

Table 7: Average monthly temperature range (presented as average daily min - max) for the period of record and 2019 for each meteorological station in the Quabbin Reservoir and Ware River watershed. Note: daily air temperature was not recorded at the meteorological station in Ware, MA (USC00198793) in 2018-2019, or at the Barre (USC00190408) station in June 2019.

Month	Barre (°F)		Belchertown (°F)		Orange (°F)	
	1985 - 2018	2019	1985 - 2018	2019	1998 - 2018	2019
Jan	12.1 - 33.1	13.77 - 34.04	15.03 - 32.27	15.53 - 33.75	12.28 - 32.16	14.12 - 32.83
Feb	12.57 - 35.23	14.68 - 37.11	15.93 - 36.08	15.71 - 36.07	13.77 - 35.45	17.96 - 37.11
Mar	20.93 - 43.99	18.87 - 45.83	24.69 - 43.85	21.28 - 43.15	23.1 - 44.09	22.09 - 43.99
Apr	31.26 - 56.33	34.63 - 60.43	34.88 - 57.37	35.27 - 57.43	33.07 - 57.83	36.96 - 58.62
May	41.61 - 67.83	42.76 - 65.08	47.09 - 69.74	44.58 - 64.23	44.53 - 69.38	46.41 - 66.88
Jun	50.43 - 75.7	-	54.77 - 75.85	54.34 - 76.47	54.03 - 76.77	54.93 - 78.39
Jul	55.8 - 80.92	58.83 - 88.32	61.38 - 82.59	62.16 - 85.08	59.22 - 82.22	62.77 - 87.44
Aug	53.73 - 79.16	54.5 - 85.33	58.91 - 80.32	57.72 - 81.23	57.84 - 80.86	57.43 - 82.58
Sep	46.15 - 72.1	45.5 - 76.98	53.12 - 73.98	50.5 - 74.28	50.03 - 73.7	48.5 - 74.66
Oct	35.06 - 59.78	38.41 - 61.86	41.4 - 60.83	42.52 - 60.36	38.16 - 60.39	41.96 - 61.89
Nov	26.88 - 48.66	25.15 - 46.24	31.49 - 48.97	26.64 - 45.37	28.78 - 49.05	25.19 - 45.2
Dec	17.72 - 37.06	15.9 - 34.9	23.37 - 38.48	20.09 - 37.55	20 - 38.18	19.23 - 37.81

3.1.1.2 Precipitation

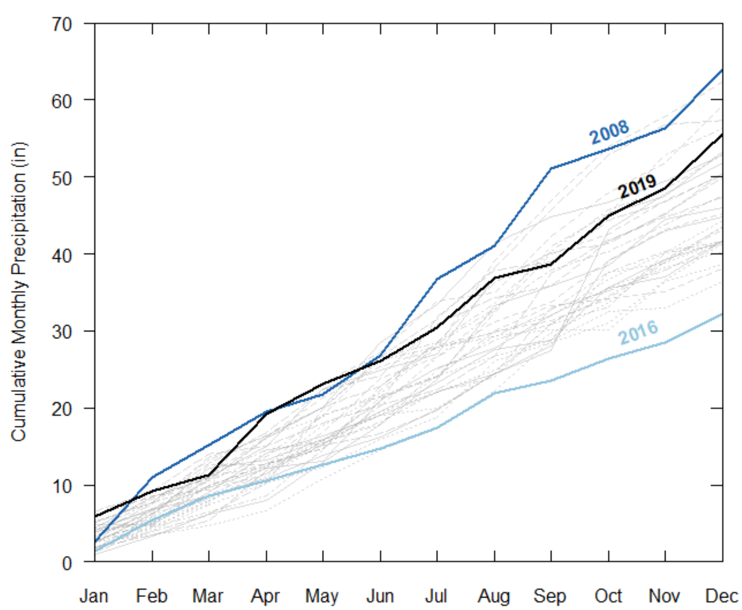
Daily precipitation has been recorded at the Belchertown monitoring station since 1939. In 2019, the total annual precipitation was 55.63 inches, exceeding the long-term average (46.87 inches) and ranking as the sixth highest annual precipitation total on record (Figure 5). Monthly precipitation totals were generally greater than the long-term median monthly total precipitation, with the exclusion of March, June, and September 2019 (Table 8). Total annual snowfall for Belchertown, MA in 2019 was 54.6 inches and occurred during the months of January, February, March, and December.

Several counties that encompass the Quabbin Reservoir and Ware River watersheds (Hampden, Hampshire, Franklin, and Worcester) were classified as in D0 level drought for consecutive weeks during the months of September and October 2019. Hampden county was also classified as D0 level drought for consecutive weeks from August 6 through 27, 2019.

Table 8: Average total monthly precipitation for the period of record and 2019 for each meteorological station in the Quabbin Reservoir and Ware River watersheds. Note: precipitation was not recorded at the meteorological station in Ware, MA (USC00198793) in 2019.

Month	Barre (in)		Belchertown (in)		Orange (in)	
	Average	2019	Average	2019	Average	2019
Jan	3.37	4.73	3.37	5.90	2.57	3.98
Feb	2.86	2.63	2.87	3.25	2.75	2.55
Mar	3.48	2.31	3.58	2.08	3.23	1.42
Apr	3.89	8.26	3.51	7.96	3.11	6.98
May	3.84	3.24	3.82	3.84	3.43	2.64
Jun	4.15	3.49	4.37	3.07	4.64	4.36
Jul	3.81	5.08	4.25	4.35	3.40	5.05
Aug	4.87	4.01	4.98	6.49	3.88	3.13
Sep	4.33	1.00	4.47	1.73	4.47	1.33
Oct	4.63	6.13	4.73	6.24	4.42	5.50
Nov	3.78	3.59	3.64	3.67	3.08	1.50
Dec	3.72	6.61	3.60	7.05	3.28	5.34

Figure 5: Annual cumulative monthly precipitation totals for Belchertown, MA (USC00190562). Colored lines indicate maximum and minimum annual precipitation (2008, and 2016, respectively) for the period of record (2008-2019).



3.1.1.2.1 Snow

Result 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, 2019c; DWSP, 2020b).

3.1.2 Streamflow

Mean daily streamflow for the East Branch Swift River in 2019 ranged from 2.12 to 1,000 cfs with an average mean daily streamflow of 111.85 cfs (Figure 6). Streamflow in the East Branch Swift River was generally within the normal to above normal range for the duration of 2019, with an extended period of low streamflow during August through October 2019. Above-normal peaks in January through March coincided with episodic snowmelt and/or precipitation events. The maximum streamflow occurred on January 26, 2019 in response to unseasonably warm air temperatures (max. temperature of 49°F and 55°F on January 25 and 26), rain-on-snow conditions, and subsequent snowmelt. Normal to above-normal stream flow was observed for much of February, from mid-April through May 2019, and the latter half of December 2019, with above-normal flows following precipitation events. Above average annual precipitation totals likely contributed to the observed deviation from normal flow ranges during these intervals.

Mean daily flows for the West Branch Swift River ranged from 0.7 to 268 cfs, with an average mean daily streamflow of 27.1 cfs in 2019 (Figure 6). Mean daily streamflow in 2019 was generally within the normal range, with above normal flows related to snowmelt and/or precipitation events, and below normal flows corresponding to periods of prolonged heat with comparatively less new precipitation (e.g., September 2019). The maximum streamflow in the West Branch Swift River occurred on April 27 following a precipitation event in excess of two inches as recorded at the Belchertown station.

Quabbin Reservoir elevation remained above normal operating range through April 2019 and above the spillway watch trigger of 528 ft through July 15, 2019. The maximum elevation of Quabbin Reservoir recorded in 2019 was 530.79 ft BCB on April 28, 2019 (Figure 7). Quabbin Reservoir elevation declined into normal operating level ranges during July 2019 and remained within normal operating ranges through the end of 2019.

Figure 6: Hydrographs of mean daily streamflow for (a; top) East Branch Swift River in Hardwick (USGS Gauge No. 01174500), (b; middle) West Branch Swift River in Shutesbury (01174656), and (c; bottom) the Ware River at the Intake Works in Barre (No. 01173000). Vertical lines mark sample collection dates for each watershed. The average of mean daily flows for the period of record (1987-2019 and 1995-2019 for East and West Branches of Swift River, respectively) are represented by the solid black line. The gray band denotes the normal (25th to 75th percentile) flow range for the period of record.

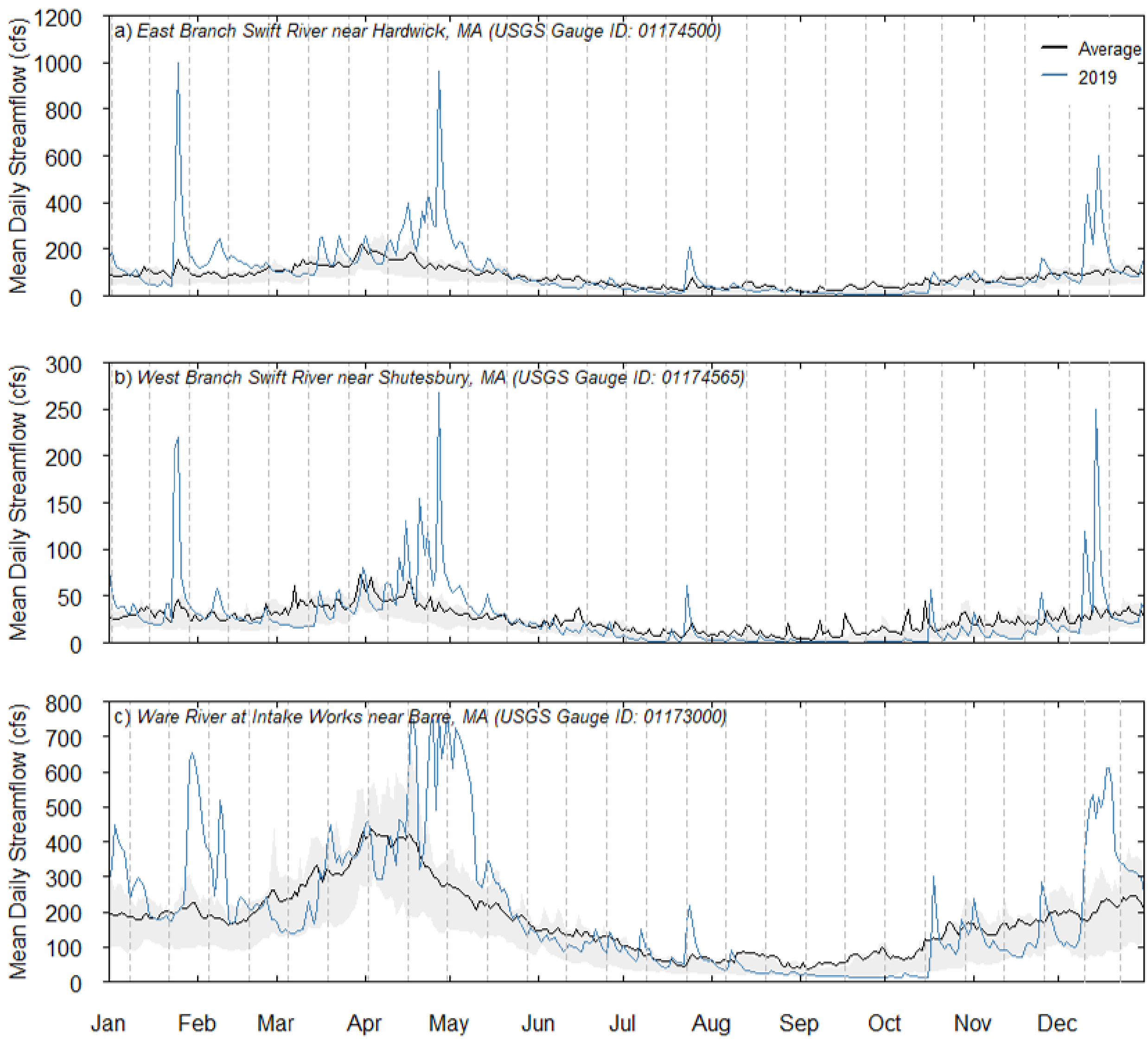
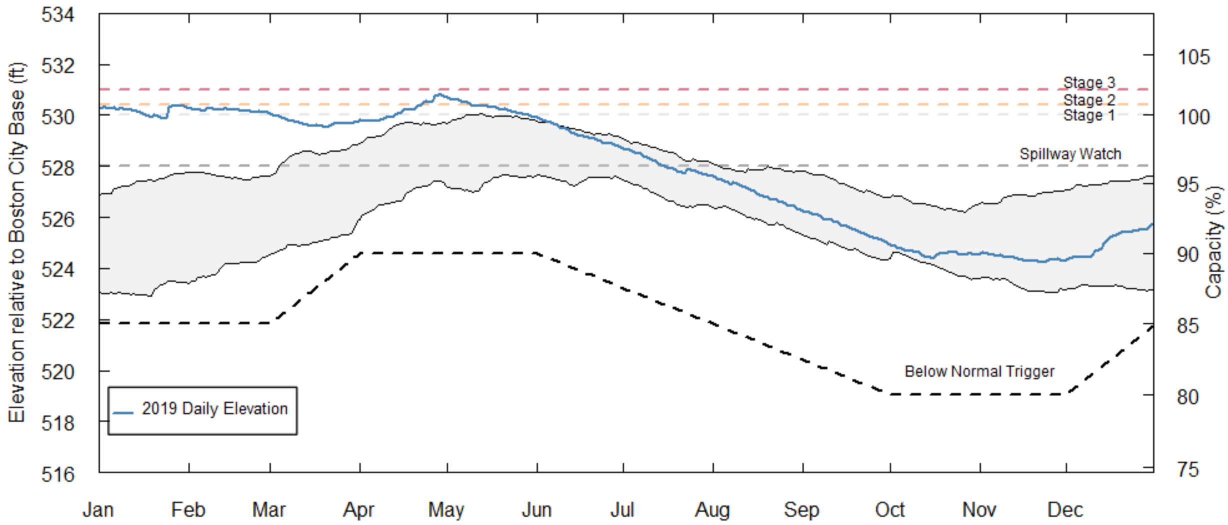


Figure 7: Daily elevation of the Quabbin Reservoir from January 1 through December 31, 2019, relative to Spillway Watch Triggers established by DWSP Civil Engineering Section. Gray band represents normal operating range.



3.2 Tributary Monitoring

3.2.1 Water Temperature, pH, and Dissolved Oxygen

Temperature in Quabbin Reservoir watershed Core tributaries ranged from -0.2 to 24.1 ˚C in 2019. In Ware River tributaries, water temperatures spanned a comparable range of -0.2 to 23.82 ˚C. Stream water temperatures in the two watersheds exhibited a distinct seasonality with maximum temperatures occurring during summer months, and minimum temperatures corresponding to winter sampling dates for both watersheds. Average seasonal water temperatures observed during 2019, with the exception of fall temperatures, were generally within 0.5 ˚C of the historic seasonal averages for Core tributary monitoring sites in Quabbin Reservoir and Ware River watersheds (Appendix C).

Dissolved oxygen concentrations in Core tributary monitoring sites in the Quabbin Reservoir and Ware River watersheds in 2019 ranged from 5.2 to 16 mg/L and 0.9 to 16.1 mg/L, respectively. Dissolved oxygen fell below the MassDEP aquatic life criteria for cold water fisheries threshold of 6 mg/L at a single site (213) during July sample events in the Quabbin Reservoir watershed. Although, dissolved oxygen remained above the MassDEP aquatic life criteria threshold of 5 mg/L for warm water fisheries during this time. This period of relatively low dissolved oxygen (5.2 to 5.9 mg/L) observed at site 213 in 2019 coincided with an extended period of low flow across watershed monitoring sites, coupled with elevated air temperatures (Figure 6; Tables 7-8). Concentrations of dissolved oxygen remained above the aquatic life criteria for cold water fisheries in all other Core tributary monitoring sites in the Quabbin Reservoir watershed for the duration of 2019. Dissolved oxygen remained below 5 mg/L at Core monitoring site 121B in the Ware River watershed for the months of June through August 2019. This particular location represents the outlet of Moulton Pond/ inlet of Thayer Pond, in the eastern extent of the Coldbrook and Longmeadow sanitary district. The area immediately upstream of site 121B is characterized by an inundated stretch of floodplain that potentially allowed for periods of stagnancy during which time dissolved oxygen concentrations may have declined. Concentrations of dissolved oxygen were below aquatic life criteria (4.9 mg/L) on a single date at site 108 in 2019.

The pH values in Core monitoring tributaries in the Ware River watershed ranged from 5.47 to 7.07 in 2019. Seasonal median pH of Core monitoring tributaries in the Ware River watershed was generally greater in 2019 than the median pH for the period of record, excluding patterns observed at 121B (Appendix C). pH in Core monitoring tributaries in the Quabbin Reservoir watershed ranged from 4.23 to 7.21 in 2019. Median pH values observed in Core monitoring tributaries were generally approaching or below the minimum established standards for Class A inland waters as established by MassDEP (6.5 to 8.5) in 2019, consistent with prior observations throughout the period of record (DWSP, 2019a). Spatial variability in surface water pH may be attributed to variations in watershed characteristics and meteorological drivers (e.g., changes in contributions from acid rain). The established pattern of inter-site variability in pH was preserved in the 2019 record.

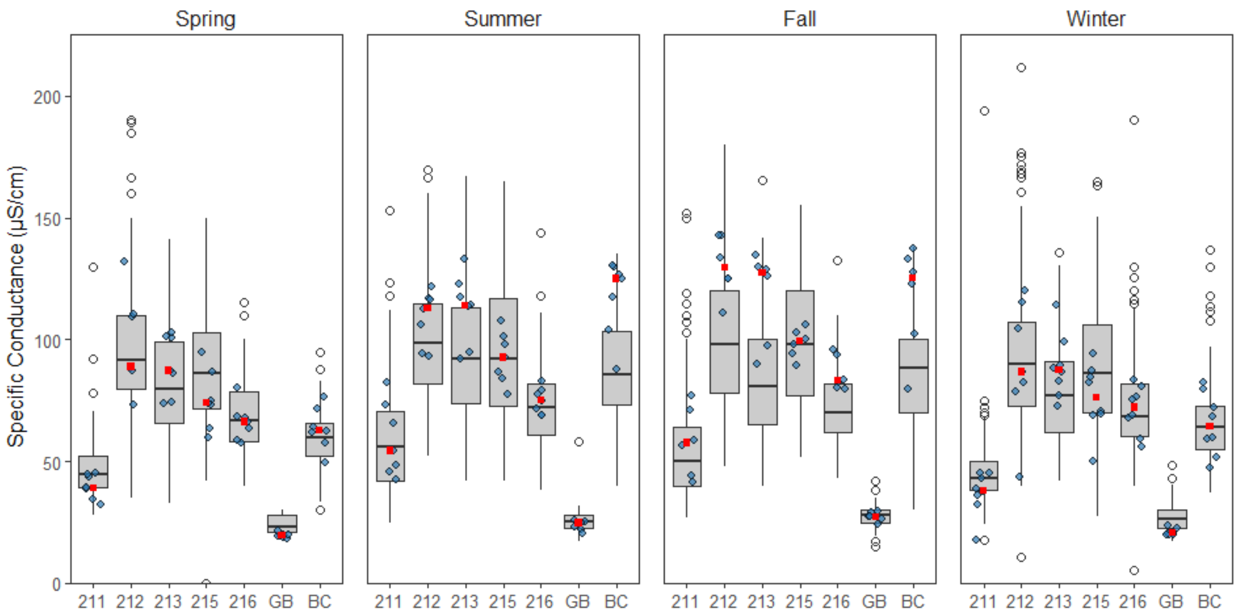
3.2.2 Specific Conductance and Dissolved Salts

Specific conductance ranged from 17.7 to 143 µS/cm in Quabbin Reservoir watershed Core monitoring tributaries and from 40.5 to 395 µS/cm in Core monitoring tributaries in the Ware River watershed during 2019. 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 2019. 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 2019 (Figure 8). Specific conductance was generally elevated during periods of low flow (June through October 2020; see Section 3.1.2) and declined with increasing streamflow.

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 observed in Core monitoring tributaries in the Ware River watershed ranged from 7.75 to 52 mg/L and from 1.5 to 18.9 mg/L in Quabbin Reservoir watershed tributaries in 2019. Concentrations of Cl observed in 2019 ranged from 1 to 39.7 mg/L1 in and from 11.4 to 115 mg/L in Quabbin Reservoir and Ware River watersheds, respectively. The secondary MCL Cl in drinking water (250 mg/L) established by the US EPA was not exceeded in any Core tributary samples collected in 2019 from the Quabbin Reservoir or Ware River watersheds. Seasonal dynamics in Na and Cl in Quabbin Reservoir and Ware River watershed tributaries mirrored that of specific conductance in 2019.

Spatial and temporal patterns in specific conductance and associated concentrations of Na and Cl observed in 2019 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 summer months of 2019 likely served to buffer stream Cl concentrations. 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 8). Median annual concentrations of Na, Cl, and specific conductance were generally greater in tributaries within the Ware River watershed, relative to DWSP monitoring sites in the Quabbin Reservoir watershed in 2019 (Tables 9-10). 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 (Table 2). An approximate 1:1 molar ratio of Na to Cl observed in the majority of Core monitoring sites suggests a halogen source for Na and Cl ions to the watersheds (e.g., road deicers) for these sites (Appendix C). Specific conductance at EQA monitoring sites in the Ware River watershed increased significantly from the prior monitoring period (2015). A detailed discussion of statistics for specific conductance, Cl, and Na in EQA monitoring sites during 2019 is presented in Appendix B.

Figure 8: Boxplots depicting the seasonal distributions of specific conductance observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median specific conductance of 2019 for each site is represented by the red square. The solid black line represents the historic 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.



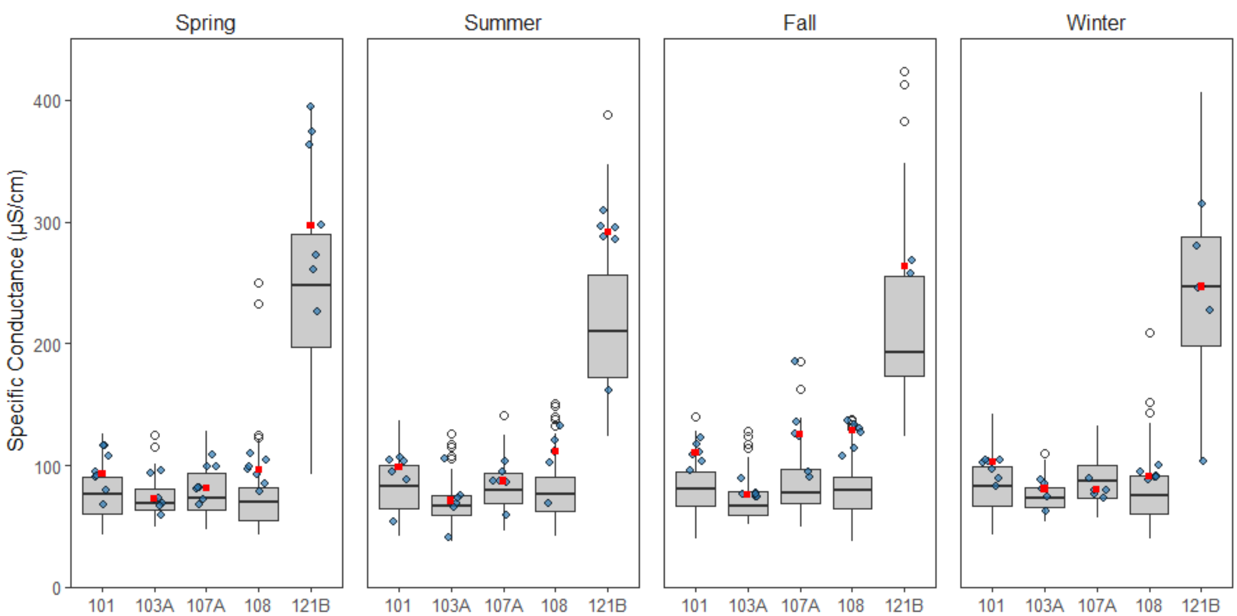


Figure 9: Time series of sodium (Na), chloride (Cl), and specific conductance (SC) measured in Quabbin Reservoir watershed core tributary sites in 2019.

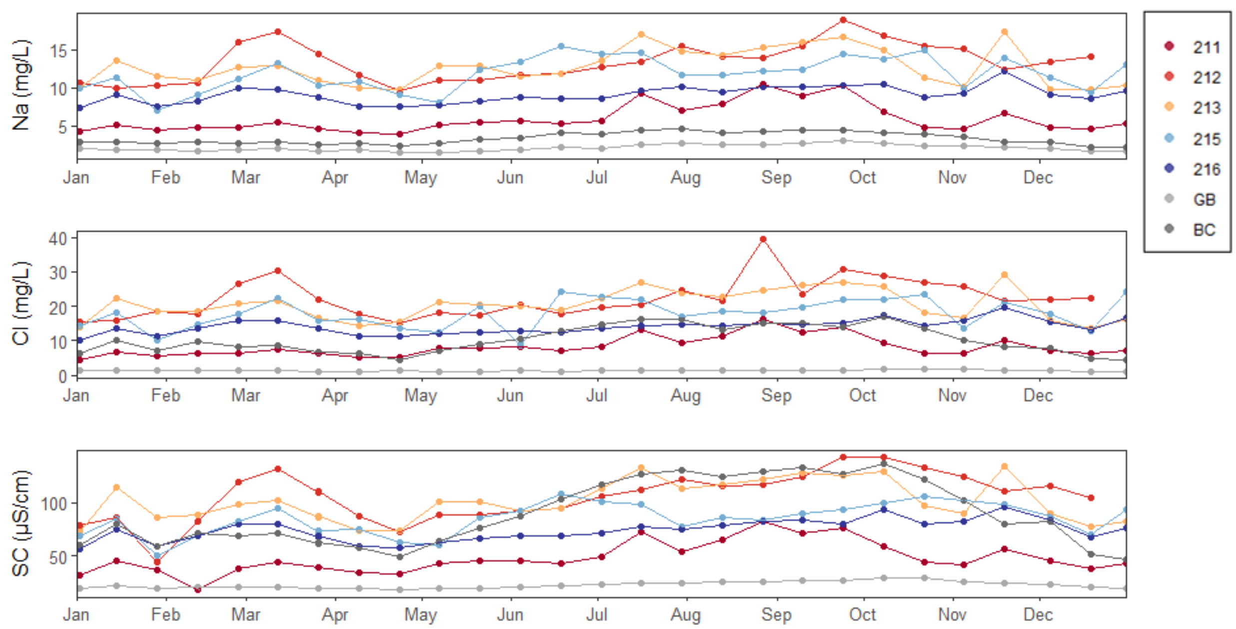


Figure 10: Time series of sodium (Na), chloride (Cl), and specific conductance (SC) measured in Ware River watershed core tributary sites in 2019.

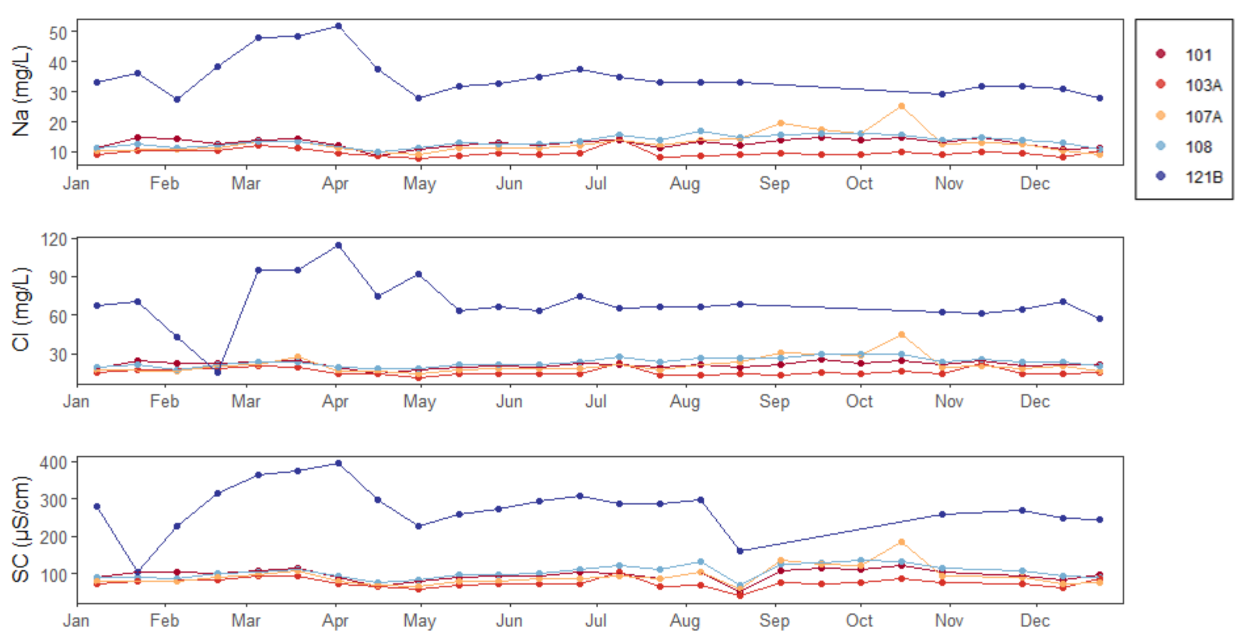


Table 9: Descriptive statistics (minimum, median, average, and maximum) for specific conductance, Na, and Cl in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2019.

Site	Season	Specific Conductance (µS/cm)					Sodium (mg/L)					Chloride (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
211	Spring	7	32.5	39.1	39.8	45.3	6	3.9	4.9	4.8	5.5	6	5.1	6.8	6.6	7.8
	Summer	7	42.7	54.4	59	82.6	7	5.3	6.9	7.3	10.5	7	7.1	9.2	10.5	16.4
	Fall	6	41.6	57.6	58.2	77	6	4.6	6.7	7	10.2	6	6.2	9.7	9.7	14
	Winter	8	17.7	38.2	37	45.5	8	4.3	4.8	4.8	5.3	8	4.5	6.4	6.2	7
212	Spring	7	73	88.9	98.5	132.2	6	9.6	11.4	12.5	17.4	6	15.1	18	20.2	30.3
	Summer	7	93.1	112.8	108.9	121.7	7	11.7	13.3	13.3	15.4	7	17.7	20.3	23.4	39.7
	Fall	6	111	129.5	130.1	143	6	12.4	15.5	15.7	18.9	6	21.5	26.3	26.1	30.6
	Winter	7	43.8	86.8	90.3	119.9	7	9.9	10.7	12.1	16	7	15.3	18.4	19.8	26.6
213	Spring	7	74.1	87.3	89.6	103	6	9.8	11.9	11.5	12.9	6	14.5	18.7	18.3	21.4
	Summer	7	92.1	114	112.6	133	7	11.5	14.3	14	16.9	7	18.8	22.8	22.7	26.8
	Fall	6	90	127.5	117.9	134.7	6	10.1	15.5	14.4	17.4	6	16.5	26	23.8	29.3
	Winter	8	72.9	87.6	88.9	114.2	8	9.7	10.6	11	13.5	8	13.4	17.3	17.4	22.3
215	Spring	7	60.1	73.9	75.3	94.8	6	8	10.5	10.6	13.2	6	12.3	16	16.6	22.2
	Summer	7	77.3	92.7	92.7	108	7	11.6	13.4	13.3	15.4	7	8.4	18.4	18.7	24.4
	Fall	6	89.6	99.3	98.6	106.4	6	10	13.8	13.2	14.9	6	13.5	21.7	20.3	23.4
	Winter	8	50.2	76.4	76	94.1	8	6.9	10.6	10.3	13.1	8	10.0	16.2	16.2	24.1
216	Spring	7	57.9	66.3	66.1	80.3	6	7.5	8	8.2	9.8	6	11.1	12.3	12.7	15.9
	Summer	7	69.1	75.1	75	83.2	7	8.5	9.4	9.3	10.1	7	12.3	14.5	13.9	15.1
	Fall	6	79.8	83.1	86	96	6	8.8	10.2	10.1	12.2	6	14.4	15.4	16.1	19.5
	Winter	8	56.1	72.3	71	83.3	8	7.4	8.8	8.6	10	8	10.1	13.6	13.7	16.6
GB	Spring	7	18.1	19.5	19.6	21.3	6	1.5	1.7	1.7	2	6	1.1	1.1	1.1	1.2
	Summer	7	20.7	24.8	23.8	25.9	7	1.8	2.5	2.3	2.8	7	1.1	1.3	1.3	1.4
	Fall	6	24.1	27.4	27.3	29.6	6	2.2	2.6	2.6	3.1	6	1.4	1.5	1.5	1.6
	Winter	8	19.7	20.6	20.9	23.4	8	1.7	1.9	1.9	2.1	8	1.0	1.2	1.2	1.4
BC	Spring	7	49.7	62.7	63.5	76.5	6	2.4	2.7	2.7	3.2	6	4.2	6.8	7	9
	Summer	7	87.7	125	117.3	130.6	7	3.4	4.2	4.1	4.7	7	10.6	14.7	14.1	16.3
	Fall	6	79.8	125.2	117.1	137.2	6	3	4	3.9	4.5	6	8.1	13.8	13	17
	Winter	8	47.2	64.2	65.1	82.5	8	2.1	2.8	2.7	3	8	4.3	7.5	7.3	10.3

Table 10: Descriptive statistics (minimum, median, average, and maximum) for specific conductance, Na, and Cl in Core tributary monitoring sites in the Ware River watershed during 2019.

Site	Season	Specific Conductance (µS/cm)					Sodium (mg/L)					Chloride (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
101	Spring	8	68.3	93.4	95.6	116	7	8.8	12.3	12.2	14.5	7	14.4	19.5	19.8	24.4
	Summer	6	53.8	98.9	91.8	106.6	6	11.4	12.9	12.8	14.1	6	18.9	20.3	20.4	22
	Fall	6	95.6	110.1	109.9	122.6	7	12.6	14	14	15	7	20.3	22.5	22.7	25
	Winter	7	83	102.9	97.7	104.8	6	11	12.2	12.7	14.6	6	18.5	21.8	21.7	24.5
103A	Spring	7	59.5	72.4	75.8	95.6	7	7.8	9.5	9.6	12.2	7	11.4	14.3	15.5	20.7
	Summer	6	40.5	71.1	71.7	105.9	6	8.4	9	9.9	14.4	6	12.8	14.1	15.1	22.4
	Fall	6	74.3	76.2	78	89.2	7	8.9	9.4	9.5	10.2	7	13.7	14.7	15.7	22.1
	Winter	5	62.9	80.7	78.3	88.7	5	8.3	10.3	9.7	10.6	5	13.9	14.9	15.8	17.9
107A	Spring	8	67.7	81.7	86.3	108.3	7	9.3	11.2	11.4	13.7	7	14.2	17.8	18.8	27.1
	Summer	6	59.2	87.3	86.4	103.4	6	11.4	13.1	13	14.4	6	17.7	19.9	20.1	23.4
	Fall	6	91	125.3	126.2	185.2	7	12.4	16.2	16.6	25.2	7	18.8	28.1	27.4	45
	Winter	5	73.5	80	80	89.9	5	9.2	10.5	10.5	11.5	5	16	16.9	17.9	20
108	Spring	7	78.5	96.5	95.2	110.4	7	10	12.7	12.2	13.5	7	18.3	21.4	20.9	23.4
	Summer	6	68.7	111.5	107.9	132.6	6	12.7	14.4	14.6	16.8	6	21.2	25.1	24.8	27.3
	Fall	6	108	128.7	125	136.6	7	13.8	15.6	15.1	16.1	7	23.8	26.4	26.9	29.8
	Winter	6	88.3	91.1	92.7	100.7	6	10.8	11.8	11.9	13	6	17.6	20.7	20.5	23.2
121B	Spring	7	225.9	297	312.7	395	7	28.1	37.6	39.9	52	7	62.9	91.8	85.7	115
	Summer	6	161.5	291.5	272.7	309.2	6	33	34.1	34.5	37.5	6	63.6	66.4	67.5	74.7
	Fall	2	257.9	263.3	263.3	268.7	3	29.4	31.8	31	31.9	3	61	62	62.4	64.2
	Winter	6	103.7	246.7	236.6	315.1	6	27.4	32.1	32.3	38.3	6	15.2	62.1	54	70.7

3.2.3 Turbidity

Turbidity in Core monitoring tributaries in Quabbin Reservoir and Ware River watersheds was within historic ranges for the entirety of 2019 (Figure 11). Turbidity ranged from 0.11 to 4.4 NTU in Quabbin Reservoir Core monitoring tributary and from 0.37 to 5.2 NTU in Ware River watershed tributaries (Tables 11-12). Turbidity levels in Core tributary monitoring sites in the Quabbin Reservoir watershed remained below the five NTU SWTR requirement for the entirety of 2019. Turbidity levels exceeded five NTU on a single date at DSWP site 108 in the Ware River watershed in 2019 (although, these standards are not directly applicable to non-intake waters). Turbidity levels above one NTU were largely associated with samples collected from Core monitoring tributaries in the Ware River watershed during the summer and fall of 2019, or high flow events in either watershed.

Turbidity levels in 2019 increased during the summer months and declined during the winter, with peaks corresponding to precipitation events and/or higher sediment mobilization following meteorological events. Seasonal dynamics (e.g., the timing and relative magnitude of seasonal changes) 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 2-4 NTU) than in Quabbin Reservoir tributaries (generally below 1.5 NTU). Variability in turbidity dynamics observed across watersheds/sites may be attributed to land use differences across sites, localized meteorological effects, and sub-catchment hydrology, thus are not necessarily indicative of long-term trends. Turbidity levels observed in 2019 were generally consistent with those of previous years, indicating the continued high quality of surface waters in the Quabbin Reservoir and Ware River watersheds.

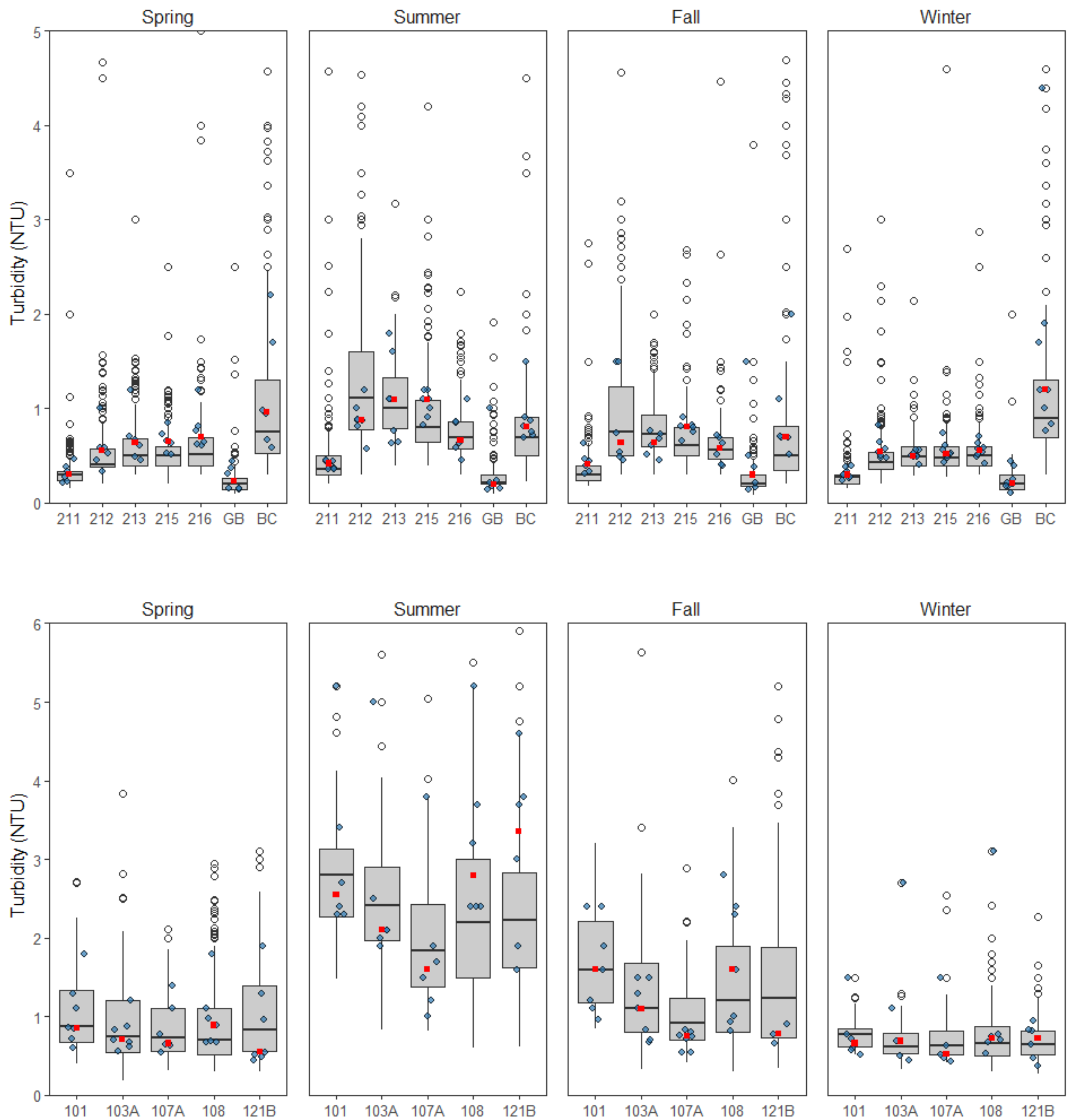
Table 11: Descriptive statistics (minimum, median, average, and maximum) for turbidity in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2019. Censored data were substituted with one-half the detection limit for calculations.

Site	Season	Turbidity (NTU)				
		Count	Min	Med	Avg	Max
211	Spring	6	0.22	0.31	0.32	0.47
	Summer	7	0.36	0.42	0.41	0.46
	Fall	6	0.31	0.42	0.43	0.63
	Winter	8	0.24	0.3	0.31	0.4
212	Spring	6	0.33	0.56	0.58	1
	Summer	7	0.57	0.88	0.89	1.2
	Fall	6	0.45	0.64	0.87	1.5
	Winter	7	0.48	0.54	0.58	0.83
213	Spring	6	0.45	0.64	0.69	1.2
	Summer	7	0.64	1.1	1.09	1.8
	Fall	6	0.45	0.65	0.63	0.77
	Winter	8	0.41	0.50	0.51	0.56
215	Spring	6	0.51	0.65	0.65	0.85
	Summer	7	0.82	1.1	1.05	1.2
	Fall	6	0.66	0.81	0.79	0.91
	Winter	8	0.43	0.53	0.55	0.74
216	Spring	6	0.61	0.7	0.78	1.2
	Summer	7	0.46	0.66	0.74	1.1
	Fall	6	0.39	0.58	0.56	0.72
	Winter	8	0.42	0.56	0.56	0.71
GB	Spring	6	0.14	0.24	0.26	0.44
	Summer	7	0.14	0.2	0.3	1
	Fall	6	0.14	0.3	0.49	1.5
	Winter	8	0.11	0.21	0.25	0.44
BC	Spring	6	0.59	0.97	1.18	2.2
	Summer	7	0.7	0.81	0.90	1.5
	Fall	6	0.52	0.7	0.95	2
	Winter	8	0.77	1.2	1.63	4.4

Table 12: Descriptive statistics (minimum, median, average, and maximum) for turbidity in Core tributary monitoring sites in the Ware River watershed during 2019.

Site	Season	Turbidity (NTU)				
		Count	Min	Med	Avg	Max
101	Spring	7	0.6	0.86	1.03	1.8
	Summer	6	2.3	2.55	3.05	5.2
	Fall	7	0.96	1.6	1.65	2.4
	Winter	6	0.51	0.66	0.78	1.5
103A	Spring	7	0.56	0.71	0.78	1.2
	Summer	6	1.9	2.1	2.6	5
	Fall	7	0.67	1.1	1.09	1.5
	Winter	5	0.45	0.69	1.09	2.7
107A	Spring	7	0.55	0.66	0.82	1.4
	Summer	6	1	1.6	1.85	3.8
	Fall	7	0.54	0.75	0.71	0.84
	Winter	5	0.43	0.52	0.71	1.5
108	Spring	7	0.67	0.89	0.97	1.8
	Summer	6	2.4	2.8	3.22	5.2
	Fall	7	0.82	1.6	1.69	2.8
	Winter	6	0.53	0.72	1.09	3.1
121B	Spring	7	0.45	0.55	0.88	1.9
	Summer	6	1.6	3.35	3.1	4.6
	Fall	3	0.66	0.78	0.78	0.9
	Winter	6	0.37	0.73	0.68	0.95

Figure 11: Boxplots depicting the seasonal distributions of turbidity observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median turbidity of 2019 for each site is represented by the red square. The solid black line represents the historic 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.



3.2.4 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. Fecal coliform was included in prior years (September 2017 through March 2018) to elucidate potential sources of fecal coliform to the Quabbin Reservoir, aside from wintering gulls, near the WDI. Analyses for fecal coliform was not performed in 2019.

Elevated bacteria results from Quabbin Reservoir and Ware River tributaries that fall outside of seasonal normal (25th to 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. Follow-up sampling has previously attributed elevated *E. coli* concentrations to wildlife activity, recent precipitation, or findings were inconclusive. All follow-up samples (n=4) collected in 2019 resulted in *E. coli* concentrations that represented a return to seasonal normals for the given Core tributary monitoring site.

3.2.4.1 Total Coliform

Total coliform in Quabbin Reservoir Core monitoring tributaries ranged from 86 to greater than 24,200 MPN/100-mL and from 122 to greater than 24,200 MPN/100-mL in Core monitoring tributaries in the Ware River watershed in 2019 (Tables 13-14). Median total coliform concentrations for samples collected during June through August 2019 in the Ware River watershed exceeded the summer sample median concentration for the period of record. The median total coliform concentration of samples collected in September through November 2019 exceeded the fall sample median for the period of record in the Quabbin Reservoir watershed (Tables 13-14). Total coliform results were within seasonal ranges for the period of record for most Core sites monitored by DWSP in 2019 (Appendix C). Historical maximum total coliform concentrations were observed on a single date in samples collected from Gates Brook in the Quabbin Reservoir watershed (Appendix C).

3.2.4.2 E. coli

E. coli concentrations ranged from less than 10 to 1,350 MPN/100-mL in Quabbin Reservoir watershed tributaries and from less than 10 to 1,470 MPN/100-mL in the Ware River watershed tributaries in 2019 (Tables 16-17). Four and seven samples exceeded the Class A Standard for single samples (*E. coli* concentrations >235 MPN/100 mL) in samples collected from Core monitoring sites in the Quabbin Reservoir and Ware River watersheds, respectively, in 2019.

Table 13: Descriptive statistics (minimum, median, average, and maximum) for total coliform in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2019. Results are reported as MPN/100-mL. Censored data were substituted with one-half the detection limit for calculations.

Site	Season	Total Coliform (MPN/100-mL)				
		Count	Min	Med	Avg	Max
211	Spring	6	108	666	677	1,270
	Summer	7	1,220	2,720	3,377	6,130
	Fall	6	1,010	3,620	4,433	11,200
	Winter	8	201	375	365	609
212	Spring	6	131	332	413	908
	Summer	7	813	1,970	2,045	3,260
	Fall	6	759	3,240	4,952	11,200
	Winter	7	130	213	322	689
213	Spring	6	134	1,087	1,866	4,350
	Summer	8	2,380	4,745	5,000	8,160
	Fall	6	860	3,435	3,057	4,880
	Winter	8	187	292	398	884
215	Spring	6	173	1,445	1,930	4,610
	Summer	7	1,620	2,250	2,553	4,350
	Fall	6	717	2,770	5,166	19,900
	Winter	8	110	238	349	987
216	Spring	6	95	630	724	1,920
	Summer	7	1,530	2,910	2,803	3,870
	Fall	6	1,170	2,045	2,332	4,610
	Winter	8	86	278	313	556
GB	Spring	6	213	729	700	1,220
	Summer	7	1,180	2,910	2,686	4,610
	Fall	6	1,110	4,280	8,943	>24,200
	Winter	8	146	226	268	480
BC	Spring	6	173	786	947	2,100
	Summer	7	1,920	8,660	7,509	13,000
	Fall	8	1,540	9,230	7,991	17,300
	Winter	8	160	383	532	1,480

Table 14: Descriptive statistics (minimum, median, average, and maximum) for total coliform in Core tributary monitoring sites in the Ware River watershed during 2019. Results are reported as MPN/100-mL.

Site	Season	Total Coliform (MPN/100-mL)				
		Count	Min	Med	Avg	Max
101	Spring	7	122	839	780	1,720
	Summer	6	2,280	7,270	9,005	>24,200
	Fall	7	842	2,480	2807	6,130
	Winter	6	169	397	878	3,450
103A	Spring	7	145	556	935	3,130
	Summer	6	3,280	6,745	9,440	>24,200
	Fall	7	959	1,660	2,127	3,870
	Winter	5	173	309	1,575	6,490
107A	Spring	7	160	801	1,040	2,720
	Summer	6	3,260	4,110	7,468	>24,200
	Fall	7	776	1,860	1,922	2,910
	Winter	5	203	327	1,158	4,350
108	Spring	7	226	733	859	1,860
	Summer	7	4,350	7,700	9,244	>24,200
	Fall	7	884	1,620	2,299	7,700
	Winter	6	197	352	1,017	4,610
121B	Spring	7	292	1,310	1,860	4,110
	Summer	6	9,800	11,200	13,133	19,900
	Fall	3	1,990	2,600	3,067	4,610
	Winter	6	171	236	852	3,650

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 results were compared to previous years. The six-month running geometric mean *E. coli* concentration remained below 126 MPN/100-mL for the entirety of 2019. Annual geometric mean *E. coli* concentrations were below Class A standards for all Core monitoring sites in 2019 (Table 15). Annual geometric means corresponding to 2019 decreased from previous years in all Core monitoring sites, aside from Gates Brook, where the annual geometric mean *E. coli* concentration (12.03 MPN/100-mL) for 2019 was greater than that of 2017 and 2018 (Table 15) but remained below 20 MPN/100-mL. Annual geometric mean *E. coli* concentrations calculated for 2019 represent the lowest annual geometric mean *E. coli* concentrations observed for the recent decade (2010-2019) in major Core tributaries (211, 213, 215, and 216) in the Quabbin Reservoir watershed and for sites 107A and 121B in the Ware River watershed.

Boat Cove Brook, in the Quabbin Reservoir watershed, has previously demonstrated an upward trend in annual *E. coli* concentrations (DWSP, 2018c; DWSP, 2019a). However, annual geometric mean *E. coli* concentrations in 2019 mark the second consecutive year that annual geometric means have decreased from the prior year. Work to assess potential bacteria sources near this sample location has been described in previous reports (DWSP, 2018c). Elevated *E. coli* concentrations observed during 2019 typically occurred following high intensity rainfall events that occurred during summer months and were attributed to resultant flushing, as no potential source of pollution was observed, and *E. coli* levels further decreased in subsequent samples (Figures 12-13). Single-sample exceedances were largely attributed to flushing during storm events and/or snow melt immediately prior to sample collection dates. *E coli* concentrations in tributaries in Quabbin Reservoir and Ware River watersheds 2019 continue to demonstrate a high sanitary quality.

Table 15: Annual geometric mean *E. coli* for Core sites in Quabbin Reservoir and Ware River Watersheds. Values below detection limits (<10 MPN/100 mL) were substituted with one-half the detection limit (MassDEP, 2018). Results are reported as MPN/100-mL.

Watershed	Site	Annual Geometric Mean *E. coli* (MPN/100 mL)									
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Quabbin Reservoir Watershed	211	18.77	13.11	19.39	11.87	14.57	13.93	33.14	15.32	18.5	10.24
	212	24.44	24.79	27.66	16.48	19.9	39.37	56.52	23.12	34.21	13.75
	213	57.42	52.96	49.44	37.41	39.97	36.36	42.74	26.87	37.85	25.29
	215	18.53	18.96	22.84	16.31	16.95	11.43	31.12	17.83	18.05	10.94
	216	19.17	29.79	18.75	16.51	15.09	12.9	24.29	13.79	19.98	10.07
	BC	28.19	16.46	31.95	16.61	25.36	30.46	55.85	73.52	41.35	34.2
	GB	20.47	15.39	24.18	13.51	10.84	12.97	14.17	9.81	9.54	12.03
Ware River Watershed	101	17.61	33.80	28.68	24.48	18.27	18.48	19.23	33.29	34.1	21.47
	103A	31.65	23.63	20.91	25.79	34.21	35.52	33.66	35.78	58.54	36.86
	107A	20.61	16.1	17.69	21.59	17.74	23.68	17.6	25.74	36.34	16.08
	108	30.92	31.89	21.22	24.92	21.68	24.92	24.98	29.25	39.55	25.75
	121B	35.17	33.99	36.47	32.79	24.83	27.67	47.4	31.37	60.51	17.53

Figure 12: Time series of *E. coli* and turbidity measured in Quabbin Reservoir watershed core tributary sites in 2019. Dashed line corresponds to Class A standard for *E. coli* (235 MPN/100-mL).

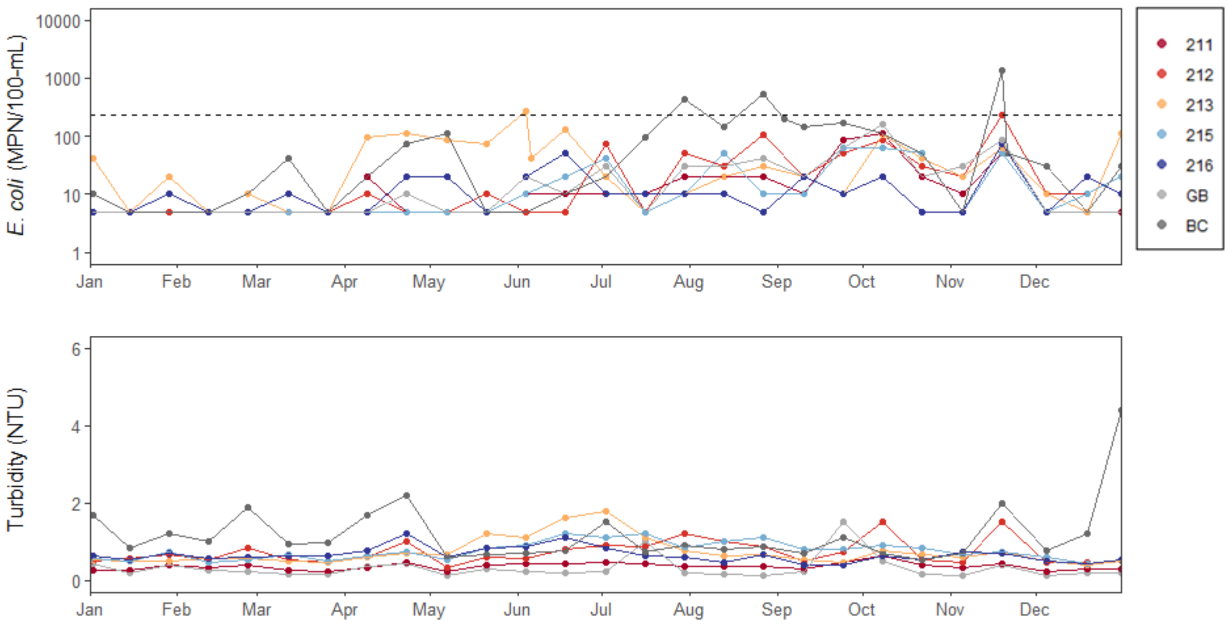


Figure 13: Time series of *E. coli* and turbidity measured in Ware River watershed core tributary sites in 2019. Dashed line corresponds to Class A standard for *E. coli* (235 MPN/100-mL).

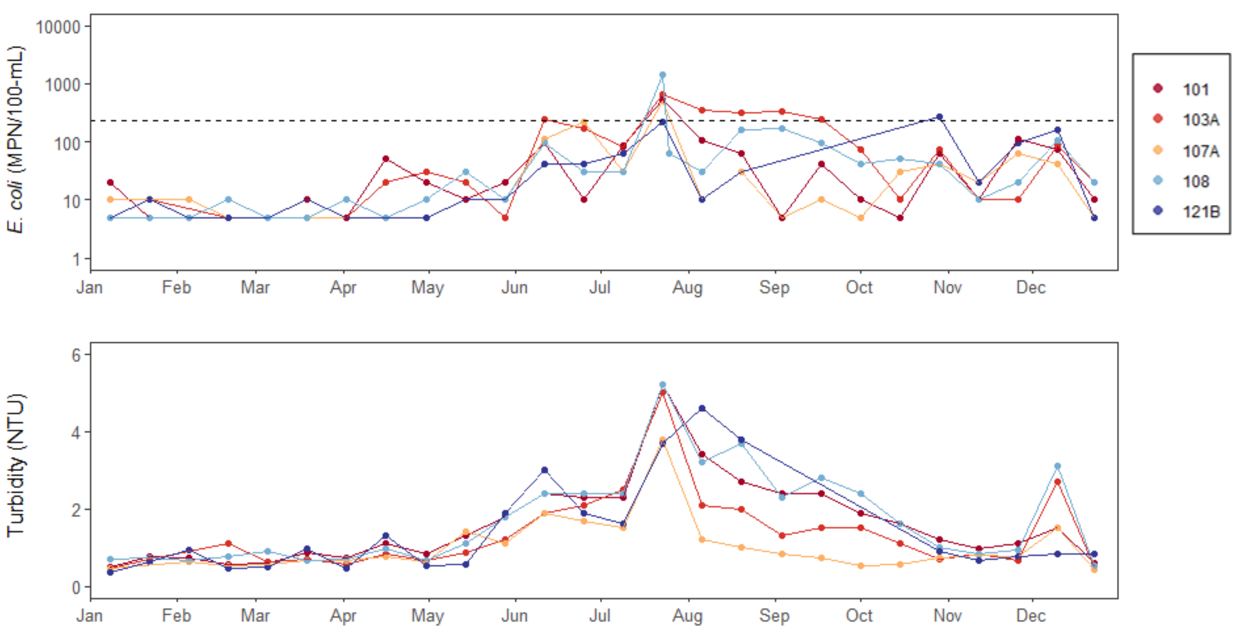


Table 16: Descriptive statistics (minimum, median, average, and maximum) for *E. coli* in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2019. Results are reported as MPN/100-mL. Censored data were substituted with one-half the detection limit for calculations.

Site	Season	*E. coli* (MPN/100-mL)				
		Count	Min	Med	Avg	Max
211	Spring	6	<10	<10	8	20
	Summer	7	10	10	14	20
	Fall	6	10	36	48	110
	Winter	8	<10	<10	<10	<10
212	Spring	6	<10	<10	7	10
	Summer	7	<10	31	40	108
	Fall	6	20	41	73	231
	Winter	7	<10	<10	6	10
213	Spring	6	<10	80	63	110
	Summer	8	<10	26	66	272
	Fall	6	10	31	44	109
	Winter	8	<10	10	26	110
215	Spring	6	<10	<10	<10	<10
	Summer	7	<10	10	21	52
	Fall	6	<10	52	41	63
	Winter	8	<10	<10	8	20
216	Spring	6	<10	8	11	20
	Summer	7	<10	10	17	52
	Fall	6	<10	15	22	74
	Winter	8	<10	<10	8	20
GB	Spring	6	<10	<10	6	10
	Summer	7	<10	30	24	41
	Fall	6	20	47	63	160
	Winter	8	<10	<10	<10	<10
BC	Spring	6	<10	31	43	110
	Summer	7	<10	97	178	537
	Fall	8	<10	129	261	1,350
	Winter	8	<10	8	13	30

Table 17: Descriptive statistics (minimum, median, average, and maximum) for *E. coli* in Core tributary monitoring sites in the Ware River watershed during 2019. Results are reported as MPN/100-mL. Censored data were substituted with one-half the detection limit for calculations.

Site	Season	*E. coli* (MPN/100-mL)				
		Count	Min	Med	Avg	Max
101	Spring	7	<10	10	17	52
	Summer	6	10	91	150	538
	Fall	7	<10	10	35	110
	Winter	6	<10	10	21	75
103A	Spring	7	<10	10	14	31
	Summer	6	84	280	301	644
	Fall	7	10	74	107	327
	Winter	5	<10	10	26	85
107A	Spring	7	<10	<10	6	10
	Summer	6	10	71	150	504
	Fall	7	<10	20	25	63
	Winter	5	<10	10	14	41
108	Spring	7	<10	10	11	31
	Summer	7	30	63	269	1,470
	Fall	7	10	41	62	173
	Winter	6	<10	8	25	107
121B	Spring	7	<10	<10	7	10
	Summer	6	10	41	67	216
	Fall	3	20	98	131	275
	Winter	6	<10	<10	32	160

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 are routinely below detection limits (<0.005 mg/L as N). Concentrations of NH_3-N in Quabbin Reservoir and Ware River watershed Core monitoring tributaries ranged from <0.005 to 0.033 mg/L and <0.005 to 0.0536 mg/L, respectively, in 2019 (Appendix C).

Concentrations of ammonia were generally within historical ranges for most Core tributary sites in 2019. Concentrations of NH_3-N was below detection limits in all samples collected from sites 211 and Gates Brook (Quabbin Reservoir Watershed) during 2019. NH_3-N concentrations observed in Ware River watershed tributaries exhibited more seasonal variability, likely due to variations in N-sources subsequent N-cycling across watersheds. 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 1.9mg/L) for the entirety of 2019.

Concentrations of NH_3-N measured at site 215 in the Quabbin Reservoir watershed in 2019 were markedly greater than median seasonal concentration observed for the period of record (Appendix C). Field observations made by DWSP staff on corresponding sample collection dates note a marked decrease in channel velocity and water clarity, and corresponding increase in relative stream stage for Fever Brook (215) in 2019, of which were attributed to the development of a beaver dam downstream from the Core site. 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 in 2019 suggest that the development of beaver dam downstream from this sampling site in early 2019 may have impacted N-cycling in the upstream reaches of this particular sub-watershed during 2019.

3.2.5.1.2 Nitrate-Nitrogen

Concentrations of nitrate (NO_3-N) ranged from <0.005 to 0.172 mg/L in Quabbin Reservoir watershed core sites in 2019 (Table 18). Concentrations of NO_3-N observed in Ware River watershed during 2019 ranged from <0.005 to 0.131 mg/L (Table 19). Concentrations of NO_3-N observed in Core tributary monitoring sites in Quabbin Reservoir and Ware River Watersheds during 2019 were generally within historic ranges, with historic maximum nitrate concentrations exceeded on a single date at Site 101 in the Ware River watershed. Concentrations of NO_3-N in Quabbin Reservoir and Ware River watersheds followed expected seasonal patterns in 2019, exhibiting relative enrichment in samples collected in March and December, and subsequent depletion in June and September, where uptake likely contributed to NO_3-N removal. Median annual concentrations of NO_3-N were generally greater in tributaries in the Ware River watershed than in tributaries in the Quabbin Reservoir watershed, likely reflective of variations in watershed characteristics combined with land use and management across the two watersheds. Concentrations of NO3-N observed in Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds were below the EPA MCL for drinking water of 10 mg/L for the entirety of 2019. NO_3-N concentrations in Quabbin Reservoir and Ware River watershed Core monitoring tributaries were within local ecoregional background levels (0.16 – 0.31 mg/L) throughout 2019.

Table 18: Descriptive statistics (minimum, median, average, and maximum) for nutrients (NO_3-N, NH_3-N, TKN, and TP) in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2019. Results are reported as mg/L. Censored data were substituted with one-half the detection limit for calculations.

Analyte	Site	Count	Min	Med	Avg	Max
NO_3-N (mg/L)	211	5	0.01	0.021	0.036	0.075
	212	4	0.032	0.063	0.065	0.102
	213	5	0.012	0.073	0.075	0.172
	215	5	<0.005	0.015	0.013	0.029
	216	5	0.007	0.046	0.05	0.119
	GB	5	<0.005	<0.005	0.011	0.04
	BC	5	0.007	0.013	0.015	0.028
NH_3-N (mg/L)	211	5	<0.005	<0.005	<0.005	<0.005
	212	4	<0.005	0.004	0.006	0.014
	213	5	<0.005	0.008	0.009	0.016
	215	5	0.005	0.023	0.022	0.033
	216	5	<0.005	<0.005	0.007	0.02
	GB	5	<0.005	<0.005	<0.005	<0.005
	BC	5	<0.005	<0.005	0.004	0.011
TKN (mg/L)	211	5	0.050	0.111	0.14	0.276
	212	4	<0.1	0.094	0.106	0.186
	213	5	0.106	0.152	0.197	0.357
	215	5	0.153	0.303	0.285	0.39
	216	5	0.12	0.271	0.259	0.347
	GB	5	<0.1	<0.1	0.101	0.22
	BC	5	<0.1	0.172	0.223	0.538
TP (mg/L)	211	5	<0.005	0.011	0.01	0.016
	212	4	<0.005	0.012	0.011	0.015
	213	5	<0.005	0.015	0.013	0.023
	215	5	0.006	0.017	0.016	0.023
	216	5	0.007	0.017	0.021	0.044
	GB	5	<0.005	0.01	0.01	0.018
	BC	5	0.008	0.02	0.02	0.029

Table 19: Descriptive statistics (minimum, median, average, and maximum) for nutrients (NO_3-N, NH_3-N, TKN, and TP) in Core tributary monitoring sites in the Ware River watershed during 2019. Results are reported as mg/L. Censored data were substituted with one-half the detection limit for calculations.

Analyte	Site	Count	Min	Med	Avg	Max
NO_3-N (mg/L)	101	5	0.01	0.038	0.039	0.063
	103A	5	0.007	0.067	0.054	0.084
	107A	5	0.026	0.039	0.041	0.067
	108	5	0.01	0.058	0.048	0.073
	121B	4	<0.005	0.096	0.082	0.131
NH3-N (mg/L)	101	5	<0.005	0.009	0.009	0.015
	103A	5	<0.005	0.007	0.01	0.028
	107A	5	<0.005	0.009	0.01	0.019
	108	5	0.007	0.017	0.014	0.02
	121B	4	0.017	0.037	0.036	0.054
TKN (mg/L)	101	5	<0.1	0.229	0.215	0.377
	103A	5	<0.1	0.187	0.204	0.356
	107A	5	<0.1	0.261	0.247	0.41
	108	5	0.156	0.31	0.301	0.48
	121B	4	0.113	0.271	0.325	0.646
TP (mg/L)	101	5	0.01	0.022	0.019	0.026
	103A	5	0.011	0.019	0.019	0.029
	107A	5	0.011	0.018	0.017	0.02
	108	5	0.008	0.019	0.02	0.034
	121B	4	0.006	0.011	0.016	0.036

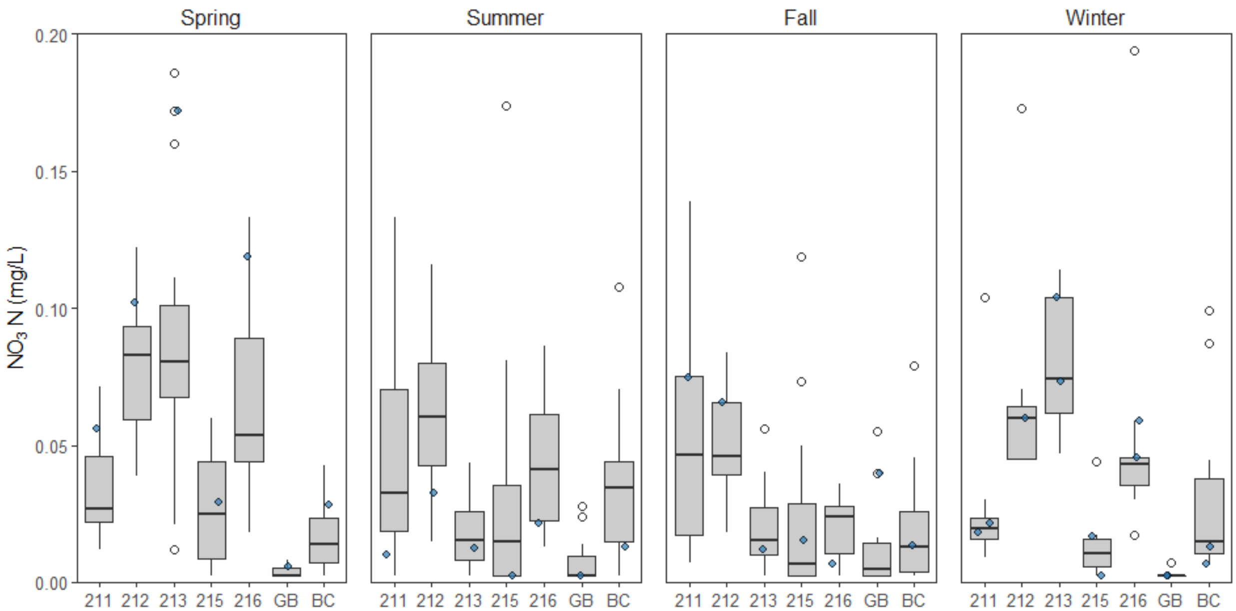
3.2.5.1.3 Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) concentrations in Quabbin Reservoir watershed core tributary monitoring sites ranged from <0.1 to 0.538 mg/L in 2019 (Table 19). Maximum TKN concentrations exceeded historical seasonal maximums at Boat Cove Brook in the Quabbin Reservoir watershed during 2019 (June sampling) (Figure 15). TKN concentrations in Ware River watershed core tributary monitoring sites ranged from <0.10 to 0.646 mg/L during 2019. The majority of TKN concentrations observed in Ware River tributaries in 2019 were within historical seasonal ranges (Figure 15). TKN dynamics in Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds mirrored that of other N-species (NO_3-N, NH_3-N) and organic content (Figure 17), with relative enrichment during summer months and in sites with greater season UV_{254} absorbance. TKN concentrations in Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds measured in 2019 were generally within local ecoregional background concentrations (0.1 – 0.3 mg/L; Appendix A), but with some exceptions for sample sites with a greater percentage of wetland cover or for samples collected immediately downstream of a wetland area (e.g., 215 in the Quabbin Reservoir watershed and 121B in the Ware River watershed).

3.2.5.2 Total Phosphorus

Total phosphorus (TP) concentrations measured in Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds in 2019 ranged from <0.005 to 0.044 mg/L in the Quabbin Reservoir watershed and from 0.006 to 0.036 mg/L in the Ware River watershed. Concentrations of TP in Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds in 2019 were generally consistent with historical ranges, with spring and summer samples (March and June, respectively) below seasonal median concentrations for the period of record, and/or laboratory detection limits (Figure 16). Historic seasonal maximum concentrations of TP observed in 2019 occurred at sites 108 in the summer sample (June) in the Ware River watershed and at site 216 in the Fall (September) in the Quabbin Reservoir watershed. TP concentrations in Core tributary monitoring locations in the Quabbin Reservoir and Ware River watersheds remained comparable to ecoregional background concentrations (0.012 -0.023 mg/L) for TP during 2019.

Figure 14: Boxplots depicting the seasonal distributions of NO_3-N observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The solid black line represents the historic 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.



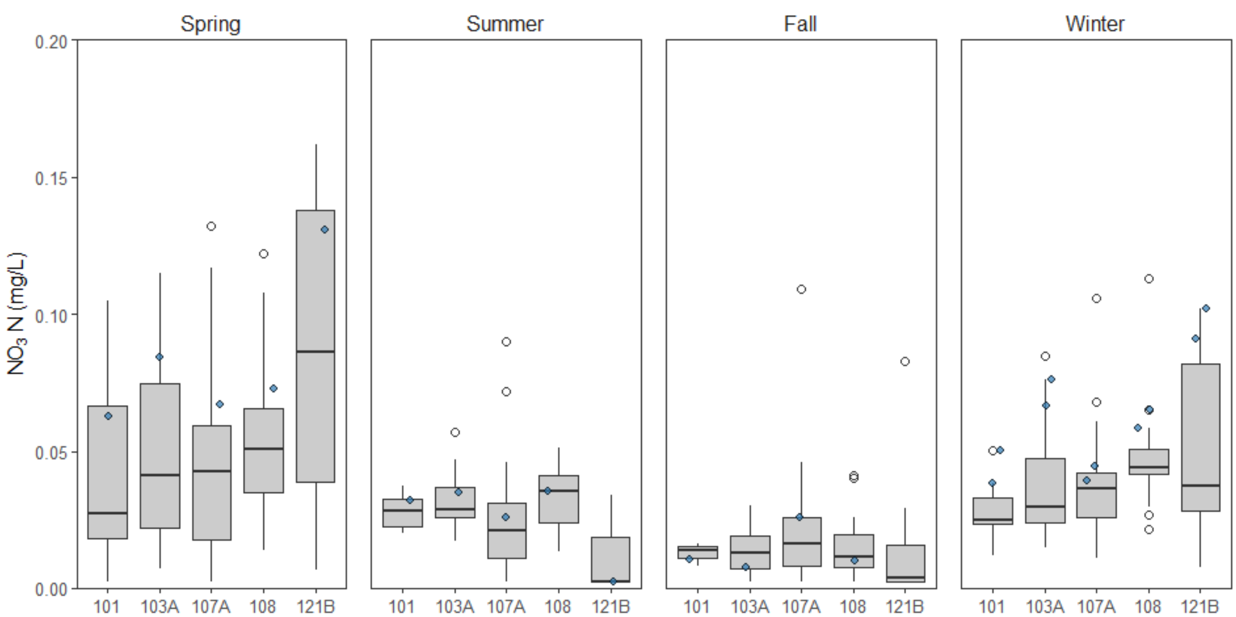


Figure 15: Boxplots depicting the seasonal distributions of TKN observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The solid black line represents the historic 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.

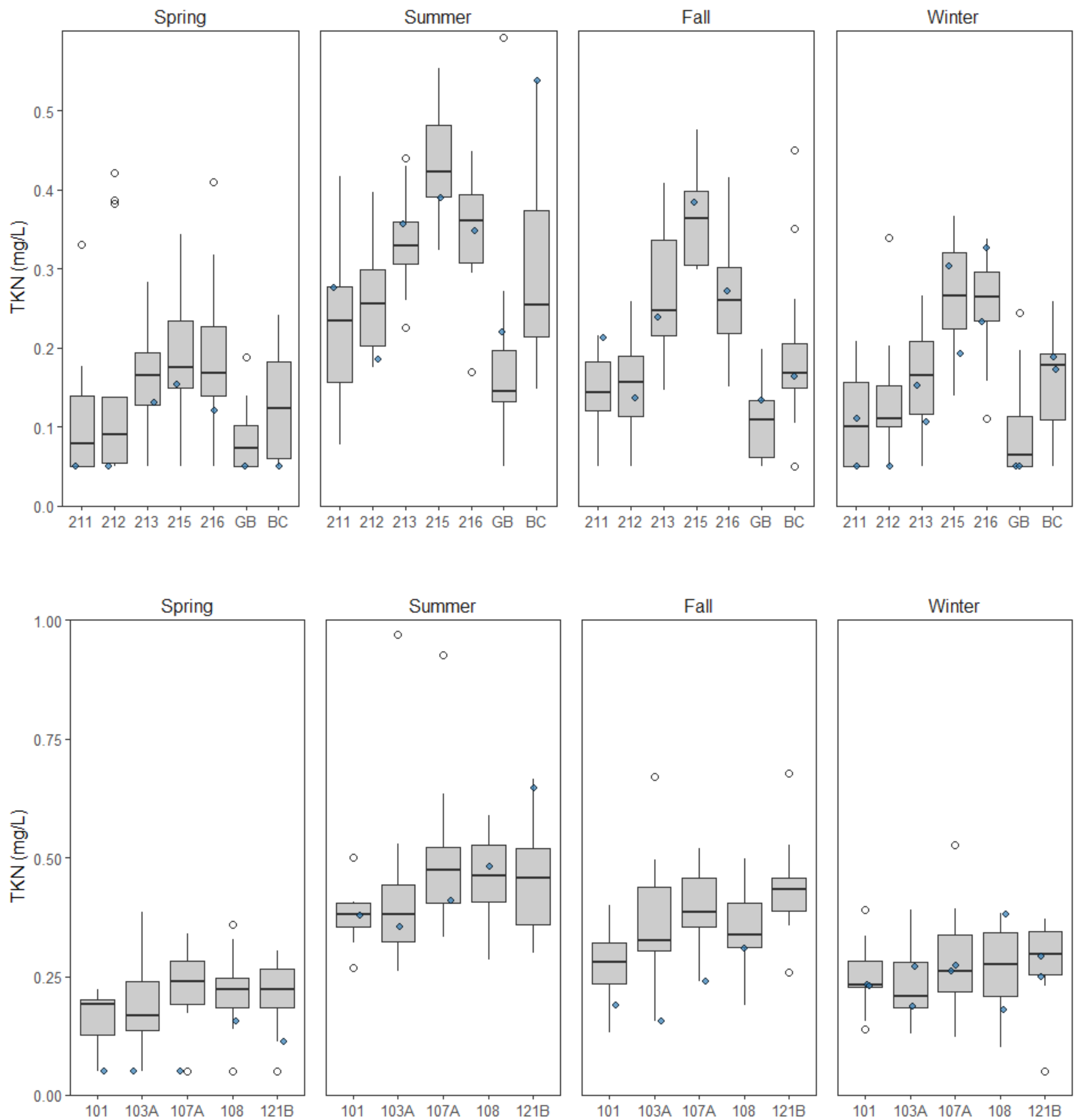
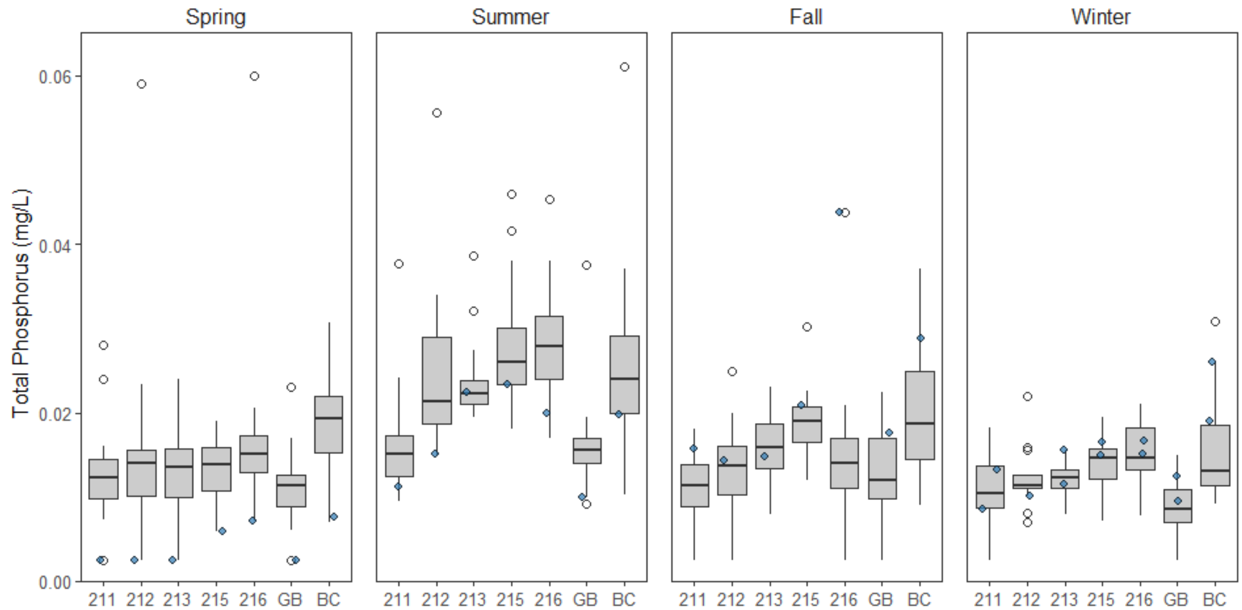


Figure 16: Boxplots depicting the seasonal distributions of total phosphorus (TP) observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The solid black line represents the historic 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.



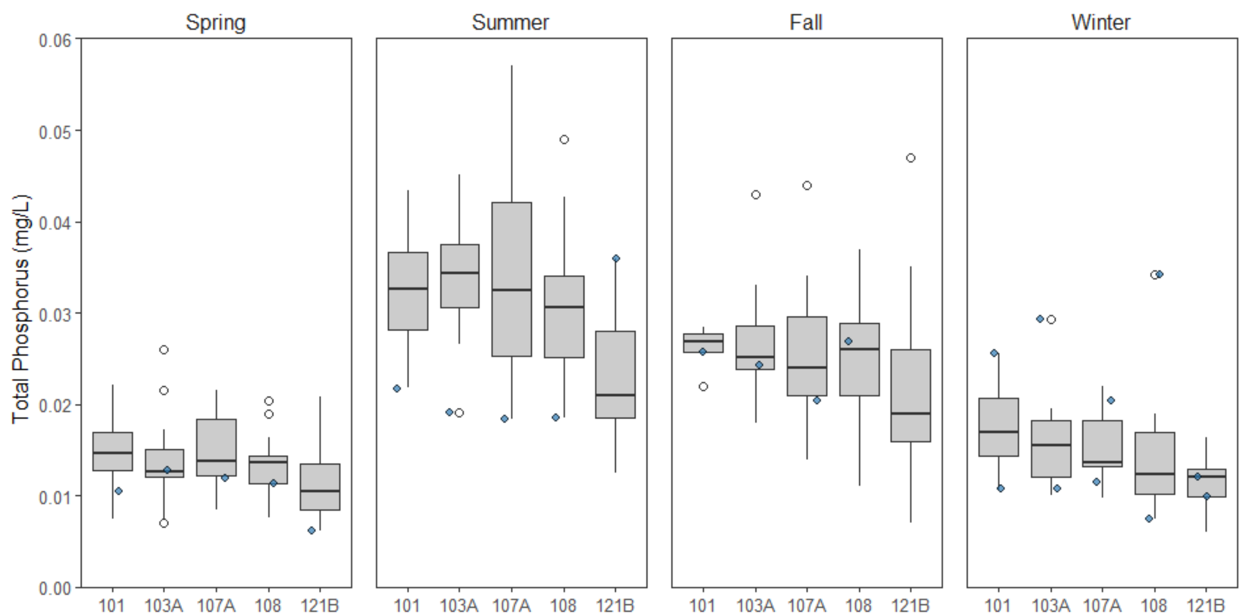
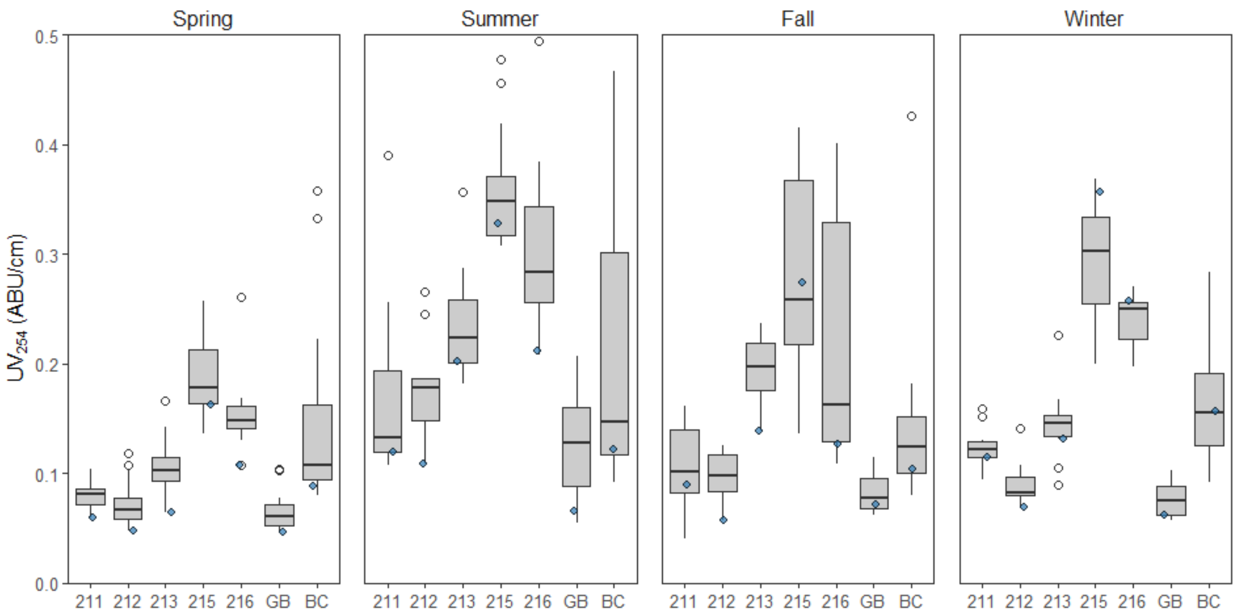


Figure 17: Boxplots depicting the seasonal distributions of UV_{254} observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median UV_{254} of 2019 for each site in the Ware River watershed is represented by the red square. The solid black line represents the historic 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.



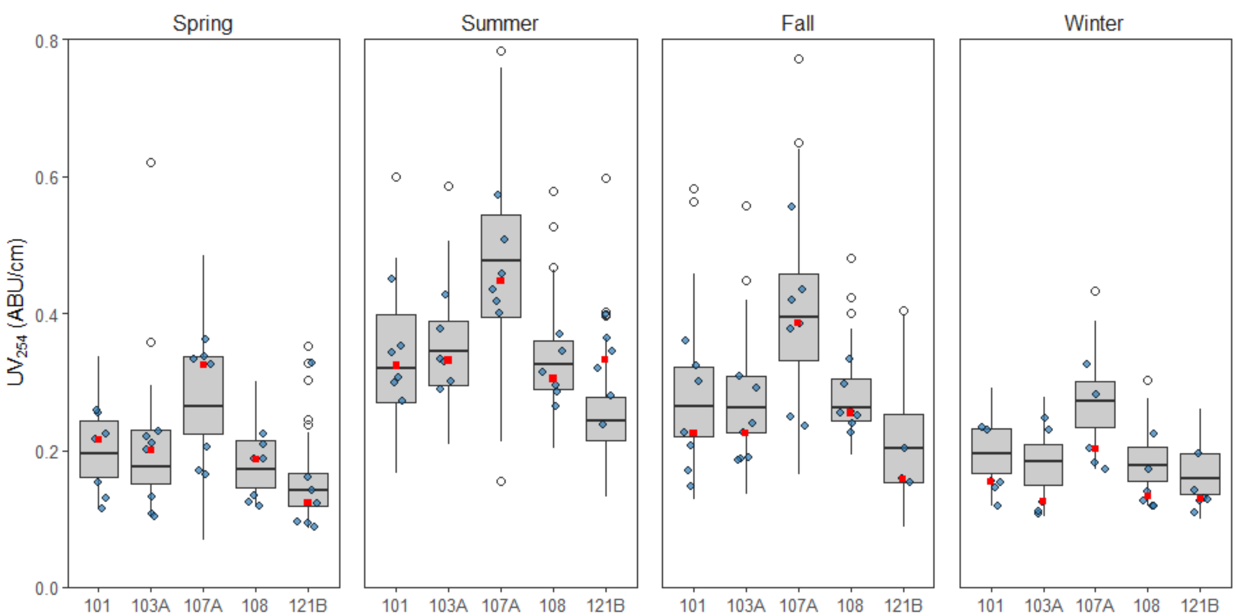


Table 20: Descriptive statistics (minimum, median, average, and maximum) for UV_{254} in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2019.

Site	UV_{254} (ABU/cm)				
	Count	Min	Med	Avg	Max
211	4	0.060	0.102	0.096	0.120
212	4	0.048	0.064	0.071	0.109
213	4	0.065	0.135	0.135	0.203
215	4	0.163	0.301	0.281	0.357
216	4	0.108	0.169	0.176	0.257
GB	4	0.046	0.064	0.062	0.072
BC	4	0.089	0.113	0.118	0.157

Table 21: Descriptive statistics (minimum, median, average, and maximum) for UV_{254} in Core tributary monitoring sites in the Ware River watershed during 2019.

Site	Season	UV_{254} (ABU/cm)				
		Count	Min	Med	Avg	Max
101	Spring	7	0.115	0.216	0.193	0.259
	Summer	6	0.272	0.324	0.337	0.450
	Fall	7	0.148	0.226	0.248	0.359
	Winter	6	0.119	0.154	0.173	0.235
103A	Spring	7	0.103	0.201	0.172	0.228
	Summer	6	0.289	0.331	0.343	0.427
	Fall	7	0.185	0.225	0.232	0.309
	Winter	5	0.108	0.125	0.164	0.247
107A	Spring	7	0.165	0.325	0.271	0.361
	Summer	6	0.401	0.447	0.465	0.573
	Fall	7	0.235	0.385	0.379	0.555
	Winter	5	0.172	0.202	0.233	0.326
108	Spring	7	0.119	0.187	0.169	0.225
	Summer	6	0.265	0.305	0.313	0.37
	Fall	7	0.226	0.255	0.266	0.333
	Winter	6	0.119	0.134	0.15	0.224
121B	Spring	7	0.088	0.124	0.147	0.328
	Summer	6	0.237	0.332	0.324	0.399
	Fall	3	0.153	0.159	0.171	0.202
	Winter	6	0.109	0.129	0.138	0.195

3.2.5.3 UV_{254}

UV_{254} absorbance in Quabbin Reservoir Watershed Core tributary monitoring sites ranged from 0.046 to 0.357 ABU/cm in 2019. UV_{254} absorbance in Ware River watershed Core tributary monitoring sites ranged from 0.088 to 0.573 ABU/cm in 2019 (Tables 20-21). Seasonal UV_{254} absorbance measured in Core tributary monitoring sites in the Quabbin Reservoir watershed were below historic season median absorbance values for the majority of Core tributary monitoring sites in the watershed during 2019 (Figure 17). Median UV_{254} in Core monitoring tributaries in the Ware River watershed in 2019 trended below seasonal medians for the period of record aside from samples collected during spring months (March through May). The timing of seasonal variability in absorbance values of UV_{254} was comparable between Ware River and Quabbin Reservoir watersheds for 2019 (e.g., maximum UV_{254} absorbance peaked during summer months for both watersheds, coincident with warmer water temperatures). Variations in sampling frequencies (e.g., quarterly vs. biweekly) in Core monitoring tributaries in the Quabbin Reservoir and Ware River watershed may serve to mask inter-watershed differences.

3.2.5.4 Calcium and Alkalinity

Calcium (Ca) monitoring in Quabbin Reservoir tributaries began in 2010 to assess the risk of colonization by aquatic invasive organisms (e.g., zebra mussels). 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). Monitoring for Ca began in tributaries in the Ware River watershed in 2018.

Ca concentrations in Quabbin Reservoir watershed Core sites in 2019 ranged from 0.85 to 13.5 mg/L (Appendix C). The range of Ca observed in Core monitoring tributaries in the Ware River watershed was 1.84 to 13.8 mg/L Ca (Appendix C). The 12 mg/L Ca threshold was exceeded at Boat Cover Brook in the Quabbin Reservoir Watershed in samples collected during the summer and fall months and at site 121B in the Ware River watershed during the summer of 2019. During this time pH at both locations remained below 7.4, thus these sites remain at low risk for colonization by zebra mussels. Ca concentrations in Quabbin and Ware River tributary sites were generally elevated during mid-late winter (January to February) and during summer months (June through August). The timing of seasonally elevated stream calcium concentrations relative to low streamflow conditions suggests that groundwater contributions may be a source of elevated calcium to 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 and long-term trends in calcium concentrations observed in tributaries to the Quabbin Reservoir.

Alkalinity data from Core tributary monitoring sites in the Quabbin Reservoir and Ware River watersheds 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 Massachusetts. The ARM criteria are based on average results for the month of April (Godfrey et al., 1996), with the ARM endangered threshold value corresponding to 5.0 mg/L.

Alkalinity of Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds ranged from 0.7 to 20.8 mg/L and from 1.75 to 25.8 mg/L, respectively, in 2019. Maximum annual alkalinity for each site was typically recorded in samples collected during the summer (June) or fall (September). Alkalinity measured in Quabbin Reservoir and Ware River watershed tributaries during the month of April 2019 indicates that the majority of Core monitoring tributaries in either watershed were within the ARM Endangered category (alkalinity of 2-5 mg/L) for 2019. For sites 212 and 213 in the Quabbin Reservoir watershed and sites 108 and 121B in the Ware River watershed, April alkalinity concentrations fell within the ARM Highly Sensitive (5-10 mg/L alkalinity) threshold, suggesting that these waters are less sensitive to the impacts of acid rain deposition than those that fall within the Endangered category (<5 mg/L alkalinity). No tributary sites monitored during 2019 were classified as Critical (alkalinity of 0-2 mg/L) or Acidified (alkalinity of <0 mg/K and pH <5), the two most vulnerable classifications. Maximum annual alkalinity concentrations for each Core monitoring site occurred in the summer or fall samples (June or September, respectively), consistent with prior monitoring periods.

3.2.6 Special Investigations

3.2.6.1 Forestry Water Quality Monitoring

3.2.6.1.1 Long-term Forestry Monitoring

Long-term monitoring for the potential impacts of timber harvesting on water quality is conducted by DWSP at two sites in the Quabbin Reservoir watershed. Monthly grab samples have been collected at the Middle Branch Dickey (MBD) Brook and the East Branch Underhill (EBU) Brook 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. Monthly sampling at MBD and EBU continued through 2019.

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 measures of precipitation, stream flow, and concentrations of solutes corresponding to key points 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. In addition, this work ultimately serves to inform the potential for long-term impacts of timber harvesting on water quality within the Quabbin Reservoir watershed.

Efforts related to long-term monitoring of water quality in MBD and EBU in 2019 included the annual re-installation and routine maintenance of water level loggers and precipitation gauges, downloading of field data, monitoring of weather forecasts, continued development of field procedures (including the incorporation of Teledyne ISCO 6712 Portable Samplers to methodologies), sample and data collection during three events, and associated data analysis. Harvesting within EBU watershed is anticipated for 2020. Event-based sample collection at MBD and EBU for at least four events will be conducted in 2020.

3.2.6.1.2 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. The Environmental Quality Section reviewed forestry lot proposals, inspected sites, and updated the forestry water quality monitoring database in 2019. Field review of proposed DWSP timber lots was conducted in the Ware River and Quabbin Reservoir watersheds. Post-harvest monitoring for turbidity did not occur at any sites in the Quabbin Reservoir watershed or Ware River watershed in 2019, as no stream crossings were identified during site inspections. No further issues were identified in 2019.

3.2.6.2 Environmental Quality Assessments

3.2.6.2.1 Quabbin Reservation Sanitary District

Water quality in surface water in the Quabbin Reservation sanitary district in 2019 was generally comparable to that of previous monitoring periods (Appendix B). Statistically significant elevated *E. coli* counts were observed in Boat Cove Brook (BC) and attributed to episodic flushing or extended periods of exceptionally low flow and higher temperatures than observed in 2009, rather than the result of potential physical or biological changes to the Winsor subdistrict. Elevated specific conductance results for 2019 were also noted for Boat Cove Brook (BC), relative to 2009 monitoring. Specific conductance of all sites within the Quabbin Reservation sanitary district increased temporarily, as streamflow decreased below the observed normal ranges for gauged tributaries between July through December 2019. Elevated specific conductance in Quabbin Reservation monitoring sites during 2019 likely reflects contributions from groundwater, and a lack of dilution from recent precipitation inputs. Monitoring of EQA sites in the Quabbin Reservoir watershed will shift to sites within the East Branch Swift River sanitary district in 2020. Monitoring of tributaries in the Quabbin Reservation sanitary district is anticipated to resume in 2023.

3.2.6.2.2 East Branch Ware River Sanitary District

Water quality in surface water in the East Branch Ware River sanitary district in 2019 was generally comparable to that of previous monitoring periods (Appendix B), with some exceptions. Most notable, specific conductance was significantly greater in 2019 than previous monitoring periods at all sites within the East Branch Ware River sanitary district. This pattern of increasing specific conductance has also been observed in surface waters in other tributaries to the Ware River watershed over the past several years (DWSP, 2019a). Monitoring of EQA sites in the East Branch Ware River sanitary district will continue in 2020.

3.2.6.3 Water Quality Database

Over 200,000 individual historical data records were imported into the water quality Access database following QA/QC procedures in 2019. Historical water quality data included both 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 2017. Records of historical plankton densities (2007-2017) were also digitized, evaluated for QA/QC purposes, and uploaded to the Access database in 2019 via import-scripts generated using R. DWSP staff began digitizing historical (2007-2017) presence/absence records for individual phytoplankton taxa in 2019. Digitized historical presence/absence will be assessed for QA/QC and imported to the Access database via import-scripts generated in R. Additional R-scripts were developed in 2019 to improve workflows for downloading and storing data generated as part of event-based sampling and paired watershed analyses conducted by DWSP (Section 3.6.1.2). Concentration data are converted to event loads and imported into the Access database. Data generated from Quabbin and Ware River watershed monitoring in 2019 and prior years are available upon request. Work related to DWSP data-management remains ongoing.

3.3 Reservoir Monitoring

Water quality of the Quabbin Reservoir in 2019 consistently met 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 2019 for the purpose of evaluating the physical, chemical, and biological dynamics of the Quabbin Reservoir.

General trends in water column characteristics can be inferred from depth profiles of physiochemical parameters, 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. Complete depth profiles of various physiochemical water quality parameters (temperature, pH, dissolved oxygen, specific conductance, pH, chlorophyll *a*, and phycocyanin) in the water column in the Quabbin Reservoir were collected approximately monthly between April and December 2019 (Appendix C).

3.3.1 Water Temperature

The approximate timing of Quabbin Reservoir stratification (e.g., spring stratification and fall turnover) may be inferred from temperature profile data collected by DWSP (Figure 18). Shifts in the timing and extent of the various stages of stratification may have profound implications on water quality, ecology, and primary productivity. Temperature remained relatively stable in the hypolimnion throughout stages of Quabbin Reservoir stratification in 2019, with temperatures ranging from 4.04 to 26.33 °C for all DWSP monitoring sites (Table 22). Temperatures were greatest at the surface during summer months and decreased with depth when the water column was stratified. The temperature profiles from DWSP monitoring sites 202 (Figure 18) and 206 (Appendix C) suggest that a shift from isothermal to conditions indicative of the early stages of stratification occurred between April 25 and May 16, 2019. Fall turnover likely began following sample collection on October 2, 2019 and was fully accomplished by November 21, 2019, as inferred by the shift in reservoir temperature profiles from stratified to fully isothermal during this period (Appendix C). The timing of reservoir stratification and mixing during 2019 was consistent with previous years.

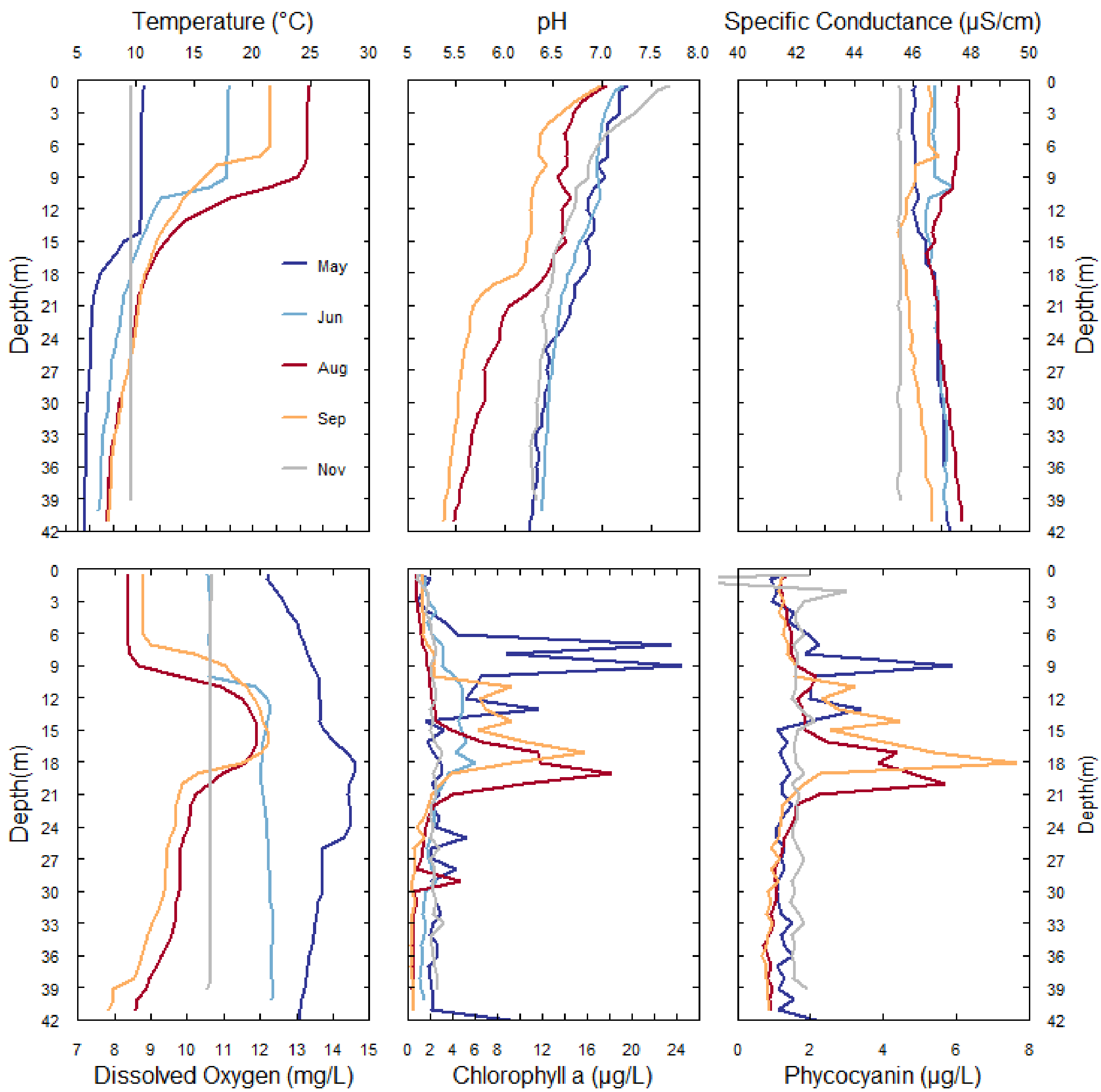
3.3.2 Dissolved Oxygen

Concentrations of dissolved oxygen in Quabbin Reservoir followed expected seasonal patterns in 2019 (Fig 18). Changes in concentrations of dissolved oxygen in Quabbin Reservoir generally coincided with changes in water temperatures, followed stratification stages, and rose with increases in phytoplankton abundance (Section 3.3.7). Elevated dissolved oxygen concentrations observed below the thermocline (during stratification) were observed alongside increased phytoplankton activity present throughout the latter half of 2019 (Section 3.3.7). Dissolved oxygen remained above 10 mg/L throughout the entire water column at DWSP monitoring site 202 through June 2019 and exceeded 10 mg/L in November and December 2019. As stratification strengthened in late June 2019, waters below the thermocline were isolated from atmospheric influence, and dissolved oxygen concentrations declined with depth, reaching a minimum concentration of 2.06 mg/L at 18 m at DWSP site Den Hill on October 2, 2019 (Table 21). The mean dissolved oxygen concentrations in 2019 remained above 10 mg/L for all DWSP monitoring sites in Quabbin Reservoir (Table 21), sustaining concentrations required to support cold water species (MassDEP 314 CMR 314 4.05(3)(a)1). Depletion in dissolved oxygen are generally most pronounced during the late stages of stratification (typically August through October). Following fall turnover in late October, oxygen was again able to disperse through the water column and was approximately 10.6 mg/L throughout the water column at site 202 on November 21, 2019.

Table 22: Descriptive statistics (minimum, median, average, and maximum) for physical water quality parameters monitored in Quabbin Reservoir during 2019 monitoring period. Statistics provided include measurements conducted in conjunction with monthly Quabbin Reservoir water quality monitoring (April through December). Profile data collected in conjunction with biweekly phytoplankton monitoring or follow-up investigations were not included in these calculations to avoid introducing bias to shallower depths monitored during the latter efforts. Phycocyanin concentrations below detectable levels were replaced with BDL. * Maximum phycocyanin concentrations observed at Den Hill were measured at a depth of 20-m on September 11, 2019. As the approximate depth of Den Hill is 19-m, this measurement was likely influenced by turbidity associated with sensor contact with the bottom of Quabbin Reservoir. Phycocyanin readings at 19 to 20-m depth at Den Hill were between 1-1.8 µg/L on other dates.

Analyte	Site ID	Count	Min	Med	Avg	Max
Temperature (°C)	202	399	5.03	9.28	10.4	24.85
	206	284	4.95	9.99	11.94	25.56
	Den Hill	165	4.04	10.43	11.95	26.33
Dissolved Oxygen (mg/L)	202	399	7.24	10.98	11.11	14.61
	206	284	7.63	11.23	10.78	13.4
	Den Hill	165	2.06	11.07	10.04	12.68
Dissolved Oxygen (% Sat.)	202	399	62	101.2	100.4	124.3
	206	284	68.8	100.9	100.5	118.5
	Den Hill	165	18.6	98.7	93.6	111.7
pH	202	399	5.26	6.41	6.34	7.69
	206	284	5.33	6.37	6.3	6.98
	Den Hill	165	5.26	6.27	6.17	6.79
Specific Conductance (µS/cm)	202	399	45.5	46.8	46.8	48
	206	284	45.5	47	47	48.4
	Den Hill	165	46.8	47.8	48	50.3
Chlorophyll *a* (µg/L)	202	399	0.26	2.23	2.69	24.34
	206	284	0.5	2.41	3.07	29.55
	Den Hill	165	0.98	2.49	3.08	16.11
Phycocyanin (µg/L)	202	399	BDL	1.53	2.64	11.68
	206	284	BDL	1.49	1.63	8.15
	Den Hill	165	0.98	1.68	1.92	26.76*

Figure 18: Select depth profiles of temperature, pH, specific conductance, dissolved oxygen, chlorophyll a, and phycocyanin collected by DWSP at Quabbin Reservoir monitoring site 202 in 2019. (See Appendix C for depth profiles on select dates for DWSP monitoring sites 206 and Den Hill). May 2019 profile corresponds to early stages of stratification of Quabbin Reservoir. June profile signifies full thermal stratification of Quabbin Reservoir. Profiles corresponding to August and September 2019 mark the proliferation of *Chrysosphaerella* in Quabbin Reservoir at site 202 in 2019. The depth profile collected in November 2019 suggests fall turnover occurred during October or early November 2019, homogenizing the water column.



3.3.3 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 climatic factors (e.g., freshwater inputs). Generally, pH within Quabbin Reservoir is unremarkable, ranging from above neutral (pH = 7) to slightly acidic (pH < 7), and has not exhibited strong temporal trends since the onset of routine monitoring by DWSP. Quabbin Reservoir water remains slightly acidic with median pH at DWSP monitoring sites ranging from 6.27 to 6.41 in 2019 (Table 21). Alkalinity was generally greatest at Den Hill in 2019, relative to other DWSP monitoring sites. Alkalinity remained low (<5 mg/L), and exhibited little variability with depth, stratification, or seasonality in Quabbin Reservoir during 2019 (Appendix C).

3.3.4 Specific Conductance

Specific conductance measured in the Quabbin Reservoir has historically been quite low, relative to other water bodies in the northeastern United States, which may often exceed 1,000 µS/cm in highly urbanized watersheds. The relatively low observed specific conductance measures in Quabbin Reservoir waters are likely a reflection of land 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. Specific conductance measured in Quabbin Reservoir waters was within the historical ranges during 2019, ranging from a minimum of 45.5 µS/cm at sites 202 (and 206) to an annual maximum of 50.3 µS/cm at Den Hill (Table 22).

3.3.5 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 1.2 NTU during 2019 (Table 23), within the historic range of turbidity observed at DWSP monitoring sites. Contributions from major tributaries to the Quabbin Reservoir during high streamflow, and shoreline erosion may contribute to instances of elevated turbidity measured in Quabbin Reservoir. The maximum turbidity observed in 2019 (1.2 NTU) was measured on October 2, 2019 at Den Hill. An extended period of low streamflow occurred during 2019 and may have contributed to the relatively low variability observed in turbidity levels of Quabbin Reservoir in 2019 (Section 3.1)

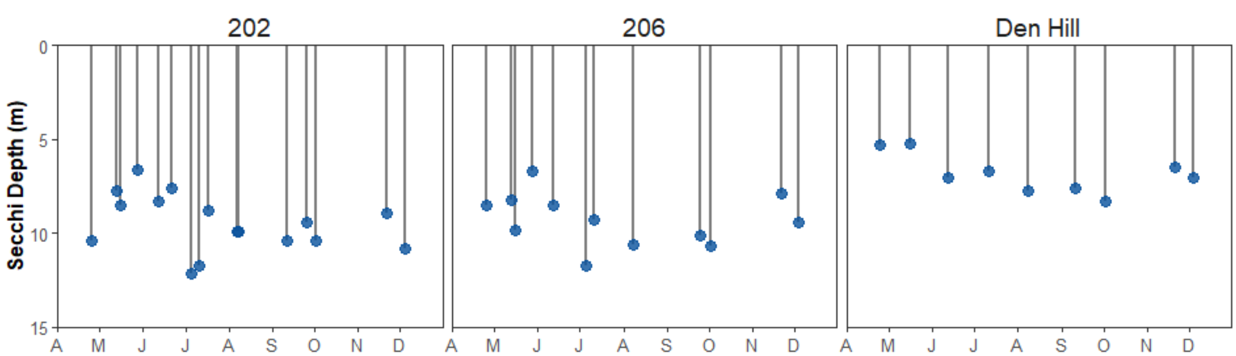
Table 23: Descriptive statistics (minimum, median, average, and maximum) for turbidity monitored in Quabbin Reservoir, DWSP monitoring site 202, for 2019 monitoring period. Detect limits were <0.05 NTU for turbidity. Censored data were substituted with one-half the detection limit for calculations.

Turbidity (NTU)					
Depth	**Count**	**Min**	**Med**	**Avg**	**Max**
Surface	9	0.19	0.26	0.31	0.67
Mid	9	0.23	0.3	0.32	0.64
Deep	9	0.16	0.25	0.25	0.52

3.3.6 Secchi Disk Depth/Transparency

Water in the Quabbin Reservoir generally demonstrates exceptional clarity, with Secchi disk readings exceeding 13-m (DWSP, 2019a) (Figure 19). Secchi disk transparency in Quabbin Reservoir during 2019 was generally consistent with previous monitoring, mirroring seasonal patterns of phytoplankton dynamics (Worden, 2000; DWSP, 2019a) and turbidity. Secchi disk transparency ranged from a minimum of 5.2-m at Den Hill on May 16, 2019, to a maximum of 12.1-m at site 202 on July 5, 2019 (Figure 19). Transparency at the Den Hill site is characteristically lower than sites 202 and 206, reflecting the nearby contribution of large riverine inputs from the East Branch Swift River and the Ware River (when diverting) (Figure 2). 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. Reductions in Secchi disk depth during summer months in 2019 may have been influenced by elevated concentrations of the chrysophyte, *Chrysosphaerella* (Section 3.3.7). Secchi disk depth typically increases following turnover; however, phytoplankton densities continued to negatively impact water transparency for the remainder of the year, resulting in the lowest average annual Secchi disk depth observed at DWSP monitoring sites 202 and 206 since regular transparency monitoring began in Quabbin Reservoir in 2008 (9.46-m and 9.28-m, respectively).

Figure 19: Secchi disk transparencies measured in 2019 in Quabbin Reservoir at DWSP monitoring sites 202, 206, and Den Hill (x-axis = months).



3.3.7 Nutrient Dynamics

Patterns of nutrient distributions in Quabbin Reservoir in 2019 were consistent with those documented previously by Worden (2000) and historical ranges observed in Quabbin Reservoir. Prominent seasonal, spatial, and vertical variations were present, likely due to the interactions of demand by phytoplankton in the epilimnion and metalimnion, the decomposition of organic matter in the hypolimnion, and the timing and extent of terrestrial-derived sources of nutrients delivered via riverine loading to the Quabbin Reservoir.

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

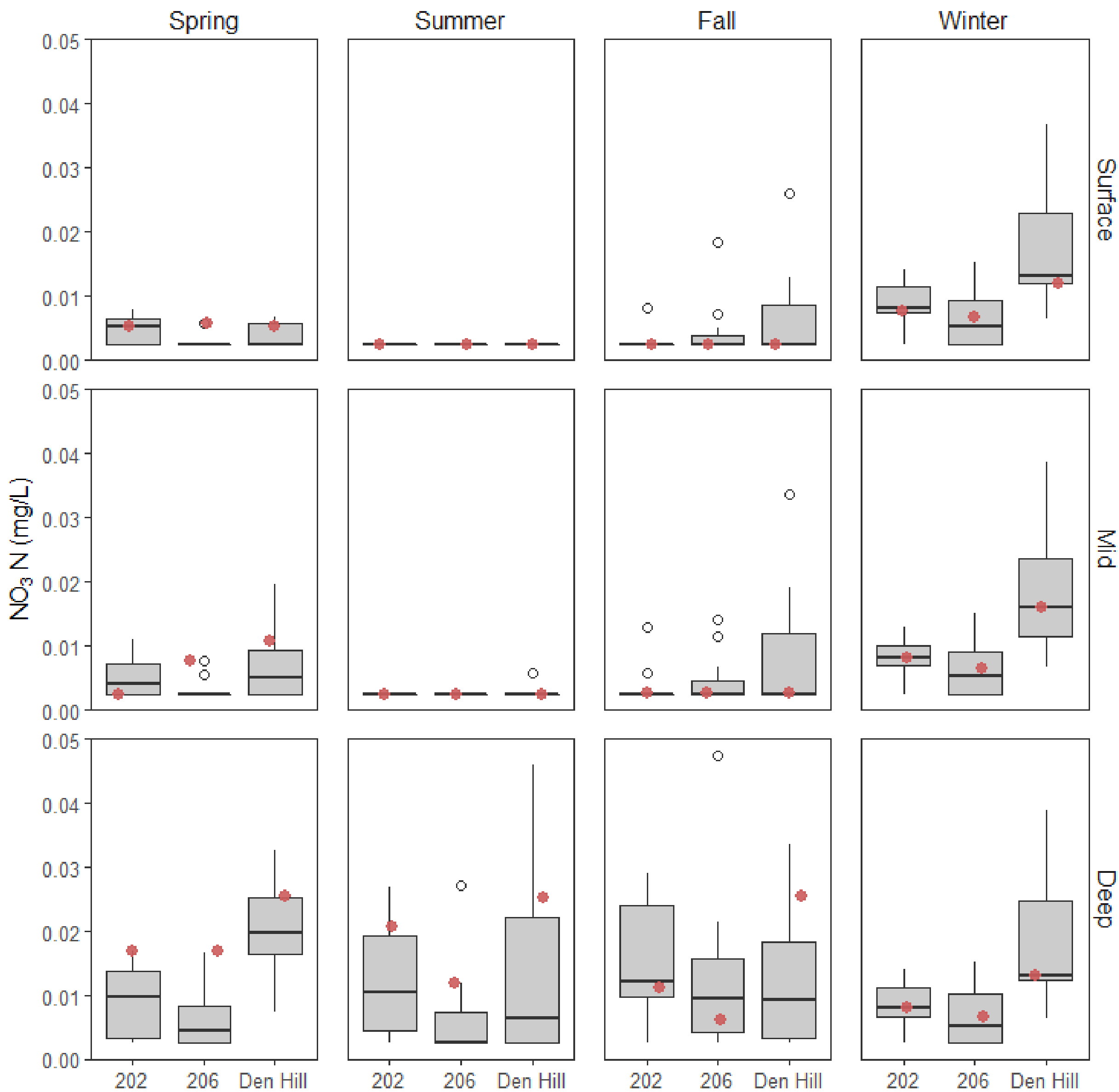
Concentrations of nitrate (NO_3-N) and ammonia (NH_3-N) ranged from <0.005 to 0.021 mg/L and from <0.005 to 0.02 mg/L, respectively, and exceeded historical maxima for samples collected from the epilimnion across several DWSP monitoring sites in spring 2019 (May) (Figure 20, Appendix C). Maximum NO_3-N and NH_3-N concentrations observed in 2019 occurred in the hypolimnion samples collected at Den Hill. Concentrations of NO_3-N and NH_3-N were generally elevated in the hypolimnion and at Den Hill relative to other sites (Fig 20, Appendix C). Concentrations of NO_3-N and NH_3-N were below detection limits (<0.005 mg/L) in all samples collected from the epilimnion during the summer and fall of 2019, attributed to uptake by phytoplankton during this time. NO_3-N and NH_3-N concentrations approached historic median concentrations for the period of record for all sites in samples collected in December 2019, following fall turnover.

Concentrations of total Kjeldahl (TKN) measured in Quabbin Reservoir ranged from <0.05 to 0.246 mg/L in 2019 (Table 24). TKN concentrations in Quabbin Reservoir exhibited little temporal variability in 2019 and were typically elevated in samples collected at Den Hill, similar to other nutrients. Seasonal concentrations of TKN in Quabbin Reservoir in 2019 were below historical seasonal median concentrations in the epilimnion except for in samples collected in July 2019. Historic ranges for TKN were not exceeded in 2019.

Table 24: Descriptive statistics (minimum, median, average, and maximum) for nutrients (NO_3-N, NH_3-N, TKN, TP, Ca, and Si) monitored in Quabbin Reservoir, DWSP monitoring site 202, for 2019 monitoring period. Ca was monitored at mid-depth only. Detect limits were <0.005 mg/L for NO_3-N, NH_3-N and TP, and <0.1 mg/L for TKN. Censored data were substituted with one-half the detection limit for calculations.

Analyte	Depth	Count	Min	Med	Avg	Max
NO_3-N (mg/L)	Surface	4	<0.005	<0.005	<0.005	0.008
	Mid	4	<0.005	<0.005	<0.005	0.008
	Deep	4	0.008	0.014	0.014	0.021
NH3-N (mg/L)	Surface	4	<0.005	<0.005	<0.005	0.0056
	Mid	4	<0.005	<0.005	<0.005	<0.005
	Deep	4	<0.005	0.006	0.008	0.02
TKN (mg/L)	Surface	4	0.116	0.12	0.12	0.124
	Mid	4	0.104	0.132	0.135	0.17
	Deep	4	<0.1	<0.1	0.089	0.135
TP (mg/L)	Surface	4	<0.005	<0.005	<0.005	0.006
	Mid	4	<0.005	<0.005	<0.005	0.007
	Deep	4	<0.005	<0.005	<0.005	0.006
Si (mg/L)	Surface	4	2.03	2.18	2.18	2.32
	Mid	4	1.83	2.09	2.08	2.31
	Deep	4	2.23	2.5	2.54	2.93
Ca (mg/L)	Surface	0	-	-	-	-
	Mid	4	1.95	2.01	2.01	2.08
	Deep	0	-	-	-	-

Figure 20: Boxplots depicting the seasonal and vertical distributions of NO_3-N observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected quarterly in 2019 are signified by the red points. The solid black line represents the historic 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.



3.3.7.2 Total Phosphorus

Concentrations of total phosphorus (TP) measured in Quabbin Reservoir ranged from <0.005 to 0.007 mg/L in 2019 (Table 24). TP concentrations were below detection limits (<0.005 mg/L) in 53% of samples collected in 2019 (n=19), and in the epilimnion at all sites during the summer and fall months. Samples collected in the spring (May 2019) at DWSP sites 202 and Den Hill, were elevated relative to other seasons (July, October, and December). TP increased at the Den Hill monitoring site following fall turnover, although values remained comparable to or below winter median concentrations for the period of record (Appendix C). TP concentrations following fall turnover remained below detection limits for sites 202 and 206. TP concentrations were below the 10 µg/L threshold for classification as an oligotrophic water body (Carlson, 1977) in all samples in 2019.

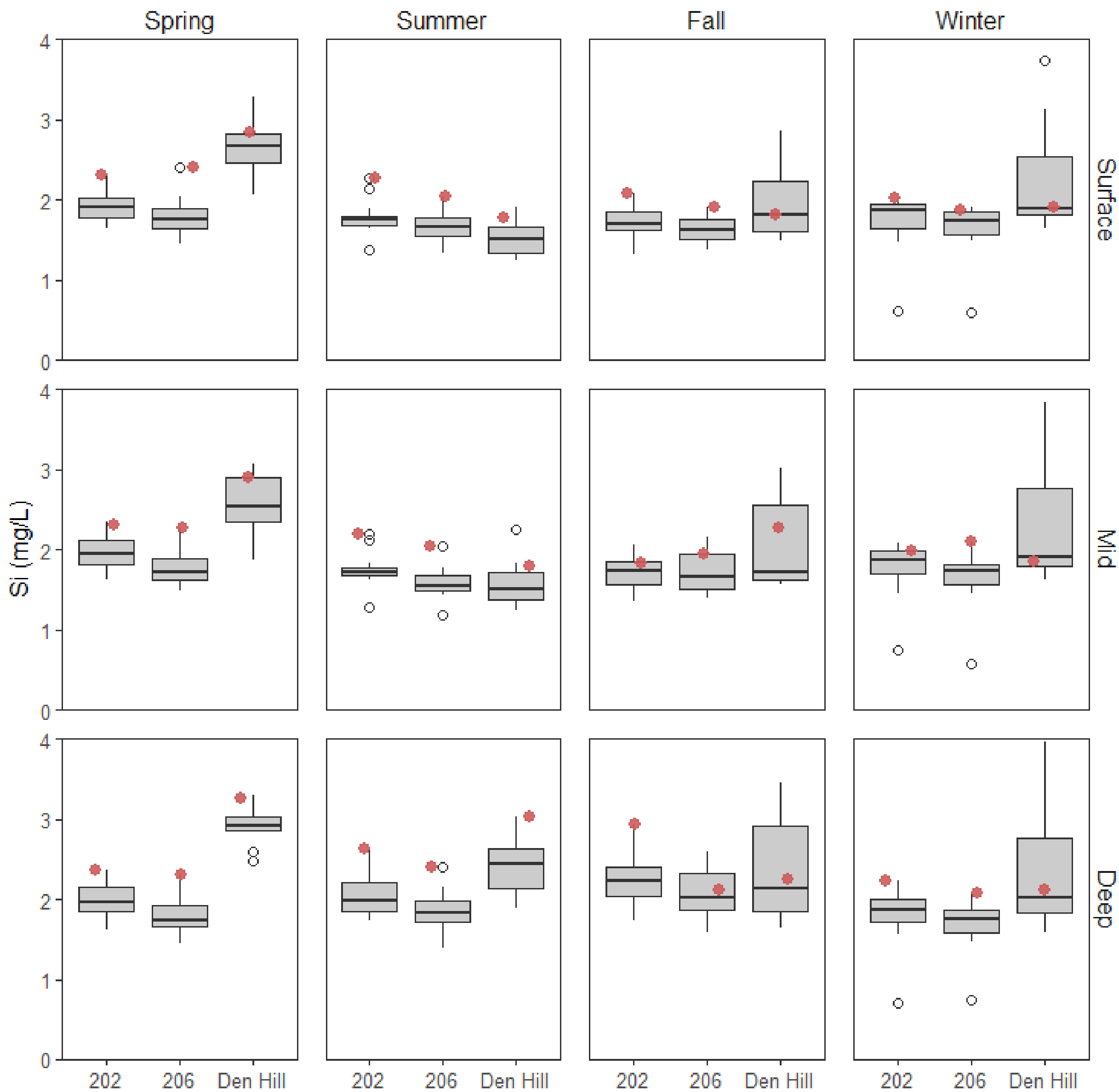
Above normal streamflow during April and May may have resulted in subsequent loading of phosphorus and other nutrients (namely, NO_3-N and NH_3-N) to Quabbin Reservoir and the resultant concentrations observed in spring (May) samples at DWSP sites 202 and Den Hill. NH_3-N and TP depletion may serve to limit the growth of phytoplankton in Quabbin Reservoir, as TP may act as the limiting nutrient in lakes in temperate climates (Worden, 2000). Depletion of nitrogen species and TP in the epilimnion during summer and fall may be attributed to seasonal uptake by phytoplankton (Section 3.3.7). Elevated concentrations of nutrients observed in the hypolimnion are likely the reflection of microbial decomposition of sedimenting organic matter. Monitoring of nutrients in Quabbin Reservoir will be conducted monthly in 2020.

3.3.7.3 Calcium and Dissolved Silica

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). Concentrations of calcium remained below 2.5 mg/L in 2019 (Table 24, Appendix C), consistent with previously observed dynamics in calcium concentrations in Quabbin Reservoir and demonstrating a continued low risk of zebra mussel colonization.

Silica is utilized by phytoplankton, particularly diatoms and chrysophytes (Reynolds, 2006). Silica concentrations in Quabbin Reservoir during 2019 exceeded seasonal median concentrations of silica observed since 2005 (Figure 21), although remained below 4 mg/L (Table 24, Appendix C). Concentrations of dissolved silica in Quabbin Reservoir exhibited spatial and temporal gradients consistent with seasonal productivity and riverine loading of dissolved silica to the Quabbin Reservoir. Spatial gradients in dissolved silica concentrations observed in Quabbin Reservoir are likely the result of proximity of sample sites to localized inputs (e.g., riverine loading). Dissolved silica concentrations were greatest at Den Hill, similar to patterns observed in turbidity and UV_{254} across monitoring sites (Section 3.4.3), and likely the result of the proximity of Den Hill to the confluence of the East Branch Swift River with the Quabbin Reservoir. Silica concentrations in the Quabbin Reservoir were generally lower in the epilimnion during the summer and fall, consistent with previous results and likely attributed to uptake by phytoplankton (e.g., diatoms) and lack of substantial riverine inputs during an extended period of below-normal streamflow observed during the summer and fall of 2019 (Section 3.1). Silica monitoring will be conducted monthly during 2020.

Figure 21: Boxplots depicting the seasonal and vertical distributions of silica observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected in 2019 are signified by the red points. The solid black line represents the historic 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.



3.3.7.4 *UV$_{254}$*

UV$_{254}$ in Quabbin Reservoir is impacted by contributions from major tributaries and reservoir circulation and mixing. Spatial trends in UV$_{254}$ are largely reflective of localized inputs (e.g., elevated UV$_{254}$ at Den Hill relative to other monitoring sites) (Figure 22). UV$_{254}$ was greatest at Den Hill, and generally higher in spring and winter 2019 samples (Table 25). For Den Hill samples, this pattern may be attributed to potential increased loading from the East Branch Swift River during the spring and winter months, when streamflow was high, compared to lesser influx of organic matter during the summer and fall sampling events, when streamflow was comparatively lower. For all Quabbin Reservoir monitoring sites, UV_{254} levels observed in 2019 exceeded seasonal medians for the period of record. UV_{254} in Quabbin Reservoir ranged from 0.0269 to 0.0769 ABU/cm in 2019, with maximum values exceeding the historic range for sites 202 and 206.

Figure 22: Boxplots depicting the seasonal and vertical distributions of UV_{254} observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected in 2019 are signified by the red points. The solid black line represents the historic 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.

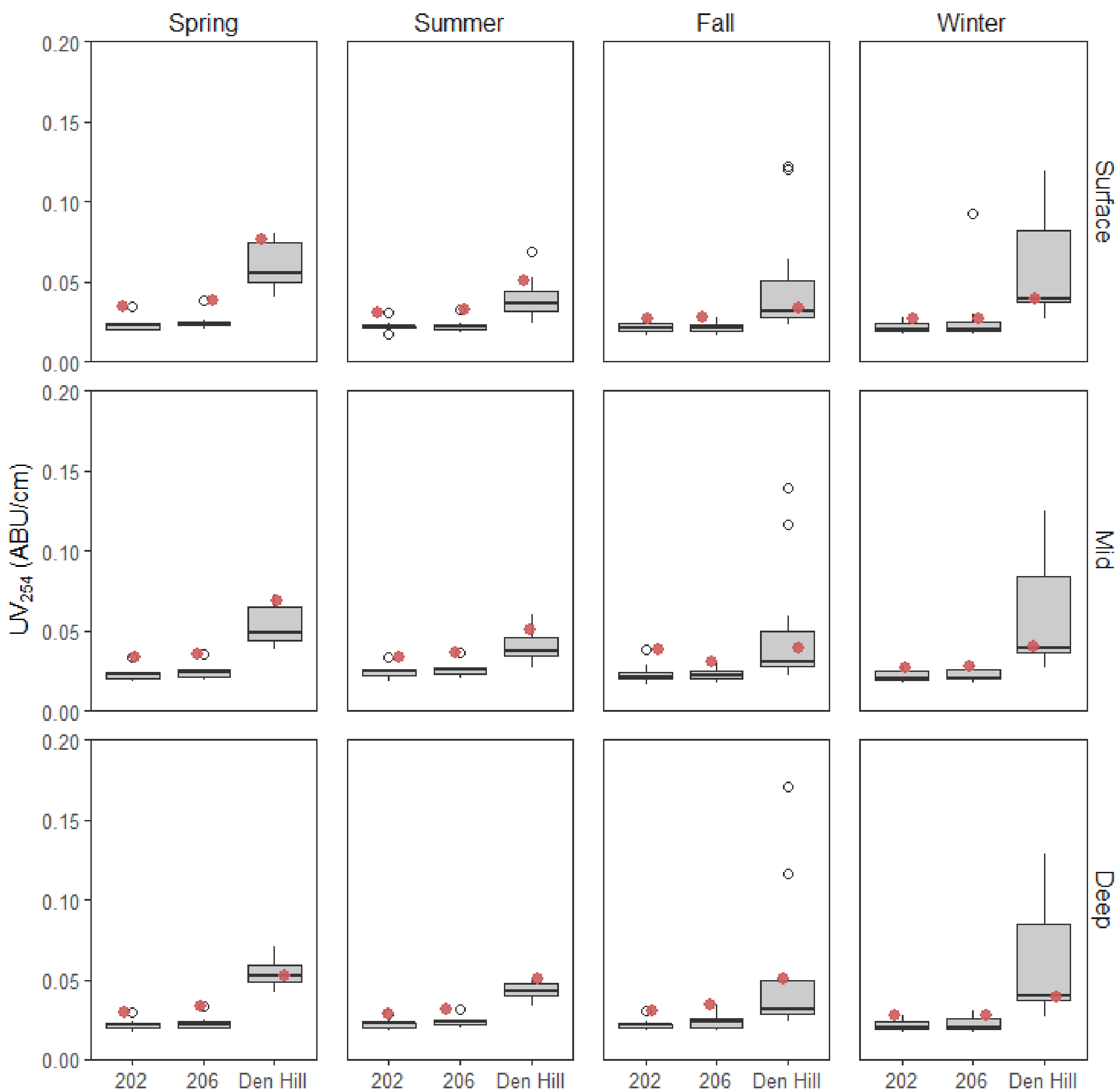


Table 25: Descriptive statistics (minimum, median, average, and maximum) for UV_{254} monitored in Quabbin Reservoir, DWSP monitoring site 202, for 2019 monitoring period. Detect limits were <0.0001 ABU/cm for UV_{254}. Censored data were substituted with one-half the detection limit for calculations.

UV_{254} (ABU/cm)					
Depth	**Count**	**Min**	**Med**	**Avg**	**Max**
Surface	4	0.0271	0.029	0.0299	0.0344
Mid	4	0.0271	0.0335	0.033	0.038
Deep	4	0.0272	0.0292	0.0291	0.0309

3.3.8 Phytoplankton

Samples for enumeration of phytoplankton were collected from Quabbin Reservoir monitoring sites 202 and 206 on 40 and 12 days in 2019, respectively. The annual routine sample collection for enumeration of phytoplankton began on January 03, 2019. Following this collection, weather conditions prevented sample collection until April 25, 2019. Routine samples were collected from monitoring site 202 approximately biweekly from May through September (weather permitting) and monthly from October through April (weather and ice conditions permitting). Routine samples were collected approximately monthly at site 206 (weather and ice conditions permitting). Additional, follow-up, samples were collected at site 202 in response to elevated densities of nuisance taxa (e.g., *Chrysosphaerella*) in the latter half of 2019.

Samples for routine monitoring were collected at depths ranging from 3 to 5-m (corresponding to epilimnion) and at the approximate interface of the epilimnion and metalimnion (generally between 8 to 13-m). Exact sample depths within these layers were selected based on concentrations of dissolved oxygen, chlorophyll *a,* measured *in situ* at the time of sample collection. Samples were periodically collected at additional depths based on results of these *in situ* readings. Density thresholds for several nuisance taxa (including *Chrysosphaerella* and *Dinobryon*) are routinely used by MWRA and DWSP to guide monitoring decisions (Table 26).

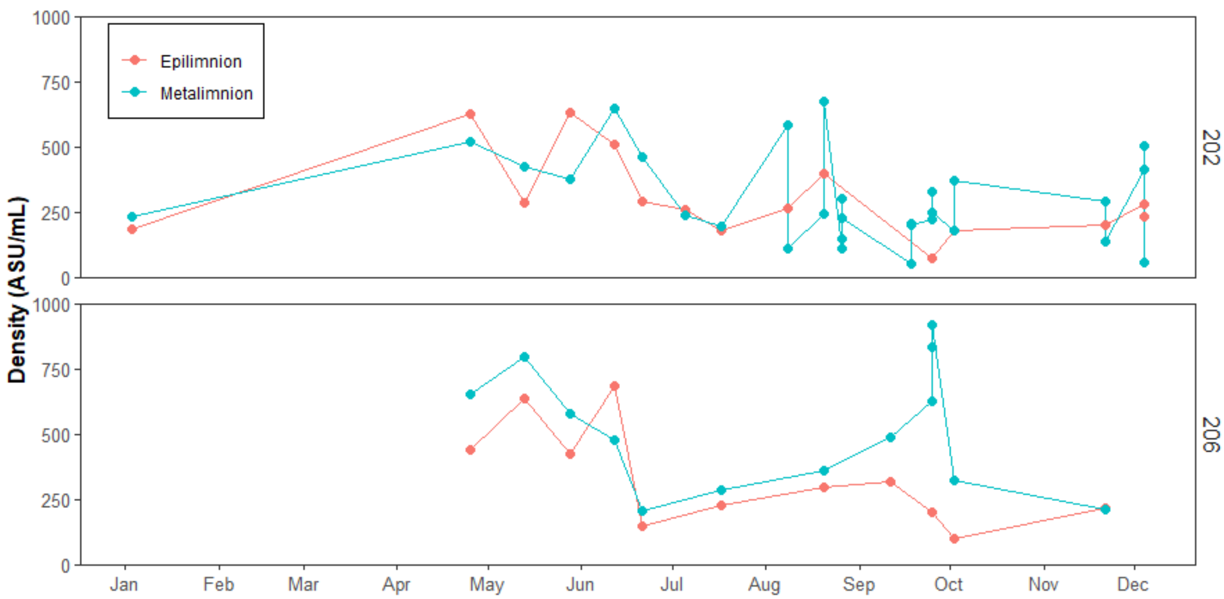
Table 26: Phytoplankton monitoring thresholds for various nuisance organisms in MWRA source waters (e.g., Quabbin Reservoir, Site 202).

Nuisance Organism		Early Monitoring and Treatment 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

The Quabbin Reservoir supports a phytoplankton community typical of many oligotrophic systems located in the temperate zone (Worden, 2000). The most frequently observed taxa in samples collected from Quabbin Reservoir in 2019 were diatoms (*Asterionella, Cyclotella*, *Synedra*, and *Urosolenia*), chrysophytes (*Chrysosphaerella and Dinobryon*), and cyanophytes (*Aphanocapsa* and *Microcystis*).

Consistent with other oligotrophic systems in New England (Carlson, 1977; Wetzel, 1983), phytoplankton densities observed in Quabbin Reservoir in 2019 were relatively low, with the exception of a proliferation of Chrysophytes during much of the latter half of 2019. Diatoms (largely *Asterionella* and *Urosolenia*) dominated the water column through June, and again in December, in routine samples collected from Quabbin Reservoir in 2019. Total phytoplankton densities decreased into July 2019 (Figure 23) and offered a shift in community composition to favor more diversity than the cooler water column of the preceding months (Figure 24), consistent with previously observed patterns of seasonal succession in Quabbin Reservoir (DWSP, 2019a). Total phytoplankton densities in samples collected from site 202 in 2019 generally exceeded total densities observed in 2018.

Figure 23: Total phytoplankton densities observed in routine samples collected from the epilimnion and metalimnion, Quabbin Reservoir sites 202 and 206, during 2019.

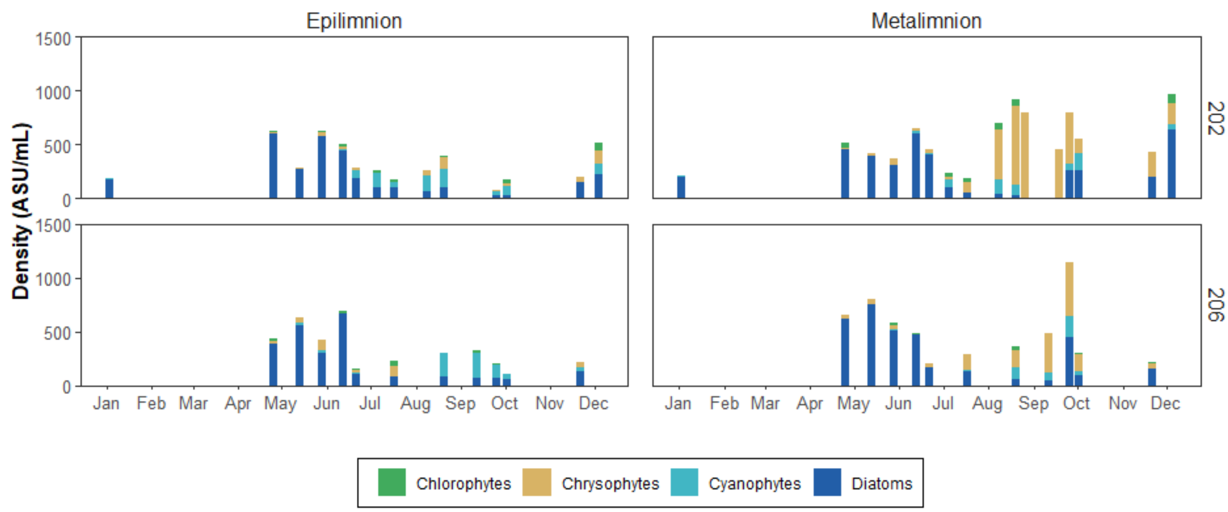


Chrysophytes are routinely detected at low densities throughout the water column in Quabbin Reservoir, typically remaining below the early monitoring triggers established by MWRA and used routinely at Wachusett Reservoir (Table 26). In 2019, *Chrysosphaerella* was the dominant taxa observed in routine samples collected at site 202 from August through October, exceeding early monitoring thresholds on several dates in 2019. *Dinobryon* was observed in excess of 200 ASU/mL in samples collected from the metalimnion (16 to 18-m) at site 206 on September 25, 2019. Densities of *Synura* exceeded 10 ASU/mL in samples collected from the epilimnion and the metalimnion in routine samples collected from site 202 on August 8, throughout September (11, 18, and 25), and on November 21, 2019 (Figure 24). *Synura* densities observed in routine samples from site 206 exceeded 10 ASU/mL in routine samples collected from the metalimnion on September 11 and 25, 2019. *Uroglenopsis* remained below 100 ASU/mL in all routine samples collected in 2019.

Total cyanophyte densities remained low (below 300 ASU/mL) throughout 2019 in Quabbin Reservoir, with *Aphanocapsa* and *Microcystis* comprising the dominant Cyanophyte taxa observed. *Dolichospermum* was not observed at countable densities in routine samples collected from Quabbin Reservoir in 2019. *Uroglenopsis,* a chrysophyte, remained below 100 ASU/mL in all routine samples collected in 2019.

Monitoring for phytoplankton in Quabbin Reservoir will be conducted approximately biweekly at site 202 and monthly at site 206 in 2020. In the instance that an exceedance of an early monitoring trigger is observed, phytoplankton monitoring will be increased, as appropriate.

Figure 24: Phytoplankton group total densities, collected from the epilimnion and metalimnion, Quabbin Reservoir sites 202 and 206, during 2019 routine sampling.



3.3.8.1 *Chrysosphaerella in Quabbin Reservoir, 2019*

Chrysosphaerella are a genus of freshwater golden algae (within the chrysophyte class) that exist as solitary cells or colonial organisms (Guiry and Guiry, 2020). Chrysophyte blooms are responsible for nuisance taste and odor properties of water (Lin, 1977; Watson, 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). To date, compounds produced by chrysophytes have not demonstrated toxicological properties (AWWA, 2010).

Additional phytoplankton monitoring in Quabbin Reservoir, specifically location 202 near the CVA intake, was performed in 2019 in response to customer complaints from CVA communities concerning undesirable metallic taste and odor characteristics of finished water. Phytoplankton sampling frequency at site 202 was increased from biweekly to daily, excluding weekends, from August 8 through August 26. Sampling transitioned to two to three times per week from August 26 through September 30, to weekly in October, biweekly in November, and monthly during December 2019. The maximum recorded *Chrysosphaerella* density (669 ASU/mL) for site 206 (in proximity to Shaft 12, where water is drawn into the Quabbin Aqueduct) in 2019 was collected at 15-m on August 9. *Chrysosphaerella* densities above early monitoring triggers were not observed at countable densities at Shaft 1 (Quabbin Outlet, West Boylston) during a period of active Quabbin Reservoir transfers (July 9 and September 12, 2019). The maximum *Chrysosphaerella* density (1,051 ASU/mL) for 2019 at site 202 was recorded on August 7, at a depth of 17-m. Samples collected on August 13 demonstrated a decrease in *Chrysosphaerella* densities and the presence of many degraded *Chrysosphaerella* colonies. *Chrysosphaerella* densities generally trended lower thereafter but remained above the early monitoring trigger level (100 ASU/mL) through September. Prior to 2019, *Chrysosphaerella* were not detected above early monitoring triggers (100 ASU/mL) by DWSP staff, aside from 149 ASU/mL (9-m site 206) on July 5, 2018, and 138 ASU/mL (3-m site 202) on June 1, 2017. 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.

Chrysophytes and the factors controlling the proliferation of chrysophyte blooms have been the focus of numerous investigations (Bird and Kalff, 1987; Sandgren et al., 1995; Paterson et al., 2004; Gastrich et al., 2004; Schroeder et al., 2009). Climatic and hydrologic drivers in recent years, combined with characteristics of Quabbin Reservoir, likely contributed to favorable conditions for the proliferation of *Chrysosphaerella* observed in 2019. The *Chrysosphaerella* bloom was likely the result of contributions from multiple factors. Additional research and monitoring may reveal critical information relative to chrysophyte bloom development in the Quabbin Reservoir and aid in future management decisions throughout the MWRA water supply system.

3.3.9 Bacteria

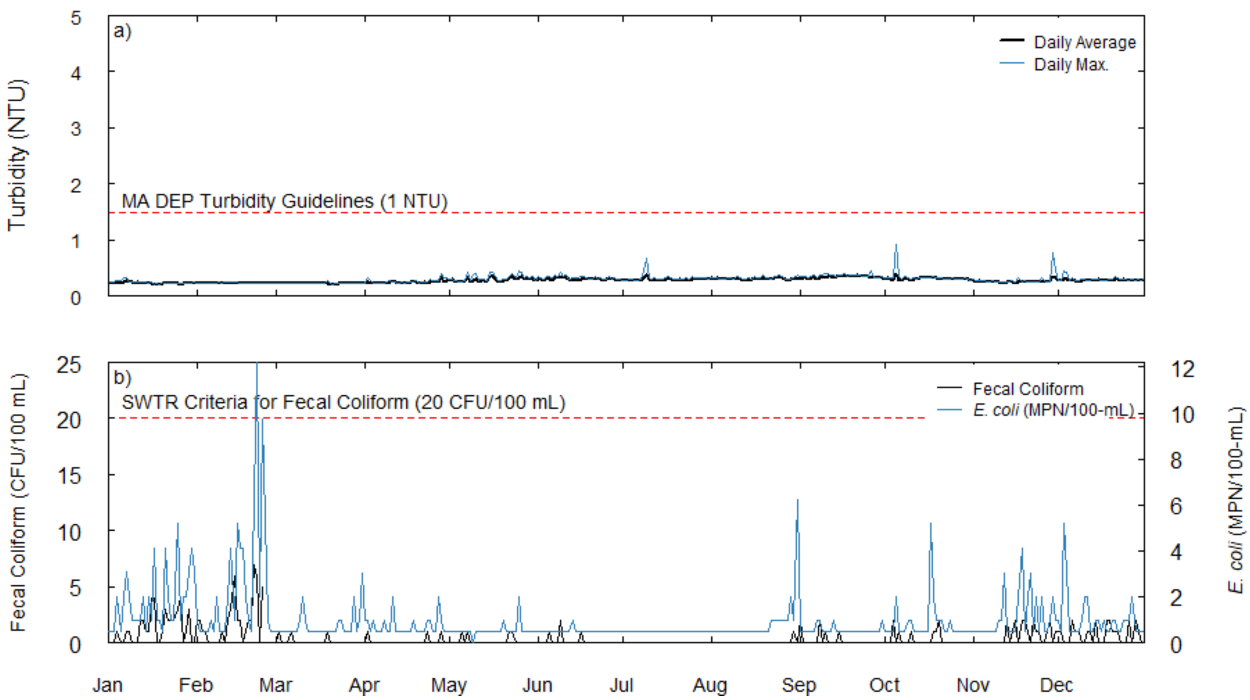
A population of waterfowl that roost on Quabbin Reservoir during fall and winter months have been identified as the primary sources of fecal coliform and *E. coli* to the Quabbin Reservoir (Wolfram, 1996). Additional sources may include semi-aquatic wildlife, and inputs from major tributaries to the 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 2 CFU/100-mL in samples collected by DWSP from Quabbin Reservoir in 2019. *E. coli* was not detected in samples collected by DWSP in Quabbin Reservoir in 2019.

The MWRA monitors bacteria levels and turbidity of Quabbin Reservoir water daily prior to disinfection (e.g., via the Winsor Dam Intake) to ensure compliance with the SWTR. Monitoring is performed by MWRA at the BWTF in Ware, MA.

Turbidity is monitored daily by MWRA via an on-line turbidity meter inside the BWTF. Average and maximum daily turbidity levels in Quabbin Reservoir source water measured at the BWTF ranged between 0.27 to 0.30 NTU and 0.41 to 0.92 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 2019 (Figure 25). Fecal coliform bacteria were not detected above 20 CFU/100-mL in samples collected at the BWTF (Figure 25). 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 (0.42 and 0 CFU/100 mL, respectively). *Cryptosporidium* was not detected in biweekly samples (n=26) of raw water at the BWTF in 2019. A single *Giardia* cyst (0.02

cysts/L) was observed on February 26, 2019. Monitoring for *Cryptosporidium* and *Giardia* will continue to be conducted on a biweekly basis at the BWTF in 2020. No violations of drinking water standards for these organisms occurred during 2019.

Figure 25: a) Results of daily average and maximum turbidity, and b) fecal coliform and *E. coli* monitoring of Quabbin Reservoir source water, Winsor Dam Intake, performed at BTWF.



3.4 Macrophyte Monitoring and Management

Portions of Quabbin Reservoir and select ponds within the Quabbin Reservoir and Ware River watersheds are periodically assessed for the presence of aquatic invasive species (AIS) by DWSP staff. Several AIS have been documented through these efforts. *Myriophyllum heterophyllum* (variable leaf water-milfoil) is the most frequently encountered AIS in the watersheds and is also well distributed in portions of Quabbin Reservoir. Distribution of this species and other AIS encountered during surveys in recent years are summarized in the following sections. Management of AIS within these watersheds is currently limited with one project funded by MWRA and several others conducted by private lake/pond associations.

Approximately 29 miles of shoreline were assessed for the presence of AIS in 2019. Shoreline assessments entailed visual observations of the littoral zone via a kayak or small boat. This total does not include areas surveyed within the Quabbin Reservoir, portions of the Ware River, and small ponds located on Prescott Peninsula with water levels too low to survey by kayak.

3.4.1 *Myriophyllum heterophyllum*

Five of the water bodies surveyed in 2019 contained *M. heterophyllum* (variable leaf water-milfoil). In these water bodies, this plant was abundant and widely distributed. It is also well established in sections of the Quabbin Reservoir and the Ware River. Despite repeated annual management, *M. heterophyllum* in the basin above the Shaft 8 intake along the Ware River and in sections above the railroad bridge along the Ware River 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, weather conditions often do not provide for a complete freeze and the presence of *M. heterophyllum* upstream of the Shaft 8 intake continue to repopulate this area.

M. heterophyllum above the Route 122 bridge increased substantially from 2018 to 2019. Large, dense beds were found along both the eastern and western shorelines where previously small, scattered patches have grown together (ESS Group, 2019). Davey Resource Group was contracted by MWRA to physically remove plants via raking from land/boat. This work was focused mainly on the Shaft 8 basin and then moved upstream above Route 122. Many plants were found growing in water too deep to facilitate this type of harvesting and therefore remained unmanaged. Below the bridge and just above Shaft 8, plants were sparsely distributed over a larger area, but overall densities were lower. Reduced plant numbers in the basin area afforded the Davey Resource Group staff additional time to focus on removal of *M. heterophyllum* above the bridge. This added effort may provide improved results in 2020. However, these upriver infestations will continue to provide a source of plant fragments able to recolonize the Shaft 8 basin. 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 will be on keeping the basin above the intake as free of *M. heterophyllum* as is feasible.

A pioneer infestation of *M. heterophyllum* was found in Comet Pond in 2018. Plants were removed via hand harvest late in the season by pond residents with DCR assistance and then again by AE Commercial Diving Services, Inc. using diver assisted suction harvesting (DASH) in August 2019. Several weeks later, DCR Lakes & Ponds divers revisited the site to remove a small number of plants that were missed due to visibility issues and/or regrowth. Management via physical methods is anticipated to continue in 2020.

3.4.2 *Phragmites australis*

Phragmites australis (common reed) is an invasive species which is widely distributed throughout the region including within the Quabbin Reservoir and Ware River watersheds, and the Quabbin Reservoir. This species spreads using three different methods: seeds, stolons, and rhizomes. As more plants mature to reproductive age, seed production and dispersal increases. Not only will plant numbers increase as seeds are spread but the likelihood of seeds being carried to other water bodies also increases. Stolons, runners that are on the top of the soil, and rhizomes, which grow 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. *Phragmites*, once established, aggressively colonizes the shoreline and is nearly impossible to eradicate using physical methods such as cutting below the surface of the water, hand pulling or covering with black plastic. Herbicide use would be the easiest and most effective means of reducing plant numbers but is currently not under consideration by DWSP. Some success has been documented using a combination of several different methods, especially if stands are small and newly established. Ideally, small, isolated populations should be targeted for management before they become established. Early removal is far more effective, utilizes fewer resources and has less of an environmental impact.

Phragmites was widely distributed in the Quabbin Reservoir in 2019. Stands of *Phragmites* were not observed in any other water bodies surveyed in 2019.

3.4.3 *Cabomba caroliniana*

Cabomba caroliniana (fanwort) was absent in the water bodies surveyed for AIS in 2019, aside from Queen Lake in Phillipston and Demond Pond in Rutland, MA. At Queen Lake, numerous rooted plants and fragments were found in the boat launch and beach area, along the western shoreline, and in the northeastern sections including several coves. *C. caroliniana* has been present in this water body for several years and distribution and density appear to be increasing each year. Plants were especially abundant in the large cove on the western shoreline where plants were "topped out" and dense at the time of the survey.

Members of the Demond Pond Association contracted with SOLitude Lake Management to manage *C. caroliniana* via herbicide treatment in 2018 and 2019. A survey conducted one week following the 2019 treatment showed large numbers of plants remaining; however, this timing may not have been enough for the treatment to have an effect. Cyanobacteria (later identified as *Microcystis*) was present at the time of the survey as a thick green scum and suspended colonies were readily visible to the unaided eye. DWSP understands the association plans to continue herbicide treatment for invasive species when funds are available.

3.4.4 *Utricularia inflata*

Utricularia inflata (swollen bladderwort), was documented at Whitehall Pond in 2017 and has been found each year since. Long Pond was not monitored this year, but *U. inflata* was found there in 2017 as well. *U. inflata* was found in Quabbin Reservoir at Boat Launch Area 2 in 2017 but not during surveys in 2018 or 2019.

3.4.5 *Iris pseudacorus*

In 2013, *Iris pseudacorus* (yellow flag iris), a relatively aggressive invasive species that closely resembles the native blue flag iris, was documented at Connor Pond in Petersham where it has colonized large stretches of the western shoreline and has become densely distributed in many small coves. This plant continues to spread at an accelerated rate. It is now found along the shores of the East Branch Swift River, in Pottapaug Pond and occasionally at the boat launch at Boat Launch Area 3 in Hardwick. A steady supply of seed pods continues to be produced and released from the plants established in Connor Pond. These pods can float along with water currents and infestations may worsen as plant density and distribution increases. In 2019, the fragment barrier at Area 3 was repositioned to catch floating seed pods more effectively. This will be an ongoing problem with no readily available solution.

Several small patches of *I. pseudacorus* were documented at Demond Pond. Members of the pond association were notified of the locations of each patch of plants and hand harvesting was recommended. These locations will be monitored during 2020.

3.4.6 *Lithrum salicaria*

Lithrum salicaria (purple loosestrife) was found at two pond locations in 2019 as well as in the Quabbin Reservoir. This plant is somewhat difficult to notice when not in bloom so it is possible that the presence of this invasive may be more widespread than believed. Ongoing annual surveys, conducted at different times of the season, may facilitate documentation of infestations not previously observed. At the time of the survey, populations were sparse at both locations. Low population densities of purple loosestrife are not conducive to the introduction of *Galerucella*, a beetle that is widely used to control this invasive plant. Because *Galerucella* feeds exclusively on purple loosestrife, to be an effective method of control, plant numbers must be significant enough to support a reproducing population.

3.4.7 *Rorippa microphylla*

Rorippa microphylla, (one-row yellowcress) is widely distributed in Massachusetts (USDA, 2020) and can be found in most streams and ponds within the watersheds.

Densities of *R. microphylla* do not seem to increase significantly in water bodies where it has become established. It is edible and may be kept in check by herbivores. In the past, this observation did not seem to be holding true for the population established in Peppers Mill Pond. In 2016, the patch there had increased in size from several plants to a large patch which was approximately 50 by 10 feet in size. One possible explanation is related to the water depth where plants were growing. This plant tends to grow mostly in shallow water where herbivores can easily feed. In Peppers Mill Pond, the patch of *R. microphylla* was in a relatively deep section of the pond where herbivory would be difficult for many animals except for aquatic species. Interestingly, *R. microphylla* was not found in Peppers Mill Pond during the 2017 survey. It was once again documented in 2018 and a small patch was observed in 2019.

To date, impacts from infestations of *R. microphylla* seem to be minor. It is widespread throughout the Quabbin Reservoir and Ware River watersheds and all New England and has subsequently been found in the Wachusett Reservoir watershed. It is likely being transported as seeds by wildlife, water currents, and possibly with gear used by anglers.

3.4.8 *Myosotis scorpioides*

Myosotis scorpioides (true forget-me-not) is not truly an aquatic plant but inhabits wet, disturbed shorelines. It was first documented at Quabbin Reservoir approximately 12 years ago and is found throughout New England. During the 2013 macrophyte survey conducted by ESS Group, Inc., several small patches of this plant were found along the eastern shoreline of Pottapaug Pond (ESS Group Inc., 2014). These infestations, as well as several others found at a later date by DCR staff, were removed by hand pulling. Additional plants have been documented in Pottapaug Pond each year. Forget-me-nots were also found in the upper section of Long Pond, Peppers Mill Pond, Connor Pond, Lake Mattawa, in a small pond inside Gate 20, Demond and Brigham Ponds. Populations will be monitored and, if possible, removed as they are documented. However, plants multiply by seed production and spread by an extensive, 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.

3.4.9 *Najas minor*

Najas minor (brittle naiad) was documented by ESS Group in 2014 at O'Loughlin Pond. Plants were harvested using DASH. *N. minor* plants closely resemble the native naiads, and the difference between the seeds of the native and invasive plants are virtually indiscernible to the birds that feed on them. DWSP hypothesize that transport of *N. minor* seeds via avian passage is a likely method of introduction of this AIS to O'Loughlin Pond. The *N. minor* infestation in O'Loughlin Pond documented in 2014 was relatively insubstantial and dealt with quickly and efficiently by DWSP. However, as a precaution to limit the spread of *N. minor* to Quabbin Reservoir, the fragment barrier at Quabbin Reservoir Boat Area 2 was checked approximately every two weeks during the 2019 field season. Complete macrophyte surveys were conducted on July 3, and August 6, 2019. No *N. minor* plants or were documented in O'Loughlin Pond for the fifth year in a row.

3.4.10 *Potamogeton crispus*

Smaller types of watercraft are less likely to carry AIS but are not risk-free. The potential introduction of aquatic invasive species through this means was realized in 2013 with the introduction of *Potamogeton crispus* (curly pond weed), to Whitehall Pond in Rutland. Despite ongoing efforts, this plant continues to be widely distributed throughout this water body.

3.4.11 *Cipangopaludina chinensis*

Individual *Cipangopaludina chinensis* (Chinese mystery snail) were documented during DWSP AIS surveys for the Quabbin Reservoir watershed in 2011 and are mentioned here since they are an invasive species. Numerous snails were found near the boat dock at Boat Launch Area 1 where snail numbers continue to be high despite predation by ducks. In 2012, snails were found near the hangar at the Quabbin Administration Building in Belchertown. Snails were also documented in Long Pond in Rutland during the 2016 survey and at Lake Mattawa in 2017. They have been documented in each survey since the initial finding, including in 2019. These snails displace native species of snails and are thought to compete for resources; however, few studies have been conducted, so actual impacts have not been adequately determined. Snails may serve as the intermediate host for some parasites. To date, no problems have been associated with their presence, although there is anecdotal evidence that they are an intermediate host for a fish parasite.

3.4.12 Hardwick Pond AIS Management Efforts

While not part of the Quabbin watershed, Hardwick Pond is periodically monitored for AIS due to the proximity of the water body to the Quabbin Reservoir and the continued presence of several AIS in the pond. This waterbody is heavily infested with both *C. caroliniana* and *M. heterophyllum*. The threat of waterfowl carrying viable fragments of *C. caroliniana* to the reservoir is significant because many birds travel between Hardwick Pond and the Quabbin Reservoir. Residents at Hardwick Pond formed a non-profit pond association called the Hardwick Pond Preservation Association (HPPA) which worked closely with DCR Water Supply Protection, DCR Lakes and Ponds Program and with Senator Ann Gobi and her office staff to successfully acquire funding to conduct herbicide management for AIS. Concern over negative effects of herbicide treatment on a rare species present within the pond has delayed treatment to date.

4 Conclusions and Recommendations

Data generated by DWSP in 2019 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 2019. 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 2019 were largely consistent with historical data and demonstrate continued adherence to drinking water quality standards, aside from infrequent individual *E. coli* concentrations above single sample regulatory limits, attributed to flushing from preceding storm water runoff events and concentrations returned to pre-event levels upon resampling efforts. 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 tributaries to the Quabbin Reservoir and Ware River – a pattern ubiquitous with surface waters in the snowbelt region of the US. Routine nutrient monitoring results for Core tributary monitoring sites in 2019 were consistent with historical data, did not suggest the presence of any new 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 2019 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. Monitoring results derived from phytoplankton sampling indicated that conditions observed during 2019 were also similar to prior years, aside from a prolonged period of elevated chrysophytes documented at site 202 and 206 (Section 3.1.7).

4.3 Proposed Quabbin Reservoir and Ware River Watershed Monitoring Programs for 2020

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. The 2020 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 two EQA sites (211A-1 and 211B-X) monitored in 2019, and begin biweekly monitoring of five different EQA sites (216G, 216I-X, 216E-1, 216D, and 216C) in the East Branch Swift River sanitary district in 2020. Monitoring of nutrients (NO_3-N, NH_3-N, TKN, and TP) and UV_{254} in tributary core monitoring locations will be increased from quarterly to biweekly.

The Ware River watershed tributary monitoring program includes five core sites and up to five EQA sites. DCR will continue to sample biweekly at core sites, and at the five EQA sites located in the East Branch Ware River sanitary district (Table 4) in 2020. Monitoring of nutrients (NO3-N, NH3-N, TKN, and TP) in tributary core monitoring locations in the Ware River watershed will be increased from quarterly to biweekly.

All other analyses, including DWSP hydrologic and meteorological monitoring will remain unchanged from 2019.

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 2020, weather 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 and Cl concentrations collected at three depths, and Ca concentrations from a single depth. DWSP monitoring of nutrients (NO_3-N, NH_3-N, TKN, TP, and Si) and UV_{254} in Quabbin Reservoir core monitoring sites will increase to monthly (previously conducted quarterly) in 2020. Monthly analyses of TOC at three depths at core sites within the Quabbin Reservoir will be conducted in 2020. Routine monitoring for phytoplankton will be performed by DWSP weekly at site 202 during the growing season (May 1 through September 30, 2020), biweekly at 202 outside of the growing season, and monthly at site 206. *In situ* profiles of temperature, pH, specific conductance, dissolved oxygen, 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 2020. Changes to the DWSP water quality monitoring program introduced in 2020 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

A. 2019 Watershed Monitoring Parameters and Historical Context

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

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-C	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

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

Ammonia-Nitrogen

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

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

Nitrate-Nitrogen

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

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

Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) is the sum of organic nitrogen plus NH_3-N and ammonium-nitrogen (NH_4-N). It often constitutes a significant proportion of the total nitrogen present in a natural water body. Background concentrations of TKN in rivers and streams of the Quabbin Reservoir and Ware River watersheds ecoregions were found to range between 0.05 mg/L and 1.45 mg/L, with the 25th percentile value (all seasons) of 0.10 mg/L (ecoregion 58) and 0.30 mg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by EPA for the development of numerical TKN criteria for these ecoregions (US EPA, 2000; US EPA 2001a). This fraction of nitrogen is important to account for because it can be converted to other forms of nitrogen through natural processes and can contribute to unwanted plant growth in the tributaries and lakes. There are no water quality standards for TKN, however this metric includes NH_3-N, which is toxic at low concentrations and has specific regulatory thresholds (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 25th percentile value (all seasons) of 0.42 mg/L (ecoregion 58) and 0.59 mg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TN criteria for these ecoregions (US EPA, 2000; US EPA 2001a). Long-term (seasonal or annual) TN concentrations above these recommended criteria likely indicate that excess nitrogen is entering waters. Any tributaries exhibiting long-term concentrations above these recommended nitrogen criteria should be examined more closely to determine if any response variables (chlorophyll, macrophytes, turbidity, macroinvertebrates) indicate that water quality impairments are occurring.

Total Phosphorus

Phosphorus is an important macronutrient, and the limiting factor controlling algal productivity in Quabbin Reservoir. 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 25th 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 currently enforce regulatory standards for specific conductance in drinking water.

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

Turbidity

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

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

UV Absorbance

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

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

Chlorophyll *a* and Phycocyanin

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

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

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

Phytoplankton

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

Phytoplankton undergo seasonal succession, with some genera becoming more or less prevalent throughout the year. In Quabbin Reservoir, phytoplankton follow the typical pattern of a freshwater temperate water body with diatoms most common in the spring followed by a period of decreased productivity where chlorophytes (green algae) typically become more diverse but remain at low density. An increase in chrysophytes (golden-brown algae) is often observed in mid-summer, especially when the Quabbin Interflow is well established. An increase in cyanophytes is occasionally observed as these organisms take advantage of warm summer temperatures and nutrient influxes in the fall. Following reservoir turnover, diatoms often undergo a slight increase and remain dominant in the phytoplankton community throughout the winter months. While the entire phytoplankton community is assessed by DWSP biologists, MWRA and DWSP have established thresholds for five organisms. These four chrysophyte genera and one cyanobacteria genus have previously attained problematic densities in Quabbin Reservoir and could cause undesirable tastes and odors in the water supply. Once these thresholds are exceeded, monitoring frequency is increased (typically to twice weekly) and action is considered.

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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B. Watershed Monitoring Reports

2019 Quabbin Boat Inspection Program

The Quabbin Boat Decontamination program was initiated in 2009, in response to a rise in the number of aquatic invasive species (AIS) nationwide as well as to the introduction of zebra mussels into a water body in Western Massachusetts. This program was designed to minimize the risk of transporting AIS into the reservoir while still allowing for recreational use for fishing. Many anglers prefer to use their own privately-owned boats over the DCR boats for fishing at Quabbin, and while many boats are used exclusively at Quabbin, some anglers prefer to fish different water bodies as well. The Warm Weather Decontamination (WWD) program and the Cold Weather Quarantine (CWQ) processes are in place to reduce the risks associated with boats being used in multiple locations, some of which may be infested with AIS.

In 2019, 166 boats were inspected and decontaminated through the WWD process. This is down slightly from 183 last year. Information on number of boats that failed due to carpeted bunks or motors that did not run, is unavailable.

Ninety-seven boats were inspected and sealed through the Cold Weather Quarantine Program in anticipation of the 2020 fishing season. This number was slightly lower than last year when 106 boats went through CWQ. Many fishermen who went through CWQ in 2019 have used this process each year since its inception. This has enabled them to fish at Quabbin for part of the season as well as other water bodies later, while providing them with an easy means of getting their boats tagged at no cost.

CWQ was held on October 26 and November 7, 2019 in New Salem, and in Belchertown on November 9, November 14, and December 7, 2019. A snow date was set but not needed.

Interestingly, each year we see the return of numerous anglers who have resisted our program. Again in 2019, some of the boaters who utilized the WWD program and CWQ did so for the first time since the boat access restrictions were implemented. Approximately 65 boaters used the warm weather decontamination for the first time. Twenty-five boaters, who had never participated in CWQ, took advantage of the program this year. Participation in both the WWD program and CWQ were down slightly from last year.

Quabbin Fishing areas had a total of 82,001 visits since the start of our boat decontamination program with 8,498 during the 2019 boating season. This is an increase when compared to the number of private boats launched in 2018.

In past years, few, if any, boaters had heard about spiny water flea and the risks associated with this invasive zooplankton. Presently, some boaters still believe our boat decontamination program is due mainly to the threat of zebra mussels. Beginning in 2012, we began to see an interesting change take place regarding how our program was perceived. Most boaters utilizing the decontamination program understand and support our efforts to minimize the risks associated with transport of AIS. Our programs continue to gain acceptance and have now gone from being an annoyance to something we are praised for. Other states have implemented inspection and decontamination programs and are also actively educating the public through outreach. This has indirectly aided us with our efforts to inform people about AIS and has improved public perception of our programs.

Samples of biological substances collected off boats inspected during both the Boat Decontamination and Cold Weather Quarantine Programs were identified whenever possible. A new record keeping system is now in place so accurate information on identification and number of the biological contaminants that were collected is currently unavailable.

Marine species or severely degraded freshwater plants pose little to no risk of being successfully introduced to Quabbin. However, seeds, microscopic organisms and small plant fragments that may go undetected continue to pose significant risks. We must continue to pay close attention to the temperature of the water used during boat washing and require sufficient water pressure to effectively wash all areas of the boat’s hull, rollers, bunks and difficult-to-reach places of the trailer. Contact time of the water should also be noted and lengthened especially if the boat was recently launched at a site known to have AIS of concern. Education, outreach and the boat decontamination/quarantine programs help to ensure that the Quabbin Reservoir remains free of new AIS infestations.

Quabbin Self-Certification/Boat Ramp Monitor Program

In 2010, DCR implemented a successful Boat Ramp Monitor Program utilizing two full-time seasonal positions to educate boaters and to inspect watercraft at ponds with boat access. Monitors concentrated on Comet Pond in Hubbardston and Long Pond in Rutland but also spent some time at Whitehall, Demond, Brigham and Moosehorn Ponds, as well as at Lake Mattawa and Queen Lake.

Beginning in 2011, DCR did not have the funding to hire full-time Boat Ramp Monitors so the process was streamlined to encourage compliance with our requests with a minimal amount of effort and staff. Every opportunity to speak directly to boaters was taken but because our presence was reduced, a self-certification program was begun. Forms were printed and distributed to boaters. They were asked to record where they launched their boat last, when, how they cleaned it and what, if any, aquatic invasive species (AIS) were in the place they last boated.

Self-certification forms continue to be prominently displayed at both Comet and Long Ponds in a box on the kiosk near each boat ramp, along with signage directing boaters to self-certify their watercraft before launching. Parking areas at both ponds were periodically checked throughout the boating season to see if each vehicle had a self-certification form on the windshield. A letter explaining our program with directions for filling out a Self-Certification Form, as well as a blank form, was placed on any vehicle that did not display a completed form.

Since actual contact time with boaters was limited to several hours per week at most, efforts were concentrated at Comet and Long Ponds. These two ponds are used by many boaters and therefore are at risk for the introduction of AIS.

An isolated patch of *Myriophyllum heterophyllum* (variable-leaf milfoil), approximately 20 feet long and 10 feet wide, was documented during the 2018 annual macrophyte survey of Comet Pond. The milfoil was found along the western shoreline in front of a private residence. There was a collaborative effort between DCR Quabbin and several residents to remove all visible plants. Low water temperatures, a deep layer of muck and water depth hindered the removal efforts.

This invasive milfoil was found to be present again early in 2019. In August, AE Divers removed the milfoil using diver assisted suction harvesting. DCR Lakes and Ponds Program divers returned to the site at a later date and removed about a dozen plants that were either missed or regrew. The DCR Lakes and Ponds divers plan to return to Comet Pond in 2020 to assess the status of the milfoil. If plant numbers are low, they will hand harvest existing milfoil. If plant density or distribution has increased, the Comet Pond Association will rehire AE Divers. If this is necessary, they will apply for grants through DCR Lakes and Ponds to help defray expenses.

Unlike Comet Pond, where the use of large boat motors is prohibited, Long Pond is utilized by a variety of motor craft in a range of sizes from kayaks, canoes and small boats up to larger boats with powerful motors used to tow water skiers. Canoes and kayaks, although not completely risk-free, do not pose the same level of risk as motorized boats do for introducing invasive species because there are fewer places where AIS may be concealed plus they tend to dry completely between uses. Larger boats have more areas where organisms may remain undetected or wet for longer periods of time therefore the risk of introducing new invasive species to Long Pond is potentially greater. This fact was realized in 2016 with the introduction of *Utricularia inflata* (swollen bladderwort) to Long Pond. This AIS may have been introduced by water fowl but it is more likely that it was introduced as a stow away on a boat. The 2018 macrophyte survey showed swollen bladderwort to be widely distributed in Long Pond with plant densities especially high along the northern shoreline. A macrophyte survey was not done in 2019 due to an algal bloom at the Quabbin Reservoir which took priority.

Some types of plants use fragmentation as a means of spreading throughout a water body. *Myriophyllum heterophyllum*, variable-leaf water milfoil, the dominant species of plant found at Long Pond, utilizes fragmentation as one means of dispersal. Toward the end of the growing season, these plants become brittle; stems fragment, float to new locations and rapidly grow roots, eventually colonizing other locations. In their new location, they compete with and displace native species.

Motorized boats have the potential to effectively aid in the dispersal of plants that use this means of propagation. Boat activity at Long Pond has undoubtedly added to the number of variable water milfoil plants. At any time during the boating season, numerous milfoil fragments may be seen floating along the shore line especially near the launch areas. Repeated trips back and forth by boats, towing water skiers, chop up and disperse plant fragments. Areas of the littoral zone suitable for plant growth have been colonized and while there are many native species found at Long Pond, variable water milfoil is the dominant species of plant. This makes the self-certification program more difficult to administer because many of the impacts associated with AIS have already been realized. It is important that boaters not only think about the potential introduction of a new invasive species to Long Pond but also of the very real possibility of carrying fragments of milfoil from Long Pond to other water bodies.

Education continues to be the key to success for this program. By focusing on the overall program and not the specific organisms we are concerned about, boaters are beginning to think about the impacts of moving boats from one area to another, ultimately reducing the risk of introducing spiny water flea, Eurasian milfoil, hydrilla or many of the other AIS of concern. Overall, the self-certification program has been successful.

Environmental Quality Assessments for Quabbin Reservation and East Branch Ware River Sanitary Districts, 2019

Quabbin Reservation Sanitary District

DWSP staff monitored water quality at four sites within the Quabbin Reservation Sanitary District in 2019 (Table B1), previously monitored in 2009. Samples were collected biweekly and analyzed for nitrogen species (nitrate-as-nitrogen [NO3-N], ammonia-as-nitrogen [NH3-N], total kjeldahl nitrogen [TKN]), total phosphorus (TP), UV254, turbidity, alkalinity, calcium, total coliform and E. coli at EQA sites. For Core sites, nitrogen species, TP, and UV254 were analyzed approximately quarterly. In-situ measurements of specific conductance, pH, dissolved oxygen, and water temperature were collected at the time of sample collection.

Concentrations of constituents were compared to results from the prior monitoring period (2009) using the non-parametric Wilcoxon-Mann-Whitney (WMW) test (Table B2). Non-parametric statistical methods were appropriate due to non-normal distributions of the data (Helsel and Hirsch, 2002; Helsel 2012). Lastly, concentration data from 2019 was compared to regulatory thresholds/limits, when applicable.

Nutrients (nitrogen species and total phosphorus)

Nutrients are critical for plant growth. However, excess nutrients in a water supply, particularly nitrogen and phosphorus, may result in nuisance aquatic plant growth, eutrophication following bloom decay, or the proliferation of harmful algal blooms (Valiela et al., 1997; Dubrovsky et al., 2010). Concentrations of NO_3-N, NH_3-N, and TKN measured in Quabbin Reservation sanitary district sites in 2019 ranged from <0.005-0.113 mg/L as N, <0.005-0.019 mg/L as N, and <0.1-0.538 mg/L, respectively. Concentrations of TP observed in Quabbin Reservation Sanitary District sites in 2019 ranged from <0.0025 to 0.029 mg/L in 20198 (Table B3). The EPA MCL for NO_3-N in drinking water (10 mg/L as N) was not exceeded at any sites in 2019. Concentrations of nutrients measured in Quabbin Reservation sanitary district sites in 2019 were not statistically different than those of the prior monitoring period, with the exception of TKN in Cadwell Creek (211B-X), located in Winsor sub-district, which was markedly lower than concentrations observed in 2009 (Table B3). Concentrations of nutrients, measured in Gates Brook (GATE), were generally lower than other monitoring sites within the Quabbin Reservation Sanitary District in 2019. This is likely a reflection of characteristics of the sub-basin (e.g. channel slope and morphology, land use, and local hydrology) and the size of the drainage area (0.93 mi^2), relative to other sites. Intra-annual patterns in nutrient dynamics mirrored those of prior monitoring periods, with elevated concentrations of TN and TP associated with periods of high streamflow or reduced nutrient-uptake (e.g. winter months).

Turbidity and UV_{254}

Elevated levels of turbidity and organic matter in water may alter biogeochemical processes and have the potential to interfere with effective water treatment, leading to the production of harmful disinfection by-products, (Hua et al., 2005; Butman et al., 2016). Turbidity and UV_{254} measured in Quabbin Reservation Sanitary District sites ranged from 0.11-4.40 NTU and 0.04-

0.16 ABU/cm, respectively (Table B4). UV_{254} was not significantly different between monitoring years (Table B2). Wilcoxon-Mann-Whitney tests yielded significantly different results for turbidity across 2009 and 2019 monitoring periods for all sites within the Quabbin Reservation sanitary district, aside from Gates Brook (GATE) located in the Winsor subdistrict. In-stream turbidity levels were below the SWTR regulatory threshold of 5 NTU for source water intakes for the entirety of 2019. Median turbidity levels in Gates Brook and Cadwell Creek (GATE and 211B-X, located in the West Arm and Winsor subdistricts, respectively) were lower than 2009. Whereas, median turbidity levels in the remaining sites in Winsor Basin subdistrict (Atherton Brook and Boat Cove Brook; 211A-1 and BC, respectively) were slightly greater than 2009 median turbidity levels. Episodic peaks in turbidity observed during 2019 corresponded to increases in daily streamflow and subsequent organic matter mobilization which may have resulted in increased sediment loads and erosion following/during high streamflow events.

Pathogens (Total coliform and E. coli)

Pathogen levels (including total coliform and *E. coli*) in water may serve as an indication of the sanitary quality of a water supply (Ashbolt et al., 2001). *E. coli* occurrence may serve as an indicator for the presence of other, potentially disease-causing organisms, or serve as evidence of recent contamination to a water supply by fecal waste. Total coliform and *E. coli* observed in sites within the Quabbin Reservation Sanitary District in 2019 ranged from 41 to >24,200 MPN/100-mL and <10 to 1,350 MPN/100-mL, respectively. Cadwell Creek (211B-X) and Boat Cove Brook (BC) exceeded the Massachusetts Class A standard for non-intake waters (314 CMR 4.05(3)(a)4.c) single sample threshold for *E. coli* of 235 MPN/100 mL on at least one occasion in 2019. Median *E. coli* counts in 2019 were elevated in Boat Cove Brook (BC) in the Winsor subdistrict, relative to those observed in 2009 (Table B5). Elevated *E. coli* counts in 2019 relative to previous monitoring periods were not observed in all monitoring sites, suggesting that the observed increase in *E. coli* in Boat Cove Brook (BC) during 2019 was isolated to this location and did not propagate to other subdistricts within the Quabbin Reservation sanitary district. *E. coli* counts greater than historic 75th percentile ranges were observed following intense precipitation events, during warmer months (late spring into fall), and returned to pre-event levels following a return to baseflow conditions. Additionally, extended periods of below normal (25th percentile) streamflow in other tributaries to the Quabbin Reservoir occurred during the latter half of 2019 (July through December). Sources of *E. coli* to tributaries likely result from overland flow of feces of warm-blooded animals. Counts of total coliform and *E. coli* outside of historical ranges generally return to normal seasonal ranges coincident with a return to baseflow.

Specific conductance and dissolved salts (sodium and chloride)

Increasing trends in riverine conductivity and associated Cl ions in the past several decades have been linked to the application of de-icing agents for snow-management purposes in the northeastern United States (Kaushal et al., 2005; Mullaney et al., 2009; Moore et al., 2020). Specific conductance of Quabbin Reservation Sanitary District sites ranged from 18.1 to 168.2 µS/cm in 2019 (Table B6 Specific conductance measured in 2019 did not vary significantly from that of 2009 results for all monitoring sites, except for Boat Cove Brook (BC) in the Winsor subdistrict (Table B2). Specific conductance results for Boat Cove Brook (BC) in 2019 were greater than those of 2009 during the latter half of the year, coincident with an extended period of exceptionally low flow in the tributary. Sodium and Chloride monitoring began in the Quabbin Reservation sanitary district in 2019. Sodium and Chloride concentrations in 2019 ranged from 1.5 to 25.6 mg/L and from 1.0 to 41.7 mg/L, respectively. Sites with a greater percentage of developed land upstream, or those adjacent to major roadways generally exhibited elevated specific conductance relative to less developed sites (Table B6).

Summary and further readings

Water quality in surface water in the Quabbin Reservation sanitary district in 2019 was generally comparable to that of previous monitoring periods (Table B2). Statistically significant elevated *E. coli* counts were observed in Boat Cove Brook (BC) and attributed to episodic flushing or extended periods of exceptionally low flow and higher temperatures than observed in 2009, rather than the result of potential physical or biological changes to the Winsor subdistrict. Elevated specific conductance results for 2019 were also noted for Boat Cove Brook (BC), relative to 2009 monitoring. Specific conductance of all sites increased temporarily, as streamflow decreased below normal levels between July through December 2019. Elevated specific conductance in Quabbin Reservation monitoring sites during 2019 likely reflects contributions from groundwater, and a lack of dilution from recent precipitation inputs. A comprehensive analysis of water quality dynamics in Core sites throughout the Quabbin Reservoir watershed is provided in the 2019 Quabbin Reservoir and Ware River Watersheds: Annual Water Quality Report. Future monitoring of tributaries in the Quabbin Reservation sanitary district is anticipated to resume in 2021.

East Branch Ware River Sanitary District

DWSP staff monitored water quality at six sites within the East Branch Ware River Sanitary District in 2018 (Table B7), previously monitored in 2011 and 2015. Samples were collected biweekly and analyzed for nitrogen species (nitrate-as-nitrogen [NO_3-N], ammonia-as-nitrogen [NH_3-N], total kjeldahl nitrogen [TKN]), total phosphorus (TP), UV_{254}, turbidity, alkalinity, calcium, total coliform and *E. coli*. In-situ measurements of specific conductance, pH, dissolved oxygen, and water temperature were collected at the time of sample collection.

Concentrations of constituents were compared to results from prior monitoring periods (2011 and 2015) using the non-parametric Kruskal-Wallace (KS) test (Table B8). Non-parametric statistical methods were appropriate due to non-normal distributions of the data (Helsel and Hirsch, 2002; Helsel 2012). Lastly, concentration data from 2019 was compared to regulatory thresholds/limits, when applicable.

Nutrients (nitrogen species and total phosphorus)

Nutrients are critical for plant growth. However, excess nutrients in a water supply, particularly nitrogen and phosphorus, may result in nuisance aquatic plant growth, eutrophication following bloom decay, or the proliferation of harmful algal blooms (Valiela et al., 1997; Dubrovsky et al., 2010).

Concentrations of NO_3-N, NH_3-N, and TKN measured in East Branch Ware River sanitary district sites in 2019 ranged from <0.005-0.164 mg/L as N, <0.005-0.069 mg/L as N, and <0.1-0.726 mg/L, respectively. Concentrations of TP observed in East Branch Ware River Sanitary District sites in 2018 ranged from <0.005 to 0.046 mg/L in 2019 (Table B9). The EPA MCL for NO_3-N in drinking water (10 mg/L as N) was not exceeded at any sites in 2019. Concentrations of nutrients measured surface water in the East Branch Ware River sanitary district did not exceed EPA recommended criteria for Nutrient Ecoregion XIV (US EPA 2001) in 2019. Median concentrations of nutrients measured in sites in the East Branch Ware River sanitary district in 2019 were generally lower than those of prior monitoring periods (Table B8). Concentrations of nutrients, measured in the East Branch Ware River at Lombard Road (108C; located in the East Branch Ware River Headwaters subdistrict) and Comet Pond outlet (116 in the Asnacomet subdistrict), were generally lower than other monitoring sites within the East Branch Ware River Sanitary District in 2019. This is likely a reflection of characteristics of the sub-basin (e.g. channel slope and morphology, land use, and local hydrology) and the size of the drainage areas, relative to other sites. Intra-annual patterns in nutrient dynamics mirrored those of prior monitoring periods, with elevated concentrations of TN and TP associated with periods of high streamflow or reduced nutrient-uptake (e.g. winter months).

Turbidity and UV_{254}

Elevated levels of turbidity and organic matter in water may alter biogeochemical processes and have the potential to interfere with effective water treatment, leading to the production of harmful disinfection by-products, (Hua et al., 2005; Butman et al., 2016). Turbidity and UV_{254} measured in East Branch Ware River sanitary district sites ranged from 0.29-2.50 NTU and 0.055-0.95 ABU/cm, respectively (Table B10). Turbidity and UV_{254} were not significantly different between 2019 and prior monitoring periods at most sites in the East Branch Ware River sanitary district (Table B8). Median in-stream turbidity levels were generally below the SWTR regulatory threshold of 5 NTU for source water intakes but exceeded this threshold on several dates. Median levels of UV_{254} and turbidity in the East Branch Ware River at Lombard Road (108C; located in the East Branch Ware River Headwaters subdistrict) and Comet Pond outlet (116 in the Asnacomet subdistrict) were lower than other locations within the East Branch Ware River Sanitary District in 2019, a pattern consistent with that observed in 2015 and 2011. Turbidity and UV_{254} increased in the latter half of 2019 at sites along the East Branch Ware River (108 and 108A), corresponding to increases in daily streamflow and subsequent organic matter mobilization. Episodic peaks in turbidity observed during 2019 were attributed to increased sediment loads and erosion following/during high streamflow events.

Pathogens (Total coliform and E. coli)

Pathogen levels (including total coliform and *E. coli*) in water may serve as an indication of the sanitary quality of a water supply (Ashbolt et al., 2001). *E. coli* occurrence may serve as an indicator for the presence of other, potentially disease-causing organisms, or serve as evidence of recent contamination to a water supply by fecal waste. Total coliform and *E. coli* observed in sites within the East Branch Ware River Sanitary District in 2019 ranged from <10 to >24,200 MPN/100-mL and <10 to 1,470 MPN/100-mL, respectively. All sites aside from those in the

Asnacomet subdistrict (116 and 116B) exceeded the Massachusetts Class A standard for non-intake waters (314 CMR 4.05(3)(a)4.c) single sample threshold for *E. coli* of 235 MPN/100 mL on at least one occasion in 2019 (Table B11). Total coliform and *E. coli* observed in 2019 in surface water in the East Branch Ware River sanitary district were not significantly different than prior monitoring periods (2011 and 2015). Sources of *E. coli* to tributaries likely result from overland flow of feces of warm-blooded animals. Counts of total coliform and *E. coli* outside of historical ranges generally return to normal seasonal ranges coincident with a return to baseflow.

Specific conductance and dissolved salts (sodium and chloride)

Increasing trends in riverine conductivity and associated Cl ions in the past several decades have been linked to the application of de-icing agents for snow-management purposes in the northeastern United States (Kaushal et al., 2005; Mullaney et al., 2009; Moore et al., 2020). Specific conductance of East Branch Ware River Sanitary District sites ranged from 26.8-171.4 µS/cm in 2019 (Table B12). Specific conductance measured in 2019 was significantly greater than that observed during previous monitoring periods (2011 and 2015) for all six monitoring sites (Table B8). Sites with a greater percentage of developed land upstream generally exhibited elevated specific conductance relative to less developed sites (Table B12). Future monitoring will incorporate analyses of sodium and chloride to elucidate controls on potential sources of salinity to the East Branch Ware River sanitary district.

Summary and further readings

Water quality in surface water in the East Branch Ware River sanitary district in 2019 was generally comparable to that of previous monitoring periods (Table B8), with some exceptions. Most notable, specific conductance was significantly greater in 2019 that previous monitoring periods at all sites within the East Branch Ware River sanitary district. were observed in a single site within the East Branch Ware River Headwaters subdistrict. This pattern of increasing specific conductance has also been observed in surface waters in other tributaries to the Ware River watershed over the past several years (DWSP, 2019).

A comprehensive analysis of water quality dynamics in Core sites throughout the Ware River watershed is provided in the 2019 Quabbin Reservoir and Ware River Watersheds: Annual Water Quality Report. Future monitoring of tributaries in the East Branch Ware River sanitary district is anticipated to resume in 2020.

Tables

Table B1. Description of sample sites within Quabbin Reservation Sanitary District monitored in 2018.

Site Type	Subdistrict	Site Description	DWSP Site No.
EQA	West Arm	Atherton Brook, at mouth	211A-1
	Winsor	Cadwell Creek, at mouth	211B-X
Core		Gates Brook	GATES
		Boat Cove Tributary	BC

Table B2. Results of Wilcoxon-Mann-Whitney (WMW) tests for selected water quality parameters across years (2009, and 2019). *Red italicized* text indicates that results were statistically significant at α=0.05. TC = total coliform; SC = specific conductance. * Statistical tests were not performed for NH_3-N concentration data, as results were not reported prior to 2019.

DWSP Site No.	NO_3N	NH_3N	TKN	TP	Turbidity	UV_{254}	TC	*E. coli*	SC
211A-1	0.75	na	0.34	0.70	*0.01*	0.43	na	0.14	0.11
211B-X	0.65	na	*0.03*	0.51	*0.04*	0.22	na	0.23	0.30
GATES	0.53	na	0.53	0.81	0.80	0.23	na	*0.73*	0.45
BC	0.73	na	0.29	0.14	*0.00*	0.23	na	*0.02*	*0.04*

Table B3. Annual descriptive statistics for a) NO_3-N, NH_3-N, and b) TKN and TP measured at each site within the Quabbin Reservation Sanitary District. Detection limits for were <0.005 mg/L for NO3-N, NH3-N, and TP, and <0.1 mg/L for TKN. Concentrations below detection limits were replaced with one-half the detection limit for calculations.

a)

Location	Year	NO_3-N (mg/L)					NH_3-N (mg/L)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
211A-1	2009	26	<0.005	0.016	0.017	0.042	0	na	na	na	na
	2019	26	<0.005	0.017	0.030	0.113	1	0.019	0.019	0.019	0.019
211B-X	2009	26	<0.005	0.011	0.014	0.045	0	na	na	na	na
	2019	25	<0.005	0.011	0.027	0.102	1	0.006	0.006	0.006	0.006
BC	2009	4	<0.005	0.016	0.013	0.018	0	na	na	na	na
	2019	5	0.007	0.013	0.015	0.028	5	<0.005	<0.005	0.004	0.011
GATE	2009	4	<0.005	0.005	0.006	0.009	0	na	na	na	na
	2019	5	<0.005	<0.005	0.010	0.040	5	<0.005	<0.005	0.002	0.003

b)

Location	Year	TKN (mg/L)					TP (mg/L)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
211A-1	2009	25	<0.1	0.136	0.135	0.289	24	<0.005	0.011	0.011	0.026
	2019	27	<0.1	0.119	0.137	0.498	27	<0.005	0.010	0.012	0.027
211B-X	2009	25	<0.1	0.102	0.128	0.534	24	<0.005	0.011	0.013	0.058
	2019	26	<0.1	0.050	0.092	0.200	26	<0.005	0.010	0.010	0.019
BC	2009	4	0.064	0.148	0.133	0.171	4	0.007	0.015	0.014	0.019
	2019	5	<0.1	0.172	0.223	0.538	5	0.008	0.020	0.020	0.029
GATE	2009	4	0.071	0.098	0.112	0.180	4	<0.005	0.012	0.011	0.018
	2019	5	<0.1	<0.1	0.101	0.220	5	<0.005	0.010	0.010	0.018

Table B4. Annual descriptive statistics for total coliform and *E. coli* measured at each site within the Quabbin Reservation Sanitary District. Detection limits for were <2 MPN/100-mL for total coliform and <10 MPN/100-mL for *E. coli*. Concentrations below detection limits were replaced with one-half the detection limit for calculations.

Location	Year	Total Coliform (MPN/100-mL)					*E. coli* (MPN/100-mL)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
211A-1	2009	0	na	na	na	na	26	<10	<10	18	134
	2019	27	41	657	1,499	6,490	27	<10	<10	7	31
211B-X	2009	0	na	na	na	na	26	<10	7.5	22	223
	2019	26	109	654	1,888	8,660	26	<10	10	36	253
BC	2009	0	na	na	na	na	26	<10	7.5	39	504
	2019	29	160	1,850	4,359	17,300	29	<10	30	127	1,350
GATE	2009	0	na	na	na	na	25	<10	<10	21	132
	2019	27	146	1,110	2,919	24,200	27	<10	<10	23	160

Table B5. Annual descriptive statistics for turbidity and UV_{254} measured at each site within the Quabbin Reservation Sanitary District. Detection limits for were <0.05 NTU and <0.0001 ABU/cm for turbidity and UV_{254}, respectively. Concentrations below detection limits were replaced with one-half the detection limit for calculations.

Location	Year	Turbidity (NTU)					UV_{254} (ABU/cm)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
211A-1	2009	26	0.09	0.17	0.20	0.54	26	0.059	0.114	0.114	0.211
	2019	27	0.14	0.25	0.27	0.50	24	0.044	0.099	0.101	0.160
211B-X	2009	26	0.14	0.23	0.29	0.59	26	0.043	0.081	0.085	0.181
	2019	26	0.11	0.19	0.23	0.59	24	0.042	0.066	0.071	0.113
BC	2009	26	0.31	0.65	0.77	1.73	4	0.112	0.126	0.126	0.141
	2019	27	0.52	0.91	1.19	4.40	3	0.089	0.104	0.105	0.123
GATE	2009	25	0.12	0.23	0.29	0.84	4	0.062	0.085	0.093	0.139
	2019	27	0.11	0.21	0.32	1.50	3	0.046	0.066	0.061	0.072

Table B6. Annual descriptive statistics for a) specific conductance, sodium, and b) chloride measured at each site within the Quabbin Reservation Sanitary District. Na and Cl were not monitored in 2009.

a)

Location	Year	Specific Conductance (µS/cm)					Sodium (mg/L)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
211A-1	2009	26	45.0	64.0	65.8	104.0	0	na	na	na	na
	2019	28	19.0	76.1	84.7	168.2	27	5.6	11.3	12.8	25.6
211B-X	2009	26	32.0	38.0	40.2	54.0	0	na	na	na	na
	2019	27	28.4	36.1	37.6	48.8	26	3.1	3.7	4.0	7.2
BC	2009	26	38.0	69.0	68.8	95.0	0	na	na	na	na
	2019	28	47.2	79.7	88.9	137.2	27	2.1	3.0	3.3	4.7
GATE	2009	25	19.0	21.0	21.5	26.0	0	na	na	na	na
	2019	28	18.1	21.7	22.7	29.6	27	1.5	2.0	2.1	3.1

b)

Location	Year	Chloride (mg/L)				
		Count	Min	Med	Mean	Max
211A-1	2009	0	na	na	na	na
	2019	27	7.8	16.2	19.5	41.7
211B-X	2009	0	na	na	na	na
	2019	26	1.8	5.0	5.4	17.9
BC	2009	0	na	na	na	na
	2019	27	4.2	9.7	10.3	17.0
GATE	2009	0	na	na	na	na
	2019	27	1.0	1.3	1.3	1.6

Table B7. Description of sample sites within East Branch Ware River Sanitary District monitored in 2018.

Subdistrict	Core	Site Description	DWSP Site No.
East Branch Ware	Core	East Branch Ware River, at Intervale Road	108
	EQA	East Branch Ware River at Route 68	108A
		Cushing Pond Outlet at Bemis Rd	108B
East Branch Ware Headwaters		East Branch Ware River at Lombard Rd	108C
Asnacomet		Comet Pond Outlet	116
		Comet Pond Outlet Trib. Near Clark Rd	116B

Table B8. Results of Kruskal-Wallace (KS) tests for selected water quality parameters across years (2011, 2015, and 2019). *Red italicized* text indicates that results were statistically significant at α=0.05. TC = total coliform; SC = specific conductance. * Statistical tests were performed for NH_3-N concentration data from 2015 and 2019 only.

DWSP Site No.	NO_3N	NH_3N	TKN	TP	Turbidity	UV_{254}	TC	*E. coli*	SC
108	0.570	0.462	0.862	0.936	0.937	0.629	0.655	0.567	*0.000*
108A	0.573	0.113	0.521	*0.039*	0.856	0.652	0.487	0.996	*0.000*
108B	*0.018*	*0.004*	*0.000*	*0.000*	*0.001*	*0.000*	0.834	0.084	*0.000*
108C	0.417	0.432	*0.000*	*0.001*	0.859	*0.036*	0.902	0.695	*0.000*
116	*0.026*	0.120	0.386	*0.003*	*0.023*	*0.000*	0.201	0.952	*0.000*
116B	0.062	*0.000*	0.158	*0.027*	0.860	0.656	0.668	0.281	*0.003*

Table B9. Annual descriptive statistics for a) NO_3-N, NH_3-N, and b) TKN and TP measured at each site within the East Branch Ware River Sanitary District. Detection limits for were <0.005 mg/L for NO_3-N, NH_3-N, and TP, and <0.1 mg/L for TKN. Concentrations below detection limits were replaced with one-half the detection limit for calculations.

a)

Location	Year	NO_3-N (mg/L)					NH_3-N (mg/L)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
108	2011	4	0.008	0.037	0.034	0.055	0	-	-	-	-
	2015	4	0.006	0.036	0.050	0.122	4	0.007	0.018	0.021	0.039
	2019	5	0.010	0.058	0.048	0.073	5	0.007	0.017	0.014	0.020
108A	2011	26	<0.005	0.021	0.051	0.496	0	-	-	-	-
	2015	26	<0.005	0.015	0.031	0.102	23	<0.005	0.011	0.023	0.103
	2019	26	<0.005	0.014	0.024	0.067	26	<0.005	0.009	0.010	0.031
108B	2011	26	0.009	0.038	0.046	0.149	0	-	-	-	-
	2015	26	0.013	0.079	0.094	0.543	22	0.011	0.031	0.072	0.354
	2019	26	0.009	0.053	0.058	0.163	26	<0.005	0.018	0.019	0.056
108C	2011	25	<0.005	0.025	0.035	0.181	0	-	-	-	-
	2015	26	<0.005	0.035	0.057	0.227	22	<0.005	0.004	0.013	0.051
	2019	26	<0.005	0.024	0.044	0.164	26	<0.005	0.004	0.007	0.022
116	2011	26	<0.005	0.004	0.010	0.063	0	-	-	-	-
	2015	18	<0.005	0.008	0.010	0.027	13	<0.005	<0.005	0.009	0.035
	2019	23	<0.005	<0.005	0.004	0.010	23	<0.005	<0.005	0.004	0.012
116B	2011	26	<0.005	<0.005	0.009	0.044	0	-	-	-	-
	2015	22	<0.005	<0.005	0.013	0.039	17	<0.005	0.022	0.024	0.068
	2019	25	<0.005	<0.005	0.004	0.015	25	<0.005	<0.005	0.010	0.069

b)

Location	Year	TKN (mg/L)					TP (mg/L)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
108	2011	4	0.206	0.282	0.324	0.525	4	0.0083	0.0175	0.0186	0.0312
	2015	4	0.228	0.287	0.275	0.296	4	0.016	0.021	0.021	0.026
	2019	5	0.156	0.310	0.301	0.480	5	0.008	0.019	0.020	0.034
108A	2011	26	0.204	0.295	0.331	0.584	26	0.007	0.016	0.019	0.035
	2015	26	0.119	0.301	0.307	0.698	26	0.011	0.019	0.023	0.093
	2019	26	0.124	0.265	0.303	0.638	26	0.008	0.017	0.016	0.031
108B	2011	26	0.188	0.449	0.450	0.690	26	0.009	0.021	0.021	0.033
	2015	26	0.165	0.294	0.370	0.923	26	0.011	0.018	0.032	0.224
	2019	26	0.050	0.261	0.263	0.573	26	0.006	0.012	0.013	0.023
108C	2011	26	0.092	0.226	0.228	0.326	26	<0.005	0.008	0.009	0.015
	2015	26	<0.1	0.162	0.164	0.276	26	0.007	0.011	0.011	0.016
	2019	26	<0.1	0.158	0.165	0.314	26	<0.005	0.009	0.009	0.013
116	2011	25	0.135	0.186	0.200	0.314	26	<0.005	0.006	0.006	0.012
	2015	18	0.110	0.171	0.185	0.340	18	<0.005	0.007	0.008	0.025
	2019	23	<0.1	0.187	0.202	0.441	23	<0.005	0.005	0.005	0.016
116B	2011	25	0.224	0.316	0.375	0.766	26	<0.005	0.016	0.019	0.039
	2015	21	0.138	0.408	0.367	0.557	21	0.010	0.021	0.021	0.039
	2019	25	<0.1	0.234	0.310	0.726	25	0.005	0.014	0.016	0.046

Table B10. Annual descriptive statistics for total coliform and *E. coli* measured at each site within the East Branch Ware River Sanitary District. Detection limits for were <2MPN/100-mL for total coliform and <10 MPN/100-mL for *E. coli*. Concentrations below detection limits were replaced with one-half the detection limit for calculations.

Location	Year	Total Coliform (MPN/100-mL)					*E. coli* (MPN/100-mL)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
108	2011	26	189	1550	3260	19900	26	<10	36	65	331
	2015	26	75	1250	2369	19900	26	<10	26	73	905
	2019	27	197	1260	3441	24200	27	<10	30	94	1470
108A	2011	26	199	1735	3394	17300	26	<10	36	514	12000
	2015	27	148	1110	1956	7700	27	<10	20	100	1190
	2019	26	134	1390	2360	13000	26	<10	20	63	323
108B	2011	26	109	1460	2431	10500	26	<10	<10	9	52
	2015	27	161	1330	2730	15500	27	<10	<10	20	262
	2019	26	262	1625	2247	7700	26	<10	10	39	395
108C	2011	26	121	551	1038	4350	26	<10	<10	11	52
	2015	26	63	833	1766	15500	26	<10	<10	18	148
	2019	26	10	540	2135	24200	26	<10	<10	24	262
116	2011	26	<10	253	1548	24200	26	<10	<10	7	31
	2015	18	<10	110	385	1780	18	<10	<10	6	10
	2019	23	<10	295	1459	14100	23	<10	<10	9	75
116B	2011	25	323	2480	3106	10500	25	<10	<10	19	135
	2015	22	410	2035	3399	13000	22	<10	<10	67	1050
	2019	25	275	2060	3477	24200	25	<10	10	30	134

Table B11. Annual descriptive statistics for turbidity and UV_{254} measured at each site within the East Branch Ware River Sanitary District. Detection limits for were <0.05 NTU and <0.0001 ABU/cm for turbidity and UV_{254}, respectively. Concentrations below detection limits were replaced with one-half the detection limit for calculations.

Location	Year	Turbidity (NTU)					UV_{254} (ABU/cm)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
108	2011	26	0.52	1.13	1.52	3.72	26	0.127	0.213	0.252	0.527
	2015	26	0.50	1.30	1.54	3.15	26	0.145	0.227	0.232	0.400
	2019	26	0.53	1.05	1.71	5.20	26	0.119	0.225	0.224	0.370
108A	2011	26	0.50	1.13	1.23	2.52	26	0.125	0.206	0.254	0.540
	2015	26	0.46	1.03	1.18	2.53	26	0.142	0.234	0.235	0.403
	2019	26	0.59	1.05	1.24	2.50	26	0.114	0.218	0.226	0.437
108B	2011	26	0.39	0.93	1.13	2.72	26	0.077	0.251	0.243	0.358
	2015	26	0.33	0.95	1.19	7.31	26	0.093	0.154	0.153	0.242
	2019	26	0.41	0.70	0.71	1.30	26	0.082	0.123	0.135	0.255
108C	2011	26	0.42	0.66	0.70	1.05	26	0.053	0.098	0.099	0.137
	2015	26	0.34	0.58	0.79	1.76	26	0.051	0.071	0.081	0.132
	2019	26	0.29	0.75	0.74	1.30	26	0.055	0.090	0.088	0.115
116	2011	26	0.21	0.42	0.49	1.88	26	0.042	0.060	0.059	0.074
	2015	18	0.15	0.38	0.37	0.64	18	0.047	0.054	0.054	0.064
	2019	23	0.32	0.47	0.55	1.40	23	0.056	0.070	0.070	0.089
116B	2011	26	0.32	0.59	0.70	1.50	26	0.156	0.302	0.323	0.887
	2015	22	0.32	0.57	0.71	1.61	22	0.133	0.322	0.391	0.799
	2019	25	0.32	0.54	0.70	1.80	25	0.133	0.323	0.348	0.950

Table B12. Annual descriptive statistics for specific conductance, sodium, and chloride measured at each site within the East Branch Ware River Sanitary District.

Location	Year	Specific Conductance (µS/cm)					Sodium (mg/L)					Chloride (mg/L)				
		Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max	Count	Min	Med	Mean	Max
108	2011	26	56.6	74.1	76.5	108.7	-	-	-	-	-	-	-	-	-	-
	2015	26	81.1	103.6	100.9	114.8	-	-	-	-	-	-	-	-	-	-
	2019	25	68.7	102.4	104.8	136.6	26	10.0	13.4	13.4	16.8	17.6	23.3	23.3	29.8	16.8
108A	2011	26	51.9	64.3	67.1	99.4	-	-	-	-	-	-	-	-	-	-
	2015	27	69.2	91.7	90.5	116.1	-	-	-	-	-	-	-	-	-	-
	2019	25	64.7	91.4	93.9	122.3	26	9.3	12.1	12.3	16.2	25	15.0	20.0	21.1	32.9
108B	2011	26	52.6	67.8	68.3	106.5	-	-	-	-	-	-	-	-	-	-
	2015	27	84.6	108.6	112.6	184.8	-	-	-	-	-	-	-	-	-	-
	2019	25	86.7	130.1	130.9	171.4	26	13.3	18.8	18.5	23.6	26	21.2	32.3	31.5	43.2
108C	2011	26	37.0	46.6	46.8	56.5	-	-	-	-	-	-	-	-	-	-
	2015	26	46.3	54.2	55.2	65.4	-	-	-	-	-	-	-	-	-	-
	2019	26	36.0	61.0	60.3	71.7	26	4.3	7.3	6.9	8.2	26	5.7	11.7	10.9	13.0
116	2011	26	36.1	38.4	38.8	44.2	-	-	-	-	-	-	-	-	-	-
	2015	18	37.7	42.3	42.6	50.2	-	-	-	-	-	-	-	-	-	-
	2019	22	26.8	48.4	47.1	51.5	23	4.7	5.7	5.7	6.4	23	6.9	9.3	9.1	10.4
116B	2011	26	47.1	58.8	60.9	90.4	-	-	-	-	-	-	-	-	-	-
	2015	22	54.4	70.0	81.2	132.5	-	-	-	-	-	-	-	-	-	-
	2019	24	35.3	64.6	69.8	144.5	25	7.0	8.4	9.4	19.5	25	11.1	12.8	14.7	30.8

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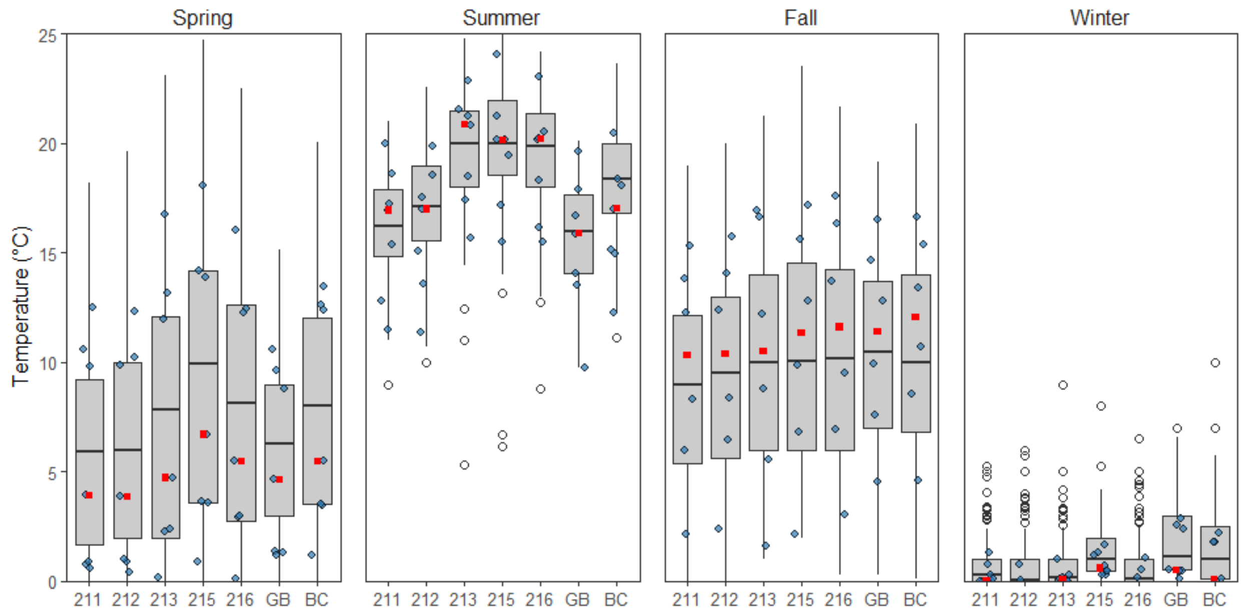
C. Figures

Figure C1. Boxplots depicting the seasonal distributions of temperature observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median temperature of 2019 for each site is represented by the red square. The solid black line represents the historic 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.



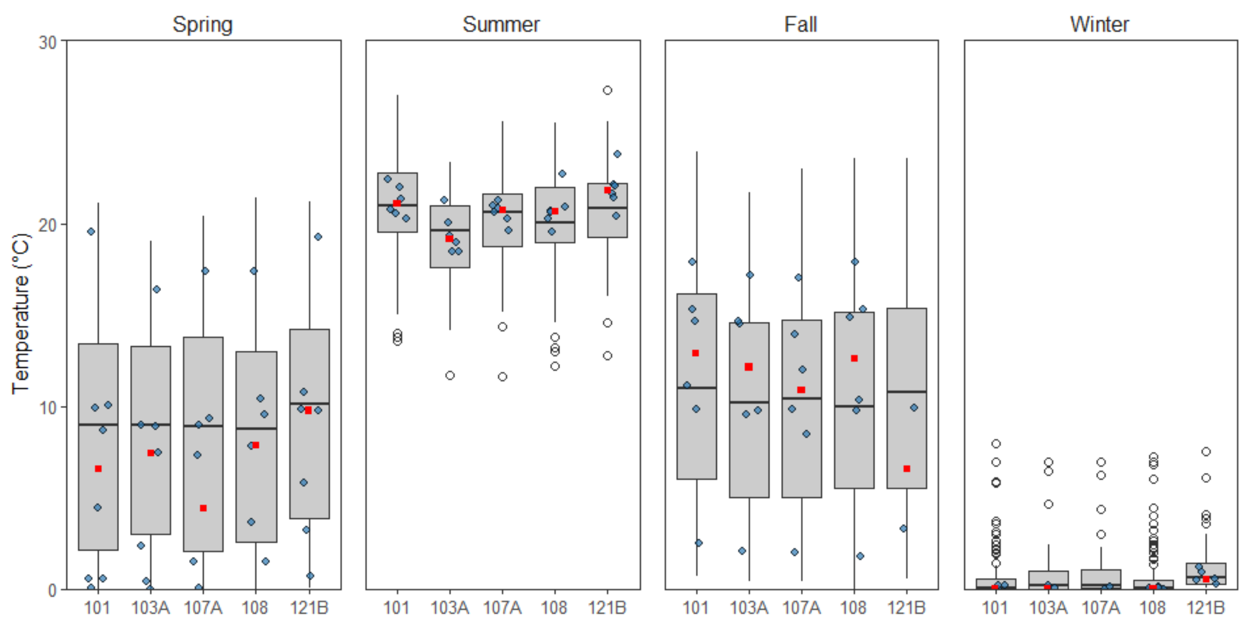


Figure C2. Boxplots depicting the seasonal distributions of pH observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median pH of 2019 for each site is represented by the red square. The solid black line represents the historic 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.

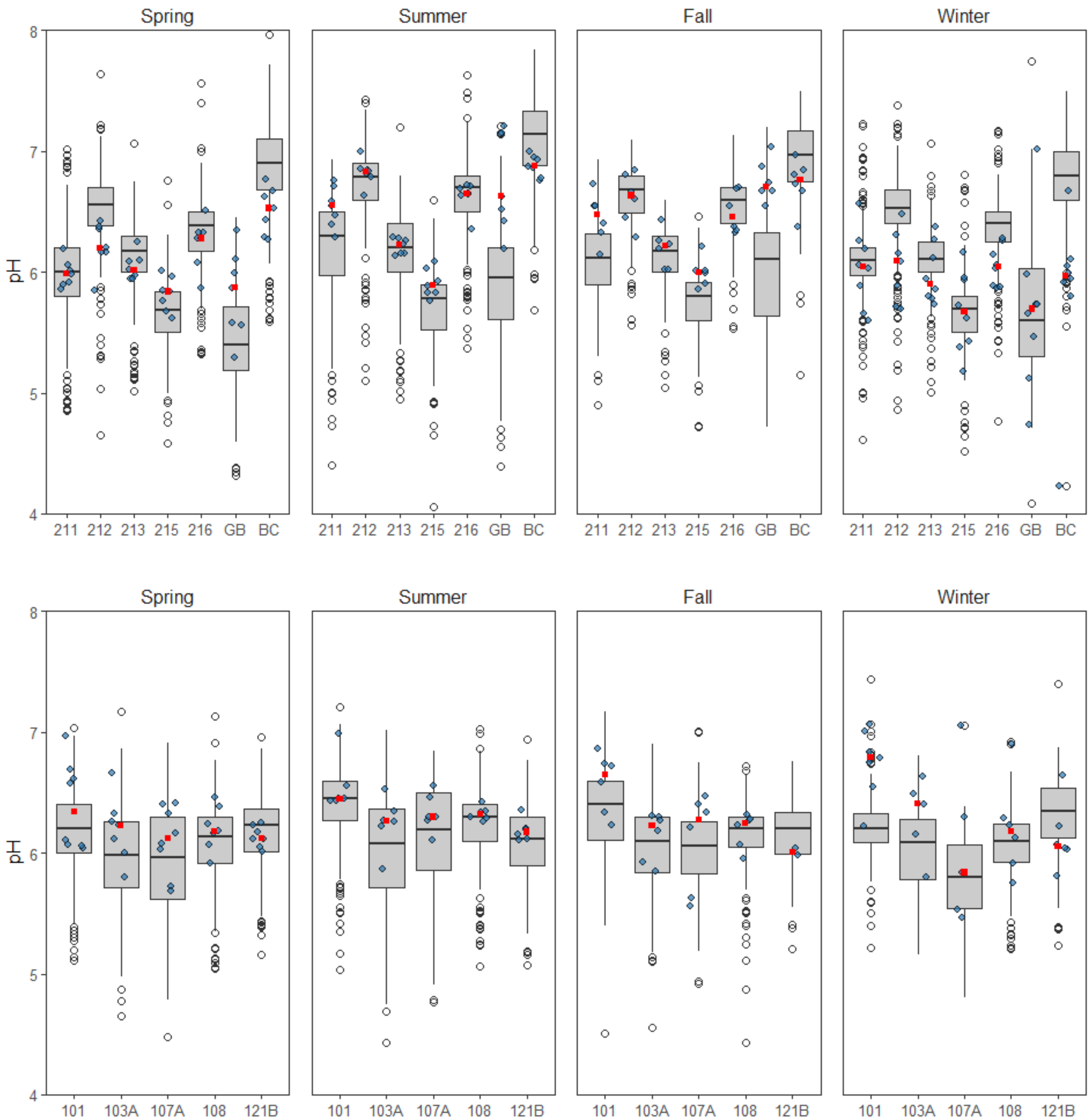


Figure C3. Boxplots depicting the seasonal distributions of dissolved oxygen observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median dissolved oxygen of 2019 for each site is represented by the red square. The solid black line represents the historic 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.

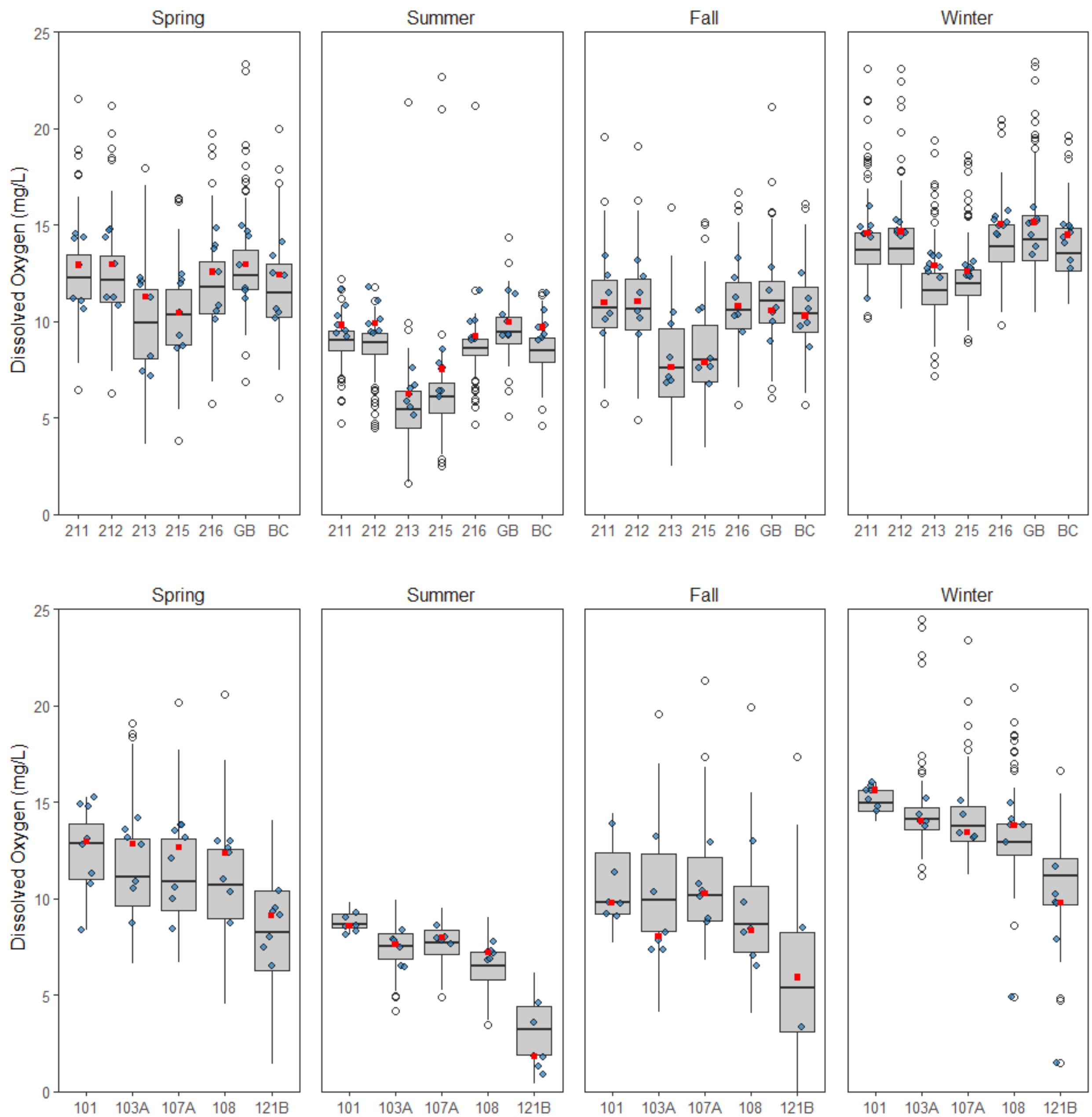
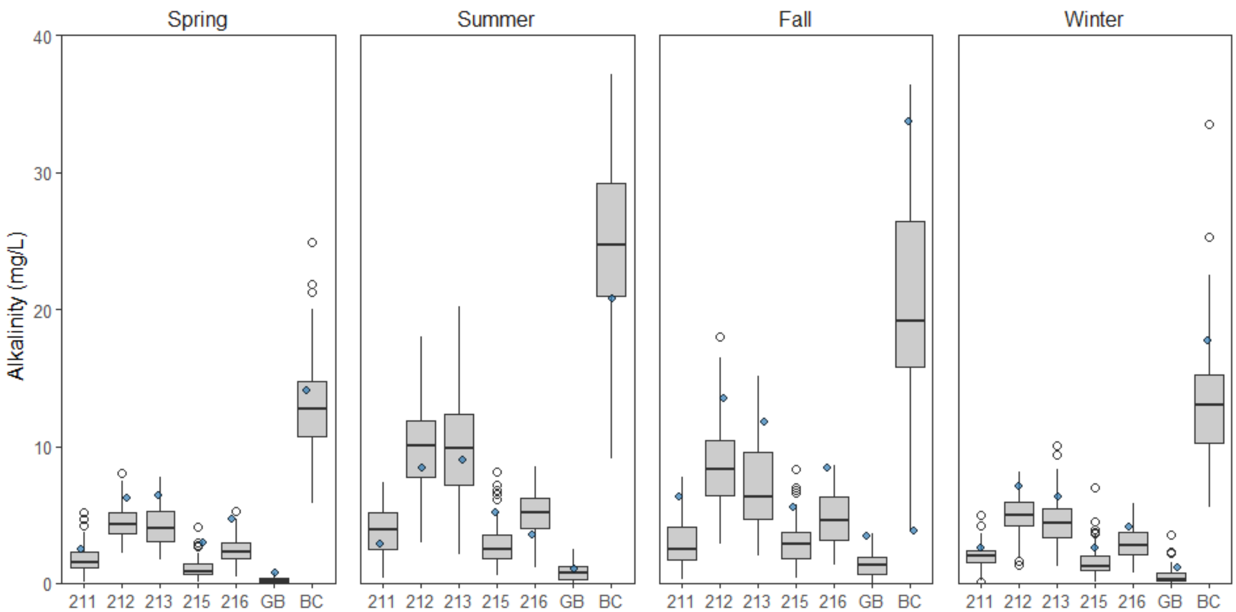


Figure C4. Boxplots depicting the seasonal distributions of alkalinity observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The solid black line represents the historic 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.



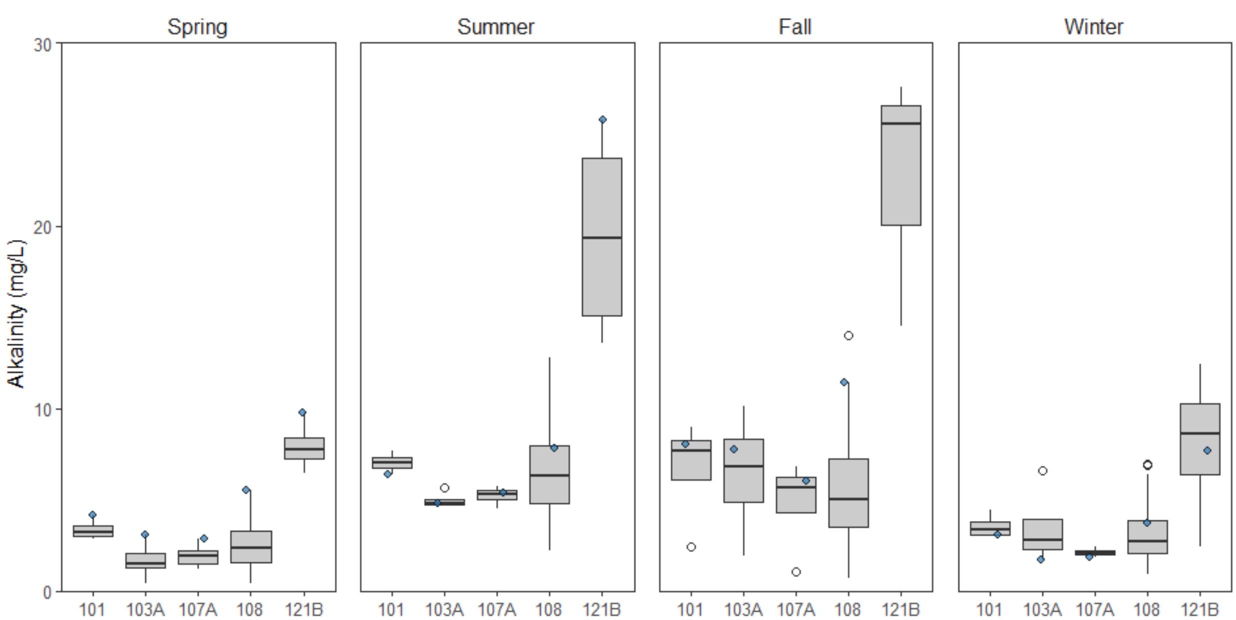


Figure C5. Boxplots depicting the seasonal distributions of Ca observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median Ca concentrations of 2019 for each site are represented by the red square. The solid black line represents the historic 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.

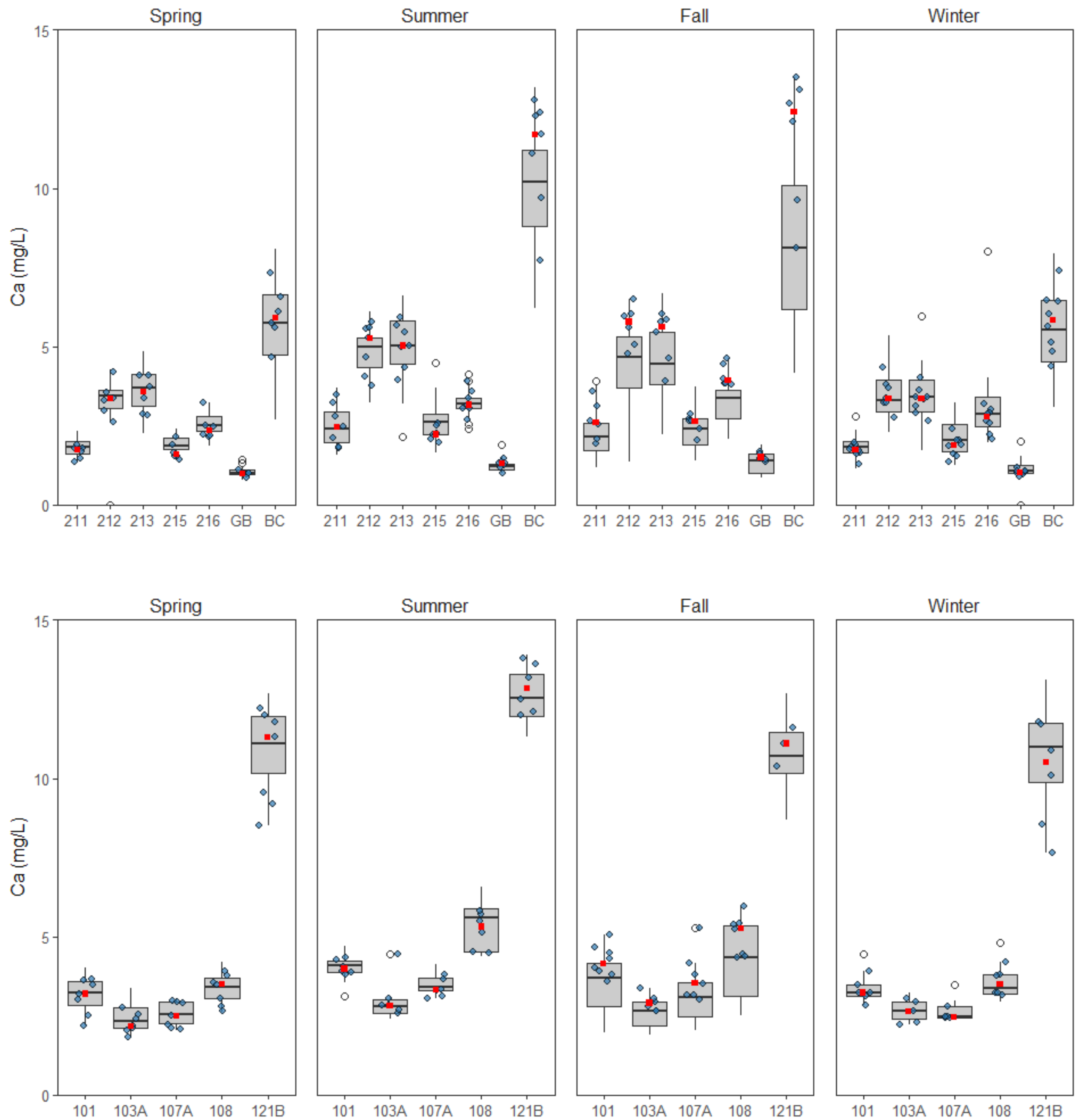


Figure C6. Boxplots depicting the seasonal distributions of total coliform observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median total coliform of 2019 for each site is represented by the red square. The solid black line represents the historic 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.

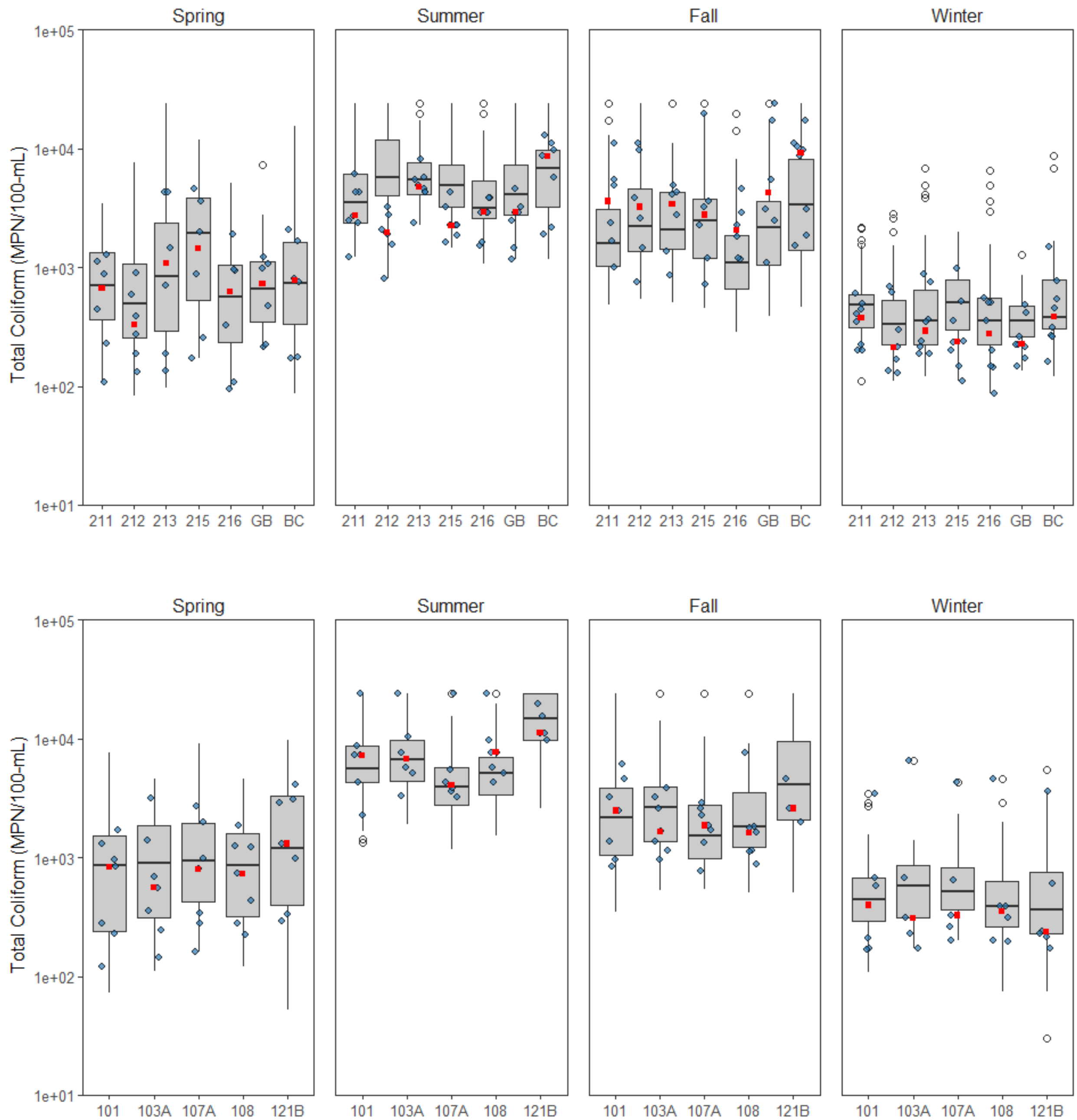
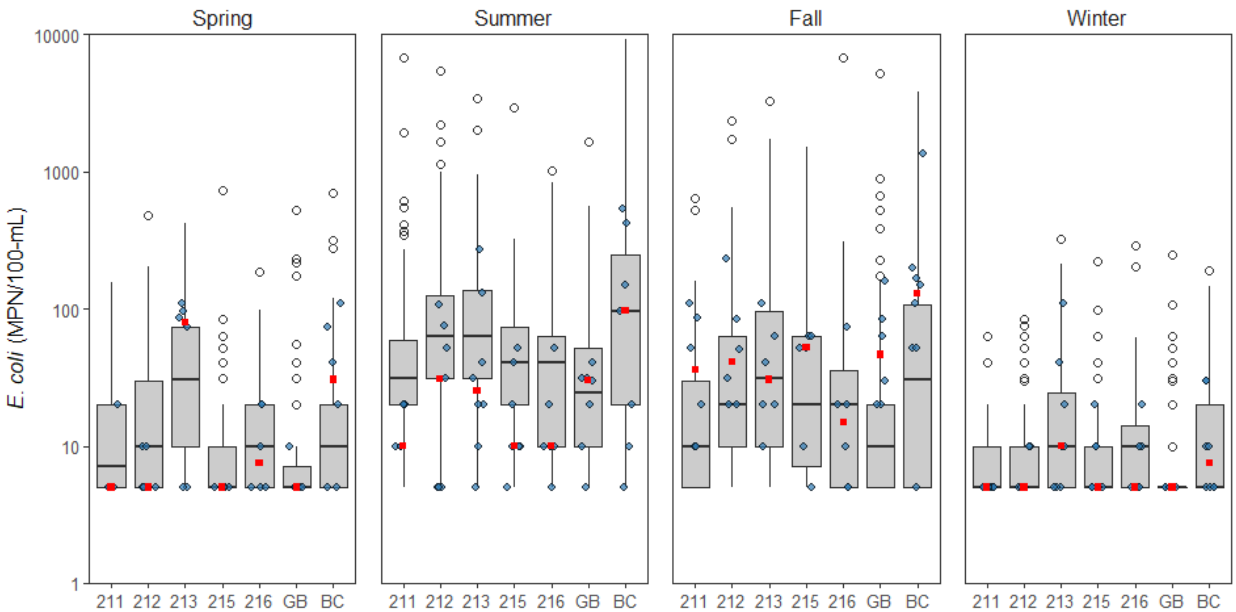


Figure C7. Boxplots depicting the seasonal distributions of *E. coli* observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median *E. coli* of 2019 for each site is represented by the red square. The solid black line represents the historic 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.



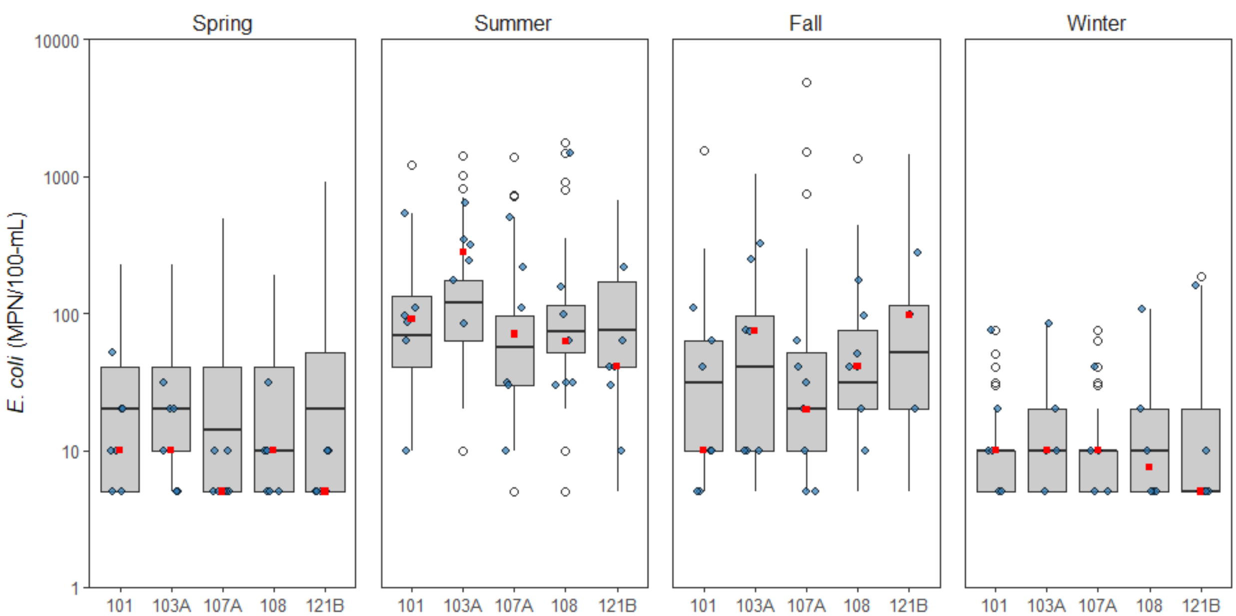


Figure C8. Boxplots depicting the seasonal distributions of Na observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites in 2019. The solid black line represents the historic median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

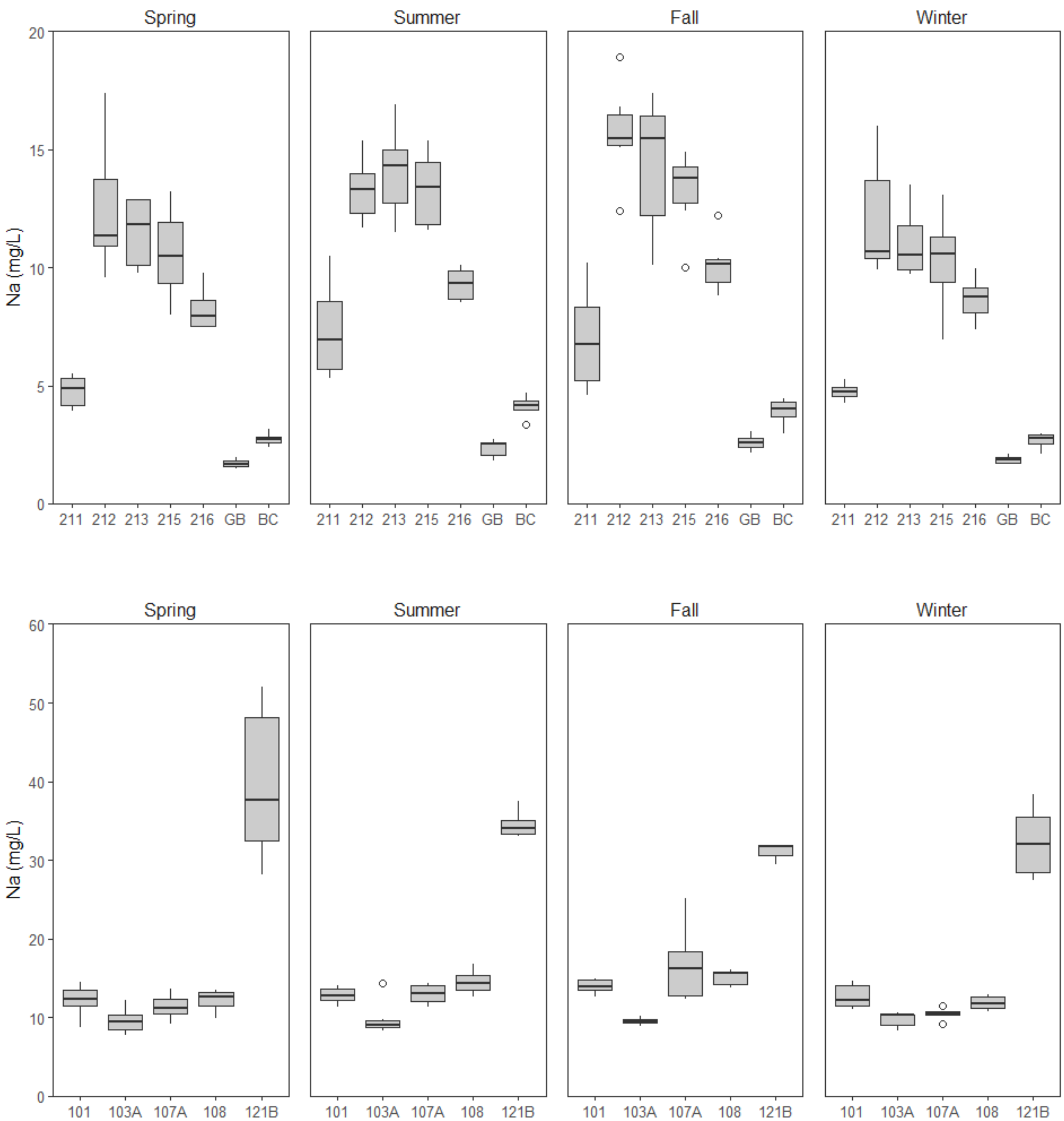


Figure C9. Boxplots depicting the seasonal distributions of Cl observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites in 2019. The solid black line represents the historic median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

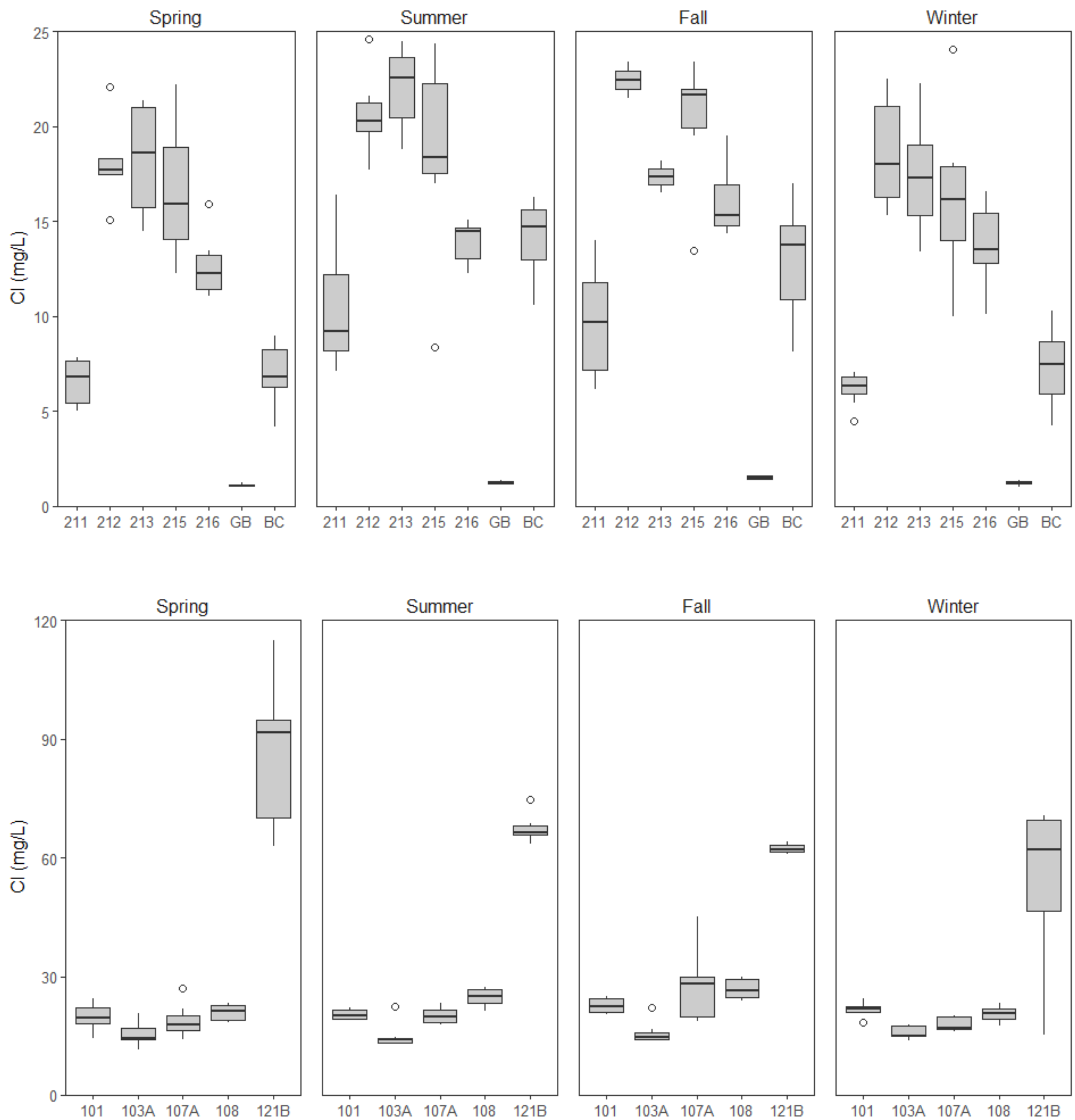


Figure C10. Boxplots depicting the seasonal distributions of NH_3-N observed In Quabbin Reservoir (top) and Ware River watershed (bottom) DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2019 are signified by the blue points. The median NH_3-N of 2019 for each site is represented by the red square. The solid black line represents the historic 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.

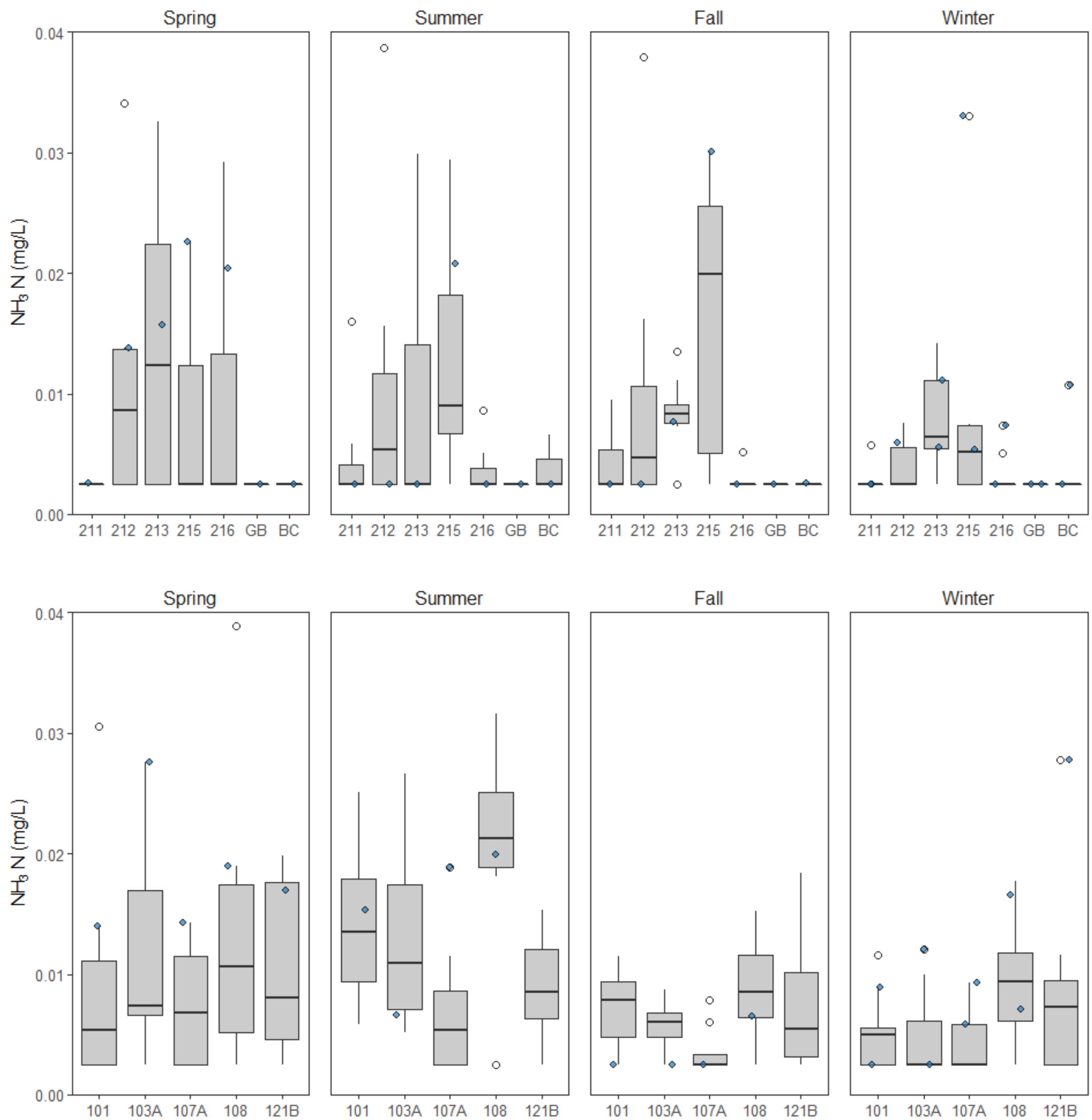


Figure C11. Select depth profiles of temperature, pH, specific conductance, dissolved oxygen, chlorophyll a, and phycocyanin collected by DWSP at Quabbin Reservoir monitoring site 206 in 2019. May 2019 profile corresponds to early stages of stratification of Quabbin Reservoir. June profile signifies full thermal stratification of Quabbin Reservoir. Profiles corresponding to August and September 2019 mark the proliferation of *Chrysosphaerella* in Quabbin Reservoir at site 202 in 2019. The depth profile collected in November 2019 suggests fall turnover occurred during October or early November 2019, homogenizing the water column.

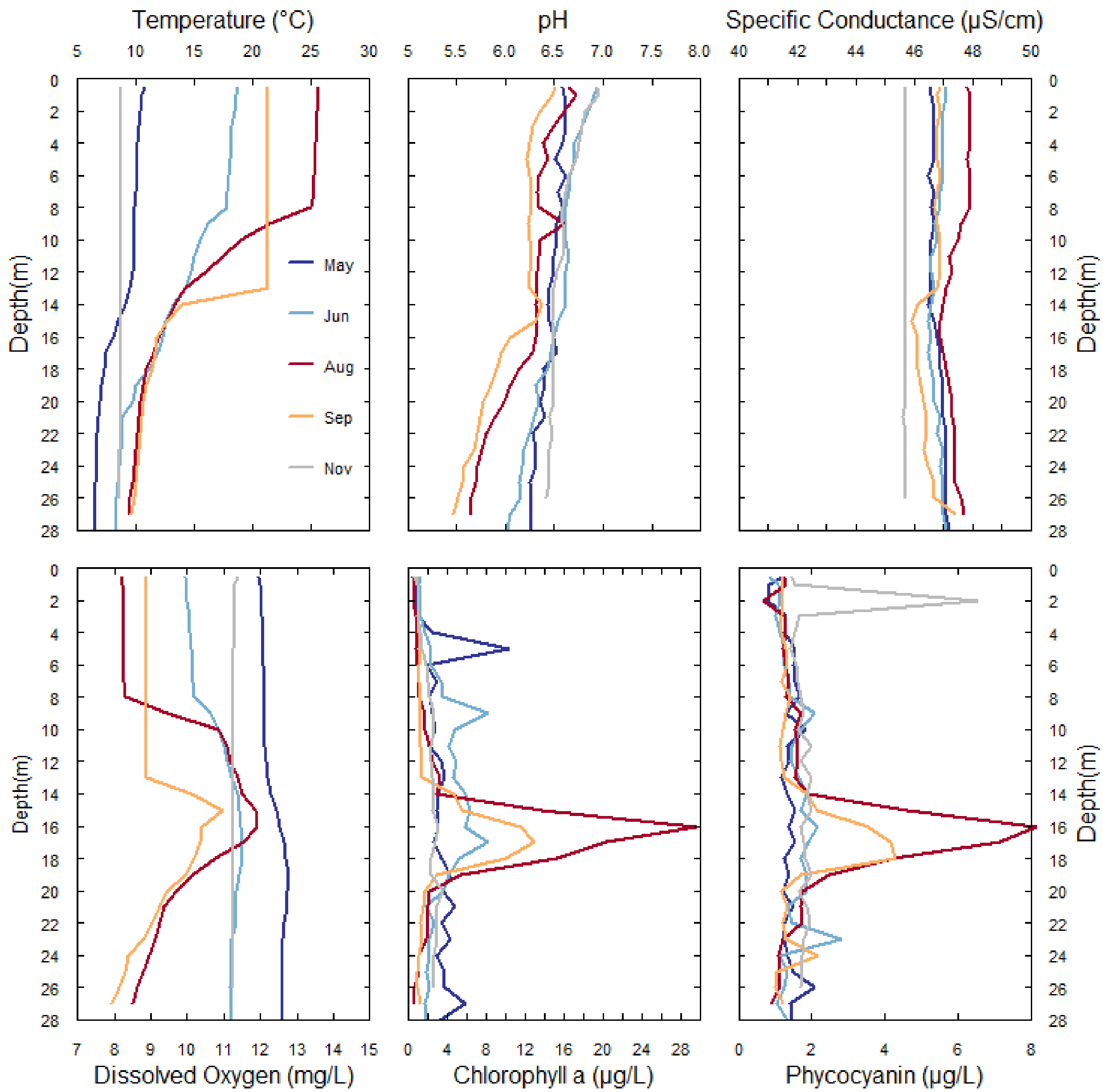


Figure C12. Select depth profiles of temperature, pH, specific conductance, dissolved oxygen, chlorophyll a, and phycocyanin collected by DWSP at Quabbin Reservoir monitoring site Den Hill in 2019. May 2019 profile corresponds to early stages of stratification of Quabbin Reservoir. June profile signifies full thermal stratification of Quabbin Reservoir. Profiles corresponding to September 2019 mark the proliferation of *Chrysosphaerella* in Quabbin Reservoir at site 202 in 2019. The depth profile collected in November 2019 suggests fall turnover occurred during October or early November 2019, homogenizing the water column.

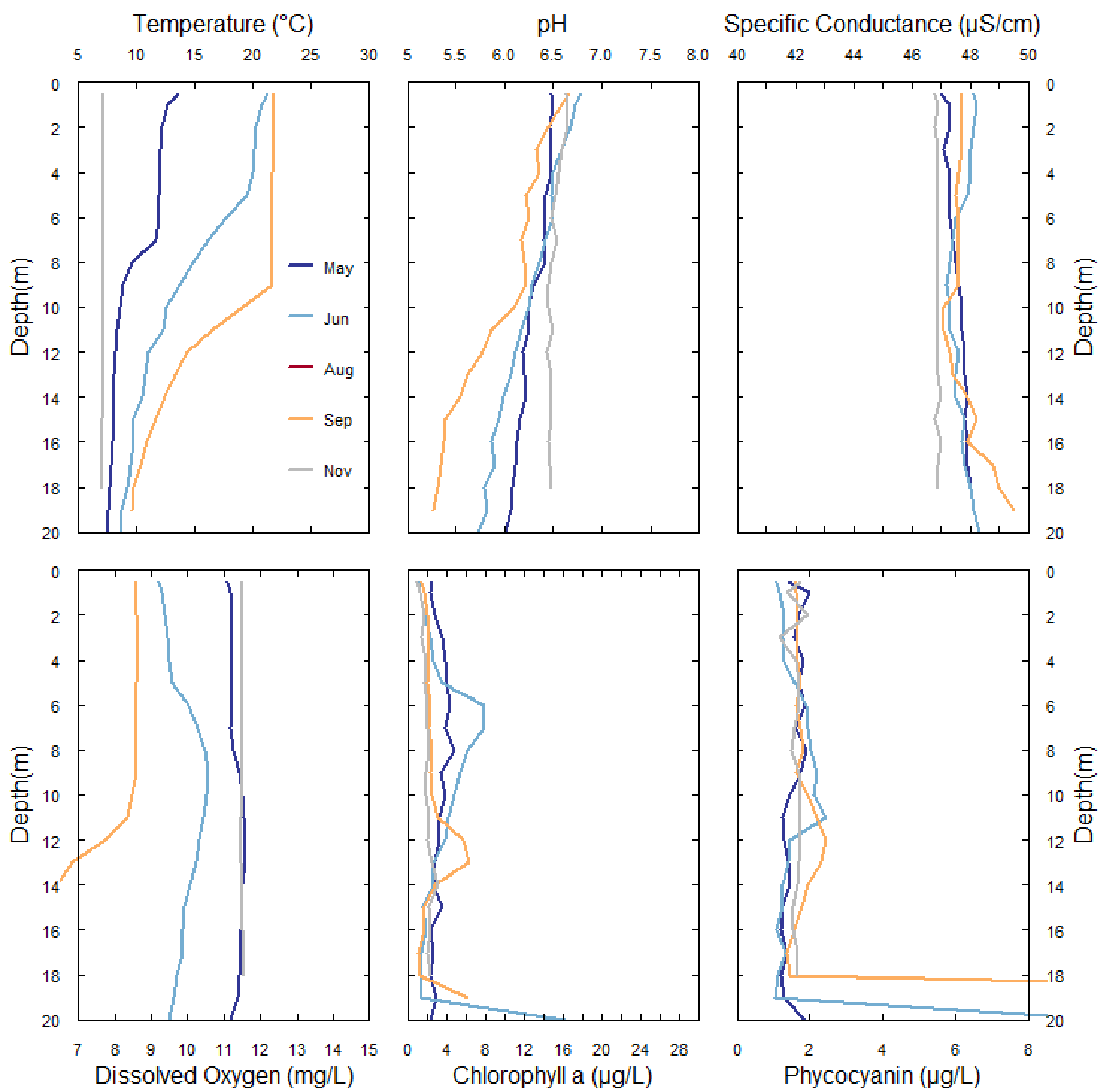


Figure C13. Boxplots depicting the seasonal and vertical distributions of turbidity observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected in 2019 are signified by the red points. The solid black line represents the historic median, 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.

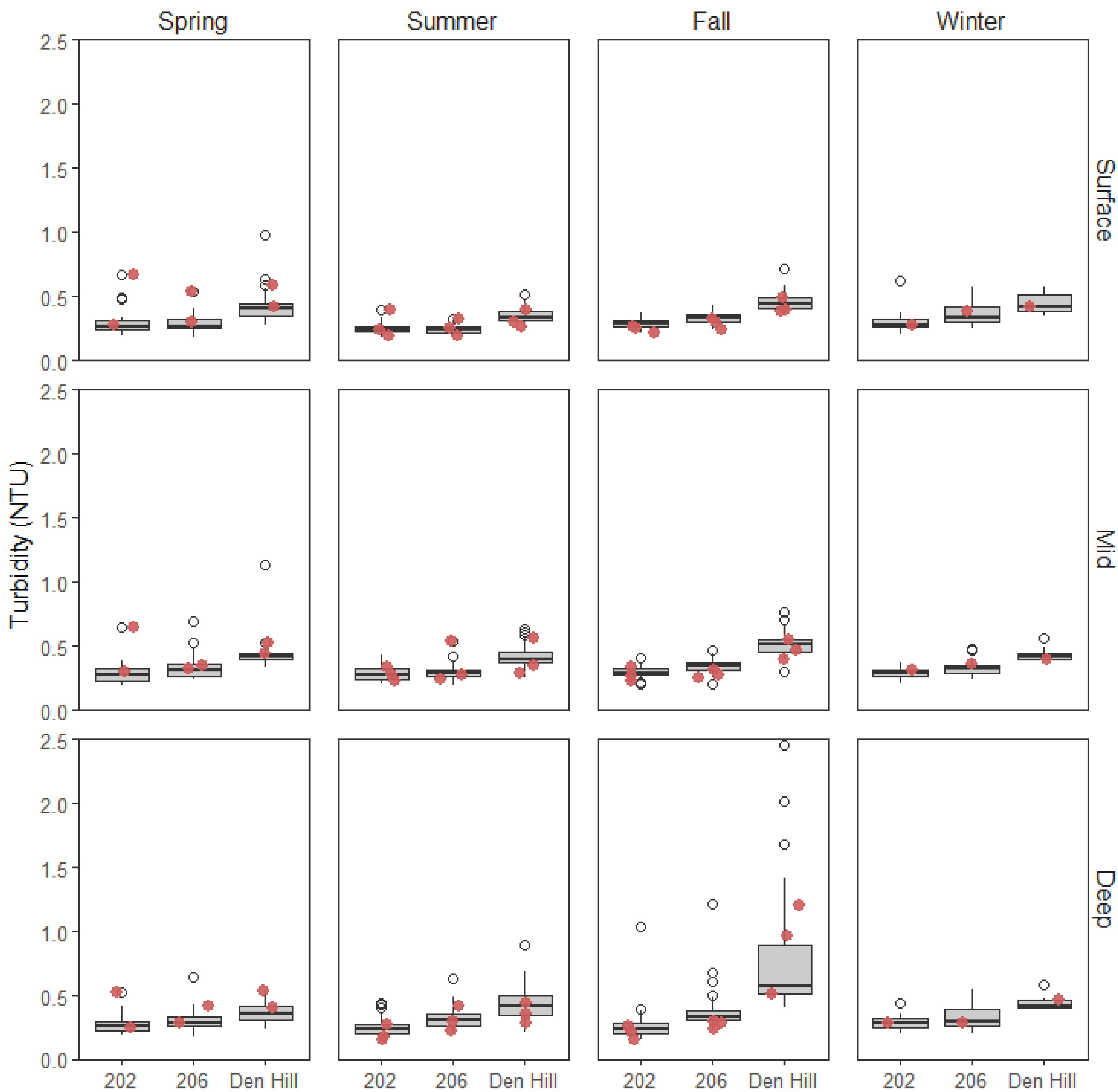


Figure C14. Boxplots depicting the seasonal and vertical distributions of NH_3-N observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected quarterly in 2019 are signified by the red points. The solid black line represents the historic 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.

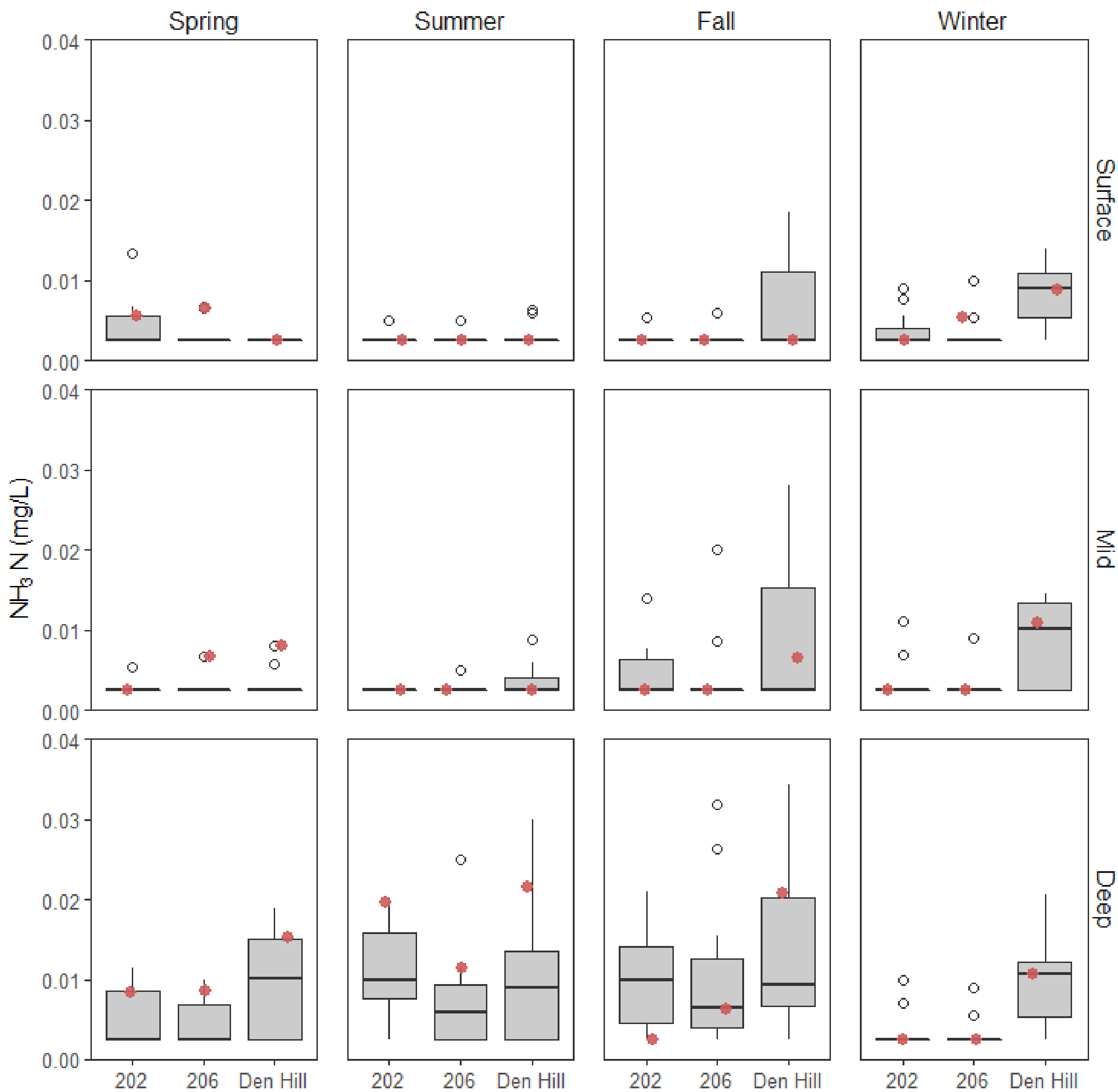


Figure C15. Boxplots depicting the seasonal and vertical distributions of TKN observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected quarterly in 2019 are signified by the red points. The solid black line represents the historic 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.

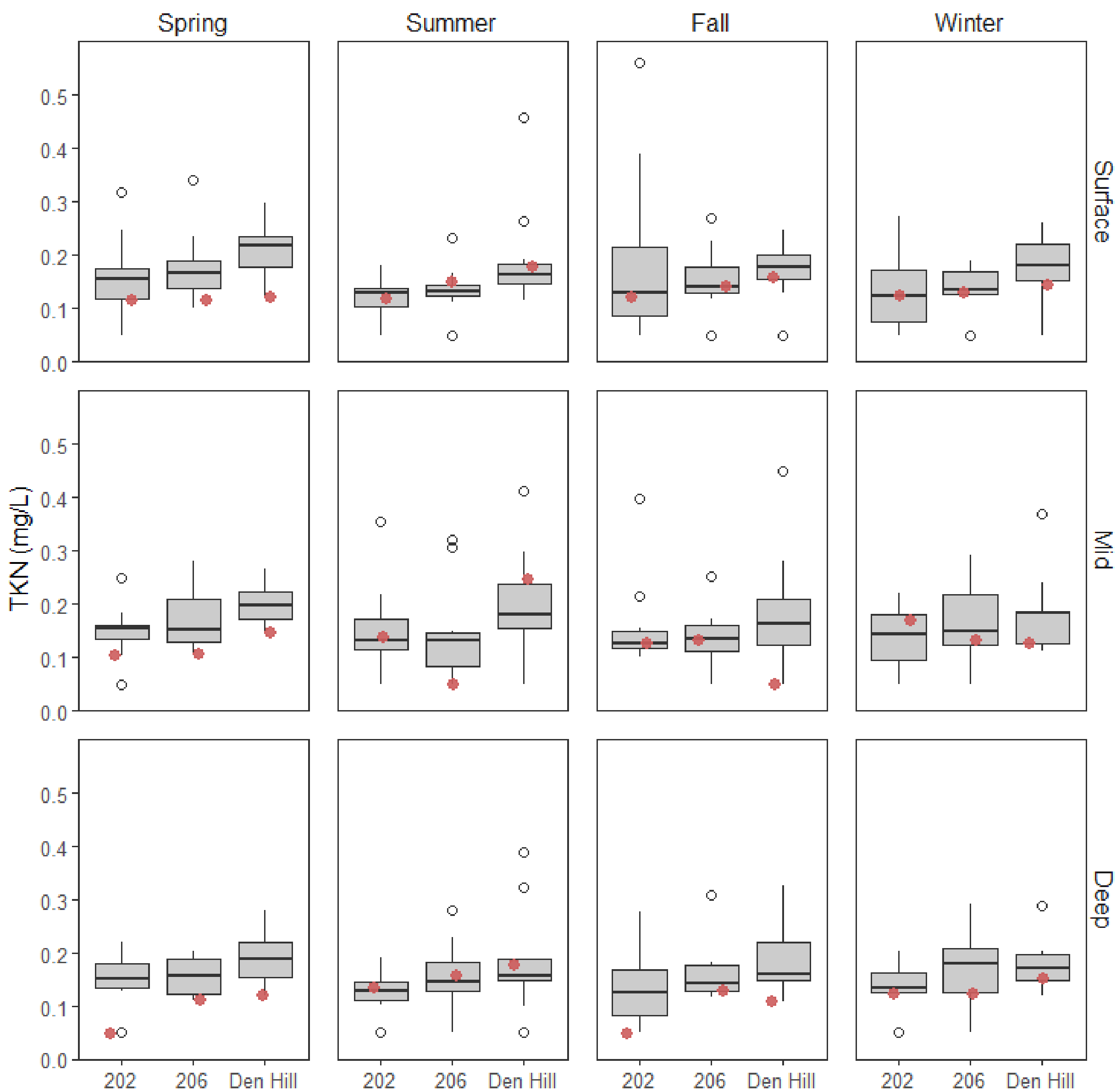


Figure C16. Boxplots depicting the seasonal and vertical distributions of TP observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected quarterly in 2019 are signified by the red points. The solid black line represents the historic 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.

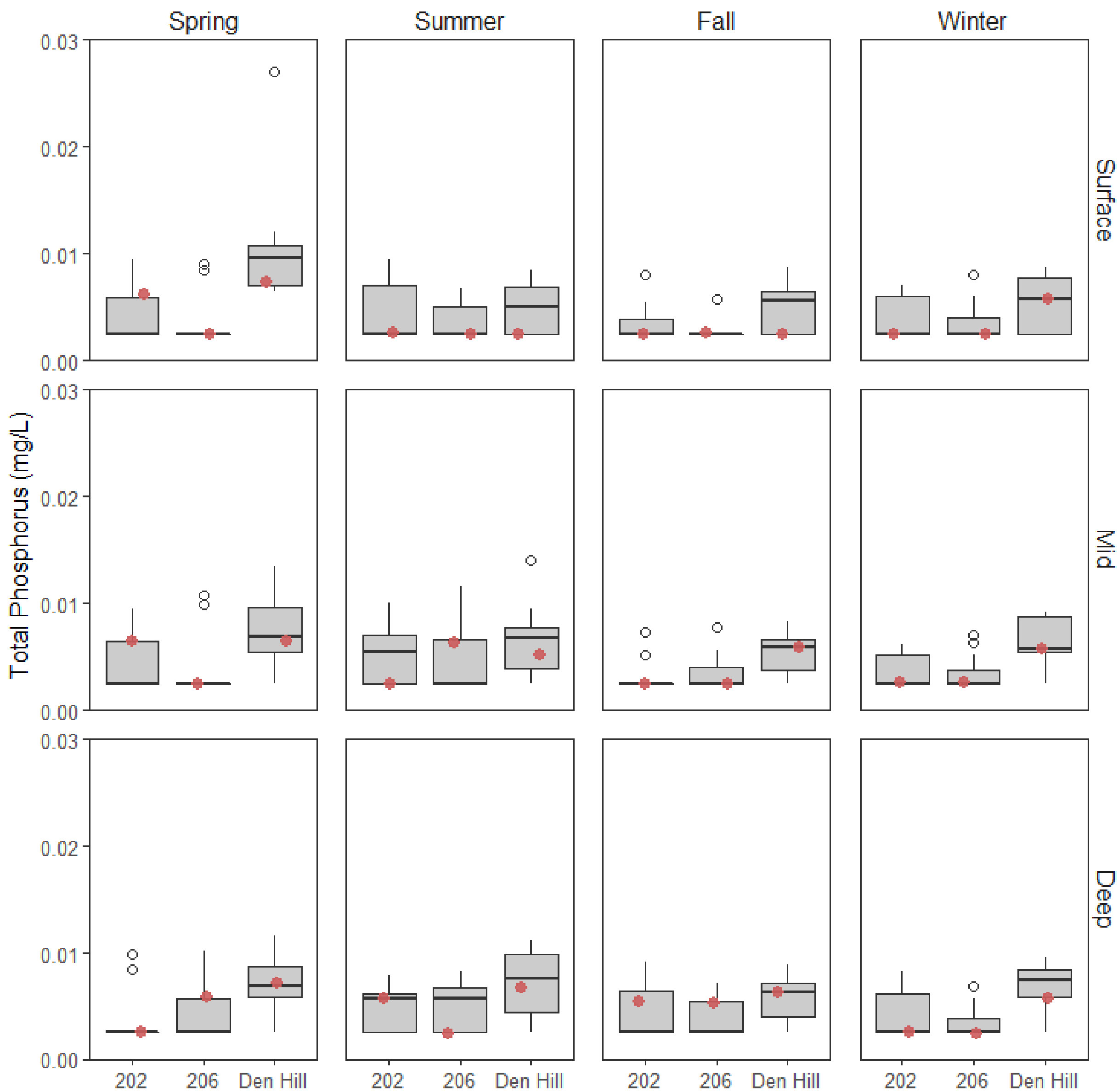


Figure C17. Boxplots depicting the seasonal distributions of Ca observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected quarterly at mid-depth only in 2019 are signified by the red points. The solid black line represents the historic 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.

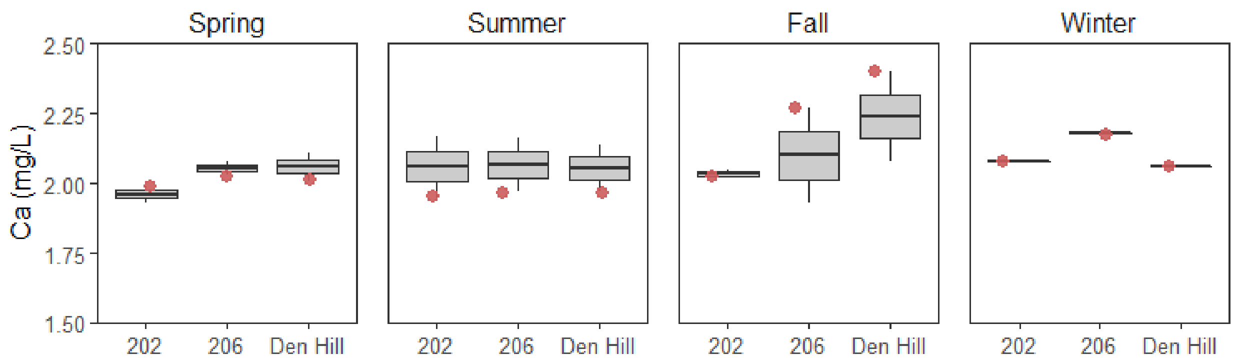


Figure C18. Boxplots depicting the seasonal and vertical distributions of total coliform observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected quarterly in 2019 are signified by the red points. The solid black line represents the historic 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.